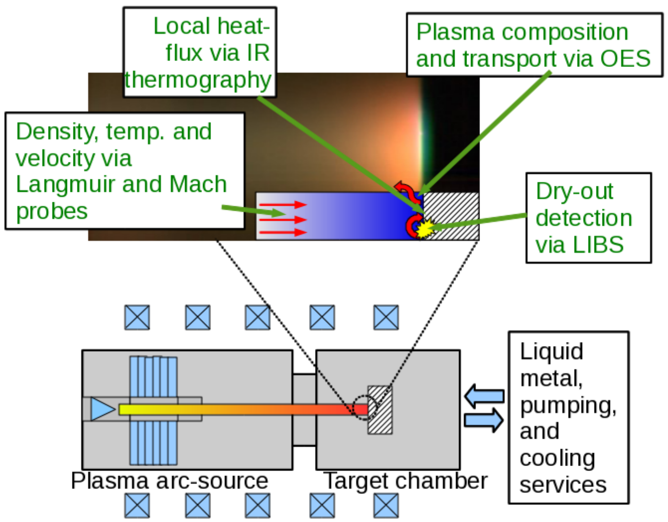
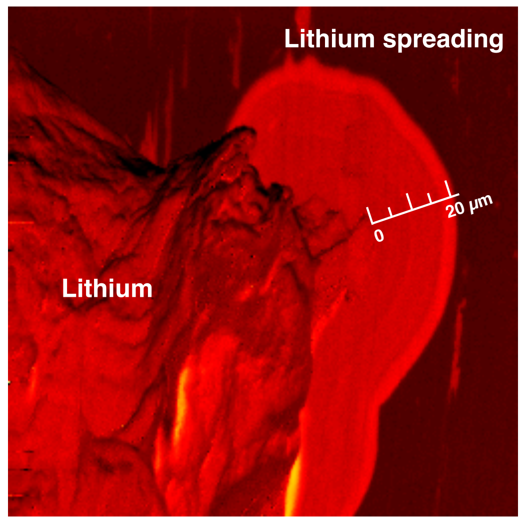
A Liquid Metal PMI/PFC Initiative

R. Maingi, on behalf of
a Liquid Metal PFC Working Group

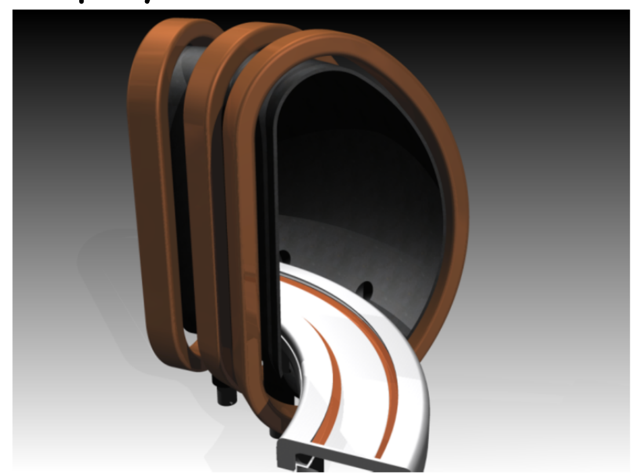
Test stands



Surface Science



Deployment in conf. device



Flowing liquid-metal divertor concept

FESAC Strategic Priorities Panel
Gaithersburg, MD
8-10 July 2014

PPPL PRINCETON PLASMA PHYSICS LABORATORY
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
PRINCETON UNIVERSITY
Stony Brook University
UCLA

Initiative - development of liquid metal PFCs for FNSF and beyond: *transformative area, ripe for US leadership*

- Update on gaps since Greenwald and ReNeW:
  Power exhaust more challenging than previously thought
  - Both steady and transient loads

- Goal of initiative is to conduct research so that liquid metals can be considered as PFC candidates for FNSF and beyond
  - Advantages and Knowledge Gaps
  - Emphasis is on Li, but Sn and eutectics to be evaluated

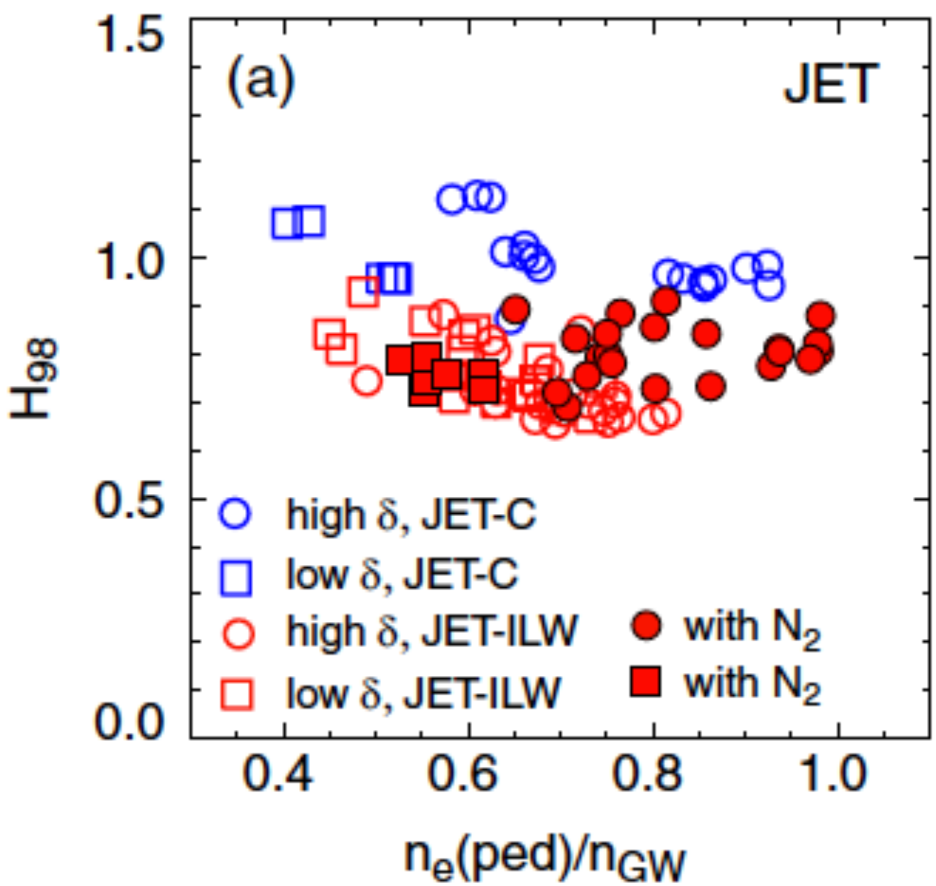
- Elements of liquid metal initiative
  - Thrust: Science and technology of liquid PFCs (*Jaworski talk*)
  - Thrust: Fundamental liquid metal surface science (*Allain talk*)
  - Thrust: Deployment in confinement devices (*this talk*)

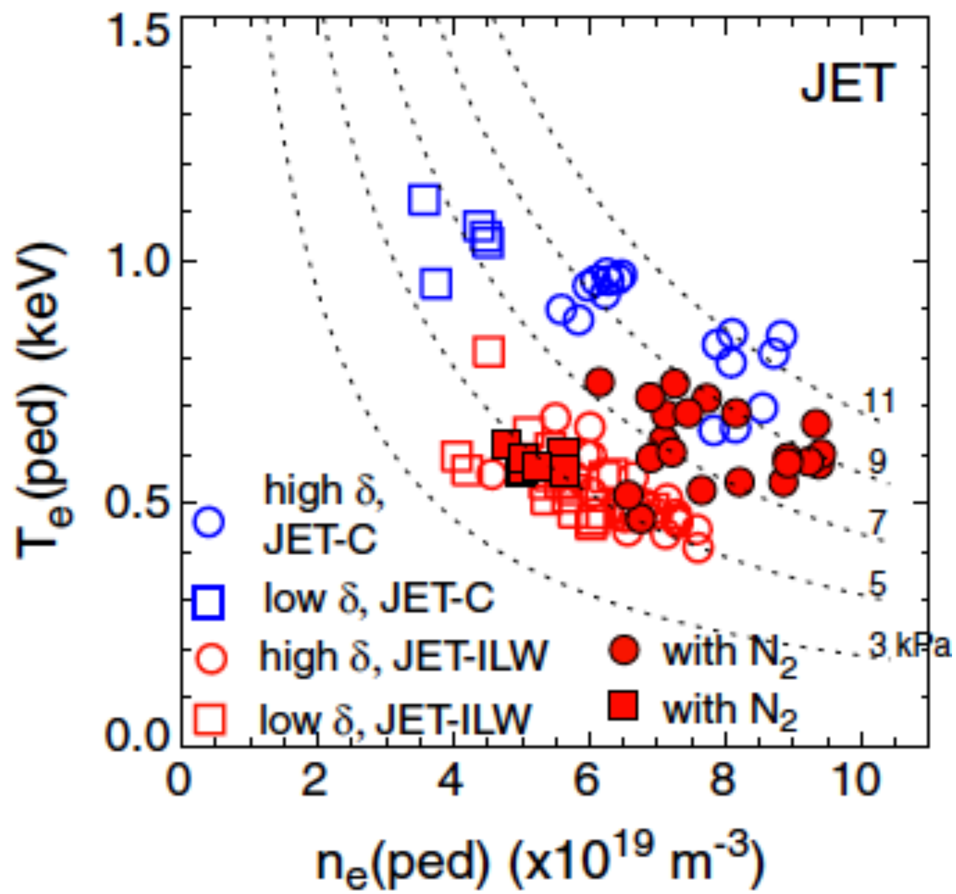
The leading solid PFC material, tungsten, has a number of challenges; focal area of worldwide PMI program

