Plans to Develop Integrated Core-Edge-Wall Plasma Solutions for a Fusion Pilot Plant with DIII-D

by

RJ Buttery

with thanks to many DIII-D colleagues

at the

IAEA Long-Pulse Technical Meeting

Vienna

Oct 16th 2024

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Work supported by US DOE under DE-FC02-04ER54698.

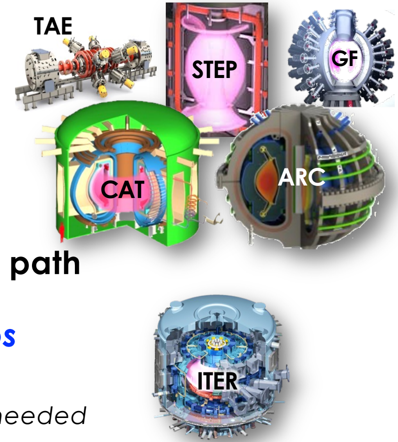
GENERAL ATOMICS

We Need to Pursue an Aggressive Path to Fusion Energy

- **Goal: Fusion energy in the 2030-40s**
  - Low capital cost: test at tractable scale
- **Challenges: Critical science & technology**

  "We do not as yet have a robust plasma configuration and scenario that will take us to commercial fusion" Cowley

- **Need: Flexible research facilities to discover path**



How do we best use our facilities to close gaps and accelerate the fusion path?

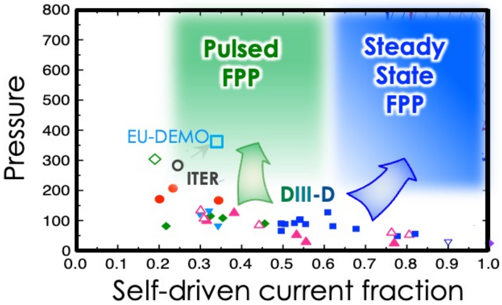
- *Established teams able to rapidly implement solutions needed*
- *Proven track records and expertise for scientific delivery*

We must work together to meet the challenge

Compact Fusion Pilot Poses Critical Plasma Research

Compact scale requires higher power densities:

- **High pressure** and **energy confinement**
  - To fuse sufficiently in compact device and retain heat for high gain
- **Power handling** and **wall compatibility**
  - To mitigate hot plasma exhaust
- **Plasma interacting technologies** and **control** must be developed



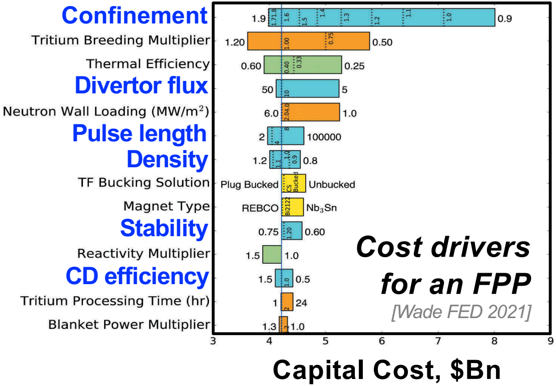
Drives research need

We need better solutions than we have now

Cost Drivers of a Fusion Pilot Plant Driven by Science <u>and</u> Technology

- **Plasma questions are key cost drivers for fusion pilot plants**
  - *Vital to develop optimal solutions*

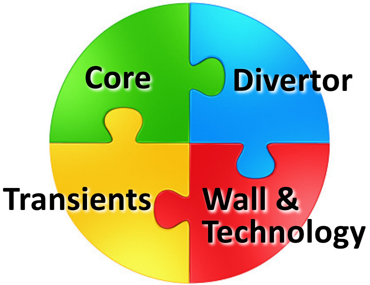
- **New technology research platforms also critical**
  - *Technology challenge driven by plasma solution*
  - *Compatibility with core plasma a vital constraint*



Plasma research vital to FPP design

An Integrated Solution Places Constraints on Each Element

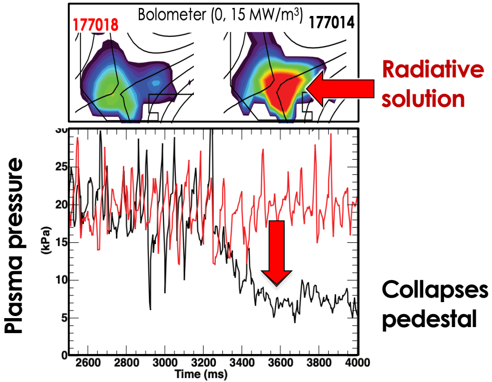
- **Each element interacts with and poses constraints on the others**
  - *Impurities: wall ←→ core & divertor*
  - *Pedestal-core ←→ divertor heat flux*
  - *Transients ←→ detachment & wall & core*
  - *Technology ←→ core conditions*
- **Need solutions for each element**
- **Vital to test interaction of elements together**



Multiple research challenges that must be solved together

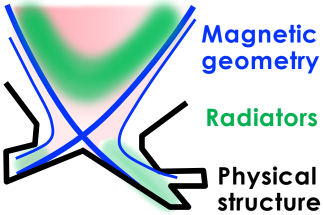
A Critical Challenge is Core-Edge Integration

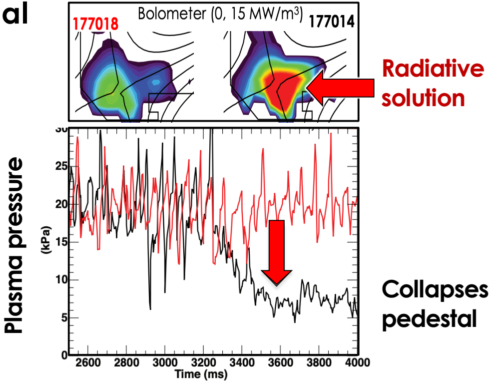
- **24/7 divertor solution must eliminate erosion → detachment**
  - But strongly dissipative techniques collapse the core:



A Critical Challenge is Core-Edge Integration

- **24/7 divertor solution must eliminate erosion → detachment**
  - But strongly dissipative techniques collapse the core
- **Resolution depends on complex physical processes and requires innovation**
  - ***What structures & geometries are required?***

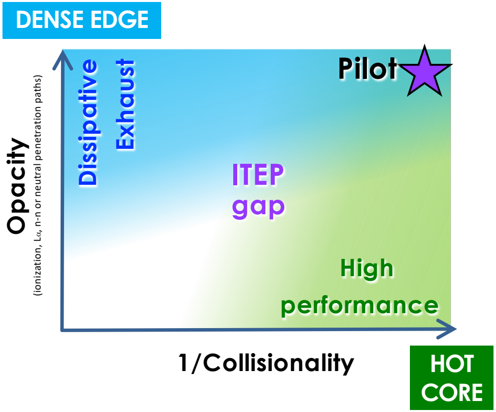




Requires innovative divertor and core solutions in relevant regimes

'Integrated Tokamak Exhaust & Performance ' (ITEP) Gap Arises

- **Tension between:**
  - High density radiative divertor solution
  - High temperature high performance core



ITEP

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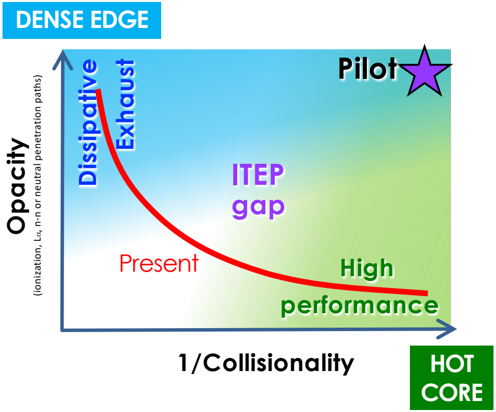

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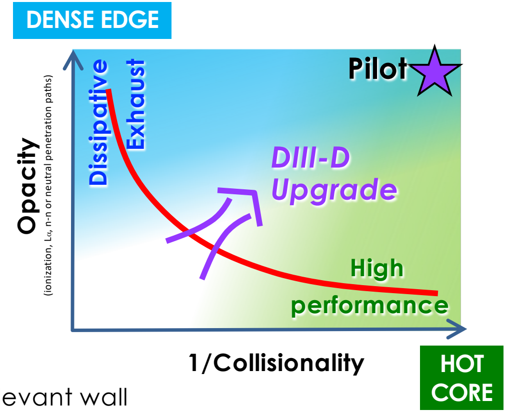
- **DIII-D pursuing by**
  - Shape, volume and current rise
  - Heating & current drive rises

  } *high pressure*
  - Advanced divertor & core configurations with relevant wall
    - ➢ ***Relevant physics regime for core-edge resolution***



Basis to develop integrated solution

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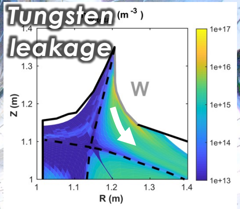
ITEP

Crucial Factor is the Wall

- **Wall a crucial constraint on the plasma solution**
  – Must tolerate core scenario
  – Influxes influence, detachment, pedestal, core performance & stability



