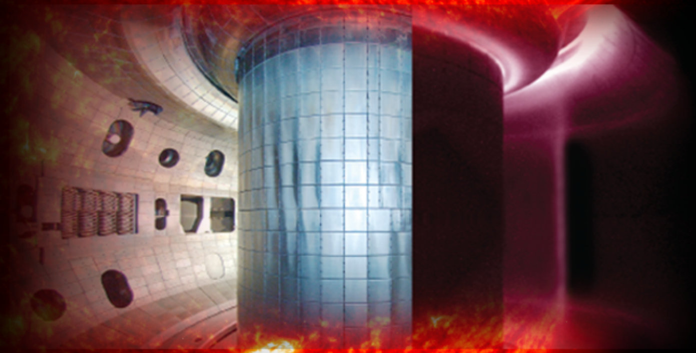
Sustained High Power Density (SHPD) Facility: Update on Community Initiative in San Diego

presented by

RJ Buttery

with thanks to DIII-D colleagues on our SHPD team



for the

PPPL Seminar

April 1st 2019

GENERAL ATOMICS

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We are here to consult with our PPPL & NSXT-U colleagues

- **Invite participation in this SHPD analysis effort**
  - Directly join discussions and analysis projects
  - Initiate a group on your favorite topic, calculate metrics, draw from equilibria being generated
- **Invite ideas and good points for SHPD analysis**
  - What are we missing? What analyses can be done? What metrics can we use?
- **Identify complementary analysis toward SHPD and wider US roadmap**
  - Provide richer data set to inform community discussions
- **Understand points of view, start to find a viable path**

- **Feel free to join our discussion and see what we are up to.**
  All material on our web at: https://diii-d.gat.com/diii-d/SHPD

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What does a Next Step Facility Look Like?

The U.S. program is embarking on a path to a fusion pilot plant

An intermediate facility has been proposed by NAS panel as part of a wider program to close the gap on the pilot

- What are its physics missions?
- What are its parameters?

We are undertaking an initiative amongst DIII-D program participants (& others interested) to understand how parameters & feature of the facility enable physics missions toward pilot

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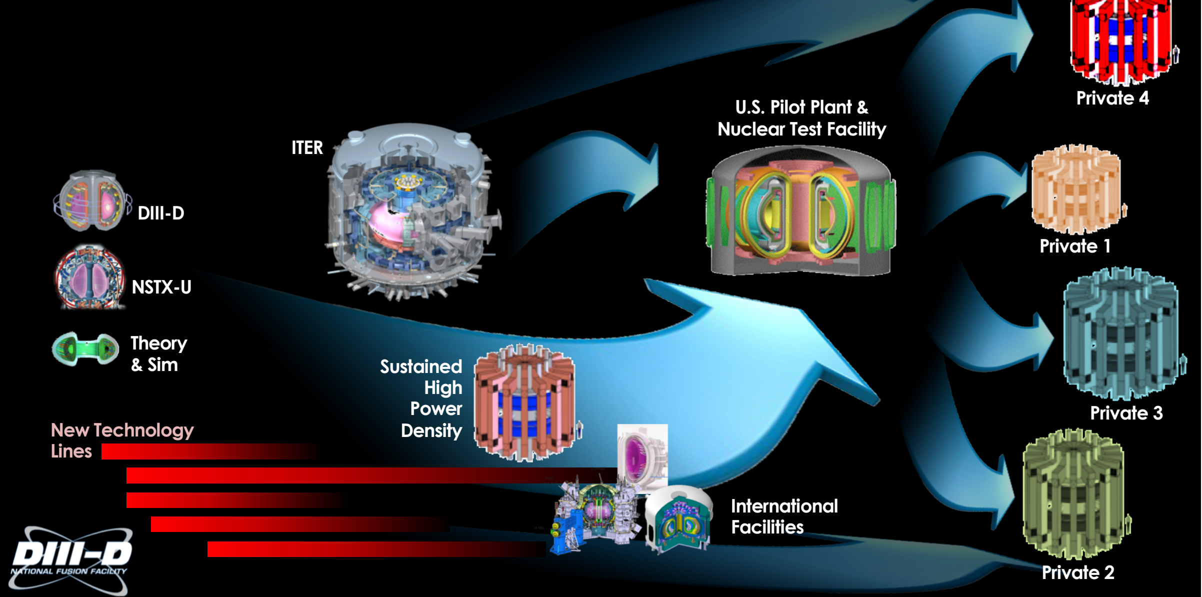
U.S. & NAS Context to Private Fusion



What this Initiative is Not

- It is <u>not</u> an attempt to determine the mission of the next step U.S. facility
  - We see choice of mission as a higher level, community-wide question & discussion
- Similarly we do not expect to fix parameters to a particular design point
  - We aim to explore a wide parameter space and design choices to inform this
- It is not an attempt to develop a DIII-D program position on SHPD
  - *DOE has merely granted that such community work can be charged to such grants*
- It is not an attempt to see what can be built in Sorrento Valley
  - *We neither rule this in or out – its important to simply understand needs from a physics mission & U.S. strategic perspective*

It is hoped this effort will lead to a white paper, understanding and capabilities that help assess how physics missions trade off with device parameters and features

Work in this effort might also be used as the basis for <u>other advocacy</u> white papers by participants in this effort or by other colleagues

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Goal of Our Present SHPD Initiative

To develop an understanding of how facility parameters tie to physics missions of an SHPD

- *to inform community discussion on what is possible / combinable as a realistic U.S. path*

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1. Physics Needs

Why an SHPD is Needed

- **There is a strong and exciting mission for DIII-D and NSTX-U**
  - Facilities being upgraded to address critical plasma physics, develop new techniques & technologies, find candidate solutions for fusion energy
- **But there remain critical plasma physics questions that go beyond what the present generation of facilities can address**
  - To sustain configuration & power handling beyond what ITER can do
  - To access reactor like physics regimes & parameters – remove extrapolation gap
  - To integrate parts of the solution that trade off against each other
- **To move to a pilot plant D-T reactor, we need to have robust plasma solutions that we can be confident work reliably**
  - Expensive and beyond scope for pilot to do all this D-D level work
- **NAS notes needs for:** "increase fusion power density", "continuous high-pressure compact plasma", "increased values of normalized size, $RB/T^{0.5}$", "larger magnetic field… and… power", **"A follow-on national facility… provide new advanced tokamak studies closer to burning plasma conditions"** "high power density research facility", "high field", "high β_N", "optimal shaping"

