The boundary plasma – currently an unstable foundation for reactor design

- Comparison of core and edge uncertainties
- How uncertainties in the heat flux width propagate to all aspects of reactor design
- General recommendations
- Role of C-Mod in addressing previous FESAC recommendations

Presented by

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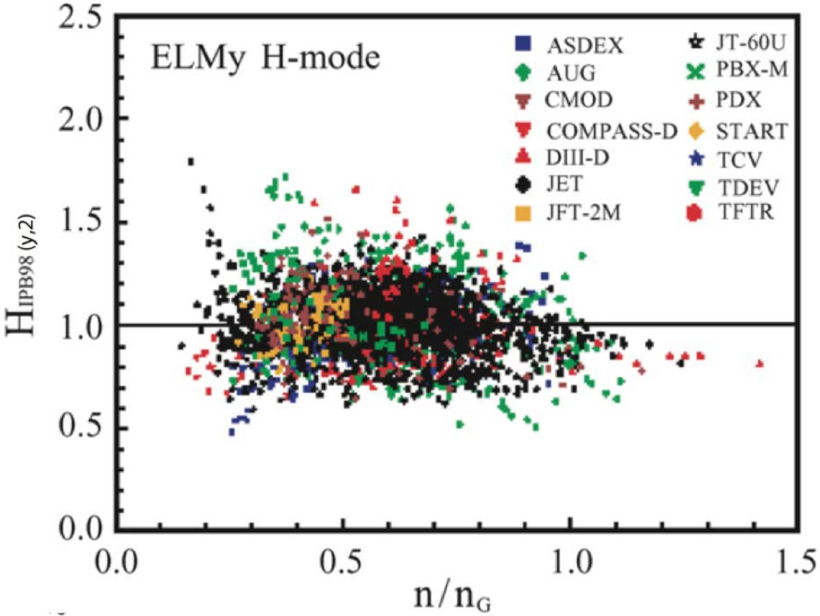
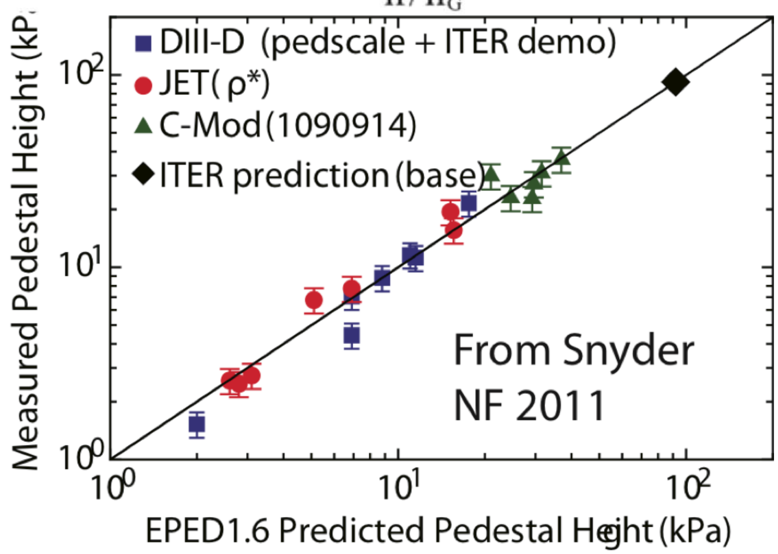
Edge ‘gaps’ in knowledge and experience greatly exceed that of core physics when projected to a reactor

- Fusion research has, over the years, been more focused on core issues in comparison to the edge plasma and the wall-interactions
  - This made sense as the tokamak and other concepts developed in order to determine the basic configuration and what performance is like
  - However, most predictions of reactor performance are based on ‘irrational exuberance’ with respect to the interactions with the surrounding Plasma Facing Components (PFCs)
- In this talk we try to address how to rectify the uncertainties in edge physics (and materials) knowledge to support ITER and guide the future US fusion program

Many years of the US program's focus on core physics have led to relatively low prediction uncertainties