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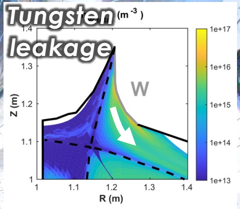
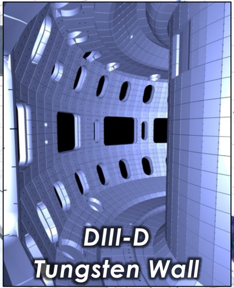
DIII-D carbon wall influences core radiation, outgassing & erosion

- *Time to confront this ➔ DIII-D moving to W wall in 2027*

- **Adapt DIII-D develop scenarios for W environment,**
  - Benefiting from key mitigations in core, pedestal & divertor
- **Test innovative new materials without carbon**
  - Better solutions needed than tungsten
- **Resolve integrated core-edge-wall-technology solutions**





Tungsten will provide a new context for DIII-D to close gaps to a fusion reactor

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DIII-D Program Focuses on U.S. Priorities for Low Capital Cost Fusion Pilot and ITER

- ✓ The Plasma Research Challenge
- **Hardware Upgrades to Close the Gap**
- Meeting the Challenge

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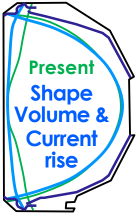
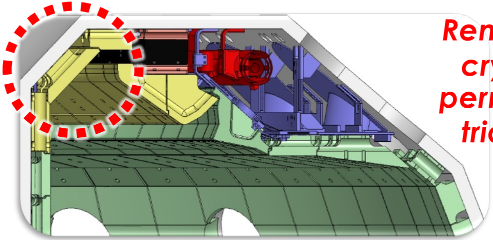
New Shape Volume & Current Rise Divertor Raises Pressure, Density and Opacity to Confront Core-Edge Challenge

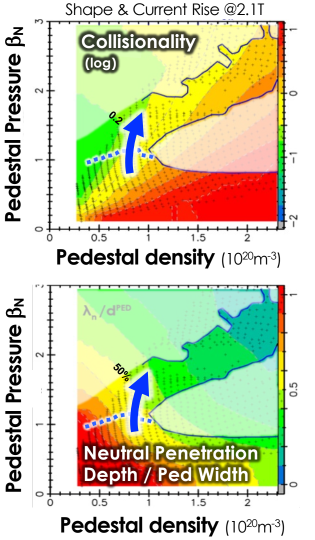
ITEP

- **Raise divertor opens large expanse in operational space**
  - Raises **pressure** and **density** access
  - Increases **opacity** & lowers **neutral penetration**
    - *Gradients become transport-defined, like FPP, rather than by neutral deposition*





Removed inner cryopumps to permit extreme triangularity & volume rise



EPED, EIRENE, SOLPS

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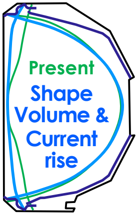
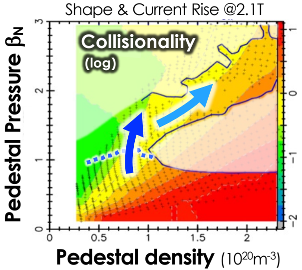
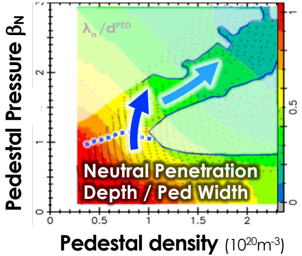




- **Increases scope of pedestal exploration**
  - **Conventional pedestals: Low collisionality & high opacity** with high energy, pressure & density
  - **More advanced pedestals: Scope limits of performance & dissipation** through shaping & control techniques



Basis for core-edge integration & resolving reactor pedestal science

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EPED, EIRENE, SOLPS

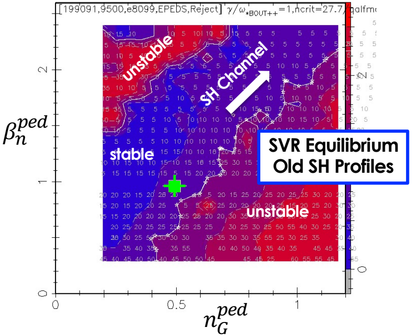
New Shape Volume Rise Divertor Commissioned, Model Validation and Scenario Development Underway

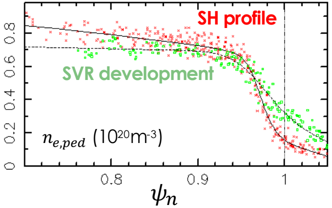
ITEP

- **Divertor pumping calibrated, diagnostics commissioned**
- **Optimizing plasma shaping, divertor interaction & shot trajectory**
  - Low ν^* front end, avoiding core MHD
    - *but presently ballooning limited*
  - Wide Super-H channel predicted
  - Profile structure important → ***optimization planned for experiments later this month***

Poised to explore limits with this new tool

EPED Pedestal Stability Simulation





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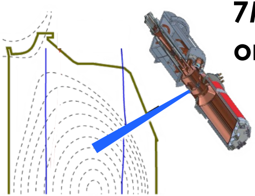
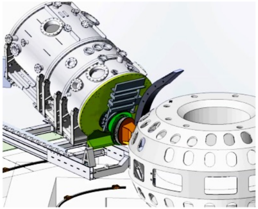
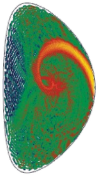
Increased Heating & Current Supports High Density and Temperature for Core-Edge-Wall Integration



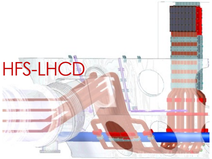
7MW ECH: directable electron heating or current drive, without fueling or torque

20MW NBI with RF sources bulk heating & current drive, on/off axis, toroidally steerable





New helicon current drive installed & testing



New HFS LHCD installed: testing in 2025

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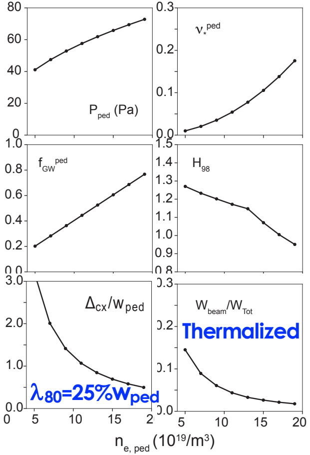
Enables: x3 energy, x2 density, $n_iT_i\tau \sim 2E20$, $q_{||} \sim 10GW/m^2$

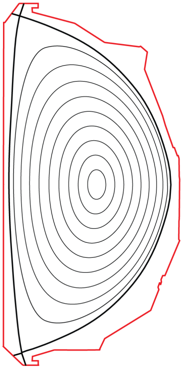
H&CD Upgrades Will Enable DIII-D to Close Gaps on Reactor-Relevant Core-Edge Integration

ITEP

- **Integrated physics simulations identify high performance solutions**
  - 2.2T, 2.5MA, 16MW NBI + 7MW EC
    - *Higher freq EC accesses $n_e \rightarrow 14\times10^{19}$*
- **Project low-collisionality at high density with conventional pedestals**
  - **Low neutral penetration depths at low ν***
  - Highest density while still peeling limited
  - Thermalized $T_e \sim T_i$ cores
  - ~30% of pilot plant $q_{||}$
- **Advanced pedestals through shaping optimization could go further**

Integrated Physics Simulation





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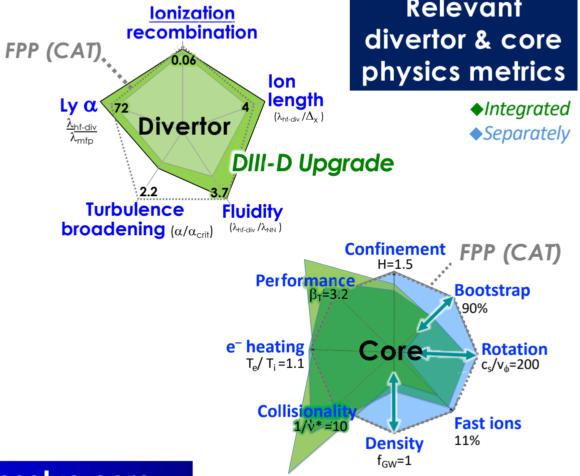

Relevant physics metrics to resolve core and divertor solutions for reactor

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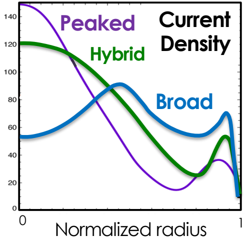
New Heating and Current Drive Enables DIII-D to Explore Candidate Power Plant Core Solutions

Core

Spectrum of plasma regimes

– From broad to peaked currents, & high bootstrap to driven currents

Regime	Strength	Challenge
Broad	β_N=5 potential; Low disruptivity	Fast ion transport wall modes
Hybrid	Efficient CD, Robustness	Current evolution β_N limit
Peaked	Good confine't no RWM	Sustainment; Tearing. Disrupts



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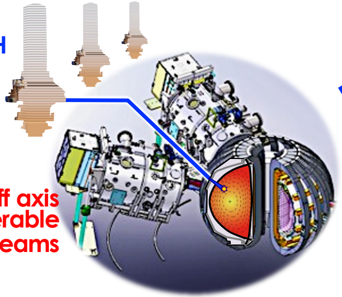
ECH & NBI provide scope to explore solutions and address key physics:



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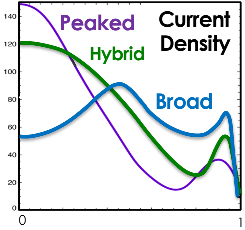
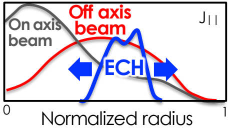


