Implications of Li divertor and other liquid-metal technologies

D.N. Ruzic and J.P. Allain

Department of Nuclear, Plasma and Radiological Engineering
University of Illinois, Urbana-Champaign

UFA Burning Plasma Science Workshop II
General Atomics, San Diego, CA
May 1-3, 2001

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Outline of Talk

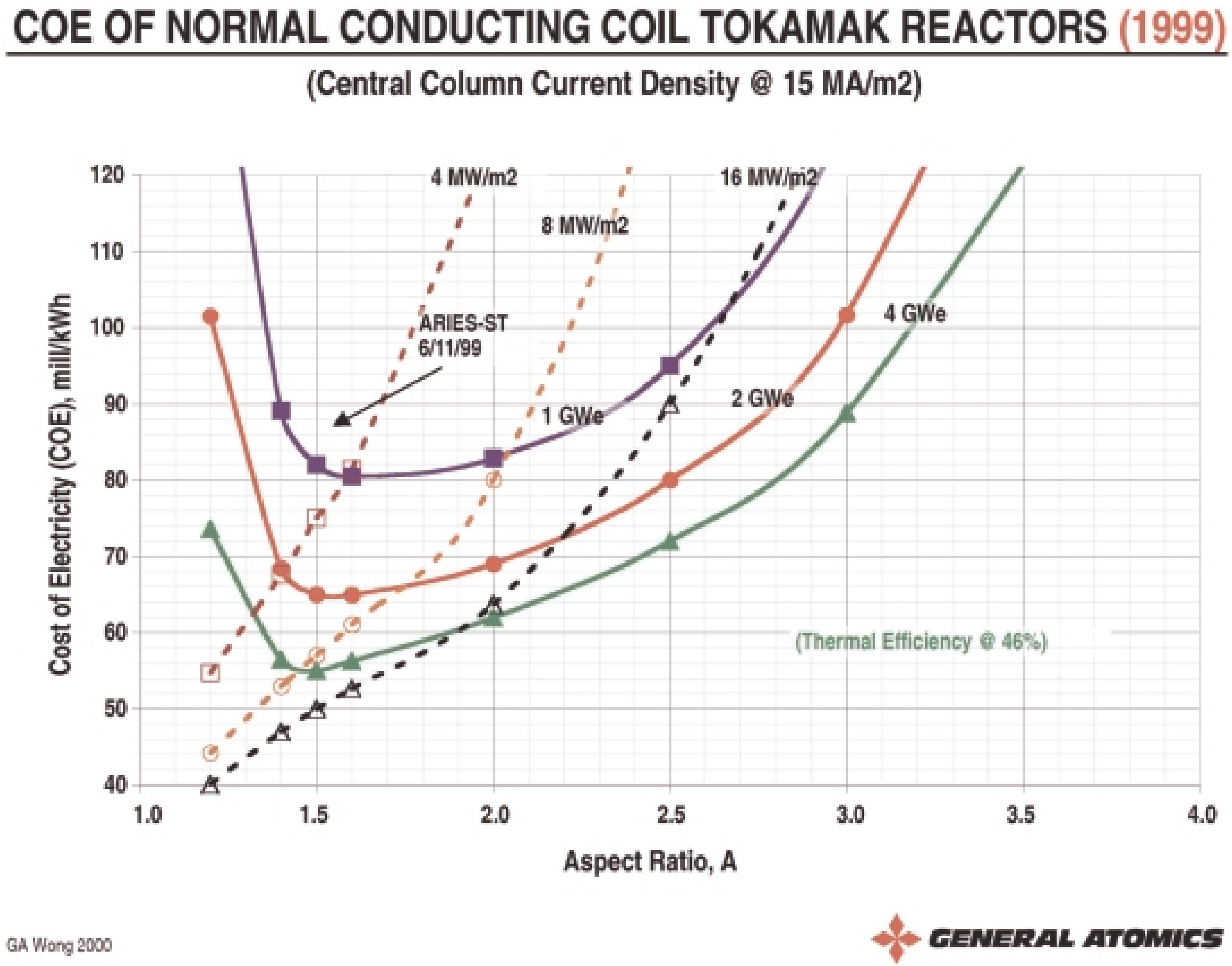
- The walls as the problem
- The walls as the solution
- Current efforts in plasma facing component science and technology
- Enabling technologies for existing/future fusion devices
- Conclusions
- Acknowledgements

Many of fusion's problems involve plasma wall interactions

- Cheaper electricity means higher power density and therefore more power to walls.
- Disruptions (unplanned and planned) severely limit lifetime and therefore desirability.

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

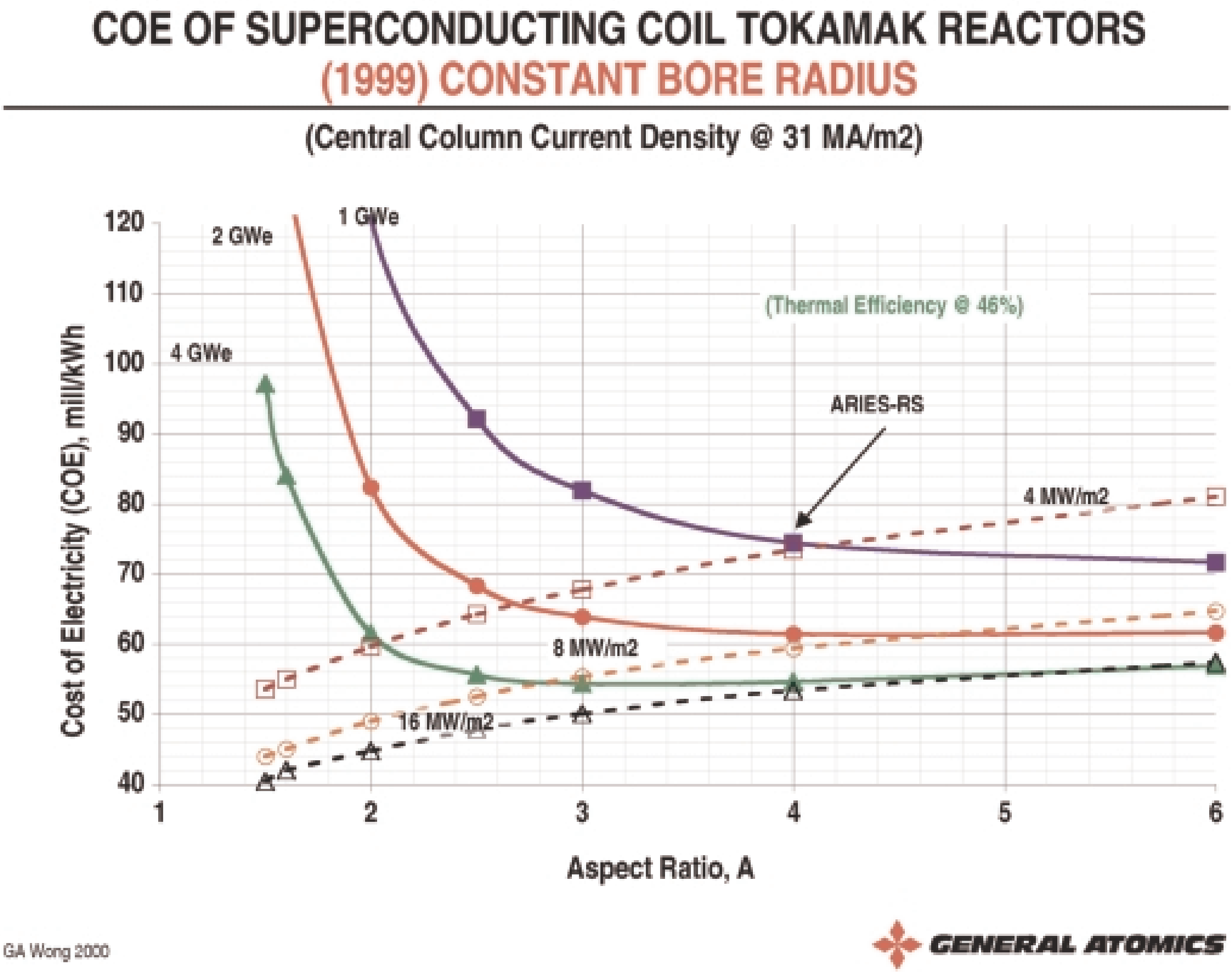
NC ARIES-RS Design Module



C.P.C. Wong, et al. "Toroidal reactor design as a function of aspect ratio"

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

SC ARIES-RS Design Module



C.P.C. Wong, et al. "Toroidal reactor design as a function of aspect ratio"

Lithium on surfaces could solve these problems and have other benefits

- Flowing liquid plasma-facing systems can rapidly remove heat.
- Continuous recovery of damaged surfaces exposed to large heat fluxes due to off-normal events as well as disruptions.
- TFTR Li pellet and DOLLOP experiments
- Possible stabilization of MHD modes by substituting a moving conducting wall for plasma rotation

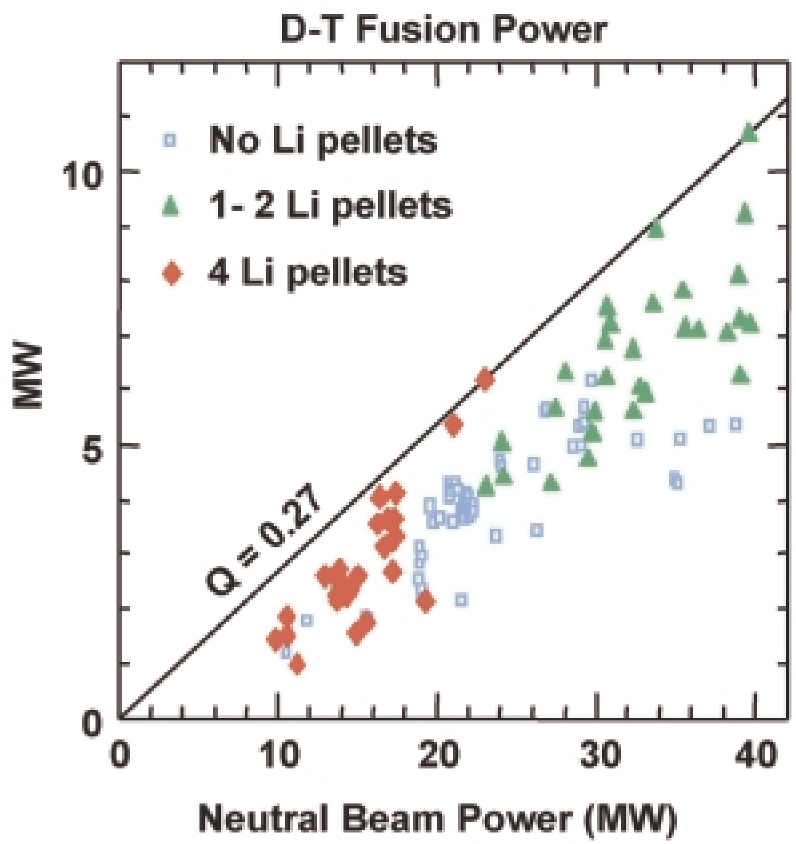
TFTR Results: Li conditioning

Li ⟶ Enhanced D-T Fusion Power

Li conditioning improved overall DT fusion power.

TFTR record fusion power shot was designed using precise Li conditioning.

