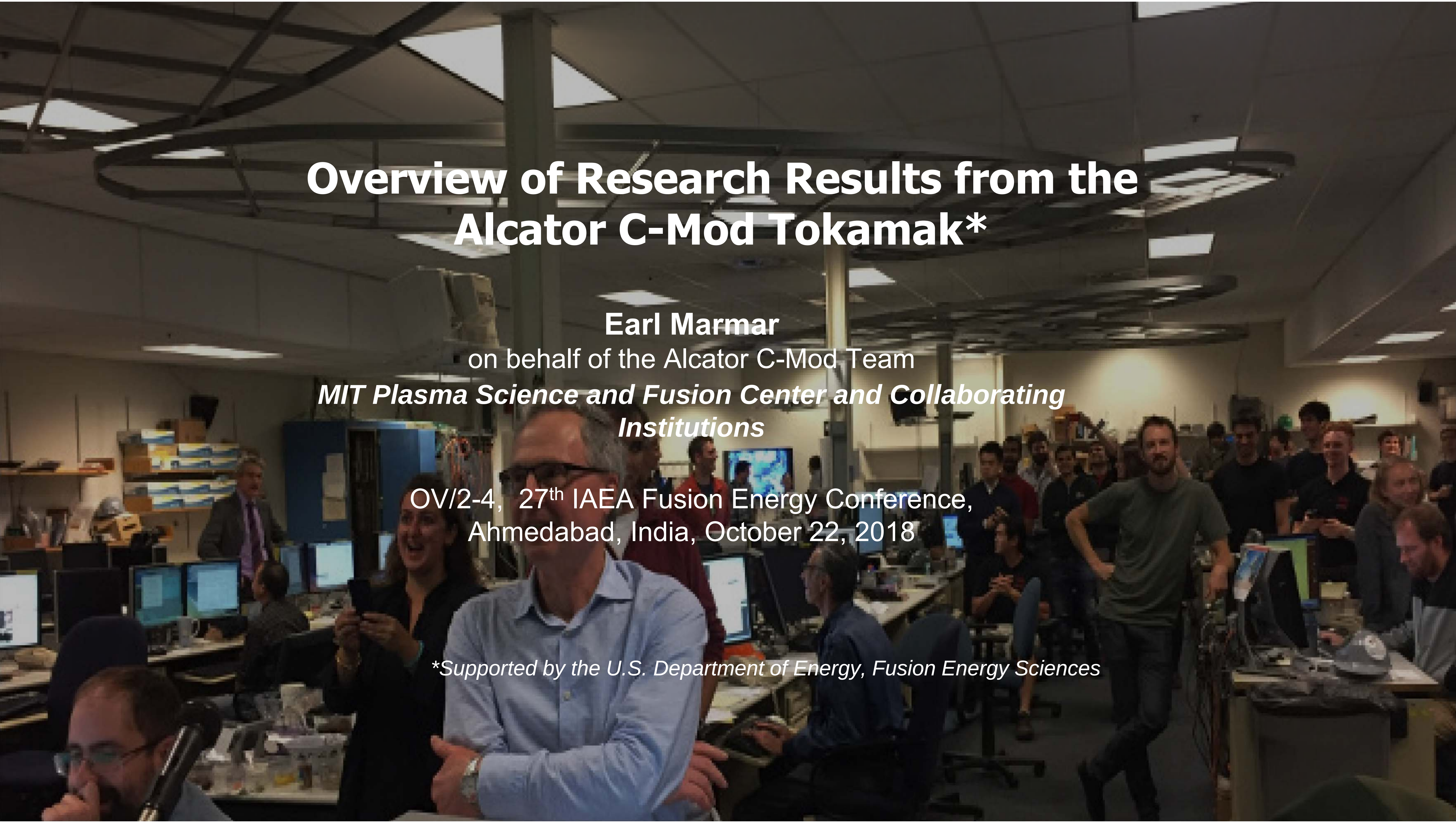


Overview of Research Results from the Alcator C-Mod Tokamak*

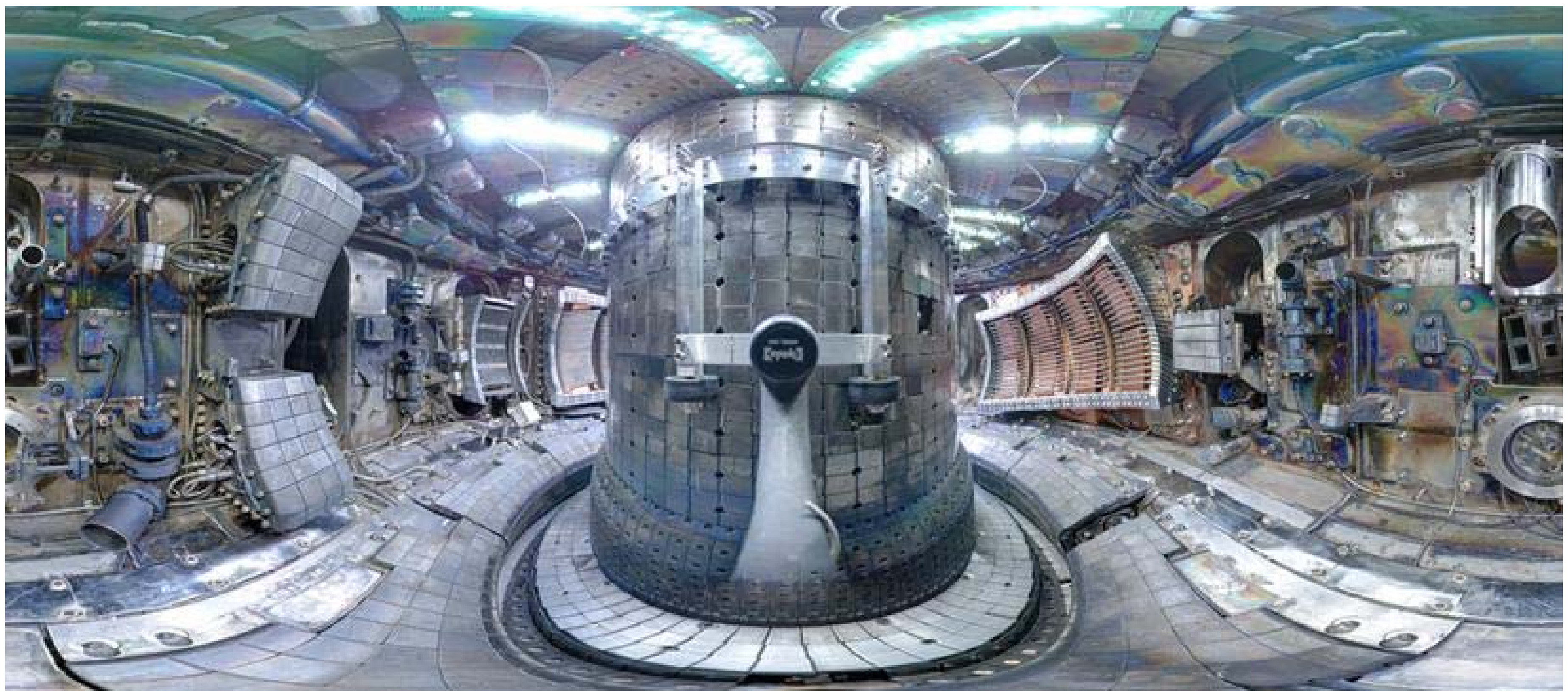
Earl Marmar
on behalf of the Alcator C-Mod Team
MIT Plasma Science and Fusion Center and Collaborating Institutions

OV/2-4, 27th IAEA Fusion Energy Conference,
Ahmedabad, India, October 22, 2018

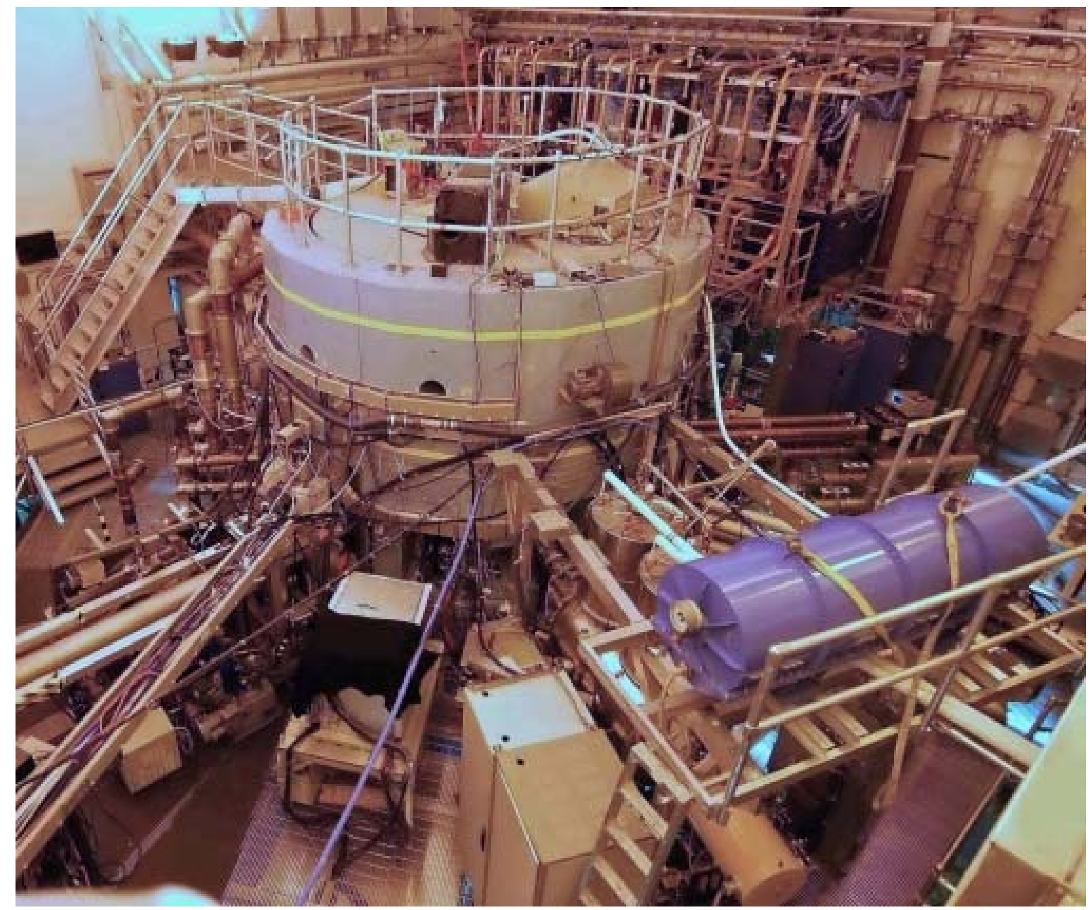
**Supported by the U.S. Department of Energy, Fusion Energy Sciences*

Compact, High B Tokamak Physics

- C-Mod Completed Operations in 2016
  - 23 highly productive years
  - Many groundbreaking physics results
  - Analysis ongoing

