Fusion Research and Spinoffs at MIT

Miklos Porkolab

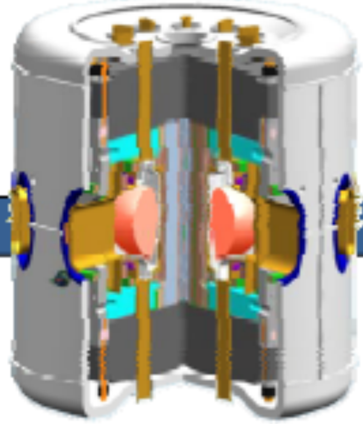
with input from

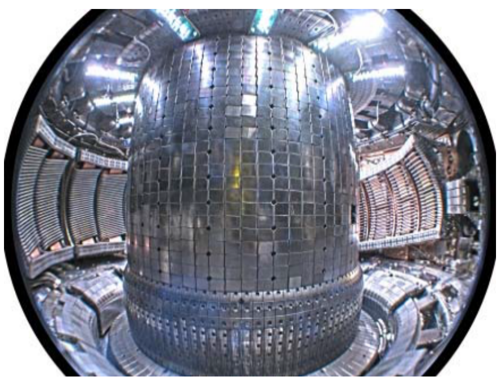
P.T. Bonoli, M. Greenwald, B. Labombard, E. Marmar, J. Minervini, R. Petrasso, R. Temkin, D. Whyte, P.P.Woskov, and S. Wukitch

Presented at the Annual Fusion Power Associates Meeting
Washington, D.C., December 16, 2014

The MIT Strategy to FNSF/DEMO:

C-Mod



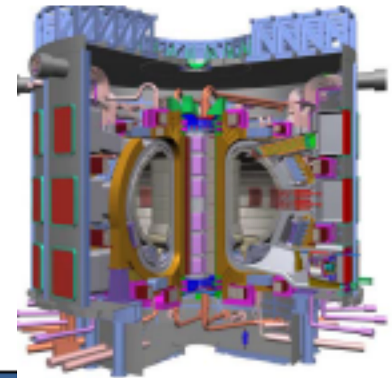


Now will operate through FY16

ADX

Could design and build by≈ 2022, to test advanced divertor geometries and demonstrate efficient ICRF and LH Current Drive

ITER



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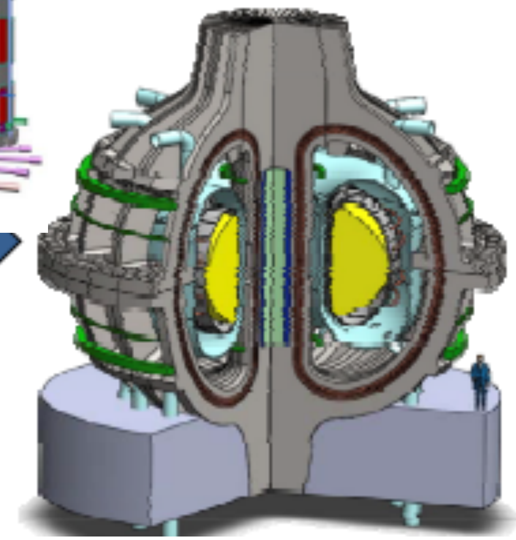
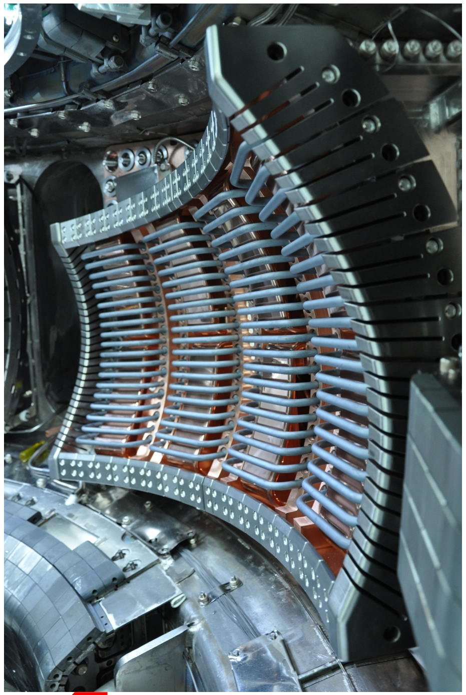


A JET size high B, steady state, HTS compact device generating 200 MWe of fusion power
(D. Whyte, students)

M. Porkolab-FPA 2014

Key research elements of C-Mod near-term

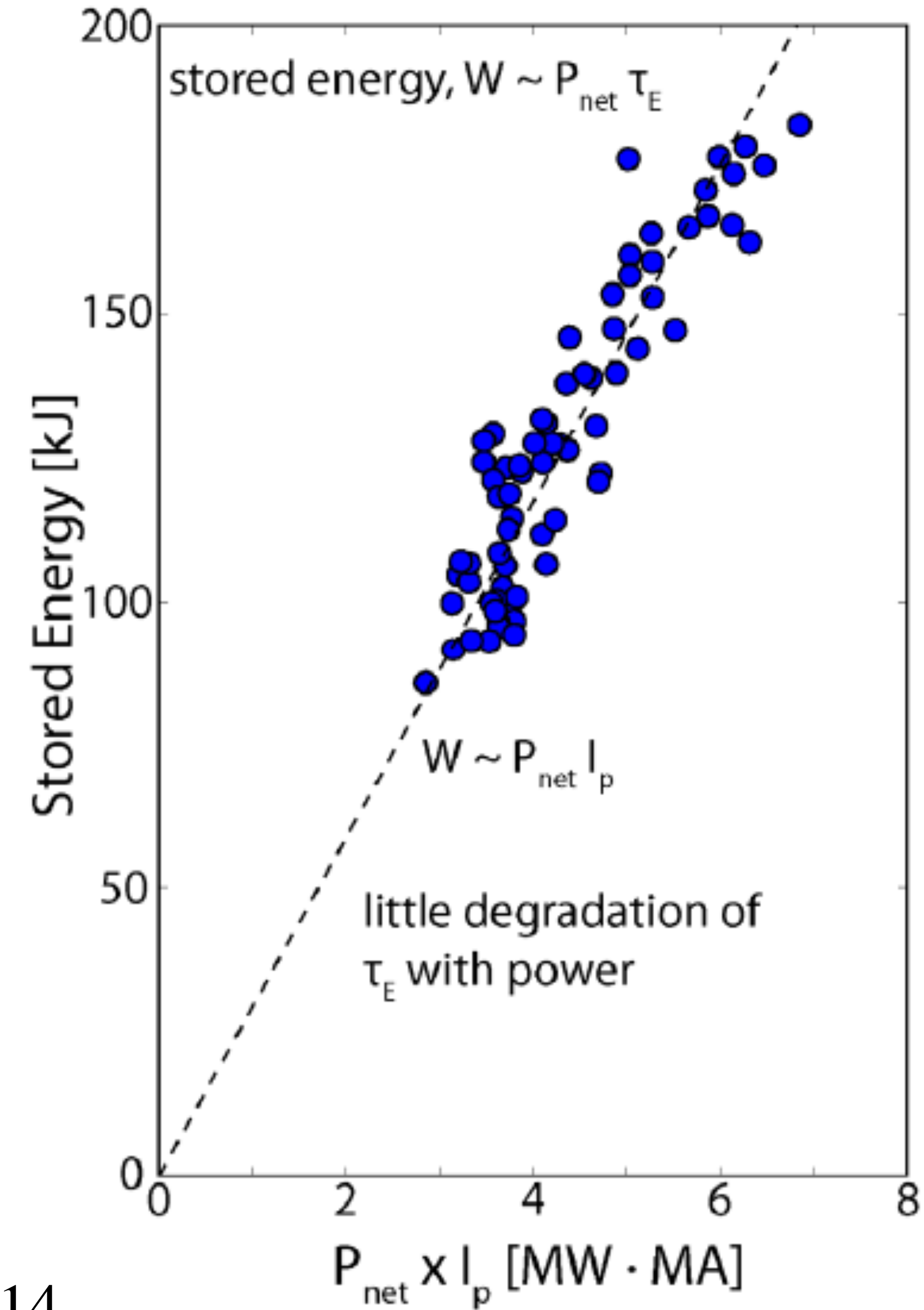


- I – mode scaling (Improved confinement w/o ELMS)
- Inter-ELM H mode pedestal modes: KBM ?
- Understand the physics of LHCD density limit
- LHRF impact on SOL plasma above the LHCD "density limit" resulting in improved confinement
- Understanding enhanced runaway loss, below the Connor-Hastie density limit – favorable for ITER
- Improved ICRF performance with "field aligned" antenna ↗
- Narrow SOL power channel scaling and the ITER inner wall design
- Future goals: solving the sustainment, exhaust and PMI challenges in an all metallic tokamak environment

