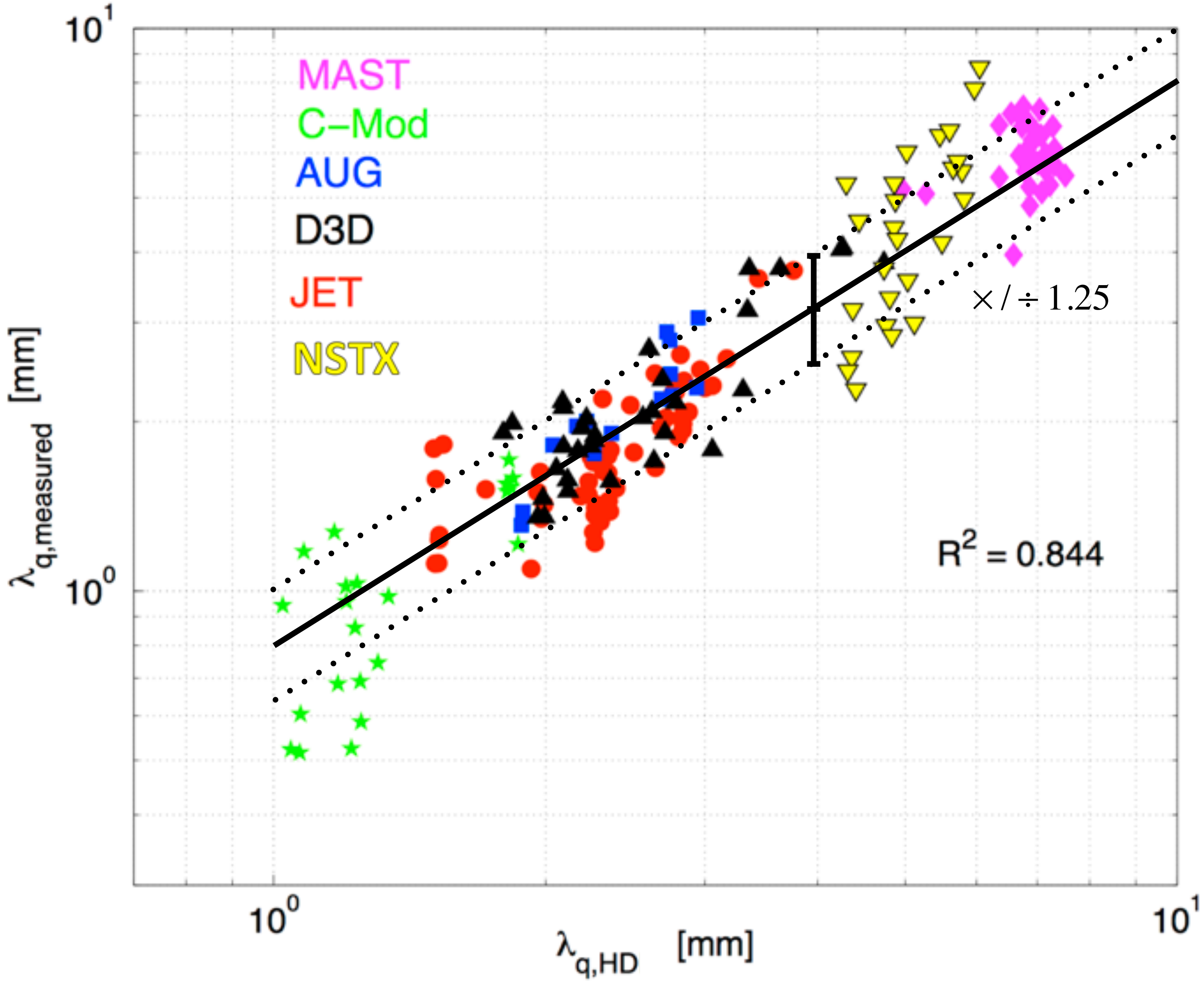
A Strategy for Resolving the Problems of Plasma-Material Interaction for FNSF

R. Goldston, B. LaBombard, D. Whyte, M. Zarnstorff

Scrape-off Width Does not Scale with R



$Data \sim 1.6\left(a/R\right)\rho_p$

$\sim HD\ Model / 1.25$

Parallel heat flux in a 2.5 GW$_{th}$, Q = 25 ITER ~ 18.5 GW/m^2

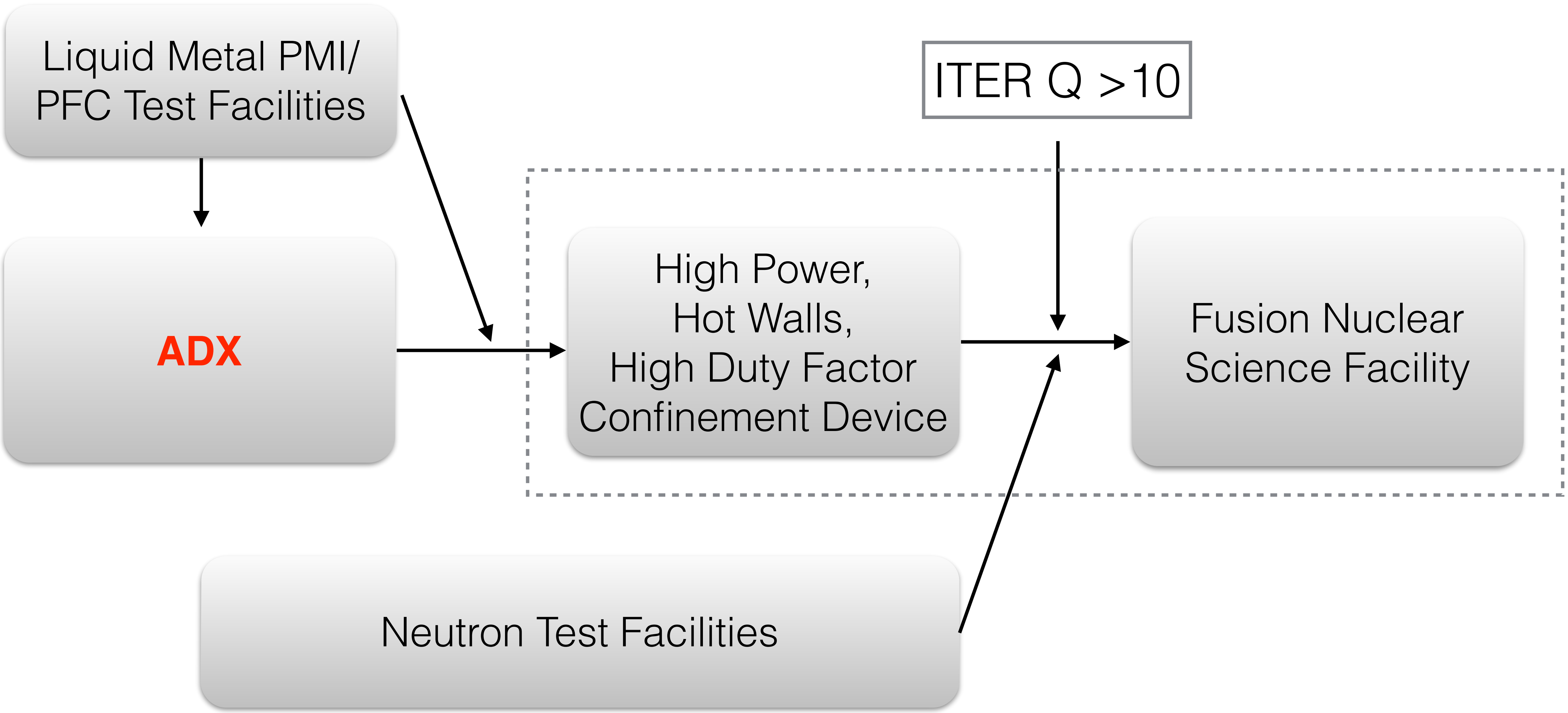
With no spreading or dissipation, 2^{o} incidence ⇒ 650 MW/m^2

Transient heat fluxes are similarly problematic (Maingi, Thursday)

Neutrons and PMI can First be Studied in Parallel

- **Mean-free path for neutrons ~ 10cm**
  PMI interactions mainly in first 1 μm
  - 10^{-5} of neutron interactions in PMI zone
- **Ions recycle > 10x, nuclear burn-up < 1/10**
  - Ion interactions in PMI zone > 10^{7} x neutron interactions
- **Neutrons do affect bulk material properties**
  - Thermal conductivity, T retention, strength/ductility, swelling
  - Surface is affected as bulk material is destroyed (C)
- **Bulk property changes affect first 1 μm indirectly**
  - Change in thermal conductivity mimicked by adjusting cooling
  - Bulk D/T retention has no significant effect on recycling
  - Strength/ductility changes affect response to thermal shock
- **Neutron & PMI studies can first proceed in parallel**
  - Material selection depends on success with both neutrons & PMI