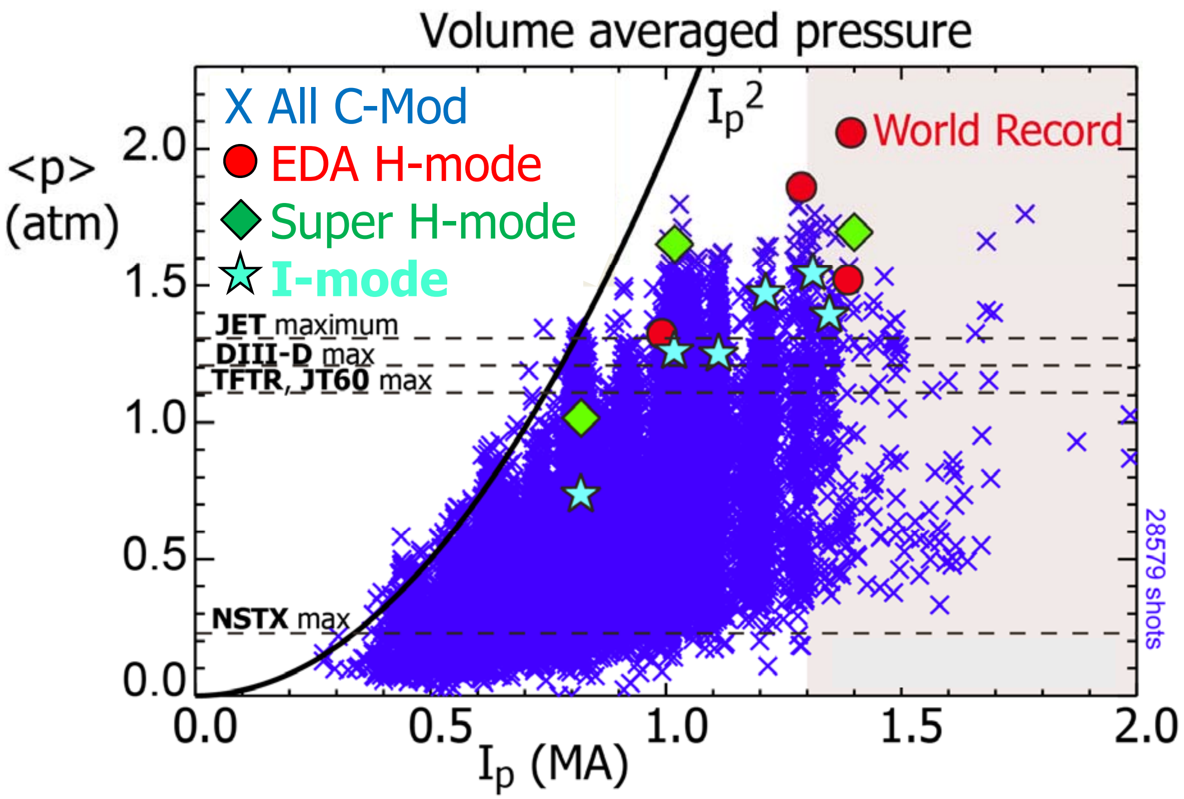


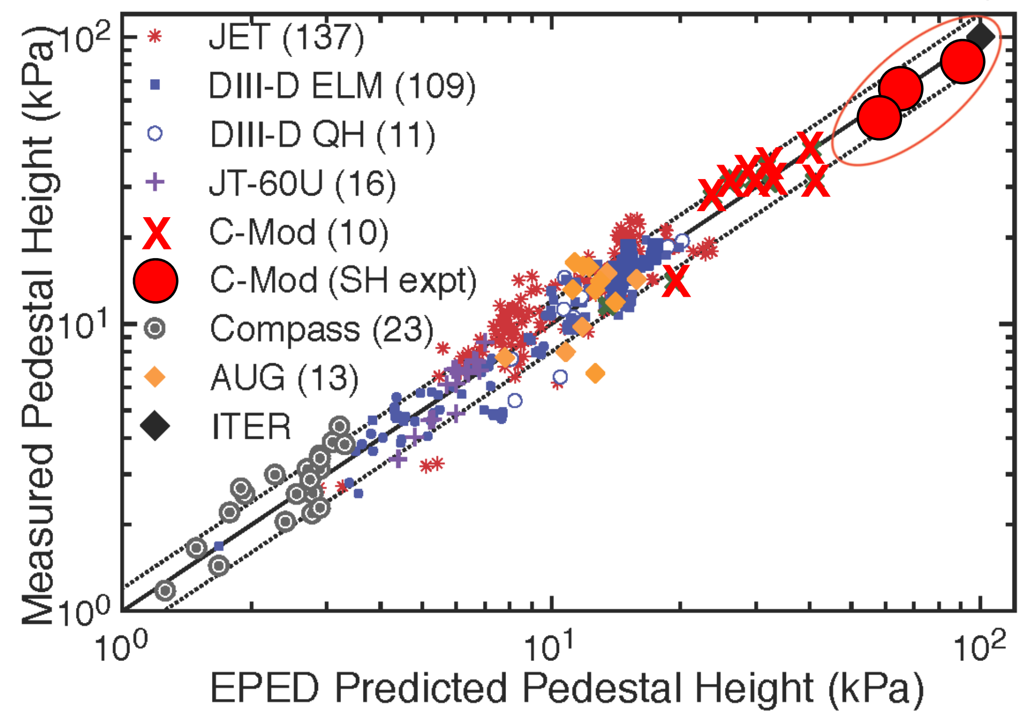
- Pointing to a high field path for future
  - High Temperature, High Field Superconductors enable compact burning plasma and reactor concepts



Achieved World Record Core and Pedestal Plasma Pressures

High Performance: $n \leq 1.5 \times 10^{21}$; $T \leq 10$keV; $\langle P \rangle \leq 2.1$ atm, $P_{ped} \leq 0.8$ atm





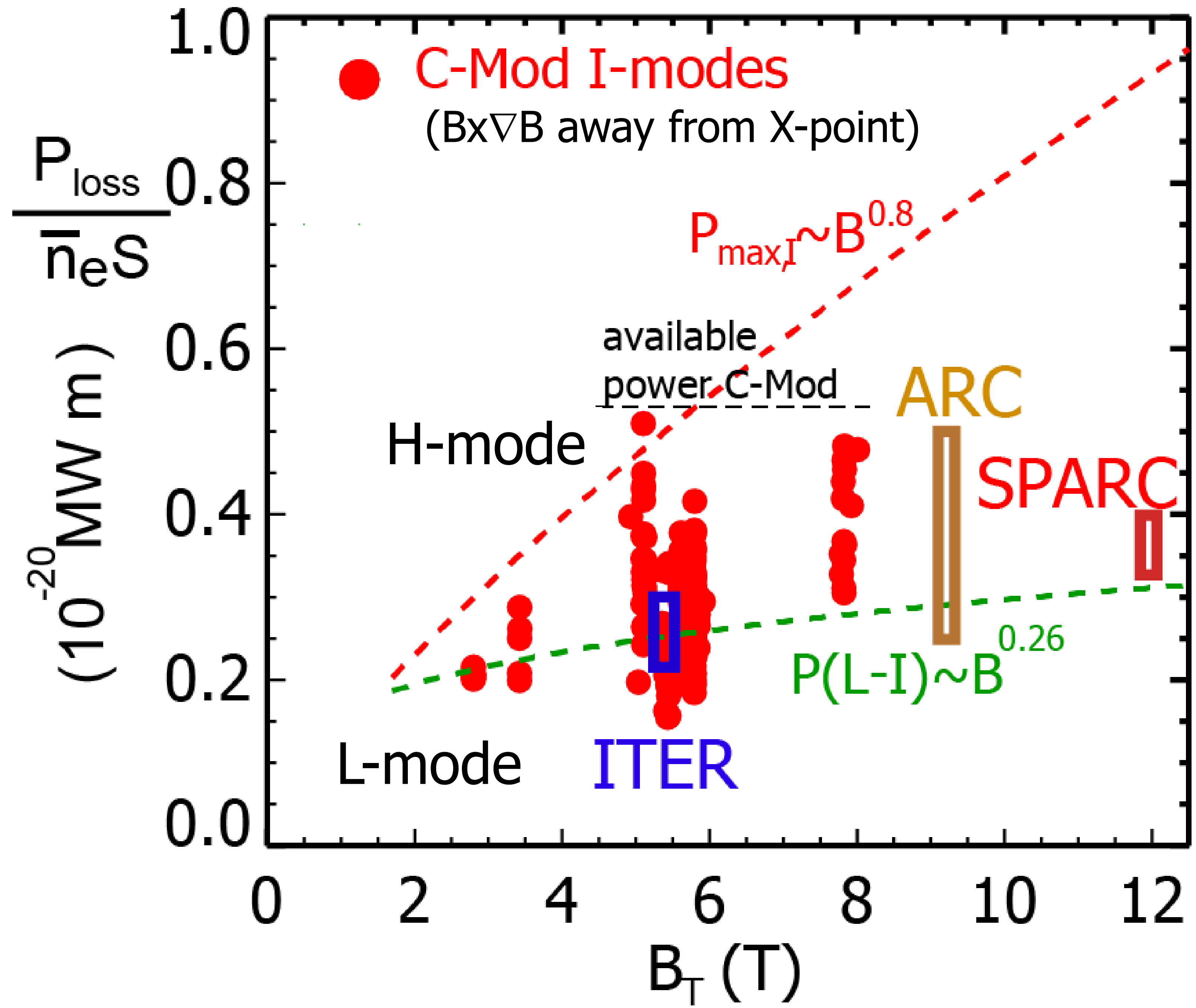
Compact/High B: R=0.67m; a=0.22m; $\kappa \leq 1.8$; **$B_0 \leq 8$T**

- All RF Auxiliary Heating & Current Drive
  - ICRF: P≤6.5MW, 50 MHz to 80 MHz
  - LHCD: P≤1.5MW, 4.6 GHz
- High Power Density: PB/R ~ 100 MW-T/m, $q_{||} \sim 3$ GW/m^2
- High-Z Plasma Facing Components
  - Vertical plate divertor

[1]Snyder, et al., IAEA FEC 2018 EX/2-4

ELM Suppressed I-mode High Energy Confinement Regime: Operating Window Widens at High B

- I-mode, primarily studied on C-Mod, has many attractive features:
  - High energy confinement, low particle/impurity confinement
  - Weak confinement degradation with power
  - No ELMs to challenge the divertor
- May be particularly attractive for the high B approach to reactors
  - H-mode threshold increases with B, suppressing the I- to H- transition at high power
- Some of the remaining challenges
  - Power handling and robustness to detachment
  - Scaling to burning plasma conditions

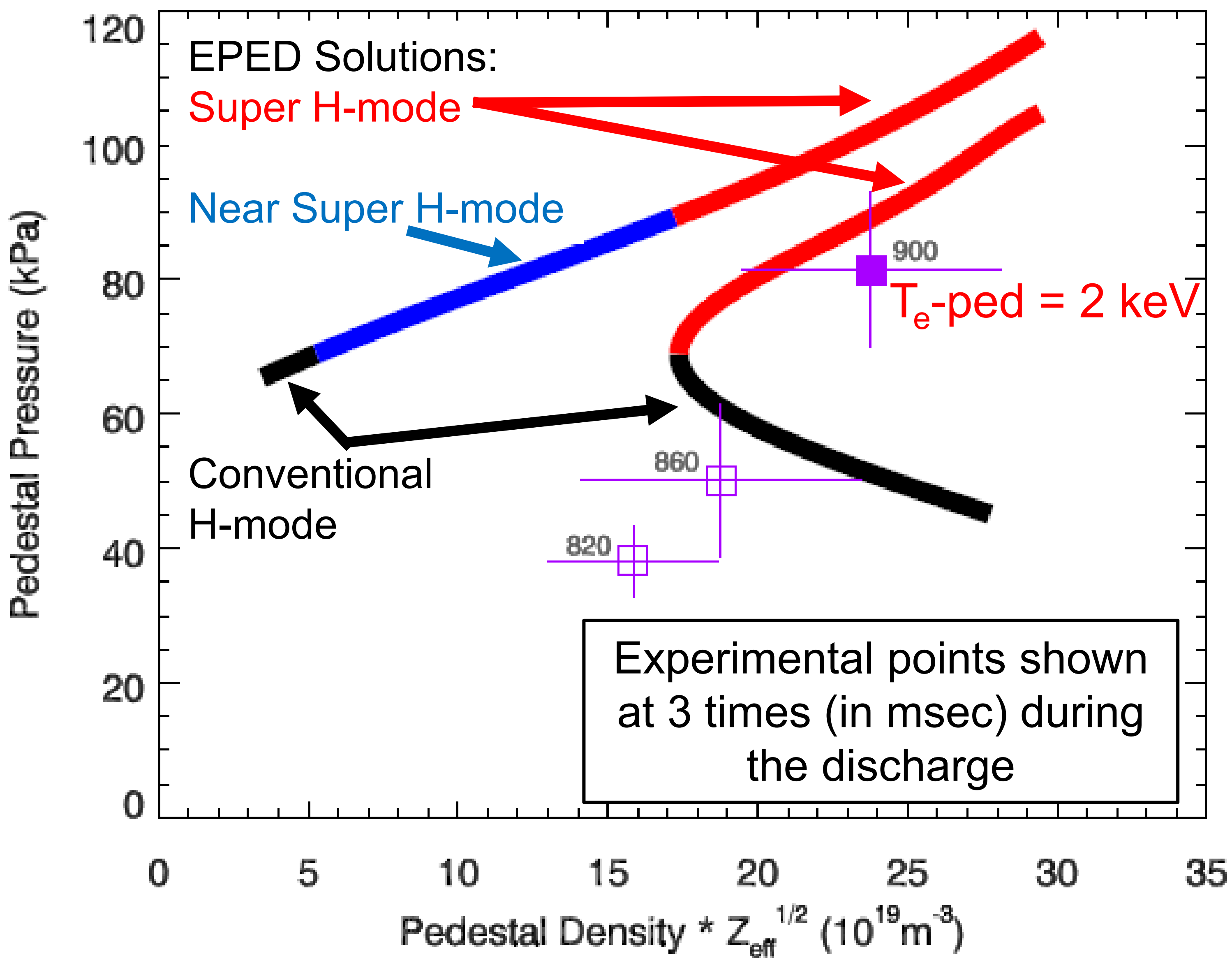


Also see Wilks, et al., IAEA FEC 2018, EX/P6-19; Happel, et al., EX/2-3

Super H-Mode: C-Mod Extends Validation of Predictions to ITER Relevant Pedestal Pressure, in All-Metal Machine[1]