Earl Marmar, IAEA, St. Petersburg, 2014; M. Porkolab, FPA, 2014

I-mode: Confinement does not degrade with input power

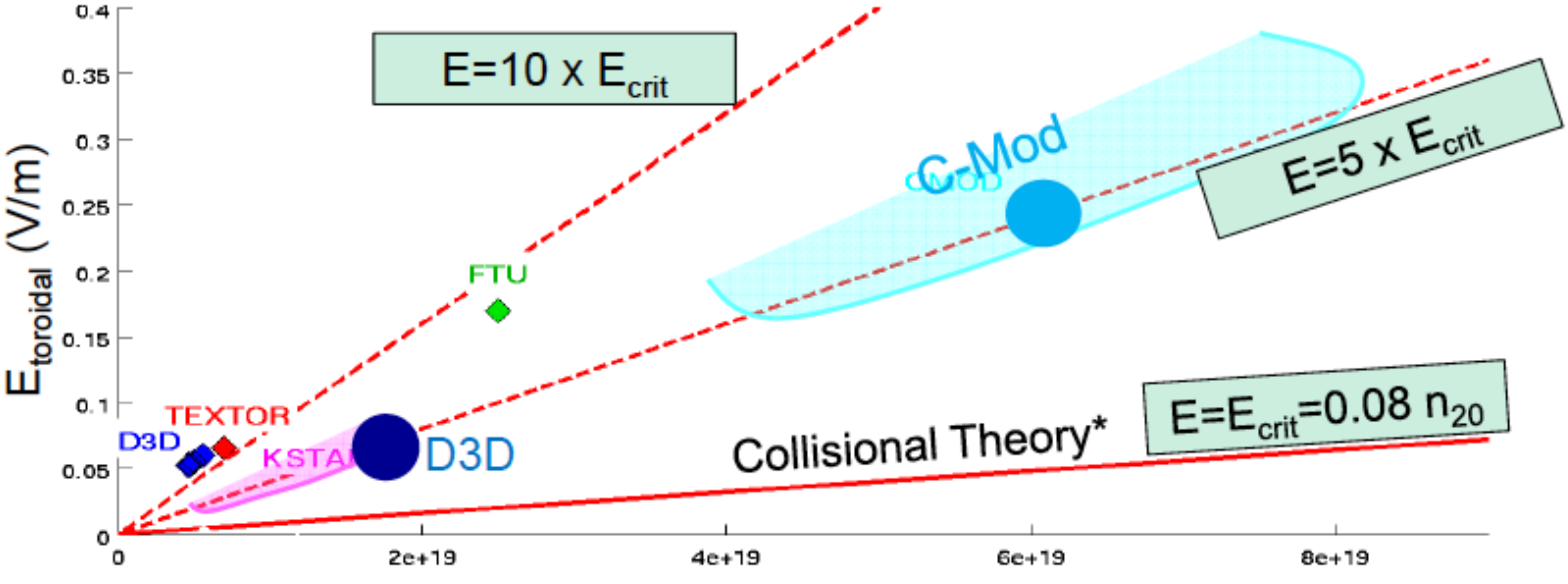
- C-Mod experiments show $P_{L\text{-}I} \propto n$, τ_E nearly indep. of P_{in}
- Very different from H-mode scaling
  - $\tau_E \propto P_{in}^{-0.7}$
  - or Stored Energy $\propto P_{in}^{+0.3}$
  - I-mode edge pedestal away from stability boundary, even at highest performance



A.E. Hubbard, et al., EX/P6-18 IAEA 2014

Runaway electron suppression requires much less density than expected from collisions

Alcator C-Mod



- Very important issue for ITER
  - Runaways must be quenched during disruptions
  - Reaching densities required for collisional suppression challenges mitigation technologies and pumping system
- ITPA joint experiments indicate challenge may be reduced
  - Anomalous loss process(es) dominate (~5x reduction in required density)
  - Mechanism(s) not yet identified

IAEA 2014

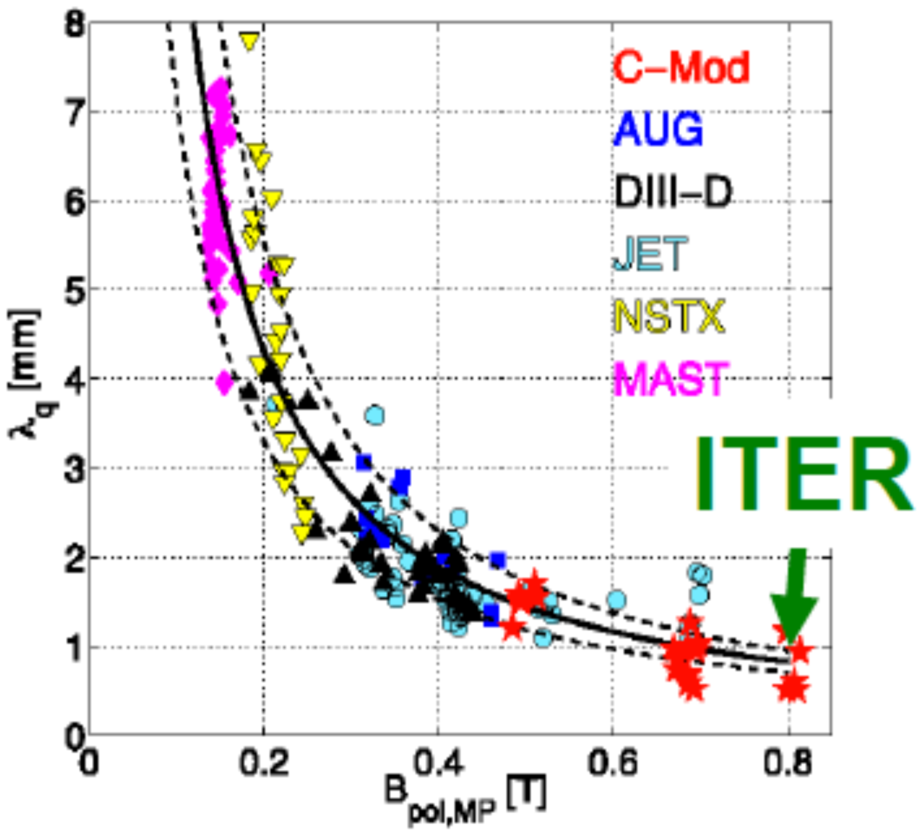
*J.W. Connor, R.J. Hastie, Nucl. Fusion **15** (1975) 415

R.S. Granetz, et al., EX/5-1

Emerging Understanding Indicates Heat Exhaust Needs Improved Solution

Heat flux width, λ_q, appears to be independent of machine size – depends only on B_{pol}.

- Scaling indicates ITER heat flux width will be **~1 mm about 1/5 of design value**!



(*low divertor recycling*, H-mode conditions)

Eich, *et al.*, NF 53 (2013) 093031

Increase radiated power?

But cold divertor plasma must remain in divetor chamber to be compatible with hot pedestal and good confinement (H98 > 1).

Heat flux into the divertor, $q_{||}$, scales as ~$P_{SOL}B/R$.

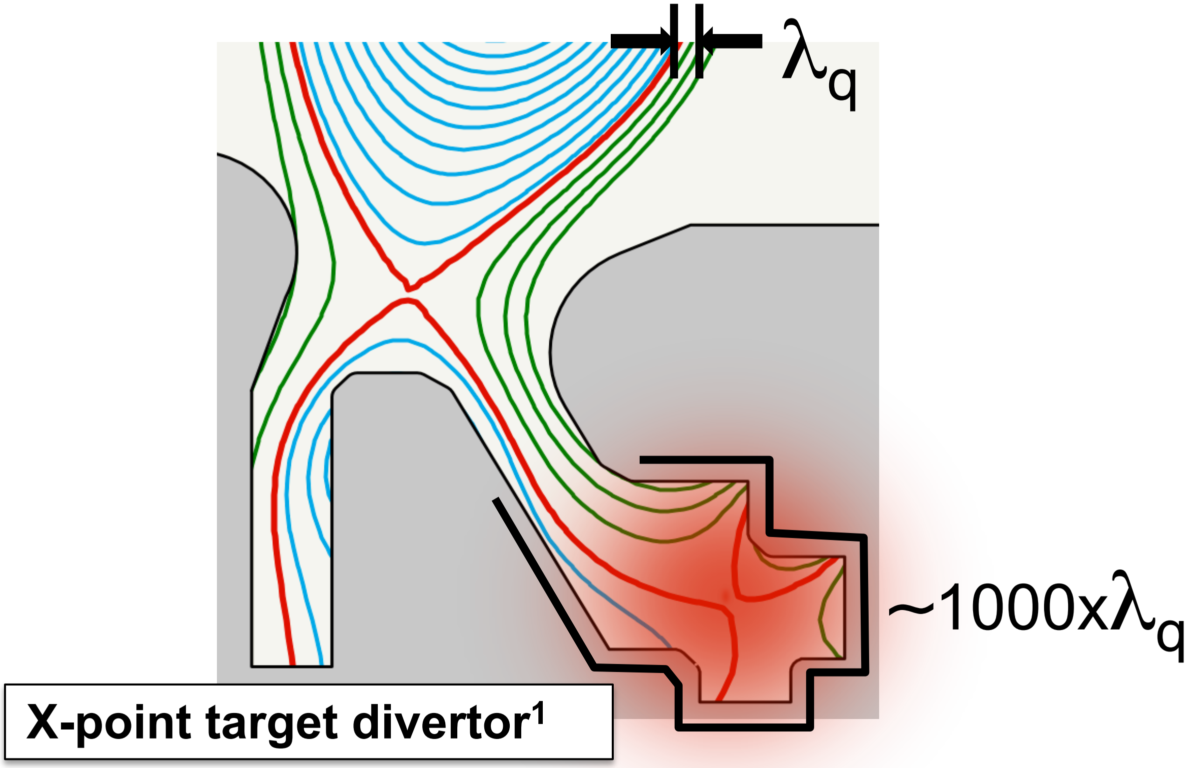
For DEMO, P_{SOL} ~ 4x ITER P_{SOL}

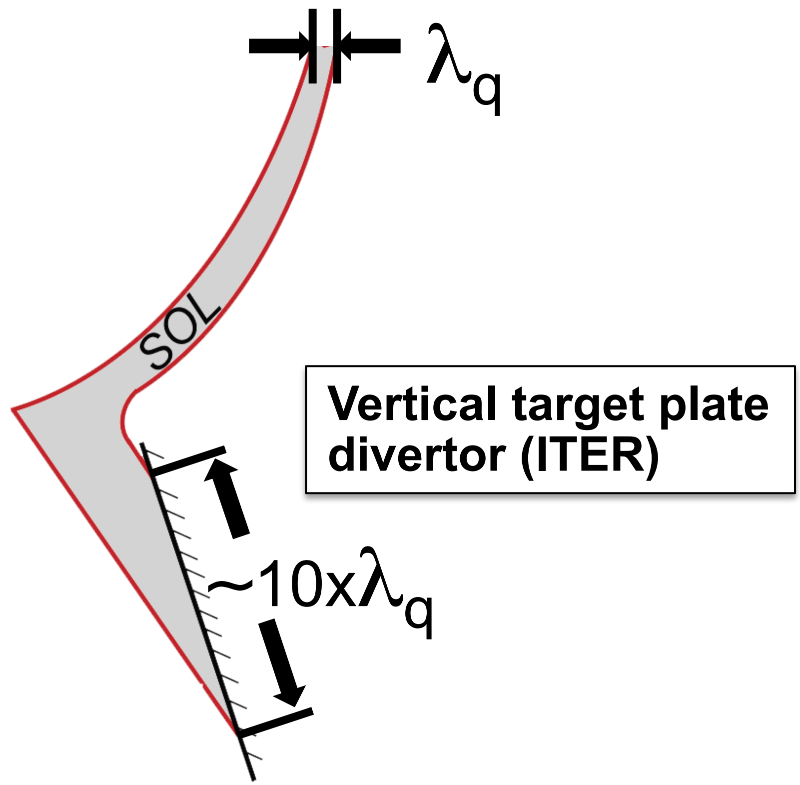
Need better solution!