H&CD tools:



Performance (β)
Wall mode kinetic damping & fast ion instabilities vs. current profile

Burning Plasma Conditions (Ω T_e/T_i P_{ei})
Turbulent transport & kinetic effects with coupled e⁻ions & low rotation

Core-Edge Integration (n, $q_{||}$)
High density and power to understand impurity and core-edge optimization

See Holcomb, Thursday

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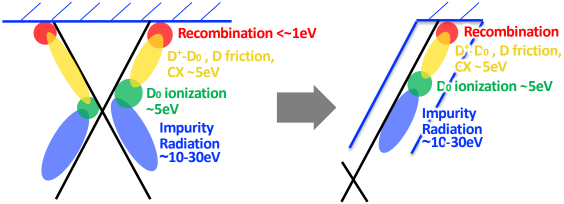
Addresses critical science & tests solutions to retire risks for FPP core

New "Chimney" Divertor Concept will Resolve Key Physics & May Offer Improved Divertor Solution

Divertor

Longer leg

- Isolates physics for model validation
- Avoids X point degradation



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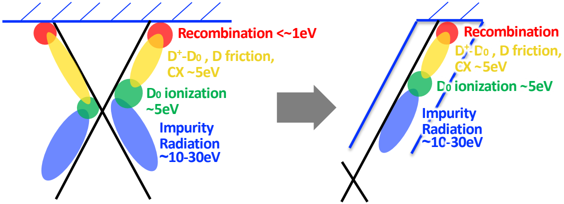
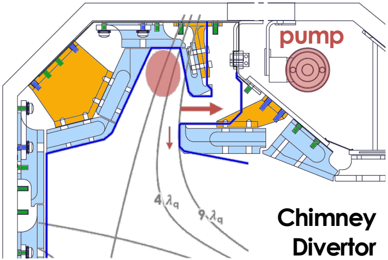
"Chimney" design improves detachment

- **Mid-leg pump** stabilizes radiation front at duct





Chimney Divertor

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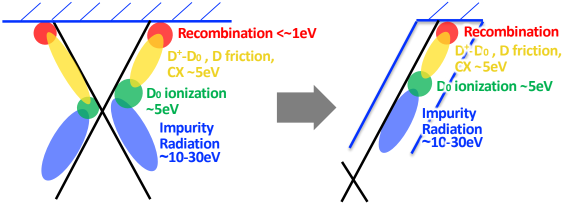
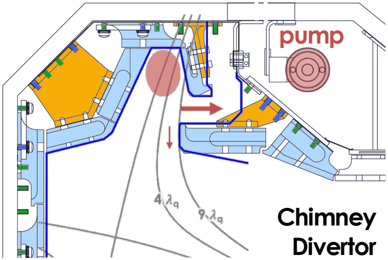
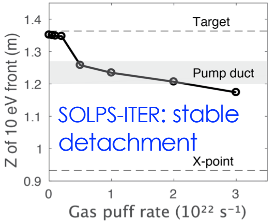
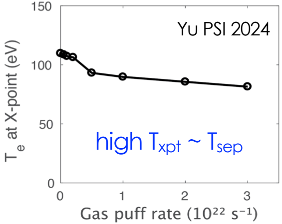




SOLPS predicts cold dense target & hot X with good stability





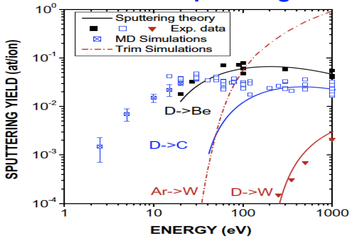
Test key principles behind divertor design

New Tungsten Wall Provides Opportunity to Close Key Remaining Gaps with DIII-D

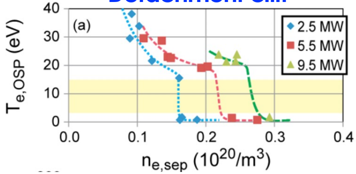
Wall & Tech

- **Removal of C provides key opportunities**
  - C predominant radiator – resolve extrinsic radiator strategy
  - C fuel retention governs detachment bifurcation
  - C provides too forgiving wall – resolve compatible solutions
- **Change to W develops solutions with relevant radiators**
  - Exploit DIII-D flexibilities & ECH to mitigate challenge
  - Use of other radiators to optimize strategies
- **DIII-D complementary to other facilities**
  - **Core-edge solutions:** shape, profile, divertor & NT flexibility
  - **High β steady state:** advanced tokamak configurations
  - **Model validation:** Large diagnostic suite
  - **Innovative materials & technology testing**

Carbon sputtering



Detachment cliff



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Expertise and advice of community appreciated

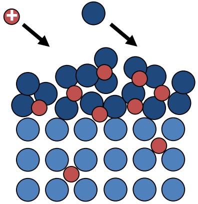
Metal Wall Removes C as Dominant Sputtering Source of High-Z and Eliminates Mixed-Material Uncertainties

Wall & Tech

- **Decoupling C co-deposition from retention studies in DiMES fusion material samples**
  - Enabling more insight into performance of various wall material fabrication routes
- **Large investments in flexible wall conditioning capabilities prepares DIII-D to address key questions for ITER and FPP with metal wall**

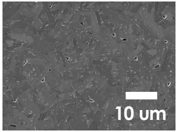
Deposited C layer
D/C ~ 10^{-1}*

W sample
D/W ~ 10^{-3}*

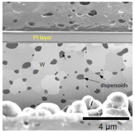


* from Roth PPCF 2008

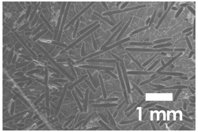
Ultra-High Temp Ceramics (UHTCs)



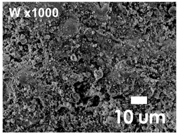
Dispersoids



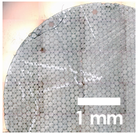
Fiber-reinforced



Plasma spray



Microstructured W/Cu



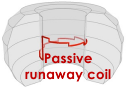
Basis to develop more advanced wall solutions

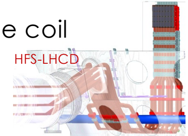
DIII-D NATIONAL FUSION FACILITY

DIII-D Accelerating Program to Test Reactor Technologies

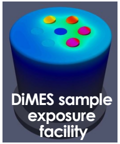
Wall & Tech

- **DIII-D brings key characteristics necessary**
  - **Flexibility**, diagnosis, relevant regimes, integration
  - **Swap out components rapidly & often**
    - Much harder in activated or tritiated devices
  - **Assess with relevant solutions** for wall divertor & core
- **Technology Group spans 1/3rd of DIII-D program**
- **Platform approach with rapid facilitated access**
  - Materials, control, diagnostics, components
- **Pursuing key innovative techniques**
  - Disruption mitigation: pellets & passive coil
  - Helicon & HFS-LHCD RF
  - Spin polarized fusion





Proven track record

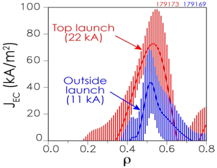


Materials interactions
- Explore degradation
- Understand transport
- Assess divertor leakage

Studies of W & ELM behavior, and new materials

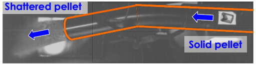
Top launch ECH

Doubled current drive efficiency



Shattered Pellet Disruption Mitigation
- Quench heat & current

Adopted by ITER



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Key capabilities that will qualify critical fusion technologies

DIII-D Engaging Private Industry to Accelerate Commercialization

- **Industry research identifies significant need***
  - Solve challenges to reduce timescale & risk
    - *50% of fusion companies want to use a user facility*
  - **Key asks:** ML, control, data, materials, diagnostics, plasma behavior, component testing, simulation, training, expertise
- **DIII-D program technology goals now align with private sector goals**
  - → ***Enables full non-proprietary collaboration***
- **New user framework enables private sector to join**
  - **Protects private IP** while sharing public IP
  - **Provides support**, training, expertise & shared leadership
  - **Partnership approach** with workshops and six companies on our PAC

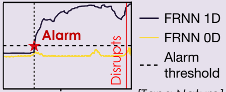
Industry examples

Materials Interactions

Tested SPARC wall material in fusion grade plasma with 4 month turnaround!

NVIDIA & MS Hardware for Machine Learning Disruption Prediction

Using DIII-D digital twin with deep learning & profile measurement



[Tang Nature]

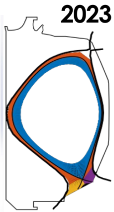
17 companies in process of joining up including non-tokamak & non-fusion

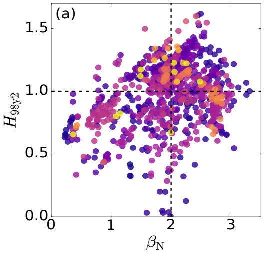
DIII-D is the key facility to support private industry engagement

*Survey of 22 fusion companies, D.C. Pace, MBA thesis

Negative Triangularity May Provide Alternate Transformational Solution for Fusion

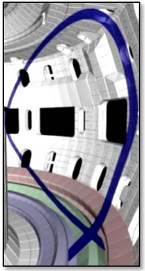
- **Negative Triangularity give high confinement with low power to divertor and no ELMs**
  - DIII-D changed hardware to test diverted 'NT'
    - *in just two weeks!*
  - Exciting results with great confinement & stability

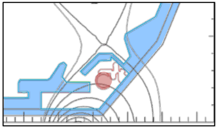




- **New closed pumped NT divertor will combine with ECH upgrade to close remaining gaps**
  - Core-edge integration: detachment with high performance core
  - Assess AT and wall compatibility

Negative Triangularity could upend the tokamak concept !