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Its vital for us to start on a next step facility ASAP

Understanding an Integrated Solution Requires Improved Performance

- **Core and divertor physics are governed by different parameters:**

core ⇔ **Pedestal** —— **Separatrix** —— **Divertor** ⇔ $q_{||}$

Collisionality, $\nu^*_{ped} \sim n^3_{ped}/P^2_{ped}$

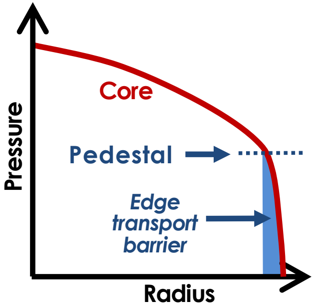
$\beta_{Nped} \sim Shaping. f_{GW}$

Pedestal physics ↑

n_{sep}

Closure & neutrals ↑

n_{div}



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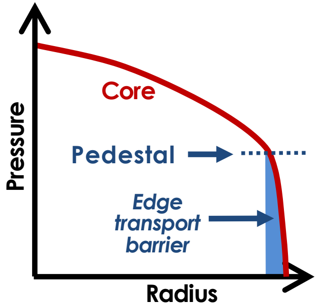
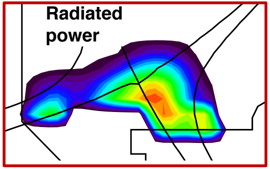
Pedestal physics (↑)

n_{sep}

Closure & neutrals (↑)

n_{div} (↓)





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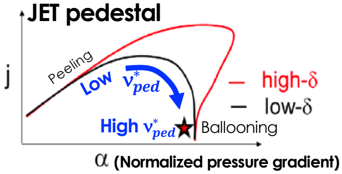
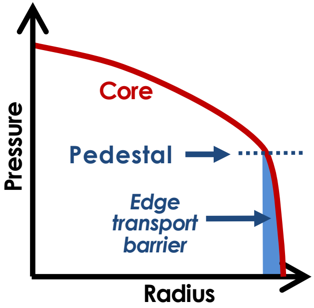
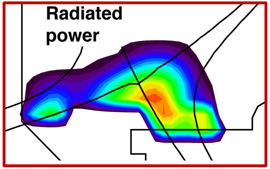


[Maggi, NF2015]





Understanding an Integrated Solution Requires Improved Performance

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Collisionality, $\nu^{*}_{ped} \sim n^{3}_{ped}/P^{2}_{ped}$

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Pedestal physics (arrow up, between Pedestal and Separatrix)

n_{sep}

Closure & neutrals (arrow up, between Separatrix and Divertor)

n_{div}

- **Core-edge solution depends on progress in each region**
  - Improved **pedestal (n_{sep}:n_{ped})** and **divertor (n_{div}:n_{sep})** solutions play a key role

Super H mode?
Shaping, a/r, …

Slots, Snowflake
Super-X, SAS…

Understanding an Integrated Solution Requires Improved Performance

- **Core and divertor physics are governed by different parameters:**

core ⟺ **Pedestal** ——— **Separatrix** ——— **Divertor** ⟺ $q_{||}$

Collisionality, $\nu^*_{ped} \sim n^3_{ped}/P^2_{ped}$

$\beta_{Nped} \sim Shaping. f_{GW}$

Pedestal physics

n_{sep}

Closure & neutrals

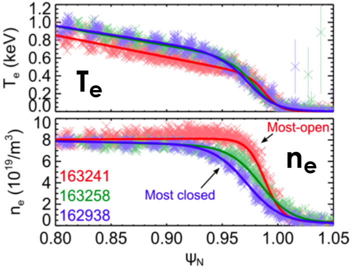
n_{div}

- Core-edge solution depen
  - Improved **pedestal (n_{sep}:n**

➡ ***High density an important governing parameter***

➡ ***Higher field needed for high density & low ν^*_{ped}***

Pedestal vs divertor closure



- **Strong interaction between these regions**
  - **Depends on opacity**

May Other Examples of Reactor Needs that Motivate Plasma Research Beyond Present Generation of Tokamaks

- ✓**Understanding pedestal projection** (high pedestal opacity low ν^*)
  - Identify density limit
- **High heat flux divertor solution – with high neutral & γ opacity**
- **High bootstrap fraction core to develop predominantly self-driven solutions**
  - High thermal fraction for relevant EP physics & RWM stabilization physics
  - High ion-electron collisionality & low rotation & ν^* for core transport projection
- **Advanced RF schemes with high efficiency and survivability**
- **Understanding wall dynamic**
- **Simply reducing the extrapolation gap**

ITER provides key complementary data & validations, but steady state reactor solutions poses additional challenges

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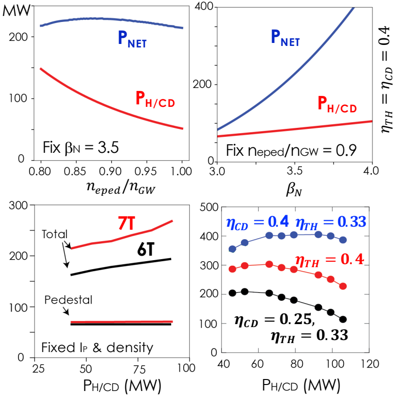
Full Physics Simulations Show Key Levering Parameters to Explore