In addition, completely suppress target erosion.

Advanced divertors have the potential to the solve power handling and erosion problems – they must be pursued.

New Concept[1]: Use a remote X-point to produce a fully detached, radiating plasma as a *virtual target*.





- Cold, fully detached divertor = ~ zero erosion

- Hot separatrix and pedestal regions = good core performance

Spread divertor heat load over the large surface area of the divertor chamber by tailoring magnetic geometry and radiation/neutral interaction zone

[1] http://www.psfc.mit.edu/research/alcator/pubs/APS/APS2013/labombard_cont-oral_APS-13.pdf

ADX: National Advanced Divertor and RF Test Facility

Mission:

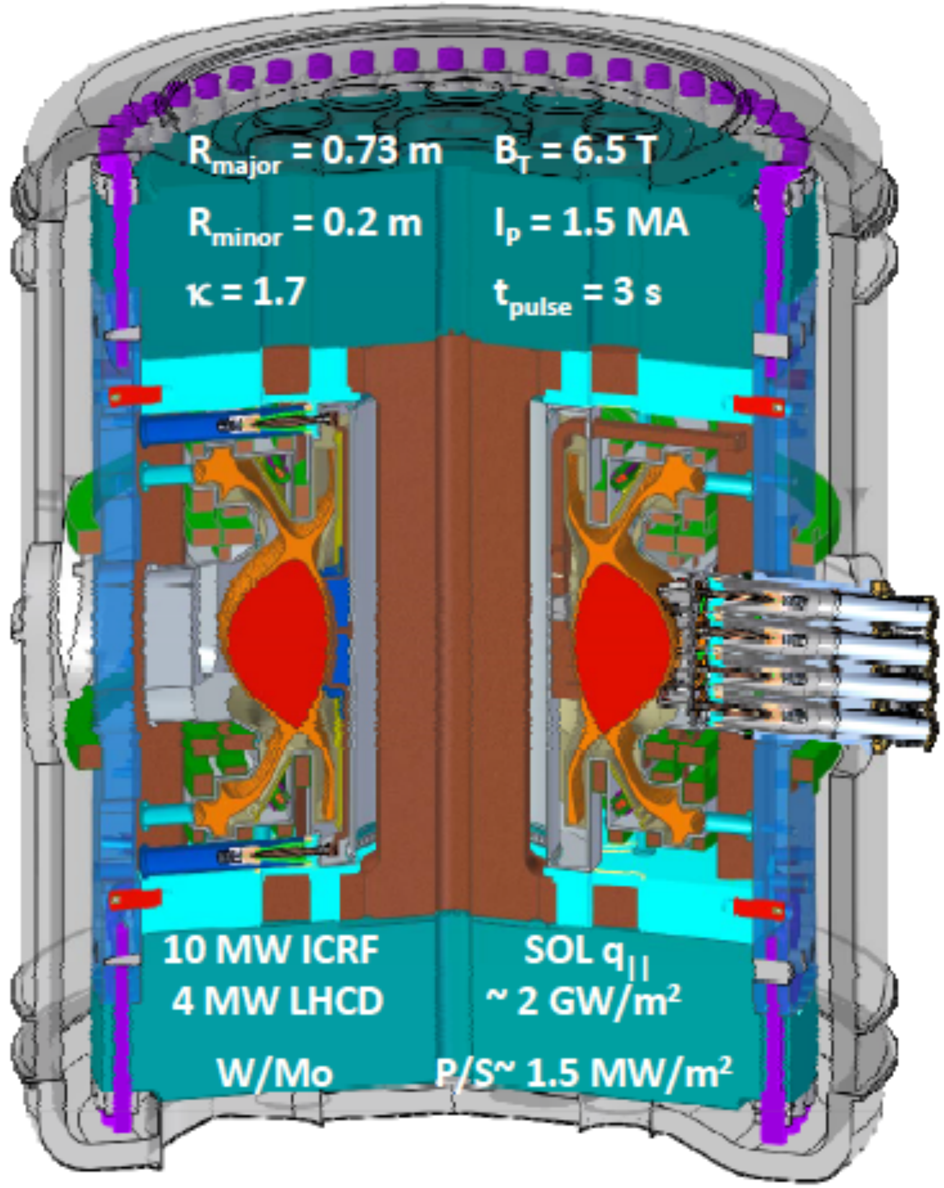
Investigate innovative divertor, PMI, and RF solutions at reactor relevant parameters, field and density, in a tokamak device with high core plasma performance.

Key Elements:

Flexible divertor poloidal field coil sets allows variety of advanced divertor concepts

Reactor-level P/S, SOL $q_{||}$ and plasma pressures

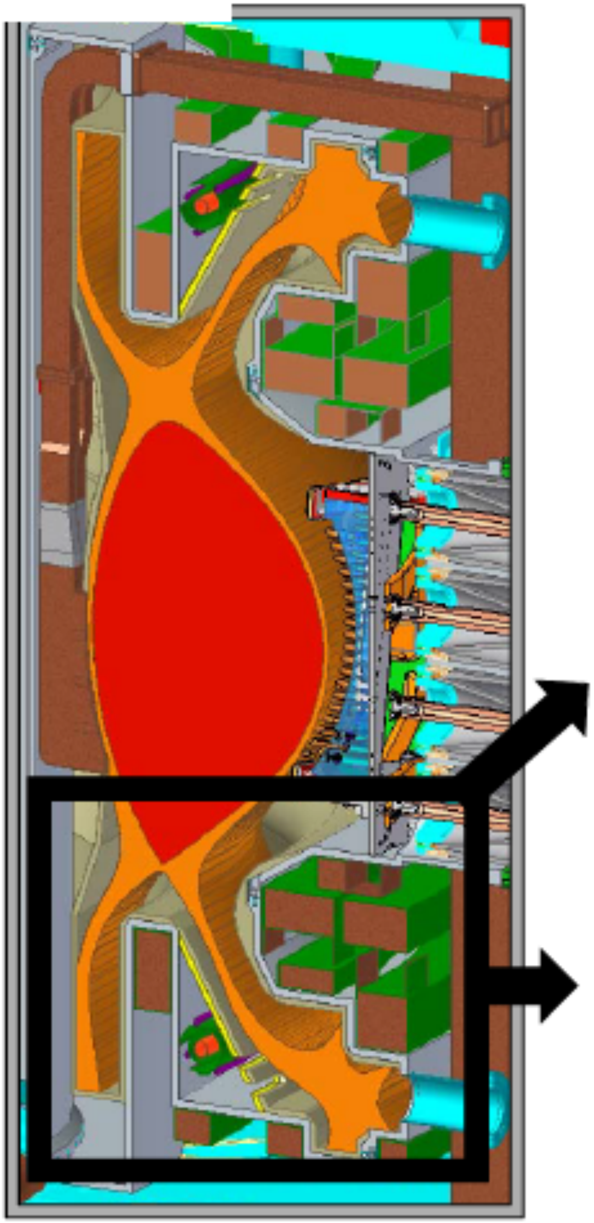
Integrated reactor-relevant RF heating and current drive systems



Advanced Divertor eXperiment

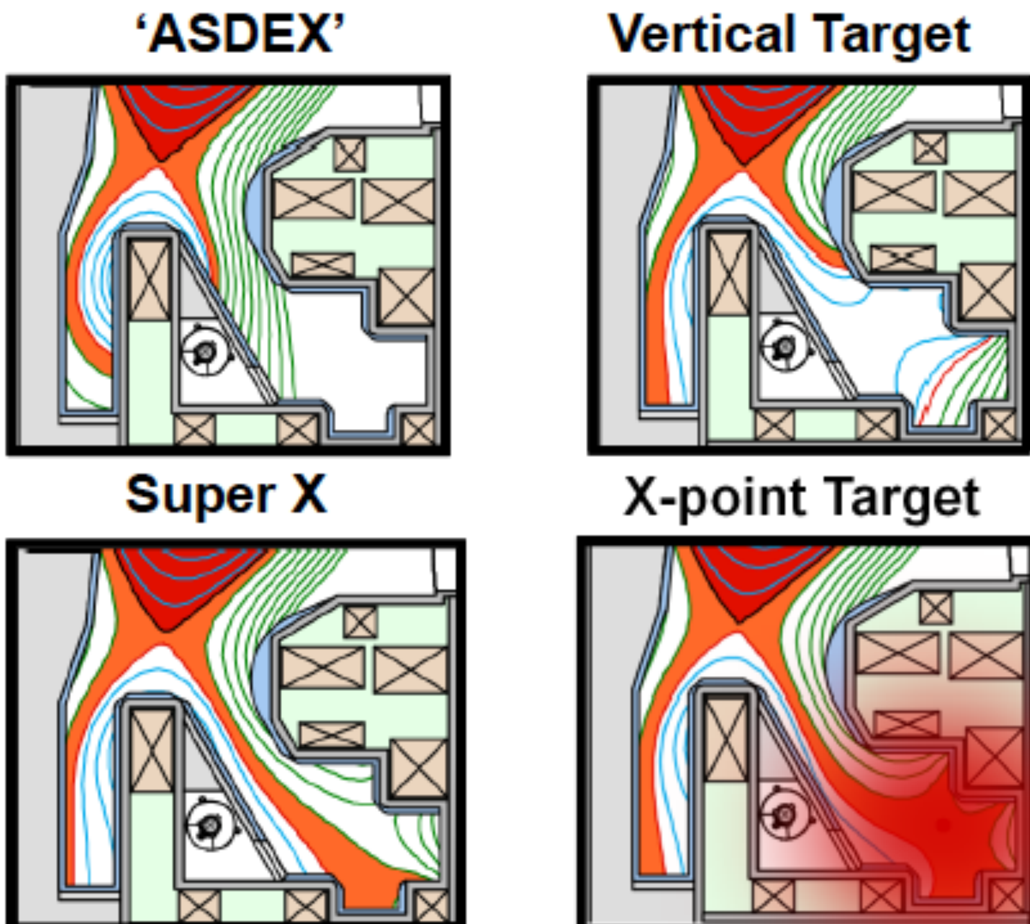
Internal PF Coils to Test Multiple Magnetic Geometries and Divertor Targets

ADX *Advanced Divertor Experiment*



PF coils may be configured for other geometries: snowflake, super X, and X-divertors.

