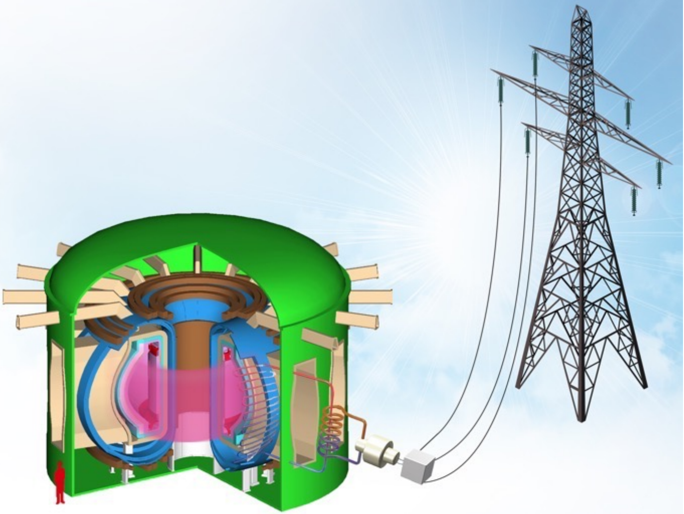
Applying Advanced Tokamak Principles to Enable a Compact Steady State Fusion Pilot Plant

by

RJ Buttery

with key contributions from

J.M. Park, J.T. McClenaghan, D. Weisberg, J. Canik, J. Ferron, A. Garofalo, C. Holcomb, P.B. Snyder



Presented at the

IAEA Long-Pulse Technical Meeting, Vienna

November 15th 2022

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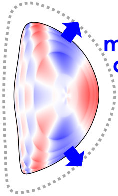
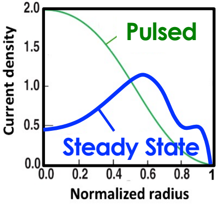
GENERAL ATOMICS

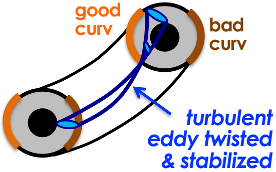
Advanced Tokamak Principles Enable Efficient Compact Fusion Power Plant Concepts

- **Shaping, broad profiles and high β improve transport and stability**
  - *High bootstrap fraction reduces need for expensive current drive*
  - *Lower current solutions with decreased loads, sustained noninductively*





$$I_{\text{steady state}} = \overset{\sim 0}{\cancel{I_{CS}}} + I_{\text{bootstrap}} + \overbrace{(I_{NBI} + I_{\text{waves}})}^{\text{expensive}}$$



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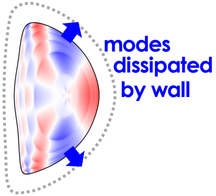

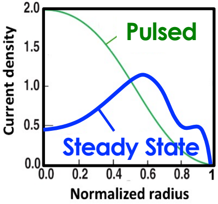

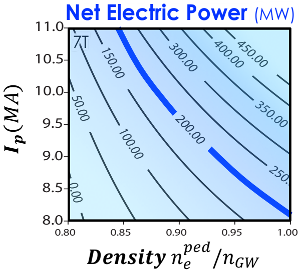

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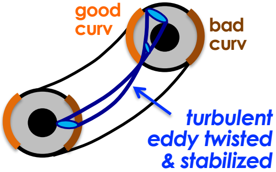
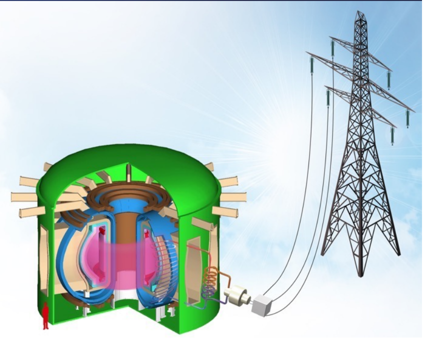


- **Integrated physics simulations project compact 200MW net electric solutions**

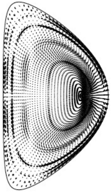
Talk Outline – Path to a Compact Fusion Pilot Plant

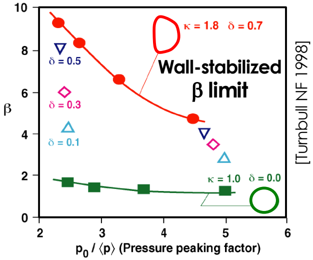
- **Principles of the steady state approach**
  - Shaping, broad profiles & high $\beta \rightarrow$ high bootstrap
  - Benefits to stability, transport, pedestal and fast ions
- **Pilot power plant projection**
  - Analytics, methodology, projections
- **Benefits and Research needs**



Advanced Tokamak Benefits from Synergy of Shaping and Broad Profiles at High β_N

- **Shaping raises ideal MHD limits**
  - Increases current carrying capacity
  - Extends eigen-structure into wall





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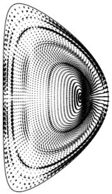

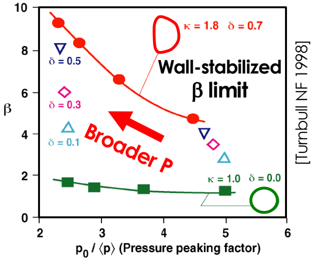

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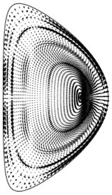