New U.S. Facilities for PMI/PFC Strategy



Liquid Metal PMI/ PFC Test Facilities

ADX

ITER Q >10

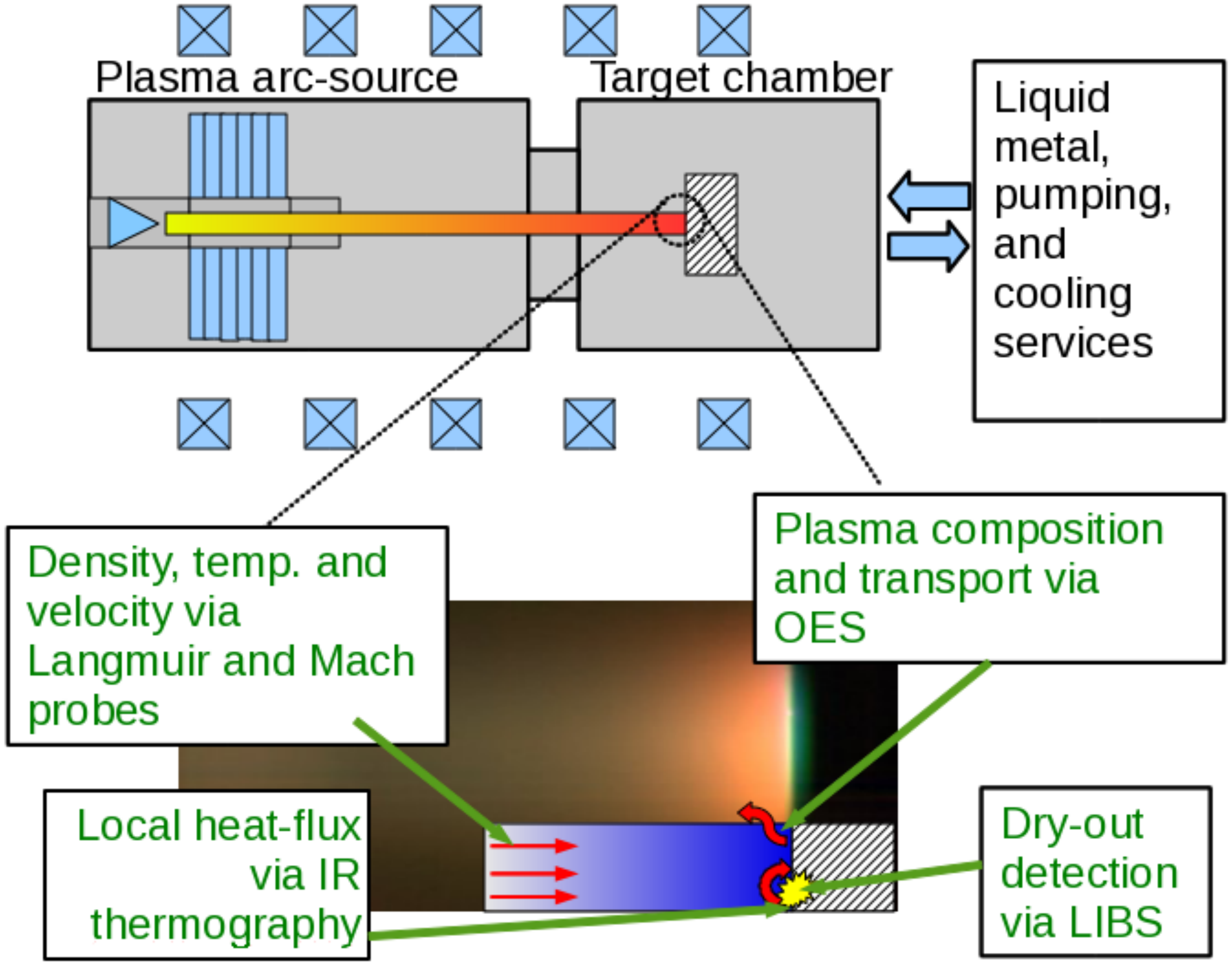
High Power,
Hot Walls,
High Duty Factor
Confinement Device

Fusion Nuclear
Science Facility

Neutron Test Facilities

Strong experimental and theoretical surface science program needed in parallel

Liquid Metal (LM) PMI/PFC Test Facility



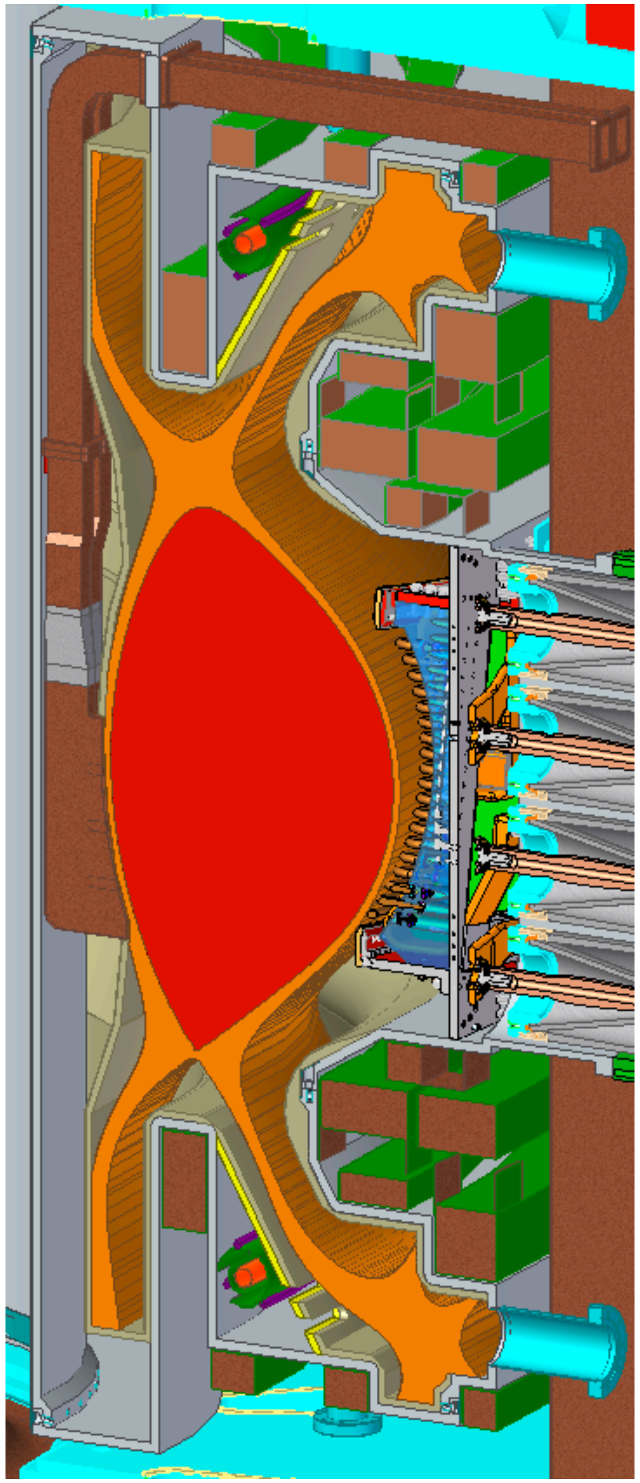
- **Liquid lithium can handle high heat fluxes**
  - Russian e-beam tests: 50 MW/m^2, Plasma focus: 60 MJ/m^2 in 1 μsec
- **Development is required in specialized facility**
  - Physics of radiative & vapor shielding, technology of LM feed & recapture
  - Gas (not water!) cooling, robust to LM coating
  - See Maingi, Jaworski & Allain on LM initiative (Thursday)

High Heat Flux Confinement Device

- **Requirements**
  - High parallel heat flux ~ PB/R
  - High poloidal heat flux ~ PB_θ/R
  - High upstream pressure

$$(nT)_{sep} \propto \frac{f_{GW} I_p}{a^2} \left(\frac{B L_{\parallel} P_{SOL}}{R \lambda_q B_p} \right)^{2/7}$$

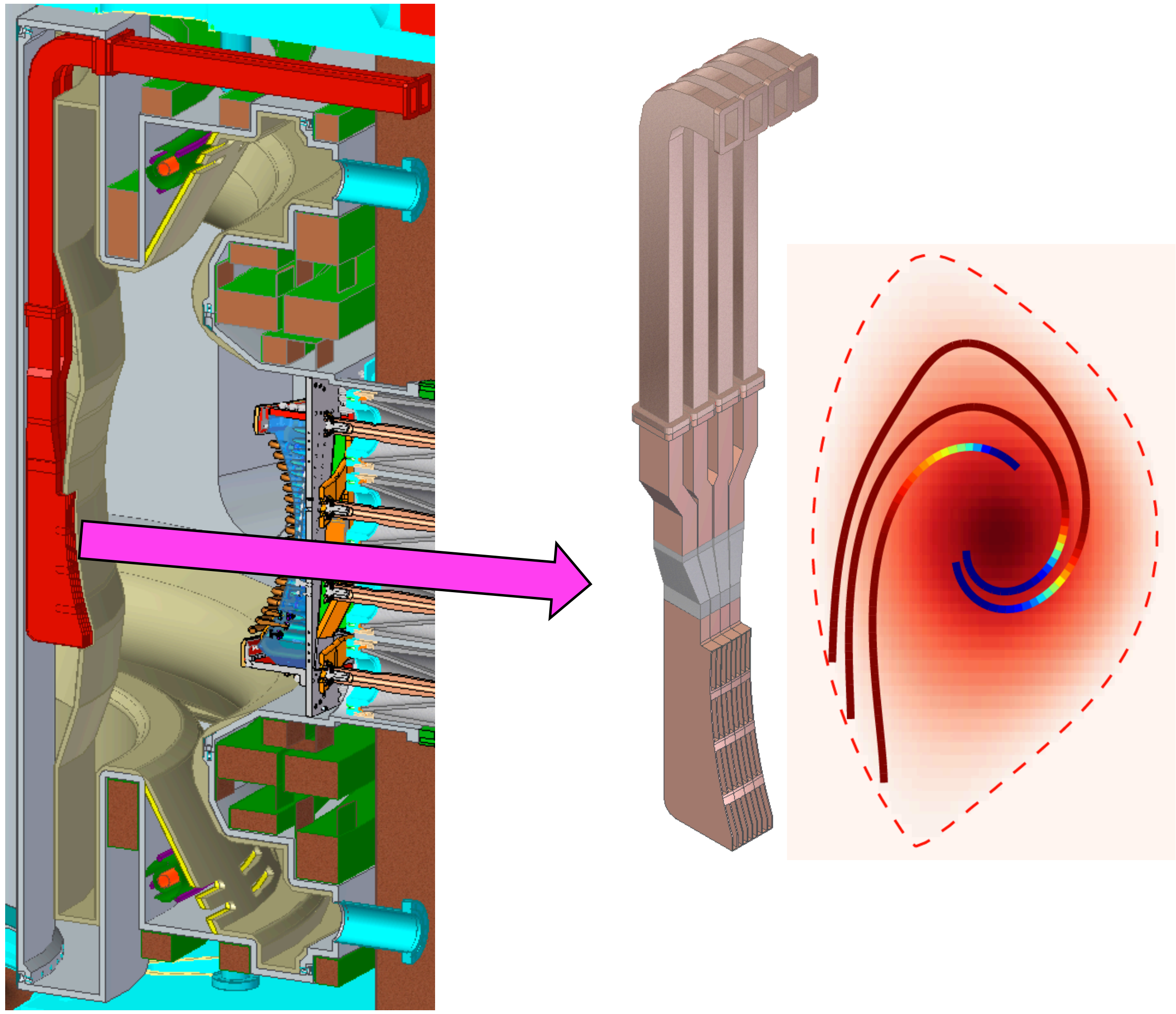
  - Poloidal field flexibility to test advanced divertor concepts
  - Tightly baffled divertor chamber
  - Ability to accommodate a range of metallic plasma-facing materials
  - Pulse length > bulk plasma, SOL & PFC surface-heating times
  - Extensive PMI diagnostics