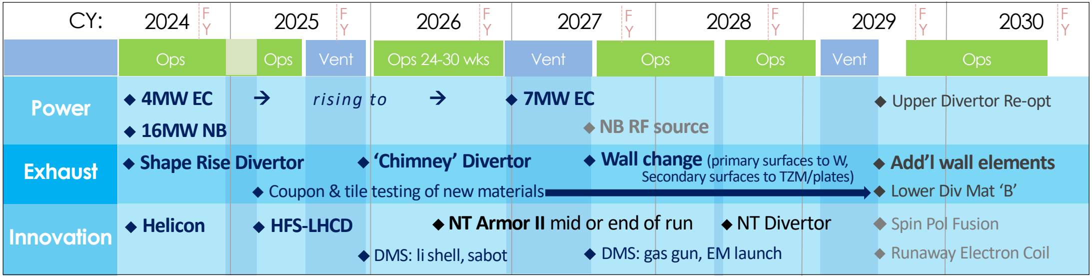


Cryo-pumped full closed NT divertor

DIII-D Program Focuses on U.S. Priorities for Low Capital Cost Fusion Pilot and ITER

- ✓ The Plasma Research Challenge
- ✓ Hardware Upgrades to Close the Gap
- **Meeting the Challenge**

Hardware Upgrades Close Gaps in Timely Manner



Grey=funding tbd

- **Closes 'ITEP' core-edge-wall integration gap by 2030**
  - Integrates power rise, wall and innovative divertors
- **Addressing multiple critical gaps on limits, physics & solutions**

Important contributions in an international context

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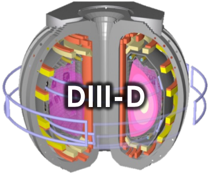
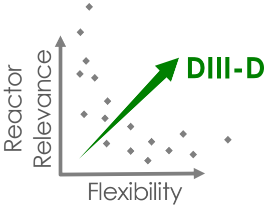
Working Collaboratively We Can Close the Key Gaps to a Fusion Pilot Plant



Develop techniques at high power density

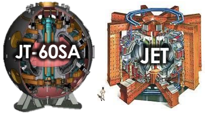
- Flexibility to resolve & integrated innovative exhaust, core and wall solutions
- High opacity, low ν*, high performance, burning plasma relevant conditions
- Physics basis to project



Long pulses test evolution & wall

- Material & PFC evolution
- Long pulse control

Larger devices test scaling



- Projection to reactor
- Operational techniques

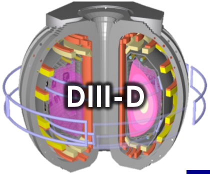
Higher field: nuclear & burn

- HTS integration
- Core-edge demonstration
- Nuclear testing

Key physics & novel techniques

- Aspect ratio & Shape
- Extreme divertor geometry
- Super Alfvénic ions & high β
- Liquid metals

Working Collaboratively We Can Close the Key Gaps to a Fusion Pilot Plant



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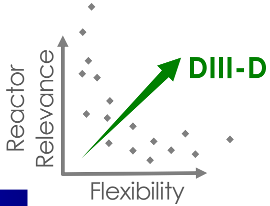

Existing facilities well placed for timely answers to crucial questions

Long pulses test evoluti

- Material & PFC evolution
- Long pulse control

- Projection to reactor
- Operational techniques

Higher field: nuclear & burn

- HTS integration
- Core-edge demonstration
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Key physics & novel techniques

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DIII-D Being Redeveloped to Confront the Challenge of a Rapid Path to Fusion Energy

- **Move to tungsten enables DIII-D to address key remaining gaps**
- **Strong facility flexibilities to confront the challenge**
- **Testbed approach to enable rapid path from fusion customers**
- **Strong focus on workforce & early career development**

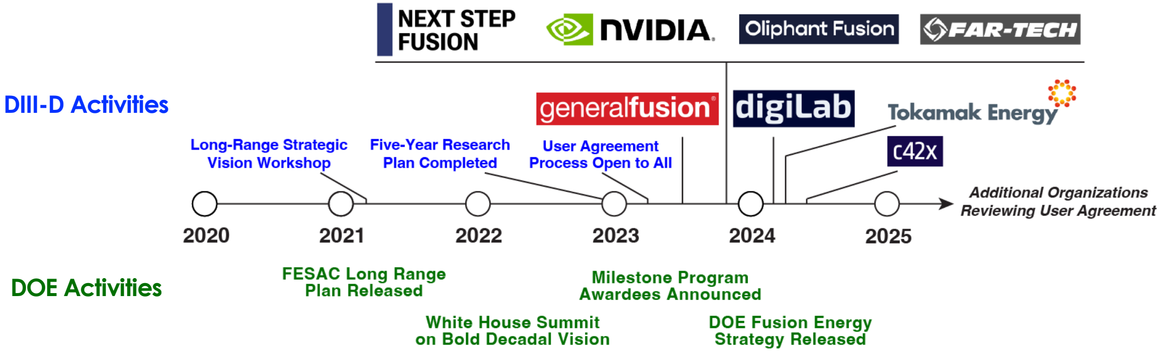
Work with international partners is key

DIII-D NATIONAL FUSION FACILITY

ADDITIONAL REFERENCE SLIDEs:

DIII-D Reduced the Barrier to Entry for Industry Partners

- **Non-proprietary User Agreement provides free access to the DIII-D Research Program in a process that can be completed in a single day**
- **Strong initial uptake leading to continued growth in industry participation**

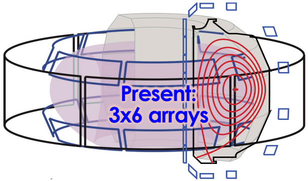


Rapid, free, flexible-scope access in as little as a day

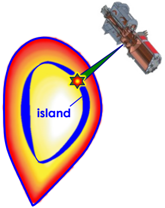
ECH Rise Provides Crucial Capability to Resolve Transient Control in Relevant Regimes

Transients

- **ELM control:** *ECH rise provides unique access to relevant **low rotation** & **collisionality 'peeling' pedestals** to resolve integrated scenarios*
  - **Resonant 3D field ELM suppression** with flexible coil arrays
  - **QH and other benign ELM regimes:** resolve controlling edge physics & ExB rotation requirements with flexible profile control
  - **Pellet pacing:** sufficient triggering and heat reduction



- **Plasma control:** *ECH rise provides unique headroom though α-like electron heating, precise deposition & profile control*
  - **Burn simulation & control** with FPP-like actuator and measurement constraints
  - **Tearing mode control** via direct island deposition or profile control
  - **Disruption avoidance:** Machine learning, faster-than-RT simulation, sensing
    - *Digital twin develops robust schemes offline for testing online*



DIII-D the key proving ground to resolve tokamak control & the non-linear multiscale physics of MHD phenomena

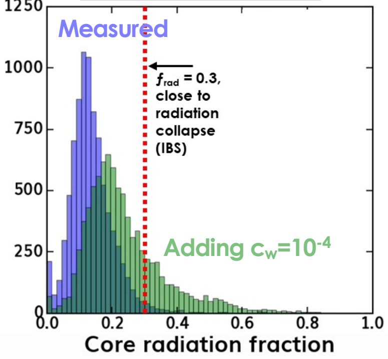
DIII-D NATIONAL FUSION FACILITY

DIII-D planning to move to metal wall: resolving key core-edge integration challenges

- **Opportunity to evaluate how of various DIII-D scenarios change with high-Z walls**
  - At a high level, compatibility/access
  - Toleration of radiative losses from high-Z impurities (stability, confinement)
  - Excellent diagnostics support model validation in a broad range of conditions

- **Development of new control techniques to maintain/recover lost performance**
  - Core ECH, ELM control, etc.