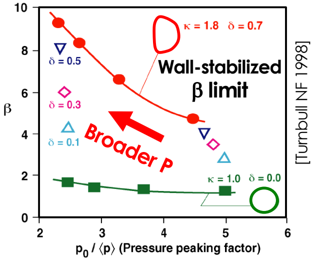

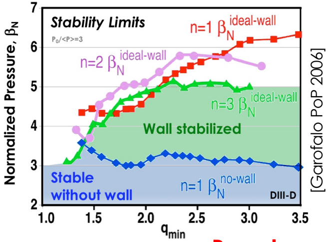

Broader current

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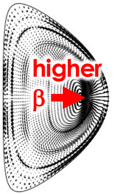

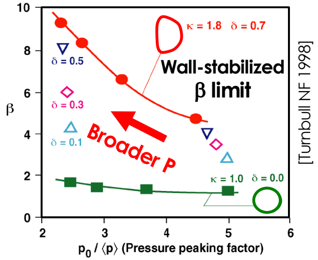

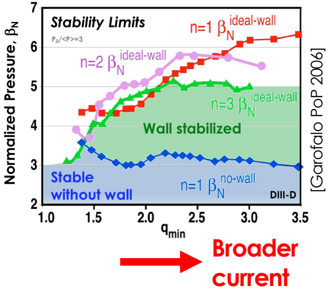

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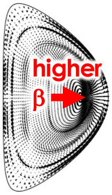
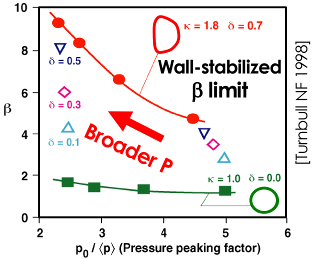
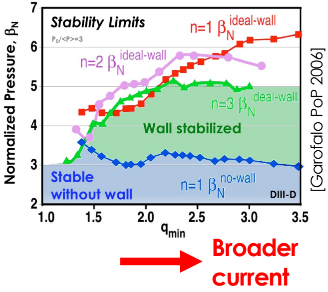
Effects combine to raise pressure in core by factor 5
- *Self-consistently generate bootstrap currents aligned with required profiles for stability*

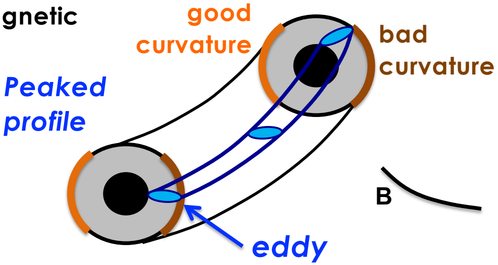






Broad Profiles Also Improve Energy Confinement

- **Particle drifts interact with low frequency electromagnetic waves causing instabilities and turbulence**
- **With peaked profiles, field lines align on bad curvature side → eddies grow radially**



[T. M. Antonsen, PoP1996]

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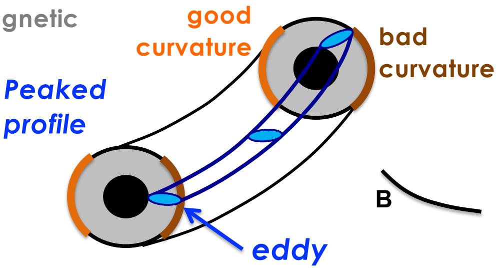

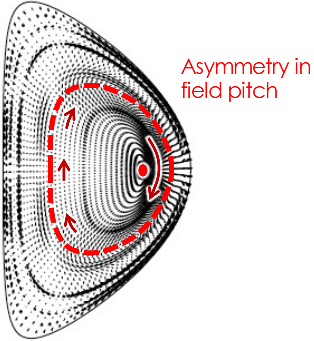

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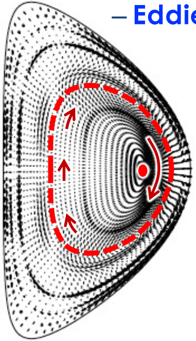

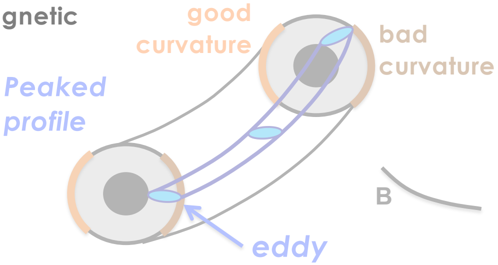

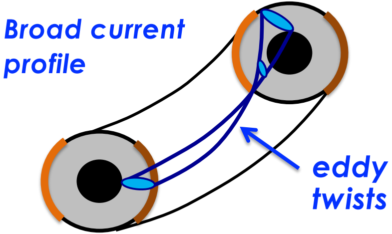

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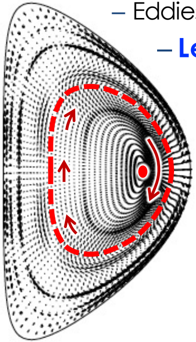

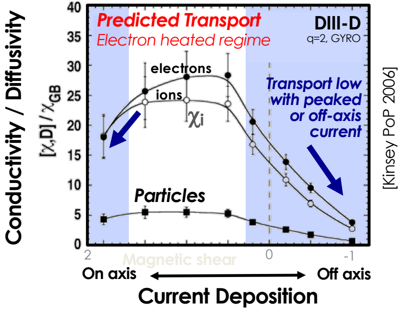

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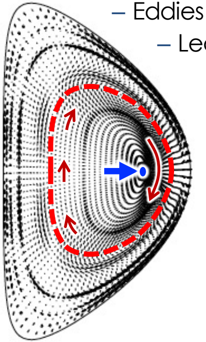
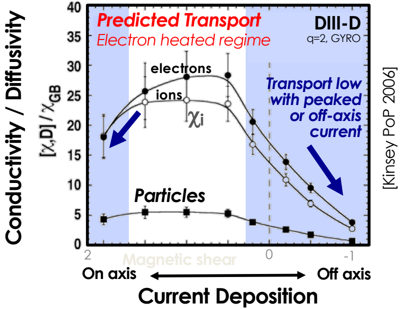
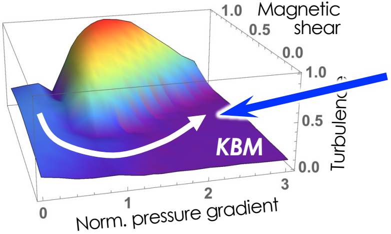
        - ***Accentuated by Shafranov shift:***
          - *Pressure further raises local shear*