- Accepted heat flux exhaust limit for W is 5-15 MW/m^2, depending on magnitude/frequency of transients allowed
  - More realistic power exhaust limit for reactors $\leq$ 5 MW/m^2, because W thermal properties degrade under neutron fluence
- W ductile-to-brittle transition (DBTT) temperature too high
  - DBTT goes up with neutron fluence; W will be brittle in some areas
- W develops nano-structures ("fuzz", bubbles, dust) with He bombardment and elevated temperatures
  - Erosion, PFC integrity and performance, tritium retention issues
- Core integration: difficult to maintain high τ_E, T_{ped} (e.g. JET)

➢ W would be more attractive if covered by liquid metal
  - Leading substrate candidate

Pedestal performance and core confinement in JET scenarios was reduced with installation of ITER-like wall

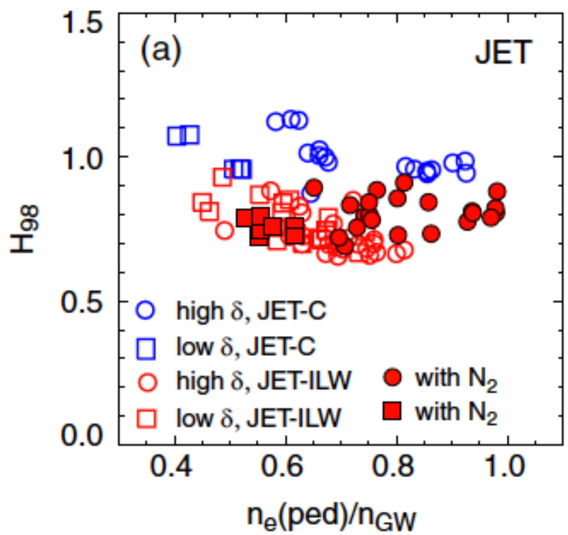


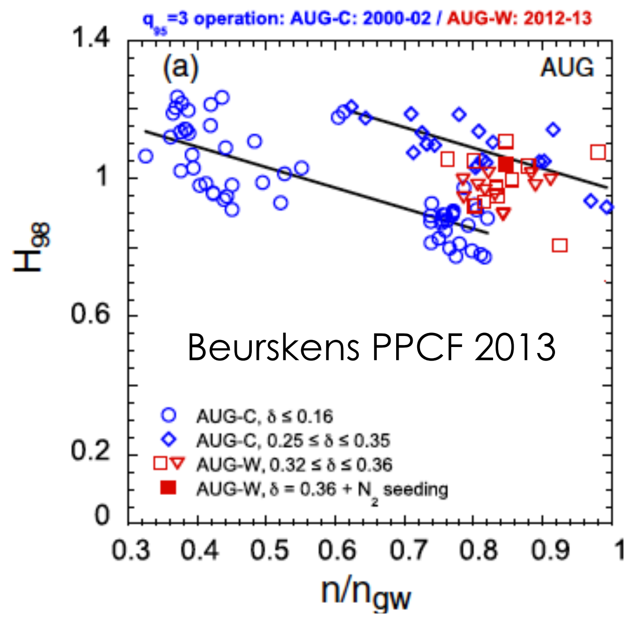


- Substantial value in development of scenarios with actual candidate PFC materials

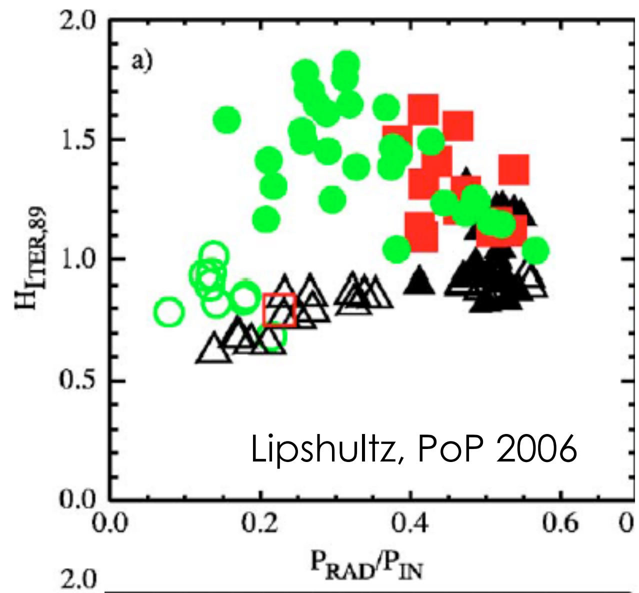
Beurskens PPCF 2013

Scenarios in tokamak discharges with High-Z PFCs can affect pedestal performance and core confinement