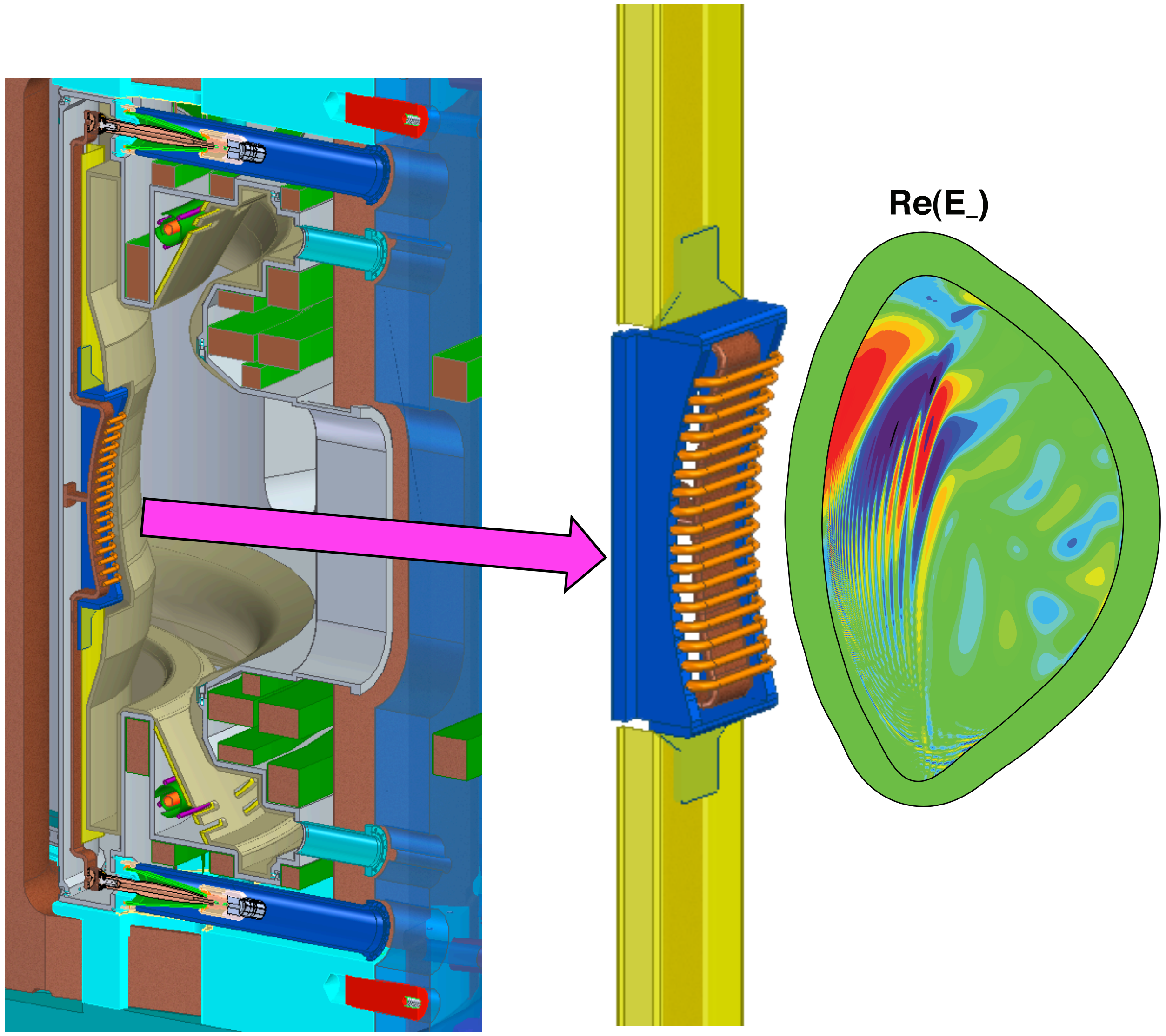


ADX meets requirements

ADX Designed to Test Inner-Wall RF Launch

PMI key issue for RF launching structures



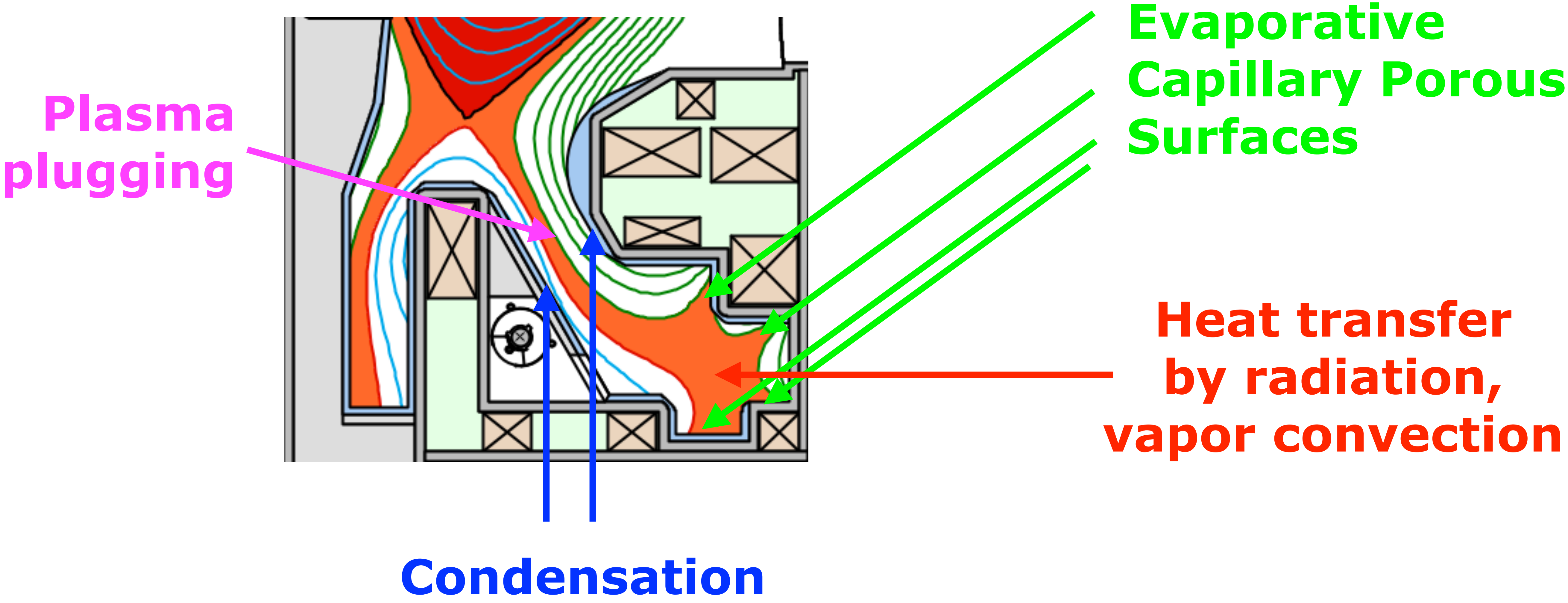


Test LH & ICRF in low-PMI launch position.

Test efficient current drive for FNSF & beyond.

Provide high power for ADX.

ADX Divertor Well Suited for Liquid Metal Tests



Plasma plugging

Evaporative Capillary Porous Surfaces

Heat transfer by radiation, vapor convection

Condensation

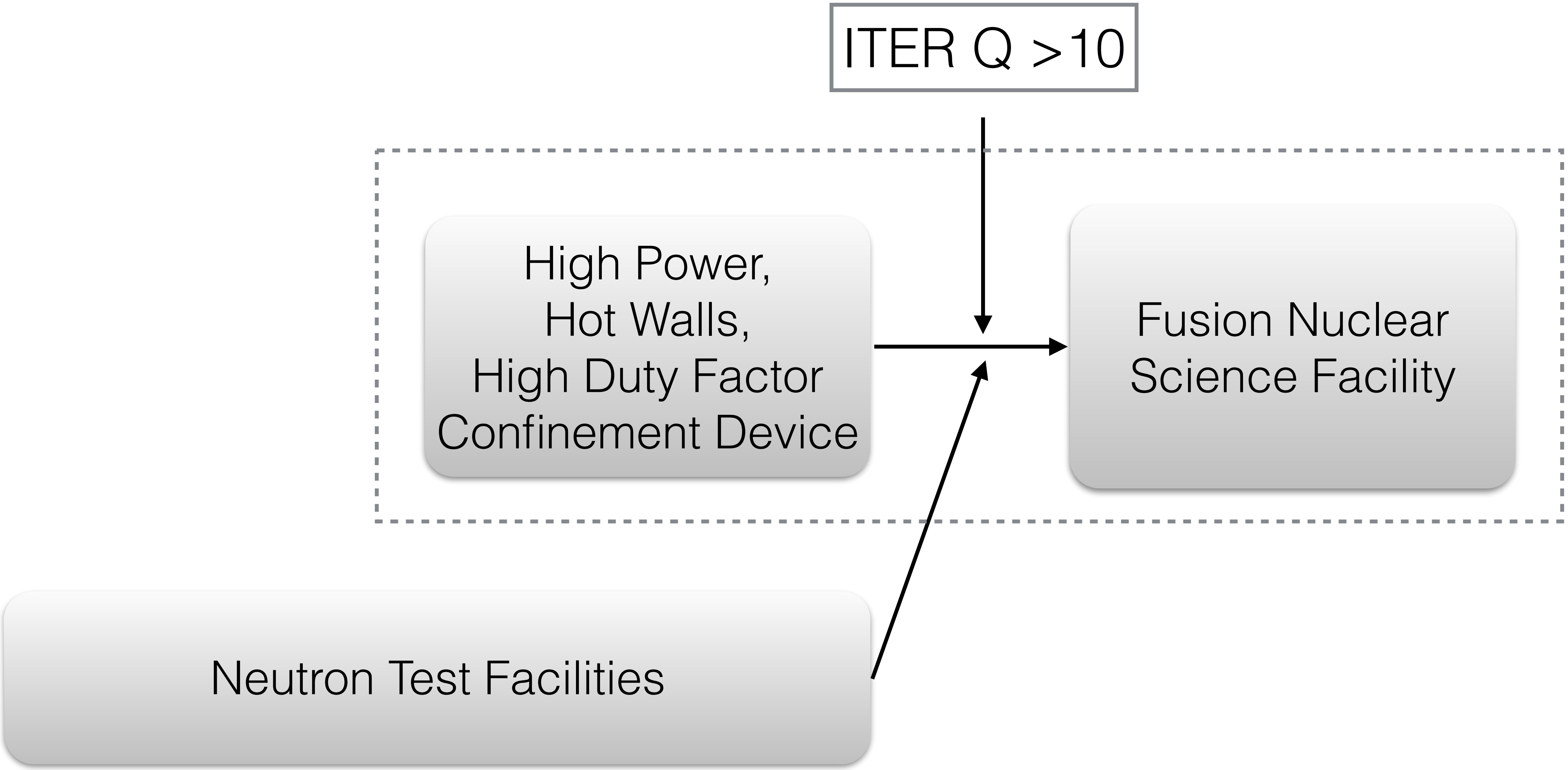
Multiple divertor geometries & materials can be tested.

