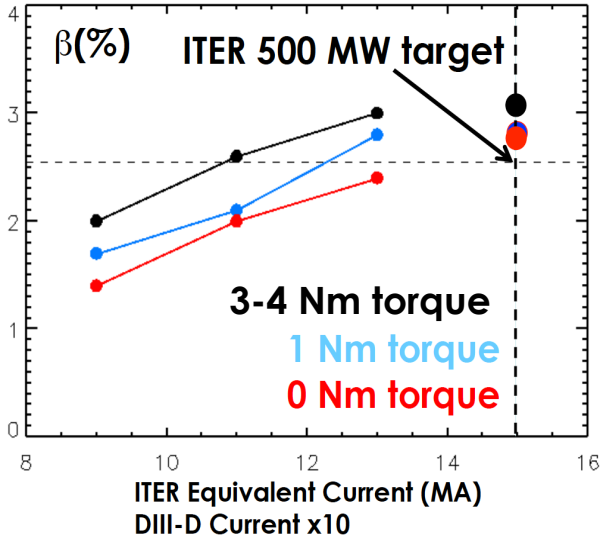
DIII-D Research Goals: Develop the Physics Basis for ITER Q=10 and Future Steady-State Tokamaks

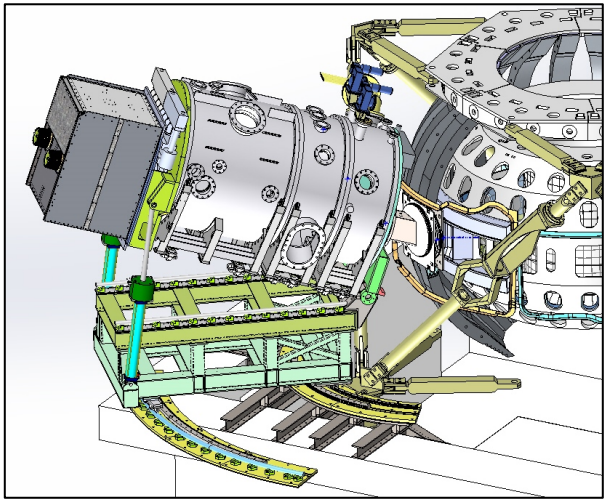
Pursue low torque, transient-free stable cores with high fusion gain

Develop advanced current profiles for high β_N and high bootstrap fraction

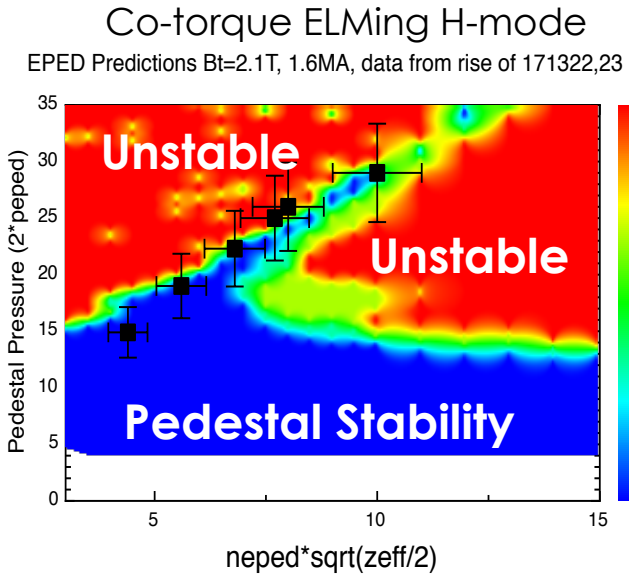
Optimize H&CD for steady-state burning plasma operation

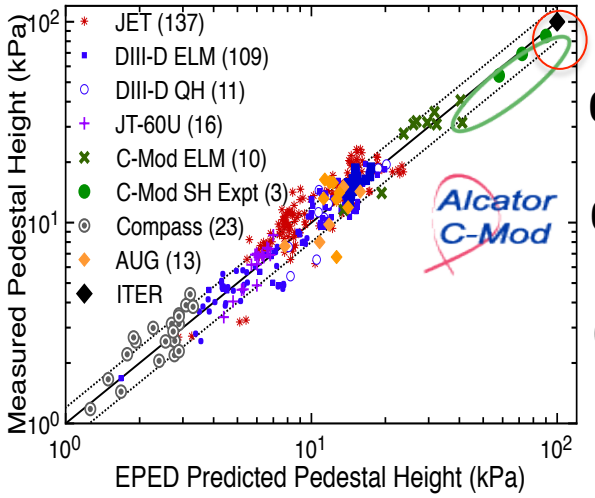
- ECCD, Helicon, and HFS-LHCD

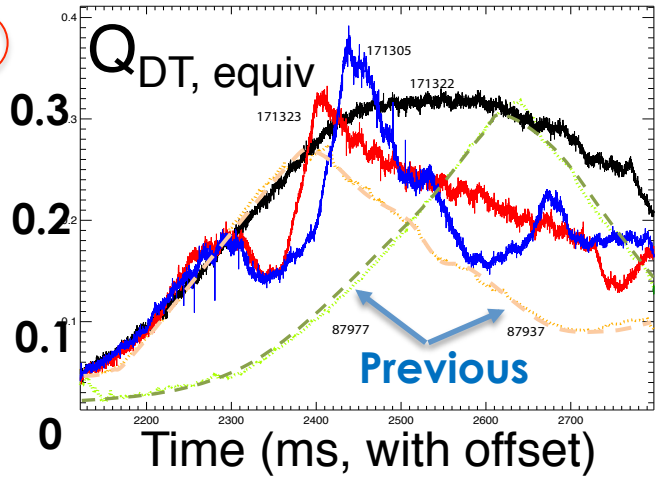




Recent Super H-Mode Experiments Yield Large Gains in Fusion Performance







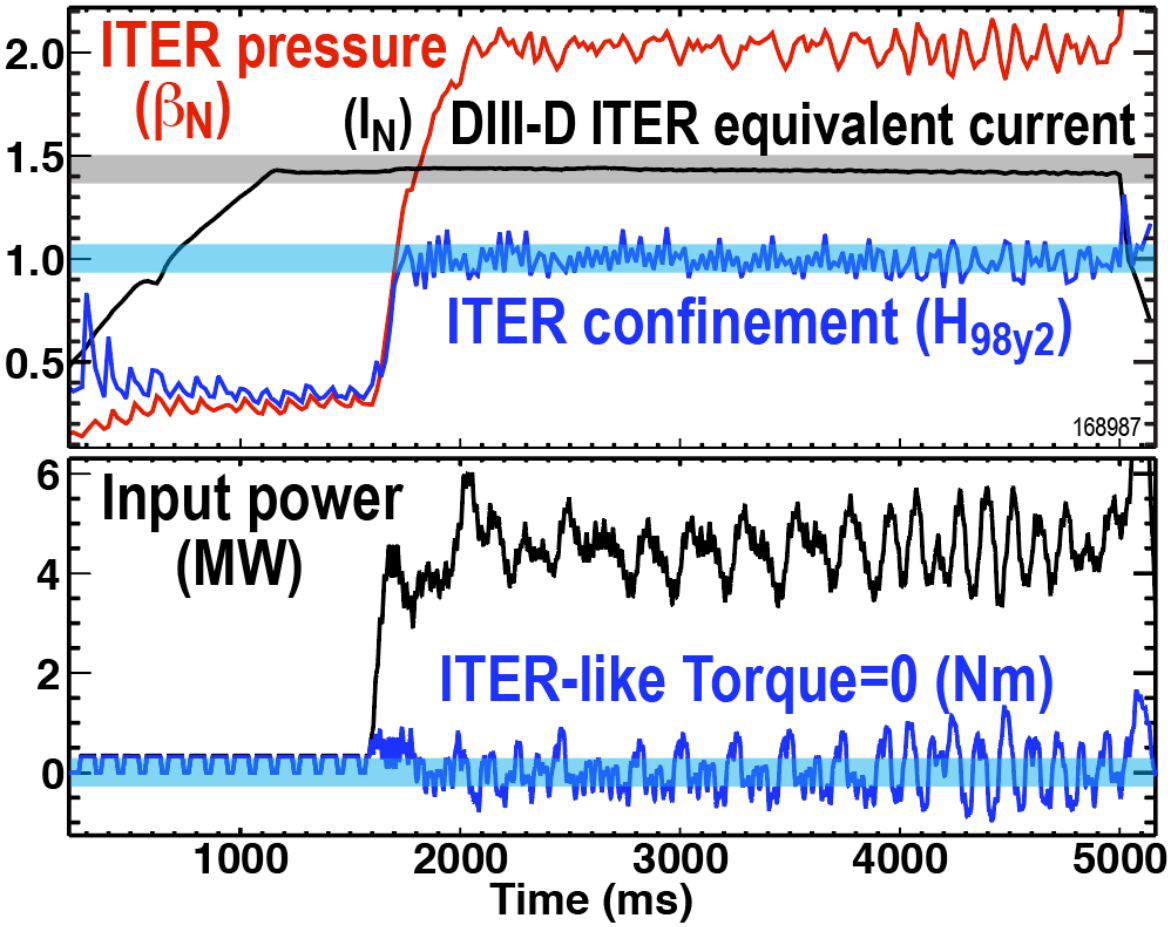
- **Pedestal stability model led to Super H-mode development with high pedestal pressure and corresponding higher global energy confinement**
- **Super H-Mode experiments on Alcator C-Mod reached ITER-like record pedestal pressure (~80kPa) on last day of operations**
- **Super H-mode experiments on DIII-D yield equivalent Q_{DT} = 0.35**