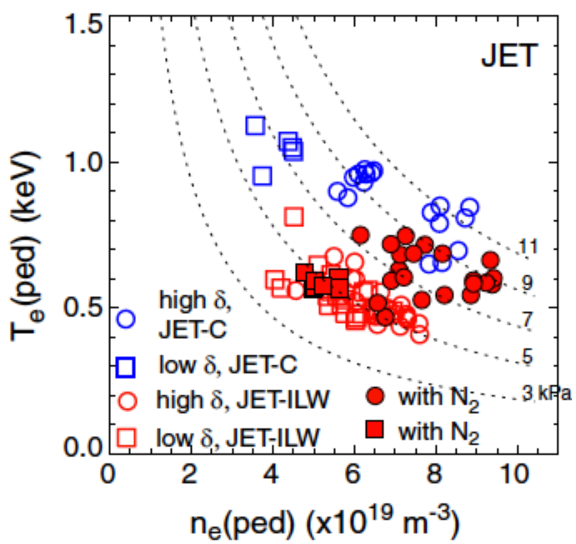




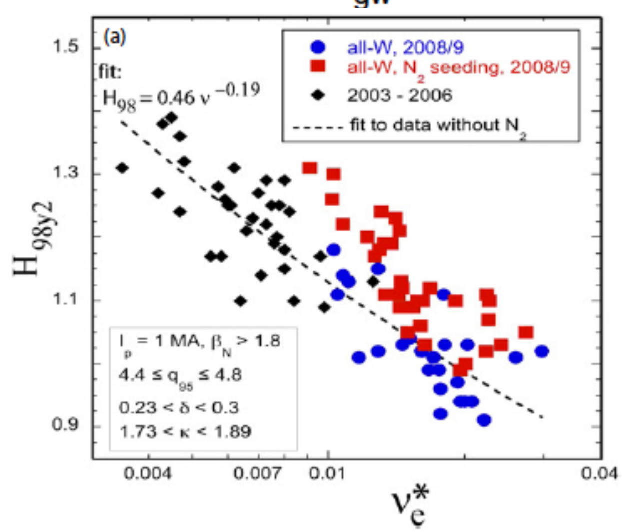
Beurskens PPCF 2013



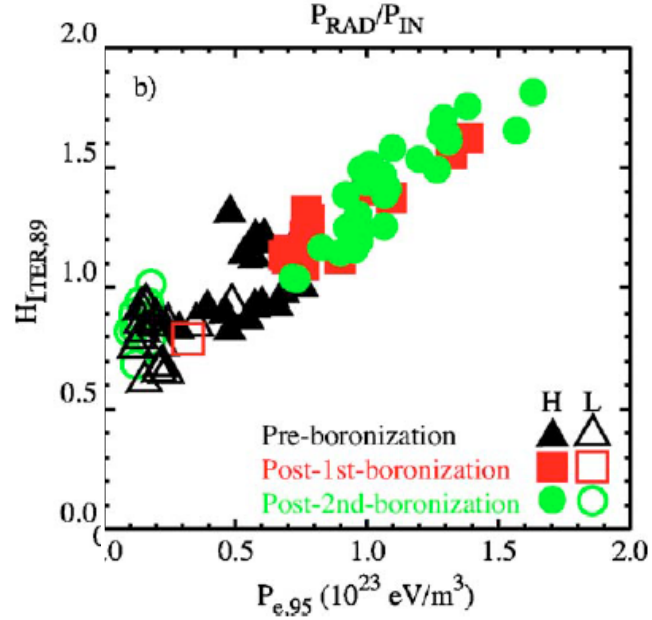
Lipshultz, PoP 2006



Beurskens PPCF 2013

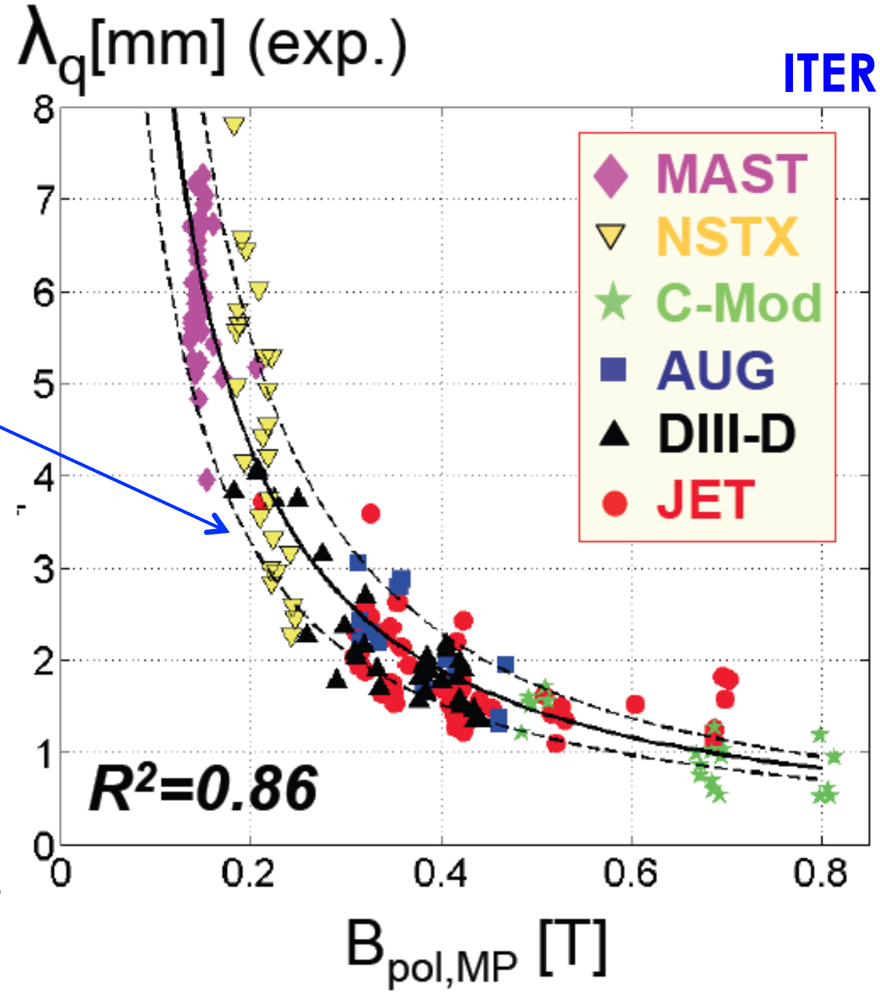


Kallenbach NF 2011



Update on gaps since ReNeW: Steady heat flux exhaust is more challenging than projected at ReNeW

- Heat flux profile measured in divertor; footprint 'width' λ_q projected to outer midplane with flux expansion
- International effort found that λ_q varies inversely with $B_{pol,MP}$
  - Low gas puff attached plasmas; some broadening and heat flux dissipation with detachment
- Projected width in ITER ~ 1/5 previous value; operating window narrows Kukushkin, JNM 2013
- *Much more challenging for reactors*



Eich, NF 2013

Impact of low λ_q^{mid} studied for ITER

Constant ⊥ diffusivities multiplied by f_{perp}=

1 : $D_\perp = 0.3\ m^2/s$, $\chi_{\perp i,e} = 1\ m^2/s$

1/2: $D_\perp = 0.15\ m^2/s$, $\chi_{\perp i,e} = 0.5\ m^2/s$

1/4: $D_\perp = 0.075\ m^2/s$, $\chi_{\perp i,e} = 0.25\ m^2/s$

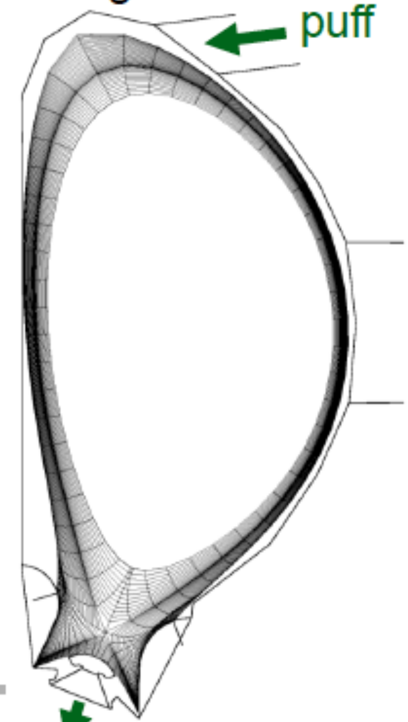
Radial grid spacing finer near separatrix for 1/2, 1/4

Full-C machine, D + He + C plasma

Flux-limited $q_{||}$

Non-linear MC neutral model

n-n and m-i collisions, no hydrocarbons



(a) Density scans with gas puff variation,

P_{SOL} = 100 MW

D ion flux from core: Γ_i = 40 Pa-m³/s or $-\Gamma_n$

(b) Same for P_{SOL} = 60, 80 and 120 MW → BC for core (scalings)

→ integrated model for the whole plasma

iter china eu india japan korea russia usa

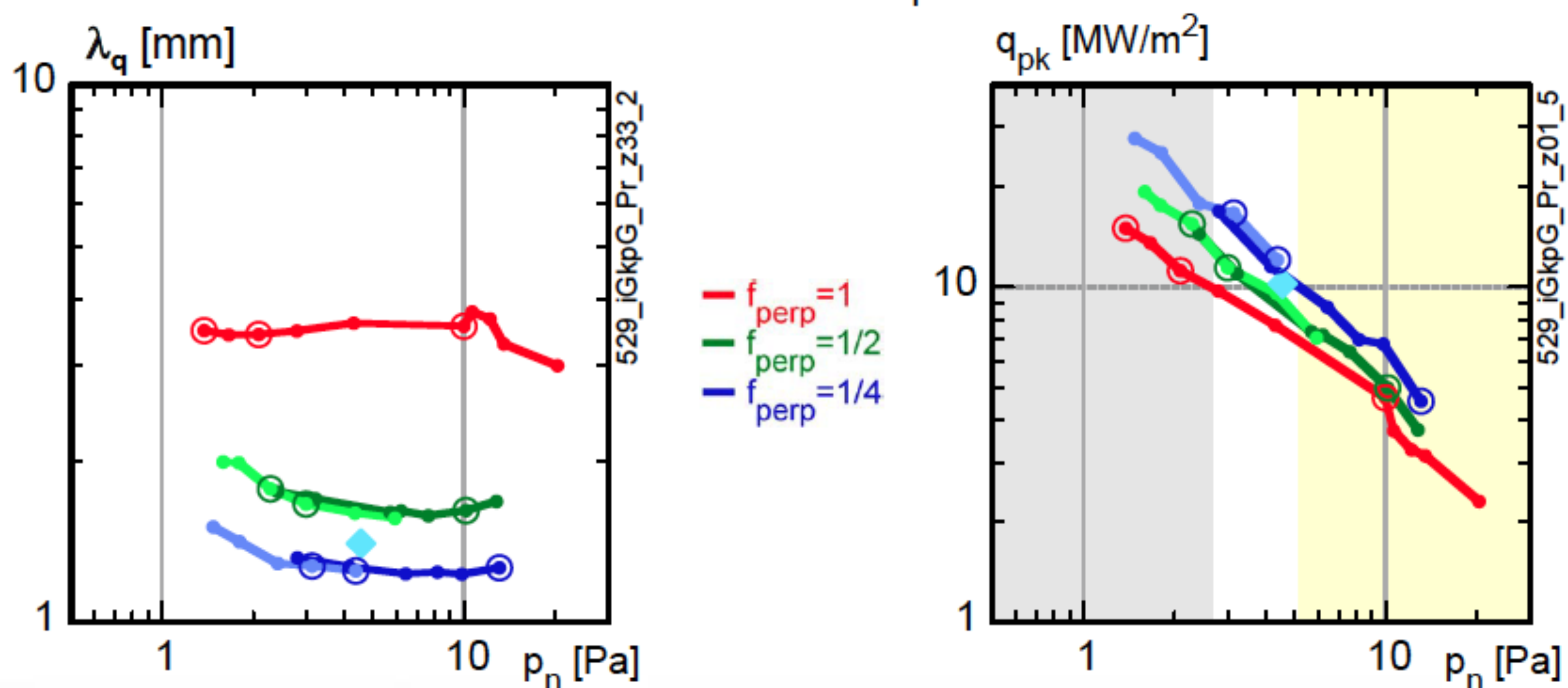
A.S. Kukushkin et al., PSI-20, Aachen, May 2012. ITER_D_7M93AL 8

Cross-field transport can be reduced to get lower λ_q^{mid}, but higher divertor neutral pressure P_n reduces q_{peak}

P_{SOL} = 100 MW

Yes, reduction of ⊥ transport brings λ_q down to ~ 1 mm…

… but increase of peak power on targets is weaker and less pronounced at higher p_n
→ q_{pk} < 10 MW/m² still exist



A.S. Kukushkin et al., PSI-20, Aachen, May 2012. ITER_D_7M93AL 9

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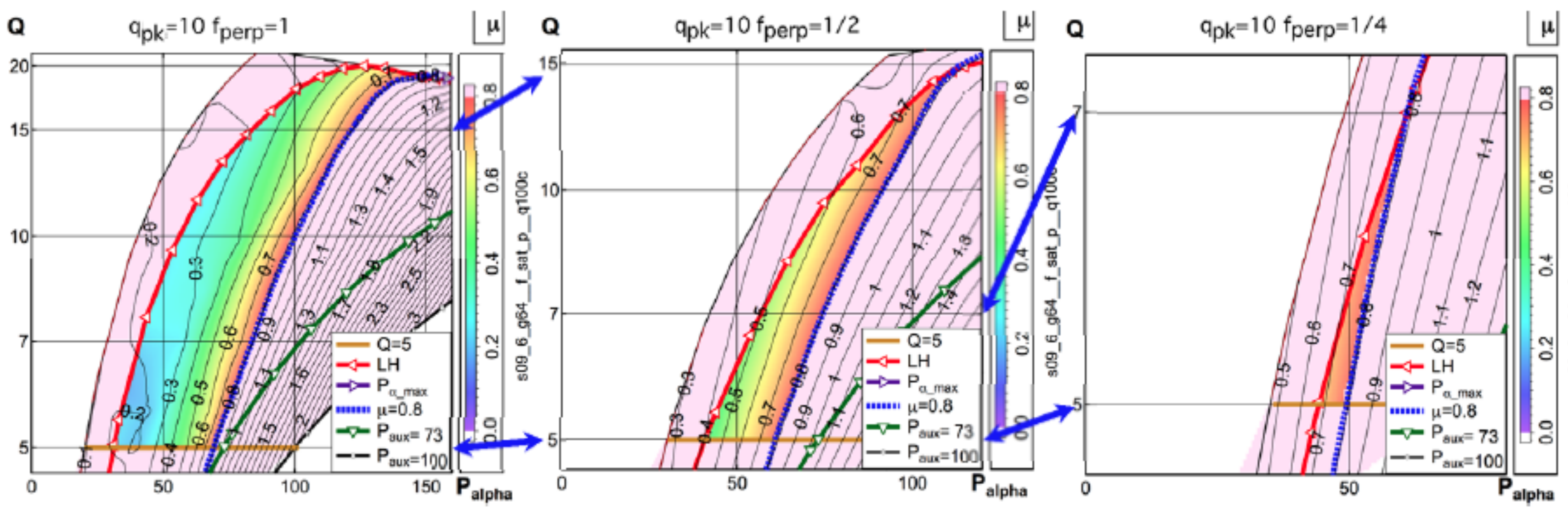
Operating window gets reduced with lower λ_q^{mid}