Small size, short pulse (low activity) ⇒ quick changes

EAST would provide long-pulse, water-cooled operation at lower PB/R, upstream pressure and flexibility.

NSTX-U plans to perform complementary LM studies.

Final Stages of PMI/PFC Strategy


ITER Q >10

High Power,
Hot Walls,
High Duty Factor
Confinement Device

Fusion Nuclear
Science Facility

Neutron Test Facilities

Full tests including steady cooling, wall material migration and T retention require high PB/R + hot walls + high duty factor.

Can decide later if this is stand-alone or first phase of FNSF.

FNSF integrates results from Neutron + PMI facilities.

Conclusions

- **PMI problems are worse than we thought even 3 years ago**
  - Both steady and transient heat fluxes
- **Neutrons can be addressed in parallel w/PMI**
  - Pass both tests, then bring them together for FNSF
- **Liquid metal PMI/PFC test facility needed**
  - Complements solid PFC test stands
- **ADX for high power, magnetic flexibility, baffled divertor**
  - World-leading parallel heat flux, upstream pressure
  - Excellent test bed for PMI/PFC, inside launch LH & ICRF
- **High power + hot walls + high duty factor still needed**
  - Can decide later if this is standalone device or first phase of FNSF

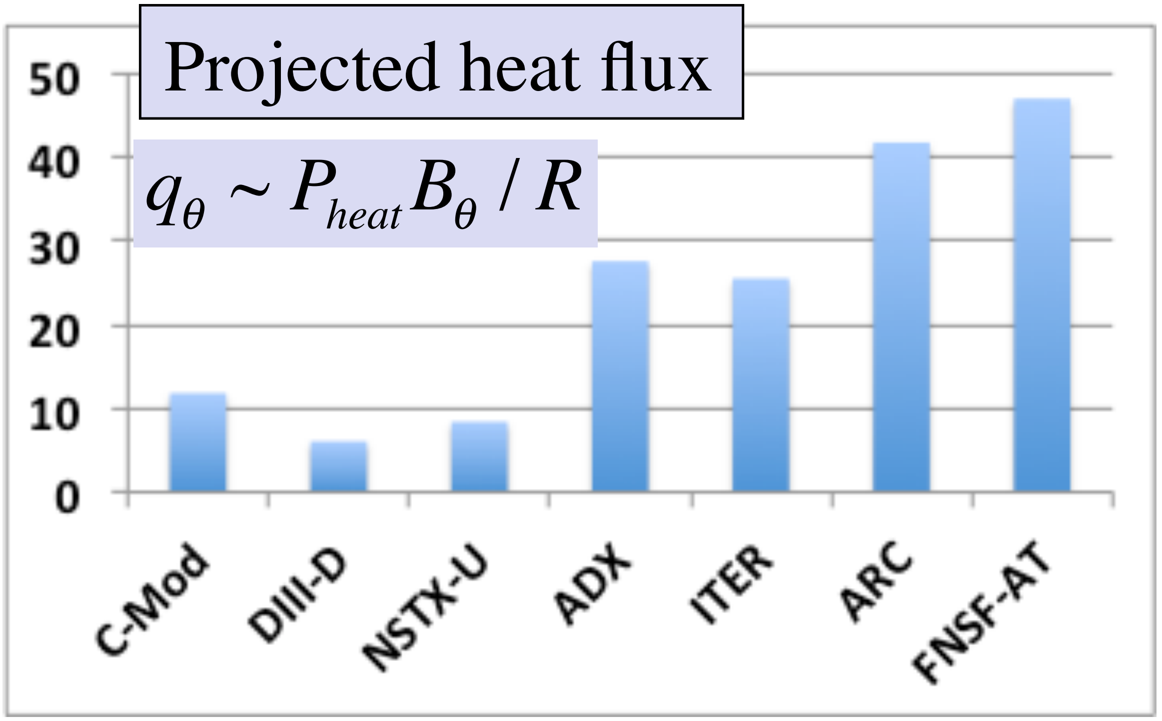
If ADX moves forward, PPPL would partner with MIT, contributing to engineering, diagnostic and auxiliary heating development, and playing a major role in the scientific research team.

Back-Up Slides

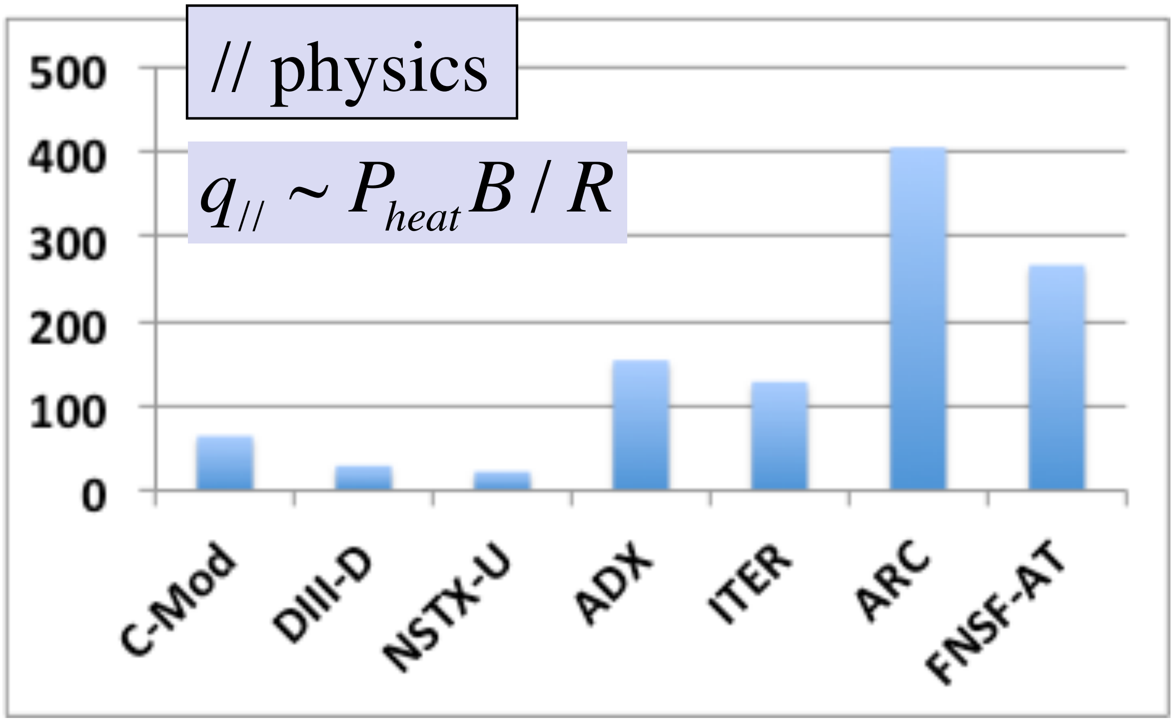
ITER PMI Technologies do Not Extrapolate

- **Requirements << Demo**
  - **Heat and particle fluxes << Demo**
    - Down by factor ~ 4
  - **Surface Temperatures << Demo**
    - Divertor: 200C – 1200C (at strike point)
    - First wall: 150C – 450C (at peak heat flux)
  - **Duty factor << Demo**
    - Few % vs. ~75%
- **⇒ Technologies much different from Demo**
  - **W divertor with CuCrZr/water cooling**
    - Can handle heat flux up to 10 – 20 MW/m^2
    - Demo W with He cooling and neutrons ~5 MW/m^2
  - **Be first wall not considered in reactor design**
    - Too low heat flux and transient energy handling capacity