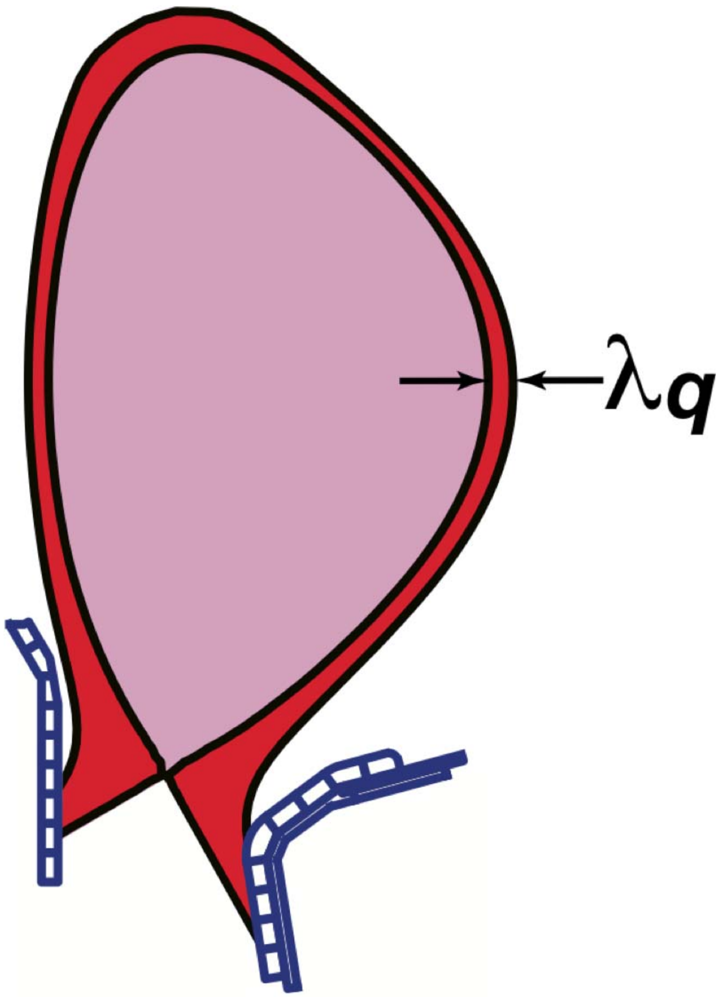
- The prediction of core characteristics (transport, MHD…) is very good based on research in US and internationally
- Pedestal physics has received attention in recent years and made great progress
- As a result, uncertainties are now relatively low (10s of %) in a number of areas, and we can extrapolate with fair confidence to ITER and reactors.
  - Issues do, of course, remain, particularly for RF-driven, steady-state scenarios and good confinement regimes without ELMs