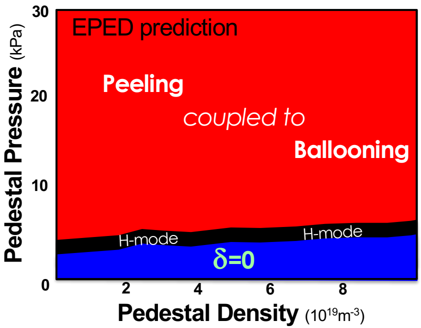




[Staebler NF 2018]

Pedestal Model Projects Strong Shaping Raises Performance

- **Peeling-ballooning modes well coupled at low shape**



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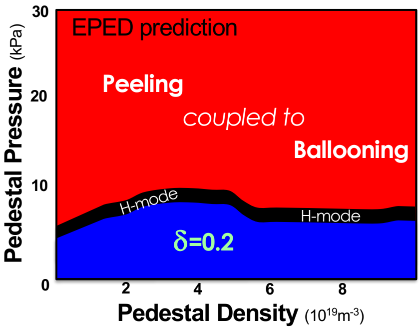
  - Opens valley in pedestal stability



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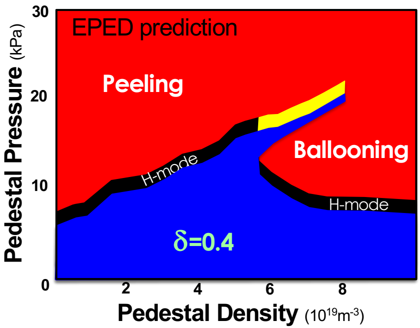

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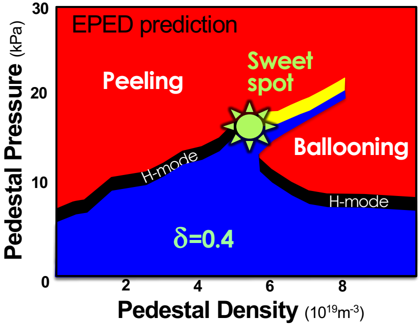

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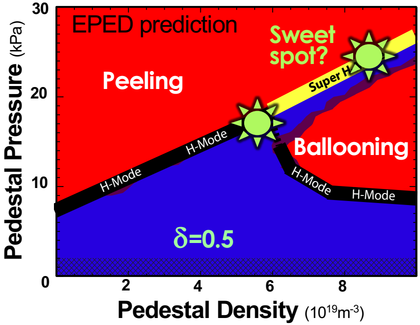

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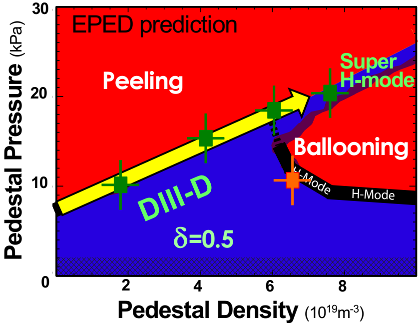
- **Super H-Mode discovered on DIII-D**
  - Record β_N=3.1 with a quiescent edge

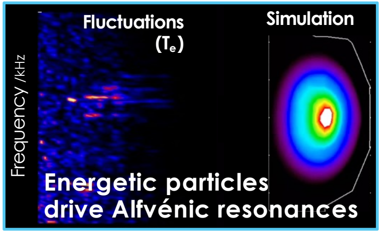


High shaping raises performance and density !

[Solomon PRL 2014, Snyder NF 2015]

Broad Current Profile Ensures Fusion Products Stay Confined

- **Potential for Alfvénic resonances in weak magnetic shear regions**
  - Overlapping modes lead to transport



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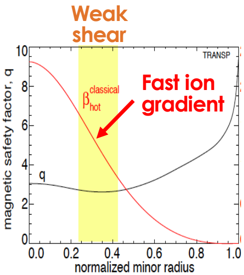

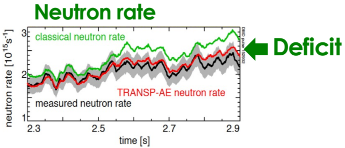

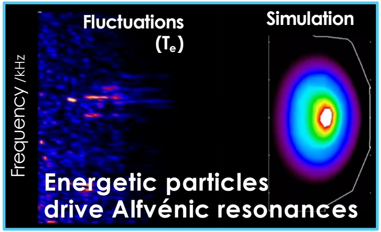

Ohmic Plasmas

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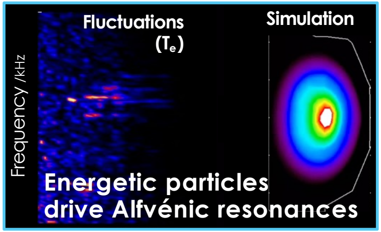
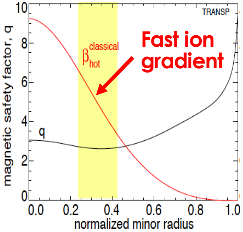
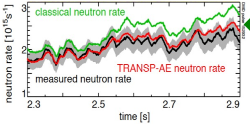