P. Snyder, APS 2017

Stable Zero torque ITER Baseline Scenario Demonstrated for the first time in DIII-D

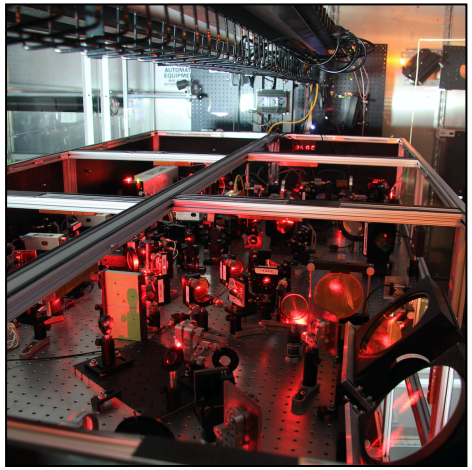
DIII-D discharges robustly simulate the first scenario in the ITER plan

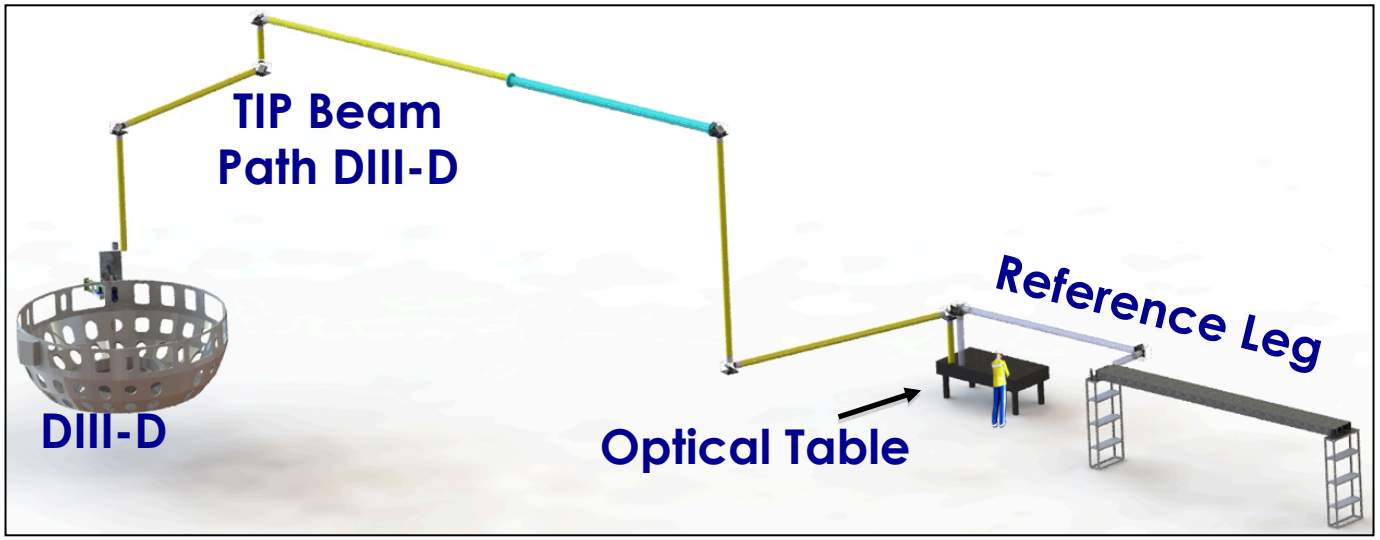
- Matched ITER shape & q_{95}
- Achieved ITER required confinement H_{98y2}=1
- Obtained fusion gain factor sufficient for Q=10
- All at ITER-similar torque in repeatable conditions



Turco, APS 2017

US Contributions to ITER: Successful Test of Prototype Toroidal Interferometer Polarimeter on DIII-D



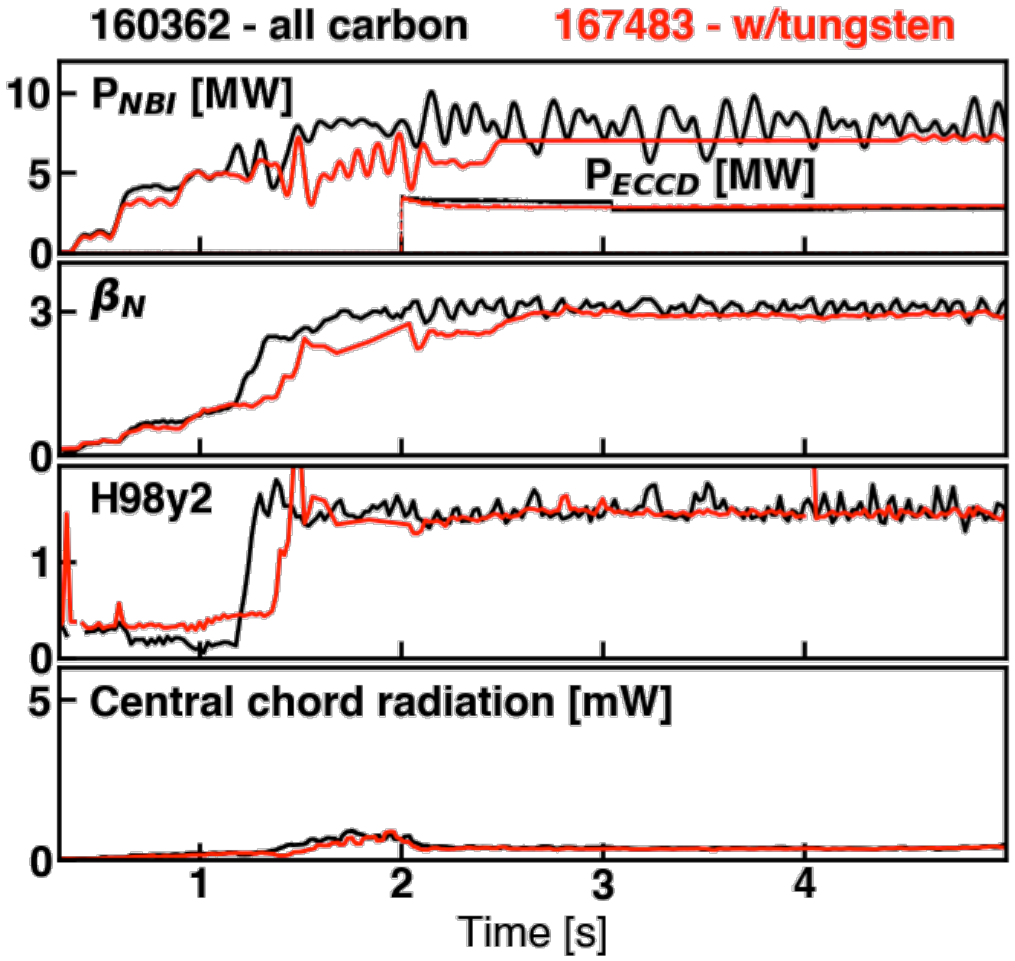


- Joint effort: UCLA-GA-PSI Two-color system (10.6μm and 5.2μm)
- Full-scale ITER prototype with 110m roundtrip path to DIII-D and back
- System includes matching 110 m reference leg
- Active feedback is used to maintain alignment

