Overview of Recent and Planned DIII-D Research to Develop Steady-State Tokamak Operation for Fusion Energy

by

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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Talk Outline

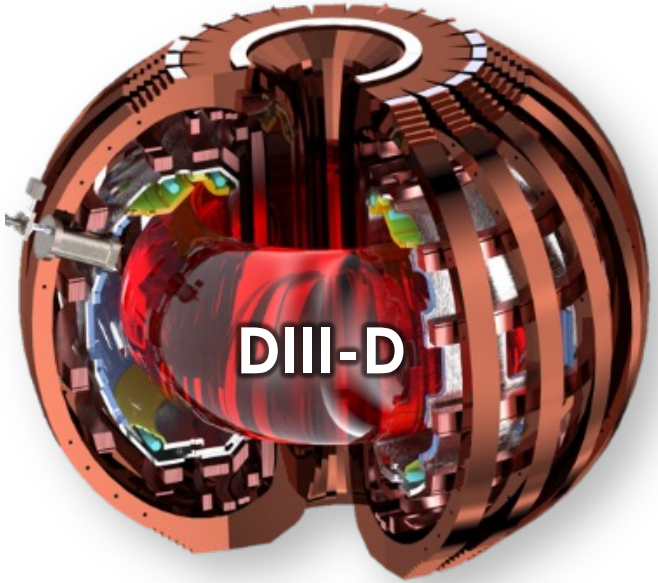
- **DIII-D Steady-State Scenario Development Goals**
  - ***ITER & Fusion Pilot Plant***
  - ***Steady state fundamentals***
  - ***Range of scenarios***
- **Status & recent progress on select scenarios**
  - ***High q_{min}***
  - ***Hybrid***
- **DIII-D upgrade plans & predictions**
  - ***Expand towards burning plasma parameters***
  - ***High-performance core-edge integration***

DIII-D Aims to Identify Long-Pulse Solutions For ITER & a Fusion Pilot Plant

- **U.S. fusion community supports ITER & endorsed building a low capital cost Fusion Pilot Plant (FPP) in the 2030's**

- **A route to low-cost FPP is to make it compact, - ITER-sized or smaller**
  - High B via HTS will help
  - High-β_NH steady-state operation for net-electric power with high availability and long plant lifetime

- **DIII-D is developing steady-state operation compatible with exhaust requirements**



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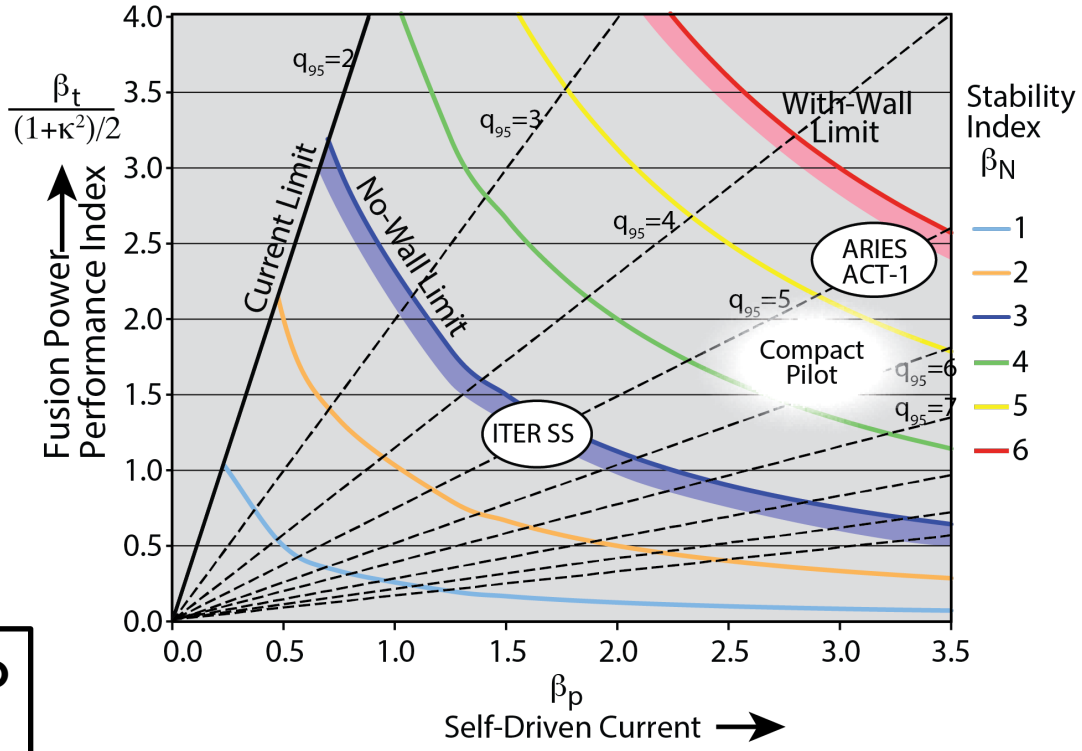
DIII-D Program Aims to Develop High-β_N Steady-State Scenarios for ITER Q=5 Mission & a Compact FPP

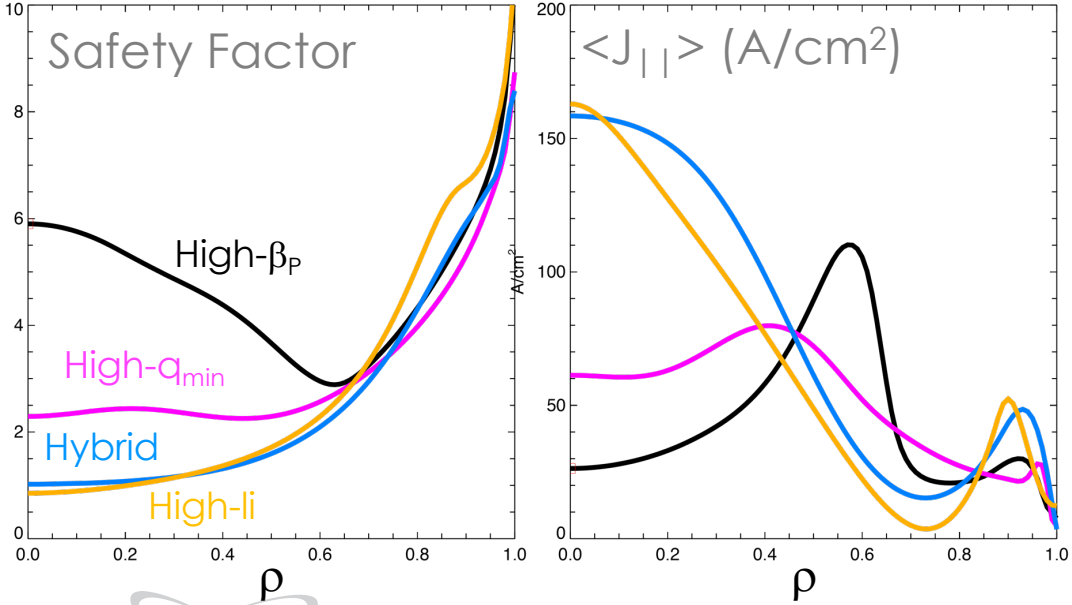
- **Indefinitely long burn durations require $I_P = I_{EXT} + I_{BS} \rightarrow I_\Omega = 0$**
- **Fusion power requires high $\beta_T \sim \beta_N/q$**
- **High bootstrap fraction requires high $\beta_P \sim q\beta_N$**



Together these drive solutions to high β_N & optimized q

DIII-D Is Investigating a Range of Possible Steady-State Scenarios

- **Typically characterized by q- or j-profile**
- **Really a continuum, but four defined:**



EFIT reconstructions of DIII-D shots

	Possible Advantages	Challenges/ Uncertainties
High β_P	Low disruptivity, high f_{BS}, high H from ITB	RWM limits; maintain ITB at lower q_{95}?
High q_{min}	High ideal MHD β_N-limits, high f_{BS}	q>2 tearing modes; high H w/o ITB?
Hybrid	Anomalous j-diffusion: q_{min}>1	Lower f_{BS}; high H w/o rotation?
High li	High-β_N w/o wall stabilization	Lower f_{BS}; requires low pedestal

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  - *High-performance core-edge integration*