Weak shear

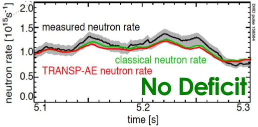


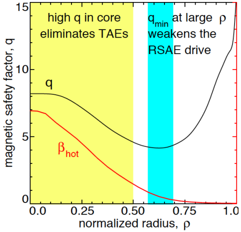
Neutron rate



Deficit

- **Broaden current profile**
  - *Moves weak shear out* →



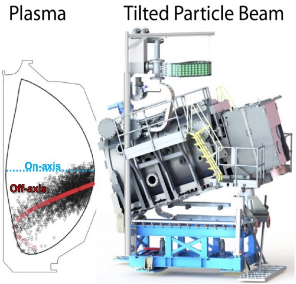


Ohmic Plasmas

[Kramer 2018]

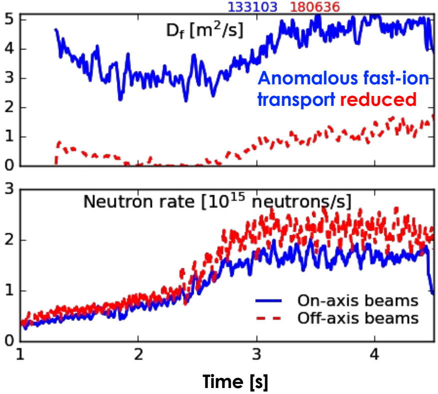
Benefits of Broadened Profiles Validated in AT Scenarios

- **Most fast-ion transport eliminated**
- **15% higher β_N accessed**



DIII-D off axis beams

DIII-D with on & ≈60% off-axis beams



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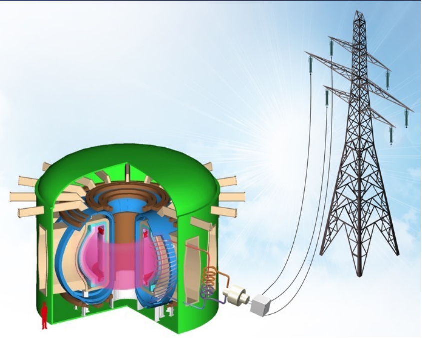

Based on Steady State Concepts Reactor Analytics Show a More Efficient & Robust Path is Possible

- **Recall fusion power:**

$$P_{Fus} \propto Pressure^2 R^3 \propto {\beta_N}^2 B^4 R^3 / q^2$$

  - Raising β_N & B will reduce required device size, R, and still leave net electric

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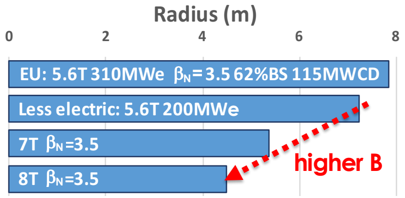
- **Start from EU 'stepladder' DEMO**
  - Adjust R to get $P_{net} = 200MW$ for given β_N & B

$$P_{net} = \eta_{th}(P_{Fus} + P_{heat}) - P_{plant} - P_{CD}/\eta_{CD}$$

  - Rapid decrease in device size possible… lower P_{elec}, **higher B**



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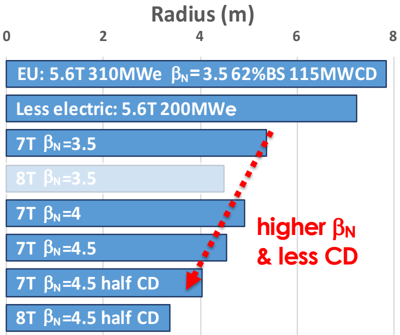
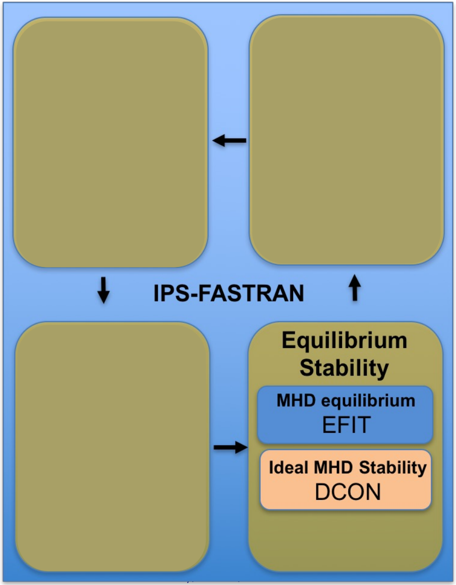
  – Rapid decrease in device size possible… lower P_{elec}, higher B, **higher β_N** & **less CD**

Can we project such a device with reactor simulation?

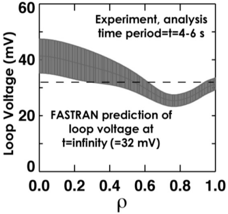


< 1/10th volume of 9m EU-DEMO!