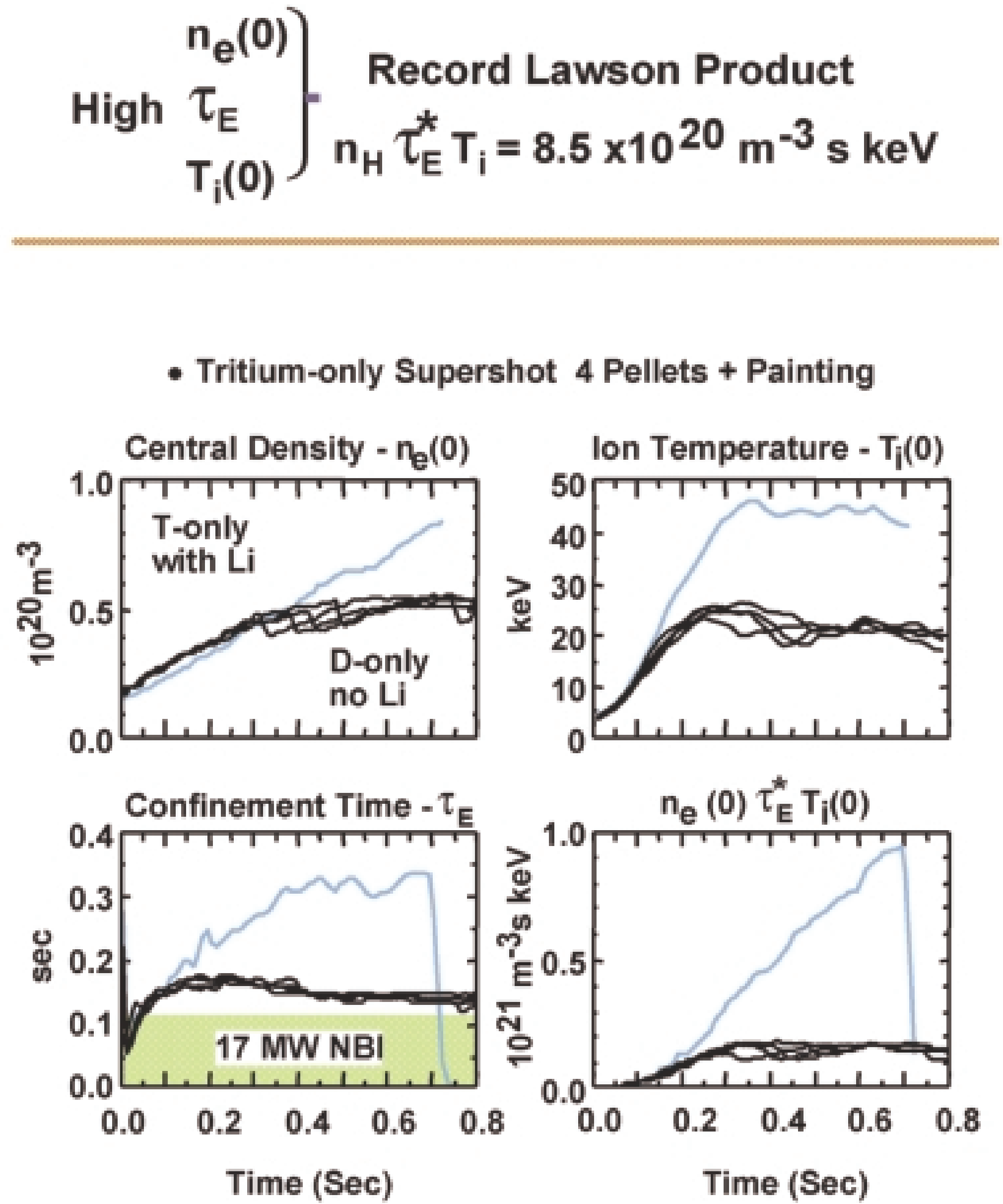
Use of less Li at higher power was because of MHD high-beta disruption limits in TFTR.



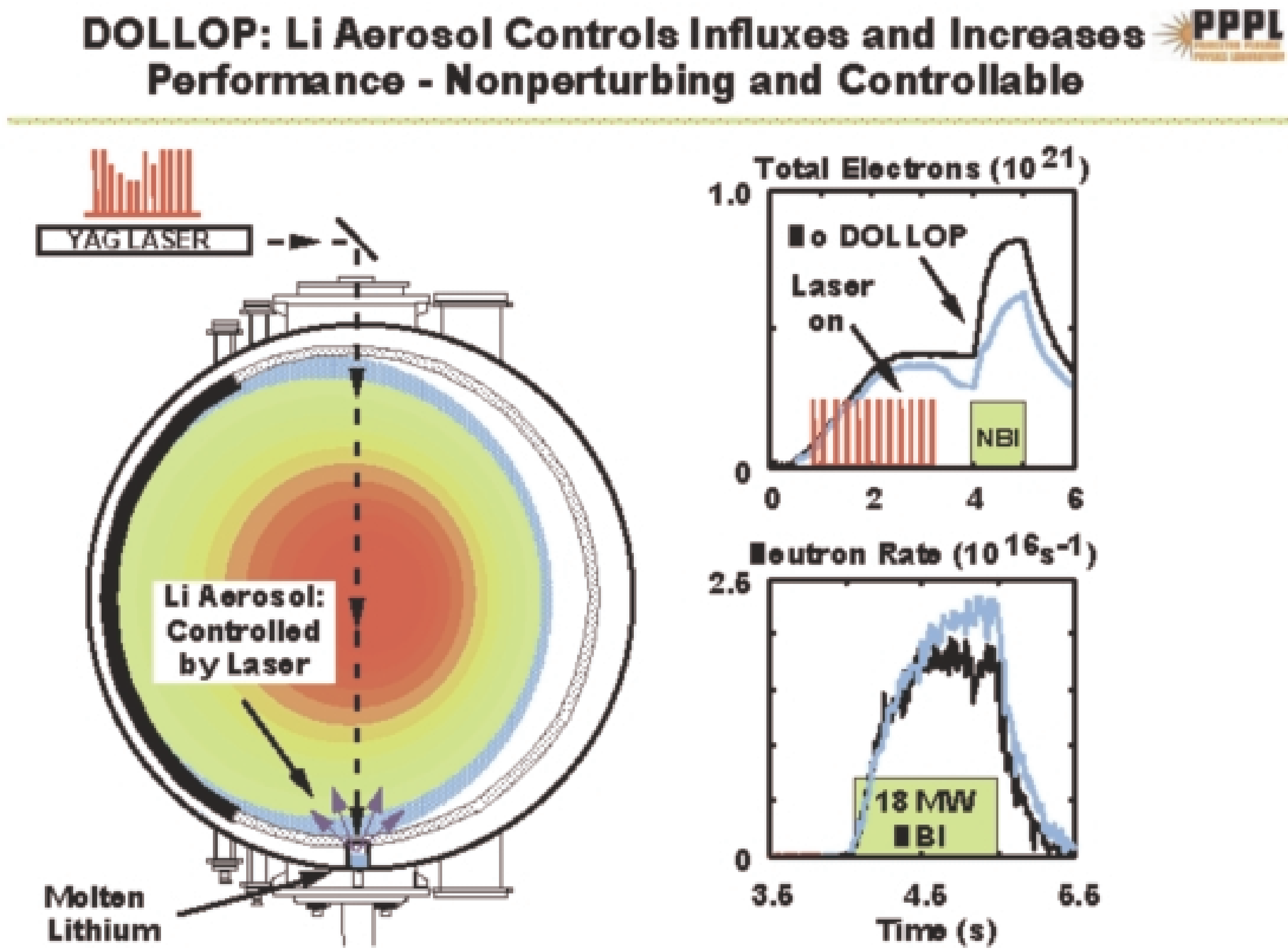
- D-T Discharges, $R_p = 2.52$ m, $I_p > 2.0$ MA

Li conditioning effect on $n\tau_e T$

All 3 factors of the fusion triple product were enhanced by Li conditioning (involving only few milligrams of Li)



TFTR Results



D.K. Mansfield, PPPL, ALPS/APEX Albuquerque, NM 2000

TFTR DOLLOP Results

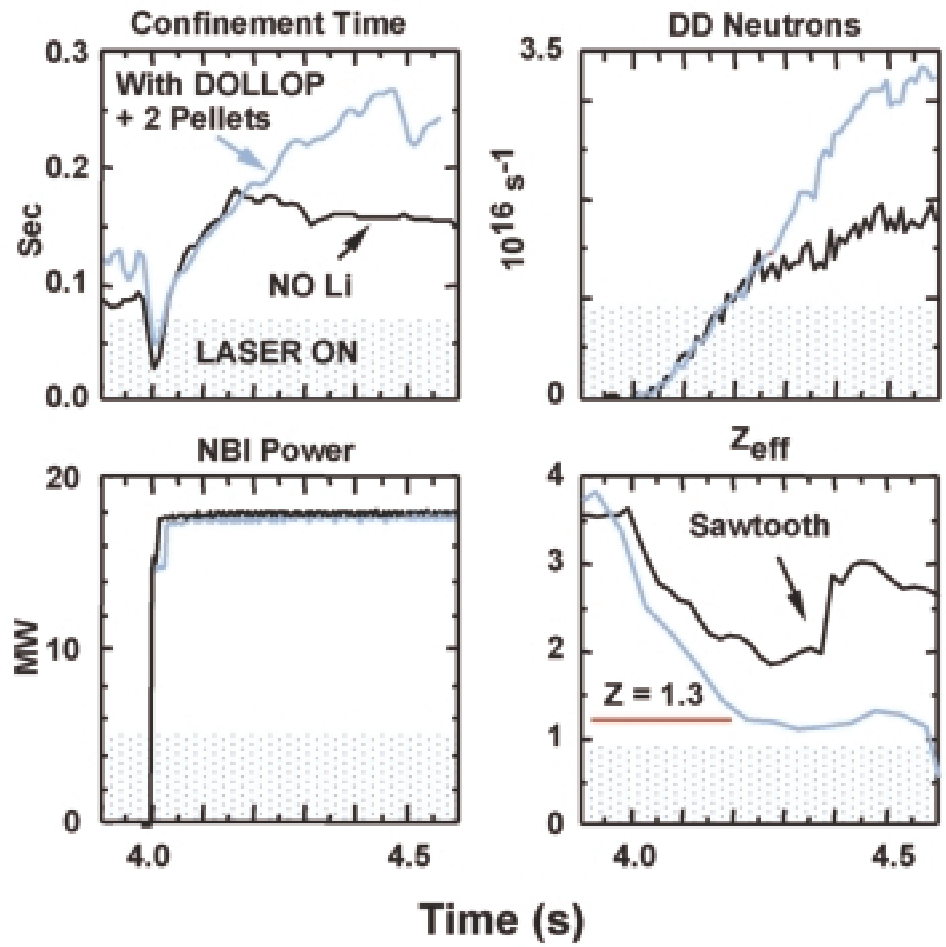
DOLLOP Has Led to Enhanced and Sustained Performance with No Harmful Effects

Three TFTR records were achieved (with NO optimization of DOLLOP)

Highest DD energy confinement (no rollover);

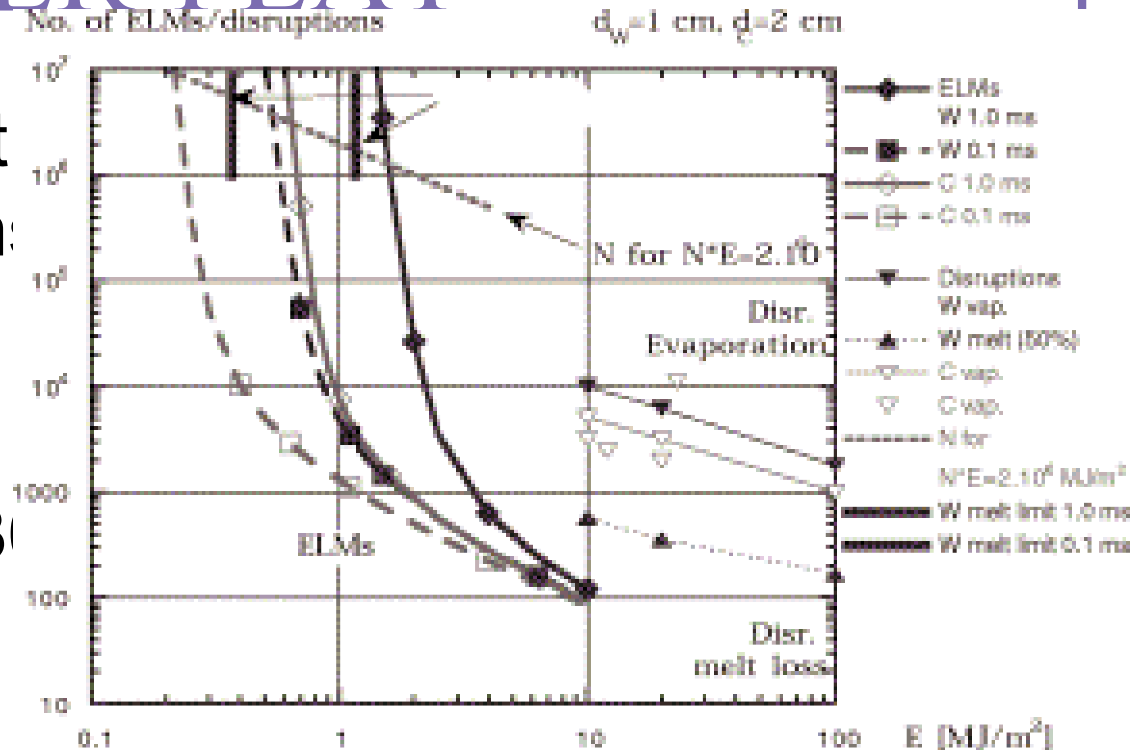
Highest Q DD;

Lowest Zeff.