Effect of adding c_W 10^{-4} to shots over the last six years



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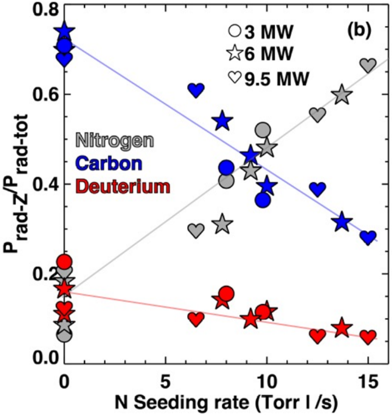
Moving to metal walls enables better understanding of divertor detachment and integration

- **Removing carbon provides direct control of radiating impurities**
  - C strong radiator, even with seeding
  - C sourcing impacts detachment access and dynamics

- **Stable/robust detachment scenarios with extrinsic impurity injection, e.g. XPR**

- **Evaluate W sourcing and leakage with extrinsic radiators**

C present even in strongest N seeding

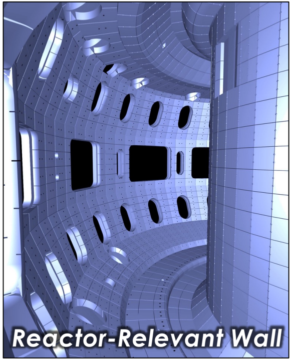


Scotti IAEA 2023

New Tungsten Wall in 2027 Will Enable Integration of Reactor Relevant Materials into Core-Edge Challenge

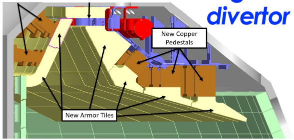
Wall & Tech

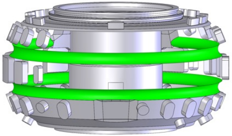
- **Crucial because of interactions with core and divertor**
  - **Material behavior with fusion-relevant plasma distributions**
    - *Without C-induced erosion*
  - **Scenarios with relevant impurity transport and radiation**
    - *Reduce carbon radiators to study radiative optimization*
    - *Increased ECH e^- heating can control impurity accumulation*
  - **Changeouts to test different materials & components are easy**
    - *Materials choices taken with US community*



- **Combine with other DIII-D material testing capabilities to assess key PMI physics & novel materials**

W coatings on divertor





Toroidal limiters test novel new materials & resolve SOL models for FPP wall design

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Tests new materials and their interaction & compatibility with the core

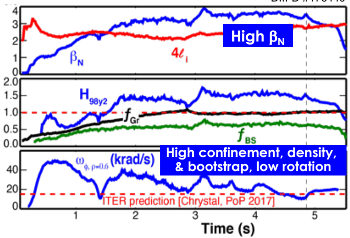
International Complementarity Examples

Long pulse development builds from DIII-D developed solutions

DIII-D

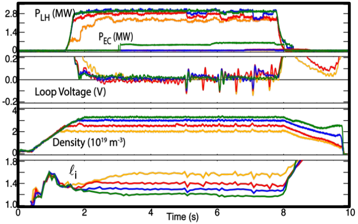
- **Flexibility to develop scenarios**
  - Improved transport
  - Alleviated ELMs
  - Mitigated heat flux

DIII-D #176440



Superconducting

- **Extend to long pulse**
  - Stability & wall compatibility
  - Heating and current drive
  - Long pulse evolution



Strong collaboration with long pulse partners

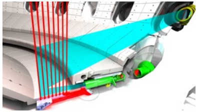
International Complementarity Examples

MAST-U and DIII-D Complement on Divertor Science → Test on DTT

DIII-D

- **Diagnose physics**
- **Reactor-relevance**
  - High power & pedestal P
  - High neutral opacity
  - Recycling
- **Detachment control**
- **Core-edge integration & AT**

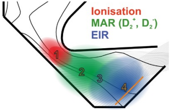
New 2D Divertor TS



+ MAST-Upgrade

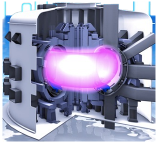
- **High closure**
- **Extreme flexibility**
  - Long radial leg length
  - Large flux expansion
  - Reduced upstream density
- **Test models of plasma-molecular reaction**

MAST-U divertor



⇨ Italian DTT

- **Closer to FPP parameters**
- **Flexible divertor and plasma shape, but less core operational range**
- **Limited access (activated)**
- **Fully operational mid 2030s**



DTT

Holistic physics basis for divertor research

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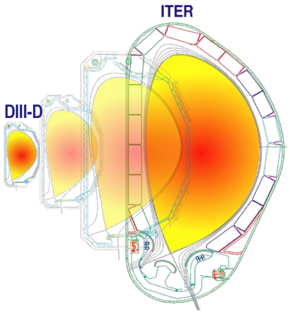
DIII-D will Enable U.S. Success in ITER for the FPP Path

Distinctive Technical Contributions

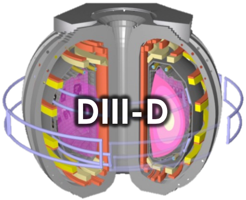
- Ramp up & early phases
- Transients and control
- Robust scenarios to deliver burn goals
- Physics to interpret & optimize performance

Programmatic Role for US in ITER

- *U.S.'s ITER simulator*
- *Train the team*
- *Develop techniques & codes on DIII-D*
  →*Validate in ITER*
  →*Bring learning to FPP*



Complementarity Between U.S. National Facilities

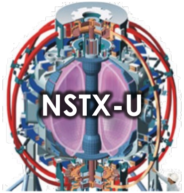


DIII-D

- Profile and shape
- Low collisionality with high opacity
- Thermalized low rotation
- Solid divertor solutions & physics for projection

NSTX-U

- Aspect ratio
- Beta & bootstrap limits
- Superalfvénic fast ions
- Liquid metal PFCs & power handling



Broaden physics basis & provide more options for FPP

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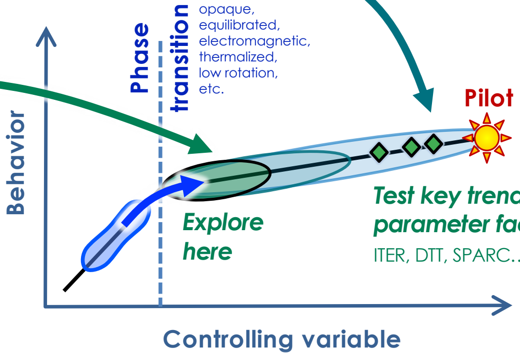
Basis of Approach

(1) Directly access some phenomena at reactor values for physics-governing parameters
e.g. β_N, collisionality

(2) Resolve techniques & science in relevant regimes & project

(3) Add the tools needed to address key issues & integration

Need flexibility to find solutions

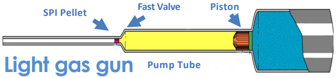


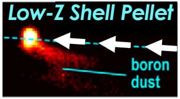
Test key trends in high parameter facilities
ITER, DTT, SPARC…

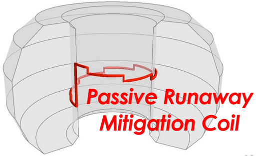
Access the right physics regimes to develop projectable solutions

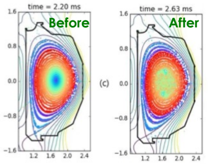
New Technologies Being Pioneered to Resolve Safe Quenching of Disruptions

- **Critical challenges**
  - **Rapid quench to avoid thermal & mechanical loads**
    - *High speed technologies for rapid response & core deposition*
    - *Advanced pellet fabrication*
  - **Prevent or dissipate energetic runaway electrons**
    - *Passive runaway mitigation coil*
    - *Disruption resilient PFCs*
- **Foundational issues**
  - **Resolve projection** through diagnosis & simulation
  - **Disruption prediction & response** to trigger quench









Complete stochastization by core impurity deposition

Disruptions remain a critical challenge for DIII-D

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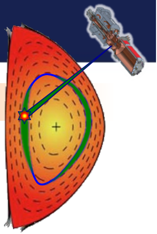
RF Rises Provide Critical Properties to Close Reactor Gaps
REWORK THIS FOR LATEST SIMULATION



EC

Lines	Power
6	3-4 MW
8	5.6 MW
10	7 MW
16-20	11-14 MW

+ additional NBI & helicon/LHCD

KEY TECHNIQUES

- Disruption mitigators
- Entry point for high q_{min} AT
- Divertor science & geometry tests
- Novel RF technologies
- FPP Diagnostics
- Perturbative transport in H-mode
- Shape rise & pedestal density & pressure limits
- Radiative techniques
- Peeling limited pedestals for ELMs
- Materials erosion & transport
- Sample & component testing

LIMITS

- ITER dual NTM/sawtooth control, Q=10
- AT stability limits
- Pulsed FPP scenarios
- ELM mitigation at low rotation & ν^*
- Component & materials at high T_e, density, $q_{||}$
- Thermalized FPP-like fast ions
- Alternate ITER scenarios
- Burn simulation
- Divertor science in opaque conditions
- ITER ramp up & steady state

CORE – EDGE INTEGRATION

- Control impurity accumulation with ECH
- Transport at low rotation, T_e~T_i, high β
- Opaque collisionless pedestals
- High performance & high dissipation core-divertor solutions with high SOL ν^*
- Materials integration with core

Key programs enabled at each stage

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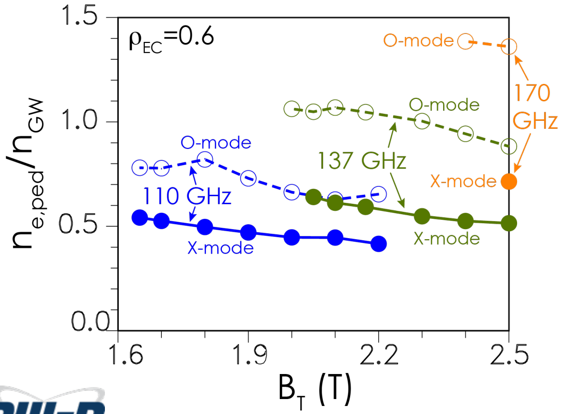
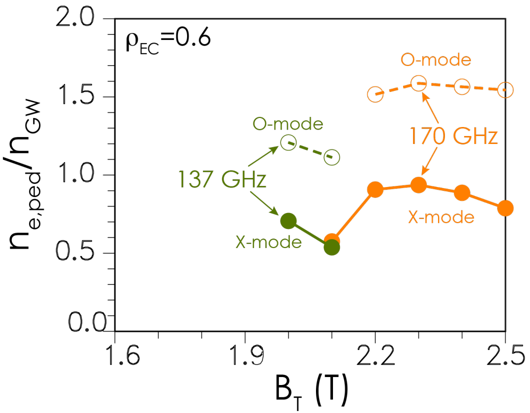
With Higher B_T, Plasmas with High Greenwald Density Fraction ($n_{ped}/n_{GW} \geq 1$) can be Accessed by ECH