- Low ν^*, high temperature peeling-limited pedestal region predicted by theory[2], observed on DIII-D[3]
- Explored on C-Mod by transitioning to H-mode from low density, low impurity content I-mode target
- Excellent agreement between EPED predictions and experiment
  - Extended pedestal pressures to 80 kPa on final day of C-Mod operation; T_e-ped = 2 keV

Record Pedestal Pressure Shot (I_p=1.4MA, q_{95}=3.2)

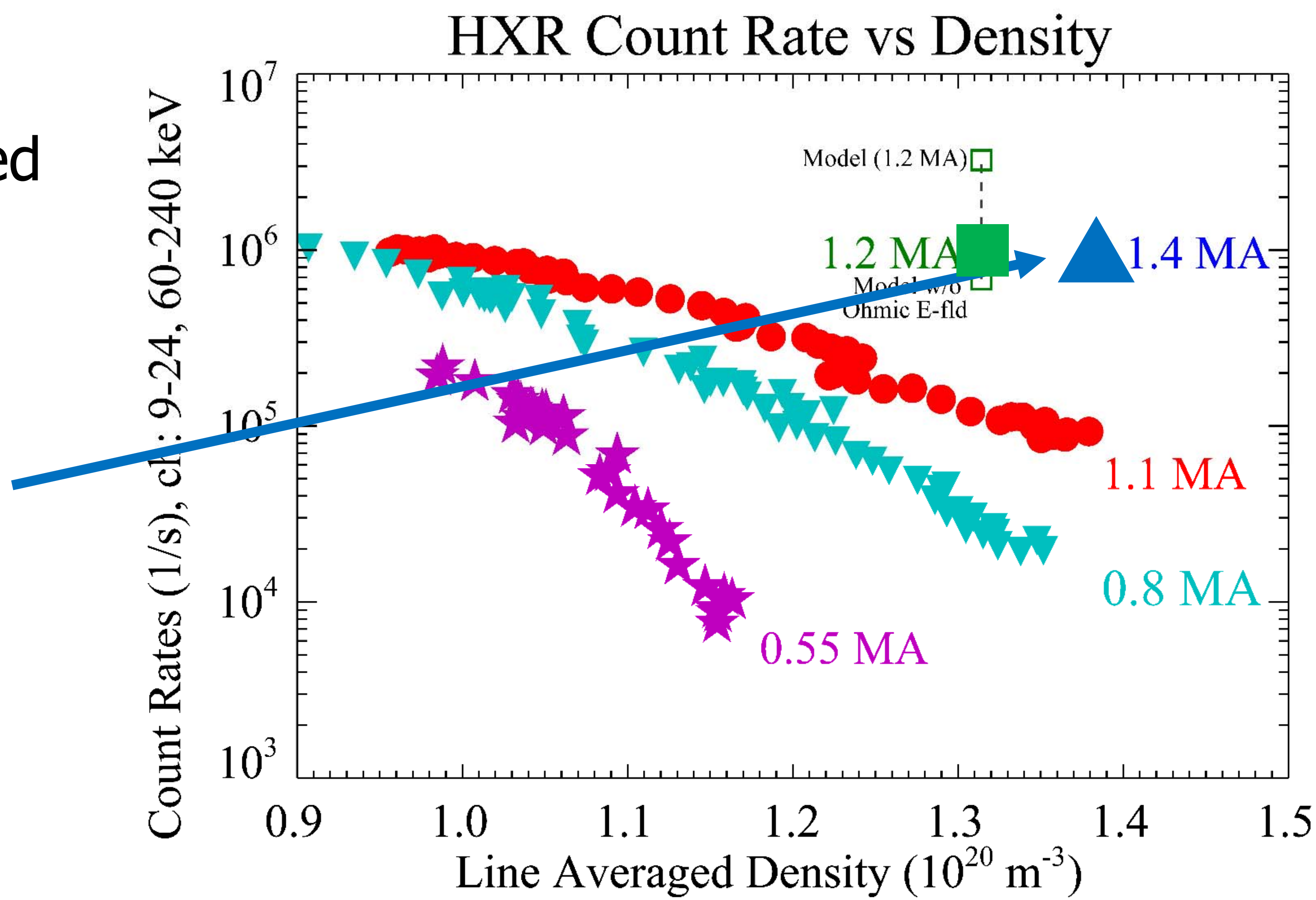


[2]Snyder, et al., Nucl. Fusion 2015
[3]Solomon, et al., Phys. Plasmas 2016

[1]Hughes, et al., Nucl. Fusion 2018; Snyder, et al., IAEA FEC 2018, EX/2-4

Non-Inductive Lower Hybrid Current Drive is Challenging at High Density

- C-Mod results[1] show anomalously low current drive efficiency and sharply decreased production of fast electrons at high density, high Greenwald fraction (f_G)
- Increasing I_p at fixed density (and thus lowering f_G) reduces the anomaly
  - Current drive efficiency matches model



[1]Wallace, et al., Phys. Plasmas 2010

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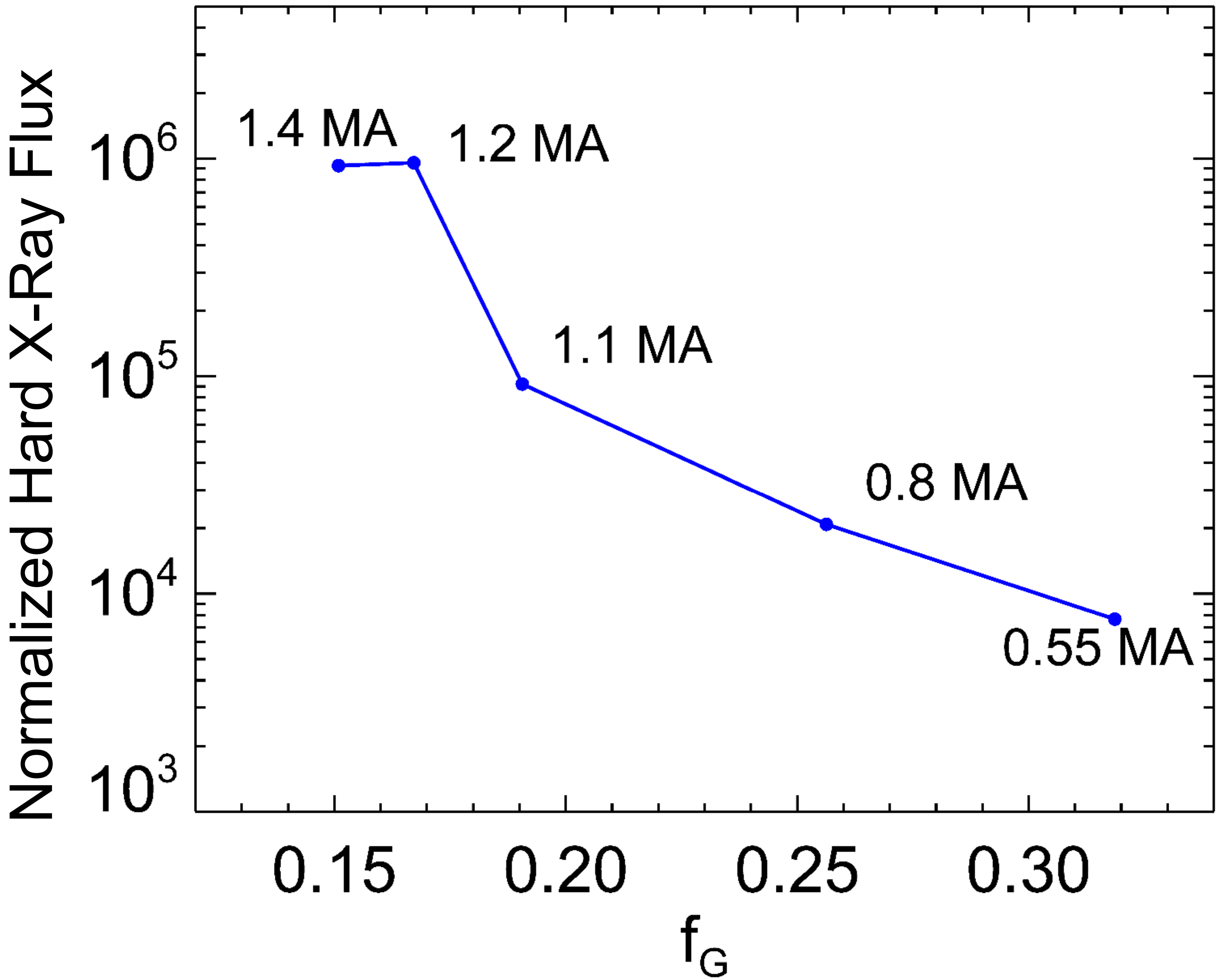

[1]Wallace, et al., Phys. Plasmas 2010

Baek, et al., IAEA FEC 2018, EX/P6-28

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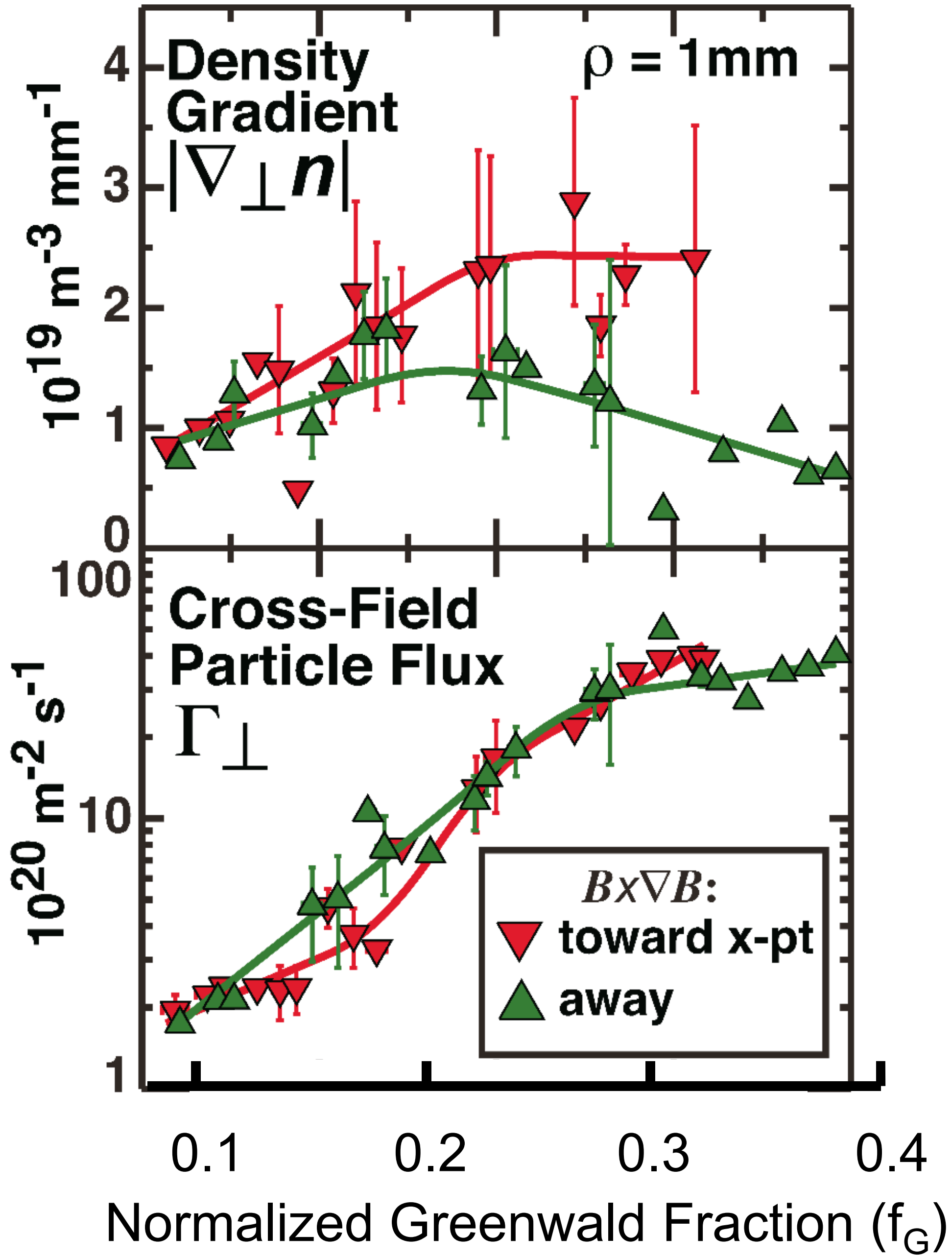