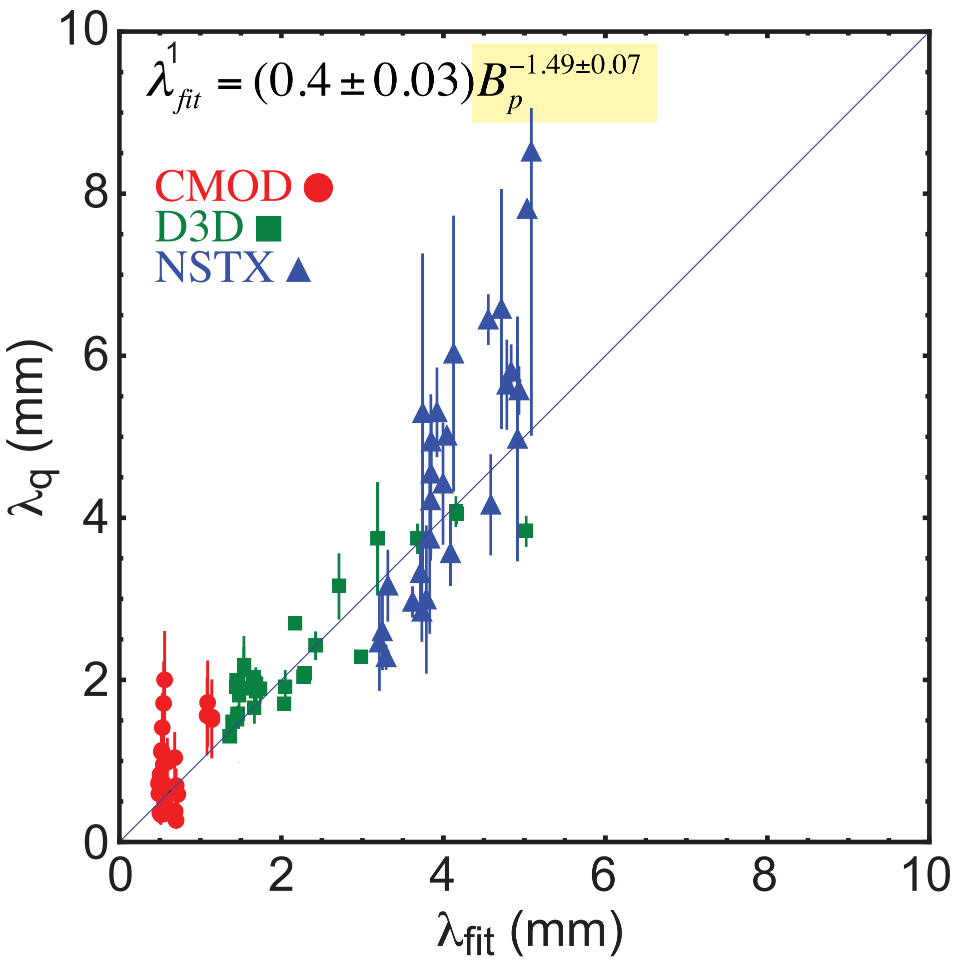
Knowledge gap: The scaling of the power exhaust channel width to ITER and reactor conditions is highly uncertain

- The power flowing along the field to the divertor is typically characterized by an exponential falloff width λq
  - Values reference to the midplane



Knowledge gap: The scaling of the power exhaust channel width to ITER and reactor conditions is highly uncertain

- A recent refocus on understanding the parallel power flow width outside the separatrix has revealed large uncertainties



Study	Physics basis	ITER λq (heat flux width)
Joint Research Thrust 2010[1-3], Eich[4]	Empirical scaling	1 mm

Note – Previous cross-machine experimental studies[5-6], led to a prediction of λq ~ 5mm

[1]M. Makowski et al, PoP 2012, [2]B. LaBombard et al, PoP 2010, [3]R. Maingi et al, PSI meeting, May 2012, [4]T. Eich, PSI meeting May 2012, [5]A. Kallenbach et al, J. Nucl. Mater. 2005, [4]B. Lipschultz et al, Nucl. Fusion 2007