Disruptions set severe limits on ITER-FEAT

- VDE (vertical displacement event 60 MJ/m2 for 300m on first wall
- Thermal quench 3 MJ/m^2 in 1 ms on divertor



G. Federici, et al. J. Nucl. Mater. 290-293 (2001) 260.

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

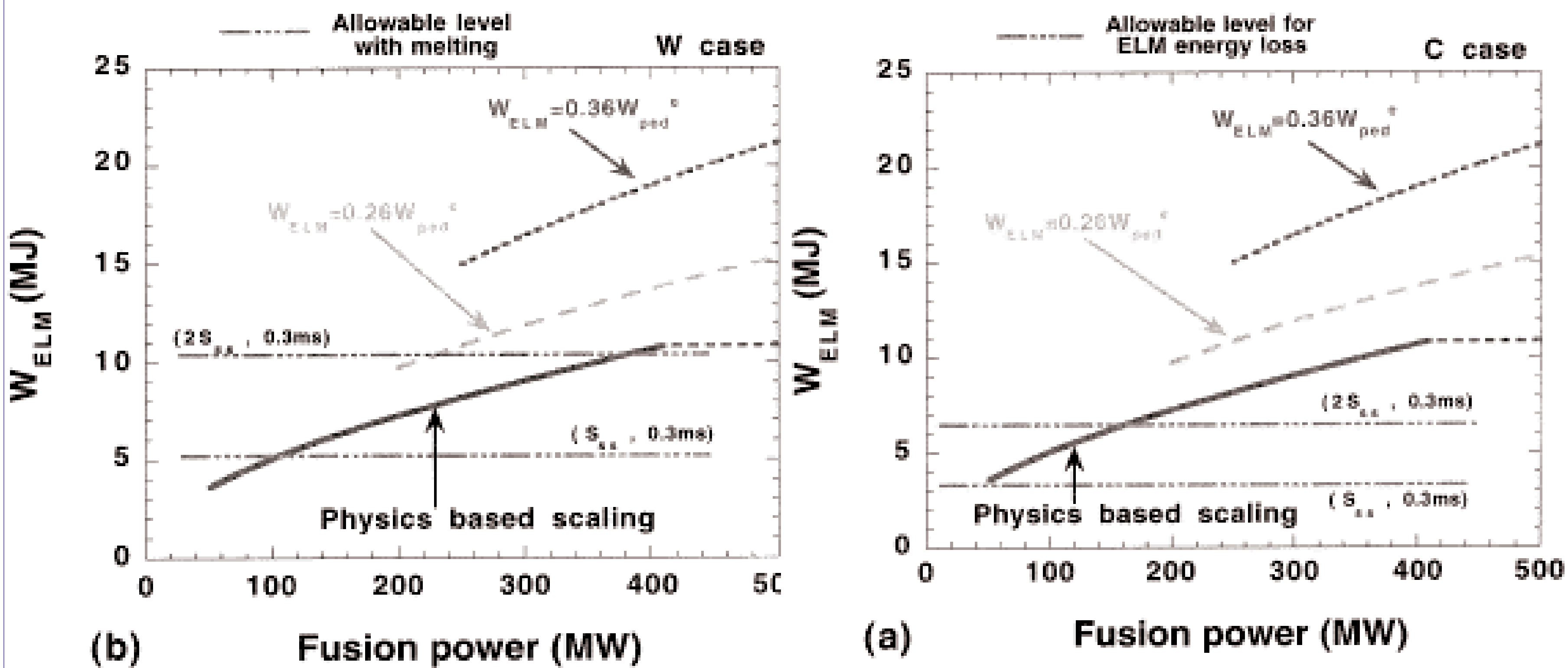
Net erosion of ITER divertor

	Case	Peak net erosion rate (cm/burn-yr)	Tritium codeposition rate[a] (g T/1000 s pulse)
1.	Reference[b]	49	14
2.	No fast-molecule chemical sputtering	49	13
3.	Y_{mol}=0.01	49	24
4.	No chemical sputtering (physical sputtering only)	9	2
5.	Carbon erosion reduced due to beryllium (from wall) mixing	47	11
6.	Beryllium divertor coating[c]	30	2
7.	Tungsten divertor coating	<0.1	~0
8.	'Shallow detached' plasma [13]	23	17

[a]Total (inner + outer divertor) resulting from vertical target sputtering.
[b]Reference: carbon coating, Case 98-semi-detached plasma, physical and chemical sputtering, non-thermal D–T molecule sputtering yield Y_{mol} = 0.001.
[c]With TPE H/Be trapping ratio data [9].

J. Brooks, D. Alman, G. Federici, D.N. Ruzic and D.G. Whyte
J. Nucl. Mater. 266-269 (1999) 58.

ELMs set power limit even for W



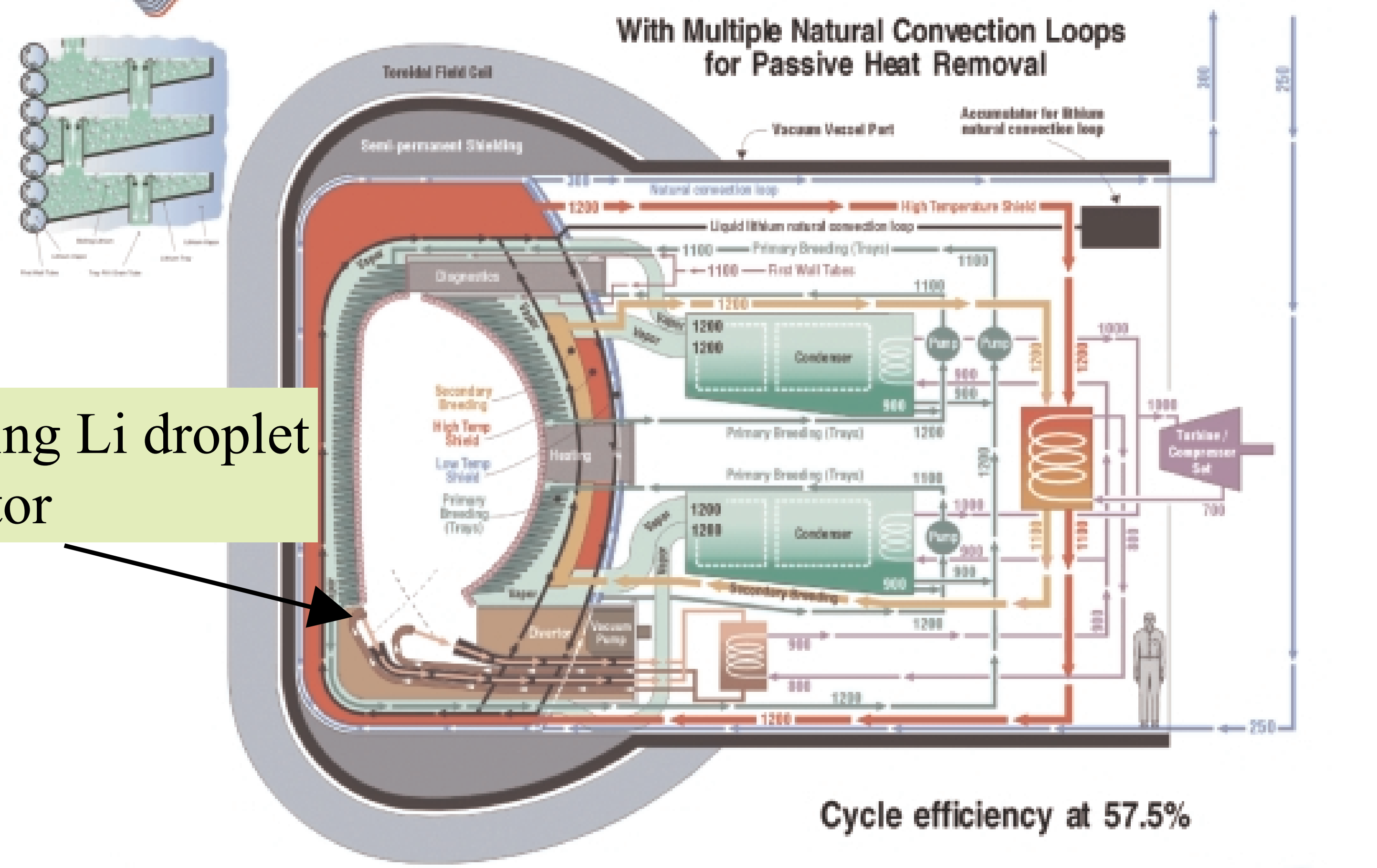
G. Janeschitz, et al., J. Nucl. Mater. 290-293 (2001) 1-11

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Plasma Facing Component Science and Technology Program

- Integrated concepts
- Lab-scale investigations
- Modeling efforts
- Near-term experiments

EVOLVE FLOW/TEMPERATURE SCHEMATIC

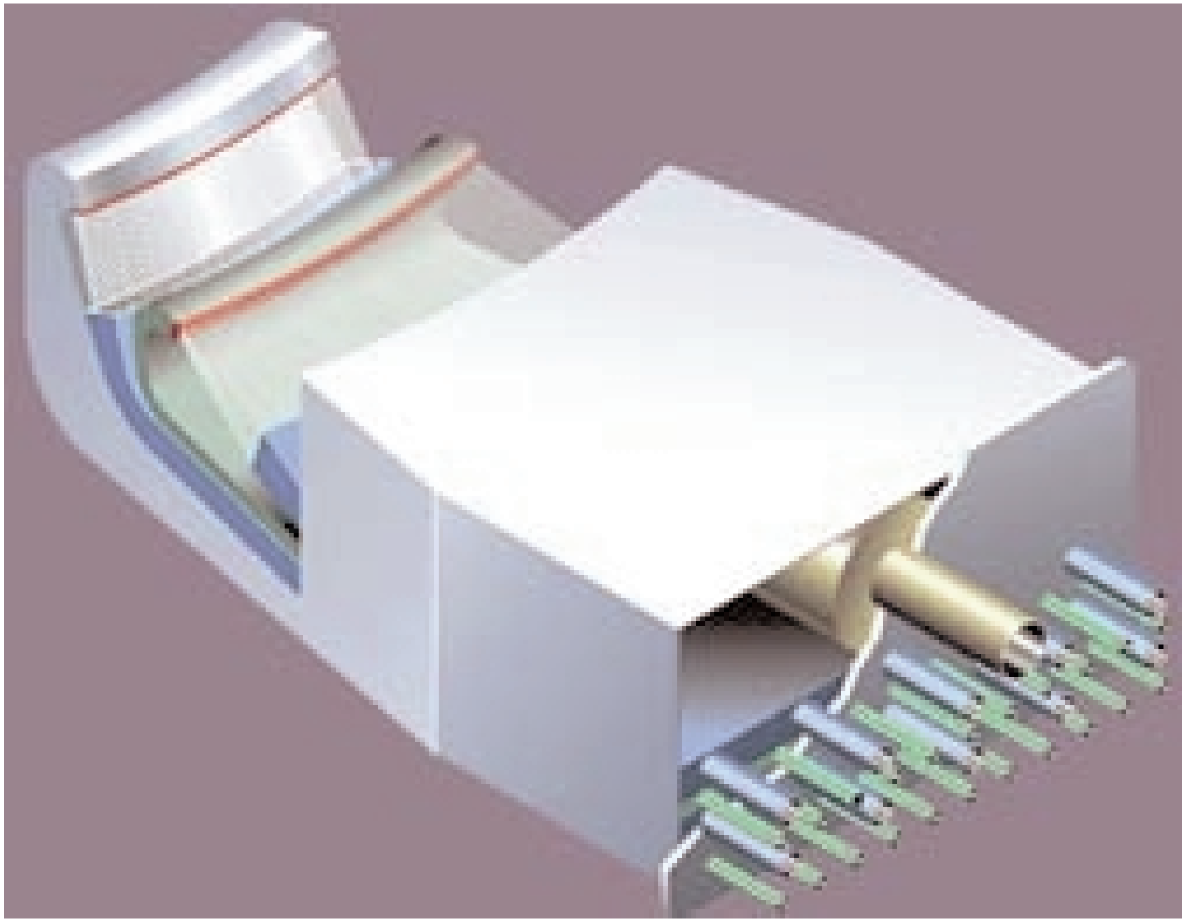


Flowing Li droplet divertor

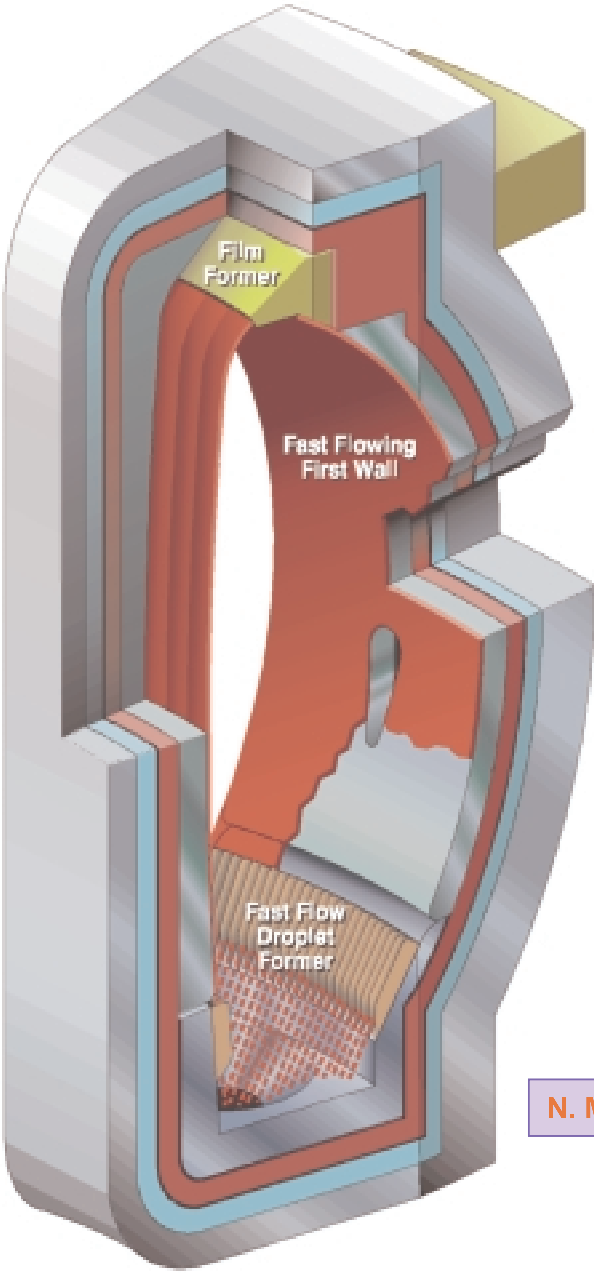
C.P.C. Wong, et al. "Exploration of Innovative Advanced Solid Wall Concepts" presented at: U.S. Fusion Chamber Technology Peer Review, UCLA, April 26, 2001

MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Flowing lithium droplet divertor cassette



R.F. Mattas, "ALPS – advanced limiter-divertor plasma-facing systems""
Fusion Engineering and Design 49-50 (2000) 127-134



CLiFF

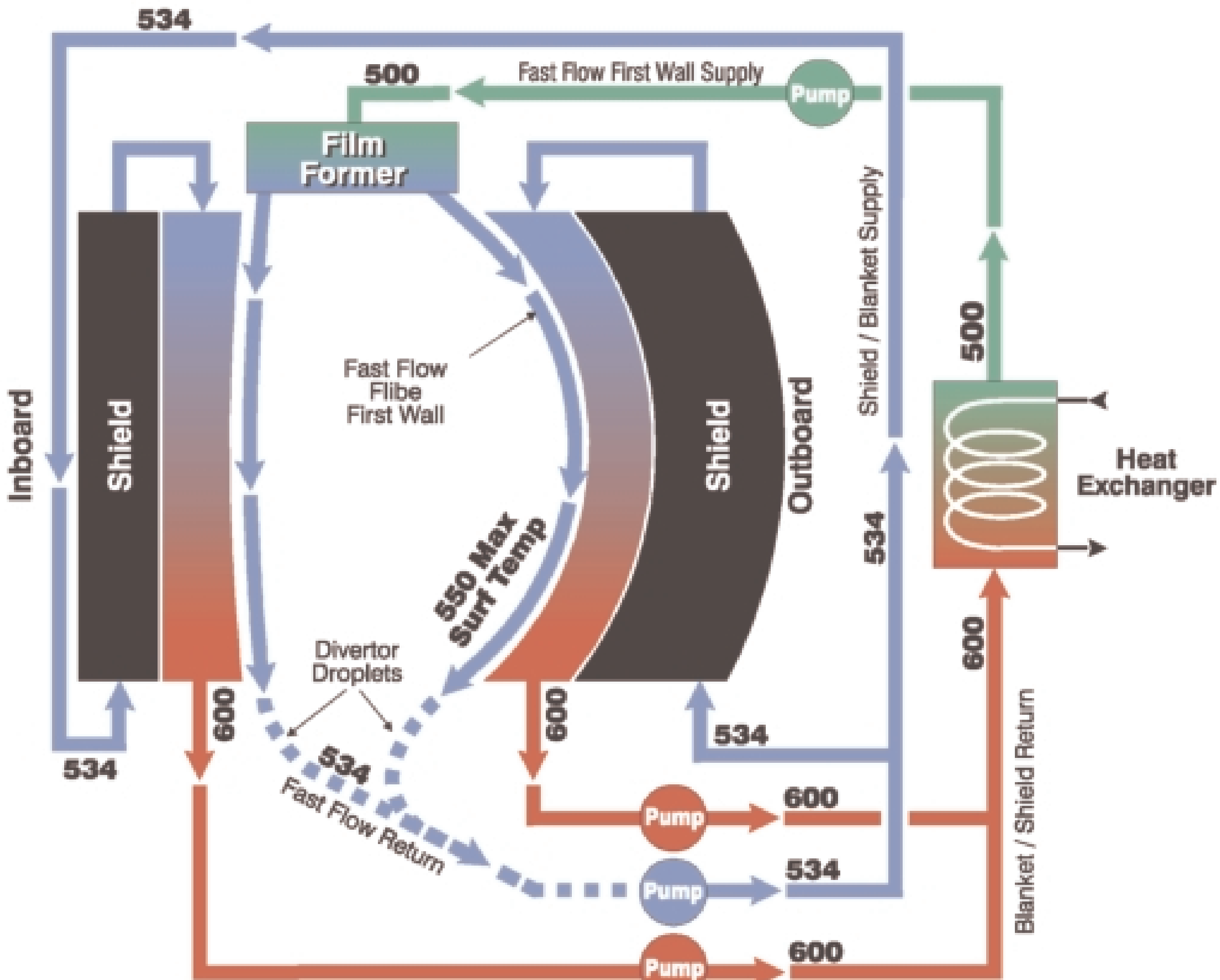
(Convective Liquid Flow First-Wall)

Conceptual sector schematic of CLiFF implementation in ARIES-RS reactor

N. Morley, et al. APEX Interim Report, UCLA-ENG-99-206, Nov 1999

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

CLiFF – Flow/Temperature Schematic

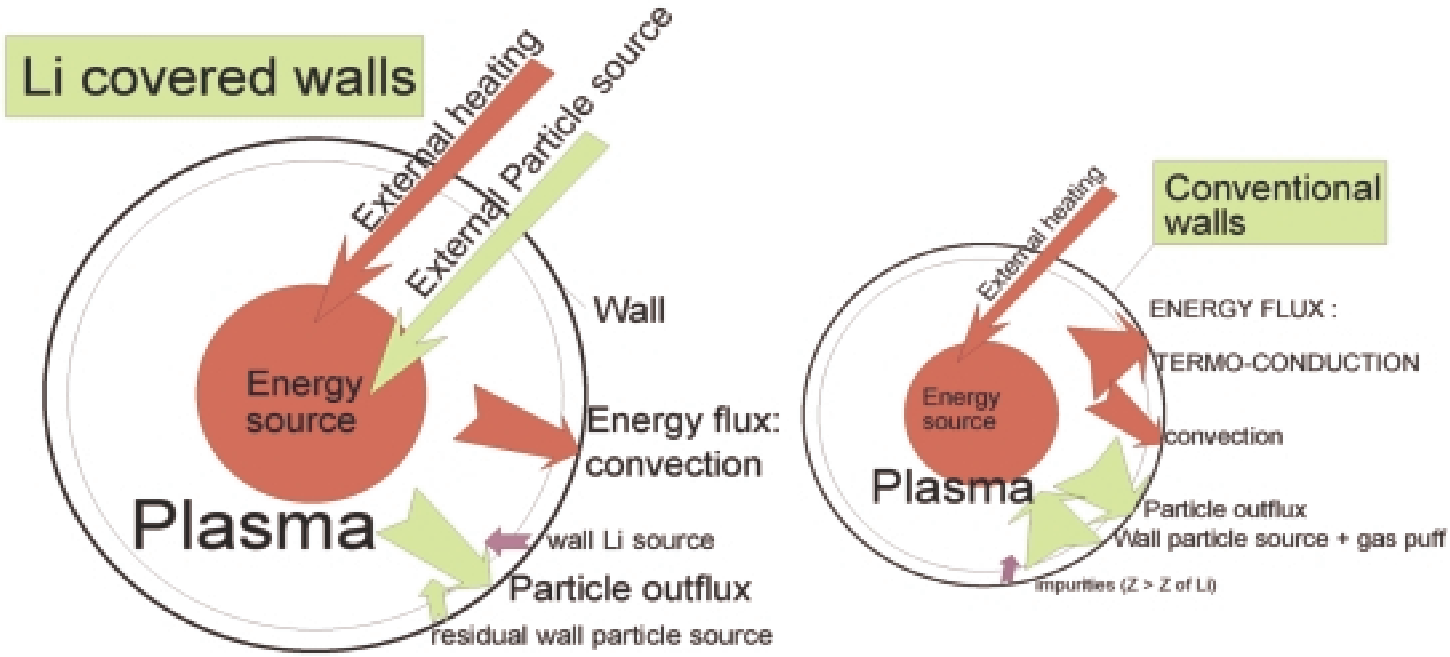


N. Morley, et al. APEX Interim Report, UCLA-ENG-99-206, Nov 1999

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

LiWalls and plasma energy confinement

Li is an excellent getter for the hydrogen plasma particles.



Lithium can be propelled along the walls
for power and particle extraction.

Leonid E. Zakharov, PPPL Theory seminar, PU, Jan.18, 2001, Princeton NJ

Improved energy confinement is extremely for igniting the plasma

$$n_{DT} \cdot T_{DT} \cdot \tau_E > 5 \times 10^{21}\, m^{-3} \cdot keV \cdot s, \quad n_{DT} \cdot T_{DT} \cdot \tau_E \propto \tau_E^2$$

Plasma profiles are determined by the particle continuity equation

$$\Gamma \equiv Snv = const = (\Gamma)_a$$

and by the energy balance

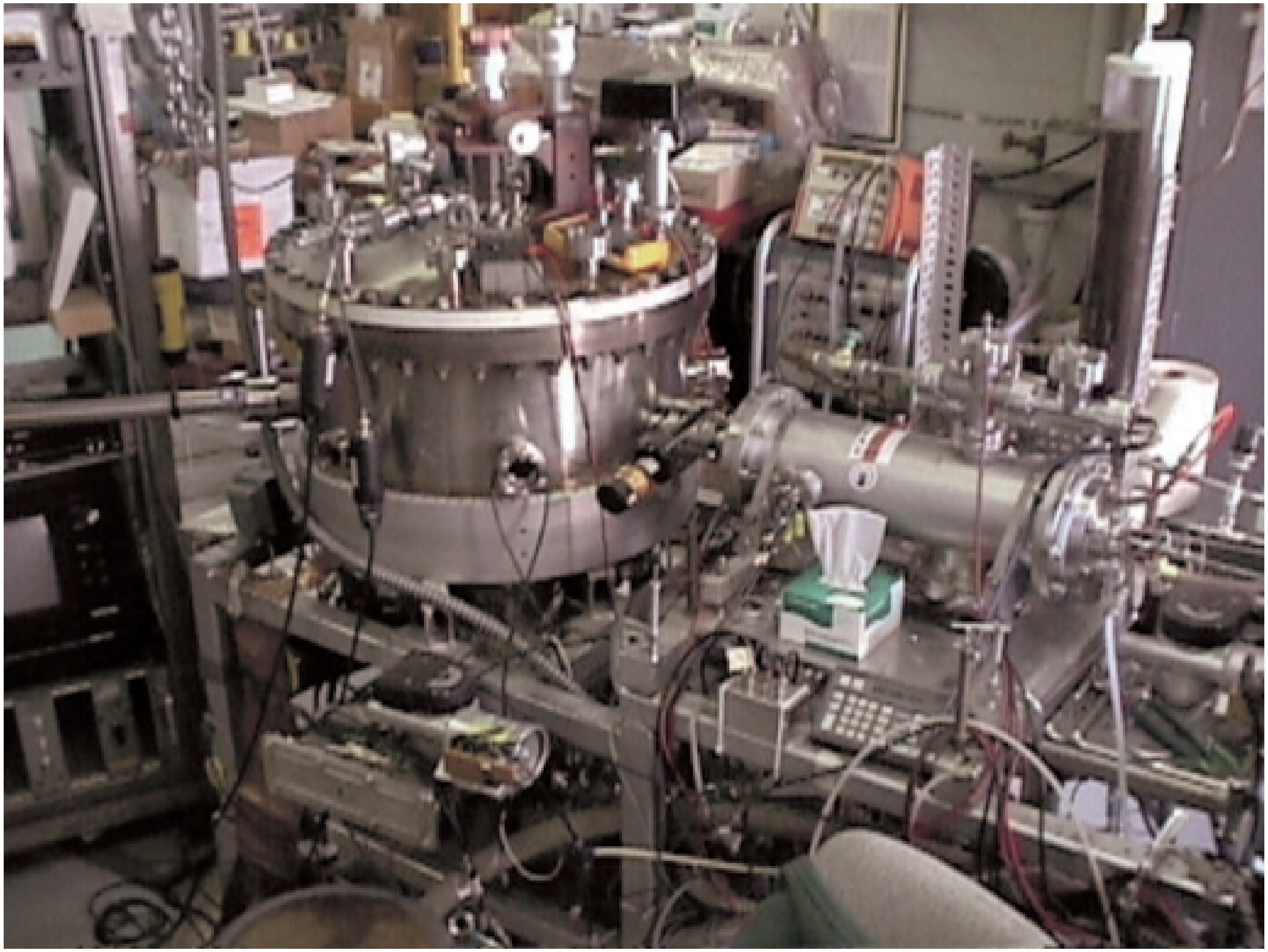
$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P_E dv$$

With perfectly absorbing walls plasma does not know the temperature of the (cold) walls and leaves no room for thermo-conduction

$$\left(\frac{5}{2}\Gamma T\right)_{edge} = \int_0^a P_E dv, \quad T_{edge} = \frac{\int_0^a P_E dv}{\frac{5}{2}\Gamma}$$ $P_E -$ heat source.