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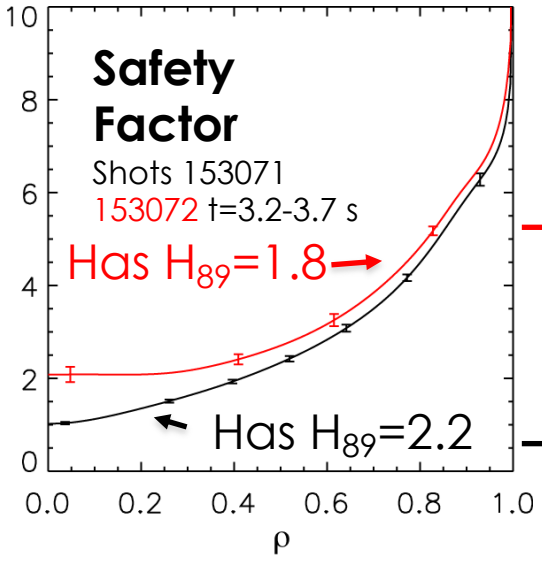
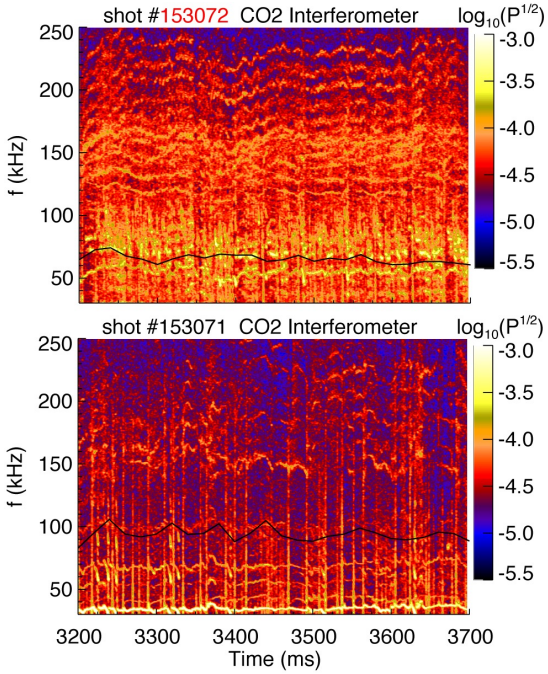
DIII-D is Exploring Two Approaches to Understanding Steady-State Operation with $q_{min}>2$

High-β_P Scenario	High-q_{min} Scenario
High density & low fast ion fraction ($W_b/W_{tot} < 15\text{-}20\%$)	Low density & high fast ion fraction ($W_b/W_{tot} > 15\text{-}20\%$)
ITB dominates, $f_{BS} > 0.7$, more self-organized	$f_{BS} < 0.7$, greater external ECCD & NBCD control of profiles
Working towards lower stationary q_{95}: $12 \rightarrow 6$	Stationary q_{95} always between 5-7
More focus on thermal transport & core-edge integration	More focus on energetic particle transport & MHD stability
Garofalo talk Tuesday	Covered here

With a High Fast Ion Fraction, High-q_{min} Plasmas Can Have Significant Alfven Eigenmode Activity & Fast Ion Loss



Cross-power density fluctuation spectrograms



Holcomb, Phys. Plasmas 2015

Compared to q_{min}~1 case, q_{min}~2 case has:

- ~4x higher average amplitude of coherent Alfven eigenmodes
- 3-4x higher inferred anomalous fast ion loss
- **This limits effective heating & ability to test higher β_N**

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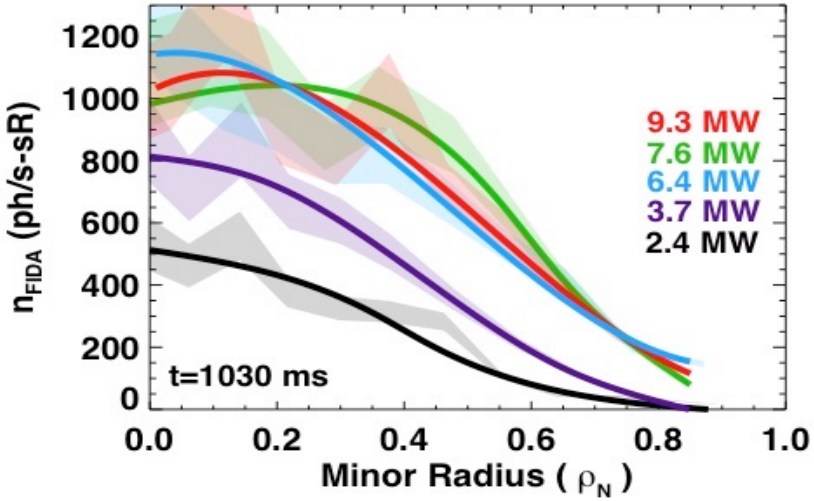
AE-Induced Fast-Ion Transport is Set by Critical Gradients

- **Alfvén eigenmode are driven by gradients in the fast-ion distribution**

- **Multiple Alfvén eigenmodes clamp fast-ion pressure profile**
  - Adding beam power causes fast ions to be redistributed or lost until gradient relaxes and Alfvén eigenmodes reach marginal stability
  - Consequence: fast-ion profile is 'stiff'

Fast-ion density measurements with on-axis NBI



Collins PRL 2016

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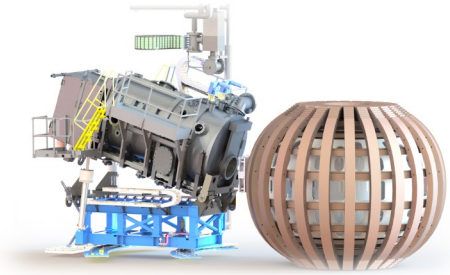
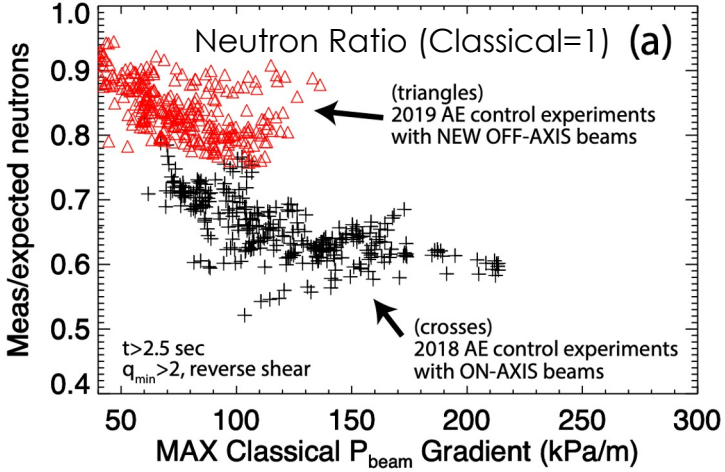
Off-Axis NBI Lowers Gradients Leading to Higher Performance q_{min}>2 Plasmas

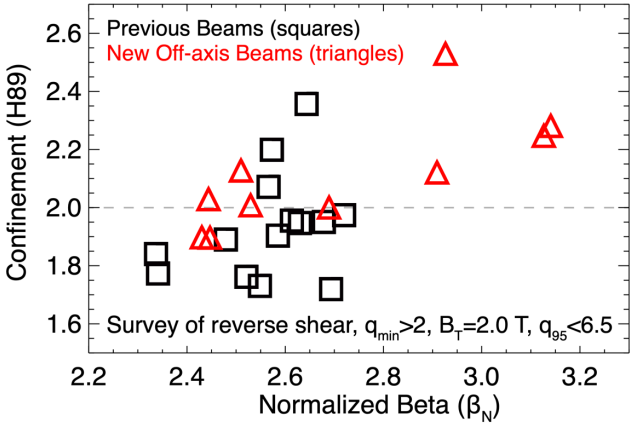
Doubled off-axis NBI power in 2019



- Using more off-axis NBI lowered classical ∇P_{beam} & AE-drive
- Measured neutrons closer to classical