General Atomics Is Manufacturing the Coils for the ITER Central Solenoid

On-axis ECCD Maintains Performance of Steady-state Hybrid Scenario with Strike Point on Tungsten Rings

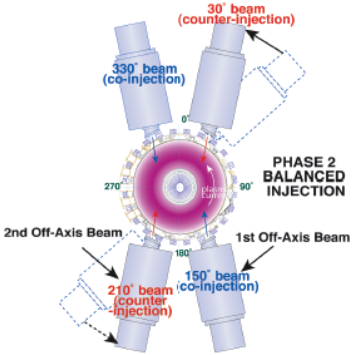
- Hybrid discharges feature broad current profile maintained by internal MHD
- β_N and energy confinement equivalent to all-carbon divertor shot
- ECCD applied on-axis
- No increase in core radiation



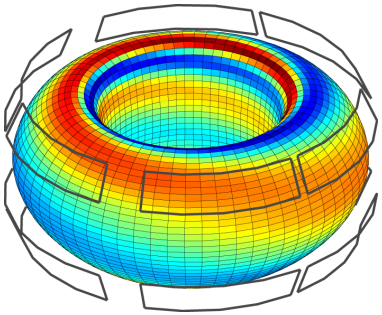
B.S. Victor/APS Conference/Oct. 2017

DIII-D Research Will Provide a Scientific Foundation for Mitigating the Risk of Uncontrolled Transients

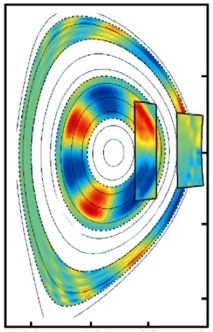
- **Unique capabilities support science of disruption avoidance and mitigation**

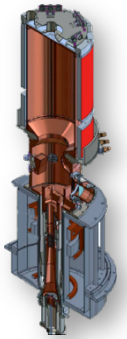


Rotation Control

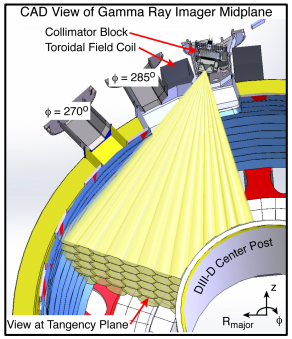


MHD simulation

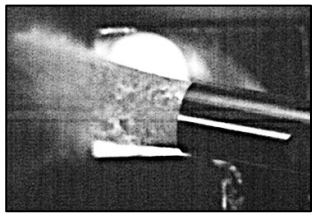




NTM control

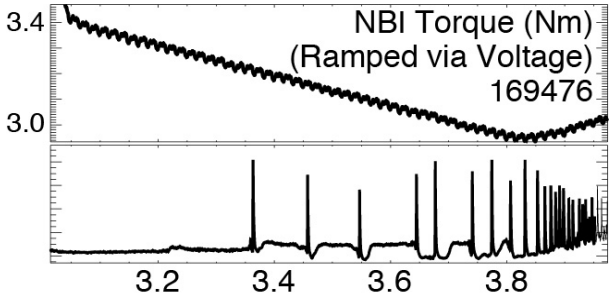


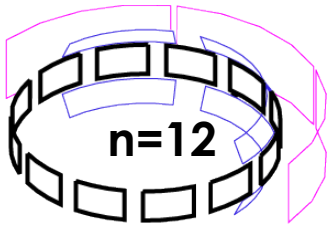
Diagnostics

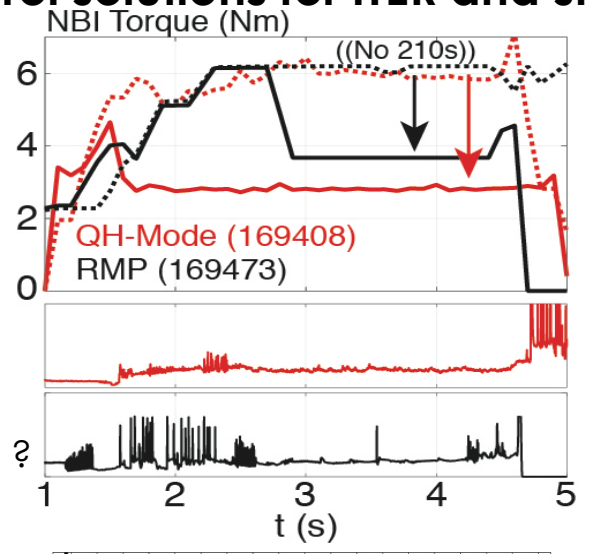


Mitigation: SPI & shell pellets

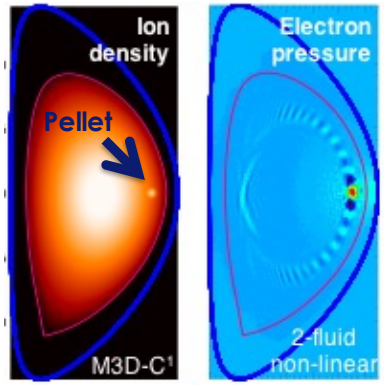
- **Explore and optimize ELM control solutions for ITER and steady state tokamaks**







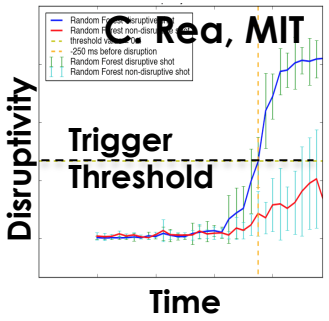
Non-linear M3D-C¹ sim. of D_2 pellet, S. Diem



Disruption Mitigation Research Aims to Provide Robust Mitigation in ITER and Steady-State Reactor

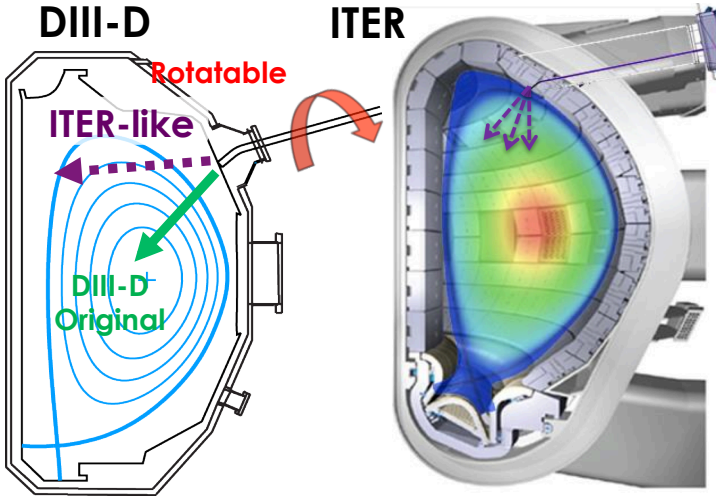
Disruption Avoidance is critical to meeting ITER or reactor goals