Allows testing high temperature target and liquid metal options.

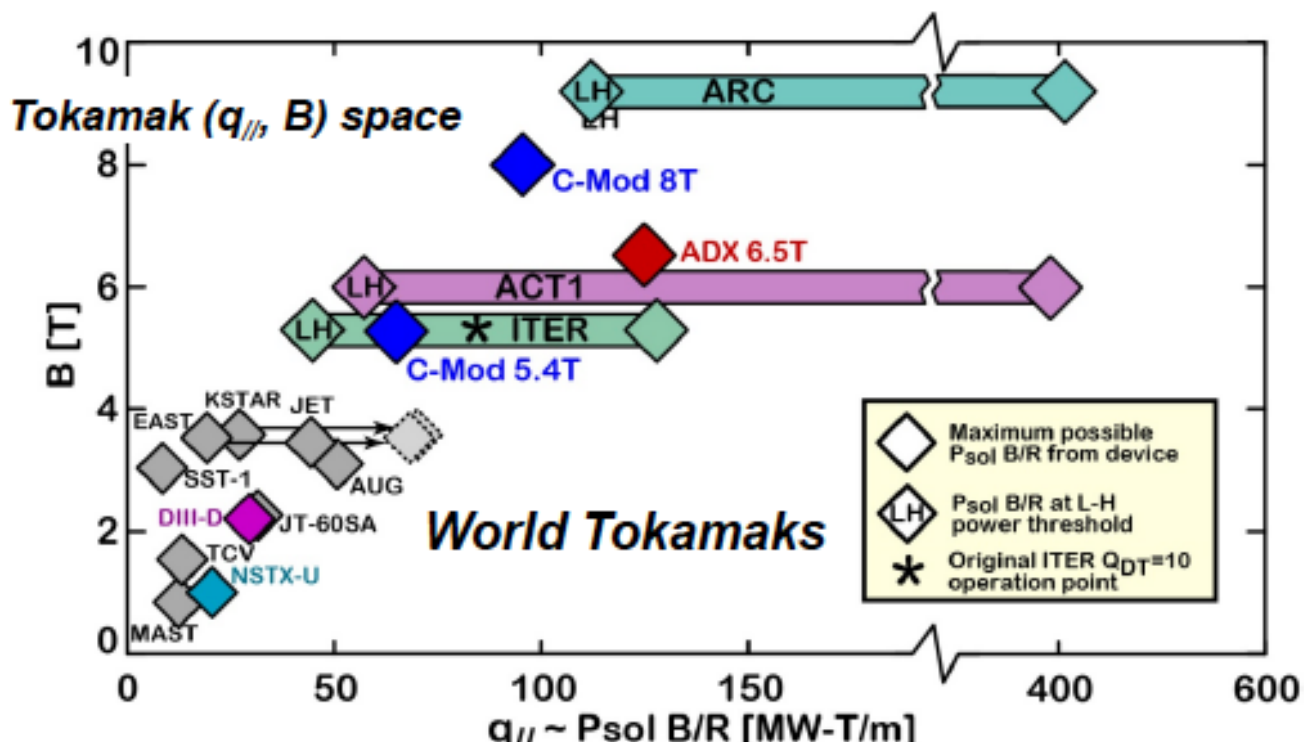


ADX Provides Ideal Platform to Test Divertor Solutions

Divertor test experiment should match divertor physics regimes in a reactor.

- Model/code extrapolation to untested regimes is unreliable.

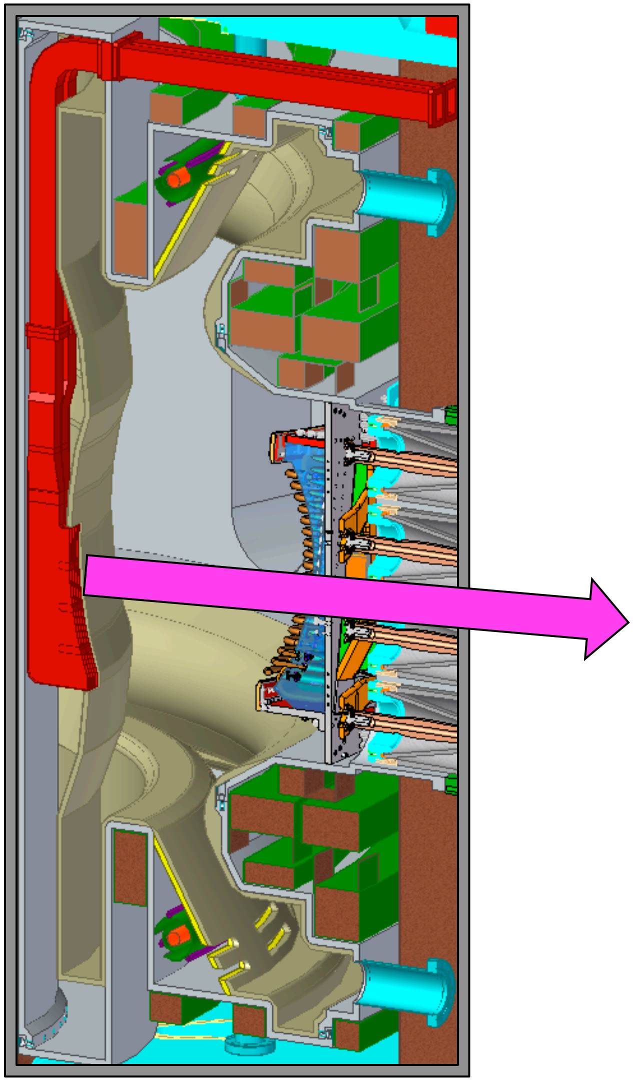
Reactor divertor conditions can be matched ($T_{e,div}$, n_{div}, key dimensionless parameters) if $q_{//}$, B and divertor geometry are matched.

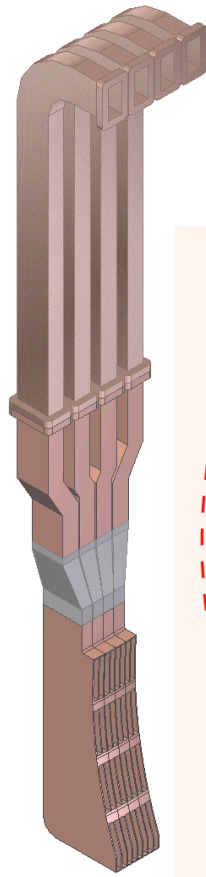


Stangeby, NF 51 (2011) 063001; Whyte, FED 87 (2012) 234.

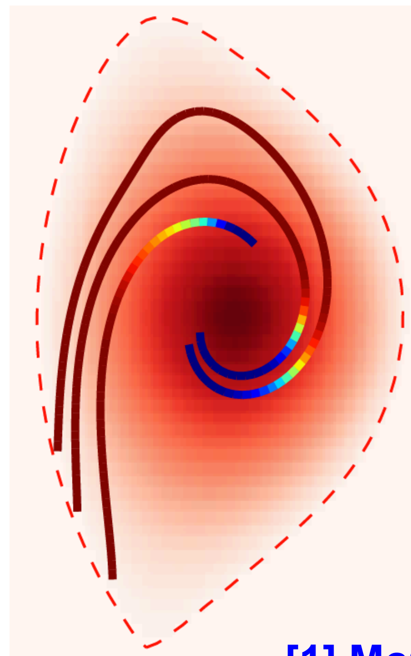
ADX *-- an important innovation platform for low PMI, reactor compatible RF actuators*

Alcator DX





Splitter and multi-junction fabrication techniques produce compact LHCD launchers that can fit on the inside wall.



- ***High B-field side***
  => lower $n_{//}$
  => penetrating rays
  => higher CD efficiency
- ***Quiescent SOL***
  => Low PMI
  => Excellent impurity screening[1]

[1] McCracken, *et al.*, PoP 4 (1997) 1681.

High field side launch is highly favorable for LHCD, as noted in VULCAN study[2].

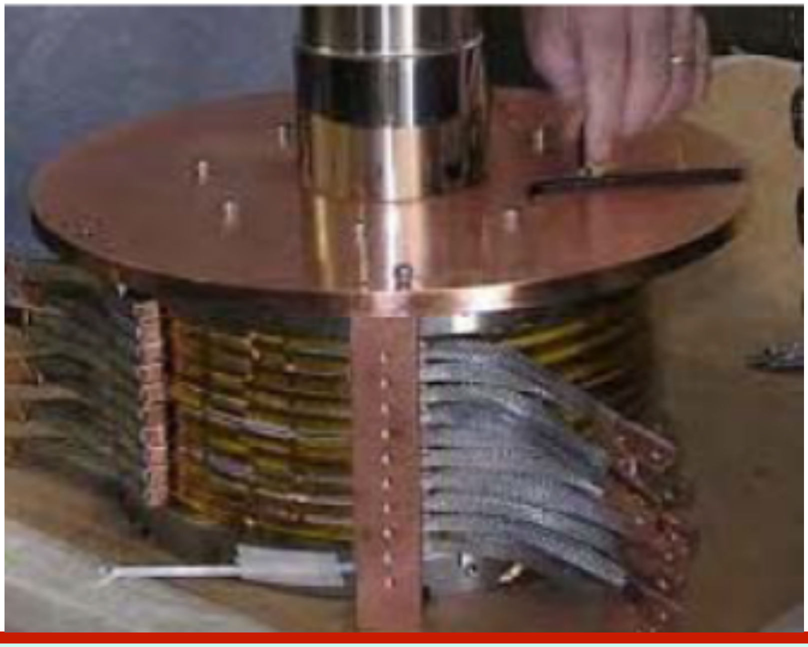
[2] VULCAN: Podpaly, *et al.*, FED 87 (2012) 215.