Achieved higher β_N & H_{89} limited mostly by available power at B_T=2 T



Collins IAEA 2020

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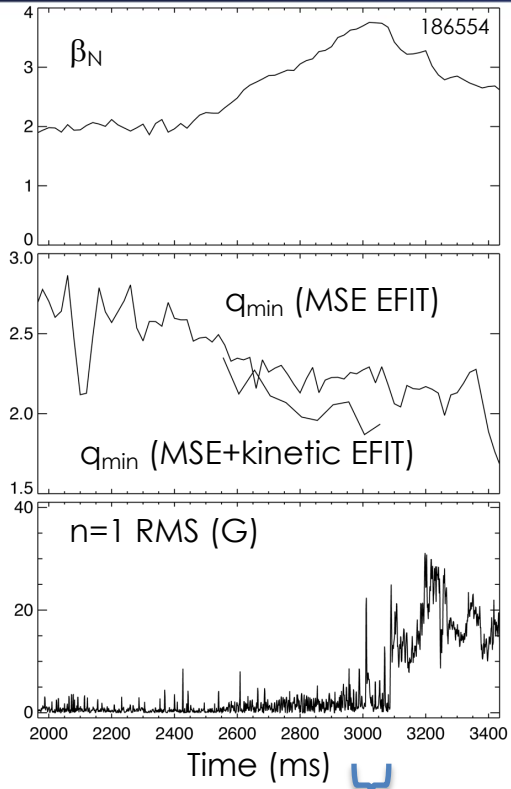
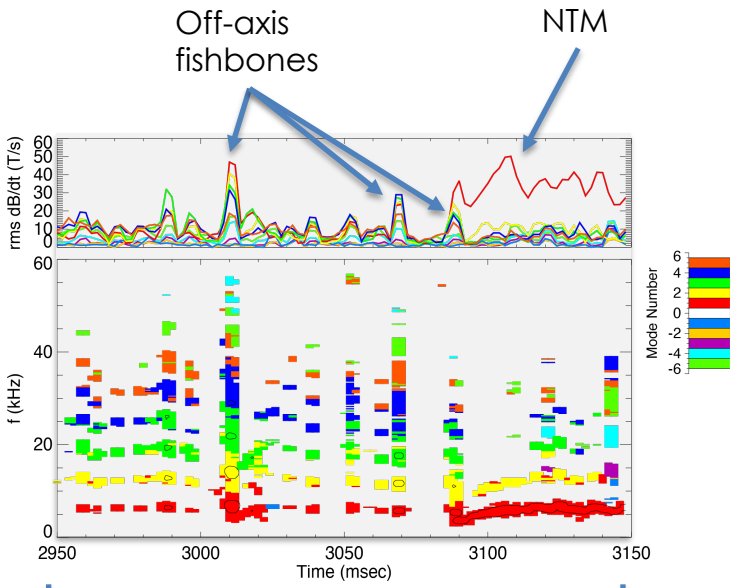
At Lower B_T and Higher β_N, Available Current Drive Was Insufficient to Robustly Maintain q_{min}>2 – Reduced Stability





- B_T=1.65 T, P_{ECCD}=1.9 MW
- q_{min} ~2 in β_N ramp
- At β_N~3.7, multi-harmonic EP-driven off-axis fishbones appear and triggers m/n=3/1 NTM
- Planned increases in wave-H&CD will help

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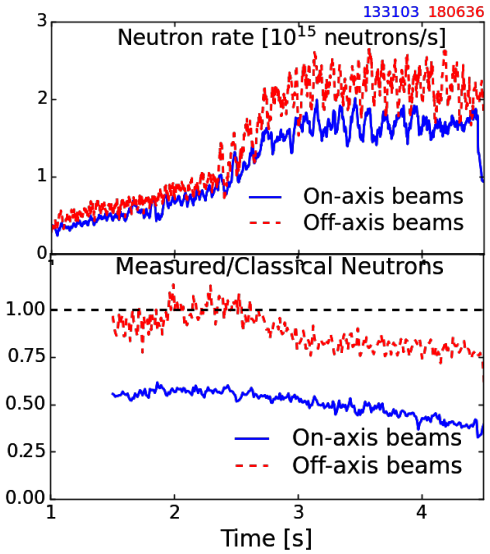
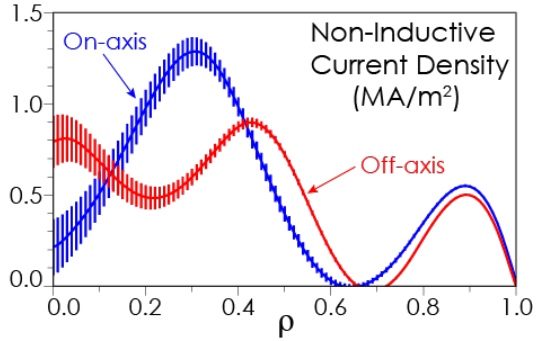
Experiment led by B. Victor, LLNL

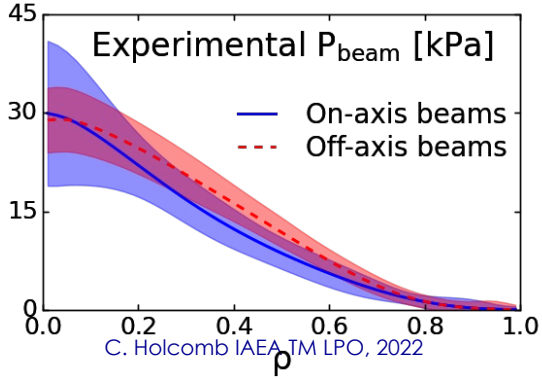
Some Progress Improving ~1τ_R-Sustained q_{min}~1.5 With β_N~3.8

Shifting ~50% NBI off-axis makes fast ions more classical

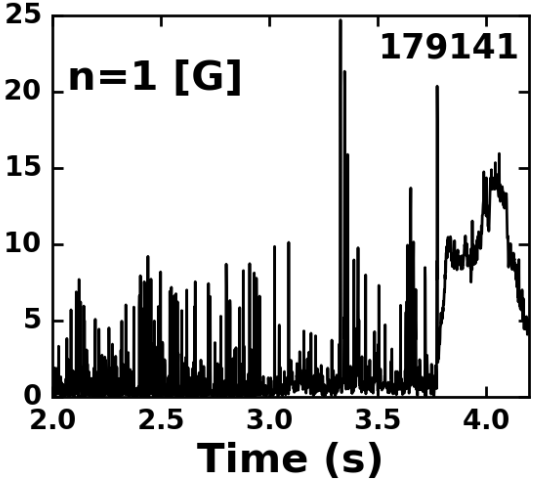


- j_{NI} & fast-ion p broadened
- Ideal-wall n=1,2,3 kink β_N limits increased ~15-25%





Strong off-axis fishbones can limit high-β_N duration by triggering 2/1 NTMs

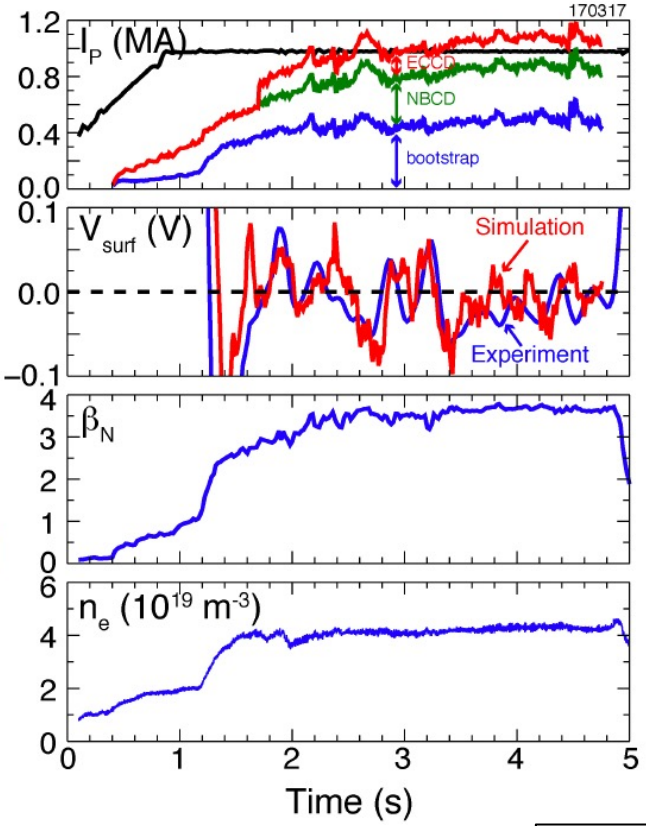


Thome, APS 2022

C. Holcomb IAEA TM LPO, 2022

"Hybrid" Scenario Shown to Be Capable of Steady State Operation With β_N=3-3.8, q_{95}~6

- 3/2 or 4/3 mode causes anomalous ψ_P-pumping & q_{min}>1
  - *Better stability without sawteeth*
- Typically f_{BS}~50%, f_{EXT}~50%
- Calculated ideal-wall n=1 β_N limits ~4-5
- Predicting how flux pumping will work at reactor scale has been a concern