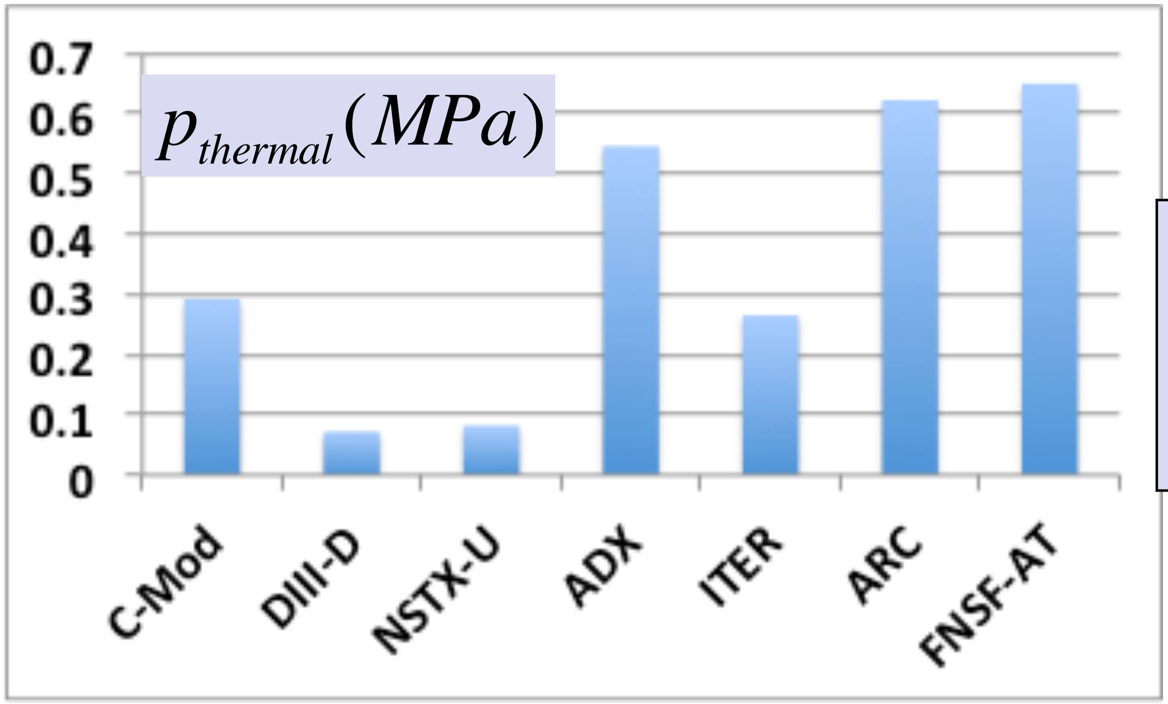
ADX provides a critically needed near-term, small-scale step into the ITER/FNSF heat exhaust & PMI parameter range


Projected heat flux

$q_\theta \sim P_{heat} B_\theta / R$


// physics

$q_{//} \sim P_{heat} B / R$


$p_{thermal} (MPa)$

Atomic & PMI physics

Whyte to Panel, June 2014

Machine Parameter Comparison

	MAST	NSTX-U	DIII-D	EAST	KSTAR	AUG	JET	JT-60SA	C-MOD	ADX	ITER	ACT1	ACT2
B_T [T]	0.84	1	2.2	3.5	3.5	3.1	3.5	2.3	5.4	6.5	5.3	6	8.75
I_p [MA]	2	2	1.5	1.5	2	1.6	4.8	5.5	1.3	1.5	15	11	14
a [m]	0.65	0.62	0.6	0.45	0.5	0.6	1.25	1.2	0.22	0.2	2	1.6	2.4
R [m]	0.85	0.93	1.75	1.85	1.8	1.65	3	3	0.67	0.73	6.2	6.25	9.8
P_{tot} (1) [MW]	7.5-12.5	8-19	23-39	10-36	14-36	27	38	41	8	14	150	405	630
P_{tot}/S (2) [MW/m^2]	0.18-0.3	0.18-0.44	0.36-0.60	0.23-0.82	0.3-0.76	0.52	0.20	0.19	1.0	1.7	0.22	0.64	0.41
$P_{tot}B/R$ (3) [MW T/m]	8-13	9-22	30-50	19-69	28-71	51	45	33	65	126	131	390	570
$\lambda_q/\lambda_q^{ADX}$ (4) ($\lambda_q \sim$ Eich)	4.7	4.2	3.5	2.0	1.8	2.9	2.3	2.1	1.3	1	1.2	1.3	1.6
$q_{\|}/q_{\|}^{ADX}$ (5) ($\lambda_q \sim$ Eich)	0.02-0.04	0.03-0.07	0.21-0.34	0.17-0.62	0.22-0.56	0.33	0.24	0.18	0.45	1	0.82	3.1	4.5
$q_{\|}/q_{\|}^{ADX}$ (6) ($\lambda_q \sim R$)	0.03-0.06	0.04-0.1	0.24-0.40	0.15-0.55	0.16-0.4	0.32	0.10	0.06	0.55	1	0.10	0.52	0.6

Table 5.1 – ADX parameters compared to world tokamaks.

(1) – Total source power from all heating systems, range shows planned or proposed upgrades to facility. In practice, the total input power is restricted by operational beta limits – not accounted for here.

(2) – Maximum plasma power density flowing through last-closed flux surface (assuming no core radiation).

(3) – Figure of merit that sets the heat flux density entering divertor ($q_{//}$), based on λ_q scaling as $1/B_{pol}$.

(4) – Heat flux channel width (λ_q) normalized to that in ADX, based on multi-machine scaling [8].

(5) – SOL parallel heat flux normalized to that in ADX, based on multi-machine scaling of λ_q.

(6) – SOL parallel heat flux normalized to that in ADX, based on λ_q scaling linearly with major radius.