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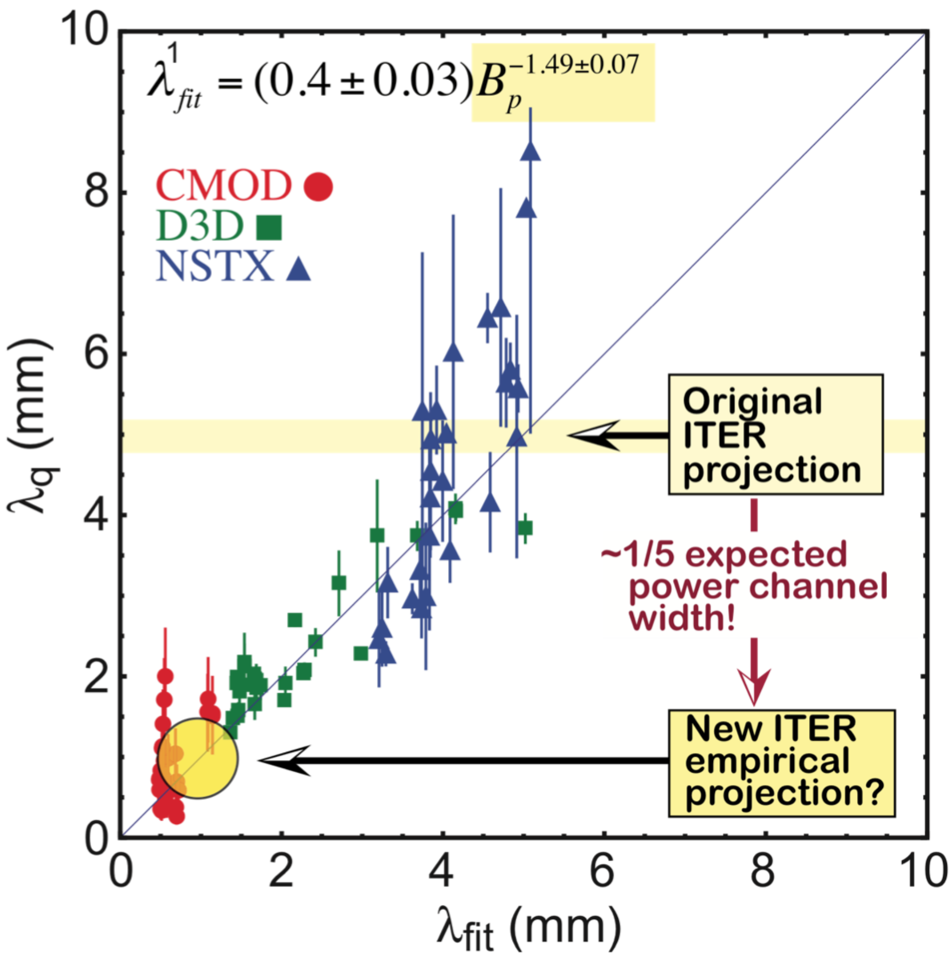
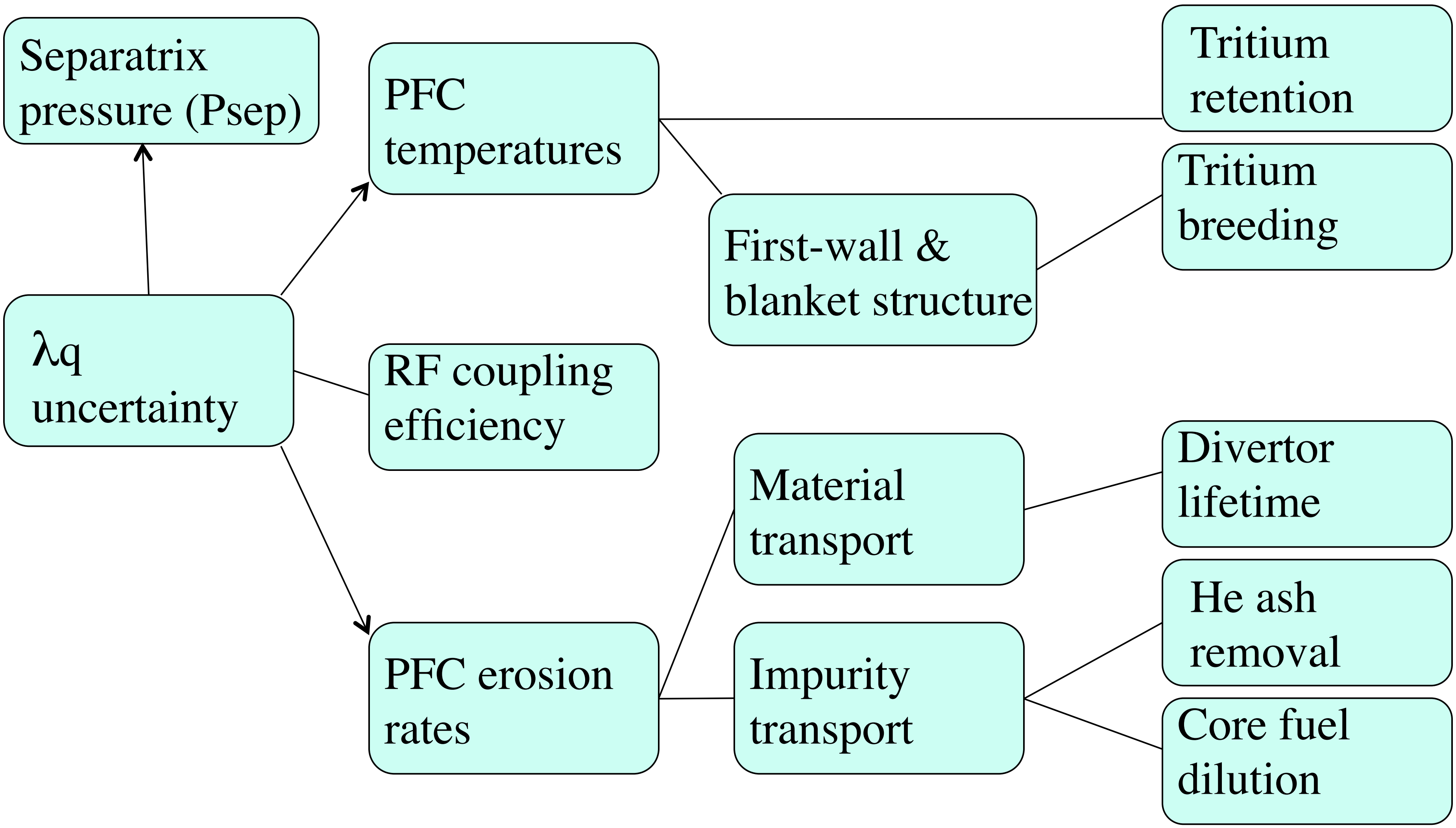