Petty, IAEA 2020

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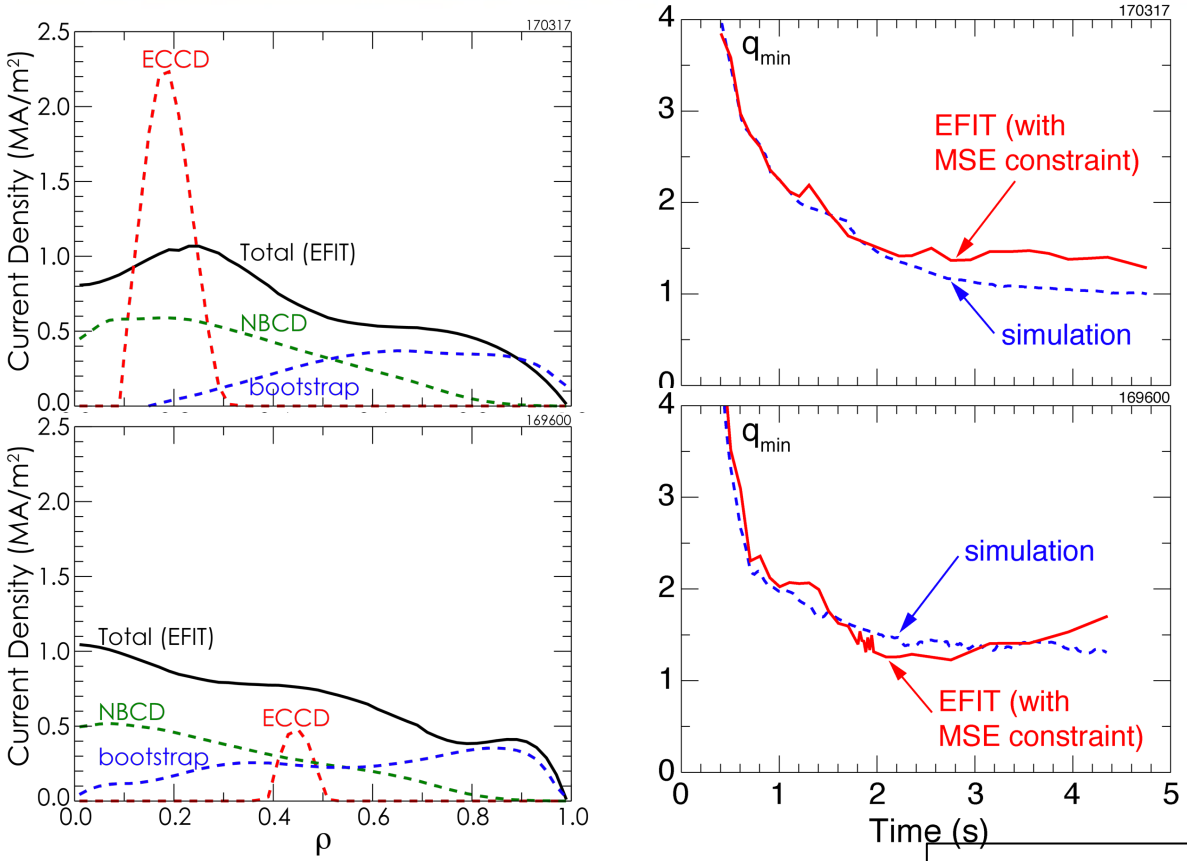
A High-β_N Hybrid Version Has Been Developed Without Anomalous Poloidal Flux Evolution

Standard near-axis ECCD with anomalous q_{min} evolution



ECCD farther off-axis: measured & simulated q_{min} agree

Petty, IAEA 2020

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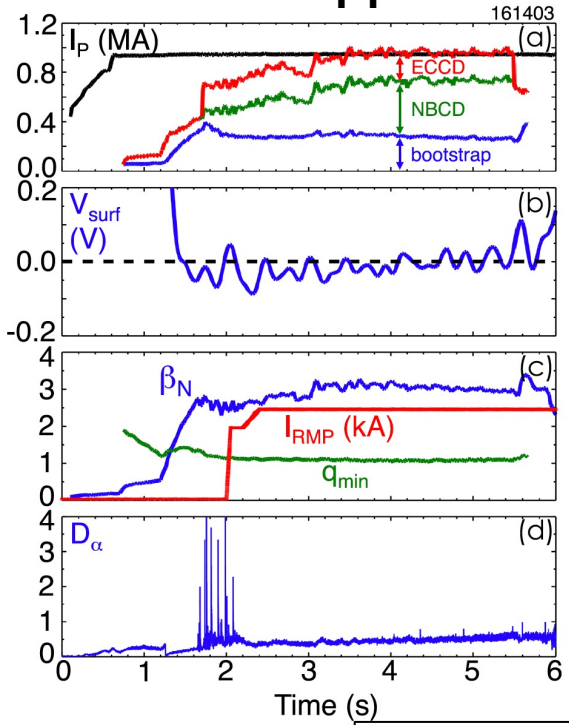
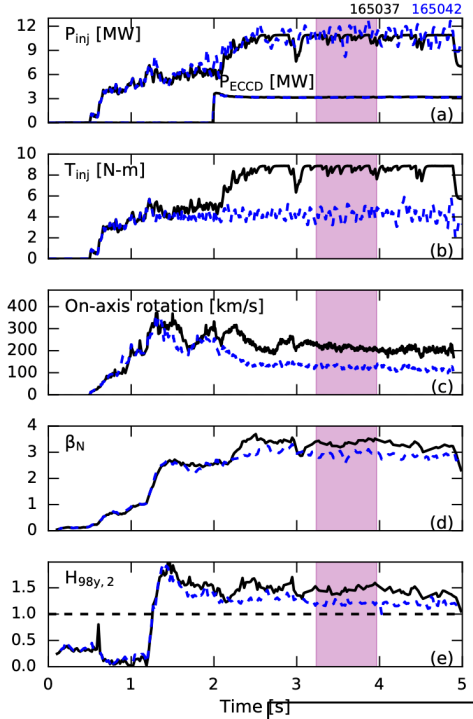
Hybrid Scenario is Being Tested in More Reactor Relevant Regimes

ITER-shaped, non-inductive, RMP-ELM-suppressed



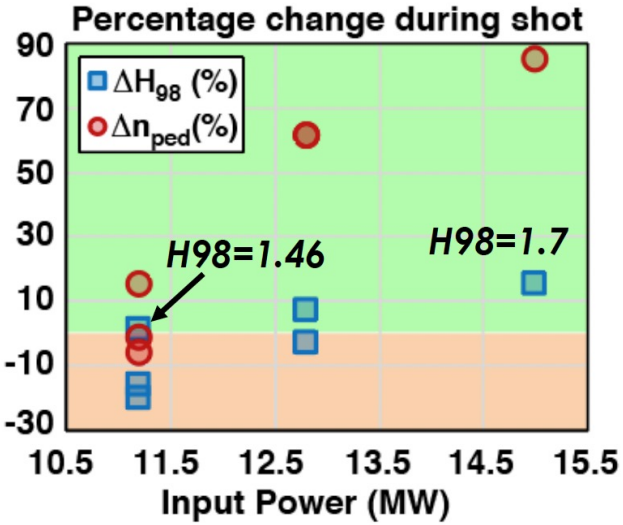
Petty, NF, 2017

Reducing torque at fixed power drops H_{98}



Thome, NF, 2021

Above power threshold, increasing density increases pedestal & H_{98}



Turco, APS, 2020

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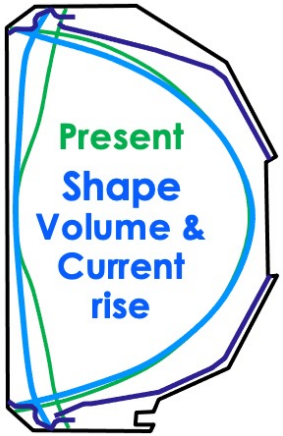
DIII-D Plans Upgrades That Will Advance Science of Steady-State Operation With Acceptable Power Loading

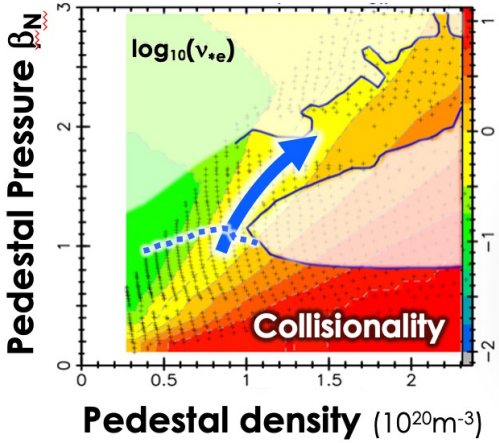
Increase volume, shaping, & B_T to 2.5 T

- **Obtain low ν^*, high density & opacity pedestals**
- **Test dissipative divertors with high performance core**

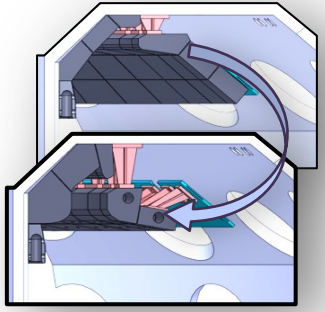


T. Osborne, GA, EPED modeling

Shape & Current Rise @2.1T



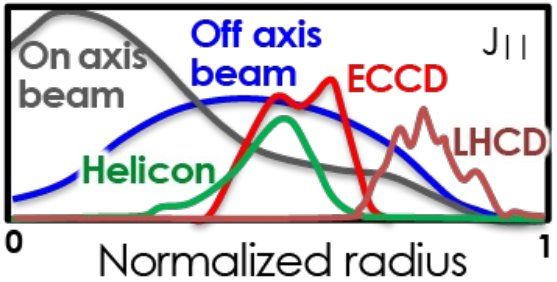
Modular divertors



Higher wave- & NBI- H&CD power

- **Test high-β_N steady-state with parameters closer to burning plasma**

CD tools:



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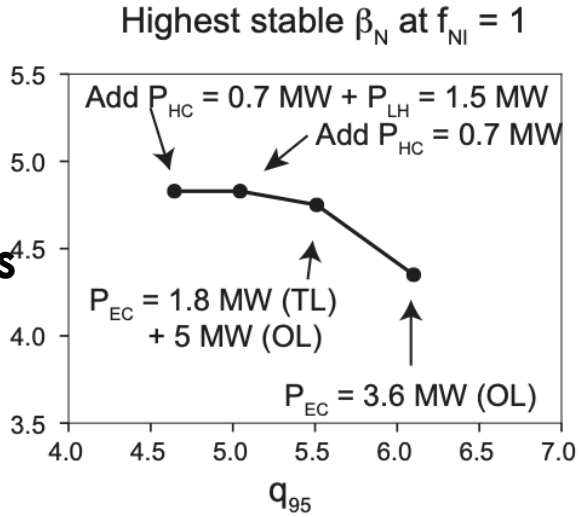
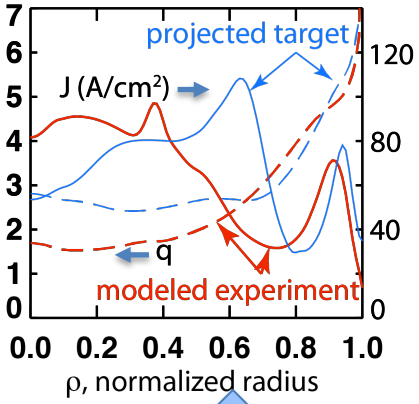
Upgrades Are Predicted to Expand Range of j(R) & p(R) With q_{min}>2 to Test Predicted Performance Limits

- **Use increased ECCD, Helicon, & Lower Hybrid to approach steady-state with β_N>4 & q_{95}<6**
- **Focus on profile requirements for high ideal MHD limits & global confinement**
- **Evaluate control requirements for RWMs, NTMs, & energetic particle modes**

J. Park, ORNL, FASTRAN modeling





New current drive will be deployed here

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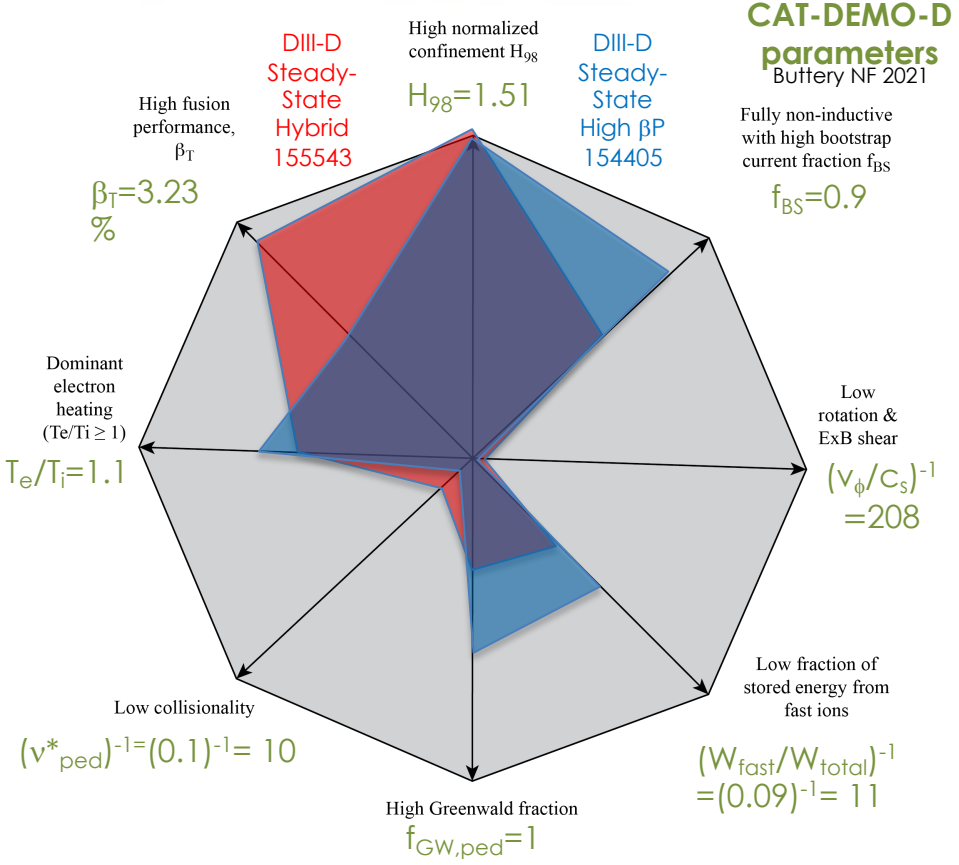
Need to Stretch to Burning Plasma Relevant Conditions: Assess & Adjust to Changes in Transport, Stability, CD

Compared to DIII-D, FPP's generally have:

- Higher e-heating, T_e/T_i
- Lower ν^*
- Higher density, f_{GW}
- Lower rotation
- Lower W_{fast}/W_{tot}

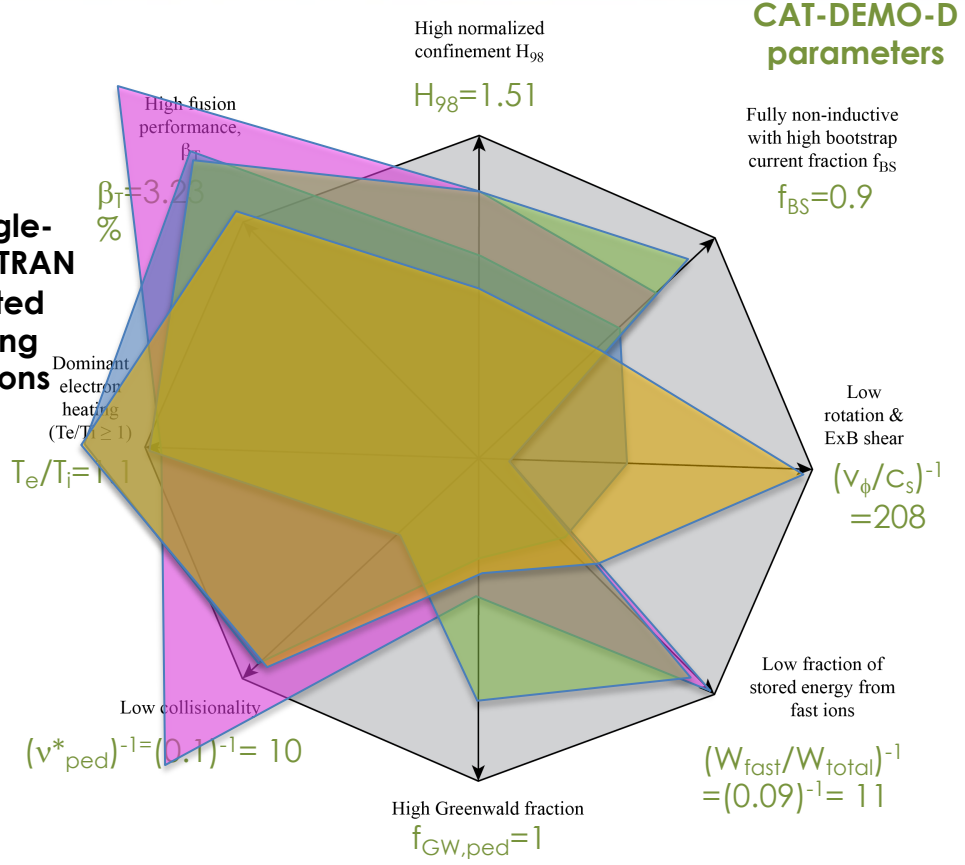


Flexible DIII-D Upgrades Will Extend Variation Range Needed for Projections

5-Year Plan Upgrades:

- 20 ECH lines (14 MW)
- 6 top launch
- 105/140/170 GHz gyrotrons
- B_T up to 2.5 T
- High shaping
- 25 MW NBI (93 keV)
- 3 MW Helicon
- 4 MW HFS Lower Hybrid