- **Projects H_{98}~1.3-1.5 leading to solutions at 4m 6-7T**
  - Converged self-consistent fully non-inductive plasmas
- **Trade-offs & optimizations:**
  - **Shaping** is key: Q~shaping^2
  - **Higher density** reduces H&CD needs
  - **Higher β_N** raises fusion performance
  - **Higher B_T** improves confinement
  - **Higher efficiencies** raise $P_{net\text{-}electric}$
  - **Dissipative divertor** vs core radiation
  - **Transients** must be controlled

➢ ***Important to develop and validate these solutions***

FASTRAN 4m 7T fully non-inductive plasmas stationary TGLF-EPED-CD-EFIT solutions



Improved physics & technology reduces required scale, fusion power, fluxes and cost

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1. Physics Needs
2. Approach of our Initiative

SHPD Initiative: Approach and Boundary Conditions

- **Identify range of potential missions (NAS, Wade FPA, reactor design needs, etc.)**
- **Identify metrics that characterize access to those missions**
- **Develop an equilibrium parameter space and facility options to span the missions**
  - Simulation and other analysis efforts
  - Simulation: Initial 1D about a center point, then some guided
- **Calculate metrics to understand how physics access changes over this range**
  - Interpret under various physics themes
  - Write **neutral white paper** to inform community

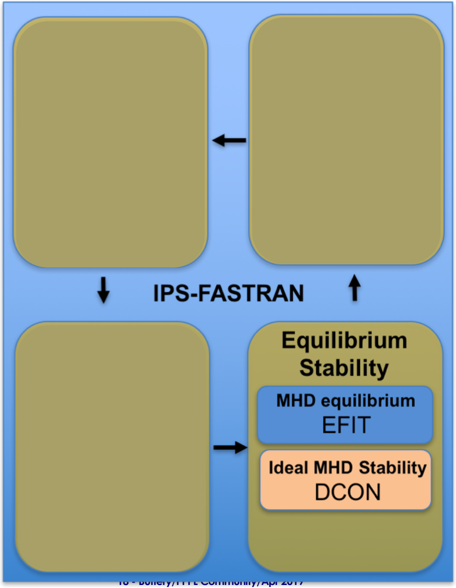
There may also be position white papers on various topics

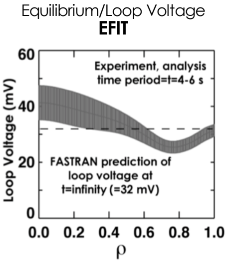
- *Not centrally coordinated, but subsets of colleagues may cluster to develop*

Boundary conditions ← not hard ones but, guided by NAS

- Something that can be started soon. Manned access as science tool. Not nuclear?
- Example trade offs to discuss: short/long pulse, hot/cold metal/C wall, …

FASTRAN Integrated Simulation Suite Provides Tool To Validate Physics Models & Project Performance





[Park Comp Phys Com 2017]

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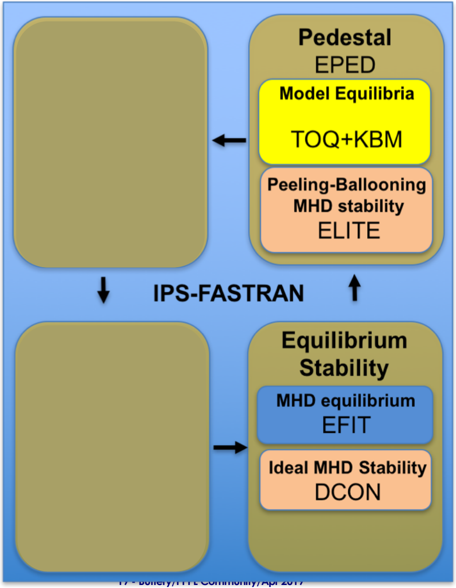
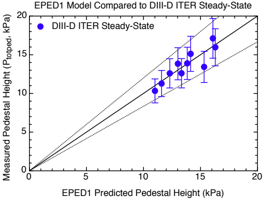
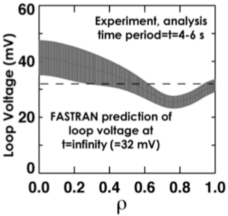


Edge Pedestal
EPED



Equilibrium/Loop Voltage
EFIT



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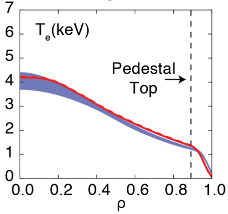
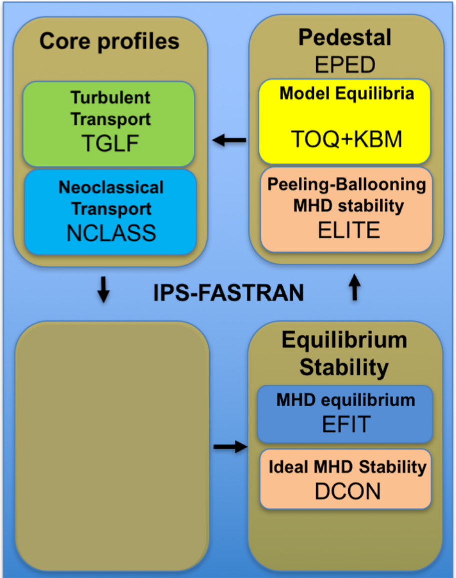
FASTRAN Integrated Simulation Suite Provides Tool To Validate Physics Models & Project Performance

Turbulent Transport
TGLF





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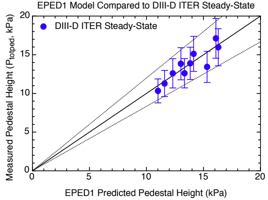

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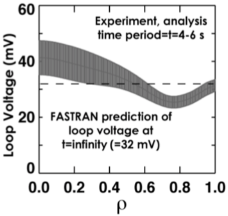