Modeled ECH density limit assuming plasma current scales to 2 MA at 2.5 T

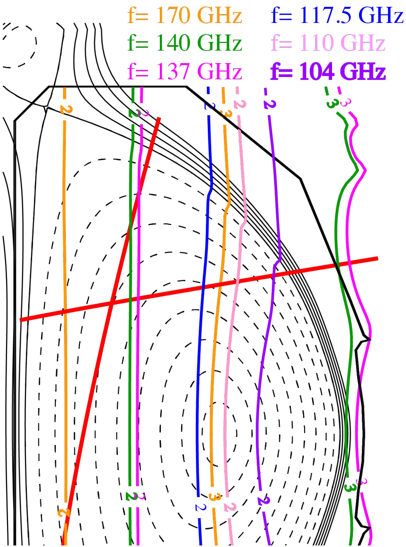
- **Outside launch ECH**



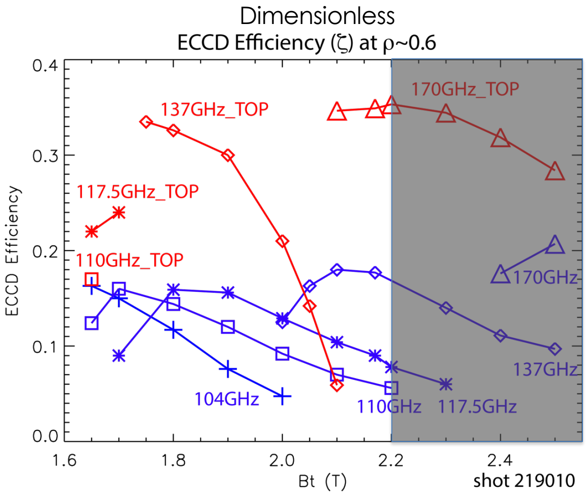
- **Top launch ECH**

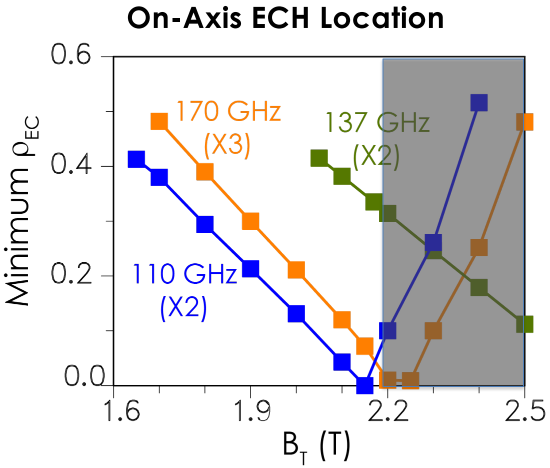


ECH at 2.2 T



Flexible Multi-Frequency (110/137/170 GHz) Gyrotrons Would Cover Whole Range of B_T in a DIII-D Upgrade





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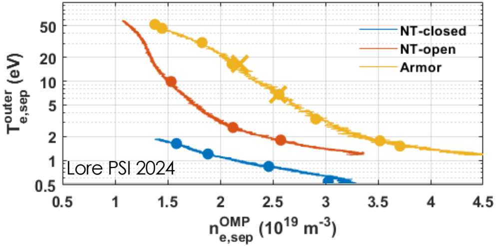
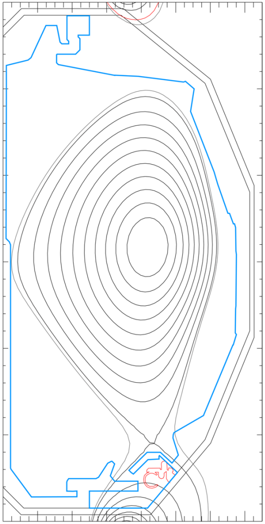
Negative Triangularity divertor design activity: improving detachment and core/edge integration

- **NT shows attractive route to performance and edge stability, but detaches at higher density than PT and degrades confinement**

- **New divertor design with changes in equilibrium, closure and pumping enable:**
  - Access to divertor dissipation at lower n_e
  - Limit confinement degradation after detachment
  - Particle control

SOLPS ITER showing detachment at lower upstream density





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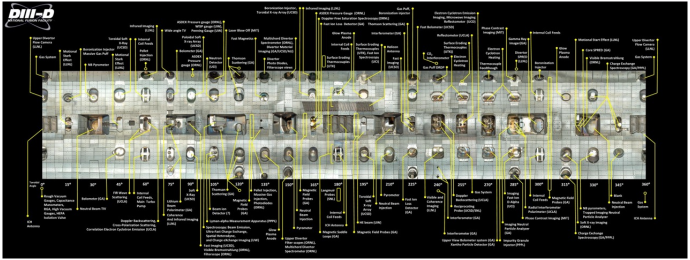
Vital to Develop Validated Physics Understanding

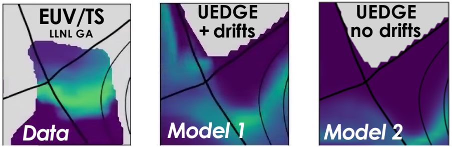
- **Comprehensive, cutting edge diagnostics resolve key science**
- **Over 20 theory groups and 70 codes engaged for validation**



Example: Role of drifts in detachment

– *Combine 2D EUV/VUV & Thomson data*

➔ ***Drifts critical to predict detachment***

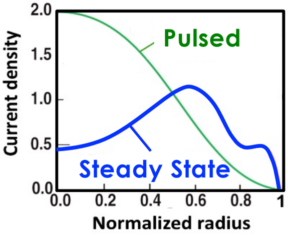


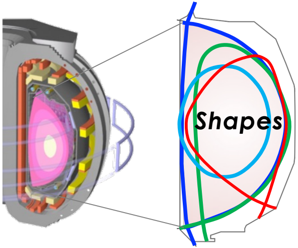
Divertor Dissipation: Impurity charge state C^{2+}

The 'why' is critical
Need confidence to adapt solutions for FPP

Core Requires High Performance Solutions

- **Wide space in profiles, shape and parameters which optimizes along two broad paths:**
  - **Steady state:** Naturally improves stability & transport through **shaping**, **profiles** & **high β**
    - *Lower current, self-driven solutions, decreasing loads & risks, sustainable noninductively*
    - ***Need to validate projected solutions***
  - **Pulsed:** High confinement with **high plasma current**
    - *Potentially increased instability, heat & stress*
    - ***Can stability be maintained?***
- **Must also resolve compatibility of scenario with divertor, wall and transient solutions**





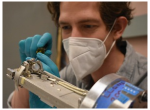
DIII-D has unique profile and shape flexibility to resolve core

A Key Strength DIII-D Brings is Workforce Development

- **DIII-D an early career development center**
  - **Leadership**: science, XPs, talks, papers, systems, PIs
  - **Mentorship program**, training, summer school
  - **Over 250 students, postdocs & interns** with PhD runtime & student support groups
- **Diversifying pathways**
  - **Under-represented groups:** internship programs, community college engagement, SDSU
  - **Next generation:** Local schools, girls Tech Trek, CuWiP, Young Women's STEM, Society of Women Engineers
- **Addressing workplace environment & opportunity**
  Invested in APS climate survey yielding major insights
  - **Environment:** code of conduct, community agreements, webinars, civil treatment, bystander & meetings trainings
  - **Open opportunities policies** with balance monitoring & double-anonymized deconflicted XP review to combat bias

Prof. Livia Casali, Early Career Award
"Innovative Core-Edge Solutions for Tokamaks"
Co-lead DIII-D Core-Edge Task Force
Professor at UT Knoxville

Shaun Haskey
Early Career Award
"Main Ion Transport and Fueling in the Pedestal"
Leader of DIII-D NB physics



A. Rosenthal
DOE Highlight
MIT PhD

GEM under-represented grad interns in Ops

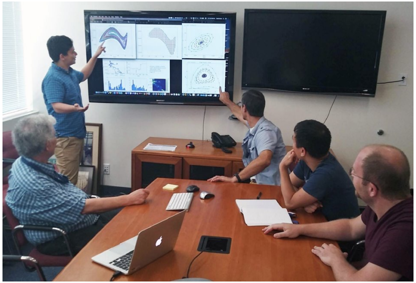
Preuss high school low income first-in-family interns

Amer. Assoc. Uni Women 8th grade camp

Seeking an enabling environment for all

FPP Mission Will Broaden Reach on Workforce Development

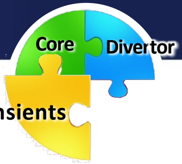
- **Expanded topical scope in technology & science will help us diversify pathways further**
  - Invited to join new "Pathways" program for MSIs
  - Facilitate development with private sector
- **New User Board energizing workforce development with 5 new bodies being formed:**
  - UB Council – Personnel Development – Nominations
  - Data & Access – DEIA Council
  - Plan to provide specialist training and Ally program