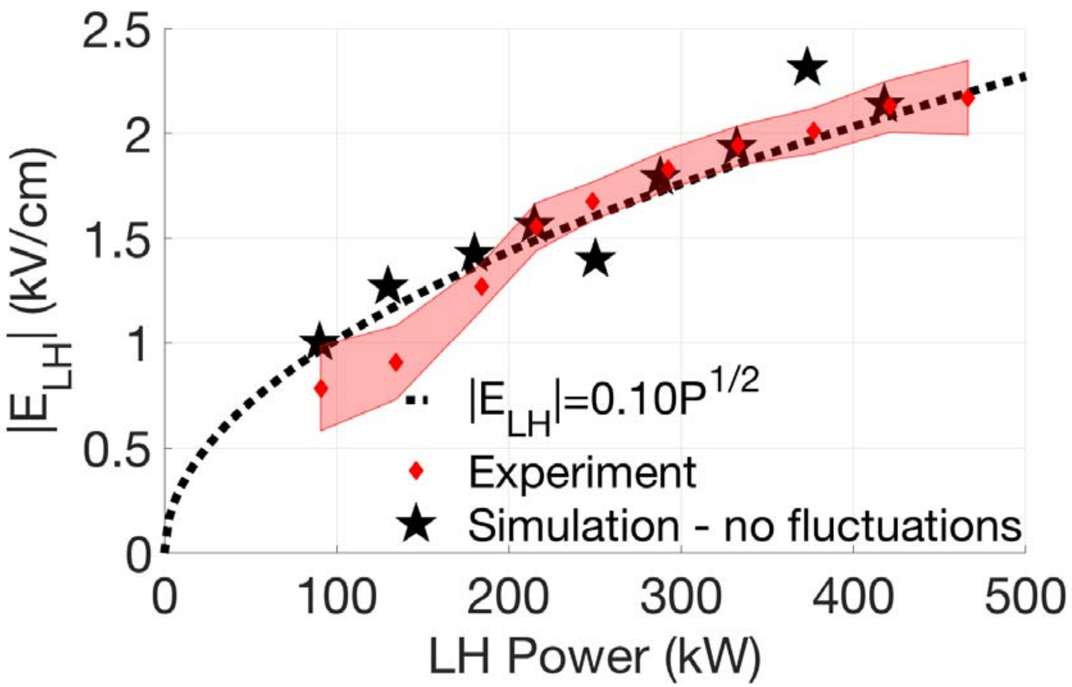
[1]Wallace, et al., Phys. Plasmas 2010

[2] LaBombard, et al., Phys. Plasmas 2008

Direct Measurement of Lower Hybrid Wave Electric Field Confirms Scattering near the Outboard Midplane[1]

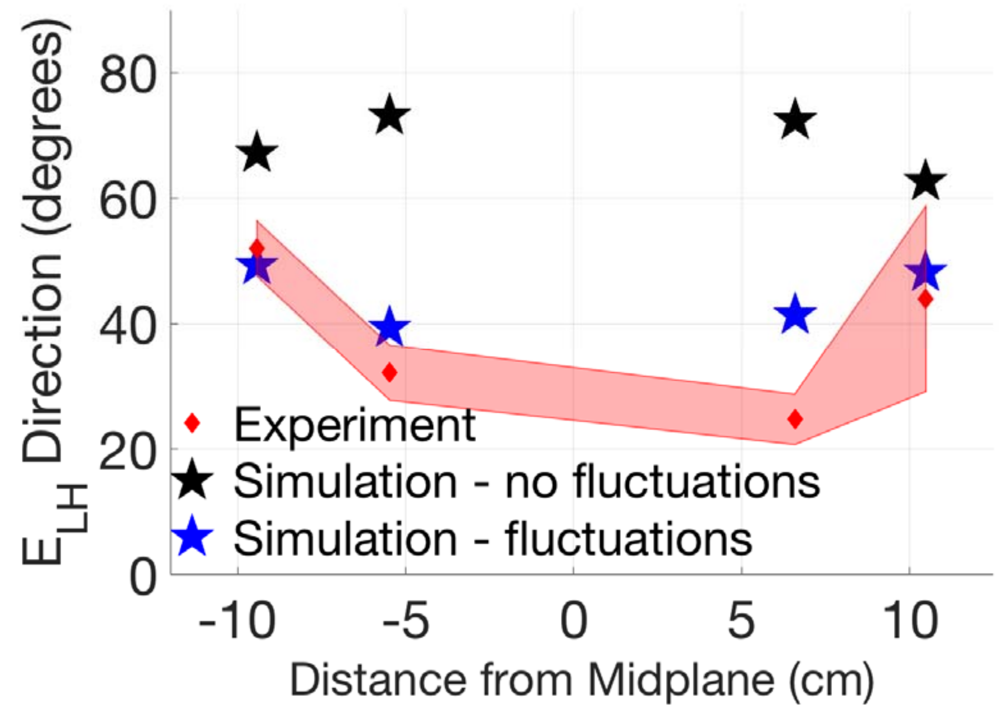
Alcator C-Mod

LH wave absorption negligible in SOL near the launcher



- Measurements of E_{LH} using Polarization Spectroscopy of Stark-split D_β spectrum confirm that LH waves are not being absorbed in the SOL

SOL density fluctuations predict LH wave scattering

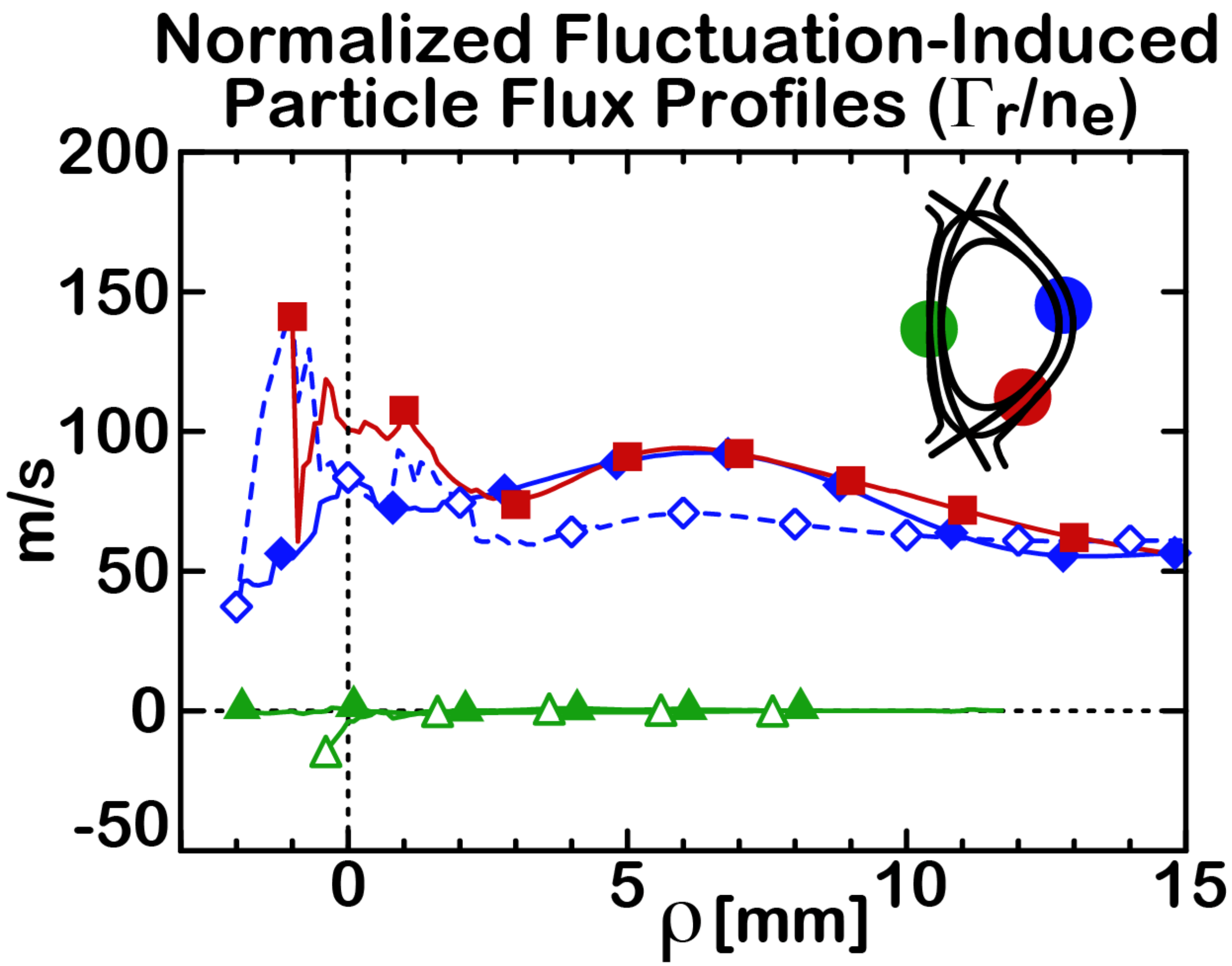


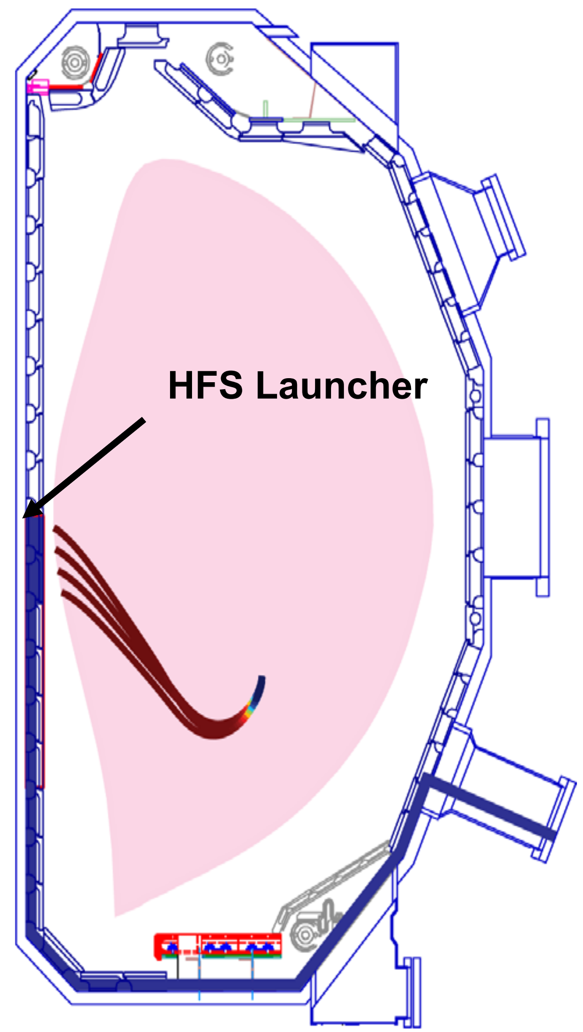
- The waves are scattered near outboard midplane
- Full-wave 3D modeling consistent with scattering due to density fluctuations

[1]Martin, et al., IAEA FEC 2018, EX/8-2

Low Greenwald Fraction is not attractive for Power Reactors
Possible Solution: High Field Side Launch

- High-field side SOL is quiescent:[1]





- Wave accessibility and damping also expected to improved with HFS launch[2]
- Plan to test on DIII-D[3]