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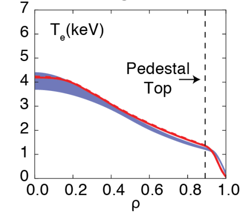
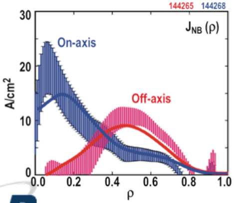
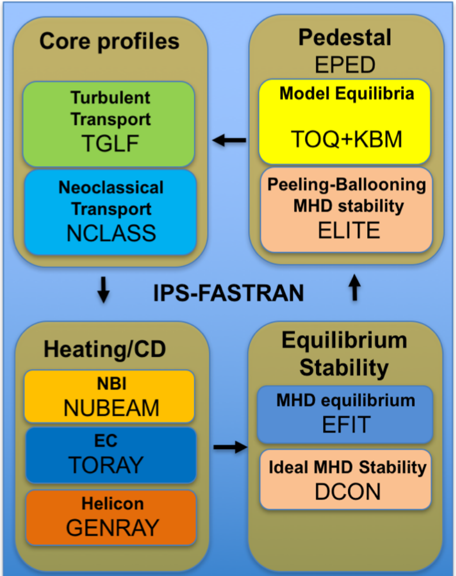
TGLF



Off-axis Current Drive
NUBEAM





Edge Pedestal
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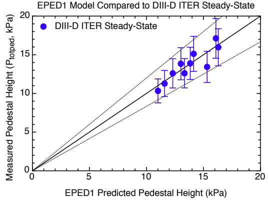

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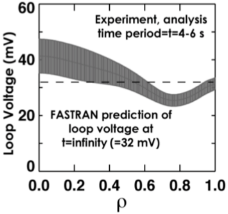

[Park Comp Phys Com 2017]

Initial List of Aspects to Consider

- **Identify representative mission set & metrics (see next)**
- **Scope out Equilibrium space with integrated physics model solutions**
  - Serves as basis to calculate range of other parameters
  - Shaping: extend codes to calculate & identify benefits
- **Consider H&CD options**
- **Shaping: extend codes to calculate & identify benefits**
- **Divertor mission, flexibility, metrics**
- **Materials/PMI – mission, choice, needs, metrics**
- **Activation and manned access**
- **Coil options – viability of shape & power needs**
- **More…?**

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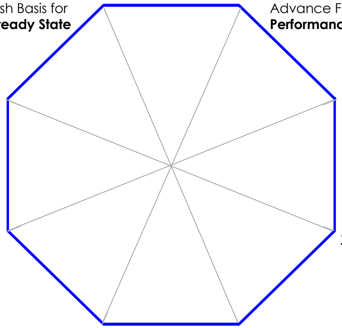
Various subtopic discussions & meetings implied or invited

Missions To Prepare For a Pilot Plant

- **Various sources and orthogonal sets** (E.g. →)



Wade, FPA,18

Key Concepts

- **Facility close physics gaps on pilot plant – develop robust solutions**
- **Alongside existing technology program & international facilities**

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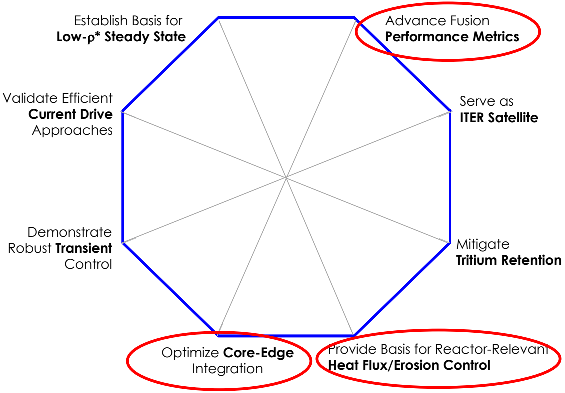
Missions To Prepare For a Pilot Plant

- **Various sources and orthogonal sets** (E.g. →)
- **Some U.S. strengths and distinctive opportunities not addressed elsewhere**



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Missions To Prepare For a Pilot Plant

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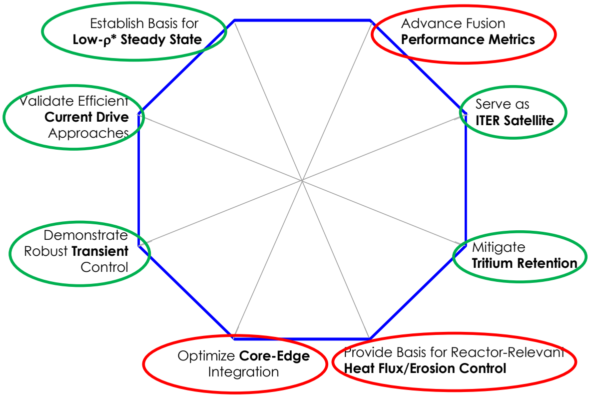
- **Some U.S. strengths and distinctive opportunities not addressed elsewhere**
  - **Some requirements to incorporate into solution / need to be studied**



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Missions To Prepare For a Pilot Plant

- **Various sources and orthogonal sets** (E.g. →)
- **Some U.S. strengths and distinctive opportunities not addressed elsewhere**
  - Some requirements to incorporate into solution / need to be studied
- **Break down to specific physics & metrics…**

Key Concepts

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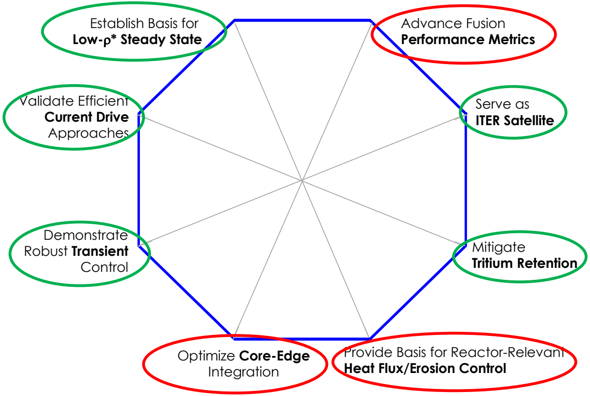

Developing a Set of Mission Metrics (in progress)

Mission	Metrics	Method
Core edge	Ped-opacity, ν^*, n_{ped}, f_{GW}, P_{ped}, δ, κ, ioniz depth. Radiation species: Rpeak, Wall Z	Formulae from simulations
Core transport	T_e/T_i, ν_{ei}, ρ^*, τ_E, Ω'	From simulations
High BS solution	f_{BS}, β_N, $\beta_{Nthermal}$, q_{95}, R/a, τ_{pulse}/τ_R, β_{Nwall}, $\beta_{Nnowall}$	From simulations
Fast ions	f_{EP}, v_{EP}/v_{alfven}, tools to accelerate ions	From simulations, plus some flexibility statements
Current drive	Te, B, flexibility, …?	
Divertor	P/R, PB/R, $q_{\|\|}$, Ly α, div opacity, radial transport & heat flux width, closure, detachment	TBD
PMI	Material, temperature, retention? Pulse length vs deposition time, heat flux	TBD
Transients	Ip (REs), B_{resped}, …? Actuators?	TBD

What missions, metrics & methods should be considered?