Window in (P_α, Q) space for $q_{pk} \leq 10$ MW/m^2

λ_q = 3.6 mm λ_q = 1.6 mm λ_q = 1.2 mm



Window limited by $P_{SOL} > P_{LH}$, $\mu < 0.8$, Q > 5 and $q_{pk} \leq 10$ MW/m^2

Still exists at λ_q = 1.2 mm but almost a point, Q ≤ 7, $P_\alpha \leq 60$ MW

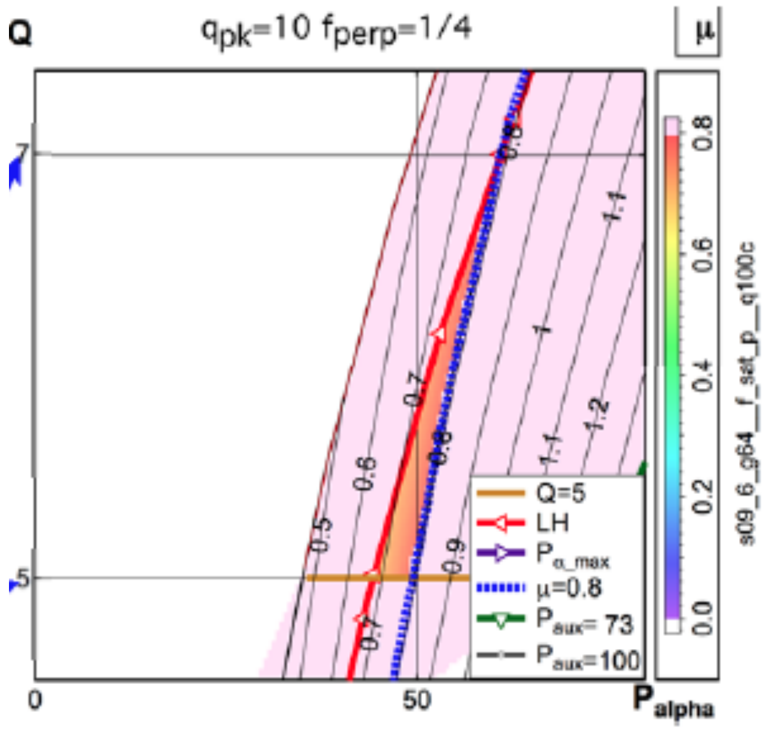
Detachment limit gets more demanding at low λ_q

iter china eu india japan korea russia usa

A.S. Kukushkin et al., PSI-20, Aachen, May 2012. ITER_D_7M93AL 25

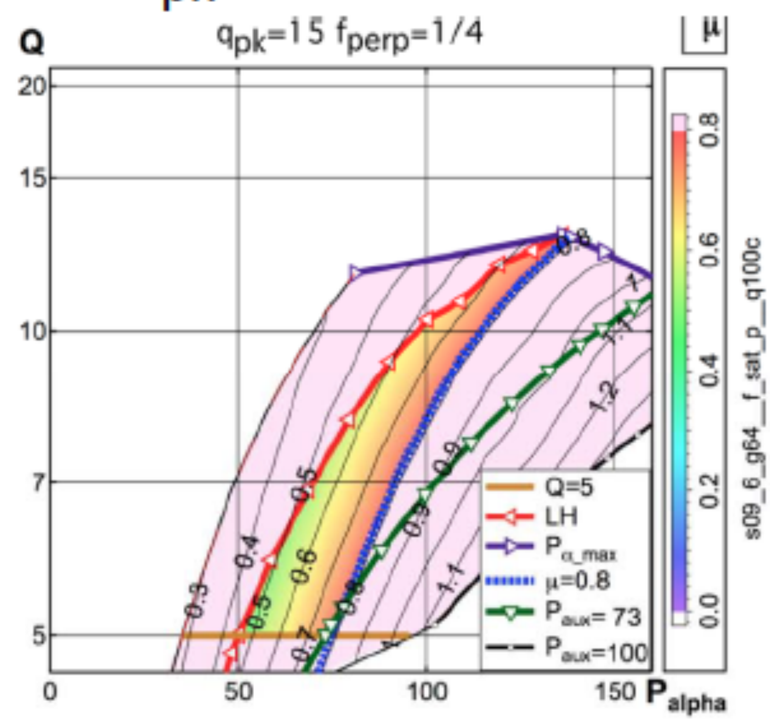
Operating window can be partly restored by increasing q_{peak}^{max} to 12-15 MW/m^2

λ_q = 1.2 mm



λ_q = 1.2 mm,

$q_{pk} \leq$ 15 MW/m^2



- Technology improvements or complete elimination of ELM transients could increase q_{peak}^{max} by 50%

Kukushkin, PSI 2012

Reactors heat exhaust more challenging when considering exhaust power normalized by device size (R, R^2, or R^3)

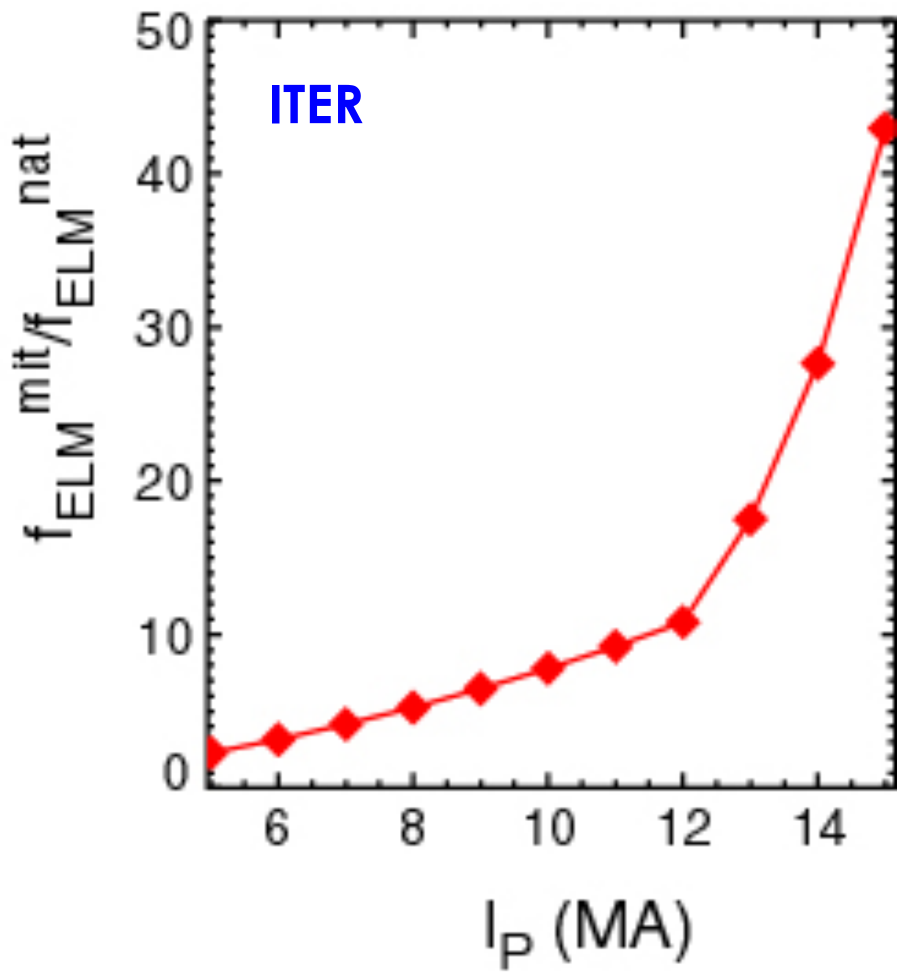
Device name Divertor: SD/XD	Heating power P (MW)	Major radius R (m)	P_{heat}/R ITER=1	P_{heat}/R^2 ITER=1	P_{heat}/R^3 ITER=1
C-Mod	3	0.6	0.26	2.7	—
DIII-D	10	1.6	0.31	0.68	—
JET	17	3	0.31	0.60	—
JT-60U	17	3.4	0.26	0.55	—
ITER	120	6.2	1	1	1
EU-A	1246	9.6	6.8	4.3	2.8
EU-B	990	8.6	6.1	4.3	3.2
EU-C	792	7.5	5.6	4.5	3.8
EU-D	571	6.1	4.9	4.9	5.0
ARIES-AT	387	5.2	3.9	4.6	5.6
ARIES-RS	515	5.5	4.9	5.4	6.2
Slim-CS	645	5.5	6.2	6.8	7.8
CREST	691	5.4	6.7	7.6	8.8