Study	Physics basis	ITER λq (heat flux width)
JRT 2010[1-3], Eich[4]	Empirical scaling	1 mm
Goldston[5]	SOL physics	1 mm
ITER model[6]	Ballooning limit + ion stepsize	5 mm
Whyte[7]	Pedestal/ SOL physics	20-25 mm

[1]M. Makowski et al, PoP 2012, [2]B. LaBombard et al, PoP 2010, [3]R. Maingi et al, PSI meeting, May 2012, [4]T. Eich, PSI meeting May 2012, [5]R. Goldston, PSI meeting May 2012, [5]A. Kukushkin et al, Contrib. Plasma Phys. 2000, [6]D. Whyte, PSI meeting May 2012

Uncertainty in λq propagates to uncertainties in multiple fusion reactor characteristics



Uncertainties are amplified by nonlinear dependencies; →

Overall knowledge gap becomes a 'chasm'.

Other ‘gaps’ in knowledge and experience

- Our white paper covers other uncertainties that are also important and need to be addressed:
  - Integrated PFC material/cooling technology at reactor temperatures that provides a larger margin for peak heat loading will increase lifetime and availability.
  - RF systems/physics that can efficiently drive current with acceptable effect on the core plasma and hardware at the first wall – at a significant distance from the separatrix
  - Core/boundary solutions that eliminate transients (ELMs, disruptions) – which will be unacceptable for a reactor. This likely means operation farther from stability limits – not the conventional approach for optimizing a burning plasma.

General Recommendations

- Based on the gaps described above we feel that if the US wants to maintain any possibility to build a reactor it must grow knowledge and experience in BOTH physics and technology – *not become just a materials research program*
- Materials research
  - Focus on niche topics (e.g. material modelling, high temperature PFC systems) in tokamaks and labs. It will be difficult to compete with larger programs (e.g. EU).
- Toroidal systems physics
  - Near term (FY13 and FY12 budget scenarios) – More focus on ITER to reduce uncertainties in the areas of λq, high-Z operation, RF launcher optimization
  - Longer term - Convert the US program to one more directly focused on the large gaps outlined in this talk, while maintaining capabilities in core plasma research
    - Take tungsten and the vertical plate divertor to as close to reactor conditions as possible (steady state, high bulk temperature, high heat loads) and if it cannot be made compatible with good core operation, then dump it (or change core ops)
    - Utilize reactor studies to formulate tests of alternative materials (C, liquid metals) and divertor geometries (e.g. snowflake); test them in toroidal experiments under high parallel heat flux conditions.
    - Dedicate significant machine and lab effort to development and understanding of RF current drive with reactor-like efficiency, core plasma compatibility and separatrix gap