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Some Clear Issues of Debate or Trade off Will Need to be Discussed

- **Long or short pulse?**
  - Long pulse tests PMI solutions, but will compromise manned access & so flexibility
- **How high in field?**
  - Improvements in fusion relevant metrics vs device activation & access
- **Tritium capability?**
- **Normal or hot walls? Wall material?**
- **HTS or copper?**
- **H&CD, internal/external 3D coils, etc…**

We see these as issues for broader community discussion to converge SHPD mission in wider roadmap

We hope our analysis can inform the degree of mission possible with various options

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Initial Parameter Range to Explore

Parameter	Range	Rationale
Paux	$1.5P_{LH} \rightarrow$ 100MW	Good H mode to budget ceiling
f_{BS}	50 to 100%	Explore self-driven solutions (adjust I_P)
BT	4 – 7 T	High density & opacities with low ν*
f_{pedGW}	60 – 120%	Core-ped-div integration
Elongation	To VS limit	Maximize controllable performance
Triangularity	0.4 to 0.9	See where benefits saturate & assess divertor challenge
Aspect ratio	2.2 – 4 (fix a^2R)	Bootstrap, EC access (code limits at 2.2)
(Fix size for now, consider R=1.4, 2m later at fixed R/a)		

High performance & fully NI, high BS

Based on earlier group wide metrics discussion and focusing conversation of Buttery, Petty, Snyder, Solomon

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High performance & fully NI, high BS (Paux, f_{BS})

Optimizations
High power, pressure
High bootstrap
High density
Divertor flux / PB/R
Lower field ($)
Lower H&CD power ($)
Size ($)

- **Make pedestal NN set → TGLF scaling tool… FASTRAN**
- **Start in center & expand in 1d**
  - Then pursue multidimensional exploration with goal to optimize key parameters →

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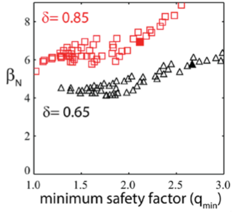
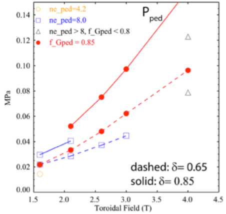
Some Scan Points Exist from 2018 NAS Exercise

- **Preliminary 4T 1.7m simulations found high bootstrap solutions:**
  - First tests not ideal: T_e>T_i, high ν∗, needs lots of helicon

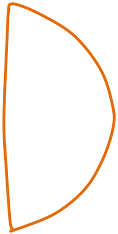
- **Equilibria studies identified high stability and.... ITER like pedestal P**



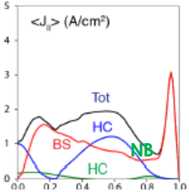


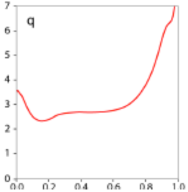
- **Loarte formula showed opaque pedestal at 4T**

Work needed to explore space and optimize

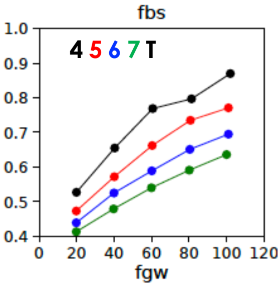


B_T (T)	4
I_p (MA)	3.25 (2.6*)
q_{95}	6.3
NB (MW) @ 120 keV, co	30
EC (MW) @ 220 GHz, 2nd	5
Helicon (MW) @ 700 Mhz	30
n_e ($10^{19}/m^3$)	19.4
β_N	3.5
f_{NI}	1
f_{BS}	0.63
$\langle n_e \rangle / n_{GW}$	0.71
W (MJ)	9.9
W_{beam}/W	0.06
H_{98}	1.18
$p_0/\langle p \rangle$	2.33





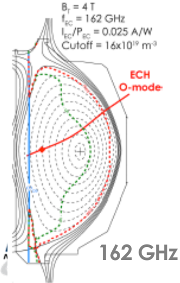
Progress So Far – We are at Early Stages



✓ **Agreed some preliminary missions to metrify**

✓ **Set ranges to explore (extendable!)**

- **Scoping tool embarking on multi-dimensional scan**
  - Single point TGLF + EPED-nn. Start in middle and work out.
- **FASTRAN work just getting started ➔**
  - Simplified assumptions to start: fixed J profile & density peaking (will do self-consistently later)
    - Initial scans in B, I_P, n, P_H ➔ Encouraging trends with density
      - *But much else to explore & directions to push*

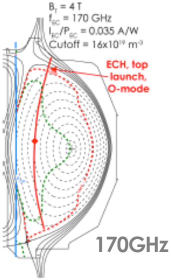


🡐H&CD analysis identifies promise options for ECH➔

← 4T O mode efficient off axis CD (25A/kW) with 162GHz unit

4T top launch 170GHz as efficient at helicon CD! (35A/kW) →

Higher frequency gyrotrons needed for higher field & on axis (up to 203GHz available, Toshiba)



All Colleagues Welcome to Join or Tap Into Effort on SHPD

We are just starting equilibria scoping to provide basis for metrics calculation and physics assessments