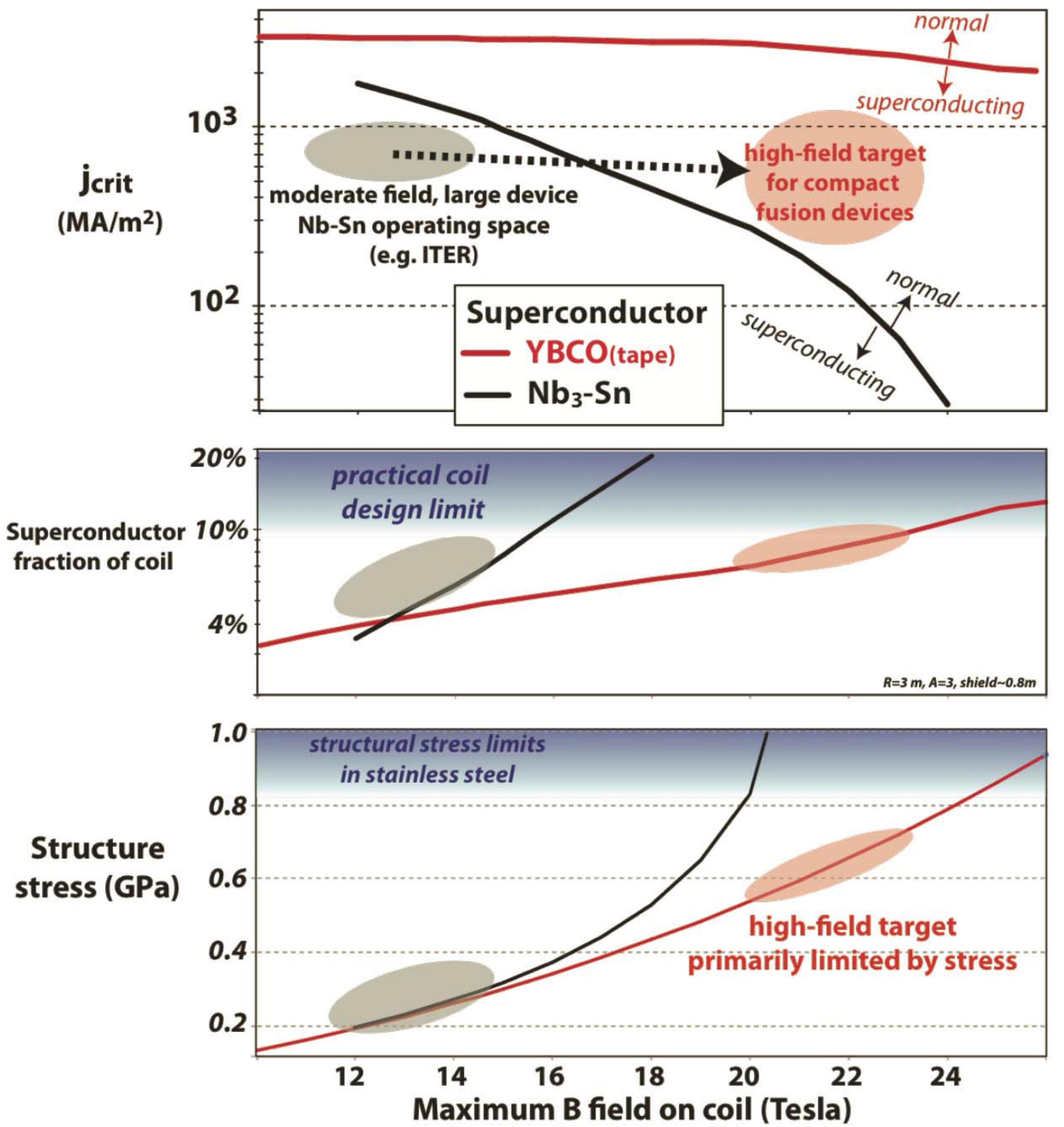
Milestone: ***(for SS burning plasma)*** **Develop robust, reactor-compatible current drive & heating techniques**

High Temperature/High Field Superconductors (HTS) Could be Game-Changer for Fusion Energy Development

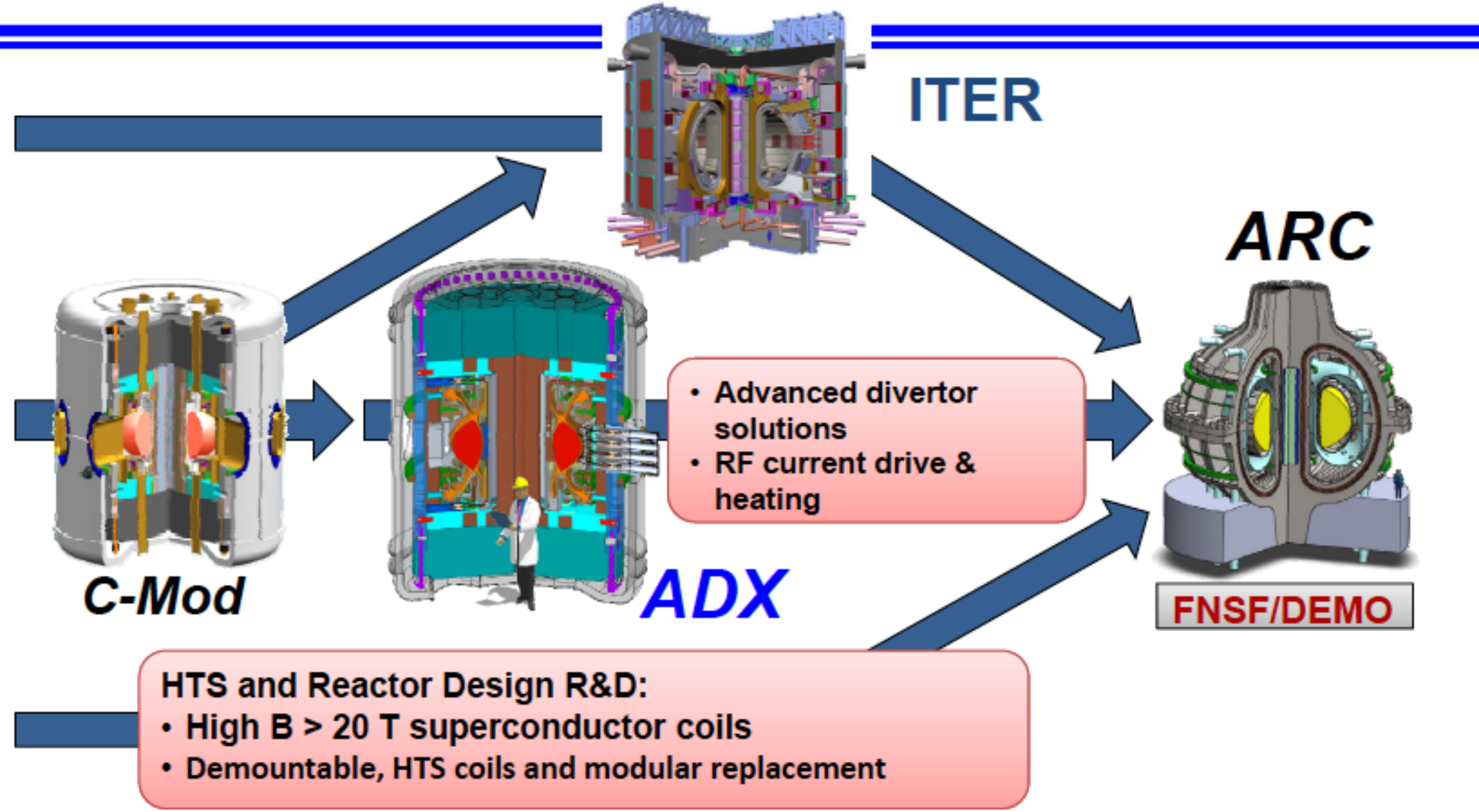
- Conventional (Nb_3Sn) superconductors limit field at the coil to 14 T
- Recent developments in HTS (e.g., YBCO) allows doubling of B field to >20T, leading to smaller FNSF
- Smaller units lead to faster development of fusion power