[1]Smick, et al., Nucl. Fusion 2013

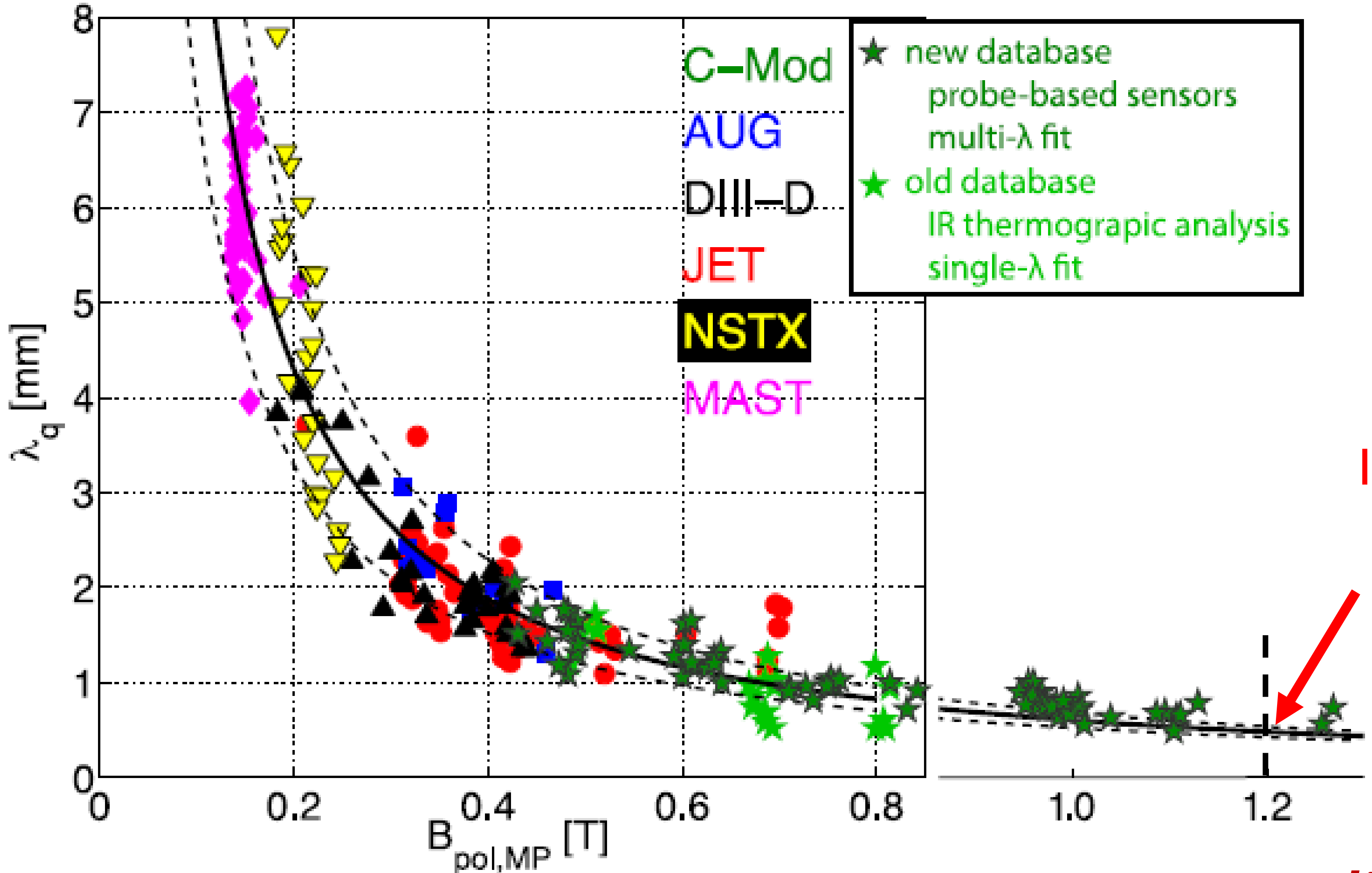
[2]Bonoli, et al., Nucl. Fusion, 2018

[3]Wukitch, et al., EPJ Web of Conf. 2017; Wallace et al., IAEA FEC 2018 FIP/3-3

C-Mod Results Show that "Eich" Scaling[1] for SOL Power Width Continues to the ITER Poloidal Field

Alcator C-Mod

λ_q database Extended with Operation at 8 Tesla[2]



Implies ITER will have λ_q=0.5 mm

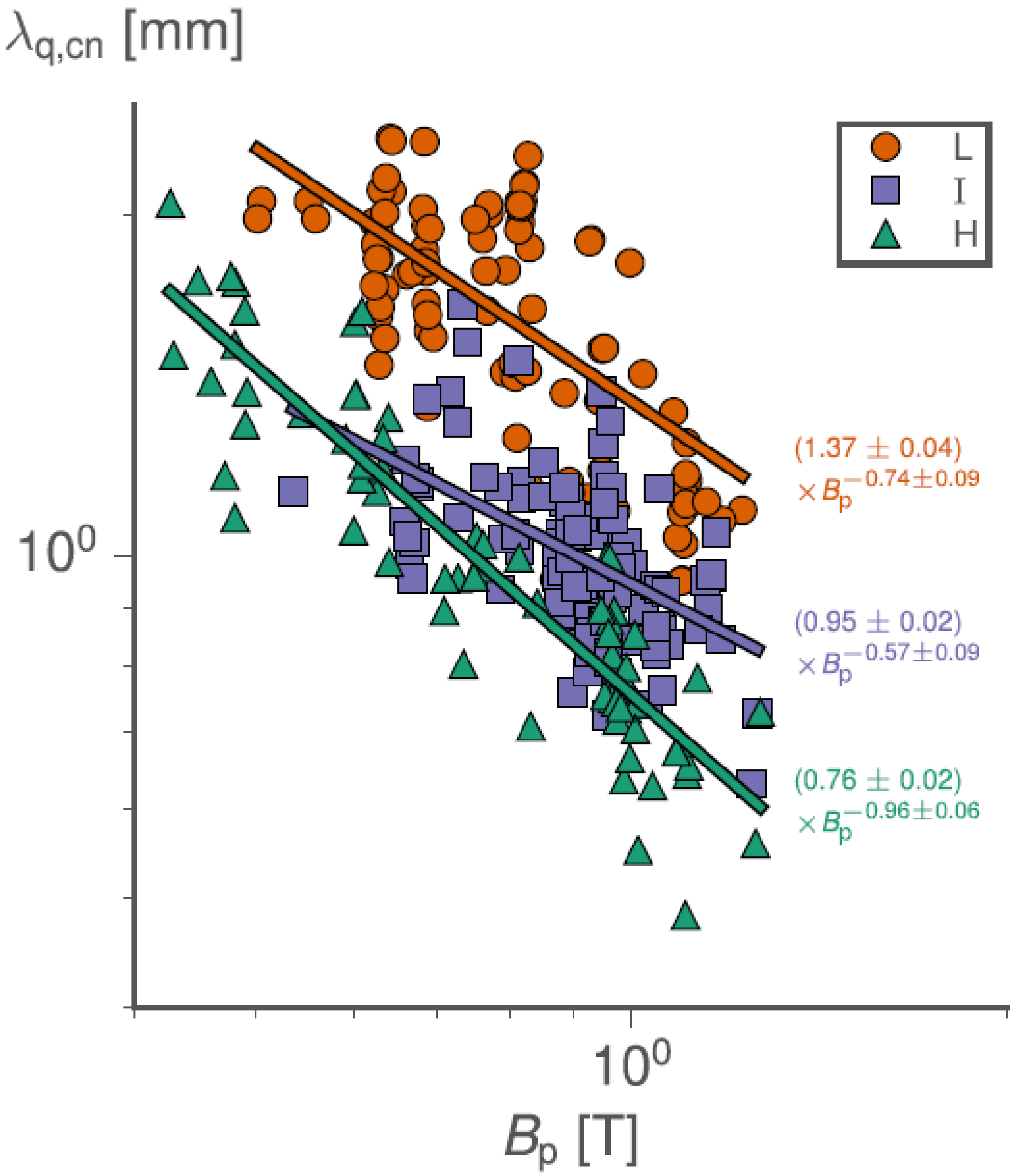
[1]Eich, et al., Nucl. Fusion 2013
[2]Brunner, et al., Nucl. Fusion 2018; Brunner, et al., IAEA FEC 2018, EX/P6-9

Original λ_q Scaling Developed for H-mode

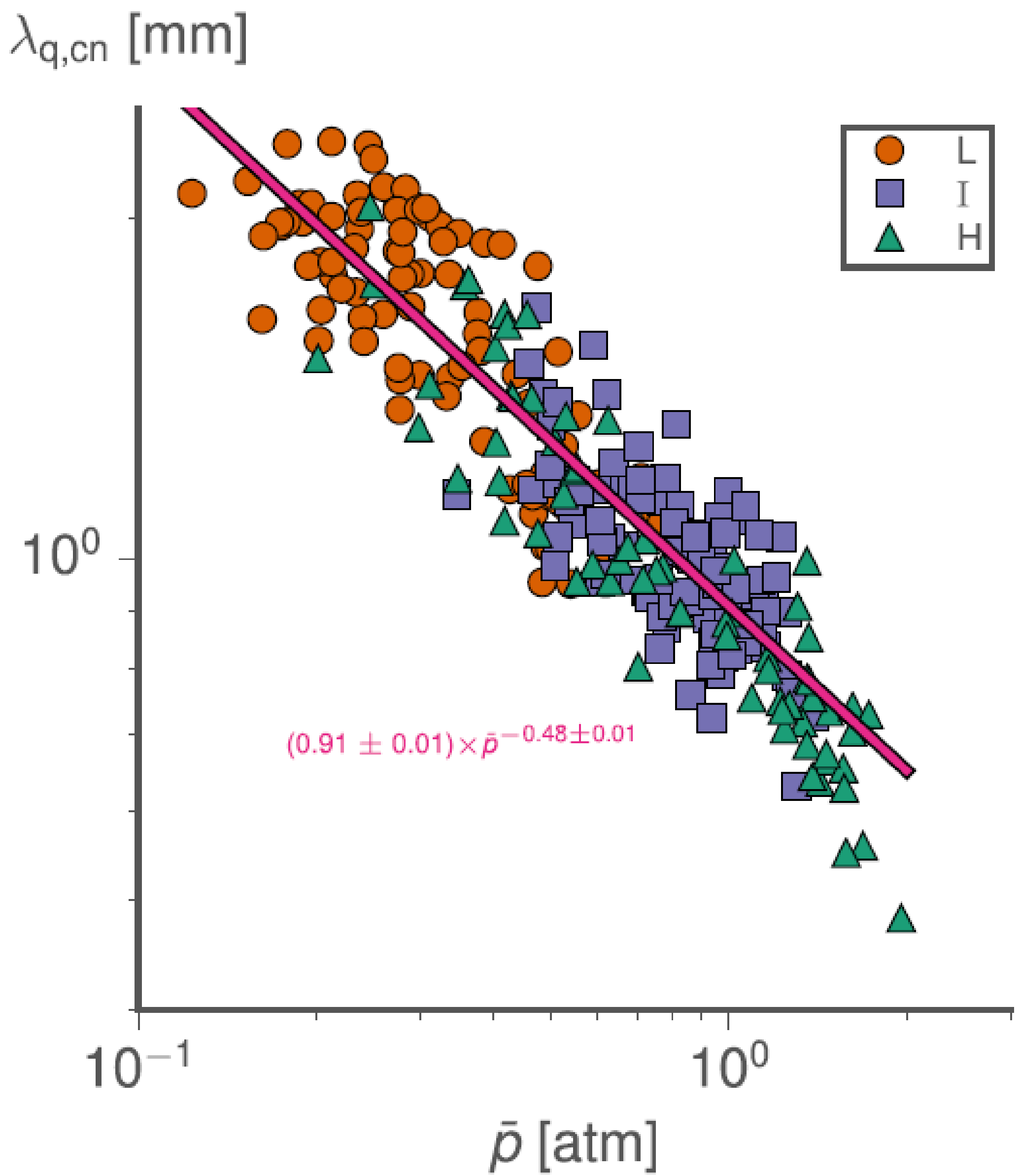
C-Mod Results[1] show $\lambda_q \propto$ Pressure$^{-1/2}$ for L-mode, I-mode and H-mode

Alcator C-Mod

Each confinement regime gives $\lambda_q \propto 1/B_p$, but with different constants of proportionality