Four single-point FASTRAN integrated modeling predictions



Provides scope to optimize away from these examples to test physics

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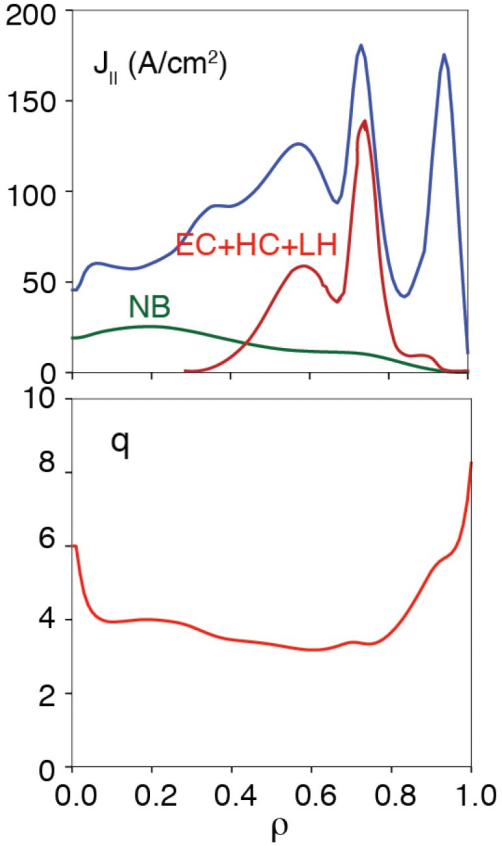
Upgrades Predicted to Access More Relevant Parameters for Core-Edge Integration

- **Pedestal has high density with low ν^***
  - $\nu^*_{ped} = 0.07$
  - $n_{e,ped}$=8.1x10^{19} m^{-3}
  - $p_{e,ped}$=48.6 kPa
- **Neutral penetration on order of pedestal width, δ_{CX}/a=0.11**
- **High performance core dominated by well-coupled thermal electrons & ions**
  - $\langle T_e \rangle / \langle T_i \rangle = 1$
  - β_N=4.2
  - H_{98}=1.29
  - W_{fast}/W_{total}=11%
  - f_{BS}=71%



Summary:

- DIII-D aims to identify steady-state or long pulse solutions for ITER and a Fusion Pilot Plant

- Significant progress being made on core steady-state scenarios

- Planned upgrades in next ~7 years will:
  - Increase profile flexibility for higher β
  - Push parameters to FPP-relevant values
  - Provide solutions for a high-performance core with an innovative exhaust solution

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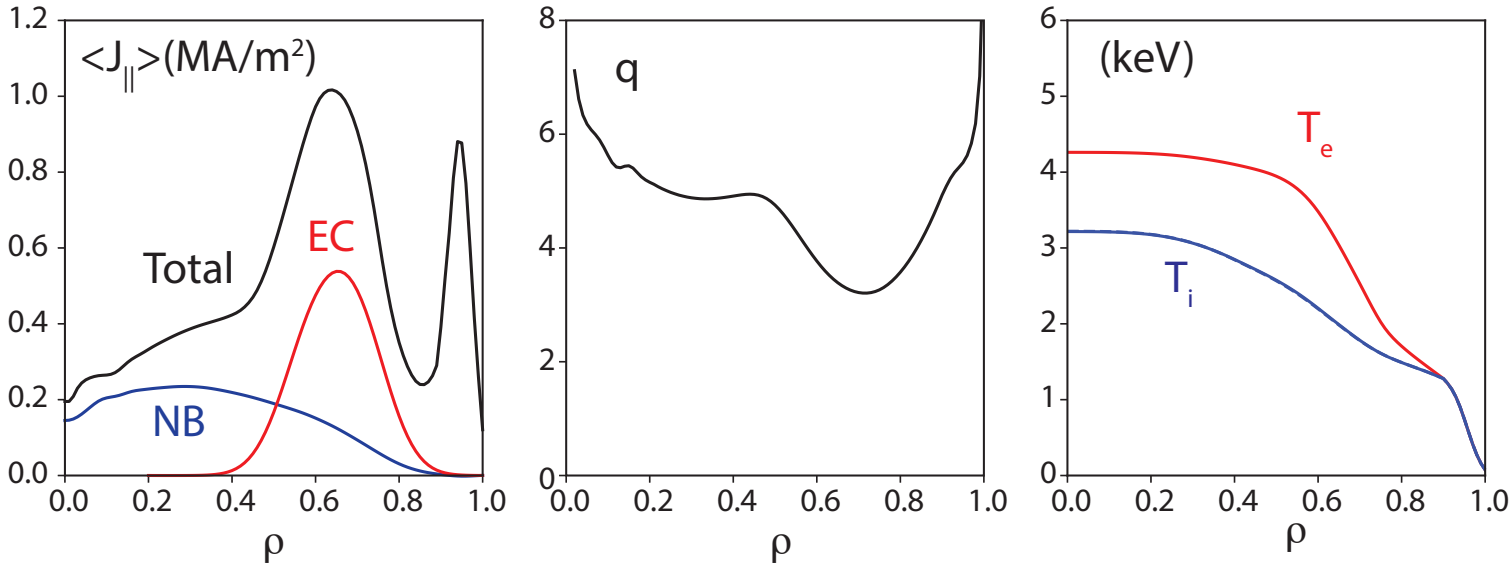
EXTRAS

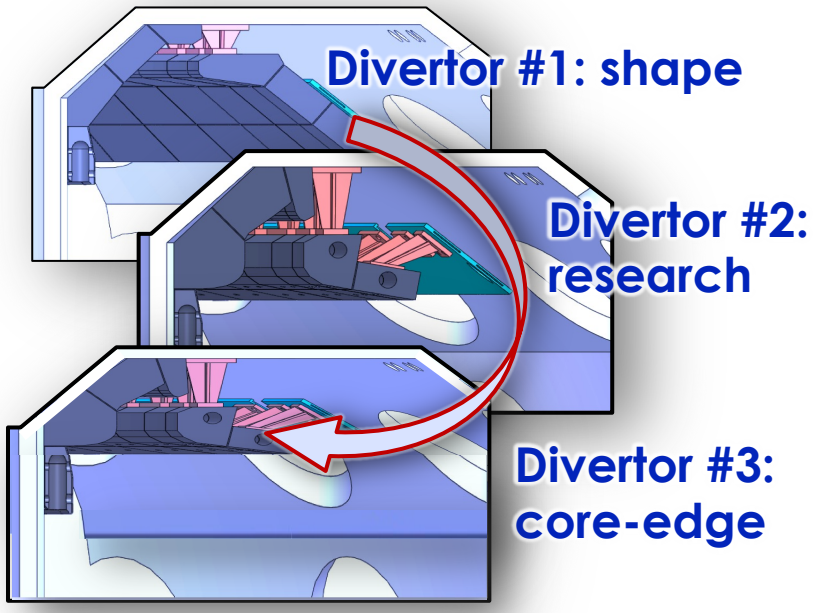
Example of Predicted Low-Rotation DIII-D Steady-State Operation:

- ω_0=18 krad/s, f_{NI}=1, β_N=4, q_{95}=5.6, B_T=1.6 T
- 12.5 MW balanced NBI + 3 MW co-NBI +14 MW ECCD



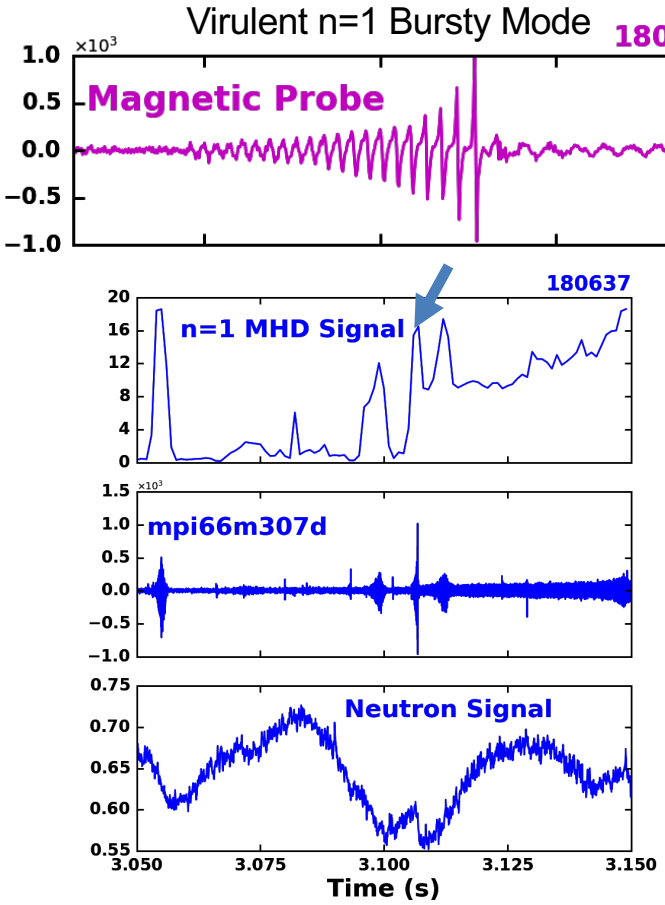
A Staged Divertor Approach is Planned to Learn How to Optimize Divertors For Long Pulse Operation