Thus, the major energy loss channel, i.e., thermo-conduction, can be eliminated with this absorbing wall boundary condition (S. Krasheninnikov, PFSC at MIT, now at UCSD).

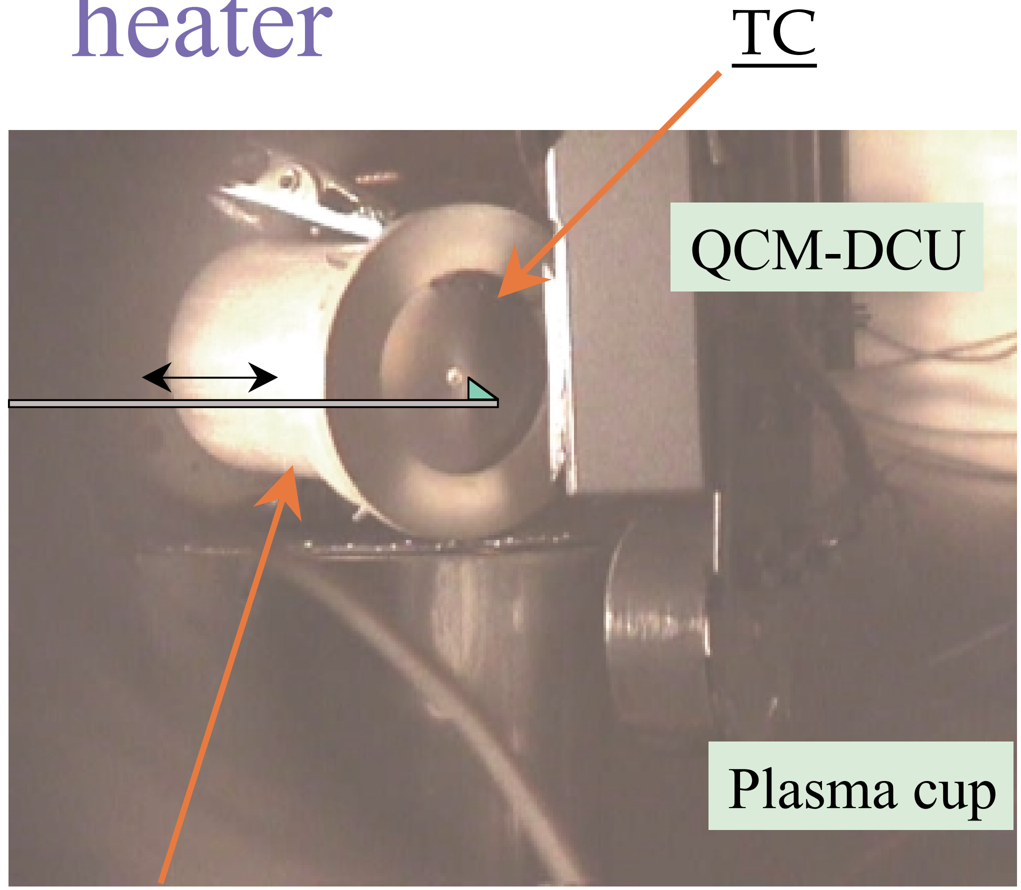
IIAX (Ion-surface InterAction eXperiment)



PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

In-situ cleaving arm design and HV heater

- Cleaving arm is designed to remove thin oxide layer formed on Li layer of liquid tin-lithium or liquid lithium sample
- Surface composition experiments show that Li segregates to the liquid Sn-Li surface[1]

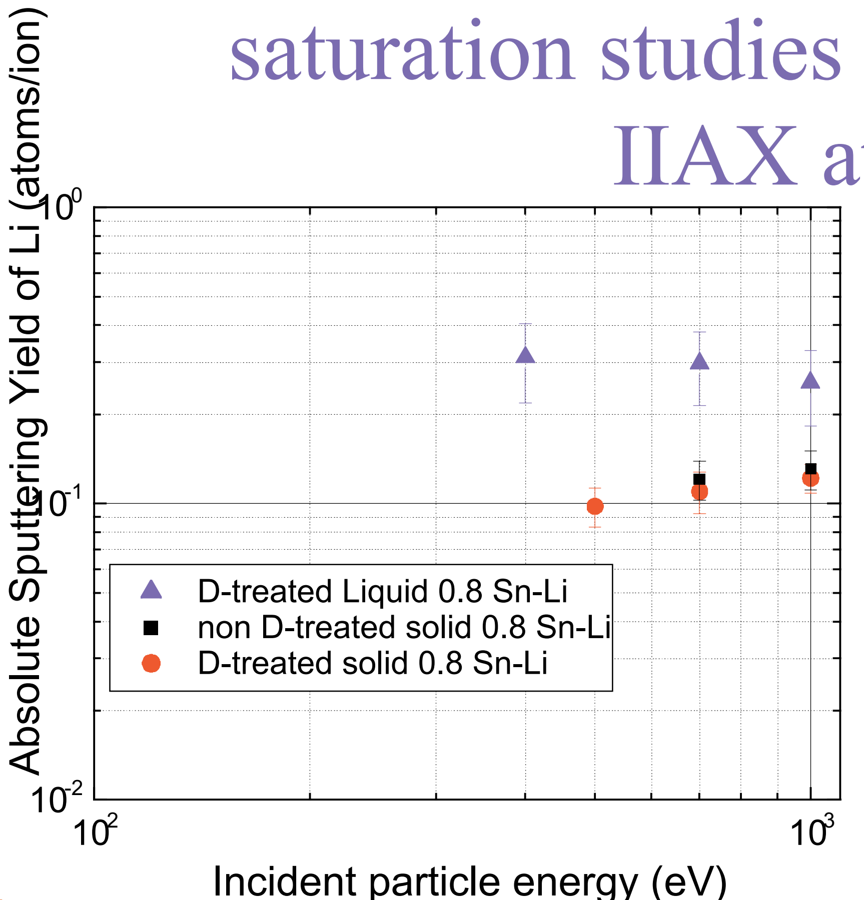


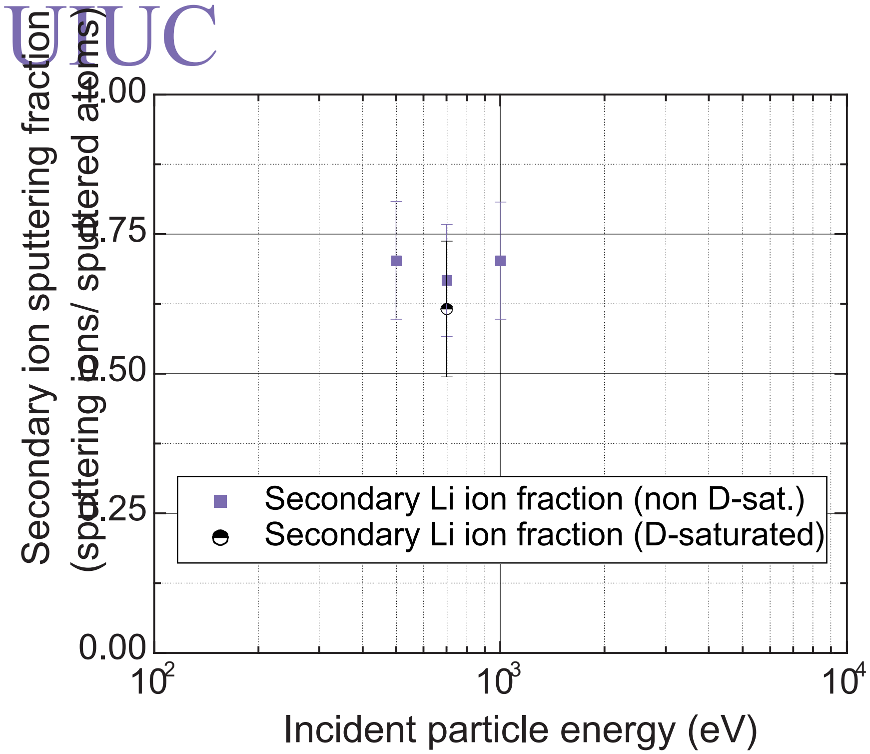
A HV heater was installed inside a BN cup.

1. B. Bastasz J. Nuclear Mater. 290-293 (2001) 19.

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Secondary ion fraction and deuterium-saturation studies of liquid metals in IIAX at UIUC



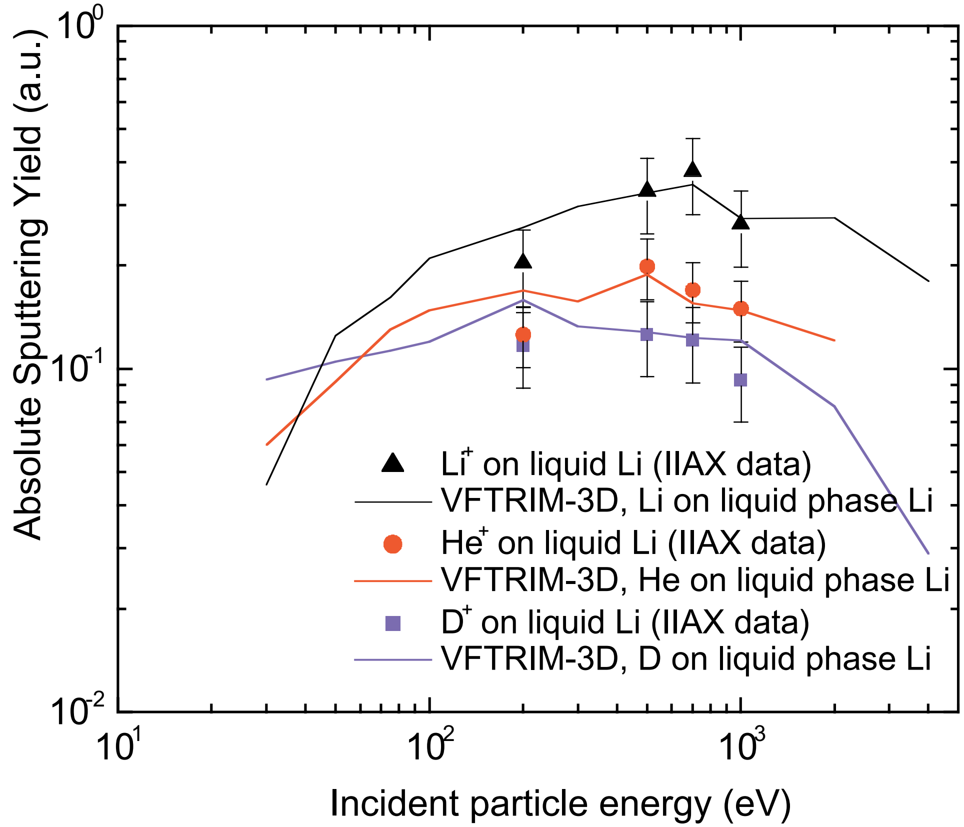


- Saturation of solid and liquid (T/Tm ~ 1) tin-lithium with D atoms results in no effect on the absolute sputtering yield of lithium.
- Ion fraction measurements show that 55-65% of sputtered atoms from D-saturated solid and liquid lithium are in an ionized state.