Device name reactor/BPX divertor: SD/XD	$f_{rad\text{-}core}$ to give same P_{SOL}/R as ITER (SD)	$f_{rad\text{-}core}$ to give same P_{SOL}/R^3 as ITER (SD)	$f_{rad\text{-}core}$ with P_{SOL}/R metric if XD is used
ITER	16%	16%	
EU-A	88%	70%	69%
EU-B	86%	73%	65%
EU-C	85%	78%	62%
EU-D	83%	83%	57%
ARIES-AT	78%	85%	46%
ARIES-RS	83%	86%	57%
Slim-CS	86%	89%	66%
CREST	87%	90%	68%

Kotschenreuther, PoP 2007

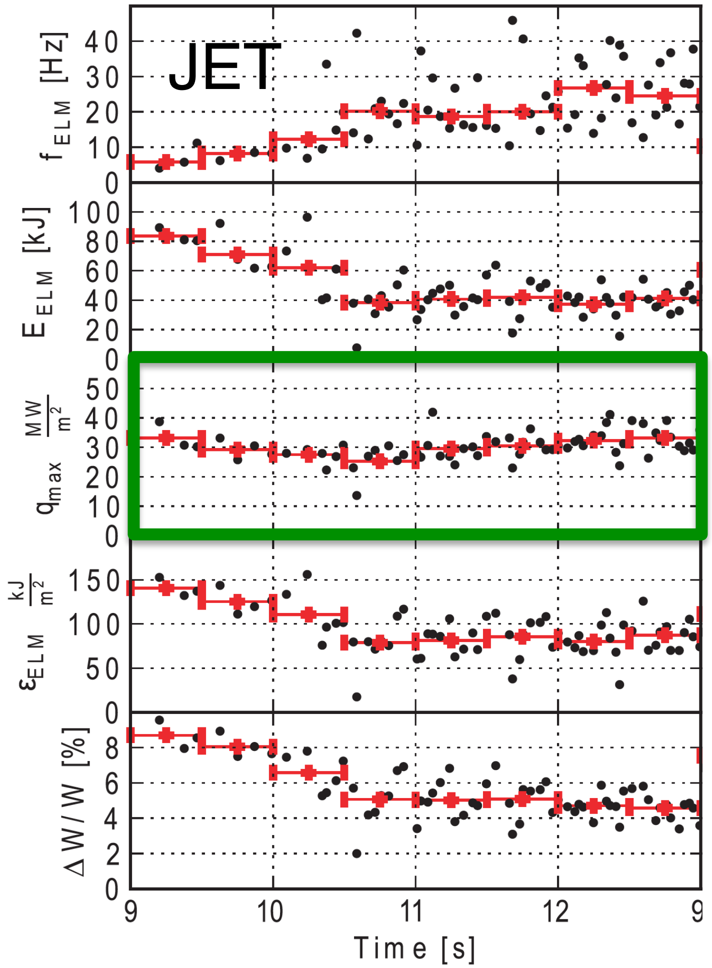
Update on gaps since ReNeW: ELM mitigation requirements are more challenging than projected at ReNeW

- <u>For ITER</u>: need 45x ELM heat flux mitigation; previously ~ 20x
  - Set energy flux limit: $\Delta W_{ELM} < 0.7$ MJ (0.2% W_p)
  - Project ELM frequency for ITER vs. I_p
    - Inter-ELM heat flux width $\lambda_q \sim 1/I_p$
  - Assess ELM damage limit for Be and needed freq. to keep core clean of W
  - Assess minimum ELM multiplier needed
    - Using $\Delta W_{ELM} f_{ELM} = \alpha P_{SOL}$

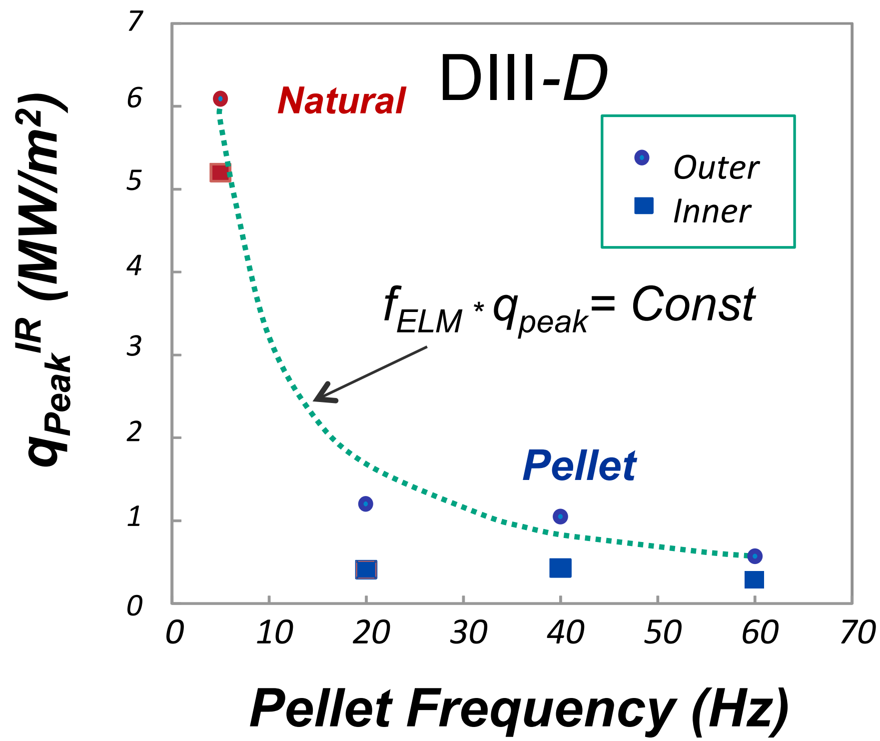


Loarte, NF 2014

ELM frequency increased in both JET and DIII-D; peak heat flux q_{peak} unchanged in JET but reduced in DIII-D



Lang, NF2013



Baylor IAEA 2012

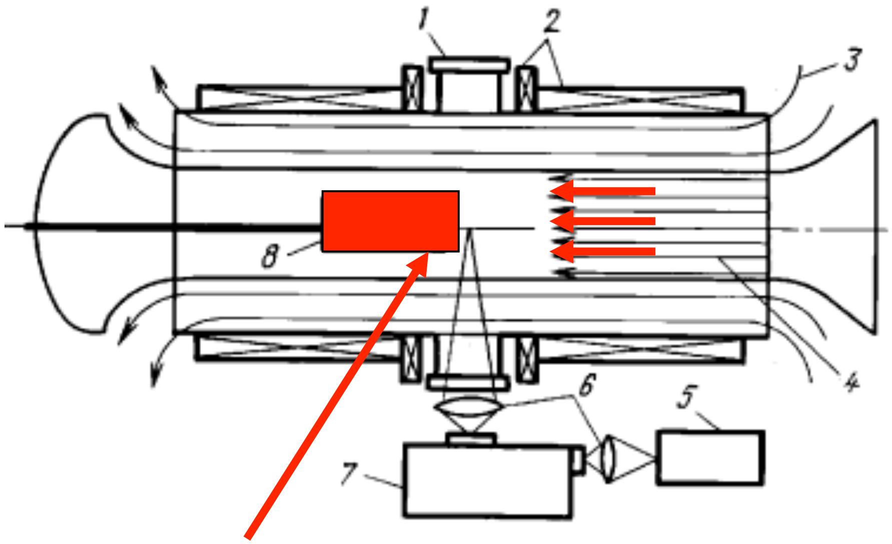
- Is the difference related to metallic vs. carbon wall?

Advantages and Knowledge Gaps for LM PFCs

- Advantages
  - Very high steady, and transient heat exhaust, in principle (50 MW/m^2 from electron beam exhausted; also 60 MJ/m^2 in 1 μsec)
  - Erosion tolerable from PFC view: self healing surface
  - No dust; main chamber material transported to divertor could be removed via flow
  - LM is neutron tolerant; protects substrate from PMI
  - Liquid lithium offer access to low recycling, high confinement regimes under proper conditions
- Knowledge Gaps
  - Reliably producing stable LM surfaces and flows
  - Understanding and controlling the LM chemistry
  - Acceptable temperature windows for specific integrated scenarios
- Goal: conduct research needed for LM PFC to be considered as a viable PFC candidate for FNSF

Simulation of disruption and ELM effect

was provided by plasma gun experiments



Lithium CPS targets

Hydrogen plasma gun:
1 **– diagnostic window;**
2**– magnetic field coils;**
4 **– hydrogen plasma flux;**
5 **– spectroscope / laser scattering ;** ***8*** **– Li target**

Initial temperature of target- 20-350^oC

Experimental conditions

	QSPA	MK- 200UG	Plasma focus
Q, MJ/m^2	4-5	15	60
t, s	$5{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$\sim 10^{-6}$
n_e, cm^{-3}	$(2\text{-}5){\cdot}10^{16}$	$(2\text{-}6){\cdot}10^{15}$	10^{18}
pulses	22	17	40

Stationary heat flux effect

Investigations was started with stationary heat flux load simulation by electron-beam experiment in SPRUT-4

vertical horizontal combined

Electron energy - 8 keV
Target area - 15 cm^2
Heat flux - 1-50 MW/m^2
CPS – Mo mesh with R_{eff}=75 μm
Init. temperature – 250^{o}C

<u>Targets withstood</u> long (5-10 minutes, time was limited by Li amount in the targets) heat loads up to 25 MW/m^2 and short (up to 15 s) excursions up to 50 MW/m^2 without cooling. <u>Successful steady state operation</u> (up to 3 hours at power flux from 1 to 11 MW/m^2) of target with heat removal and Li supply systems has been demonstrated. An ability of CPS to save functional properties after partial damage has been confirmed by the experiments with CPS refilling after target drying.