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



Equilibrium/Loop Voltage
EFIT



[Park Comp Phys Com 2017]

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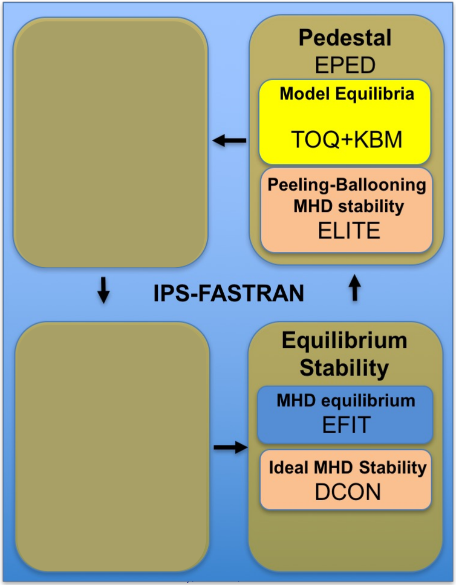
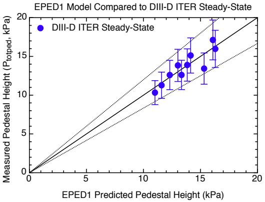


Edge Pedestal
EPED



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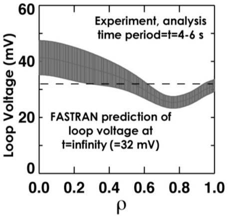
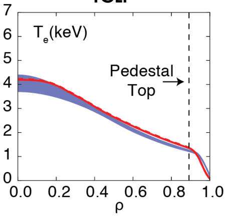
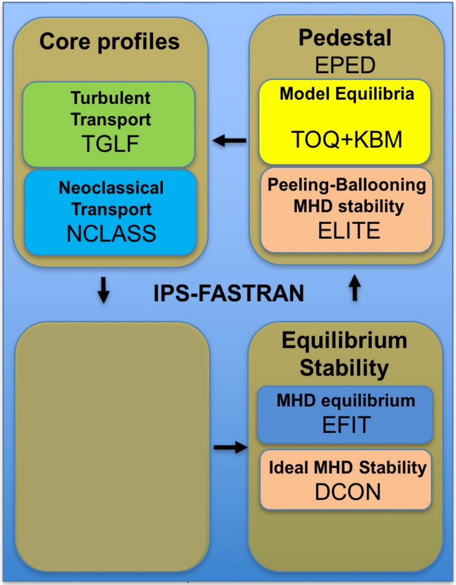


[Park Comp Phys Com 2017]

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

Turbulent Transport
TGLF





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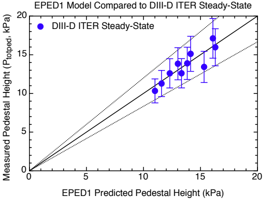

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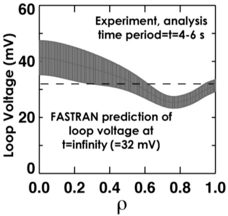

[Park Comp Phys Com 2017]

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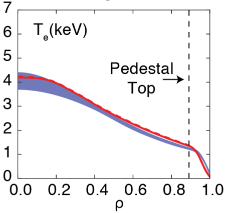
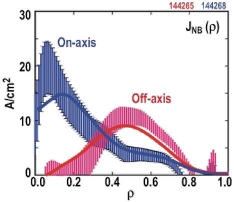
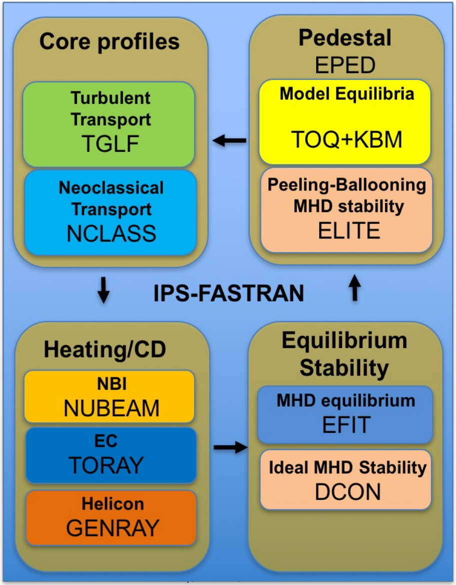
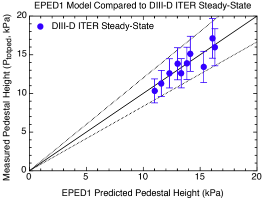


Off-axis Current Drive
NUBEAM





Edge Pedestal
EPED



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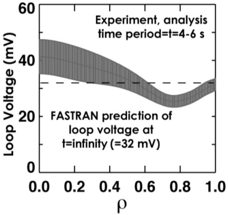
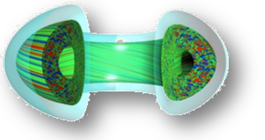


[Park Comp Phys Com 2017]

Used Integrated Physics Model to Design Device that Proves Net Electric Viability and Conducts Long Pulse Nuclear Testing

- **Goal: Prove key principles at low capital cost**
  - **Net electricity**
  - **Nuclear materials**
  - **Breeding**



- **Constraints:**

Target Parameters	*Rationale*
Net electric (200MW)	*Show fusion reactors can power themselves*
Compact scale: 3 – 6m, 5 – 9T	*Affordable*
High bootstrap fraction (90%)	*Reduce recirculating power & scale*
Tolerable/significant neutron load	*Nuclear testing mission: materials, breeding*
Tolerable divertor challenge	*Viable target for divertor research*

Set tractable challenges where we expect progress in the next few years

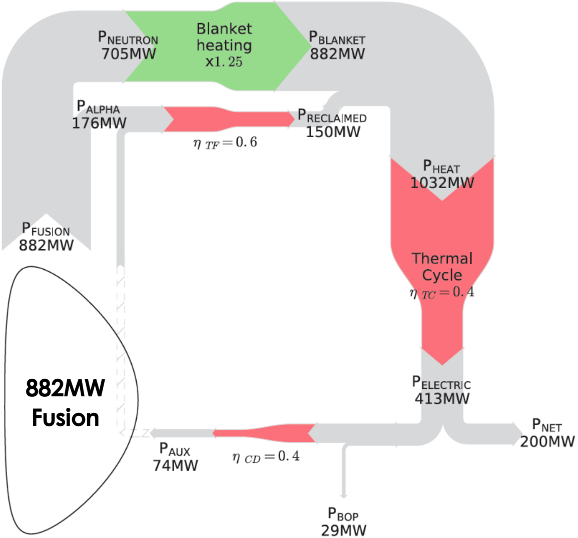
First predictive approach to reactor design!