LaBombard to Panel, June 2014

Neutron Effects are Separable

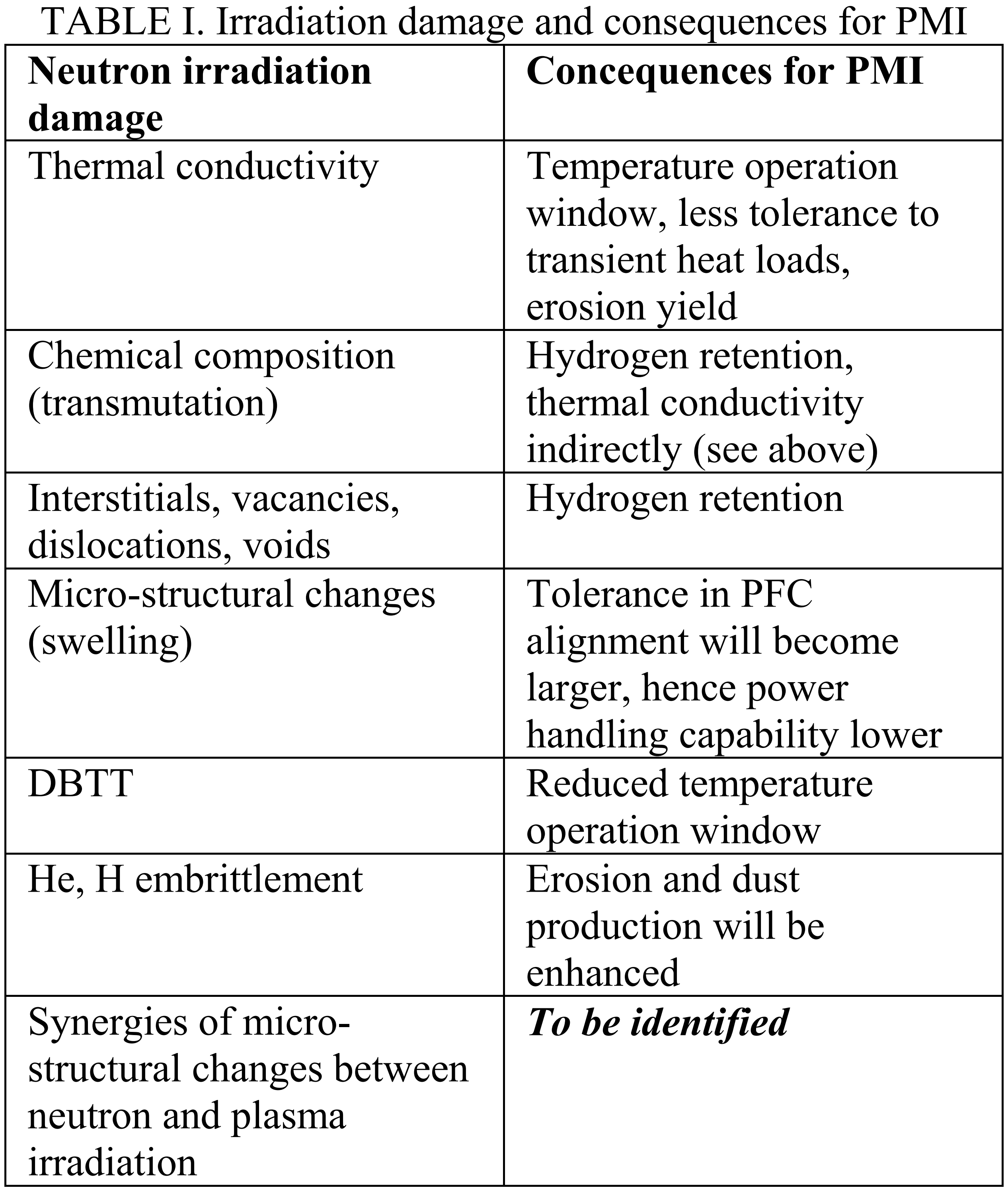


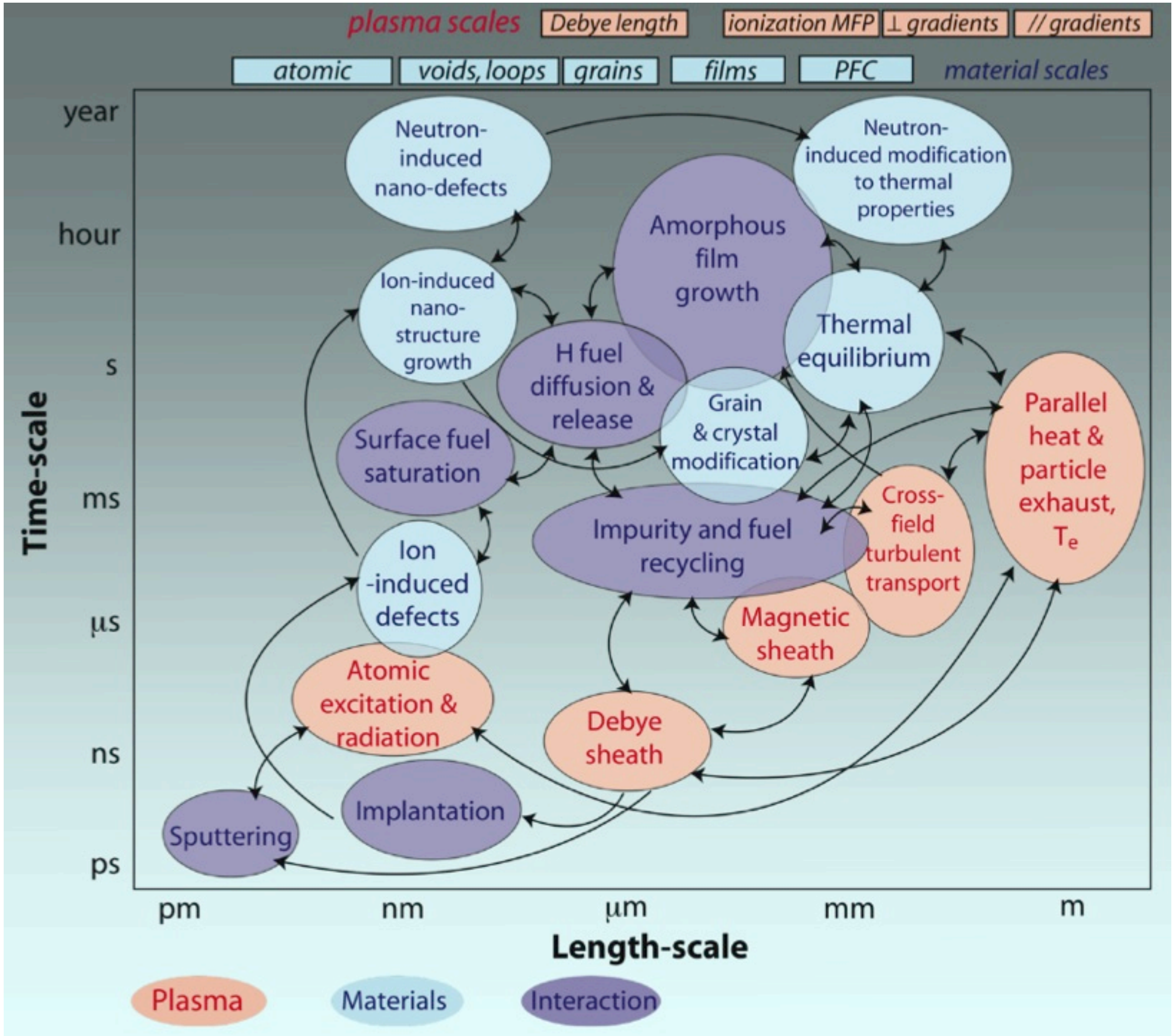
TABLE I. Irradiation damage and consequences for PMI

Neutron irradiation damage	**Concequences for PMI**
Thermal conductivity	Temperature operation window, less tolerance to transient heat loads, erosion yield
Chemical composition (transmutation)	Hydrogen retention, thermal conductivity indirectly (see above)
Interstitials, vacancies, dislocations, voids	Hydrogen retention
Micro-structural changes (swelling)	Tolerance in PFC alignment will become larger, hence power handling capability lower
DBTT	Reduced temperature operation window
He, H embrittlement	Erosion and dust production will be enhanced
Synergies of micro-structural changes between neutron and plasma irradiation	***To be identified***

(No argument for this provided in text.)

J. Rapp et al., Fusion Science & Technology, August 2013

Neutron Effects are Separable

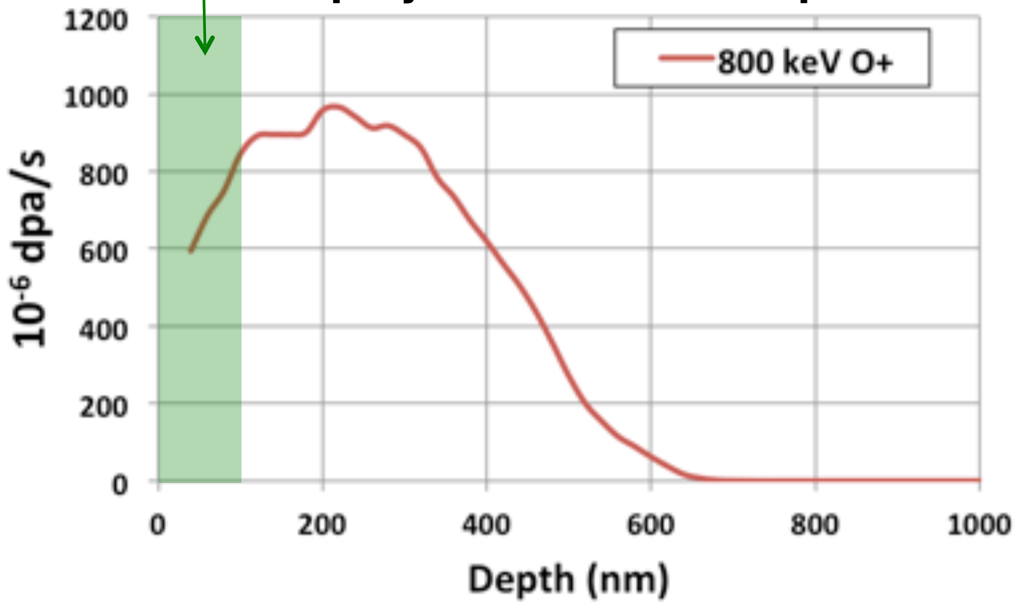


Wirth to Panel, June 2014

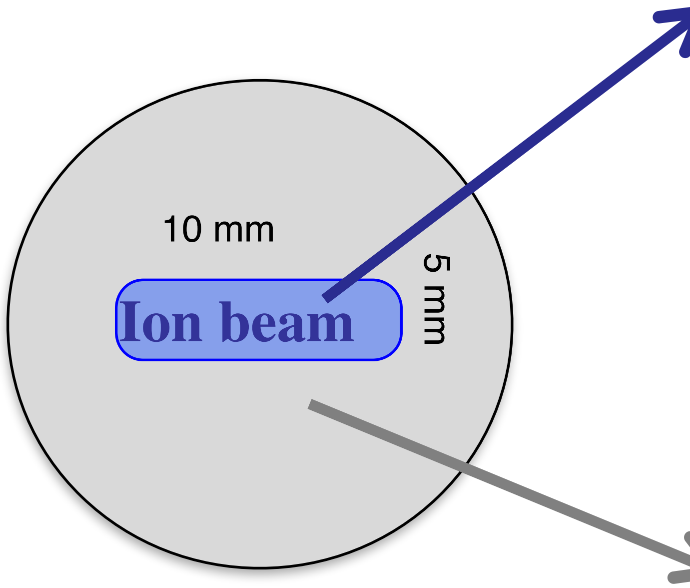
Irradiation damage makes no difference in the morphology of the nano-tendrils formed on the surface

Fuzz region

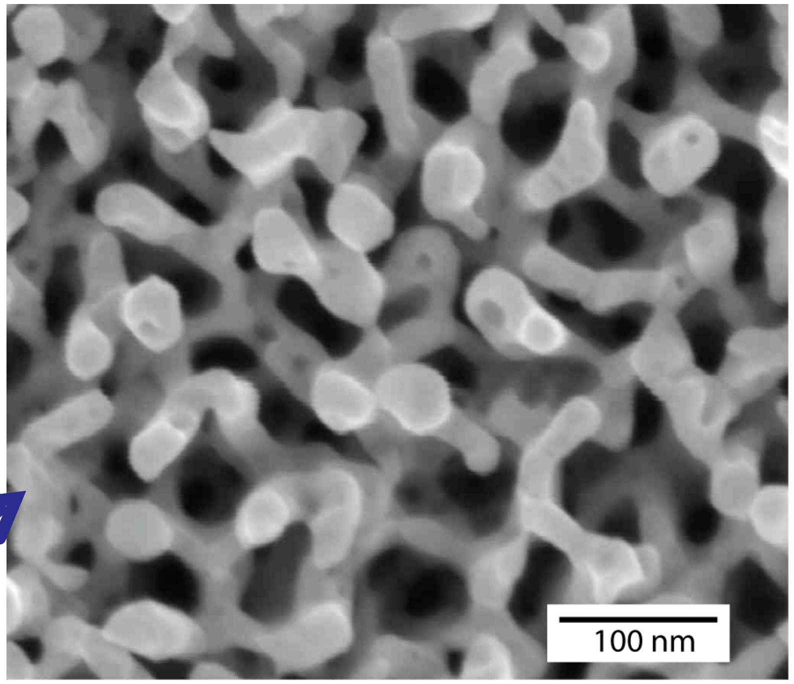
20 dpa/year = 0.6 x 10^{-6} dpa/s

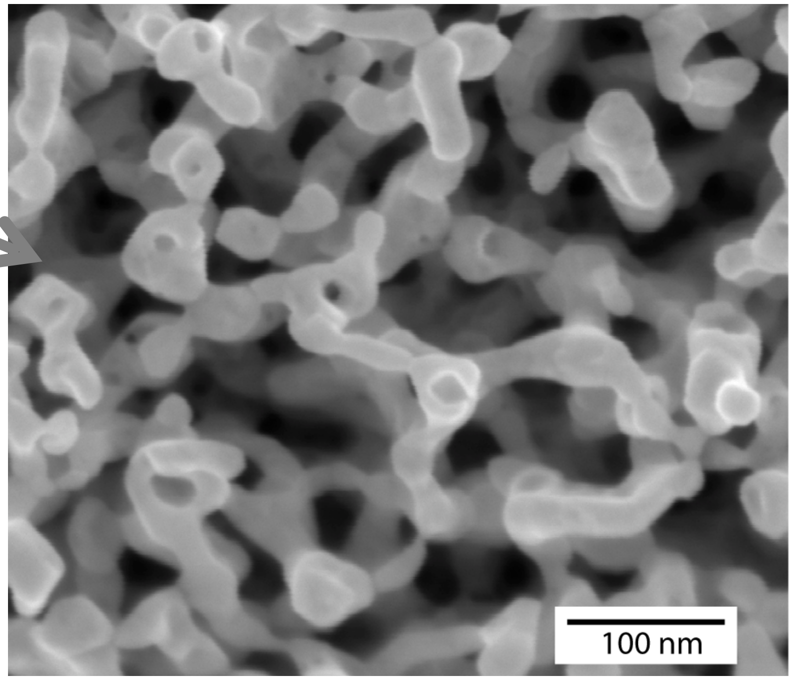


Peak damage
10^{-3} dpa/s



Tungsten sample





Reactor neutron damage simulated by energetic heavy-ion beam exposure *simultaneous with* He plasma exposure