NML testing HTS at 32 Tesla



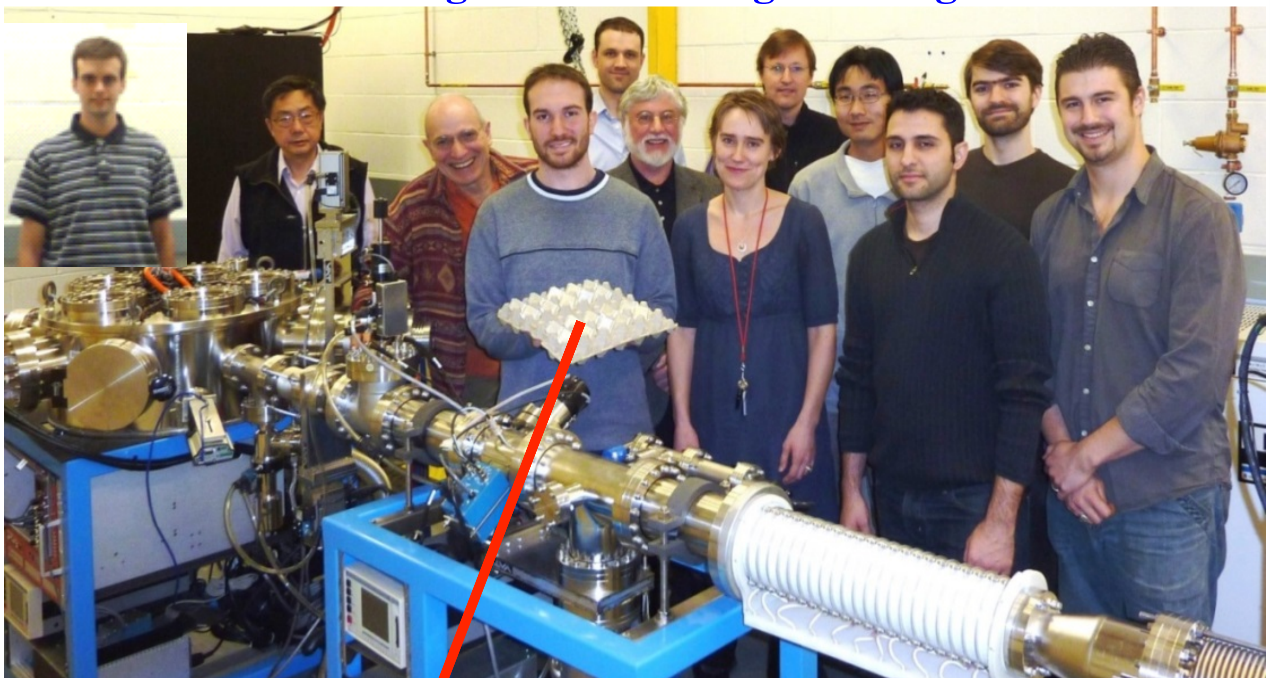


ADX is Essential Step to an Attractive Fusion Energy



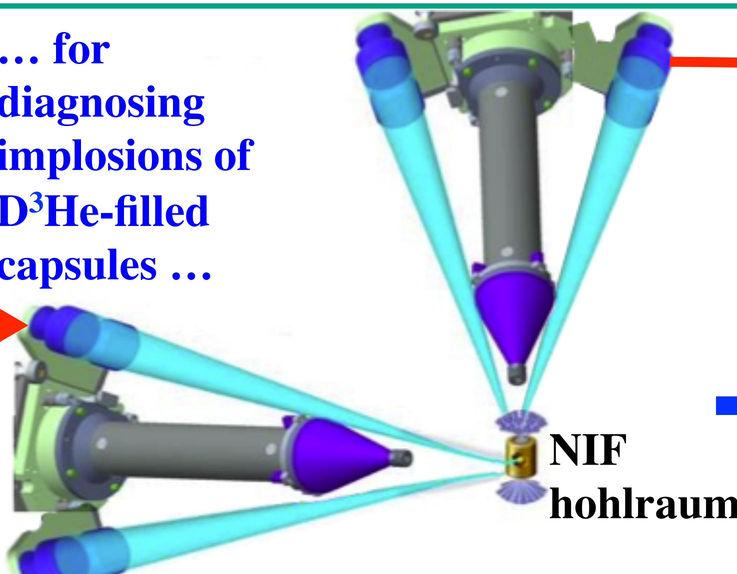
MIT develops diagnostics for OMEGA and NIF to study ICF, HEDP, and plasma nuclear physics

The MIT Accelerator Facility for Diagnostic Development is used for testing and calibrating ICF diagnostics …

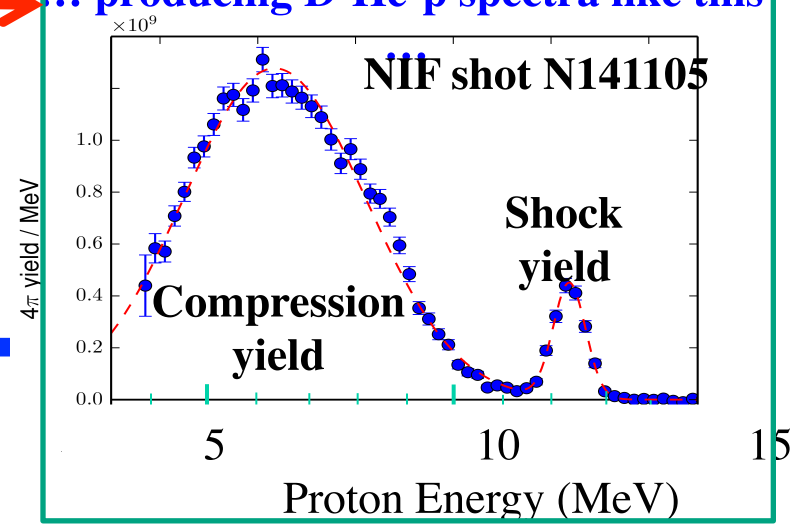


… such as compact proton spectrometers …

… for diagnosing implosions of D^3He-filled capsules …



… producing D^3He-p spectra like this



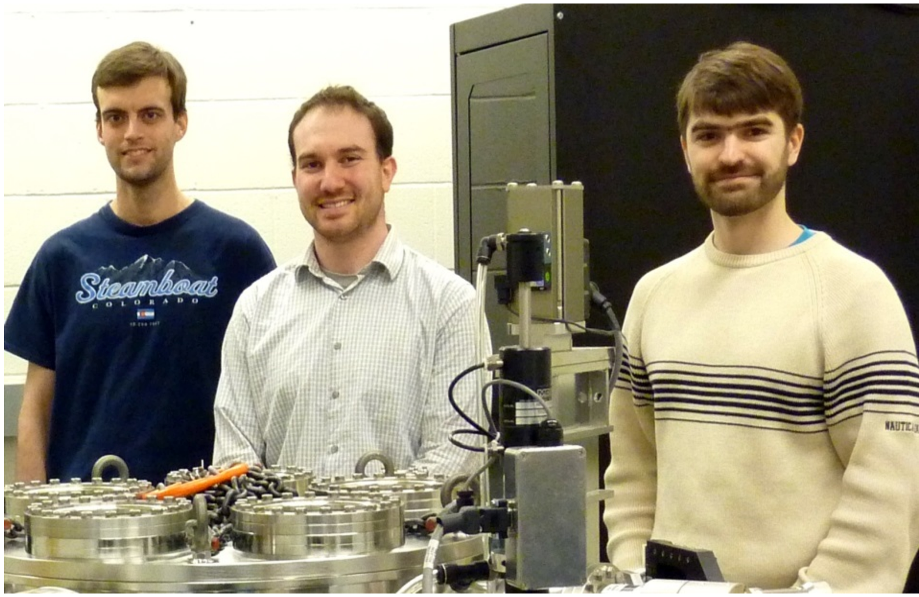
… for studying:

- **Shock and compression yields**
- **Areal densities at shock- and compression-bang times**
- **Asymmetries in areal density**

PSFC ICF/HEDP Division Recent highlights

- Recent student Dr. Mario Manuel Received the 2014 ***Marshall N. Rosenbluth Outstanding Doctoral Thesis Awa*** for demonstrating (in experiments on OMEGA) that Rayleigh-Taylor instabilities in plasmas generate ***B*** fields.

- During this academic year, three students will complete PhD theses about experiments on OMEGA and NIF.
- During the last two years, the group had 37 1st-author publications, including 24 by students (several ***PRL***s)

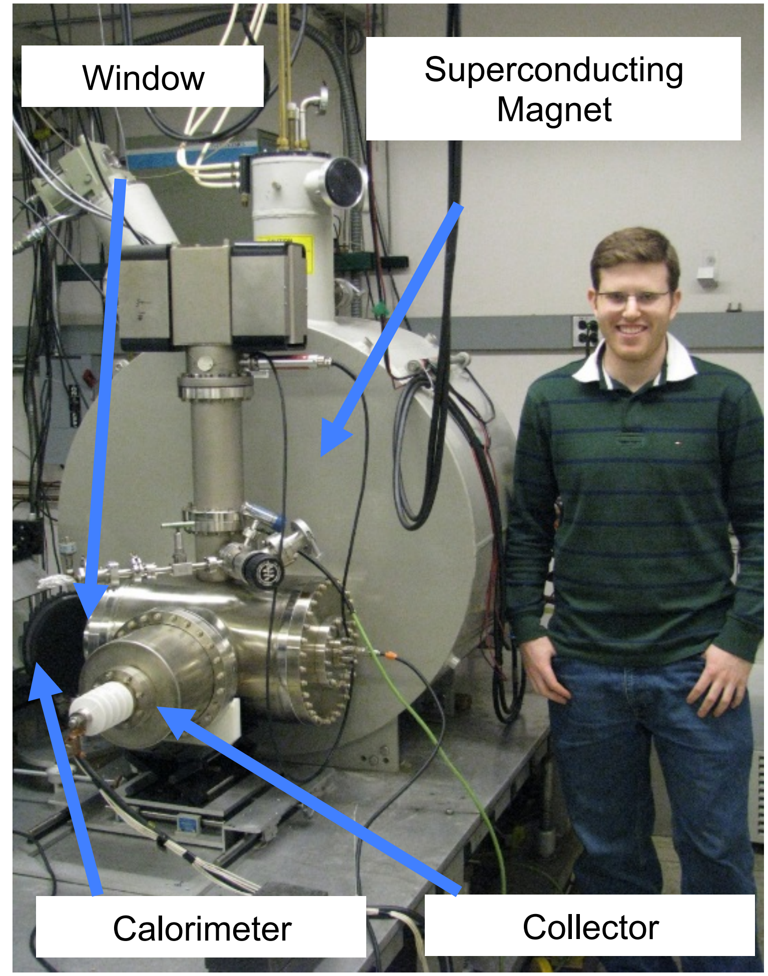


A. Zylstra, M. Rosenberg and H. Rinderknecht

Waves and Beams Division tests ECH components for ITER and develops novel ultra high frequency microwave sources

- Conduct Research with US ITER Project (ORNL) on Design and Test of Components for ITER ECH Transmission Lines
  - Also collaborate directly with ITER Organization

- Experiments on high frequency gyrotrons
  - Experimental test of 1.5 MW, 110 GHz / 124.5 GHz Two Frequency Gyrotron for General Atomics
  - Gyrotron with direct coupling to corrugated metallic waveguide, in collaboration with Calabazas Creek Research (SBIR)
- International Collaborations:
  - Collaborate with Japan and Europe on transmission lines and gyrotron research.