Compact Pilot Plant Concept Drives Needs to Minimize Power Losses At Every Stage

6T, GA Systems Code

- **Small device must minimize ➔ losses at every step**
  - Otherwise no electricity left
  - *Or they might melt!*

- **Minimize recirculating power**
  - Steady State approach
  - Efficient technology

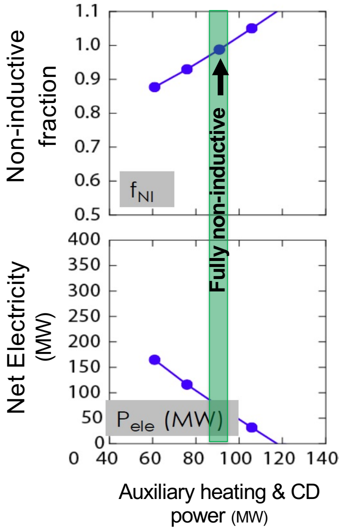


Initial Results Highlighted Importance of an Efficient System

- ‘Conservative’ present technology current drive & thermal efficiencies:
  - *5m, 5.3T, 12MA q~5, η_{th}=0.33, η_{CD}=0.25 (conservative)*

- Raising β_N to drive fully non-inductive led to reduced net electric power
  - ***Auxiliary power needed to heat plasma***

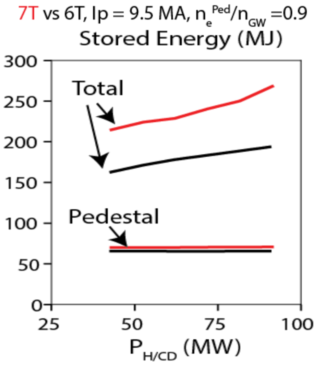
Higher β alone is not enough – energy confinement & device efficiency are key



[Buttery IAEA 2018]

Higher Field is Highly Levering to Confinement

- **Higher field improves core confinement**
  - *From gyrokinetic treatment of core turbulence*

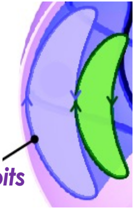


Benefits not captured by simple scaling law approach – comes from physics treatment

[Buttery NF 2021]

Increasing Density Enables More Bootstrap & Less CD Power

- **Density gradients drive bootstrap current more efficiently than temperature gradients***



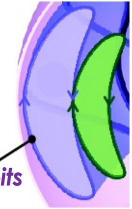
*Temperature effect depends on flows & orbits

[Buttery NF 2021]

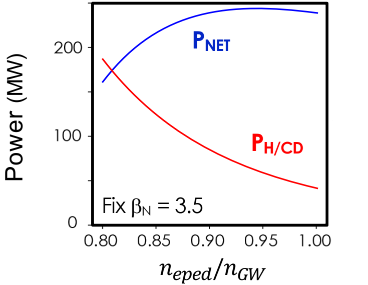
Increasing Density Enables More Bootstrap & Less CD Power

- **Density gradients drive bootstrap current more efficiently than temperature gradients***
- **For given β_N, higher density raises bootstrap fraction modestly: f_{BS} from 70% to 90%**
  - ***Decreases auxiliary current drive: 30% to 10%***

Temperature effect depends on flows & orbits



Requires density at pedestal to be close to the empirical tokamak 'Greenwald' density limit



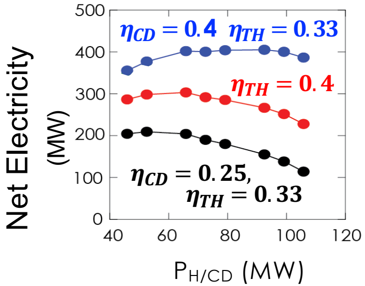
Density normalized to current

[Buttery NF 2021]

Current Drive & Thermal Efficiency Highly Beneficial to Net Electricity

- **Higher efficiencies raise net electric power & Q**
  - Or permits lower β_N, current or field solutions
- **We increased values to $\eta_{CD} = \eta_{TH} = 0.4$**
  - *In line with other reactor studies*

	η_{th}	η_{cd}	$\eta_{th} \cdot \eta_{cd}$
EU DEMO	0.33	0.25	**0.08**
C-AT Pilot	0.33→**0.4**	0.25→**0.4**	**0.08→0.16**
ARC	0.4	0.43	**0.28**
ARIES ACT1	0.575	0.4	**0.23**
ARIES ACT2	0.45	0.4	**0.18**



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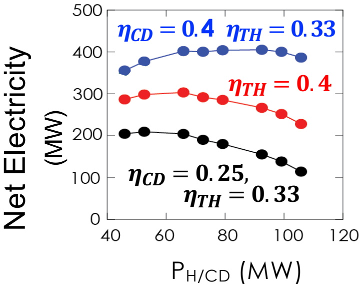