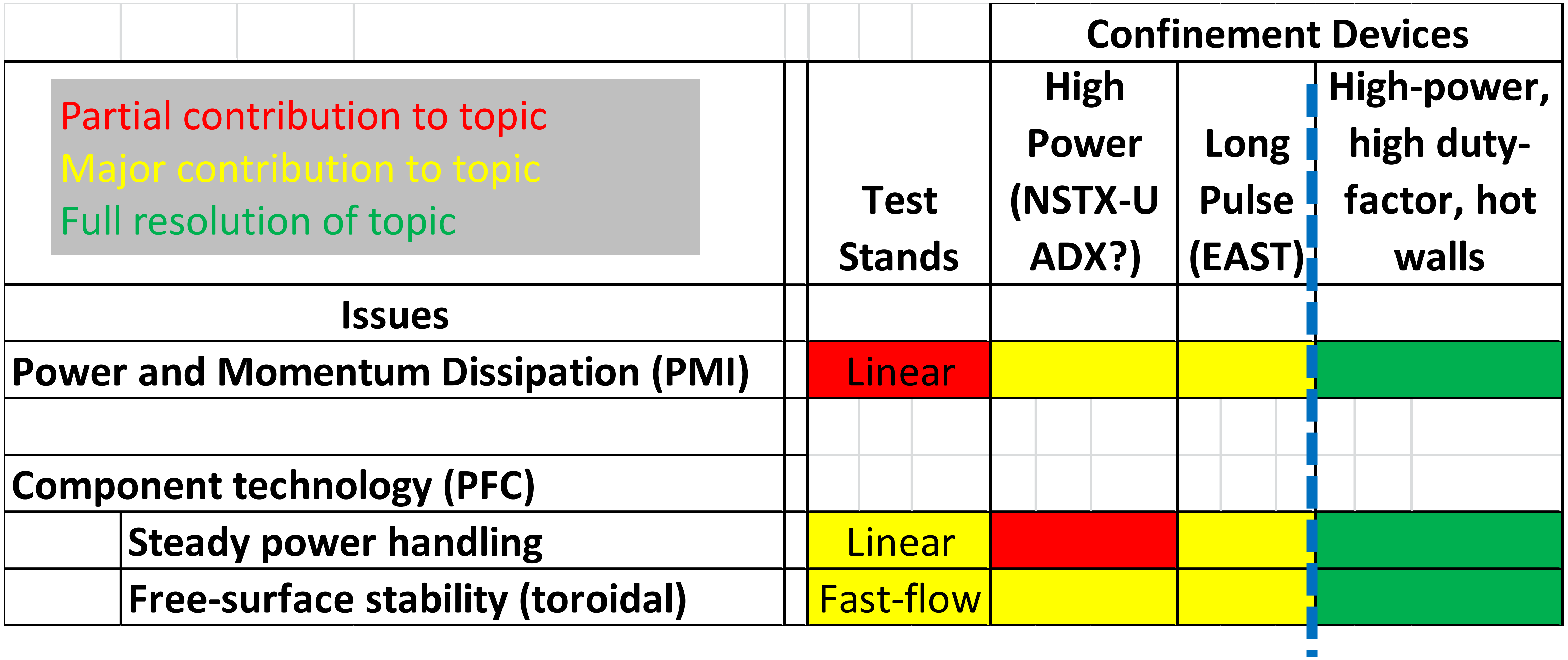
Wright, APS 2013

Demo will Require Innovation

Li Vapor-Box Divertor?

- **Assume a device ~ size of ITER with P_{fus} = 2500 MW and Q = 25**
- **4x higher loss power than ITER ⇒ 18.5 GW/m^2**
- **For 2^o field line angle, 10 MW/m^2, f_{power} > 98% (!!)**
- **For n_{sep} ~ 1.5x ITER's ~ 5 10^{19}/m^3 , p_{sep} ~ 6300 Pa**
- **Pressure balance achieved by C-X on H^o and Li^o + elastic collisions with H^o and Li^o**
- **1/2 of pressure can be balanced by Li vapor in evaporation/condensation equilibrium with 950^o C surface (Jaworski PSI 2014)**
- **H$^+$ MFP = 5mm @ 100 eV, 250mm @ 5 keV**
- **Vapor must be well confined to divertor chamber, by a combination of geometrical design & plasma flow.**
- **Easier with a condensing vapor than with a gas.**

Key facilities will address science issues and enable integrated demonstration within 10 years



🟥 Partial contribution to topic
🟨 Major contribution to topic
🟩 Full resolution of topic

		Confinement Devices		
Issues	**Test Stands**	**High Power (NSTX-U ADX?)**	**Long Pulse (EAST)**	**High-power, high duty-factor, hot walls**
Power and Momentum Dissipation (PMI)	🟥 Linear	🟨	🟨	🟩
Component technology (PFC)				
Steady power handling	🟨 Linear	🟥	🟨	🟩
Free-surface stability (toroidal)	🟨 Fast-flow	🟨	🟨	🟩

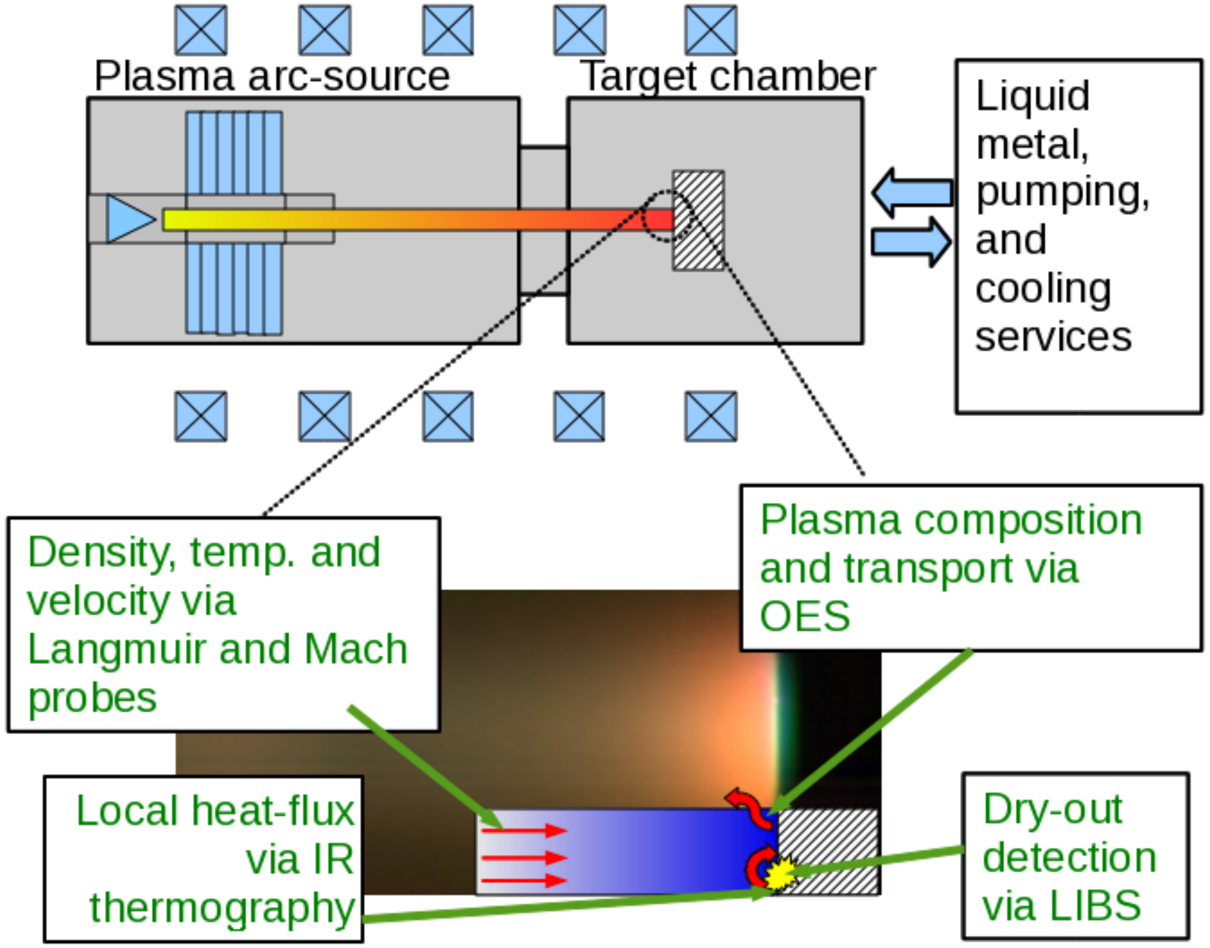
10-year goal: Competitive PFM with W

- Dedicated test stands provide fundamental physics and engineering demonstrations prior to implementation on confinement device