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

IIAX experimental and modeling data on liquid lithium erosion

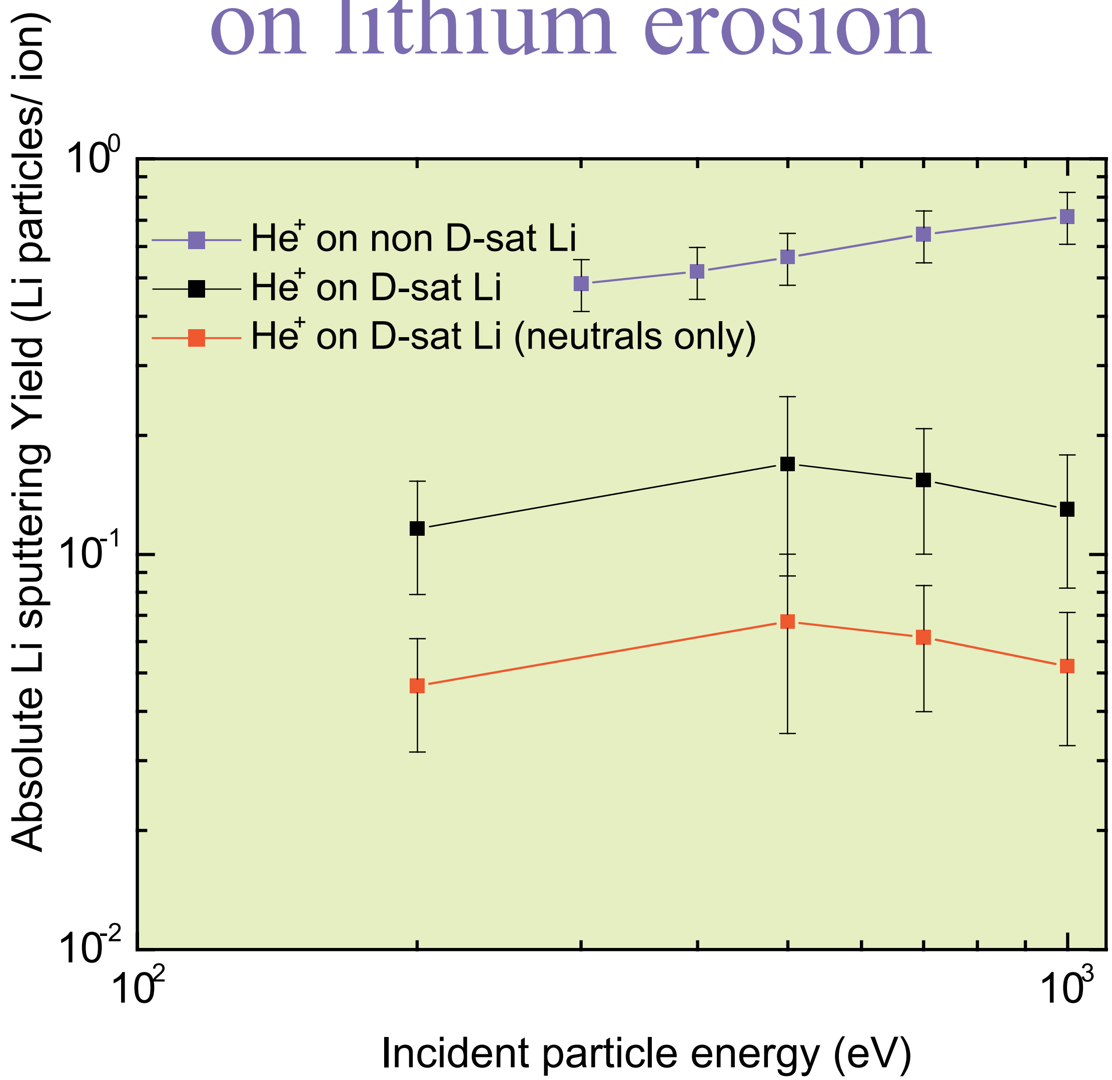
- D treated lithium yields are well below unity
- Data taken at 45 deg. Incidence and 200 C surface temperature



J.P. Allain, M.R. Hendricks and D.N. Ruzic, J. Nucl. Mater. 290-293 (2001) 180

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

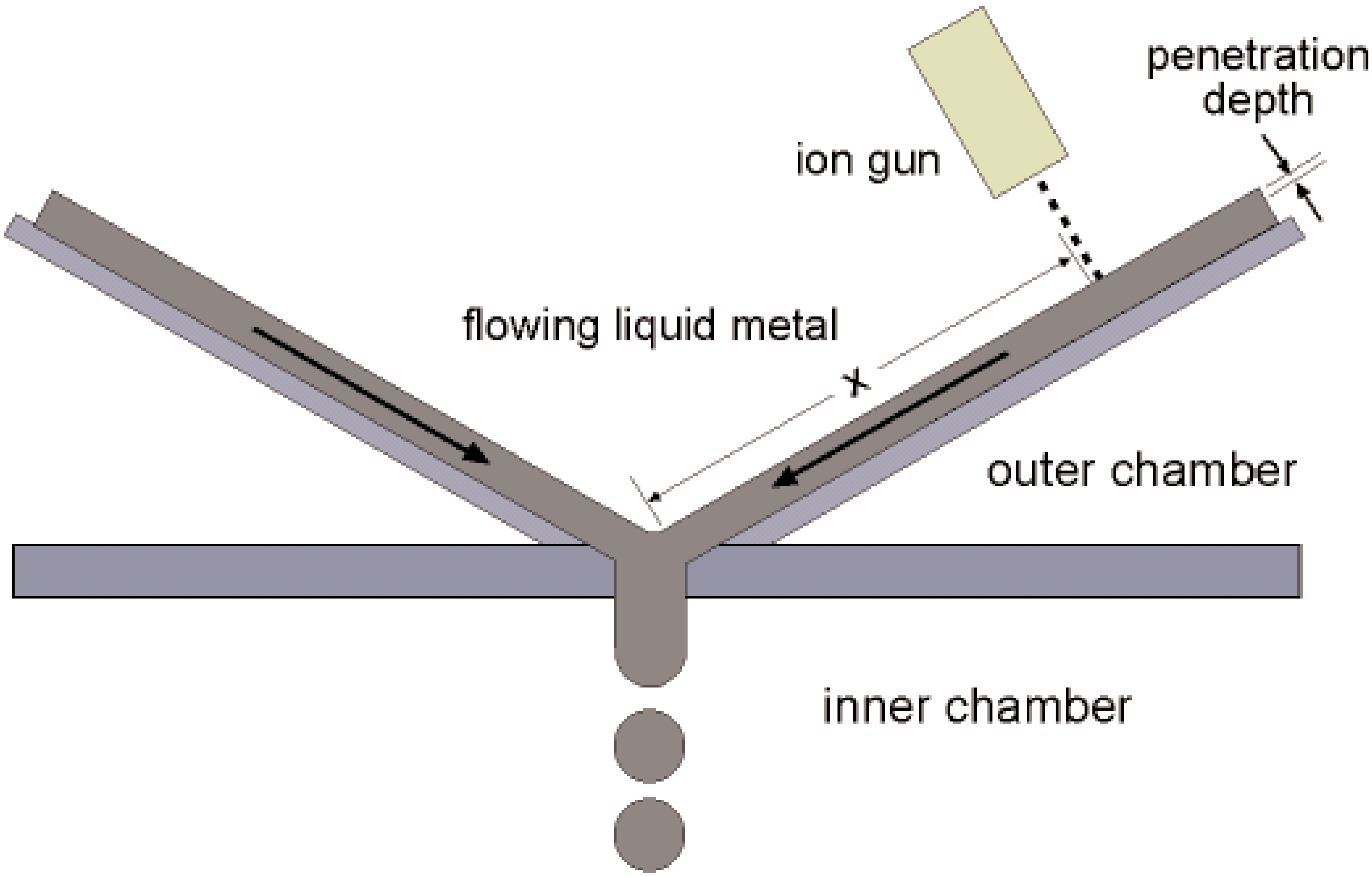
Effect of deuterium surface treatment on lithium erosion



J.P. Allain and D.N. Ruzic, Nucl Fusion, submitted 2000

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

FLIRE concept



PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

FLIRE (Flowing Liquid Surface Illinois Retention Experiment)

- FLIRE will provide fundamental data on the retention and pumping of He, H, and other gases in flowing liquid surfaces.

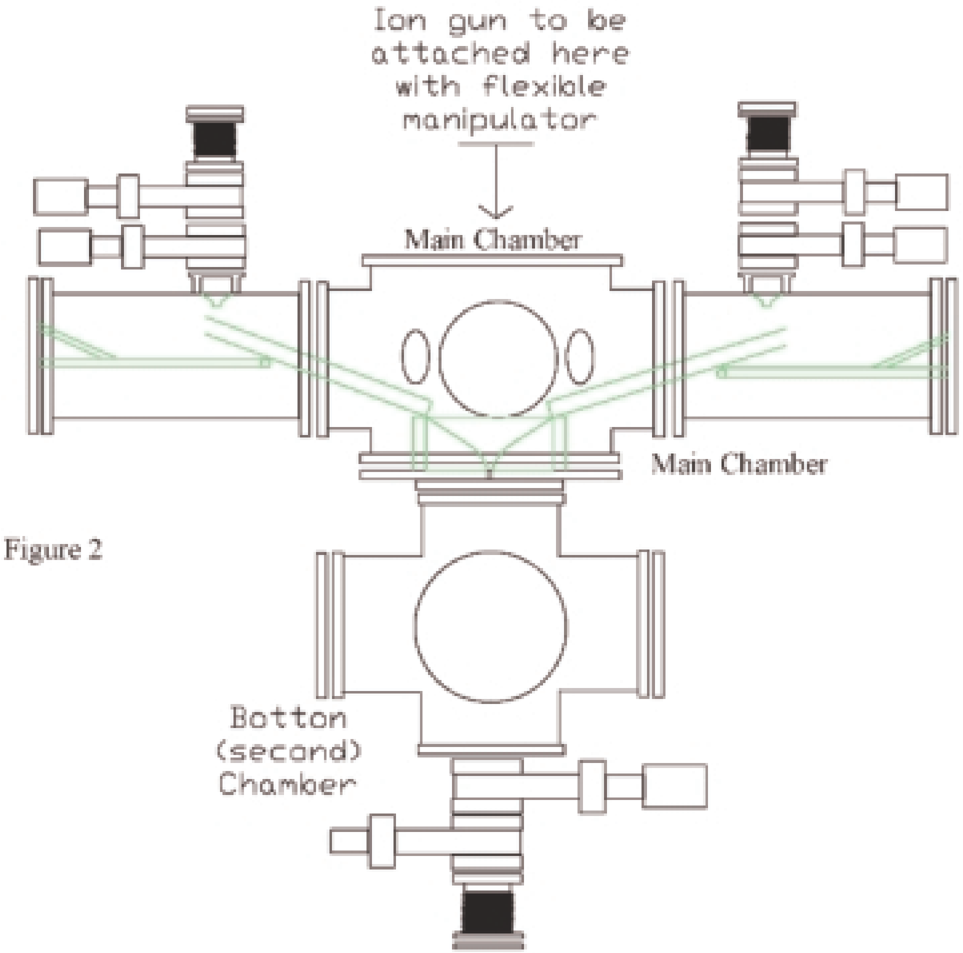
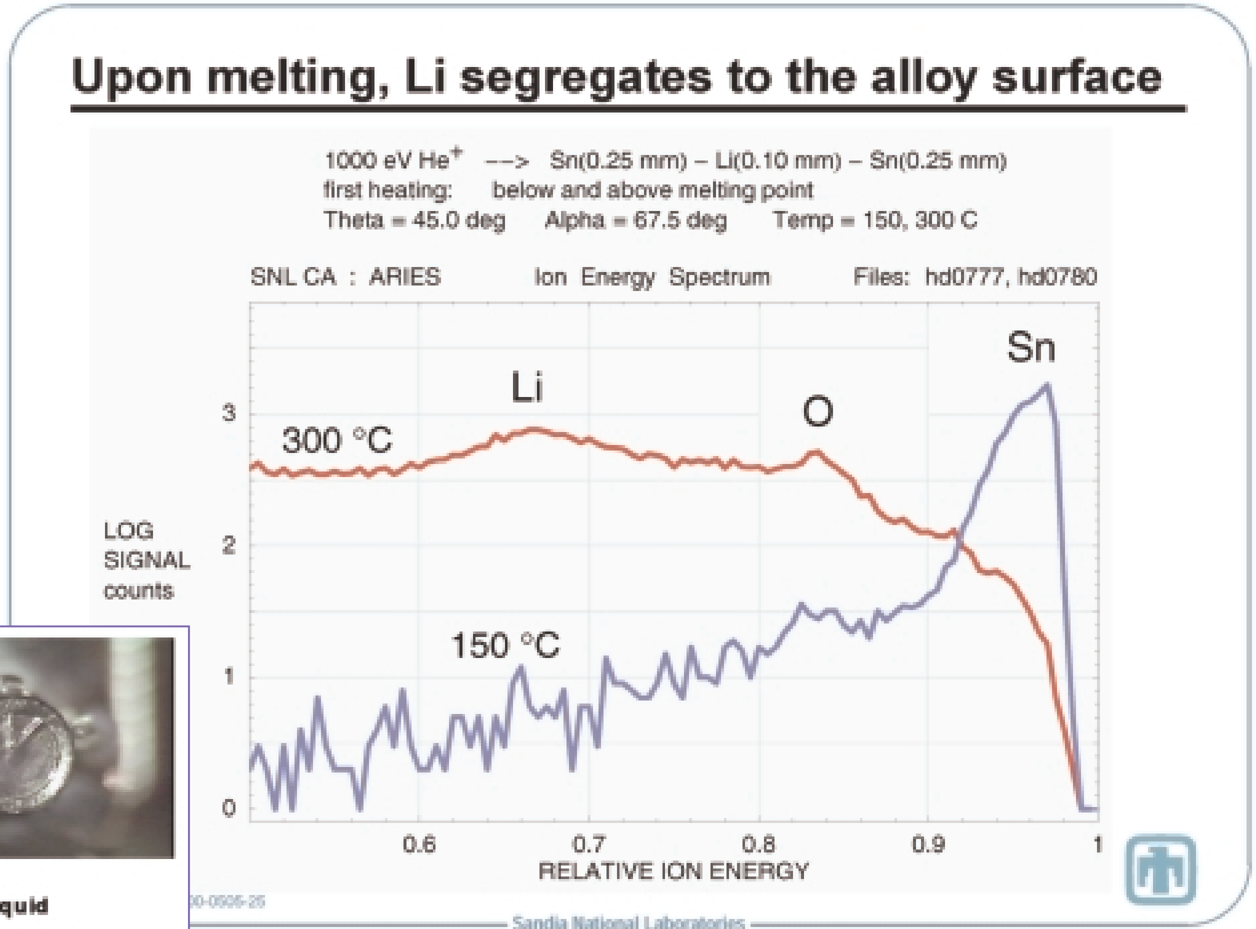