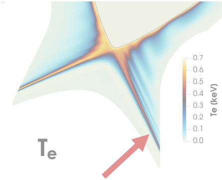
- **Apprenticeship center for engineers and technicians proposed**
  - DIII-D the ideal place with high range of roles and many institutions engaged

DIII-D will provide powerful development & preparation of the fusion workforce

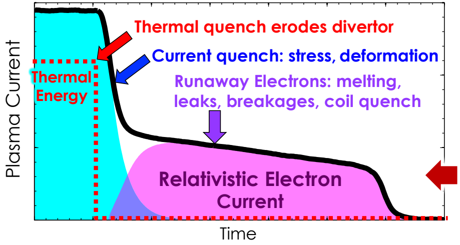
ELMs and Disruptions Must be Mitigated to Avoid Damage to Plasma Facing Components



- ELMs: Require benign-ELM core scenarios
  - Through profile & 3D manipulation tools
- **Disruptions threaten structural integrity**
  - **First line of defense: stable controlled core**
  - **Mitigation systems are a vital fallback**



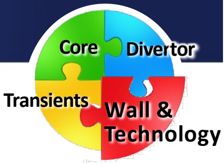
ELMs burn through high recycling divertor (JOREK)



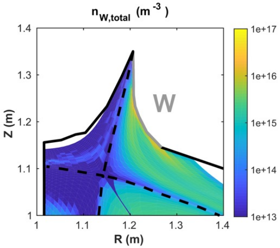
Technology & physics solutions needed

DIII-D unique flexibility in actuators to solve these problems

Wall and Reactor Components Pose Crucial Challenge for an Integrated Solution



- **Survivability & functionality need to be tested in relevant plasma conditions**
  - And impact and constraints on core fusion plasma
- **Development of FPP-compatible techniques is required**
  - ***Fewer, simpler systems, hands-off, radiation-hard***
    - ➔ *Neutron, heat & particle fluxes, temperatures, stress, space, 24/7*



Tungsten erosion & leakage in divertor

DIII-D can rapidly change out components & assess relevant interactions

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Plasma Research Gaps Called out in CPP and FESAC Long Range Plan Reports (Reference slide)

Theme	Gaps on timeline at end	FESAC Long Range Plan	CPP Gaps
Exhaust handling compatible with core	**ITEP** **Divertor**	Pages 16, 32, 33	**ITEP:** FST-SOD-3 (p70) **Div:** FST-SOD-2-p69, FST-PR-A.3 (p54), DPS-C (p21)
Core solution	**Core scenario** **Transport** **Energetic Particles**	Pages 14, 31, 32	**Core:** FST-PRD-2 (p96) **Transport:** DPS-B (p19-20), DPS-C (p21), DPS-D (p22) **EP:** FST-SOD-1 (p69)
Transients	**Disruptions** **ELMs**	Pages 13, 31, 32	**Disrupt:** FST-SOD-4 (p71), FST-PRE-4 (p101), FST-SOC-8 (p65) **ELMs:** FST-SOD-1 (p69)
Plasma interacting components	**Plasma material interactions (PMI)** **Diagnostics** **RF**	Pages 14, 31	**PMI:** FST-PR-A.3 (p54), FST-SOA-1 (p51), FST-SOA-4 (p55), FST-SOB-1 (p57), FST-SOD-5 (p72), FST-PRE-1 (p98) & DPS-I (p38) **Diag:** FST-PRE-1 (p98), FST-PRE-3 (p100), CC-1-MD (p106) **RF:** FST-SOG-3 (p83), FST-SOF-4,5 (p78)

DIII-D Upgrade Provides Unique, Vital Capabilities

- **Key capabilities that will not be available elsewhere**
  - **Change out wall, divertor, materials and components readily and often** to assess wide range of new technologies and approaches in fusion-relevant conditions
  - **Core configuration flexibility** with on & off axis H&CD & shape actuators to identify viable pulsed & steady state cores compatible with wall, divertor and transient solutions
  - **Scientific foundations to adapt solutions for the FPP** through comprehensive diagnostics and outstanding flexibility
  - **Critical control tools** for tearing, ELMs, disruptions, impurities & burning plasma simulation
  - **Integration** of technical solutions developed on these fronts
- **User facility model a crucial strength, levering dozens of groups across the US**

Fundamentally, we need a facility that can *discover* a viable approach & *pioneer* the science to project with confidence

SPARC Cannot Solve All the Issues for ARC, and Represents a High Risk Path if the Only Tool

- **Things SPARC is not designed to do:**
  - Focus on demonstration of predicted solution, rather than exploration to discover what works
  - Change out materials & components to try different PFCs. Sample & technology testing.
  - Steady state and advanced profile solutions or negative triangularity
- **SPARC has placed a series of bets on potential solutions that need to break the right way**
  - Divertor configuration. Wall solution. ELM coil set.
  - Neoclassical tearing modes can be avoided. Disruptions tolerable.
  - H/I mode access. Core impurity control. Energetic particle confinement

Critical SPARC limitations:

- No large scale replacements of wall structures (divertors, technology?)
- No snowflake divertor
- No tangential beams
- No ECH → NTMs, impurities, burn control
- Limited advance tokamak capability; reliant on freeze-in
- No Neg T capability
- No lithium
- No pellets yet
- Limited diagnostic coverage

SPARC is a great facility that offers valuable data to de-risk the FPP.
Should be part of the US plan and gain US participation.
But US must not bet the farm on SPARC generating all the answers.

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Isn't High field EXCITE (HFE) better?
Yes, No, and "its not necessarily a choice"

- **Yes** - HFE is clearly nearer to FPP, and so would reduce risk in some ways with key data closer to FPP – though SPARC, ITER and DTT do that.
- **No** – because a HFE would become more activated, and so have less personnel access for changeouts and testing.
  - *HFE will also take significant time to design and construct*
  - *HFE will cost significant $, which arguable should be prioritized to technology and milestone programs first.*
- **"Its not necessarily a choice"**
  - *Fastest way to HFE is to start on DIII-D upgrade now, as HFE can be built on DIII-D infrastructure*
  - *Once/if mission need established, design and then construction can commence in Sorrento Valley, with systems being ported onto new machine*
  - *Mission need will likely be determined in several contexts*
    - Results from milestone program
    - More specific FPP designs to identify specific tests needed.
    - Progress in international program (SPARC, JT60SA, NSTXU)
    - Attitude to risk for FPP path
    - Availability of funding, noting $1-2Bn cost + $1Bn exploitation.

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DIII-D will close clearly needed gaps ASAP
HF-EXCITE need may emerge can cane be started if so

We should wait until we understand the path and the needs

- **The D3D plan targets urgent issues we know we need to solve:**
  - *Scientific questions that must be resolved behind many solutions*
  - *Techniques for core, divertor, transients and technologies that must be tested*
    - These are shared between tokamak concepts, and offer value for beyond tokamak concepts
- **Any adjustment to research mission that emerges from SPARC, milestone program, FPP designs, etc., would build on this plan and be accelerated by it.**
  - *The investments in ECH would not be wasted, as they represent a broad transformation in the relevance of investigative regimes, not in any one particular solution.*
  - *Any research needs emerging later would build on this progress, and be accelerated by them.*
- **The investments for DIII-D in this plan can be transferred to successor devices or rebuilds if further mission or configurations needs emerge.**
  - *An upgrade is possible based on d3d infrastructure, as set out in other white papers.*
  - *Present site credits are worth around $700M, including presently funded development to 10 lines of ECH. Further investments in ECH, NBI and power infrastructure would add about $260M to site credits.*
  - *If you procure them now, they are ready sooner for such redirection*
- **DIII-D has a highly adept team and provides the facility to train and keep those personnel at the forefront.**
- **DIII-D will provide ongoing data needed to test and drive the development of theory and simulation**

Government funded projects are slow & error prone – don't build

- **DIII-D has long track record of delivering substantial upgrades, including rebuild of key systems like neutral beams, and installation of new technology.**
  - Delivered on time, with research campaigns also delivered every FY!