- Current long-pulse tokamaks do not approach DEMO parallel heat-fluxes

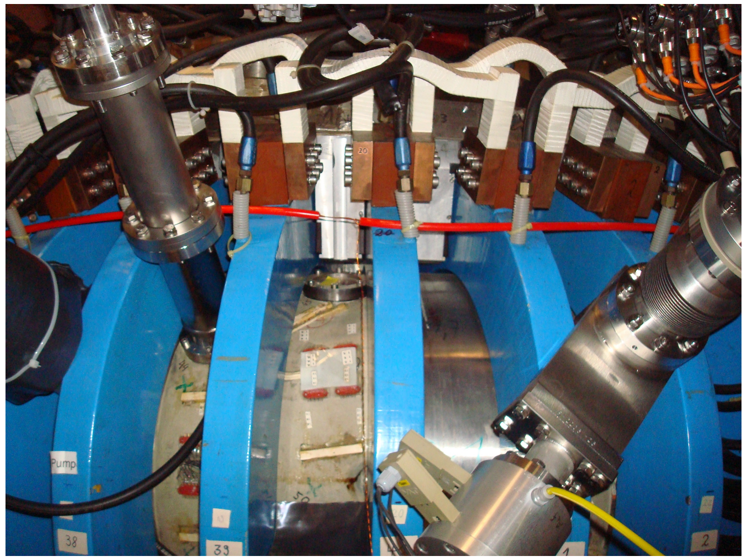
Modest investment needed to address facility requirements

- Dedicated linear device with integrated liquid lithium loop can address physics and technology goals
  - Arc-source proposed to provide divertor-relevant heat fluxes
  - Material transport, recapture requires integrated lithium loop
  - **Extensive water cooling incompatible with lithium PFCs**
- Dedicated toroidal devices can demonstration basic stability
  - Similarity experiments with GaInSn could be restarted quickly
  - Dedicated lithium facilities will address low-density fluid and hydrogen cycle aspects directly

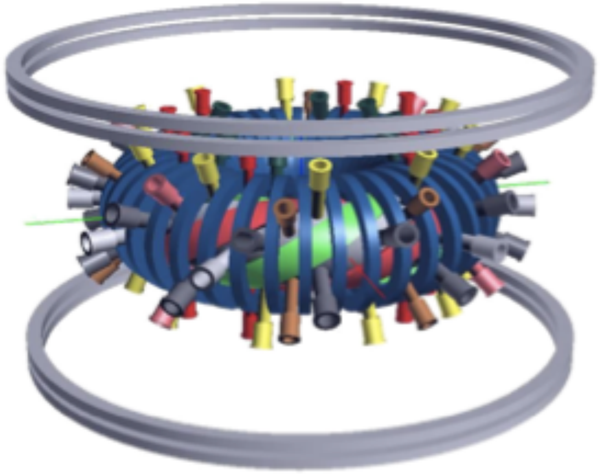



UCLA MTOR GaInSn Experiment

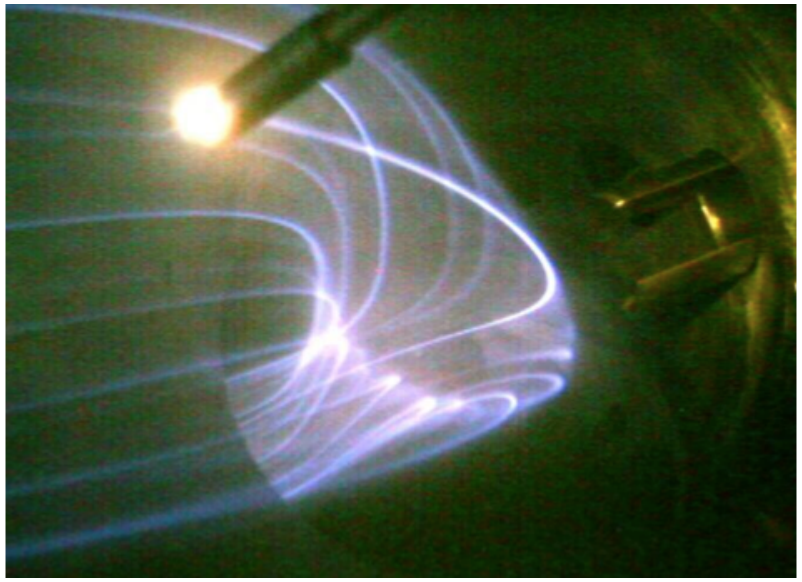
HIDRA: Toroidal Technology Test Bench



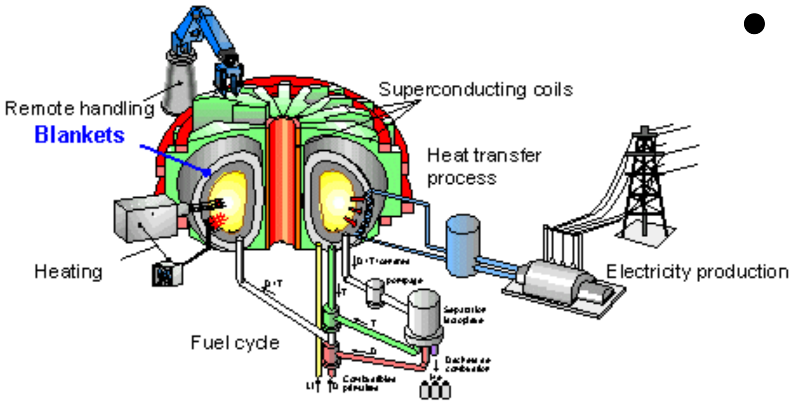
- Can test complete **axisymmetric toroidal liquid-metal flow in a tokamak**. (40 coils: B_T up to 1 T for 3 minutes or 0.3 T for 30 minutes, polloidal coils, 0.44 Volt-sec transformer)



- Can test **transient behavior** during start-up, plasma-induced eddy currents, runaway electrons, and ramp down.



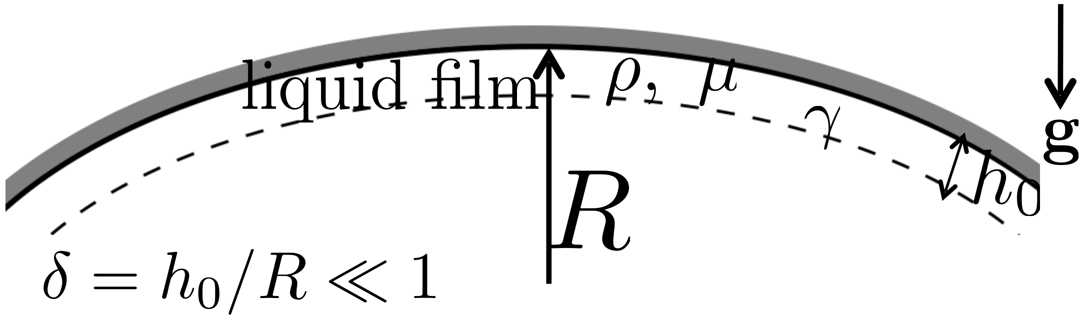
- Can test **first wall heat flux** levels and demonstration of steady state (30 minute) first wall flowing liquid metal systems.



- Can test **low-recycling feasibility**. (D absorption by lithium, liquid metal flow through field gradients, D distillation, D re-introduction)

Gap #1: Free-surface flowing liquid stability in fusion reactor environments

Theme: Horizontal layer of dense fluid over less dense fluid is unstable (drips): Rayleigh-Taylor instability



Study dynamics on the underside of a curved surface (model of a tokamak):

Approach: Experiments with model systems, numerics and theory

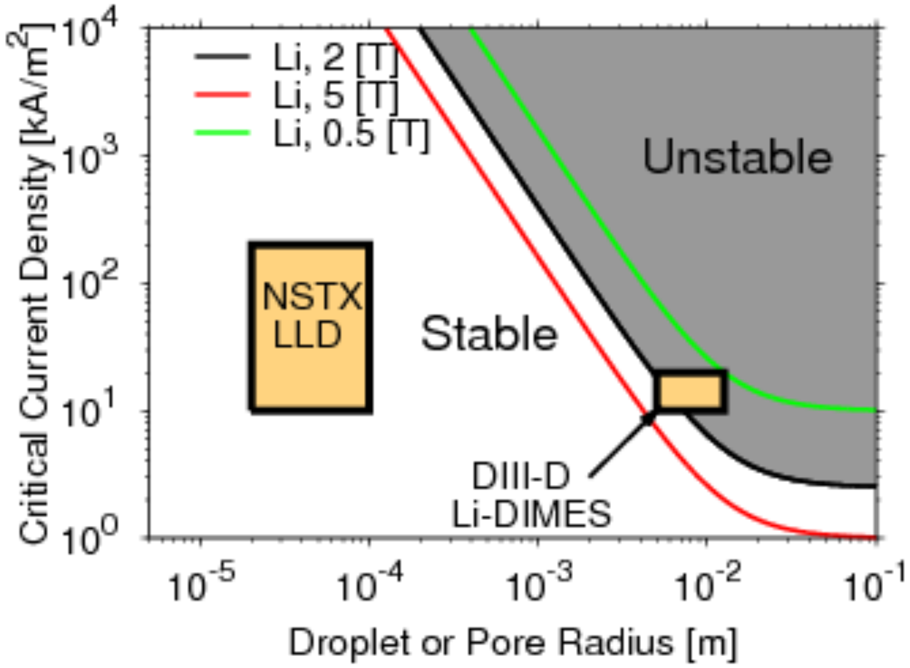
Finding: Film thickness smaller than a critical value is STABLE –fluid slides along the wall towards the bottom faster than any instability can develop

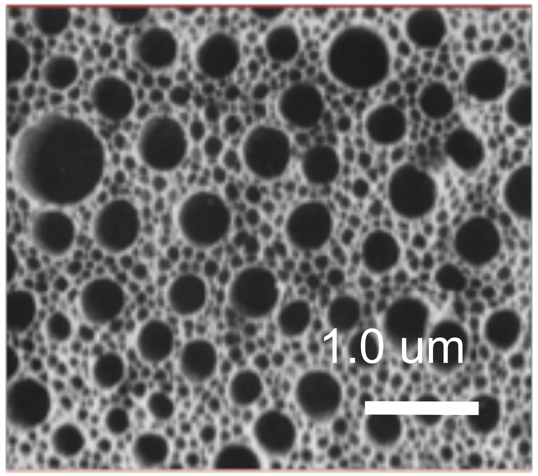
Next step: include MHD effects

$$h < \frac{8\gamma}{\rho g R}$$

Kim, Stone, to be published

Materials development of hierarchical materials (*e.g.* porous substrates) as platforms for LM PFCs





Nano- to micro-porous refractory metal substrates (Allain et al.)