Figure 2

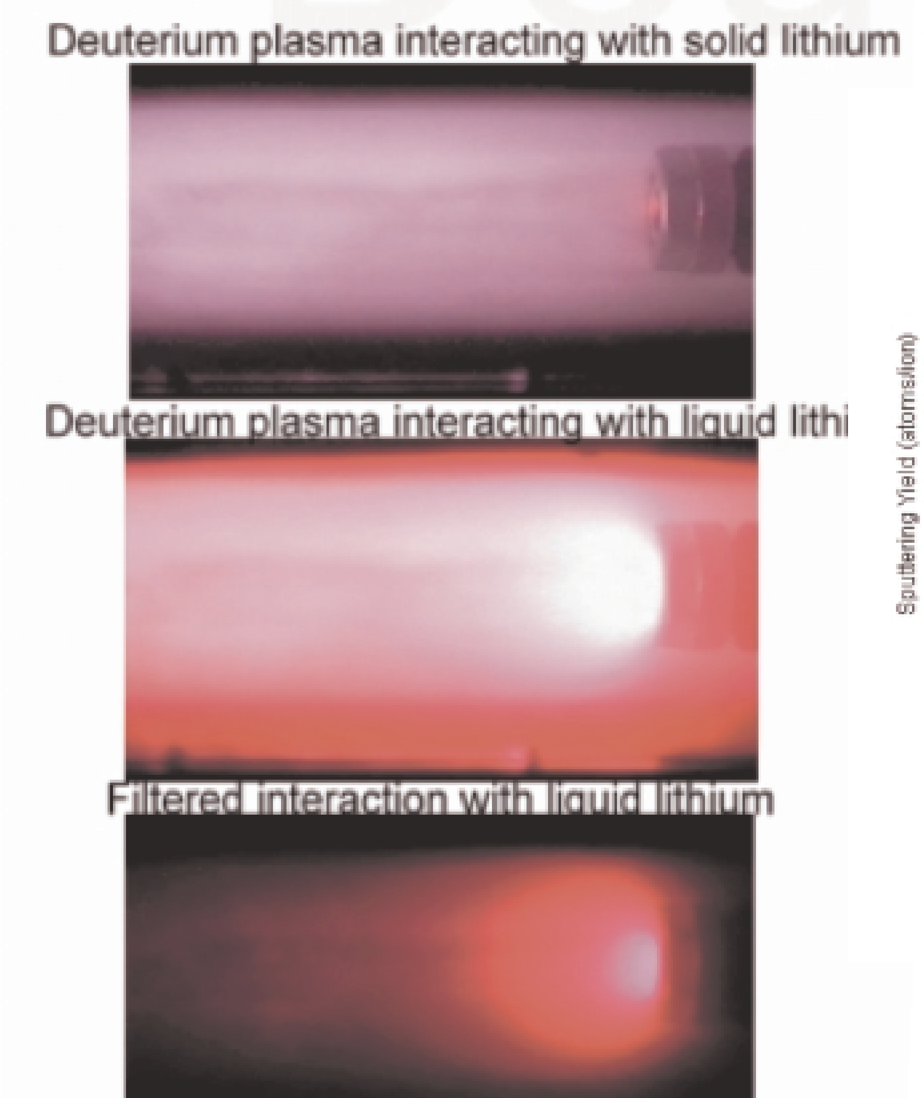
PMI Experimental efforts in ALPS

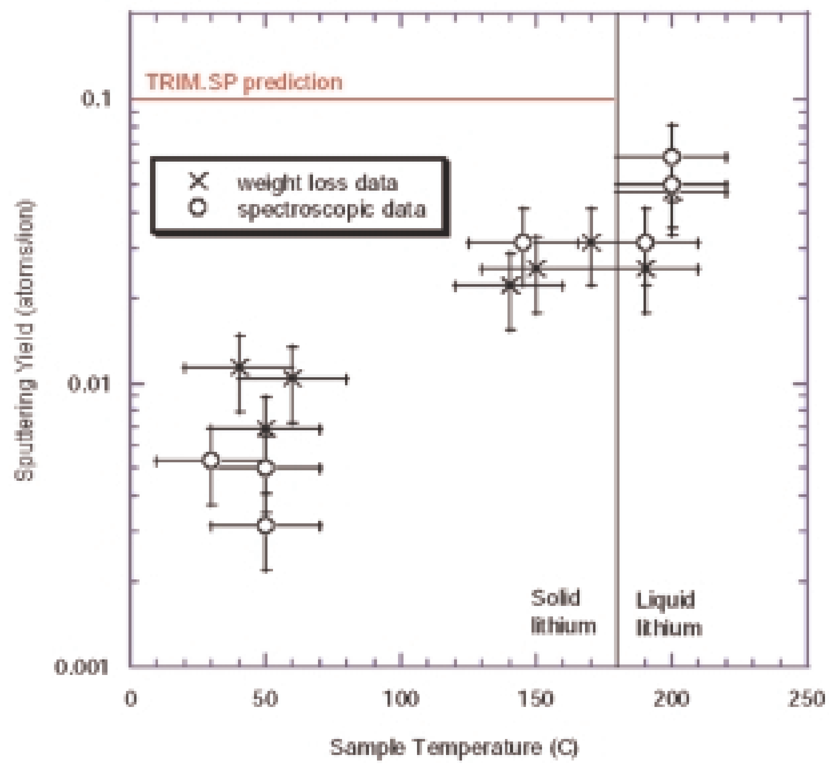


B. Bastasz, et al. SNLL

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

PISCES – glowing lithium



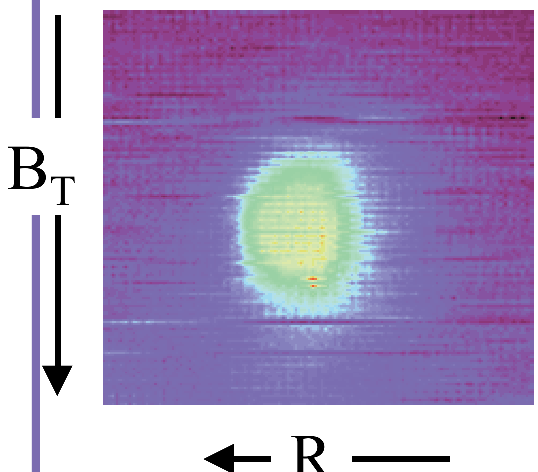


- R. Doerner, et. al., J. Nucl. Mater. 290-293 (2001) 166.

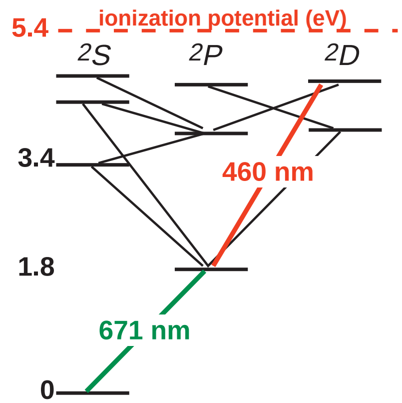
PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Lithium provides a unique opportunity to study erosion and transport in the private flux region due to its ease of erosion & excitation.

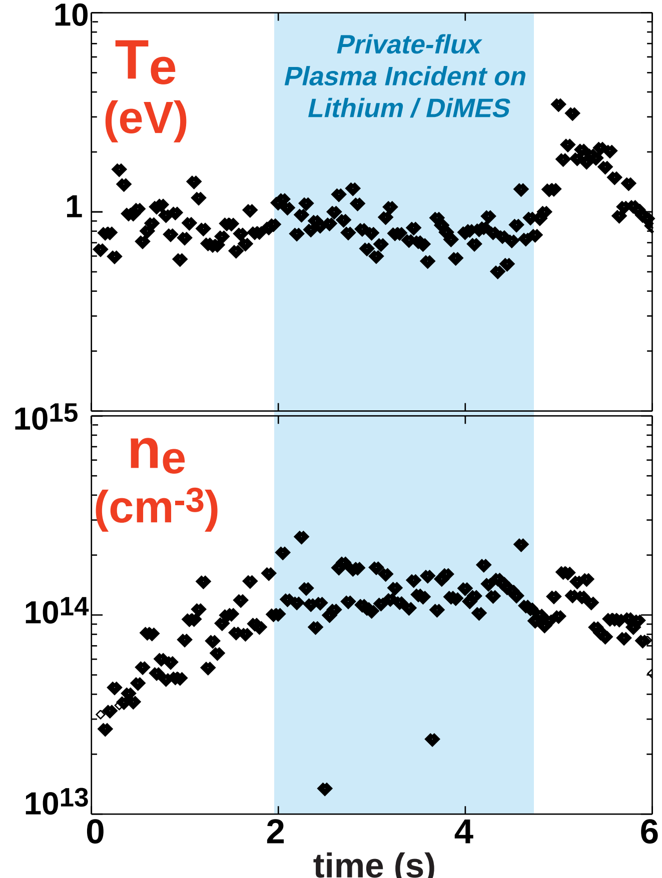
Li I Light from DiMES during PF exposure



Li I Energy Level Diagram



Private flux plasma at DiMES



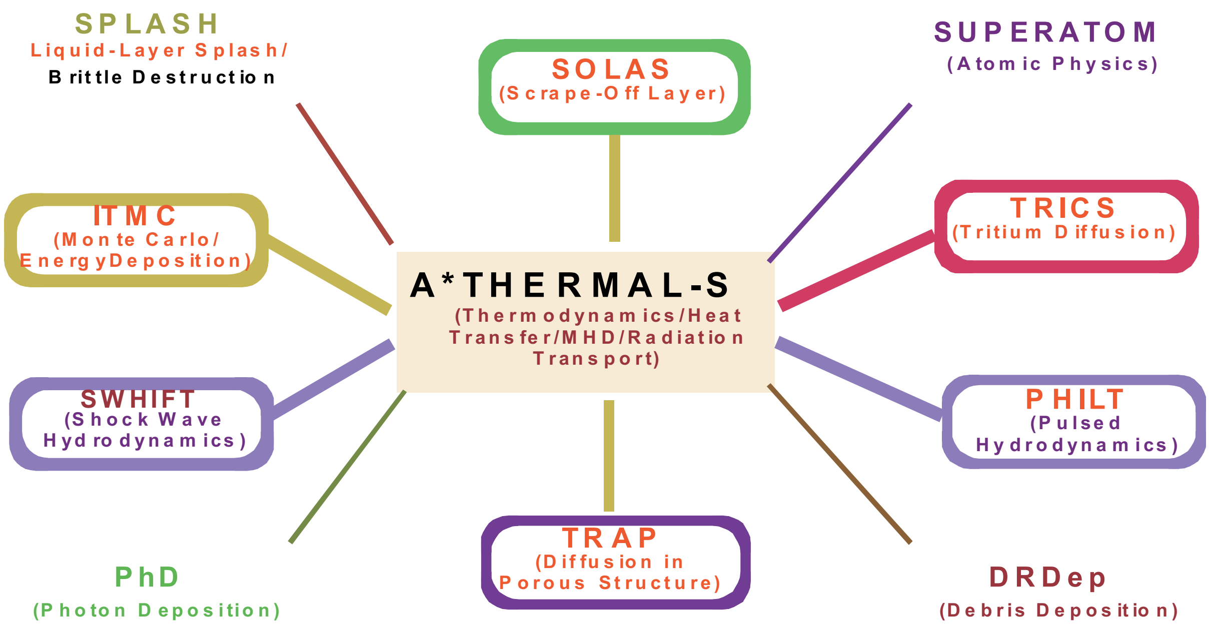
- **Lithium is sputtered in private flux (PF) plasma by charge-exchange neutrals**
- **Neutral lithium resonance line (670 nm, $E_{h\nu}$~2 eV) is easily excited by T_e~1 eV PF plasma.**
- **Lithium is quickly ionized in very cold, dense PF plasma!**