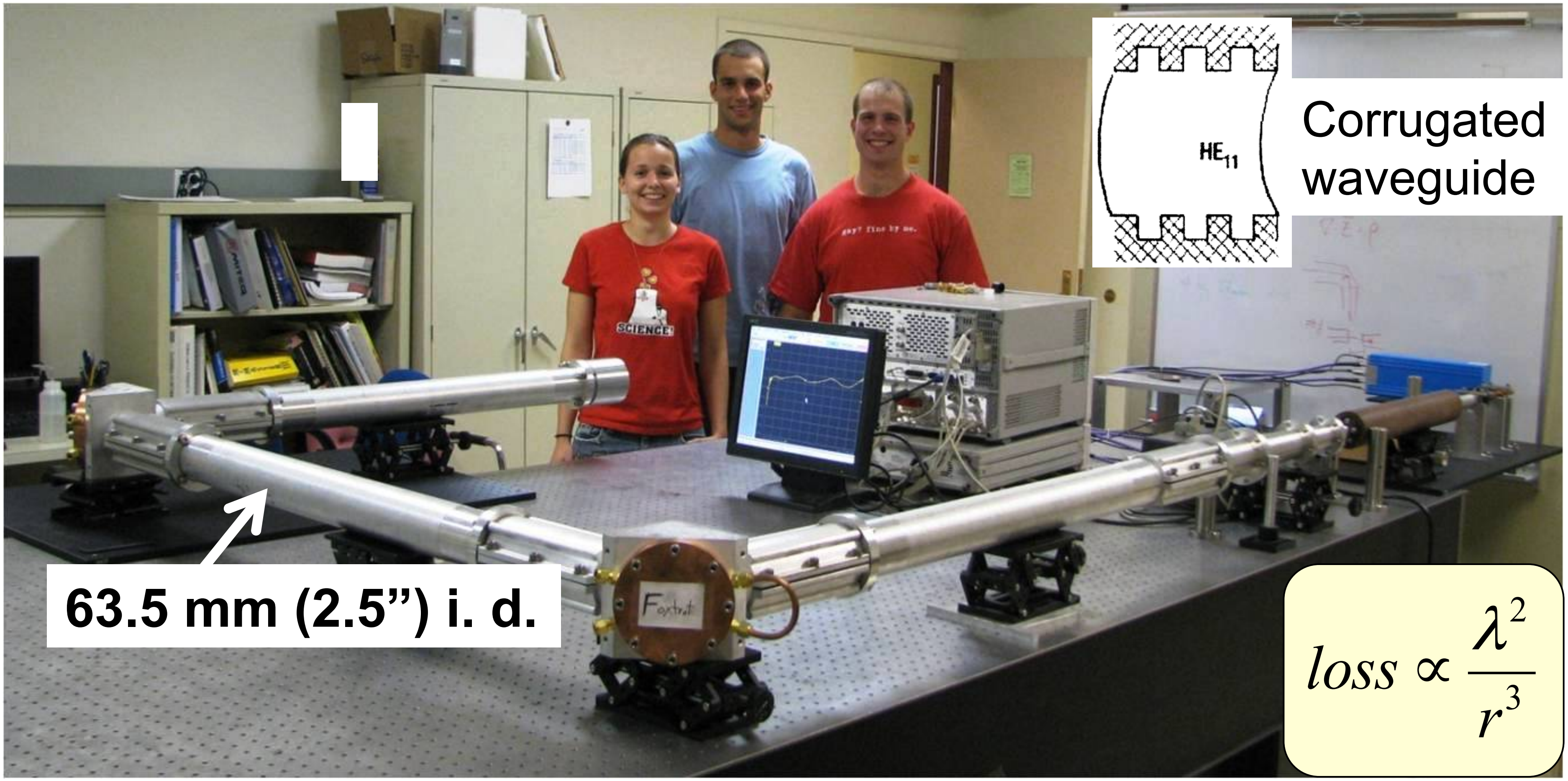


Two frequency gyrotron expt. with grad student David Tax

Rick Temkin, Division Head

Megawatt Waveguides Available

170 GHz, Megawatt Transmission Line for ITER



Theoretical straight empty transmission efficiency 90% to 2.5 km*
Increase diameter to 114 mm (4.5”), 90% transmission to 14 km*
Assuming 50% Al conductivity

*E. A. Nanni et al, “Low-loss Transmission Lines for High-power Terahertz Radiation”, J Infrared Milli Terahz Waves vol. 33, 695–714, 2012

IMPACT Technologies LLC

Paul P. Woskov, PSFC, PI

Gyrotron Drilling Full Bore:

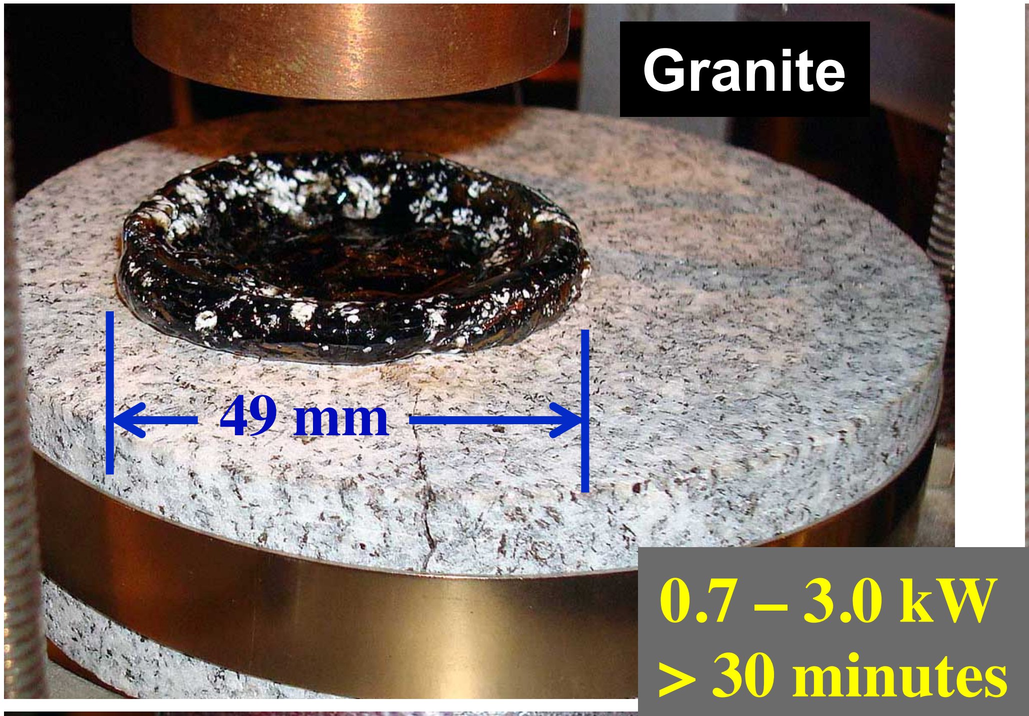
Accessing Earth's Crustal Resources with Fusion Energy Research Technology Spinoff

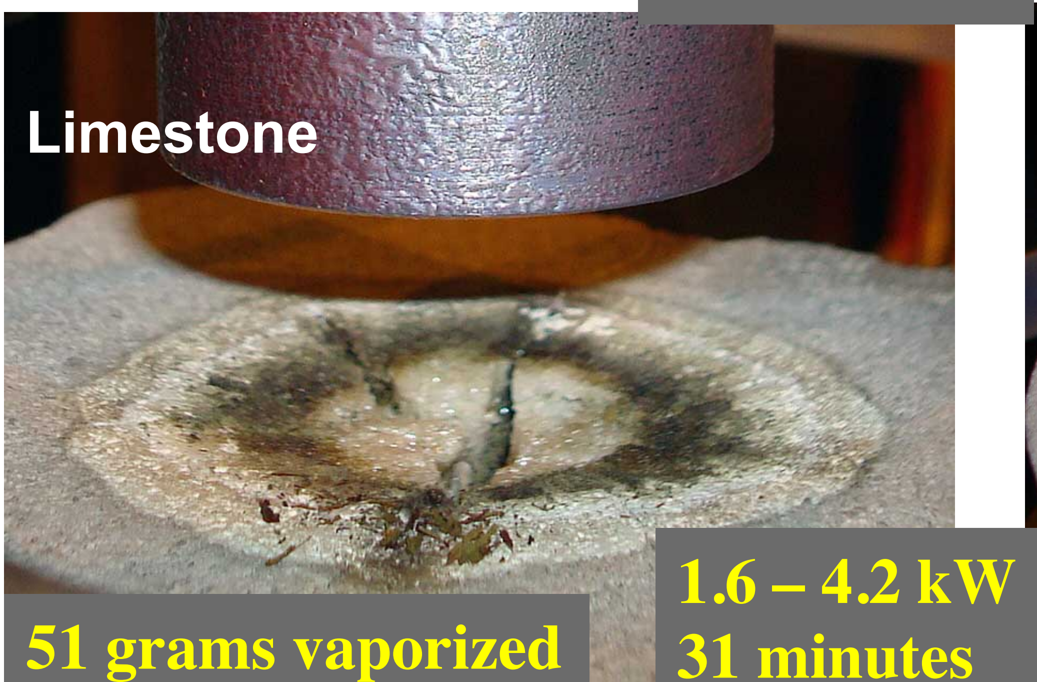
- **Important applications in need of advance in drilling**
- Enhanced Geothermal Systems (EGS)* in hot crystal rock formations
- A large potential energy resource second only to fusion**
- Nuclear waste storage in deep boreholes***
- Better biosphere isolation than near surface mined repositories