- "Active" MHD spectroscopy/NBI feedback to *avoid stability boundaries*
- *Active stabilization:* RMP feedback + synchronized ECCD
- *Real-time Prediction:* Machine learning algorithms
- Off-normal supervisor algorithms for *integrated control*



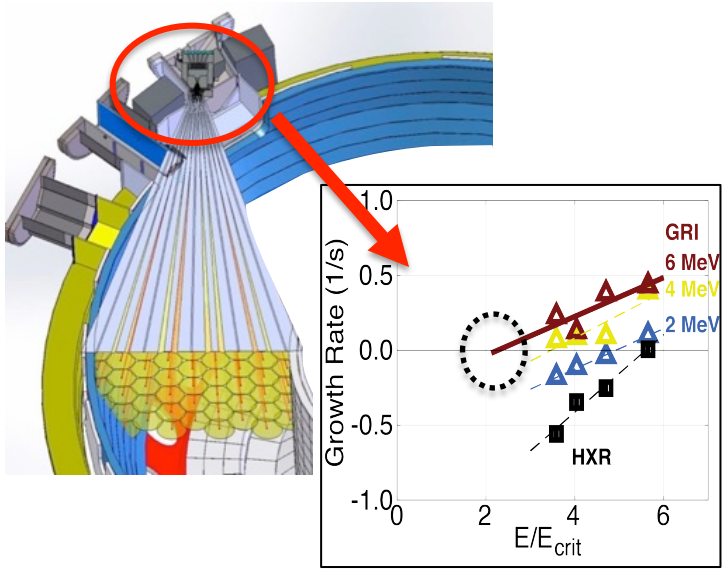
Disruption Mitigation: Testing ITER-prototype shattered pellet injectors

- Injection Geometry: ITER-like shallow trajectory reduces SPI performance *(similar to MGI)*
- Now injecting multiple shattered pellets

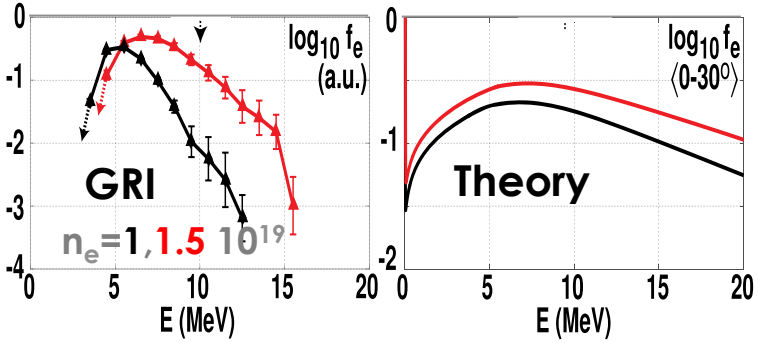


Improved Understanding of Runaway Electron Generation and Dissipation Informs Mitigation Development

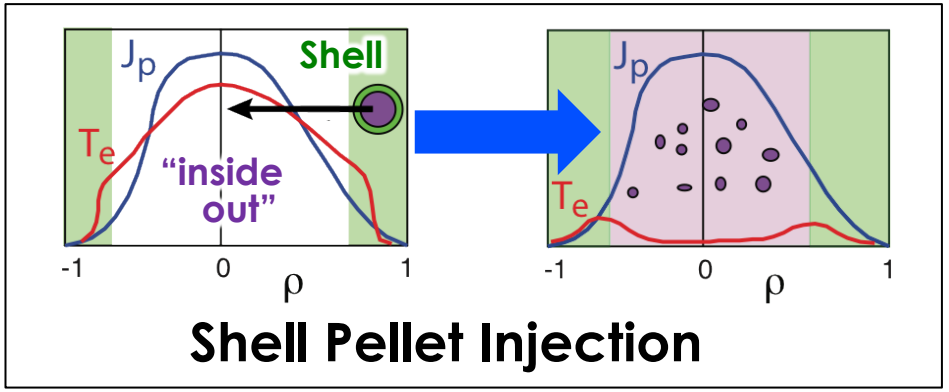
Gamma-ray Imager: Physics of RE growth and rapid dissipation



Synchrotron imaging shows RE interplay with MHD



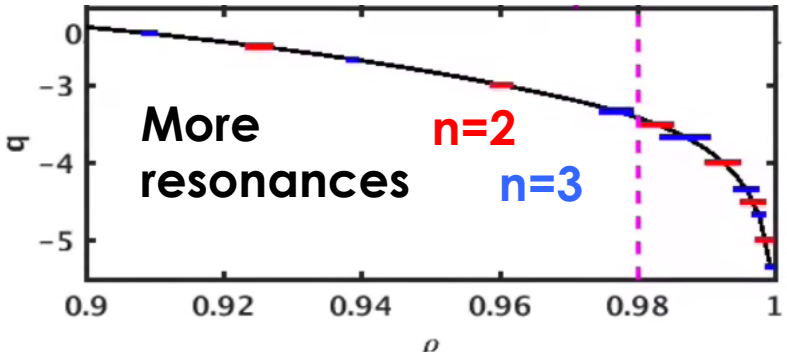
Test advanced concepts: Inside-Out

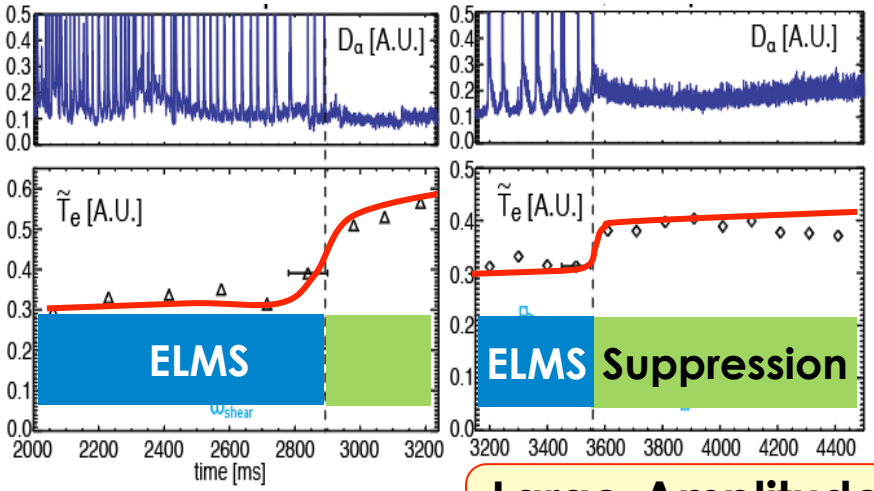


New Power Supply from ASIPP Enabling Key Insights on ELM Suppression Physics

Expands spectral flexibility significantly

Reduced RMP threshold with n=2 + n=3



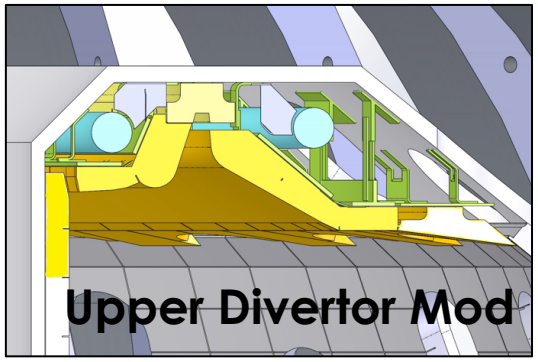


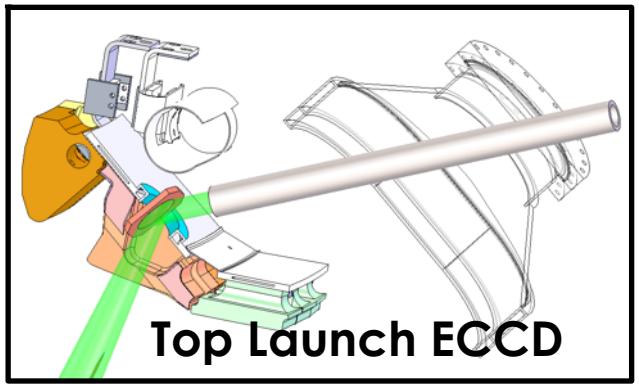
Fluctuation measurements are consistent with reduced pedestal gradients during ELM-free RMP and QH-mode operation