- **Consider what is needed in your field – set up your own discussion group**
  - Discuss with colleagues
  - Work out what physics missions, tools
  - Map onto parameter & capability range we are exploring
  - Feed back requirements into overall effort, so we understand trade-offs.
- **Join our discussions and contribute to debate with good points**
- **Use simulations being developed as a basis for further**
- **All material on web at: https://diii-d.gat.com/diii-d/SHPD**
  - Series of meeting on various themes over coming weeks

Or chat to existing participant:

Buttery, Ferron, Smith, McClenaghan, Guo, Snyder, Groebner, Park, Garofalo, Leuer, Holcomb, Paz-Soldan, VanZeeland, Wu, Osborne, Grierson, Weisberg, Solomon, Wade, Guttenfelder, Meneghini, Abrams, Leonard , Petty

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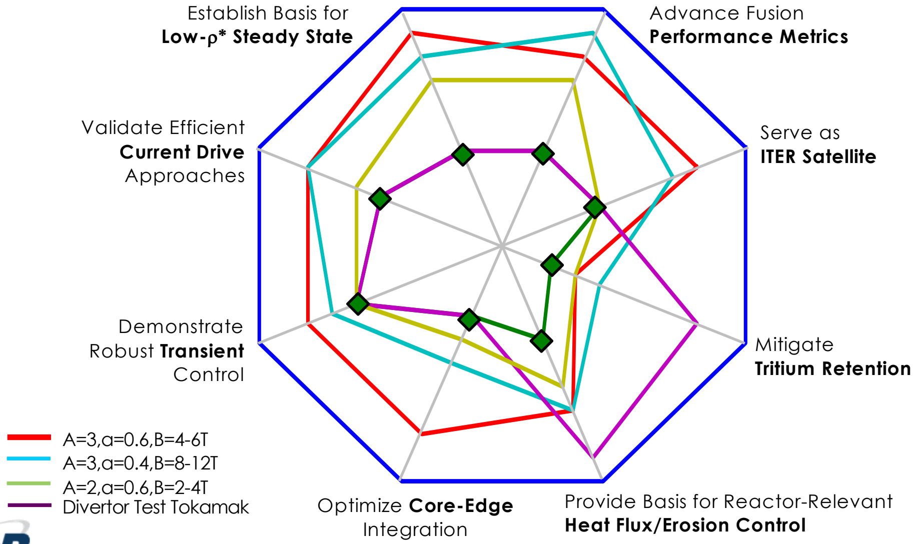
We are here to consult with our PPPL & NSXT-U colleagues

- **Invite participation in this SHPD analysis effort**
  - Directly join discussions and analysis projects
  - Initiate a group on your favorite topic, calculate metrics, draw from equilibria being generated
- **Invite ideas and good points for SHPD analysis**
  - What are we missing? What analyses can be done? What metrics can we use?
- **Identify complementary analysis toward SHPD and wider US roadmap**
  - Provide richer data set to inform community discussions
- **Understand points of view, start to find a viable path**

- **Feel free to join our discussion and see what we are up to**
  All material on our web at: https://diii-d.gat.com/diii-d/SHPD

Preliminary Assessment Suggests Largest Mission Breadth Provided by Modest Size, High Field Facility



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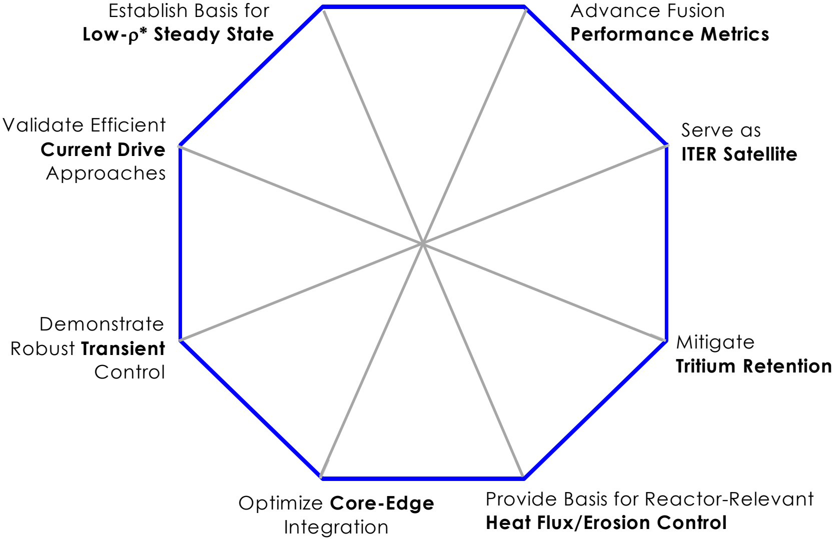
Preliminary Assessment Suggests Largest Mission Breadth Provided by Modest Size, High Field Facility



U.S. Should Innovate to Enable *Low Capital Cost* Net Electric Pilot Plant

- **Key challenges for self-sustaining reactor:**
  - **Breeding** – **Nuclear materials** – **Net electricity**
- **Should address these in a compact 'pilot plant' test facility**
  - Combine missions to remove a generation → more compelling
  - Low capital cost so affordable to go forward
  - Do not need to be at large, low-COE scale to prove approach for that scale

Power plants	ACT1	SlimCS	Korea DEMO	EU DEMO
R m	6.3	5.5	6.8	7.9
I_P MA	11	17	17	14
Pfus GW	1.8	3	2.9	2
Pnet GW	1	1	0.5	0.5

- **U.S. proposals for ARC, Compact-AT and ST-pilot**
  - *All at scale 100-200MWe, R~3-4m, A~2-3 & benefit from high temperature superconductors*
- **A pilot plant would lever U.S. ITER participation**
- **But requires additional 'enabling research'**
  - To raise fusion performance & provide required technologies

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Distinctive window of opportunity for U.S.