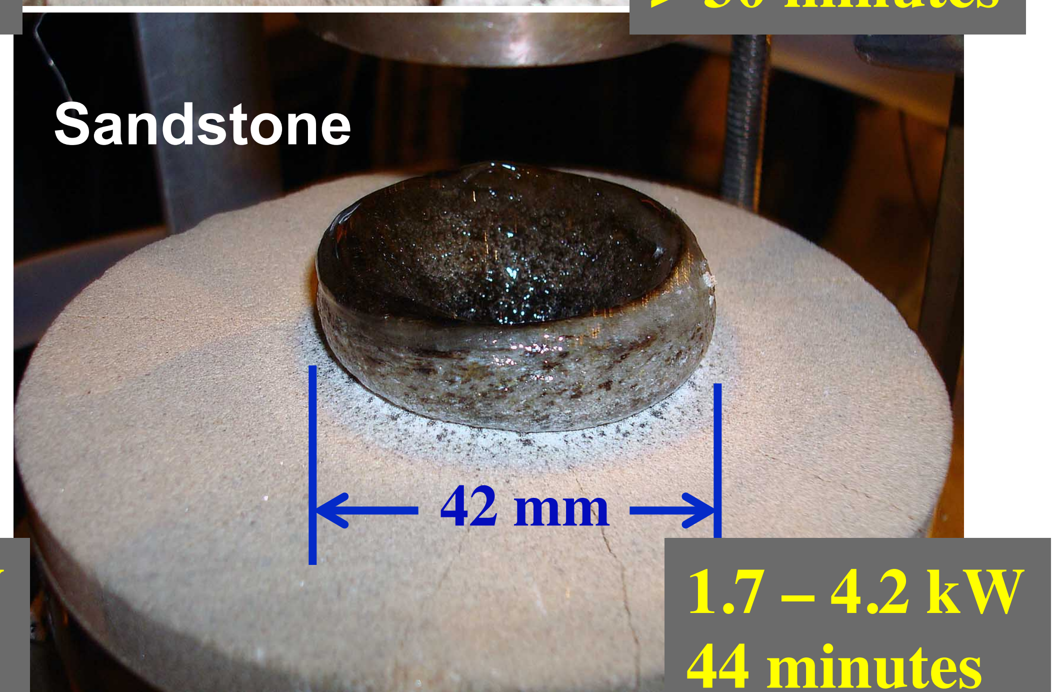
Low power (< 10 kW) tests at the PSFC at 28 GHz to be followed by high power (100 kW) 95 GHz tests next year at Kirtland AFB, NM

Low power results on flat surface samples

With Circular TE11 Down Taper to 20 mm Dia. Launch Aperture







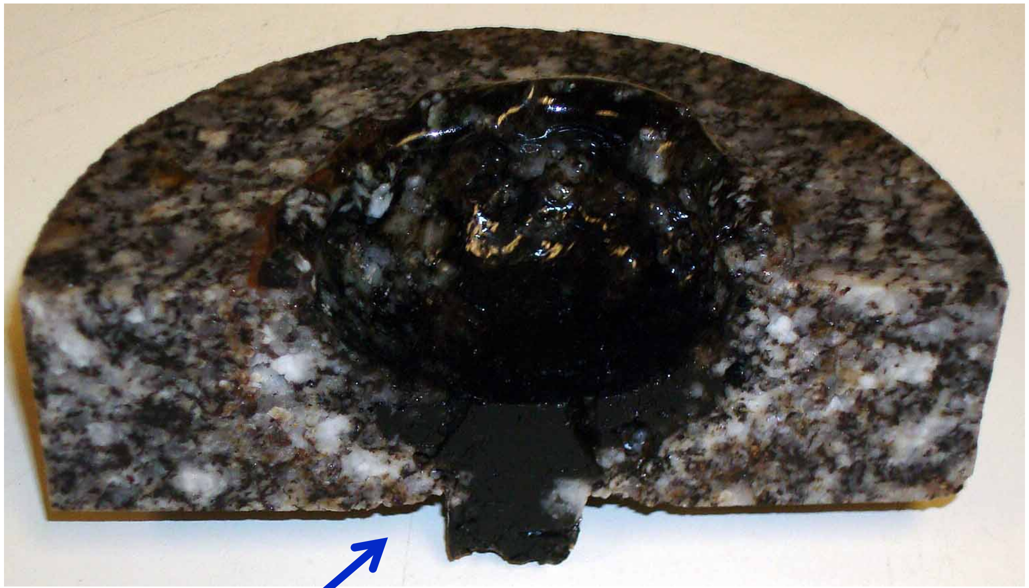
Sealing a Hole in Granite with Granite Melt

Nuclear Waste borehole could be sealed with the drilled crystalline rock melt

½" hole drilled in center

After two MMW Exposures & Redrill

After third Exposure



Hole Sealed by Granite Melt

Crater partially filled in

SUMMARY

- Significant innovation needed to go beyond ITER, both in physics and technology
- Physics innovation calls for continuing experimental plasma research
- Technology innovations require development of better materials and RF actuators
- Nuclear materials testing needs to be ramped up as budgets allow (materials, blankets and tritium breeding)
- High temperature superconducting magnets (HTS) should be developed as well as demountable magnets for ease of maintenance
- HTS results in more compact devices and lower cost development path
- Due to very long range development times, continuous education of scientists and engineers must be supported at the university level

Final Comments from Miklos Porkolab.

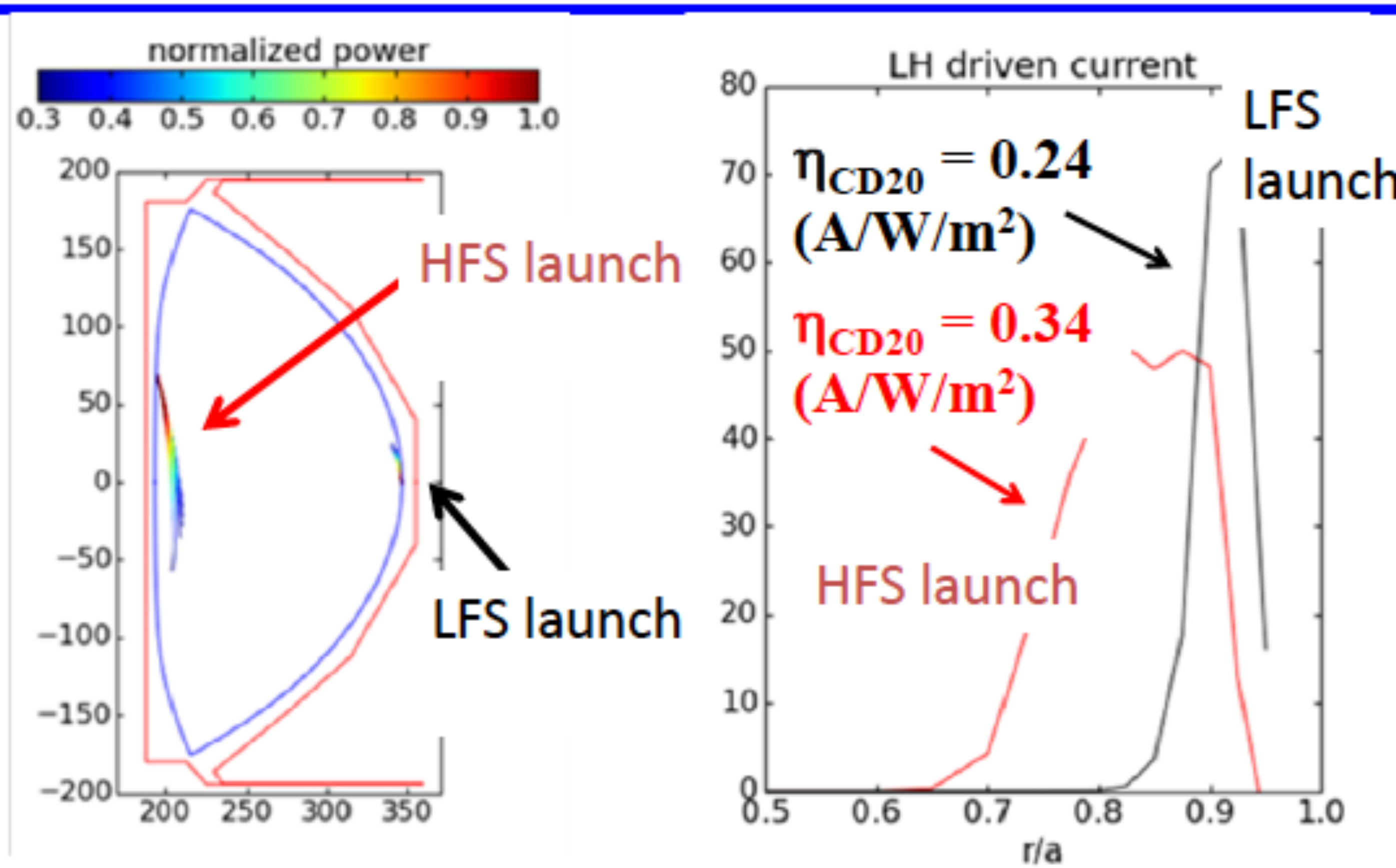
- It was a great pleasure and honor to serve for 20 years as a member of the Board of the Fusion Power Associates, including 6 years as Chairman

- Please welcome Dennis Whyte as the new Director of the MIT PSFC starting Jan 1, 2015, and I hope you will elect him to the FPA Board as I step down

- Times for fusion have never been more exciting in spite of all the challenges facing us; ultimately fusion will prevail

HFS LH Launch Shows Dramatically Improved Wave Penetration and Driven Current Profile

- GENRAY / CQL3D simulations of an FDF [1] plasma.
  - f_0 = 5 GHz $n_{//}$ = 1.9 (90% directivity) P_{LH} = 10 MW.



- Higher current drive efficiency (40% improvement) and wave penetration are demonstrated.
- Broad current drive profile is obtained for HFS launch.as needed for MHD stability.

[1] V.S. Chan *et al*, Nucl. Fusion **51** 083019 (2011).