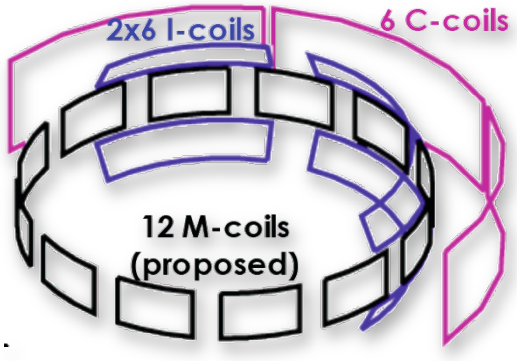
Large-Amplitude ELM Suppression Achieved in Fully Non-inductive Plasmas Relevant to the ITER SS Mission

Planned Upgrades Leverage Existing Capabilities To Advance Scientific Basis for Steady State Tokamaks

Scientific Exploration	Enabled by
Divertor model validation & optimization	Divertor mods and diagnostics
SS High beta, high bootstrap current	Co-counter Off-axis beam
Reactor-relevant current drive schemes	Top-launch EC, Helicon, HFS-LHCD
Reactor-relevant materials	Material Exposure, Migration
Electron heated regimes	10 gyrotron system
3d physics spectral flexibility (n=1-4)	New 3d coils and power supplies

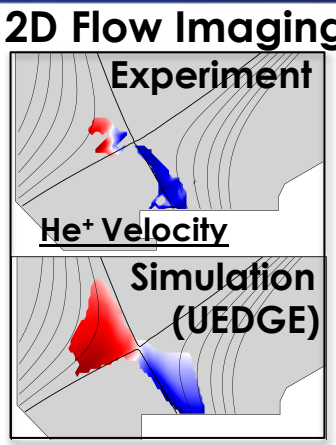


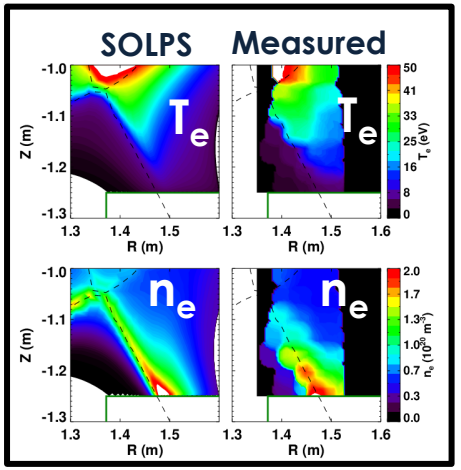


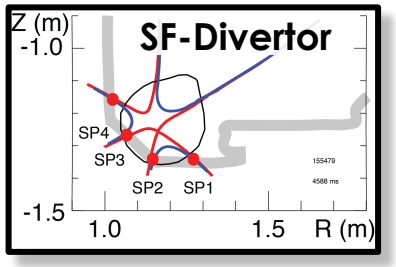


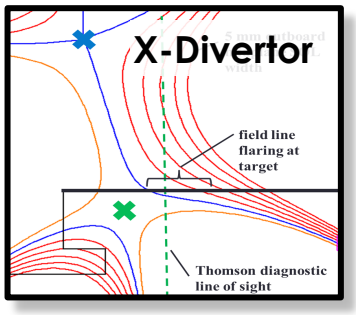
DIII-D Will Develop a Scientific Basis for Boundary Solutions Needed for Steady-State Reactors

- **Advance scientific understanding and predictive capability through *key measurements* and *extensive model validation***
  - Determine key dissipation processes
  - Resolve role of drifts and turbulence
  - Quantify role of neutrals and benefits of closure
  - Elucidate magnetic topology effects

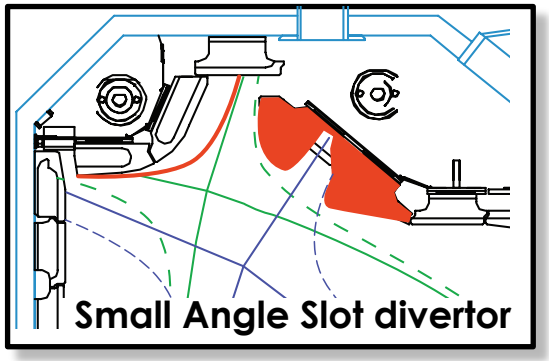






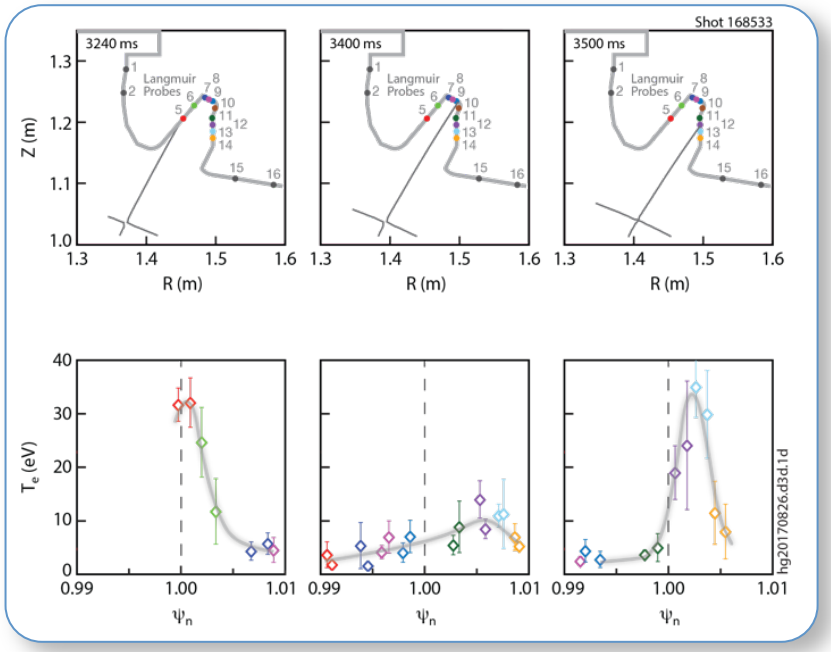


- **Develop advanced divertors compatible with high performance**
  - Maximize heat flux dissipation without degrading core
  - Staged divertor concept tests

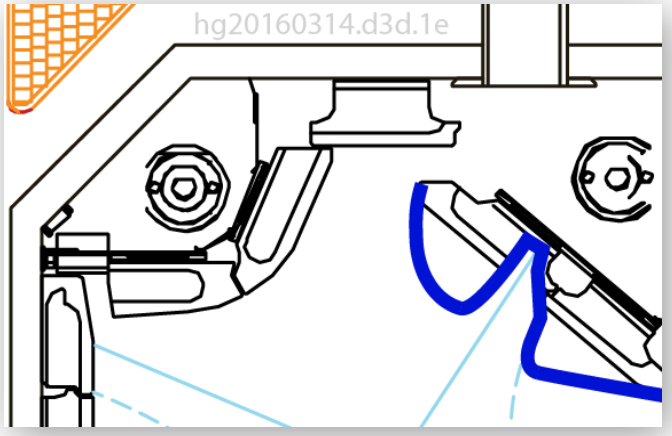


Close interaction with simulation efforts: prediction and data analysis

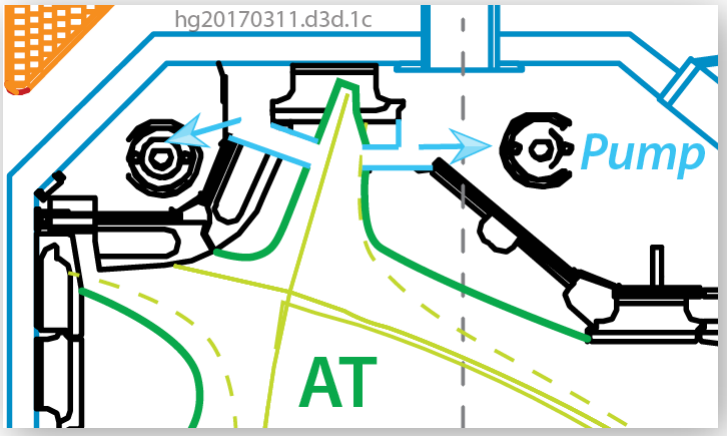
Phase I of Planned Divertor Modifications Provided Data To Compare With SOLPS Simulation