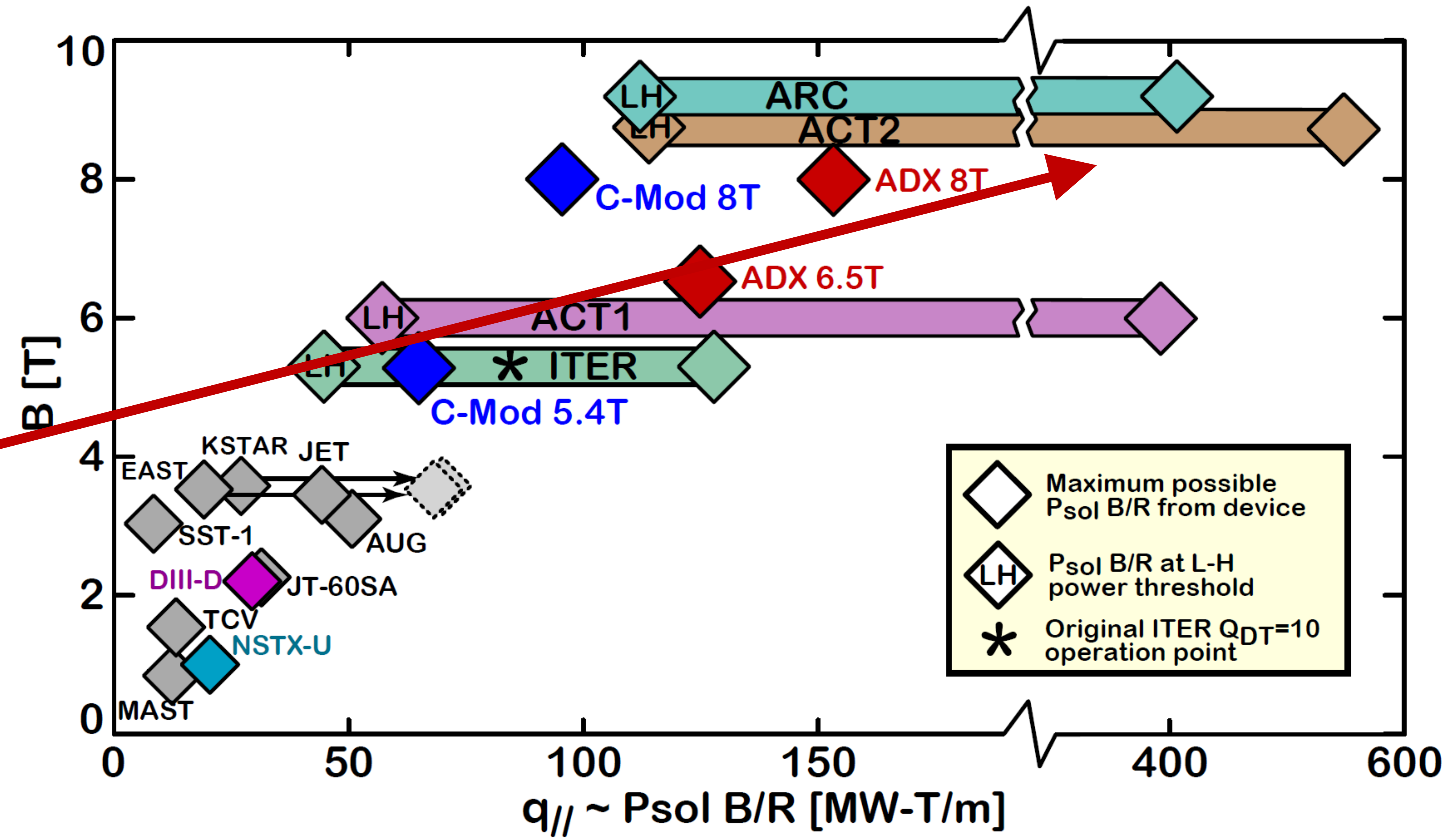
Plasma Pressure unifies all the C-Mod results



[1]Brunner, et al., Nucl. Fusion 2018; Brunner, et al., IAEA FEC 2018, EX/P6-9

Divertor Solutions Needed For Reactor Regimes

- Current experiments (and ITER) push to the limits of conventional vertical plate divertor
- New solutions will be needed for the ~5x bigger challenge anticipated in reactors

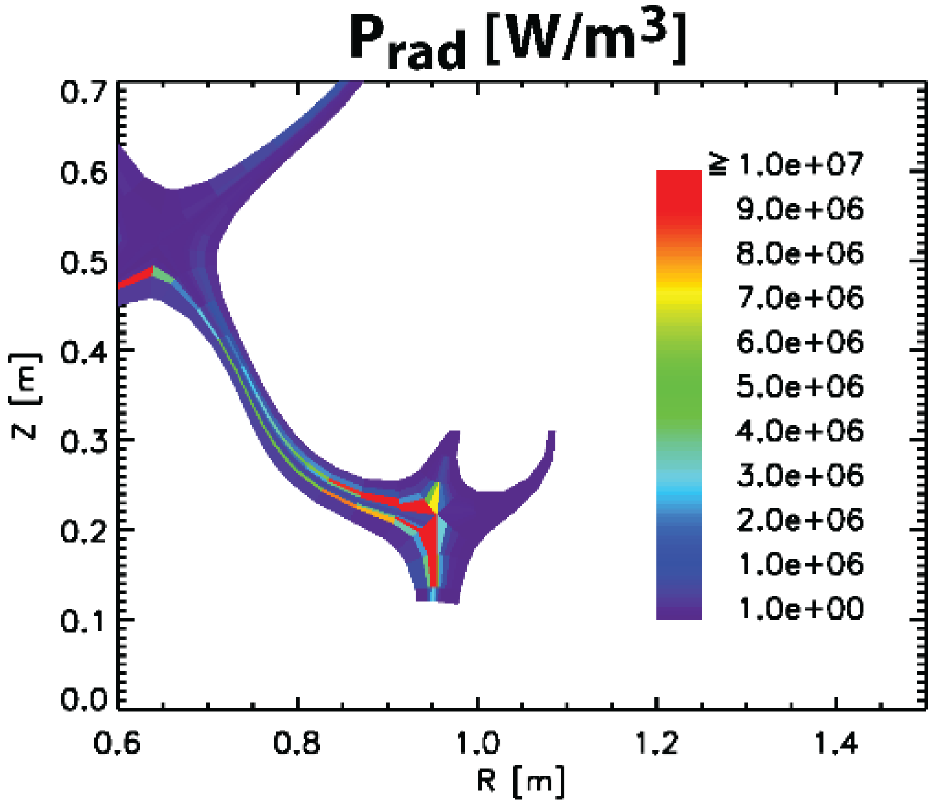


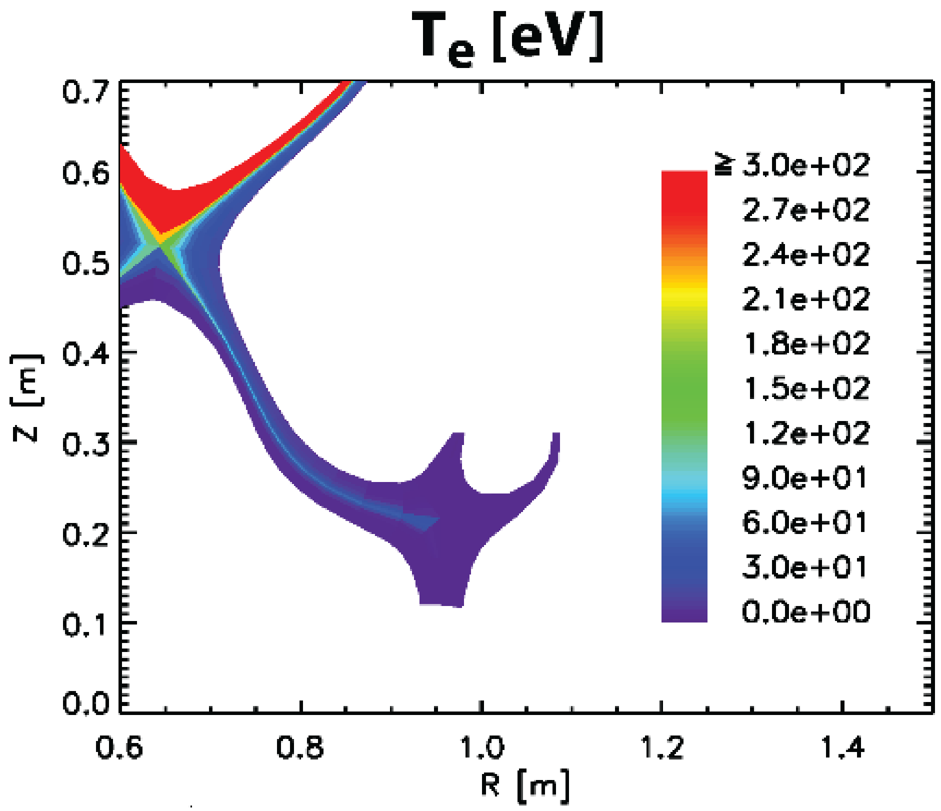
Advanced Divertor Concepts are being Developed: Must be Tested at Ultra-High Power Density

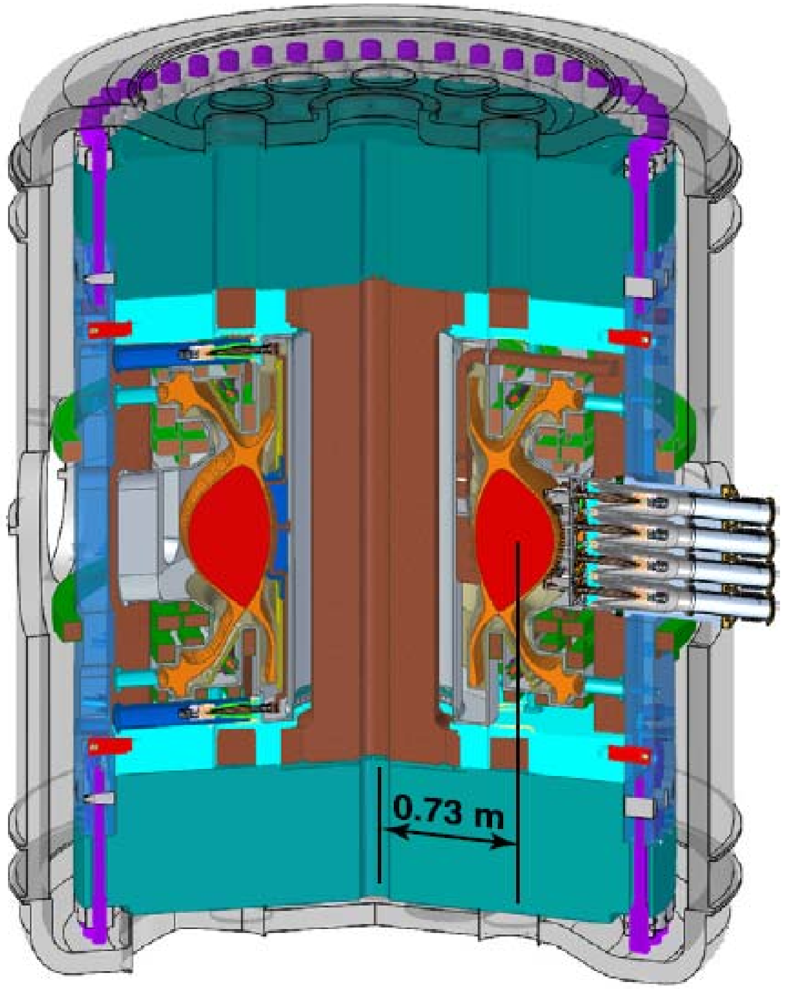
Modeling shows great promise for the long-leg X-point target concept[1]

ADX is a DTT concept that can test many advanced divertor configurations[2]

P_{rad} and T_e contours with P_{sol}= 6 MW (PB/R = 70 MW-T/m)







[1]Umansky, et al., IAEA-FEC 2018 (TH/7-2)
[2]LaBombard, et al., Nuclear Fusion 2015

Advanced Divertor Concepts Compatible with Reactor Constraints

Modeling shows great promise for the long-leg X-point target concept[1]