LM initiative has several thrusts to address knowledge gaps

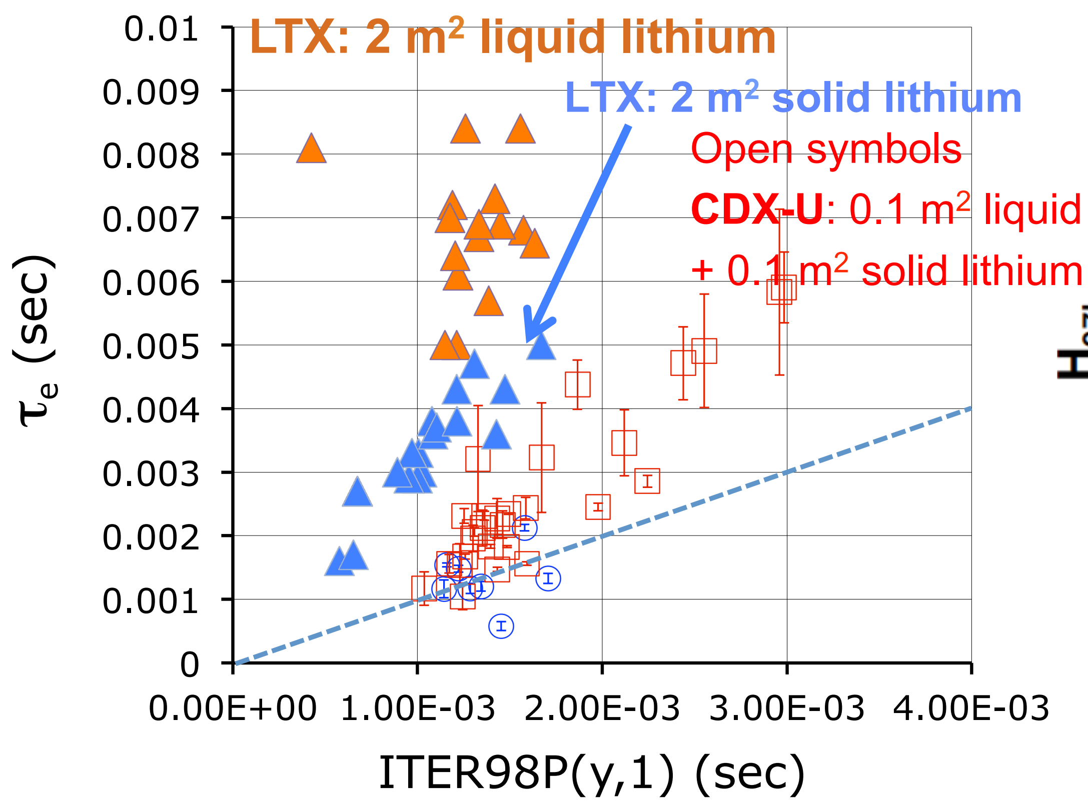
- LM PFC technology and science in flowing, self-cooled and externally cooled test systems (*Jaworski talk*)
  - Flow rates from 1 mm/sec – 10 m/sec
  - Use capillary or j x B forces to overcome MHD forces that could cause mass ejection
  - Determine operating temperature windows
  - Hydrogenic species control and He entrainment
- Fundamental LM surface science studies (*Allain talk*)
  - Keep LM surface clean for reliable flow; understand PMI
  - Predict flow of LM, including wetting and de-wetting
- Compatibility with attractive core/edge plasma (*rest of talk*)
  - Plasma power and momentum exhaust; particle control
  - Applicability of low recycling regimes with excellent confinement: target H98 $\geq$ 2, enabled by LM resilience to transients and high peak heat flux exhaust: <u>attractive for ST-FNSF</u>

Several 'new' ideas since ALPS/APEX studies

- Slow flowing (1 cm/sec) thin film (0.1 mm) liquid lithium across SS plate, driven by j x B
  - Tested successfully in HT-7 in 2012
  - First test in EAST as outboard limiter in 2014
- Continuous flow driven by thermoelectric effect: LIMITS (Liquid Metal Infused TrencheS)
  - Tested successfully in HT-7 in 2012
  - First test in EAST in 2014
- Surface tension balancing MHD forces: capillary porous systems
  - FTU, several Russian tokamaks, NSTX
  - Low recycling, low surface temperature scenario, and high recycling vapor-shielded scenario

Lithium (solid and liquid) PFCs can enhance confinement

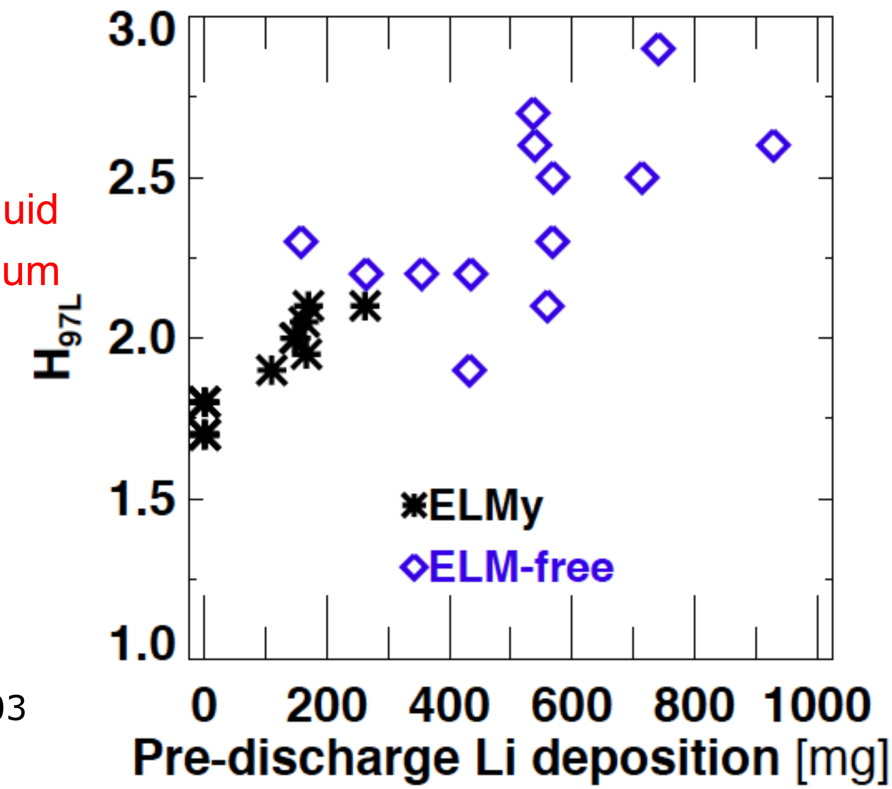
LTX



- Preliminary results: 4-5× improvement over ITER98P(y,2)