SAS I (FY17)



SAS II (FY21)

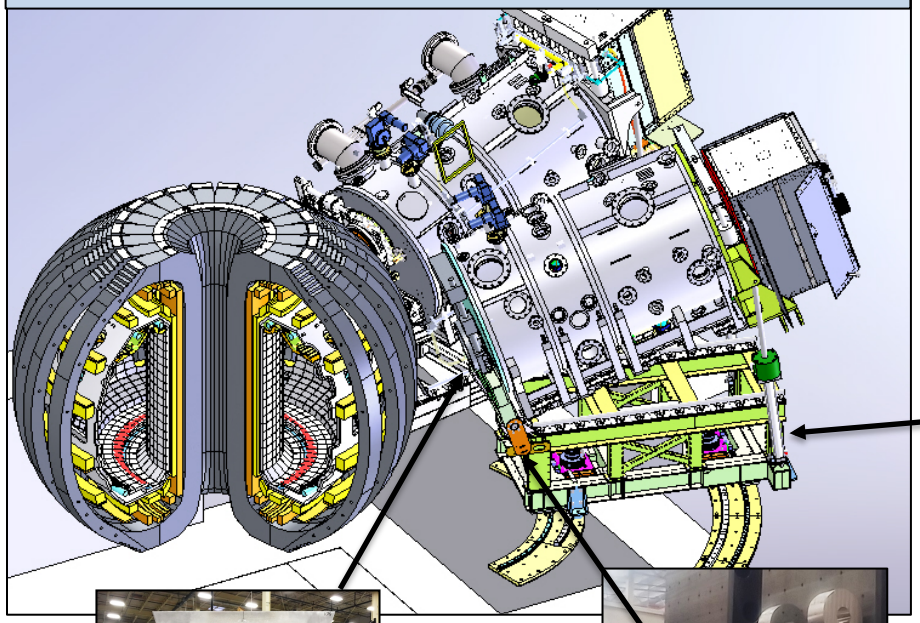


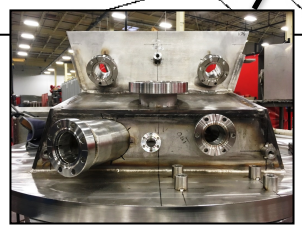
- Baffled divertor with slanted sides traps recycled neutrals
- Reduced T_e and ion flux compared to open divertor
- Phase II will provide pumping and shape to integrate with AT core

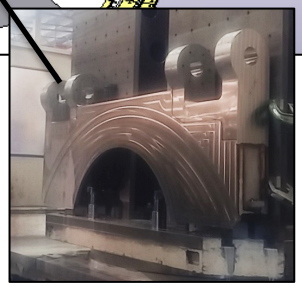
DIII-D Utilizing Flexible Heating and Current Drive Systems to Develop Path to High β Steady State

- **Move tokamak solutions from peaked to broad current profiles**
  - **β_N=5 potential with low disruptivity (High q_{min} scenarios)**

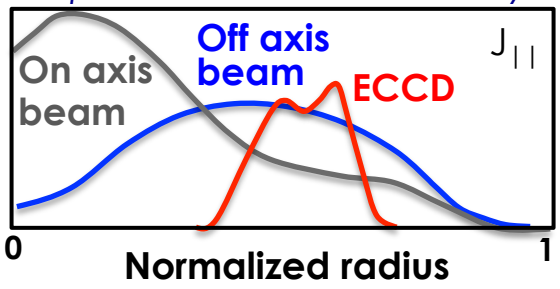
210 Co-Counter Off-Axis Beam Design







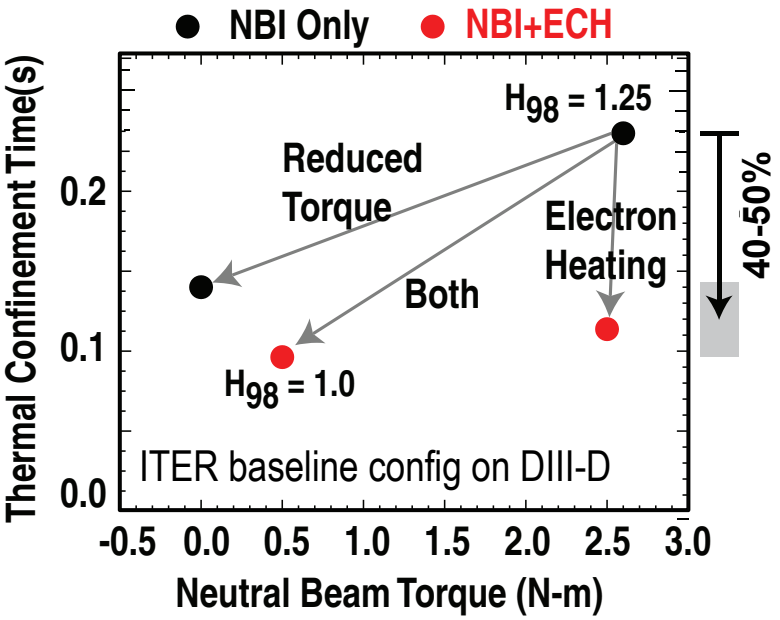
Required tools for stationarity:



Install during one-year shutdown (May 2017-2018)

Increased ECH Power Is a Critical Element to Advancing Studies Towards Reactor-Like Conditions

- **Increased off-axis ECH power and balanced NBI to**
  - Access low rotation, dominant electron heated regimes
  - Provide tearing mode control for disruption avoidance

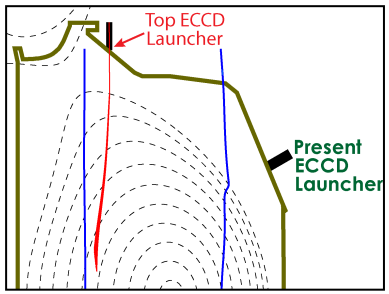


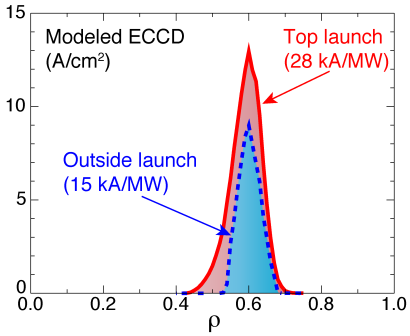
Completing installation of new 1.5MW 117.5GHz CPI gyrotron

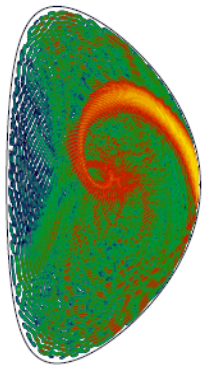
- **Replacement gryrotrons (3) (1MW 110GHz) CPI tubes**
  - 10+ year productive lifetimes
- **Expand system to advance AT and divertor program goals (10 tubes total)**

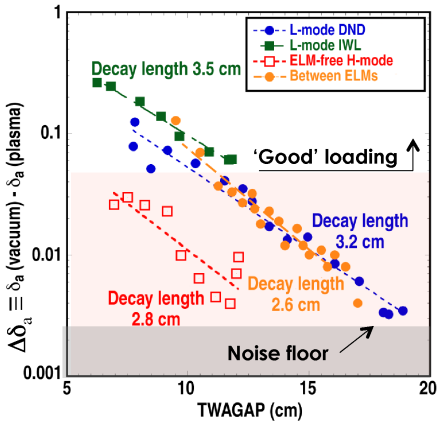
DIII-D Proceeding with Tests of Three Transformational Current Drive Technologies