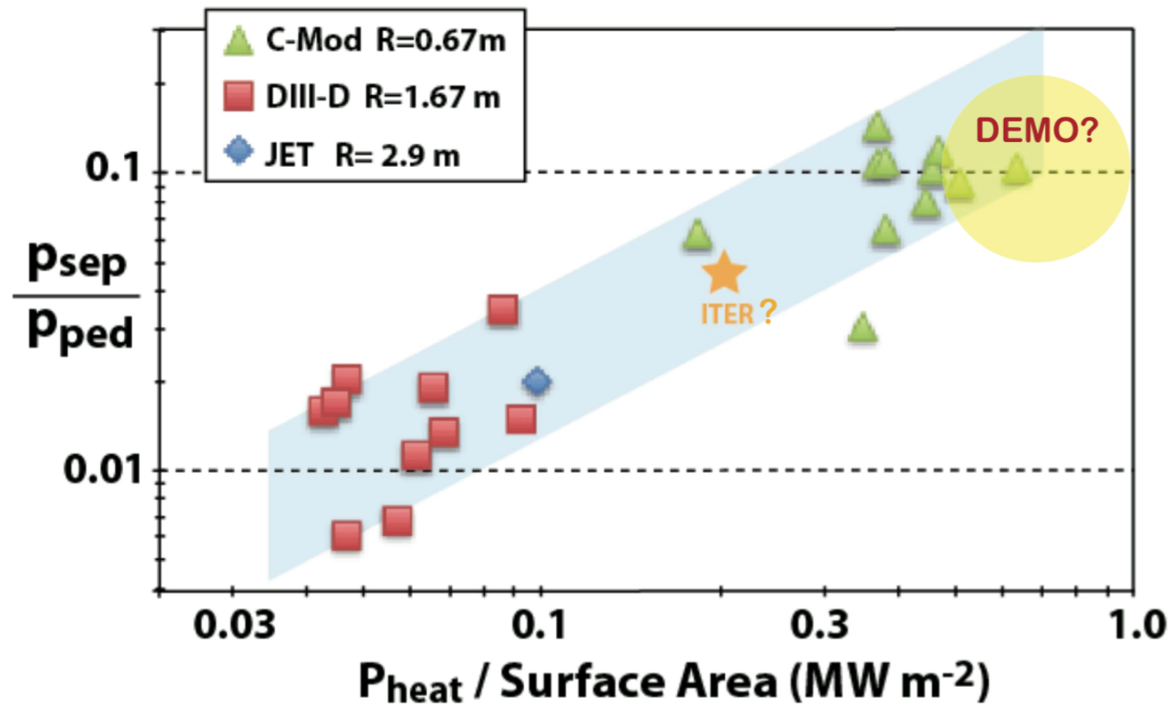
Exploit C-Mod's unique capability to match ITER as well as FNSF/DEMO divertor and SOL parameters

Parameter Description	*FNSF / DEMO*	Alcator C-Mod	DIII-D / AUG	EAST / KSTAR	JET	*ITER*
Global power density, P/S (MW/m^2)	*1*	~1	~0.3	*~0.25*	0.25	*0.25*
Magnetic field (T)	*>6*	2-8	2.5	3	3	*5.3*
Divertor density (10^{20} m^{-3})	*10-20*	10-20	1	1	3	*10*
Ambient divertor temperature (^{0}C)	*> 500*	25→*600*	25	25→?	200	*100*
Divertor material	*Tungsten?*	Mo→W	C/W	C/Mo/*W*	Be/W	*Be/W*
Pulse length (s)	*$3x10^7$*	< 4	10	<1000	10	*500*