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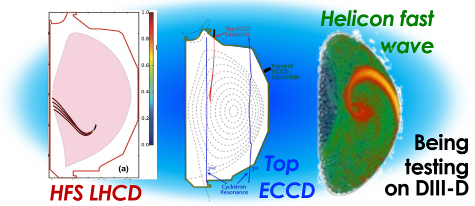
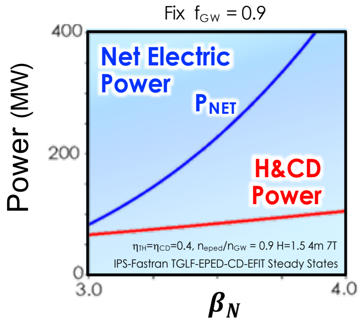
A research challenge to develop more efficient current drive



Steady State Approach Provides High Confinement Reactor Solutions at 6–7T with 200MWe

- *Higher density, field & efficiencies* ➔ β_N **becomes highly levering to net electricity**



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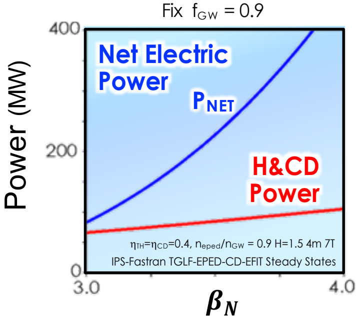

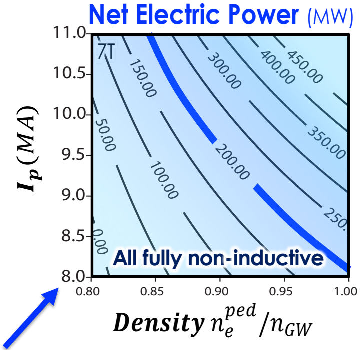

- *Family of fully non-inductive solutions at 4m radius*

[Buttery NF 2021]

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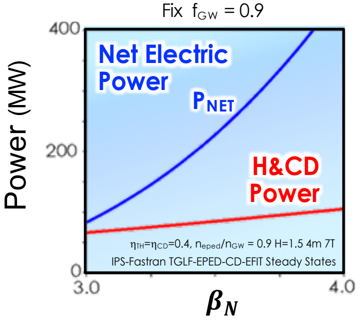
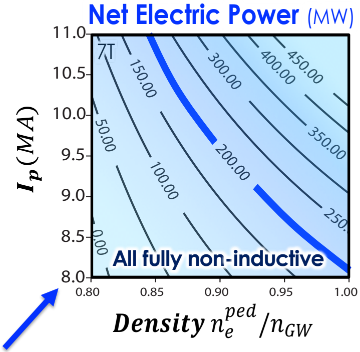




	6T	7T
I	9.4	8.1
q	4.9	6.5
β_N	4.2	3.6
H_{98}	1.3	1.5
Q	10	17
P_{heat}	84	38
P_{fus}	873	658
Neut.	2.3	1.8

R=4m, $\eta_{TH} = \eta_{CD} = 0.4$
n_e^{ped}/n_{GW}=1, 200MWe

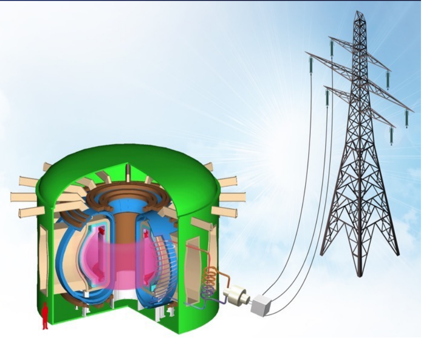
- ***Family of fully non-inductive solutions at 4m radius***

Conventional (6T) & high temperature superconductor (7T+) solutions

[Buttery NF 2021]

Talk Outline – Path to a Compact Fusion Pilot Plant

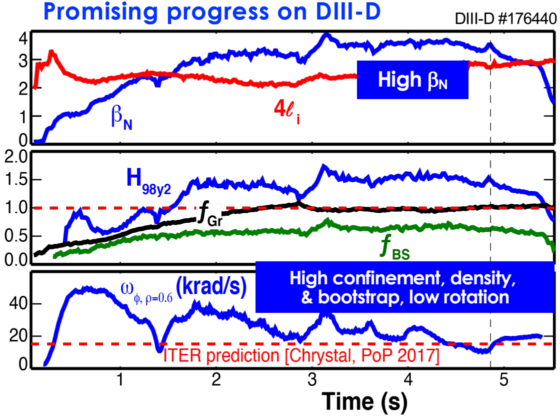
- **Principles of the steady state approach**
  - Shaping, broad profiles & high $\beta \rightarrow$ high bootstrap
  - Benefits to stability, transport, pedestal and fast ions
- **Pilot power plant projection**
  - Analytics, methodology, projections
- **Benefits and Research needs**



Advanced Tokamak Principles Bring Key Benefits to Power Plant Solution

- **Broad profiles and higher field raise energy confinement**
  - **DIII-D discharge show promising parameters**

Promising progress on DIII-D



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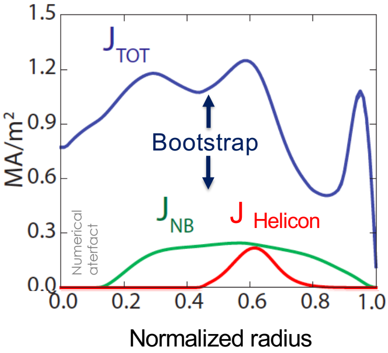
- **Higher pressure & density increase bootstrap**
  - **80-90% bootstrap current – reduce recirculating power**