- **Top launch ECCD doubles efficiency**



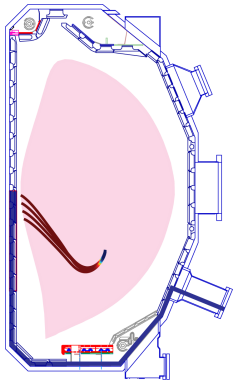






- **Helicon ready to test physics of coupling at high power**

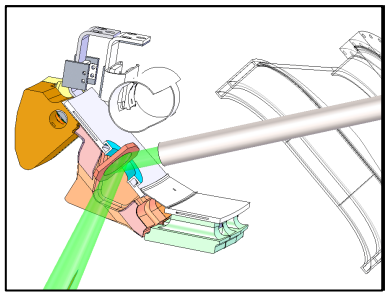
- **HFS LHCD in development**

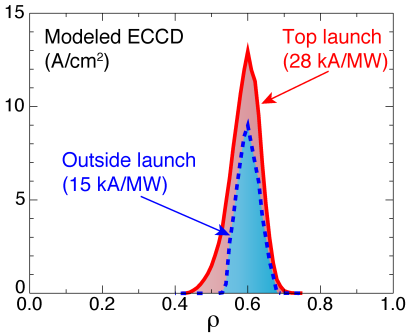


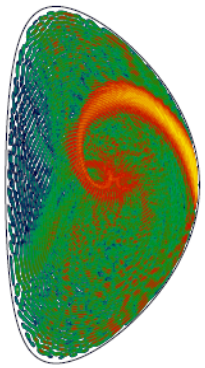
19-20 investments

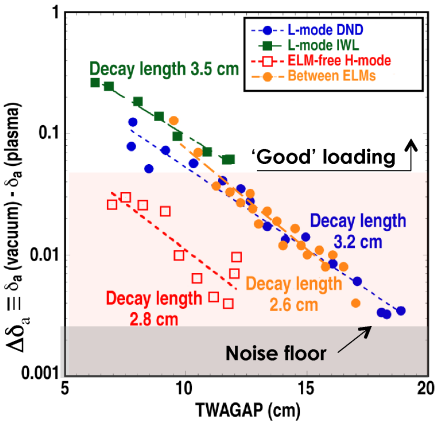
DIII-D Proceeding with Tests of Three Transformational Current Drive Technologies

- **Top launch ECCD doubles efficiency**
  - Design with GA corporate funding



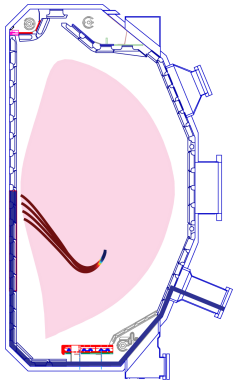






- **Helicon ready to test physics of coupling at high power**

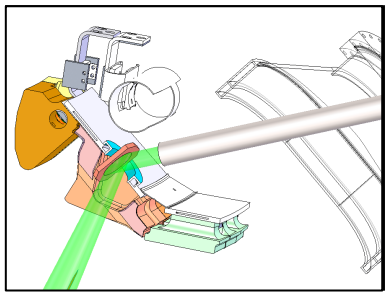
- **HFS LHCD in development**

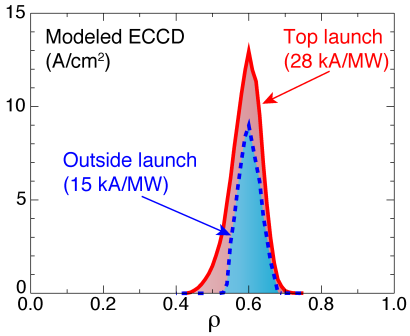


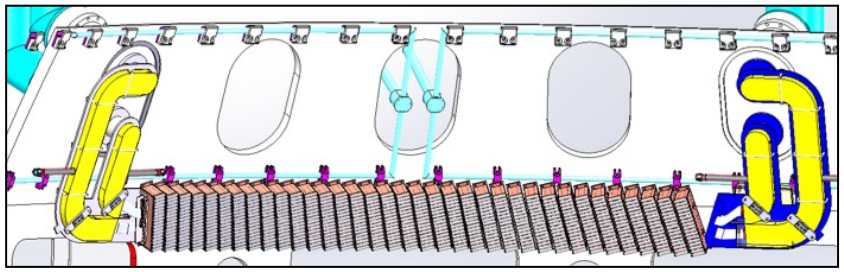
19-20 investments

DIII-D Proceeding with Tests of Three Transformational Current Drive Technologies

- **Top launch ECCD doubles efficiency**
  - Design with GA corporate funding

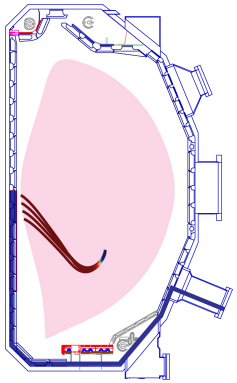






- **Helicon ready to test physics of coupling at high power**
  - Install 1MW launcher in FY19(with ASIPP)
  - Klystron from SLAC (with NFRI/KSTAR).

- **HFS LHCD in development**



19-20 investments

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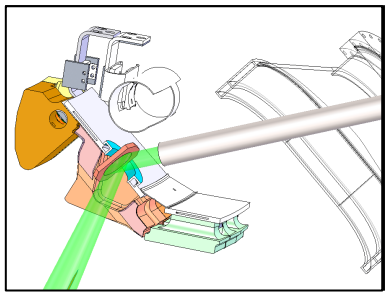
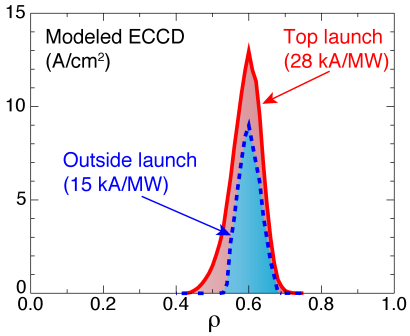
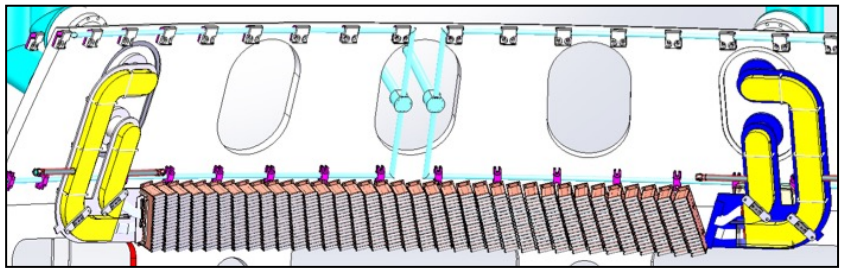
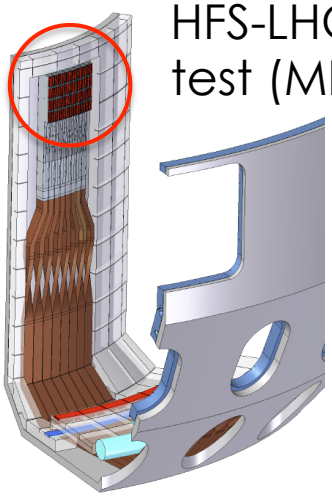




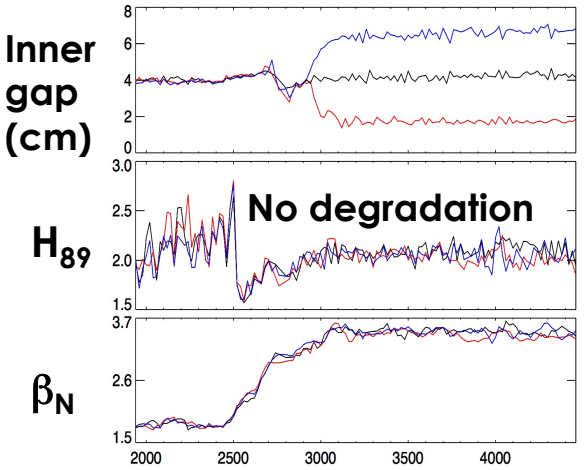


- **Helicon ready to test physics of coupling at high power**
  - Install 1MW launcher in FY19(with ASIPP)
  - Klystron from SLAC (with NFRI/KSTAR).