Research Required in Seven Areas to Enable Low Capital Cost Pilot Plant

1. **ITER participation**
   – Validated physics models & reactor knowhow
2. **Stable high performance fully noninductive core**
3. **Dissipative Divertor**
4. **Efficient current drive**
5. **Reactor materials**
6. **Demountable high temp superconducting magnets**
7. **Engineering design & breeding concepts**

Tokamak research enables ITER & pilot plant missions (items 1–4)

- ***DIII-D provides key opportunity to advance ITER and pilot plant research agendas***

Work on engineering & technologies to advance pilot plant approach (items 5–7)

These 7 missions provide opportunities for breakthroughs in understanding & performance that transform fusion prospects

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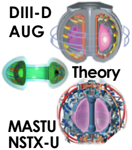
Integrated Facilities Roadmap and Mission Elements

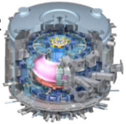
I4 **EAST, C-P:** Long pulse wall evolution studies, wear, equilibration, metal and flowing walls,



DIII-D
AUG
Theory
MASTU
NSTX-U

Underlying physics
Steady state. Novel CD
Transients. Disruption mitigation
Divertor science, closure
& magnetic geometry
Sample/tile tokamak tests
Metal walls, liquid walls

ITER

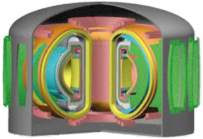


Nuclear engineering & licensing
Physics 'size' scalings. DMS projection
High power W divertor partial detachment
Opaque pedestal. Radiative optimization
Disruption avoidance
Self-heating & α physics

ITER TBM program

Breeder design
Low dpa tests
...

Compact U.S. Pilot Plant
Integrated Nuclear Test Facility



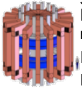
Net electric → **Nuclear testing** → **Close Fuel Cycle**

Performance
Licensing
Heat extraction
Divertor confirmation

Nuclear Optimization
Breeding technology
Component testing
(Wall/breeder change outs)

Simulation Nonlinear evolutions

Sustained High Power Density



I4,8

Steady state core: CD projection,
high bootstrap & thermal fractions,
reactor pedestal & transport
High flux divertor, hot walls: recycling
particle control, core compatibility
Component tests

PMI
Magnum PSI
PISCES
MPEX

Nuc
TPE T ret
Hipher

FPNS 14MeV
AFNS, Phoenix
spallation, GDT
10dpa 50cm³

Low dpa tests:
structure, blankets
embrittle, swel, trap

Compact VNS
GDT ST etc

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Nuclear components
High dpa 14MeV evoln

ENG
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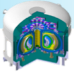
Breeding concepts
Structural elements (joints, etc.)
Stress analysis

Liquid concepts
T extraction

Pilot Full Design



CFETR
Nuclear materials
Component tests

Advanced manufacturing

HTS Joints Coils SPARC

Larger path
EU-DEMO

Config QAX Big QAX

Integrated Facilities Roadmap and Mission Elements

20s | **30s** | **40s** | **50s**

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DIII-D
AUG
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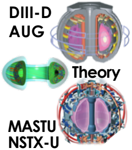

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Divertor science, closure
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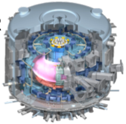

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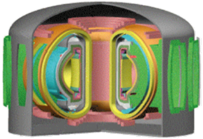

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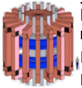

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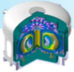
Pilot Full Design



CFETR
Nuclear materials
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Advanced manufacturing

HTS Joints Coils SPARC

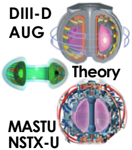
Larger path
EU-DEMO

Config QAX Big QAX

Divertor, Wall & Materials Development: Facilities Role and Time Line

20s | 30s | 40s | 50s

[14] **EAST, C-P:** Long pulse wall evolution studies, wear, equilibration, metal and flowing walls,



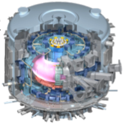
DIII-D
AUG
Theory
MASTU
NSTX-U

Divertor science
Closure
Magnetic geometry
Core mitigation

Sample/tile tokamak tests
Metal walls

Liquid metal tests
Solid-liquid

ITER



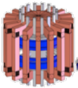
Nuclear engineering & licensing
High power tests w/ partial detachment
→ 'conventional' divertor physics scaling
W divertor behavior
Opaque pedestal

ITER TBM program
Breeder design
Low dpa tests
...

Simulation Advanced materials evolution

PMI
Magnum PSI
PISCES [16]
MPEX

Sustained High Power Density [14,8]



Steady state fusion core
High heat flux divertor
Relevant recycling
Impurity/particle control with hot metal walls
Component testing (D)
Core-edge compatibility

Nuc [17]
TPE T ret
Hipher

FPNS 14MeV
AFNS, Phoenix
spallation, GDT
10dpa 50cm³

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ENG [18]
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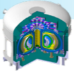
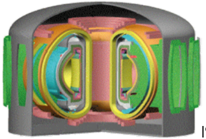