D.G. Whyte, et. al., UCSD and General Atomics

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

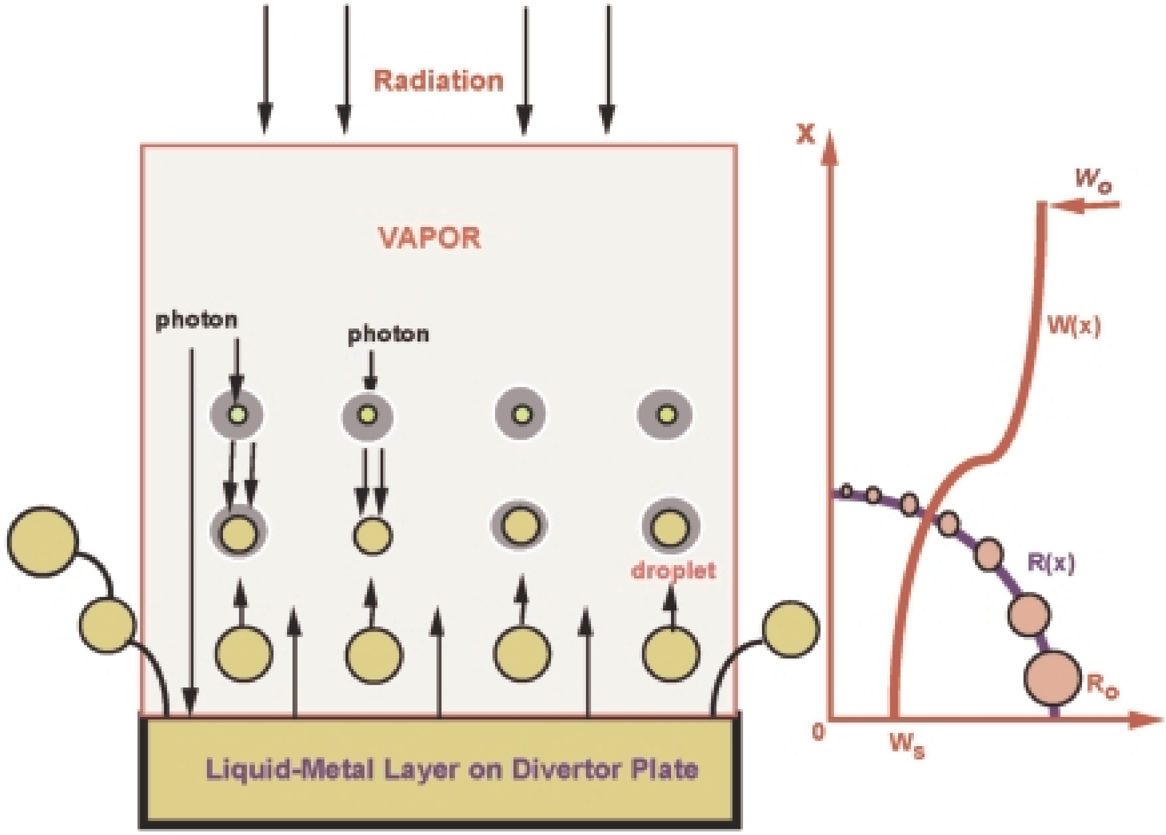
Simulation Package for High Energy Interaction with General Heterogeneous Target Systems

HEIGHTS Package



PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Droplet-Shielding Concept

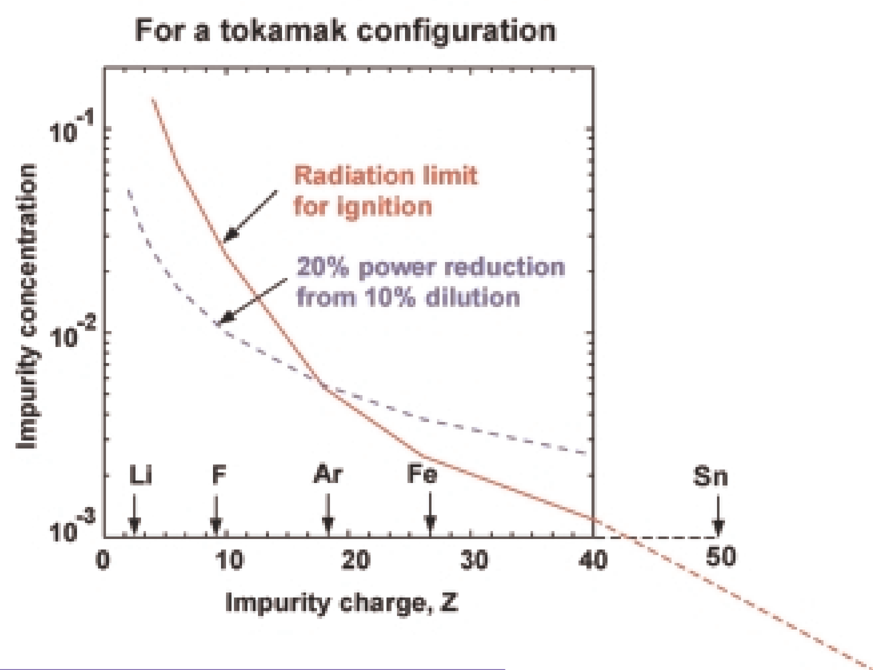


A. Hassanein and I. Konkashbaev, J. Nucl. Mater. 273 (3) (1999) 326.

Plasma-liquid surface interaction Modeling (cont.)

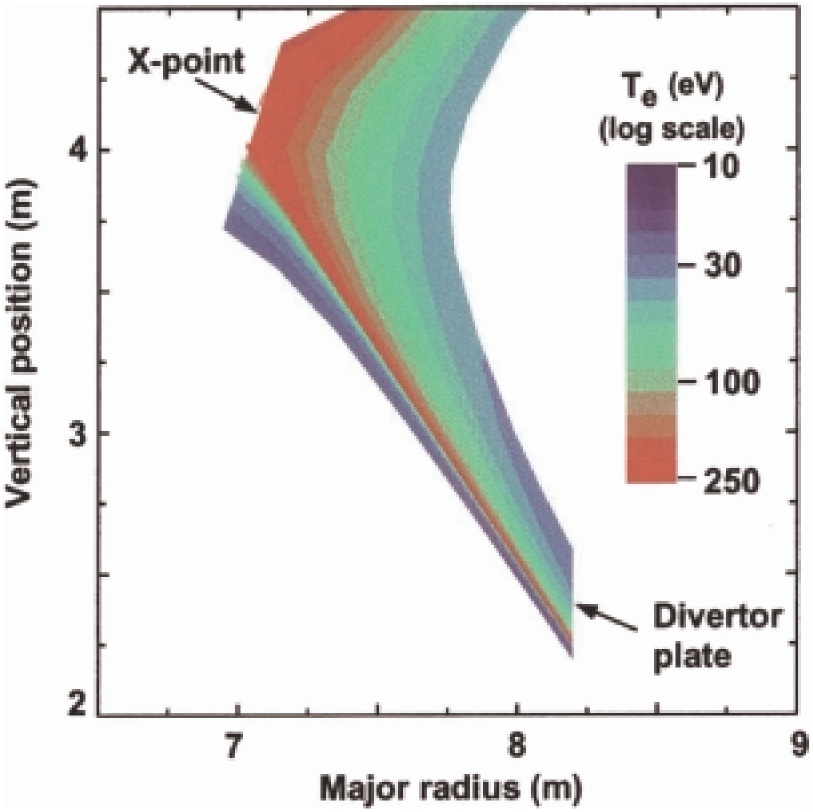
Fuel dilution and radiation set limits on core impurity concentration

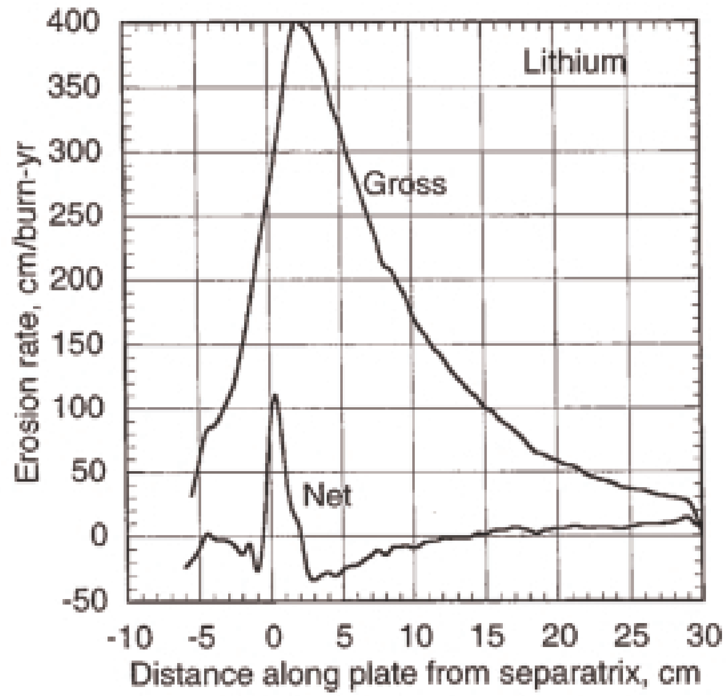
- Concentration limit set by dilution for Z < 18
- Concentration limit set by radiation for Z > 18; thus, Sn limit set by radiation



T. Rognlien and M. Rensink, LLNL

Plasma-liquid surface interaction Modeling (cont.)





Gross and instantaneous (before liquid flow) net erosion rates from WBC code

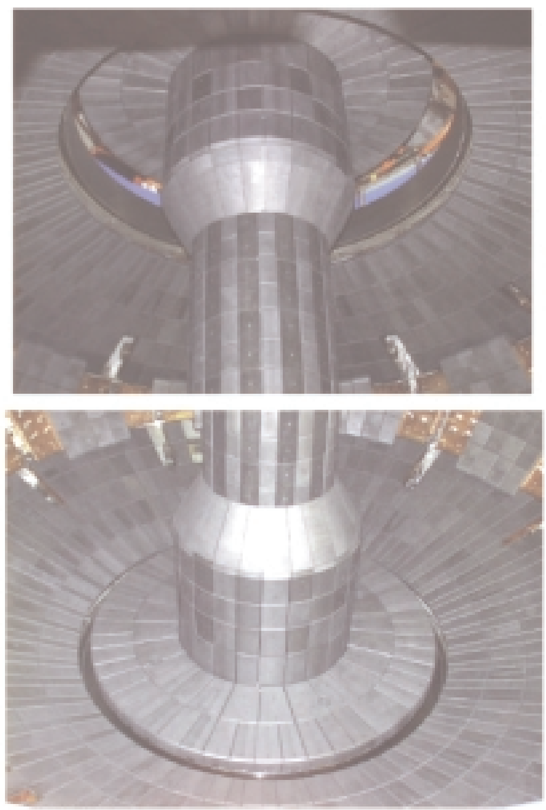
Electron temperature in outer scrape-off layer for the UEDGE plasma solution with low-recycle liquid lithium divertor

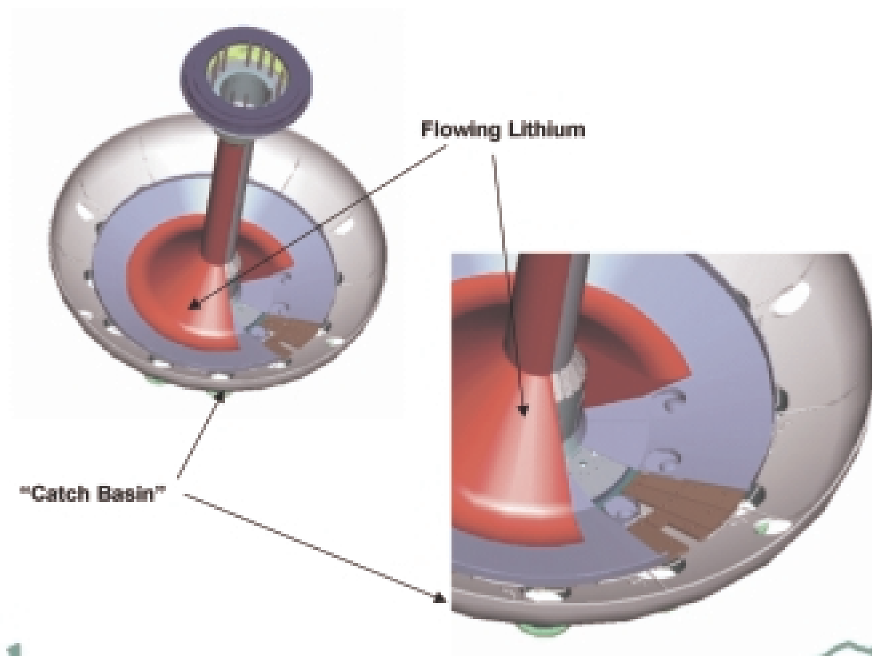
J. Brooks, et al. J. Nucl. Mater. 290-293 (2001) 185

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

NSTX: application of flowing liquid metal (i.e. ALIST)

NSTX Device configuration





ornl

UT-BATTELLE

B. Nelson and P. Fogerty

APEX Task I

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Conclusions

- Plasma interactions with the surfaces limit the desirability of fusion power
- Advances in fusion science and performance often follow new surface-related discoveries
- Wall concepts involving Li show great potential to solve many known problems
- ALPS and APEX programs are actively engaged in pursuing these solutions
- Planned burning plasma devices should consider including these – they may just be what makes it work.

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign

Acknowledgements

- DOE ALPS Program (Advanced Limiter/ Divertor Plasma-facing Surfaces)
- Richard Mattas
- Argonne National Lab
- UFA for the invitation to speak

PLASMA MATERIAL INTERACTION GROUP
University of Illinois at Urbana-Champaign