- **This project does not need substantive in vessel construction or rebuild**
  - Installation of remote ECH systems with in vessel copper mirrors
  - Based on designs already developed for lines 7-10

- ***But why hasn't DIII-D raised ECH power sooner?***
  - Insufficient investments to maintain existing power levels and keep sockets filled
    - *US provider production failures played significant role*
  - We have changed to robust suppliers (Thales, Kyoto) with established track record, and started major overhaul of systems in 2021
    - *Now ready with nearly 4MW for 2024, and on track for 7MW in 202*

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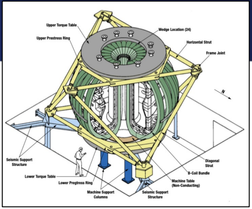
DIII-D Addressing Risks of an Aging Facility



- **Facility is operating well within established tolerances and lifetime, with no specific failures emerging or large downtimes in past 2 decades**
  - Many parts of system designed for higher field (not all)
    - *Significant design life margin in present operating conditions*
  - But ‘unknown-unknowns’ always a concern with an aging facility
- **System-wide assessment made to identify risk and mitigations**
  - Pre-emptively replace components that could lead to larger failures (e.g. SCRs, flex straps)
  - Put in place monitoring systems to check for potentially developing issues ← no concerns yet (electrical connection, anti-torque structure, coil leads, water temperatures)
  - Significant refurbishments possible, if they show signs of upcoming failure (e.g. joints)
- **Replace key systems that could lead to significant outages:**
  - Replaced cryoplant liquefier, failed I coils, MG2 cooling. Could replace compressor.
  - Upgrade investments would overhaul power systems and cooling as more power provided

DIII-D continues to run reliably, delivering high levels of operation at full performance, frequent upgrades, and any problems fixed rapidly

We know the issues, what to look for, & have strong operational experience

DIII-D an Open User Facility with Shared Leadership Model

- **Three key decision-making scientific groups led collaboratively** (LLNL, ORNL, U. Wisc, GA)
  - Determine experiments, talks, papers, hardware and diagnostic priorities
  - 21 topical areas led by universities, Nat Labs & GA
    - *Developmental leadership opportunities*
- **Collaborative development of strategy**
  - Research plans, run time priorities, facility goals
- **Oversight by independent representative bodies**
  - **Overall Approach:** new User Board represents all institutions and PIs
  - **Long Range Research Strategy:** International Program Advisory Committee
  - **Near Term Priorities:** Research Council representative of user institutions

Research lines & projects determined with DOE-FES under Cooperative Agreement

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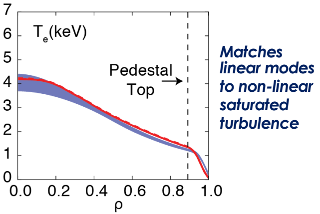
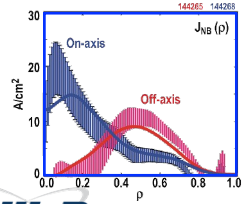
Supporting the national program, enabling ~100 institutions to pursue their priorities with established user model

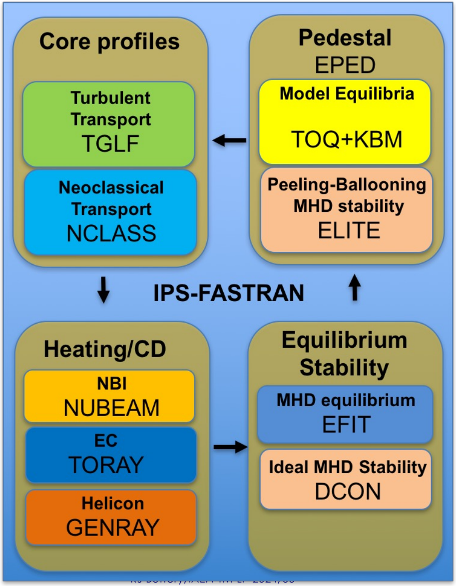
DIII-D-developed Integrated Physics Simulation Tools Utilized to Project Path To Pilot Plant (and DIII-D upgrades)

Turbulent Transport
Trapped Gyro-Landau Fluid (TGLF)

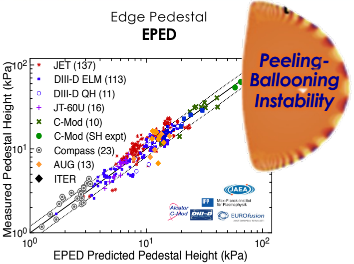


Off-axis Current Drive
NUBEAM

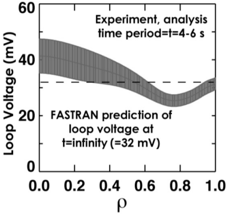




Edge Pedestal
EPED



Equilibrium/Loop Voltage
EFIT



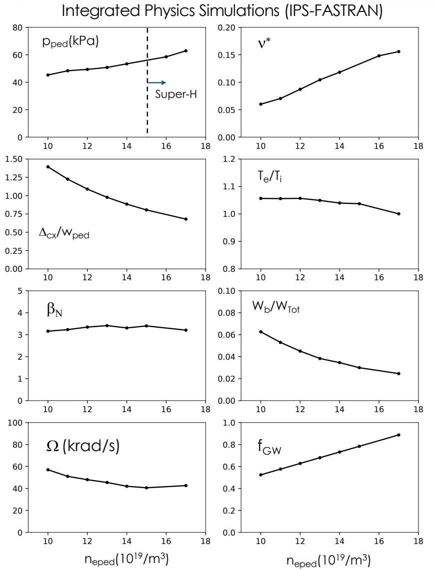
[Park Comp Phys Com 2017]

Integrated Simulation Example Point on ITEP Mission Based on 'Ready Now' Hardware

- **Based on 'ready to initiate' technology**
  - 14MW ECH: ITER& Thales gyrotrons, outside launch
    - *12 lines 3rd harm 170GHz, 8 lines 2nd harm 137GHz cutoff 17E19*
  - 20MW beams. Present field.
- **Combined key performance and opacity qualities for integrated solution exploration**
  - Neutral pedestal penetration a fraction of pedestal width
  - Low collisionality matching 'CAT' FPP
  - Thermalized low rotation core with $T_e \sim T_i$
    - *Trade-offs possible in density, q_{95}, β, etc.*

Higher power, top launch, LHCD, helicon or higher field would go further or cost less (but not assumed)

With ECH upgrade, DIII-D in right zone to resolve core-edge FPP solutions



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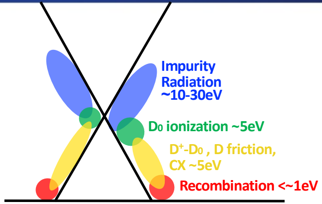
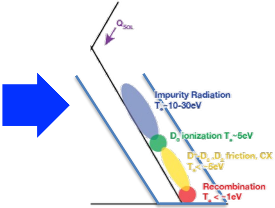
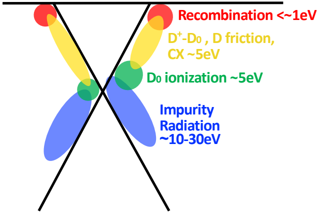


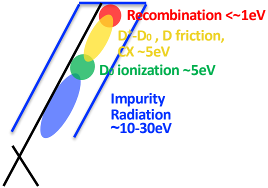
Impurity
Radiation
~10-30eV
D0 ionization ~5eV
D+-D0 , D friction,
CX ~5eV
Recombination <~1eV



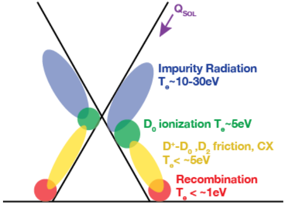
QSOL
Impurity Radiation
Te~10-30eV
D0 ionization Te~5eV
D+-D0 ,D2 friction, CX
Te< ~5eV
Recombination
Te < ~1eV



Recombination <~1eV
D+-D0 , D friction,
CX ~5eV
D0 ionization ~5eV
Impurity
Radiation
~10-30eV



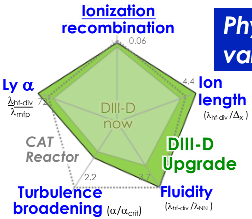
Recombination <~1eV
D+-D0 , D friction,
CX ~5eV
D0 ionization ~5eV
Impurity
Radiation
~10-30eV



QSOL
Impurity Radiation
Te~10-30eV
D0 ionization Te~5eV
D+-D0 ,D2 friction, CX
Te< ~5eV
Recombination
Te < ~1eV

Details of Divertor Parameters

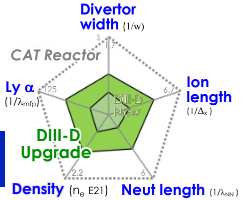
- **Performance rise places DIII-D in the relevant regimes for key divertor processes**
  - Assess key physical mechanisms (e.g. *broadening*)
  - x3 in dimensional space → test over significant range



Physics variables

Key Divertor & Core-Edge Physics:

- **Lyman α:** photon trapping
- **Ionization length:** neutrals paths compared to divertor structures
- **Recombination/ionization:** governs proportion of neutrals at the edge
- **Fluidity:** divertor becomes more fluid
- **Turbulence broadening:** radial gradients drive turbulence in SOL



Dimensional testing

Relevant regimes to explore FPP divertor physics

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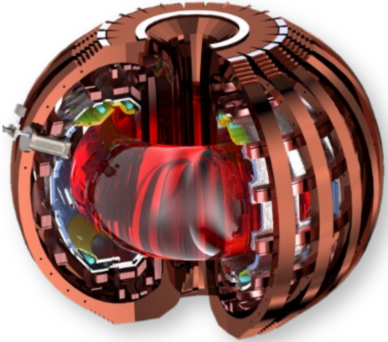
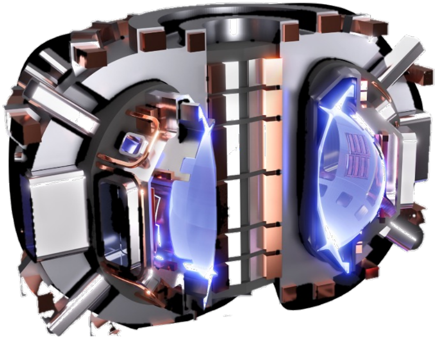
Working Collaboratively, We Can Close the Key Gaps to an FPP

DIII-D



- *Flexibility to pioneer solutions*
- *Resolve science to project them*

SPARC



- *Test behavior close to FPP parameters*
- *Proof of high field tokamak approach*

Collaborative engagement a key feature of DIII-D program

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ADDITIONAL REFERENCE SLIDEs:

Additional technical data