- **Due to its reactor power density and field, C-Mod accesses local divertor plasma parameters not available to any other tokamak in the world**
  - Reactor-level parallel heat flux densities, recycling and short ionization MFP physics
  - Grazing B field with aligned high-temperature solid tungsten divertor
  - Reactor-matched "drives" for erosion rate, re-deposition, temperature effects
  - Covers unique parameters space for SOL/PMI in worldwide program
    e.g. heat width dependence, detachment, stability
- **And, is the center for development of LHRF current drive & ICRF heating**

Exploit C-Mod's unique capability to match ITER as well as FNSF/DEMO divertor and SOL parameters

- Recent work[1] showcased how the pedestal and SOL parameters are strongly correlated.
  - Peak parallel heat flux scales with seperatrix pressure (Psep).
- The implication is that matching ITER and DEMO power densities could be essential to studying relevant plasma physics (λq and more)



– **Any serious program to address ITER and reactor 'gaps' in knowledge requires the edge, SOL & divertor plasma parameters only available at C-Mod until some new device is constructed.**

[1]D. Whyte, PSI meeting May 2012

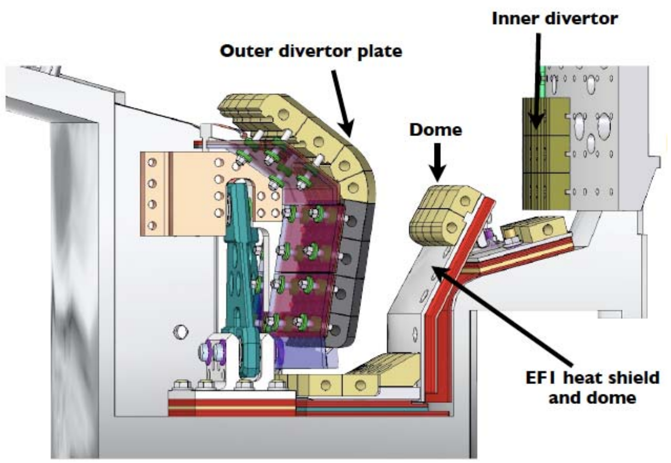
C-Mod is poised to address the 2012 FESAC materials recommendation (4.2.2)

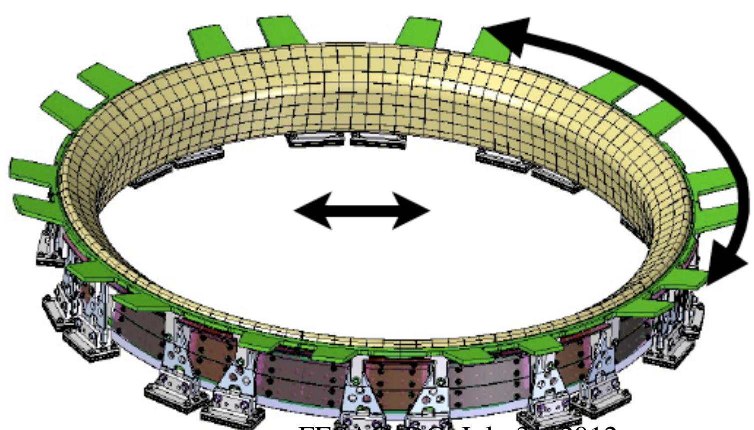
"The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten due to its projected erosion resistance, high melting temperature and high thermal conductivity."

"Important considerations are the impact on the core plasma via impurities, their response to plasma particle bombardment,… their thermal performance under high heat flux and operating temperatures above 500^{o}C."