- **HFS LHCD in development**
  - AT plasmas found compatible with low inner gaps →



HFS-LHCD test (MIT)



19-20 investments

DIII-D Proceeding with Tests of Three Transformational Current Drive Technologies

- **Top launch ECCD doubles efficiency**
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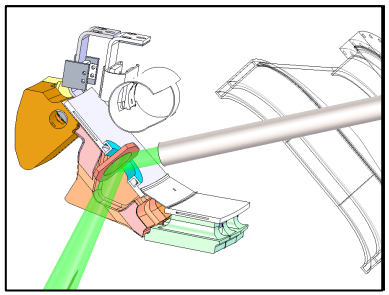
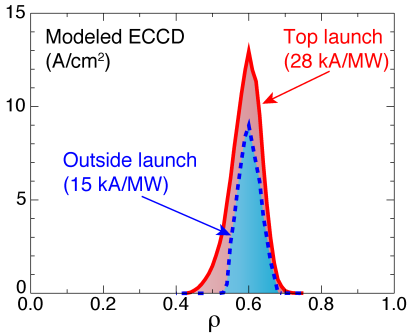
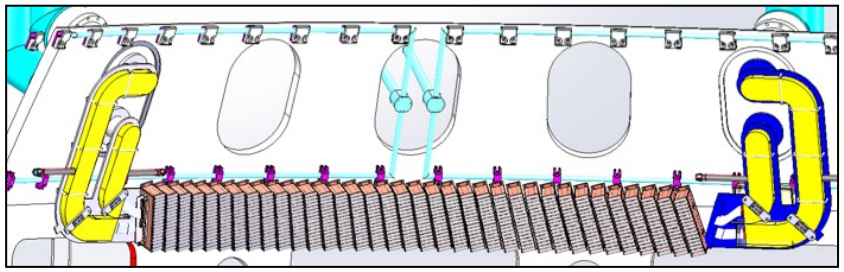
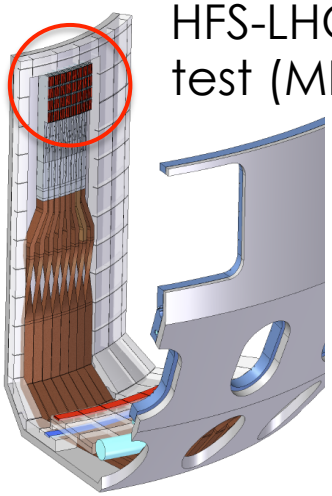




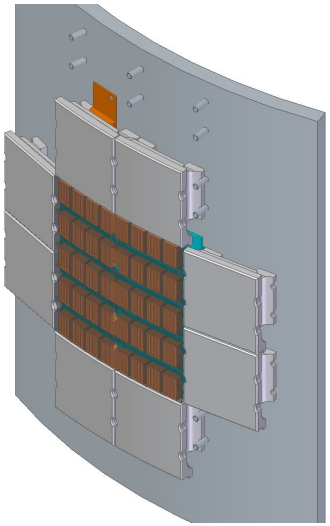


- **Helicon ready to test physics of coupling at high power**
  - Install 1MW launcher in FY19(with ASIPP)
  - Klystron from SLAC (with NFRI/KSTAR).

- **HFS LHCD in development**
  - AT plasmas found compatible with low inner gaps →
  - Possible HFS test tile in FY18, completion after LTO3



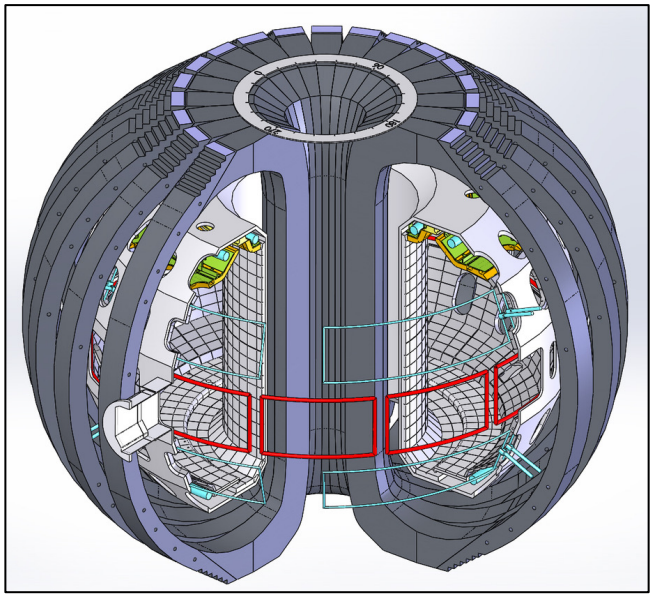
HFS-LHCD test (MIT)

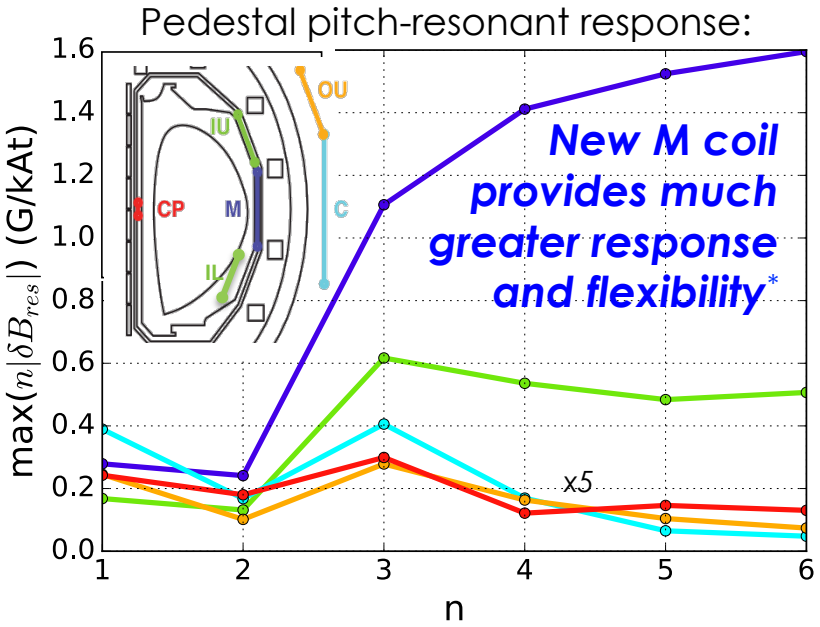


Replica Launcher test April 2018

19-20 investments

New M-Coil and 2nd Programmable Power Supply Expands Capability for 3D Studies and Transient Control





- **Power supply enables control of**
  - All 18 PF coils independently for advanced 2D shaping & divertor
  - Each I coil independently, Tor+pol spectrum simultaneously
- **New 12 coil Midplane array opens vital new research capabilities***
  - Stronger drive for NTV and n=3 & 4 rotation, spectrum optimization

DIII-D Is Advancing the Scientific Basis for Magnetic Fusion Energy Supporting Successful Operation of ITER

DIII-D results are providing a strong foundation for successful ITER operation and its scientific exploitation

DIII-D is addressing foundational scientific questions for developing validated predictive simulation

New DIII-D capabilities will enable significant steps toward developing the solutions needed for future steady-state tokamak fusion reactors