Majeski talk

NSTX



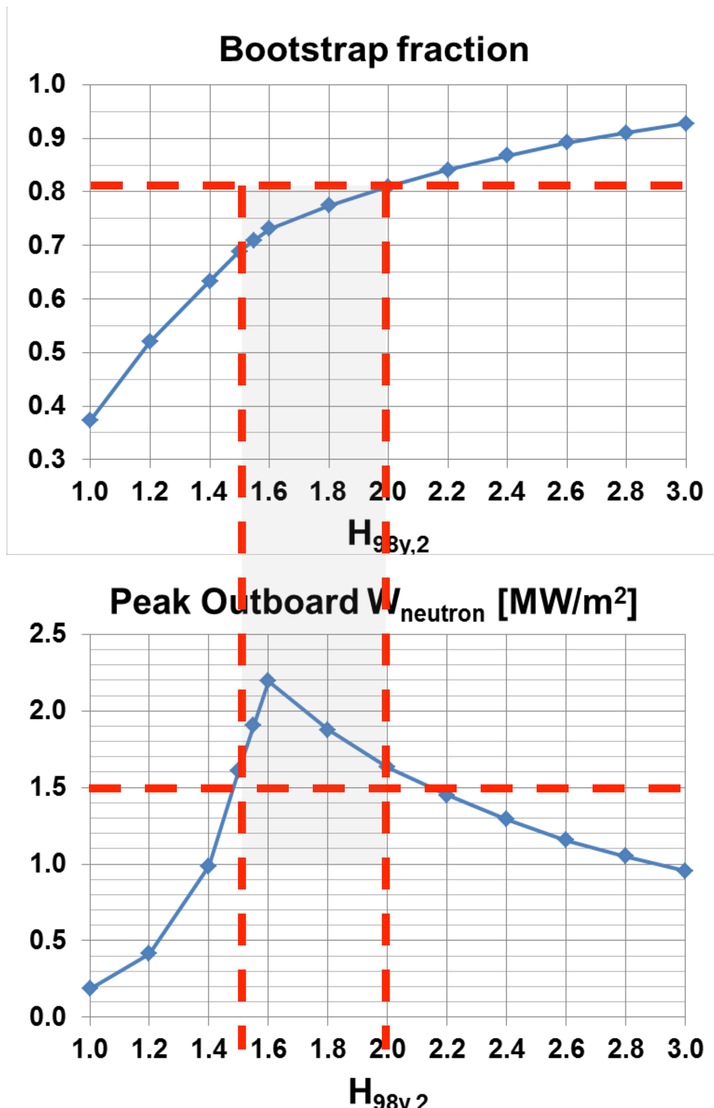
- H98y2 increased from 0.9->1.4

Maingi, PRL 2011; Boyle, JNM 2013

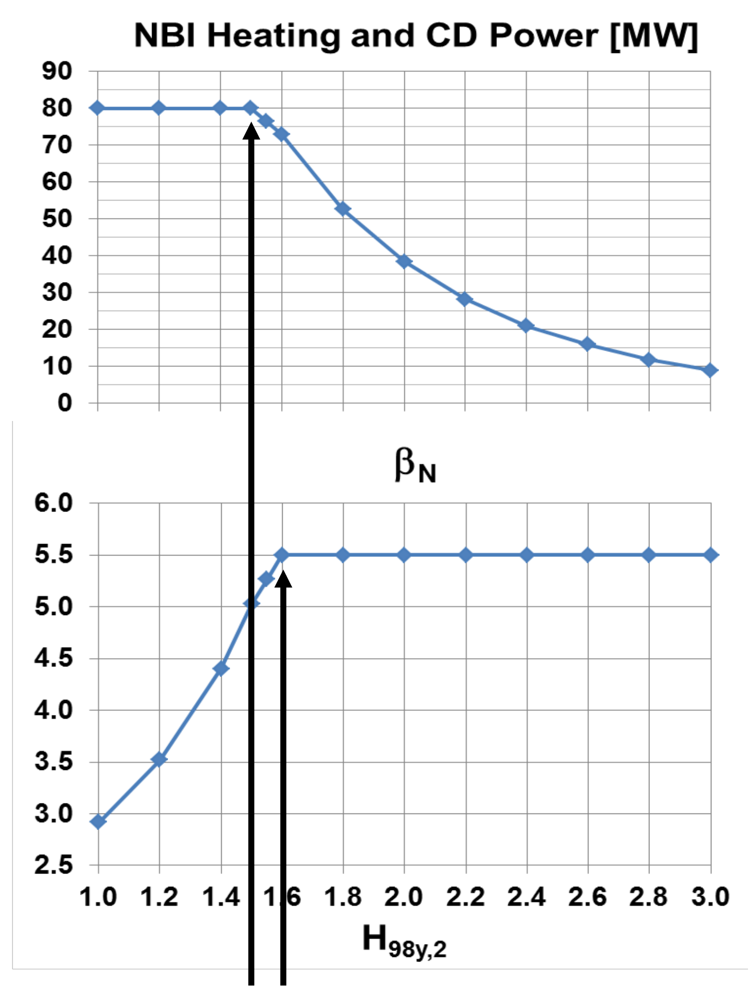
$H_{98y,2}$ range of 1.5-2 favorable for high neutron wall loading ≥ 1.5MW/m^2 (peak outboard), f_{BS} < 80% for external control

ST-FNSF

- A = 1.75
- R_0 = 1.7m
- B_T = 2.9T
- κ, δ = 2.8, 0.55
- $f_{Greenwald}$ = 0.8
- f_{NICD} = 100%
- E_{NNBI} = 0.5MeV
- P_{NNBI} ≤ 80MW



J. Menard



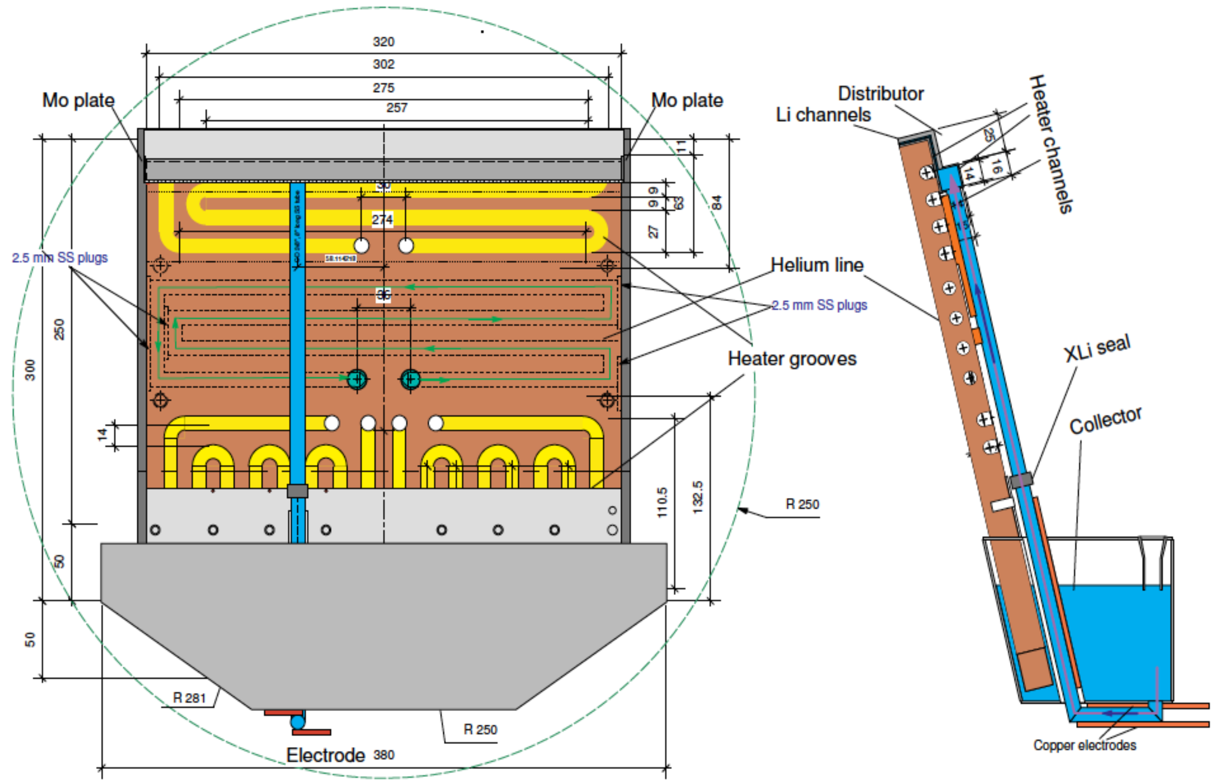
- **Power limited for $H_{98y,2}$ < 1.5**
- **Stability limited for $H_{98y,2}$ > 1.6**

Final step of the LM initiative is deployment of LM PFCs in high power, diverted confinement devices

- Assess ability of LM PFC to enable or couple to attractive core/edge plasma
  - NSTX-U: toward evaluation for FNSF (ST or AT) (*Menard talk*)
  - EAST: evaluation in long pulse advanced tokamak; very slow flowing, small midplane liquid lithium limiter being tested in 2014
  - Resources from this thrust used to deploy flowing LM system in NSTX-U, and to support system designs for EAST
  - *Complements LTX (separate funding): ultra low recycling with liquid Li*
  - *Complements European work: FTU, TJ-II, Magnum-PSI work*
- Assess compatibility with heat exhaust innovations
  - Innovative divertors (e.g. super-X, snowflake, X, or combinations) may facilitate LM deployment via 'isolated' PWI chamber
- Includes basic theory support needed for projections
  - Edge/SOL/divertor transport with LM boundary

Liquid lithium limiter delivered to EAST for deployment in 2014

- Liquid Li thin film viscous flow system tested on HT-7 and sent to EAST
- Idea is to confirm that liquid Li flow can be maintained for long periods
- To be inserted in EAST outer midplance (*see Li, Guo talk*)



Copper coupon and collector

Figure 1: Schematic of heated copper plate and small liquid lithium reservoir, to be mounted on an insertable probe for testing in EAST during the 2014 campaign

L.E. Zakharov

Computational Modeling for PSI and Edge Plasma

EDGE CODES
(UEDGE-DEGAS, B2/ EMC3-EIRENE, etc)

NEAR WALL KINETICS

MATERIAL WALL
(BCAs, MDs, XOLOTL, etc)

Plasma edge codes

- No plasma edge code is currently able to handle plasma kinetic effects
  - B2 & UEDGE use FV to discretize plasma multi-fluid equations
  - EMC3 uses MC to sample *the same* fluid equations
- Only EMC3 allows 3D fluid (B2 &UEDGE are 2D)
- Turbulence is neglected in all cases (parameters are used to reconcile anom.transp.)
- Codes consider quasineutral region only (BCs are at the sheath)

Near Wall Kinetics

- Region extending from the wall, across the sheath, to the QN region inside the plasma
- Kinetic treatment
- Detailed PMI (both electrons and ions)
- Interface between Edge codes and Material Codes
- Necessary link between Edge codes & Material Codes

Development of Near Wall Kinetics models able to interface Edge and Material codes under extreme conditions of PM interaction

Reconciliation of 2D/3D fluid modeling with plasma kinetic behavior via coupling the kinetic solver with fluid solver

Develop predictive capability, V&V plays fundamental role

→ Use HIDRA device to benchmark near wall/materials and plasma edge physics codes

→ UIUC computational resources

Thrust includes support for theory and modeling needed for extrapolability of core-edge integrated performance

- Response of divertor and pedestal plasma to LM PFCs
  - Low and high recycling liquid Li; high recycling Sn and eutectics
  - Detailed numerical calculations with SOL codes (SOLPS, UEDGE), near-wall kinetics calculations, and material response calculations (BCAs, MD, XOLOTL, …)
  - Analytic and semi-analytic calculations