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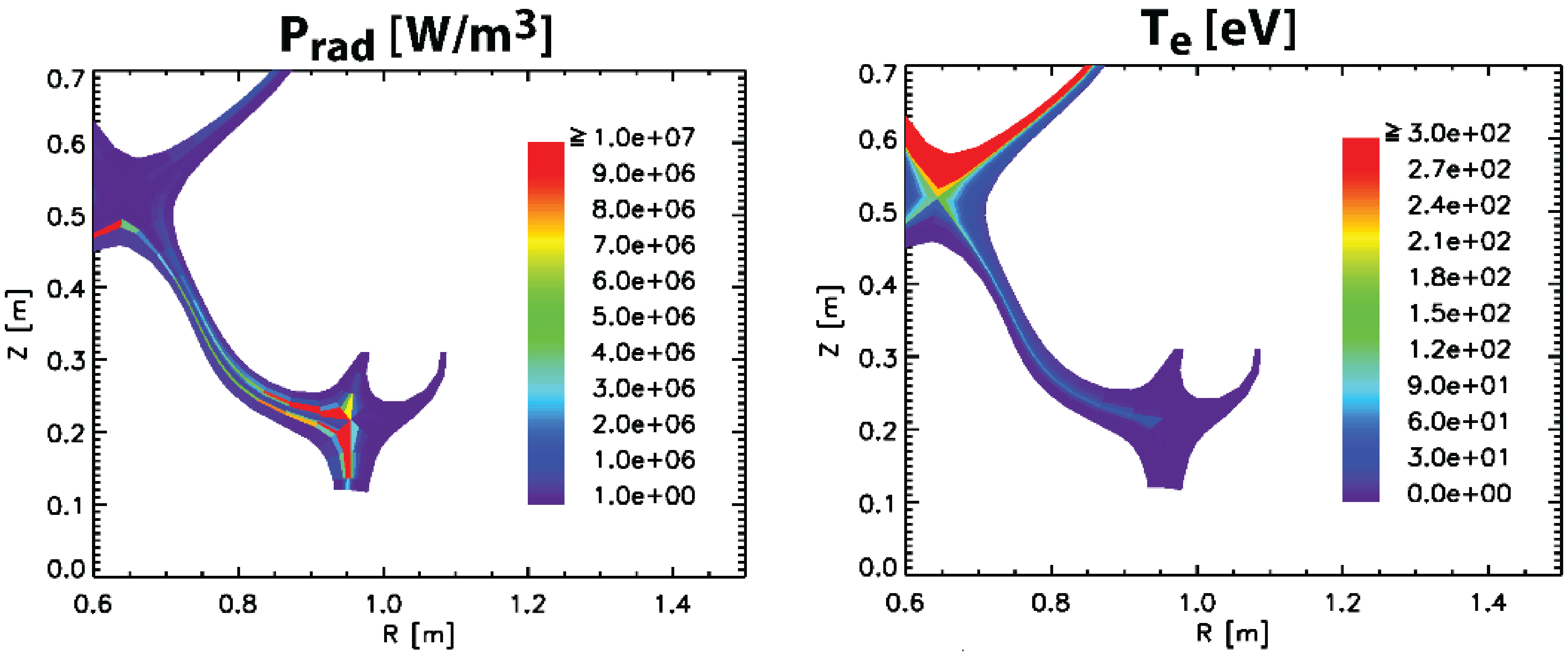
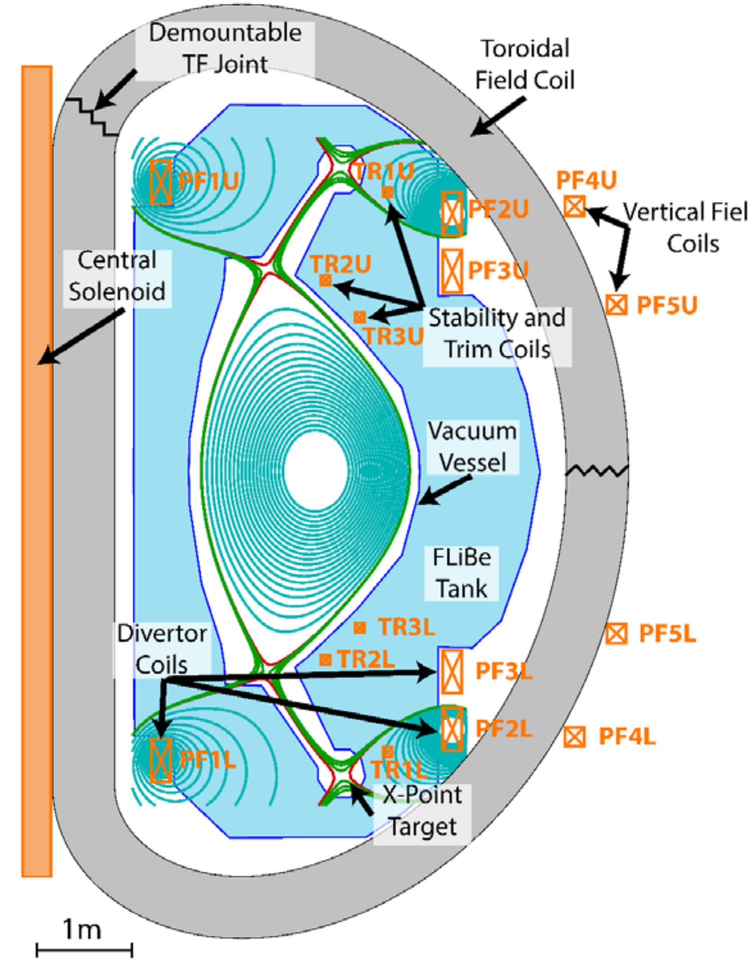


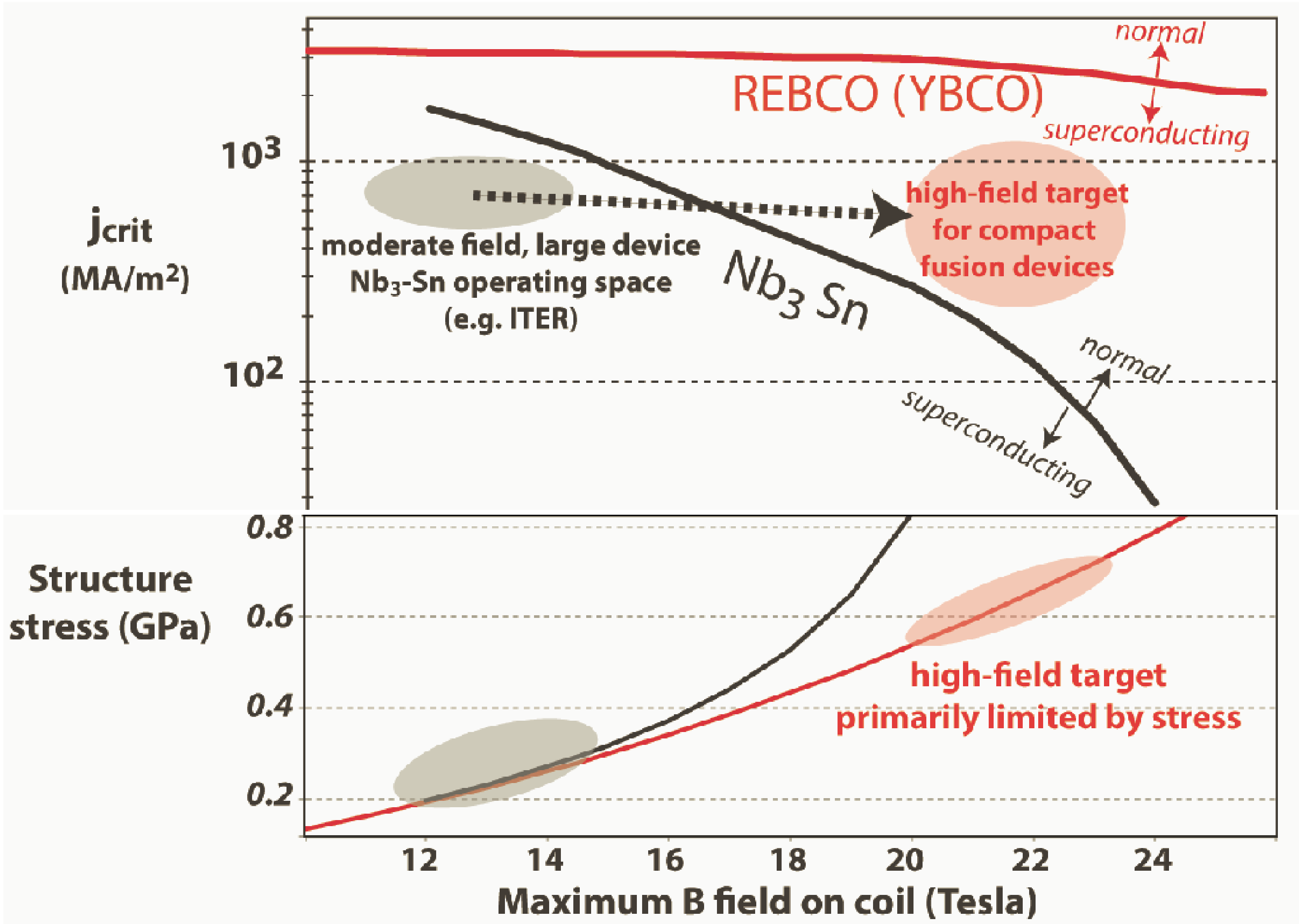
Long-Leg Divertor Compatible with Reactor Concepts (e.g. ARC[2])



[1]Umansky, et al., IAEA-FEC 2018 (TH/7-2)
[2] Kuang, et al., Fus. Eng. Des. 2018

REBCO High Temperature/High Field Superconductor: Game-Changer for High B/Compact Fusion Energy Path

- Conventional superconductor (Nb_3Sn) limits maximum on-axis B to about 5 tesla (R/a ~ 3)
- Development of High-Temp Superconductors (HTS) opens the window for increased B
  - Field limit is no longer B at the coil, but engineering stresses instead
  - Higher T (~20 K) operation also has engineering advantages, and may allow for jointed coils

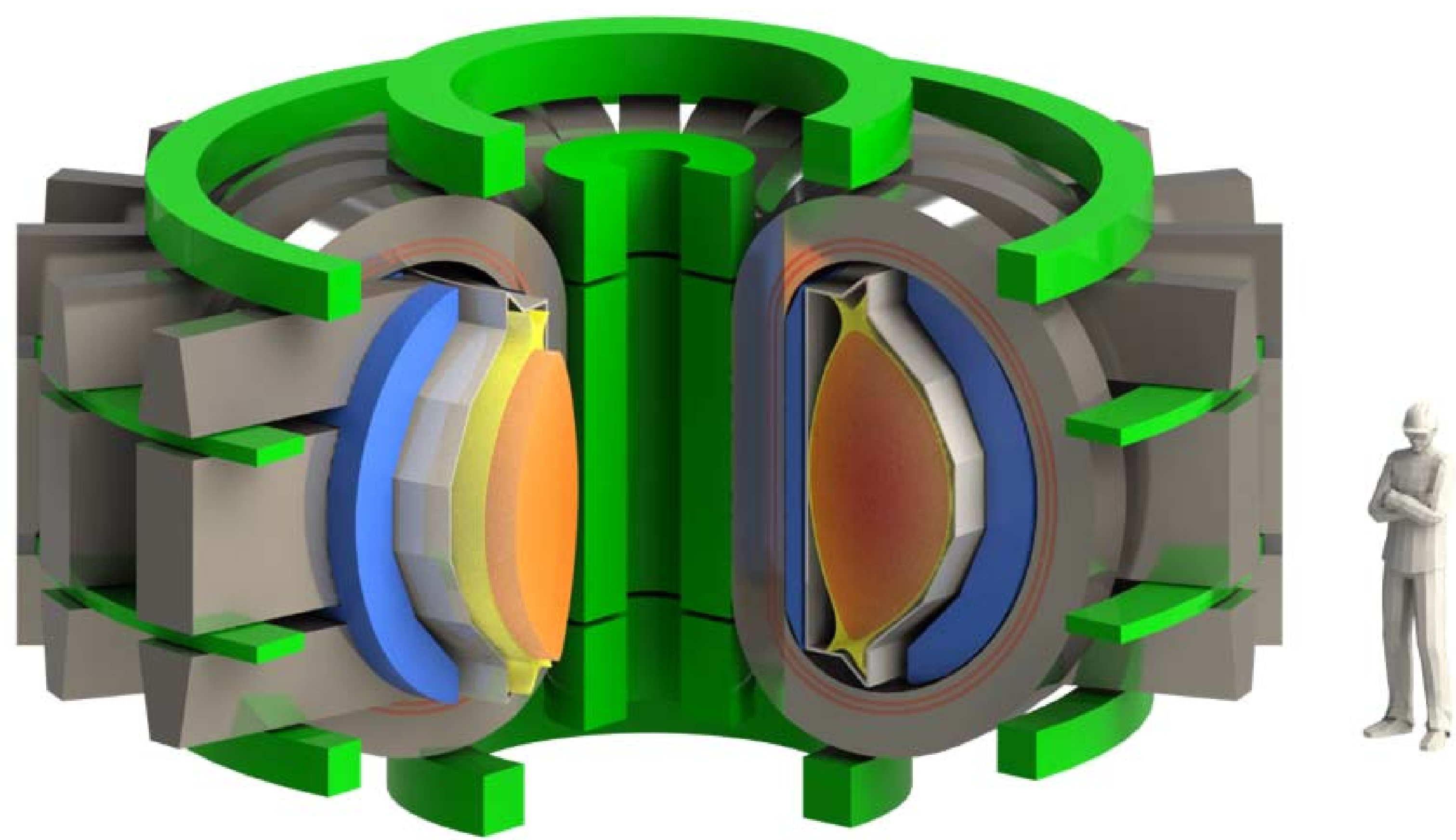


SPARC: Concept for Compact, High-Field Burning Plasma Facility

SPARC technical objectives:

- Burn D-T fuel
- Q > 2 (with headroom)
- P_{fusion} > 50MW
- Pulsed with 10s flattop burn (about 2x τ_{CR})
- ~1,000 D-T pulses, >10,000 D-D full-power pulses
- ~1 hr D-T pulse repetition rate
- ~15 minutes between D-D shots

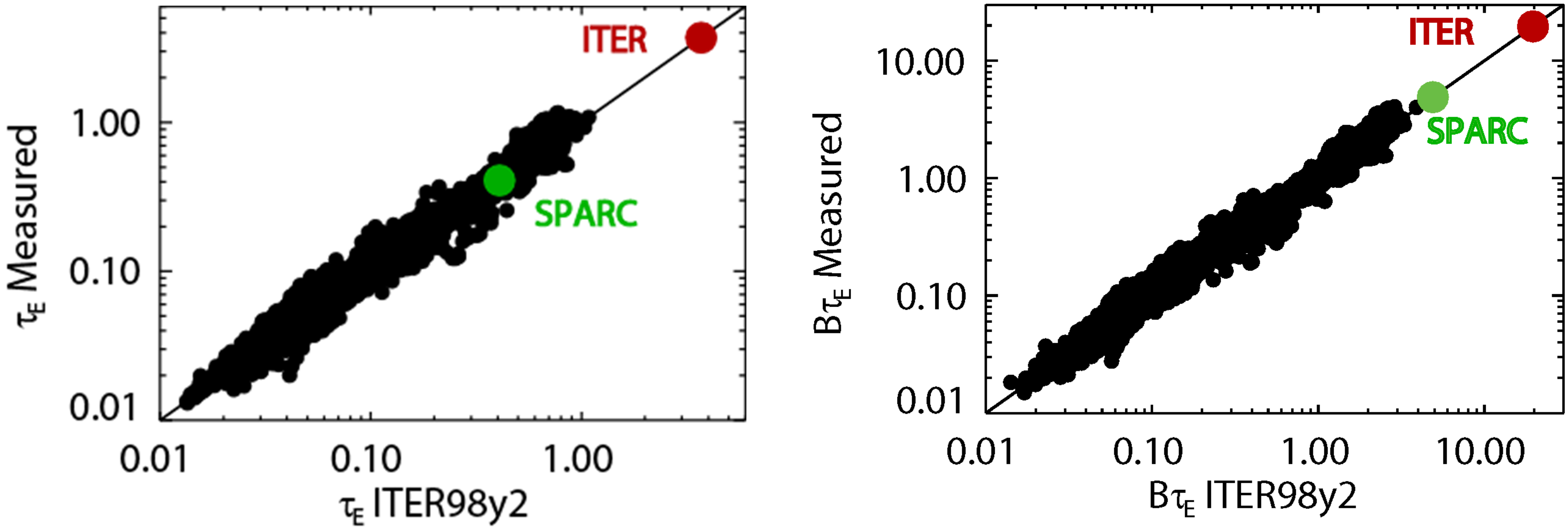
Size of DIII-D/ASDEX-U, B_0=12 Tesla



Desired Schedule:

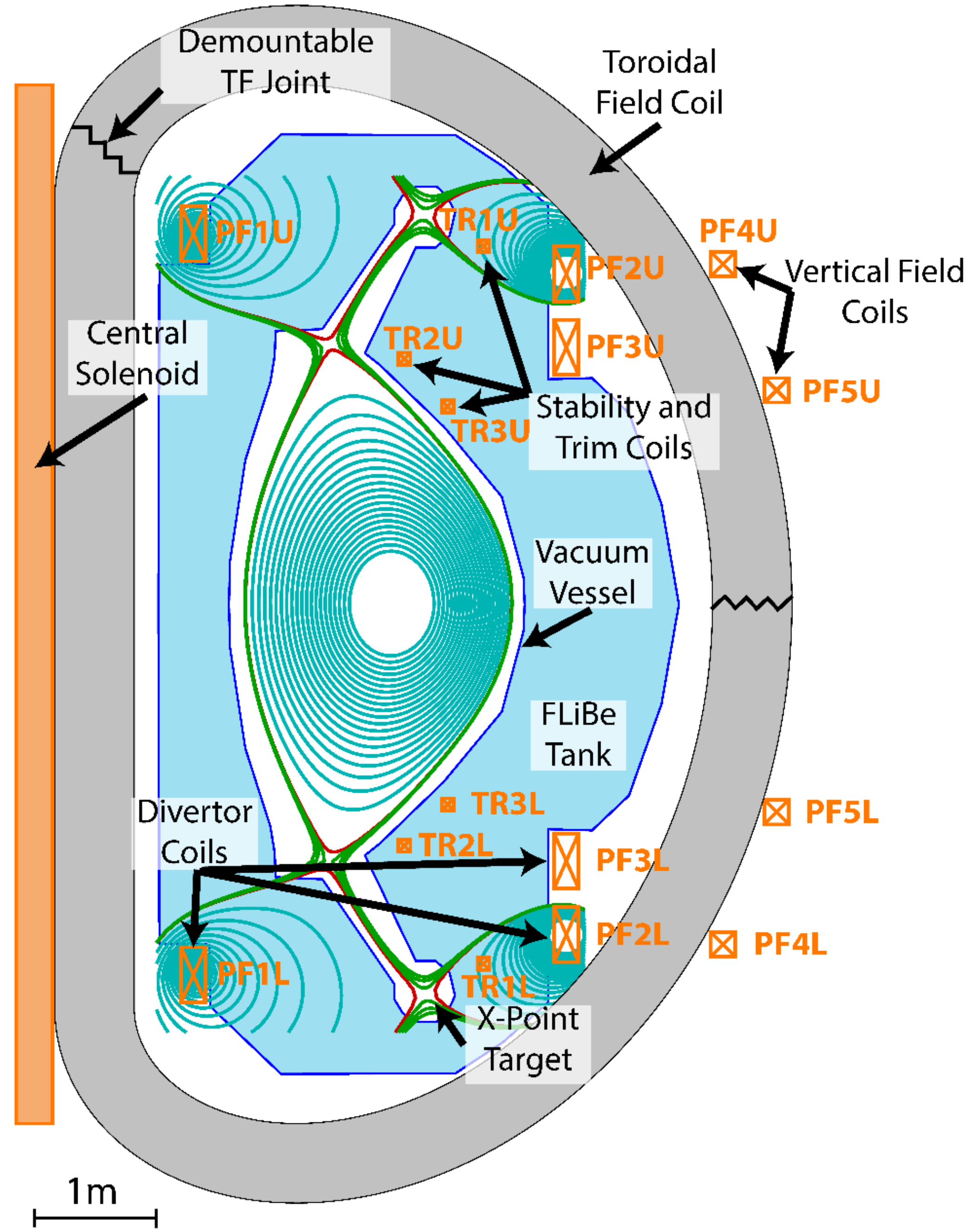
3 yrs R&D (already started) + 4 yrs construction

The H_{98}=1 Confinement Projection Puts SPARC within the Footprint of the Existing Tokamak Database



Compact High Field Pilot Plant Concept (ARC)[1] With Advanced Divertor[2]

- Recent design concept for a compact, high field, reactor using HTS magnets
  - incorporates long-leg X-point target divertor for power handling
- Joints in TF coil could dramatically ease maintainability
- About the size of JET, but at B_0=9.2 T
  - P_{fusion} ~ 525 MW
  - $P_{electric}$ ~200 MW



[1]Sorbom, et al., Fus. Eng. Des. 2015
[2]Kuang, et al., Fus. Eng. Des. 2018

MIT PSFC

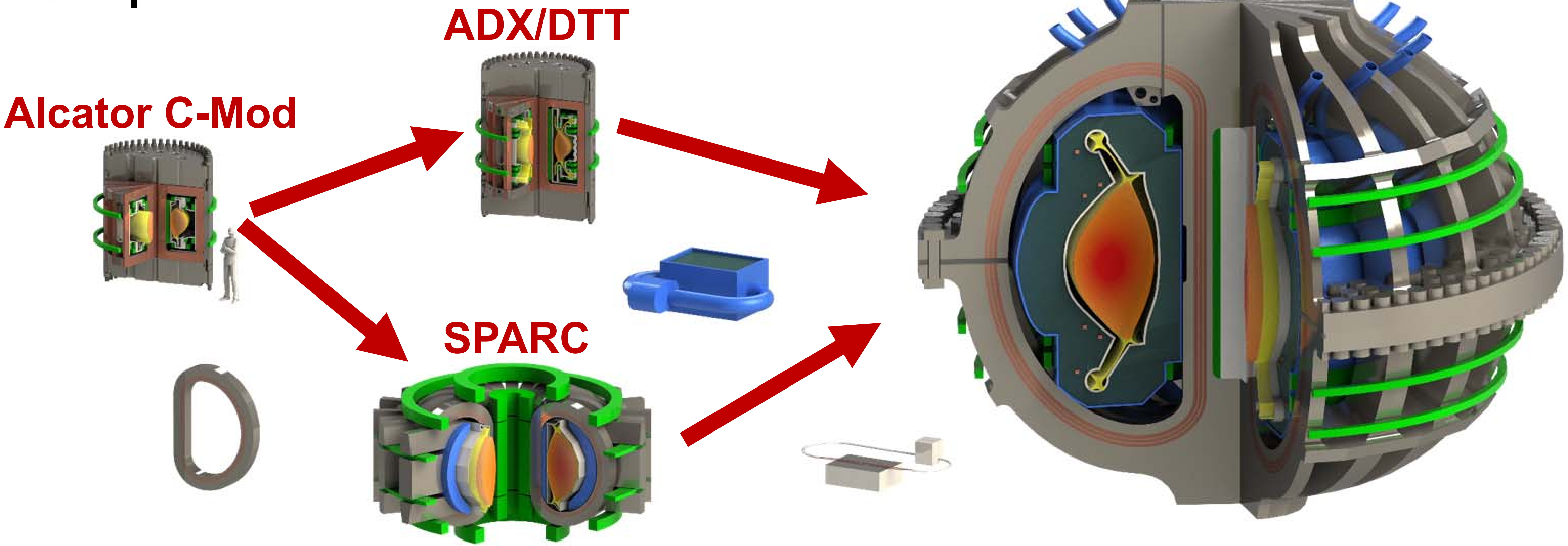
Exciting Path for Fusion Energy

SPARC

Alcator C-Mod

High-Field, High Power Density Plasma Science Experiments

ARC Pilot Plant



Magnet and Fusion Technology, Burning Plasma

Related Presentations at 2018 IAEA FEC

Tuesday Morning

- E. Tolman: Conceptual design study for heat exhaust management in the ARC fusion pilot plant, FIP/P1-22

Wednesday Morning

- P.B. Snyder: High Fusion Performance in Super H-Mode Experiments on Alcator C-Mod and DIII-D, EX/2-4

Wednesday Afternoon

- T. Tala: Core Density Peaking Experiments in JET, DIII-D and C-Mod in Various Operational Scenarios Driven by Fuelling or Transport, EX/4-4

Thursday Afternoon

- D. Brunner/M.V. Umansky: Extending the Boundary Heat Flux Width Database to 1.3 Tesla Poloidal Magnetic Field in the Alcator C-Mod Tokamak, EX/P6-9
- T.M. Wilks: Access Requirements for Stationary ELM-Suppressed Pedestals in DIII-D and C-Mod Plasmas, EX/P6-19
- R.S. Granetz: Machine Learning for Disruption Warning on Alcator C-Mod, DIII-D, and EAST Tokamaks, EX/P6-20
- S.G. Baek: Observation of Efficient Lower Hybrid Current Drive at High Density on Alcator C-Mod, EX/P6-28

Friday Morning

- M.R.K. Wigram: Performance assessment of tightly-baffled long-leg divertor geometries in the ARC reactor concept, TH/P7-20

Friday Afternoon

- E.H. Martin/G.M. Wallace: Experimental Evidence of Lower Hybrid Wave Scattering in Alcator C-Mod Due to Scrape Off Layer Density Fluctuations, EX/8-2
- M.V. Umansky: Study of Passively Stable, Fully-Detached Divertor Plasma Regimes Attained in Innovative Long-Legged Divertor Configurations, TH/7-2
- M.G. Dunne: Impact of Impurity Seeding on Pedestal Structure in ASDEX Upgrade and Alcator C-Mod, EX/P8-2