- **1st stage: pump high-δ for high pedestal performance**
- **2nd stage: larger divertor volume**
  - impacts of closure & drifts, higher density and f_{rad}, possibly other materials
- **3rd stage: optimize for a hot core & cold edge**



Two Bursty Energetic Particle Modes Begin When 2/1 Surface Enters the Plasma

- **n=1 and n=3 bursty modes observed**
- **Different magnetic signatures observed of n=1 modes with same poloidal structure**
  - Typical benign n=1 "saturated"
  - Virulent n=1 "fishbone-like"
    - Exponential growth until something stops it (i.e. triggering of tearing mode)
    - More often triggers tearing modes
    - Usually drops neutron signal

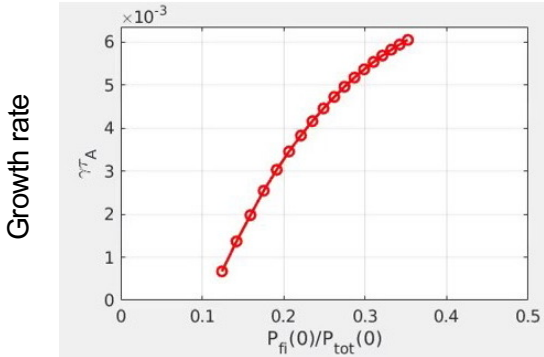


n=1 Bursty Modes Are "Off-Axis Fishbones" → a New Branch of External Kink Mode Driven by Trapped Fast Ions

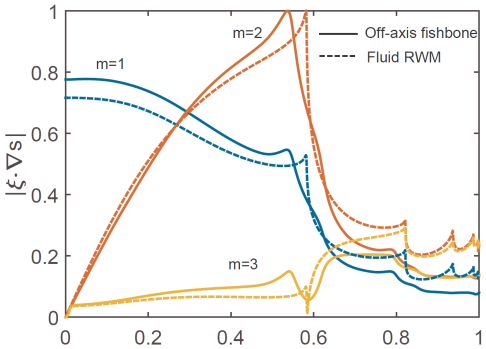
- **Referred to as off-axis fishbone mode because of frequency chirping similar to classical fishbone →**

- **MHD-kinetic Hybrid modeling with MARS-K code suggests that**
  - Driven by precessional drift motion of trapped fast ions
  - mode has a global eigenmode structure: (m=1-2,n=1) dominant, similar to fluid RWM

Work by Deyong Liu



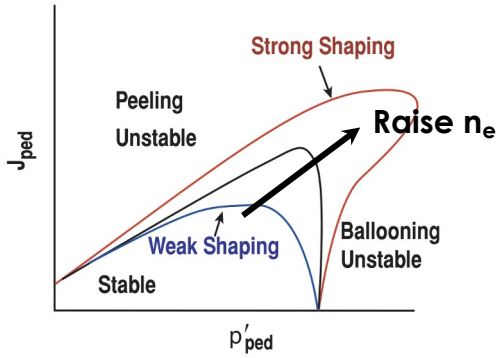
Fast-ion pressure fraction

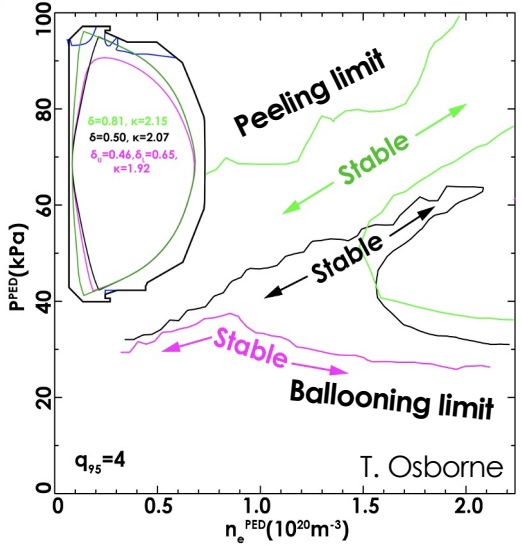


Sqrt (poloidal flux)

Peeling-Ballooning Theory Guides Pedestal Optimization Balancing High Core Performance and Dissipative Divertor

- **Strong plasma shaping opens access to high pedestal pressure gradient and current**
  - ITER and reactor relevant low ν^* are on peeling boundary
  - Increasing pedestal density and pressure improves core fusion performance
- **Higher pressure decouples opacity and ν^***
  - Achieve low $\nu^* \sim n^3/p^2$ at high n_e
  - High density increases divertor dissipation
- **Peeling limit enables pressure to increase with density**
  - Motivates increased triangularity





Prediction of High Pedestal Requires Experimental Validation

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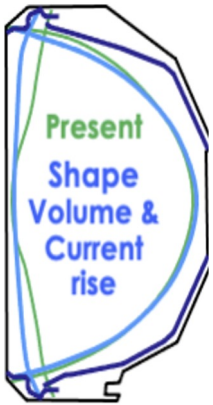
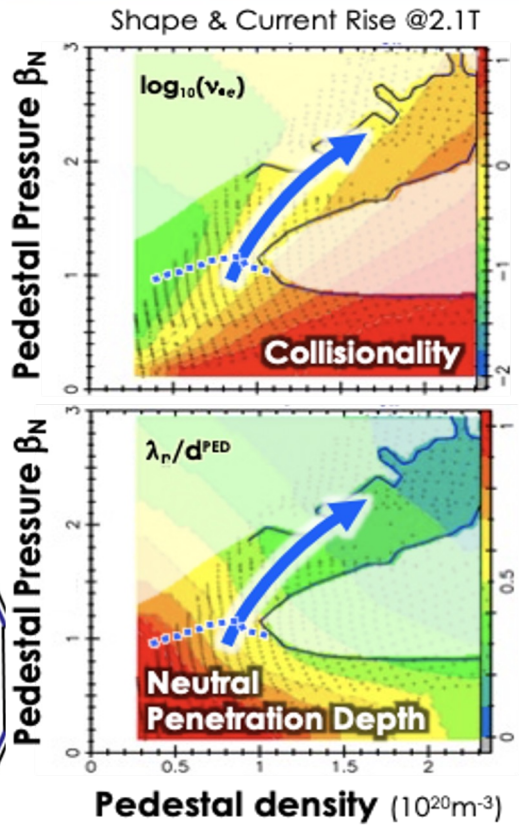
C. Holcomb IAEA TM LPO, 2022

Shape & Volume Rise (SVR) Naturally Reduces Neutral Penetration at High Pressure → More ITER Relevant

- Shape & volume rise provides higher I_p and higher density at the <u>same</u> f_{GW}
- EIRENE modeling indicates shape & volume rise accesses shallower, more ITER relevant neutral penetration
- Coupled with closed pumped divertor will further reduce pedestal ionization
- Opportunity to address role of transport vs fueling setting pedestal density structure

Reactor-relevant pedestal possible with high neutral opaqueness





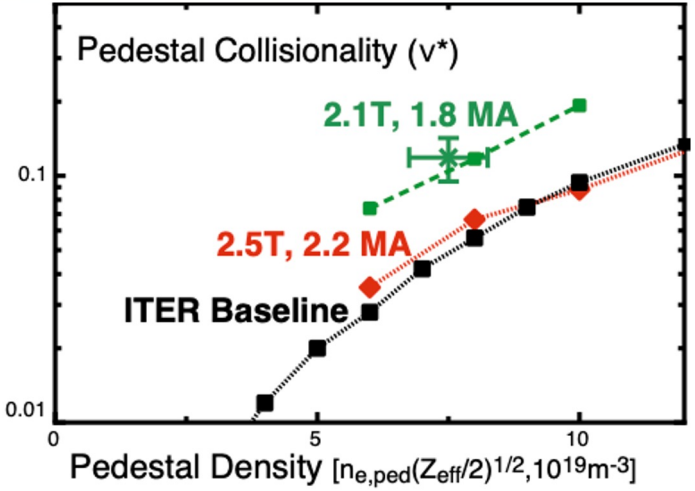
EPED,SOLPS, EIRENE

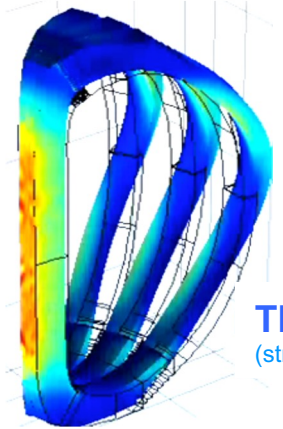
T. Osborne, L. Casali, A. Jarvinen

Upgrades to DIII-D Will Provide Access to Relevant Regimes Important for Addressing Boundary and Core-Edge Challenges