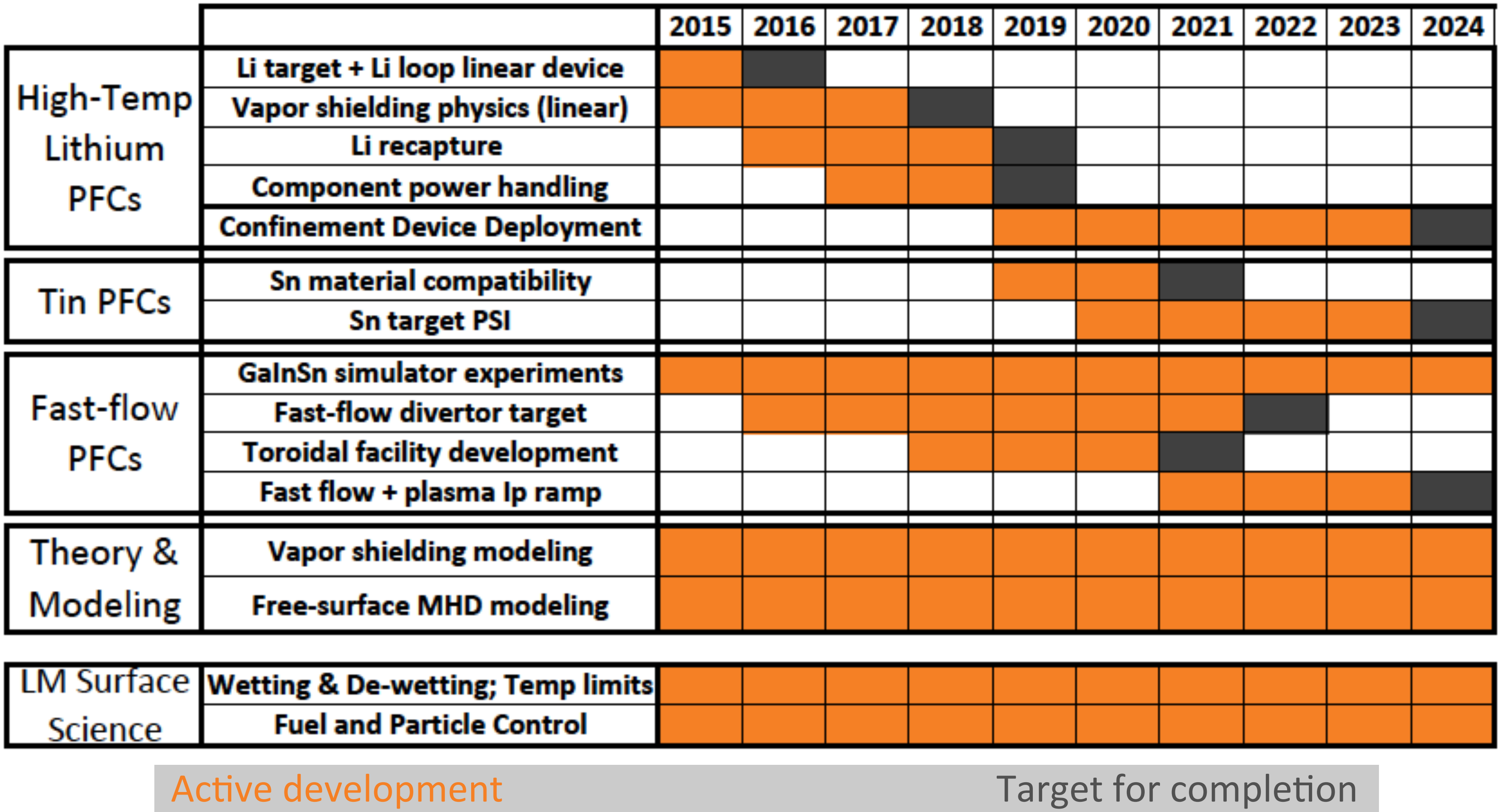
- Ideas for reducing the loading on divertors and first walls
  - First principles modeling of SOL heat flux width including e.g. non-ambipolar currents
  - Ways to broaden the SOL width, e.g. choice of magnetic geometries or LM PFCs

Summary and Required Resources

- Elements of liquid metal initiative
  - Thrust: Science and technology of LM PFCs (*Jaworski talk*)
  - Thrust: Fundamental LM surface science (*Allain talk*)
  - Thrust: Deployment in confinement devices (*this talk*)
    - Outside the scope of this initiative, but attractive: deployment in high power density systems (e.g. ADX; high $q_{||}$, hot-wall, high duty factor) (*LaBombard, Marmar, Goldston talks*)

- Resources ~ 10 M$/year for all 3 thrusts
  - Test stands and surface science thrusts somewhat front-end loaded, while deployment on confinement devices is back-end loaded
  - Enables deployment of flowing LM PFC in entire divertor on NSTX-U
  - Enables EAST system designs + collaborative research

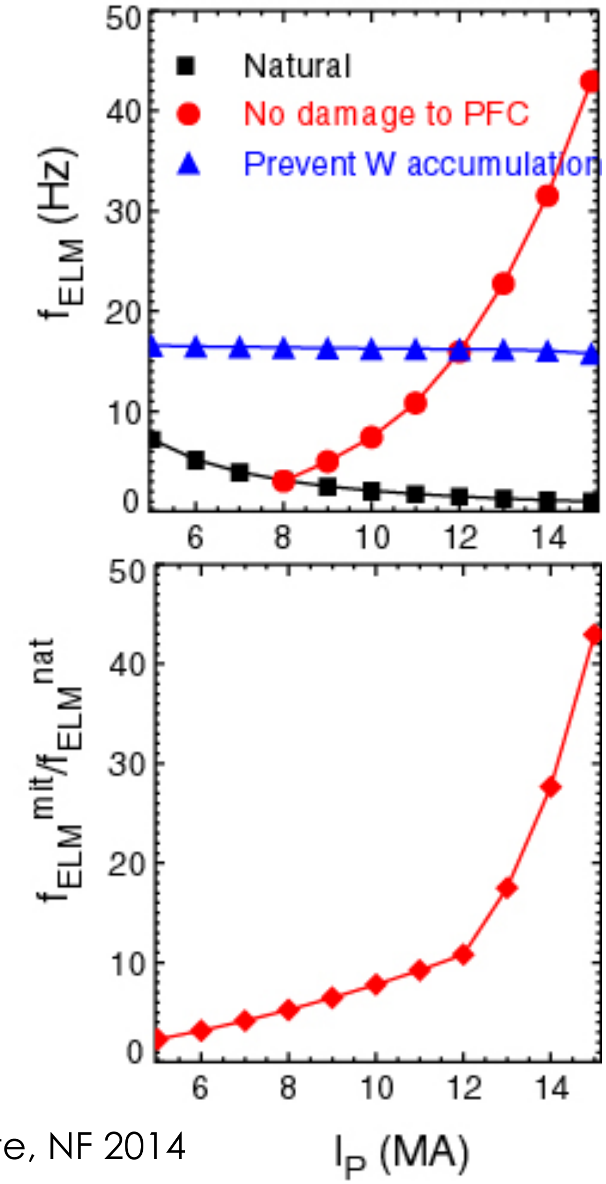
Dedicated facilities can achieve aggressive timeline for confinement device demonstrations



BACKUP

Update on gaps since ReNeW: ELM mitigation requirements are more challenging than projected at ReNeW

- Set energy flux limit: ΔW_{ELM} < 0.7 MJ (0.2% W_p)
  - 50% of damage limit, not including fatigue
- Project ELM frequency for ITER vs. I_p
  - Inter-ELM heat flux width $\lambda_q \sim 1/I_p$
- Assess ELM damage limit for Be and needed freq. to keep core clean of W
- Assess minimum ELM multiplier needed
  - Using $\Delta W_{ELM} f_{ELM} = \alpha P_{SOL}$
  - Need **45x** reduction at 15 MA



Loarte, NF 2014

First key step to ELM elimination in NSTX is recycling reduction with lithium

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

→

n_e and ∇n_e reduced
∇T_e fixed

χ_e increased ETG (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

→

J_{bs}, $J_{||}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

D_{eff} reduced, most in ELM-free (SOLPS)

→

n_e and ∇n_e
T_e and ∇T_e
increased

χ_e reduced strongly – μT stable? (GS2)

→

Edge P_e follows n_e and T_e; peak P' shifts farther from separatrix

→

J_{bs}, $J_{||}$ increased but far from separatrix; improves stability to kink/peeling modes (ELITE)

Maingi, IAEA 2012, Canik, NF 2013

NSTX-U 15 yr plan: ST physics / scenarios → integrate high-perform. core + high-Z + Li → flowing / large area liquid metals

LTX-U results

2015-2019

ST physics / scenarios:

- Non-ind. start-up/ramp-up
- τ_E vs. β , collisionality
- High β, advanced control
- Mitigate high heat fluxes
- High-Z div, Li vap. shield.

Inform choice of FNSF configuration:

- Lower A or higher A?
- Standard, snowflake, super-X?

2020-2024

High-perf. + metal walls

- All high-Z PFC substrates
- Static → flowing Li module then full toroidal, high T_{wall}
- 5s → 10-20s pulses
- Assess high-Z, high-Z + Li

Inform choice of FNSF/DEMO plasma facing materials:

- High-Z ok?, or high-Z + Li?
- Consider divertor & first-wall

2025-2029

Flowing LM divertor/wall

- Use high temp. walls + Li to sustain very high τ_E
- Flowing Li / Sn divertor
- Study LM-PFC resilience to ELMs and disruptions

Inform choice of FNSF/DEMO PFC technology:

- Slow flow, fast flow, capillary porous? Li, Sn, eutectic?
- Consider divertor & first-wall