CFETR [19]
Nuclear materials
Component tests

Compact U.S. Pilot Plant
Integrated Nuclear Test Facility



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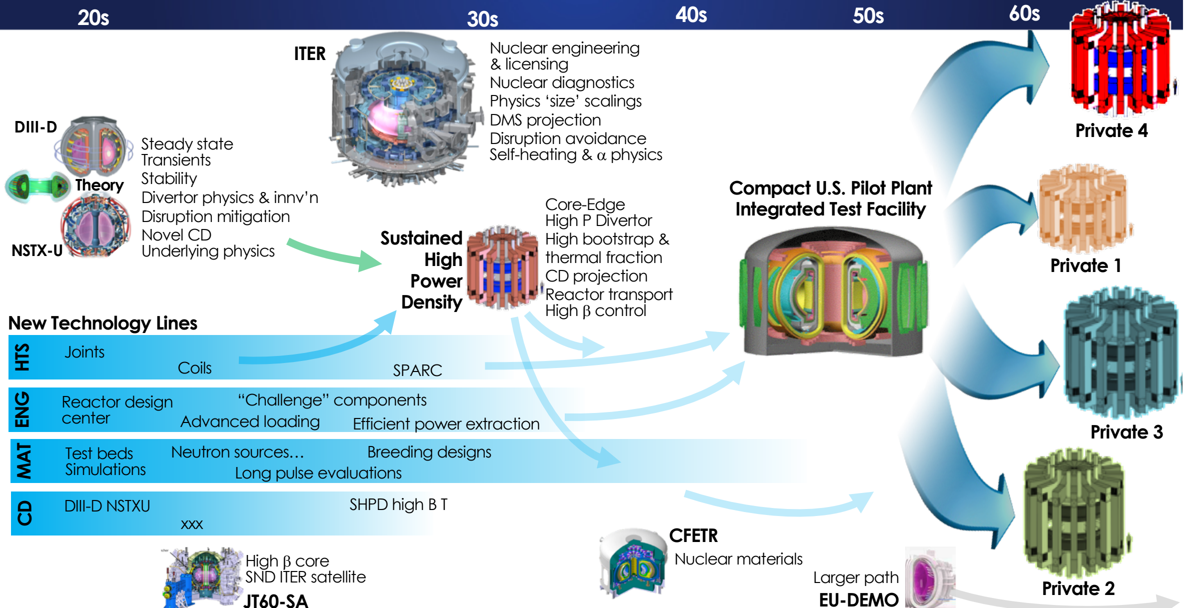
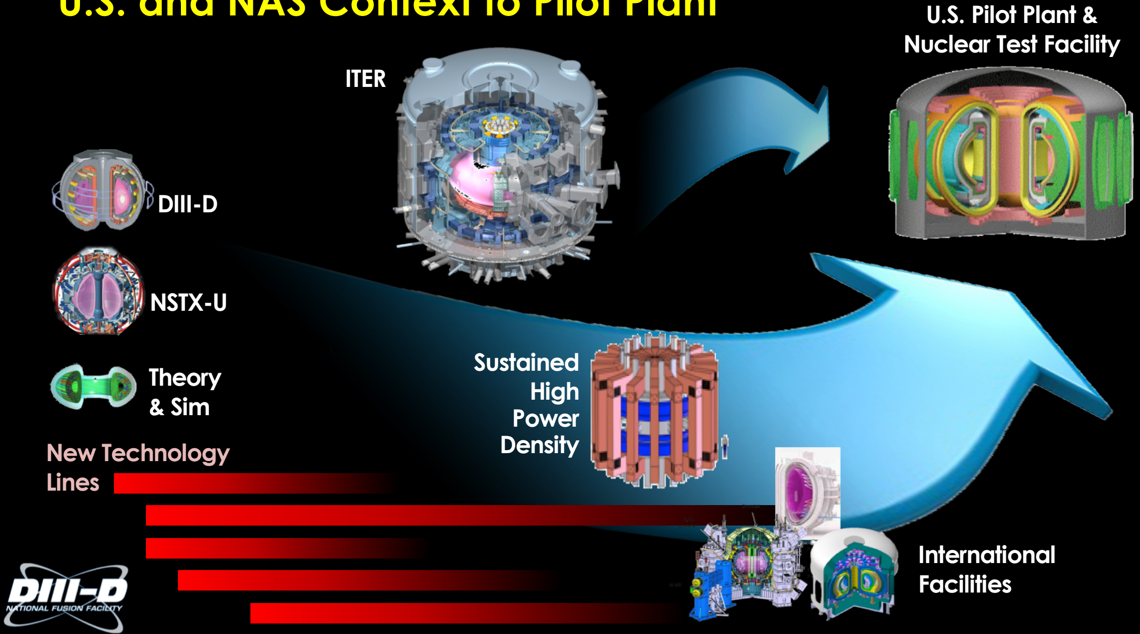
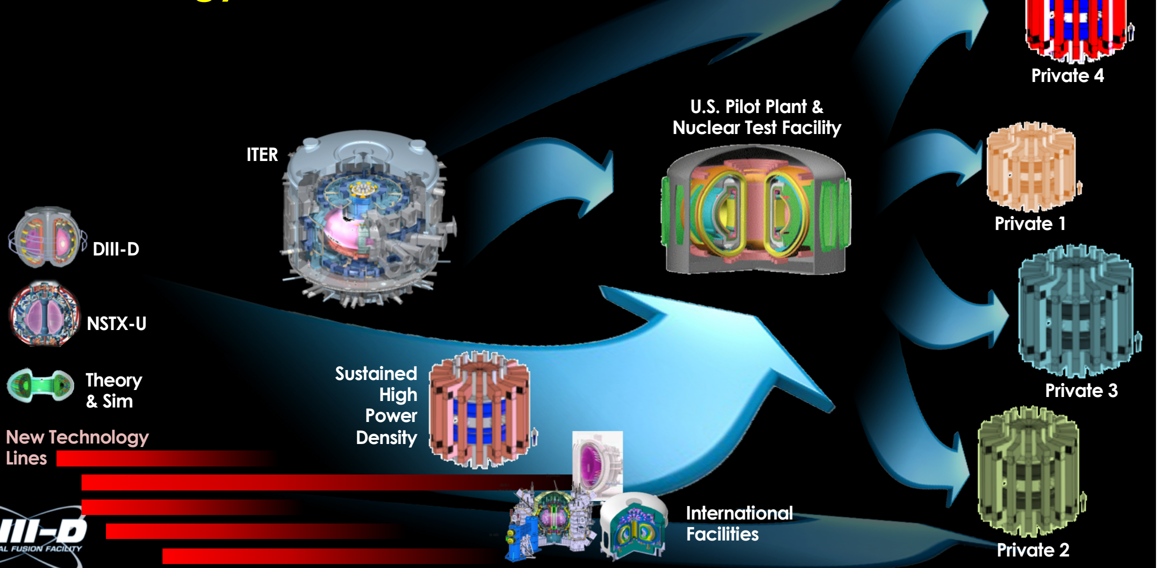
U.S. Roadmap to Private Fusion



U.S. and NAS Context to Pilot Plant



U.S. Strategy to Lead to Private Fusion



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