- **Increase to 40MW of injected power 2.5T**
- **Allow us to ask important physics questions to address underlying physics mechanisms important for dissipation**
  - Shape and volume rise gives higher current, density at same q_{95} , f_{GW}
  - For same ρ*, n, βt then $\nu^* \sim B^{-4}$
  - ITER ν^* can be achieved at double the present DIII-D pedestal density

Exploration of ITER-like pedestal collisionality possible with machine upgrades





TF Rise
(stresses)

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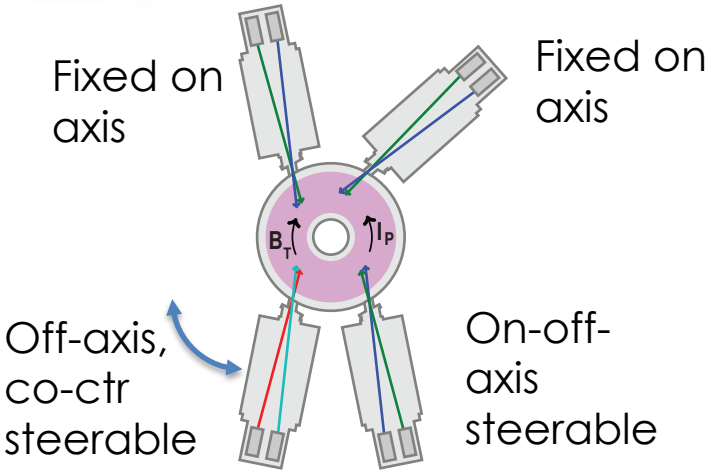
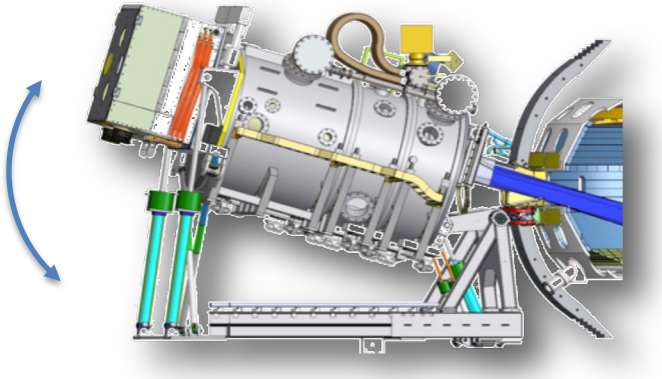
~15 MW Neutral Beam Injection With a Mix of Injection Geometries Enables Many Things

- **Feedforward & feedback control of:**
  - **Plasma stored energy**
  - **$\beta_N=(2\mu_o\langle p\rangle/B_T^2)/(I/aB_T)$**
  - **Rotation, v**
  - **Current density, J**

- **NBI-based measurements**
  - **Motional Stark Effect (J)**
  - **Charge Exchange (v, T_i, n_i)**
  - **others**





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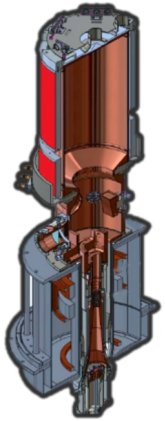
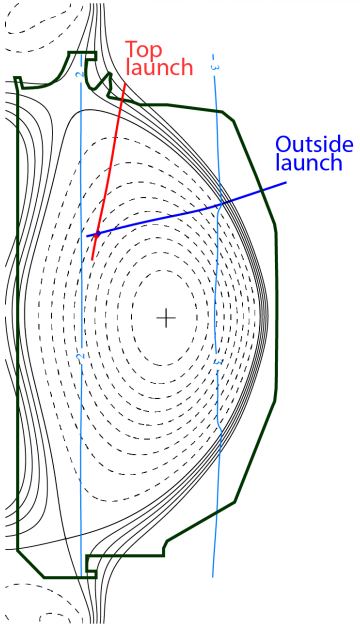
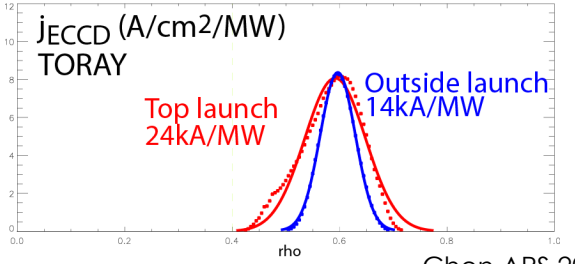
Microwave Electron Cyclotron Heating & Current Drive Provides J-Profile Control

- **Several 110 GHz gyrotrons amounting to ~3 MW delivered to plasma**
- **2nd harmonic X-mode: aim radially for only e-heating, or tangentially to drive local current**
- **Outside and top launch**
- **Can use to control magnetic islands**

ECH gyrotrons







Chen APS 2019

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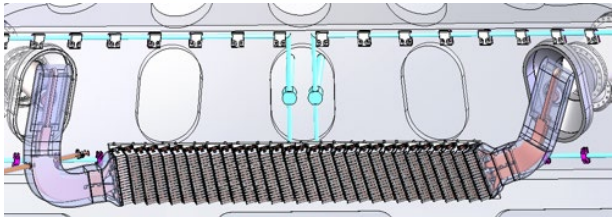
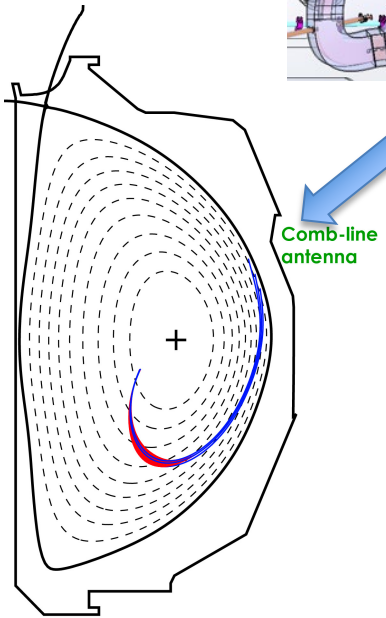
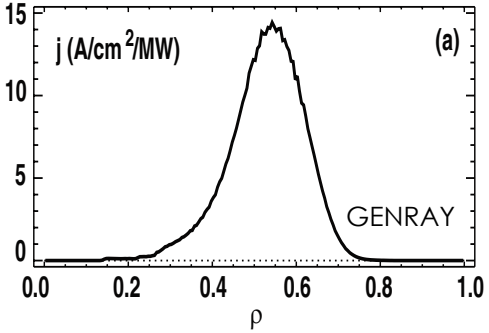
New High Harmonic Fast Wave "Helicon" 476 MHz Antenna is Installed

- **1.2 MW source power from klystron**
- **Comb-line traveling wave antenna**
  - 1 input port & 1 output port, power transfer through mutual inductance
- **Predicted to provide efficient off-axis current drive at mid-radius for advanced j-profile control at high β_e**
- **No density cut-off like ECH**
- **New next year: 4.6 GHz lower hybrid antenna to do a similar job**





Predicted
50-70kA per coupled MW
@ ρ~0.55



Prater NF 2014

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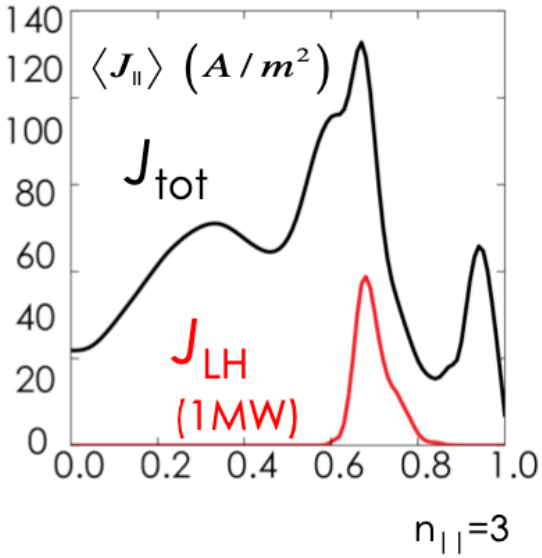
If Helicon and/or Lower Hybrid Work Well, Upgrading Them to Higher Power Enables High Density AT Scenario Tests

- **Adding 1 MW Helicon or LH raises stability margin**
- **Expands range of steady state current profiles accessible with balanced NBI**
- **Can use in place of ECCD at high density for core-edge integration**
- **14 MW ECH will be used for O-mode heating at high density**

Co-Ip NBI + 6 MW ECH
➔ β_N at limit = 4.6
Add 1 MW LH ➔
β_N=4.9, limit = 5.9



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