The new 600^{o}C, toroidally-continuous, C-Mod divertor will provide first of a kind studies of tungsten PMI in a reactor-relevant plasma + thermal environment

Install FY13, Operate FY14





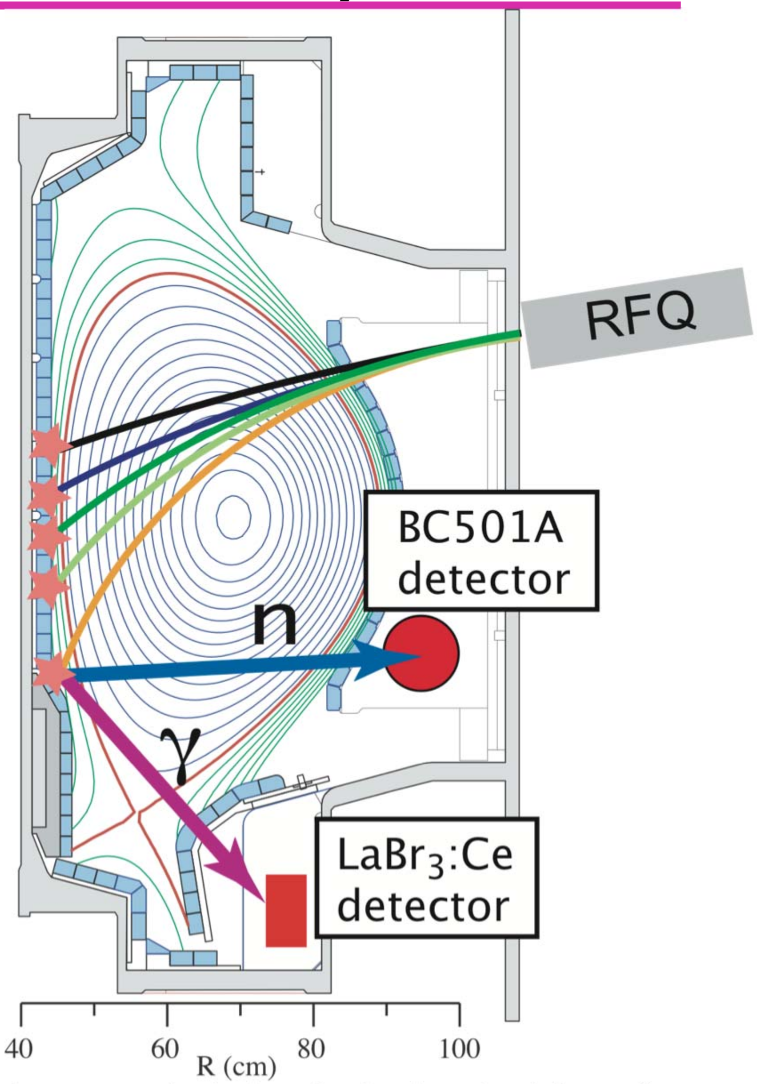
C-Mod is addressing the 2012 FESAC Diagnostics and heat flux recommendations (4.2.1 and 4.2.3)

4.2.1: 'The mechanisms governing the steady-state perpendicular power width on open field lines must be determined'

4.2.3: 'A combined initiative for both extensively diagnosing the region outside the plasma's last closed flux surface and learning about material responses to plasma exposure in real-time and during operation (in-situ) is necessary to develop and validate the physics understanding over a wide range of processes ranging from power scrapeoff width to material migration.'

C-Mod already has a world-class research program on the physics of plasmas from the pedestal to the divertor. The new Radio-Frequency Quadrupole (RFQ) is bringing a quantum advace in the capability to interrogate surfaces between discharges

Currently being installed



A cartoon depicting the basic principles of in-situ ion beam analysis of PFCs surface compositions

Parting thoughts

- *The focus of current FNSF design studies relies on extrapolation of core performance that would be at the edge of stability – leading to a complex device, that would likely suffer significant downtime and low availability. What we need instead is to be focusing on simpler designs, that stay away from operational boundaries but still achieve the economics needed.*

- *Materials solutions alone are not going to solve the knowledge/experience gaps at the plasma-boundary interface. We need to develop plasma physics solutions and to engage our US facilities (current an future) that can test and demonstrate these solutions under true reactor-level conditions.*

- *It is time to make boundary physics and PFC material issues a major priority of the US fusion program, in line with the importance of the gaps in our knowledge needed to design and predict operation in ITER and reactors.*