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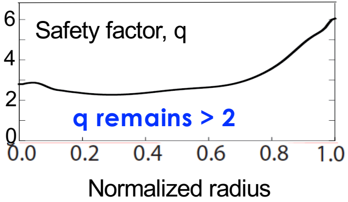
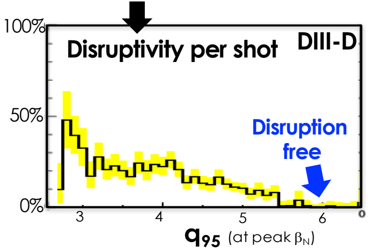
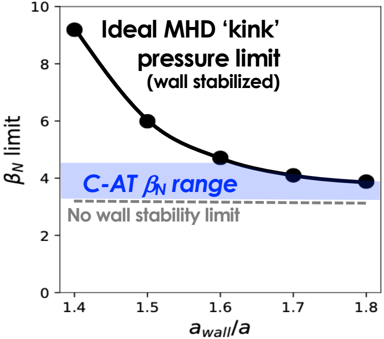
- **Broad profile & lower current improves stability**
  - **Removes low order surfaces that tear and disrupt**
  - **High β wall-stabilized even with high wall distance**
    - ***Reduced disruptivity, stresses and device risk***







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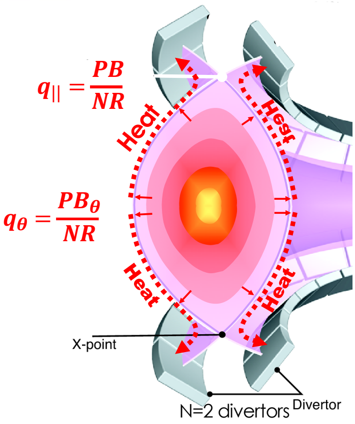
- **Lower fusion power and current reduce heat fluxes**
  - **Modest core radiation needed to reach ITER-like heat fluxes**
    - *While maintaining 'H-mode'*
  - **But a 24/7 fusion power plant will need to go further**



	ITER	C-AT	Rad'n
$q_{\|\|}$	85	85	20%
q_θ	18	18	50%

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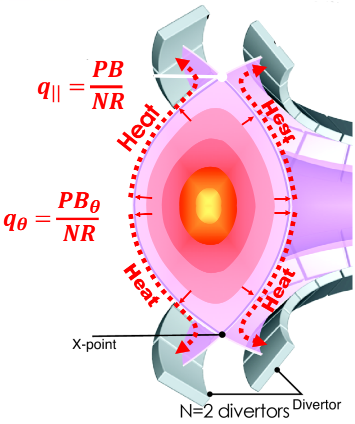
But key challenges remain…



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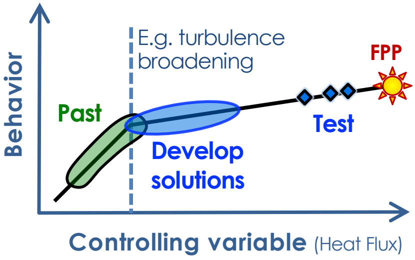
Key Plasma Physics Challenges Require Research

- **Critical plasma physics challenges**
  - **Validate core physics solution** in reactor regimes & relevant sources: stability, transport, EP, pedestal
  - **Scope the limits** of **density**, **pressure**, **confinement**
  - 24/7 **power handling solution** compatible with core
  - Compatibility with **wall materials**
  - **Control of transients** (disruptions, ELMs)
    - ***Issues common to many future concepts***



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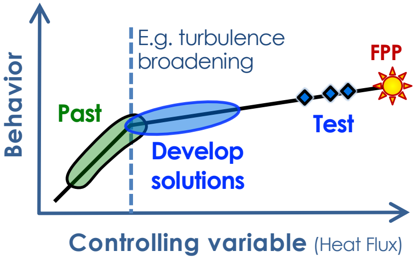
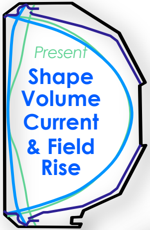


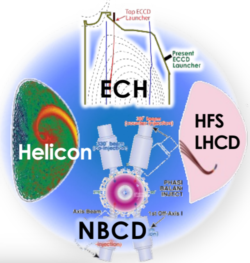
- **And critical engineering & technology challenges**
  - **Advanced bucking approach** to engineering to handle high loads
  - **Demountable HTS** for performance & nuclear testing mission
  - **Broad technology program**: Materials, breeding, power extraction, RF, reactor design, licensing, safety, etc.

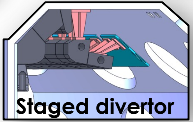
Multiple facilities needed to meet the challenge

A Major Upgrade to DIII-D is Proposed to Address Core-Edge Integrated Solutions

- **Performance rise to address integration physics and solutions**
  - Hot, thermalized, opaque, low collisionality
- **Flexibility to pioneer each part of core and edge solution, and marry them together**
  - Profiles, shape, divertor, materials, 3D
- **Technology testbed to resolve plasma compatibility**
  - Components, materials, diagnostics, RF, pellets, control
- **Scientific investigative capability to project reactor**







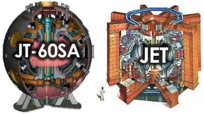
Equips DIII-D to discover the path to an FPP

Portfolio of Facilities Worldwide Have Capability to Resolve the Path to a Compact AT Fusion Pilot

Superconducting Long Pulse

- Material & PFC evolution
- Long pulse control

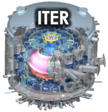
Larger scale



- Projection to reactor
- Operational techniques

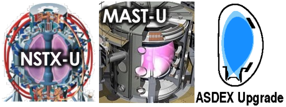
- Compatibility with metal walls

Higher Field

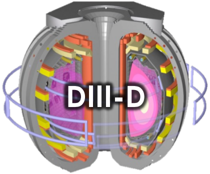


- HTS integration
- Core-edge demonstration
- Nuclear testing

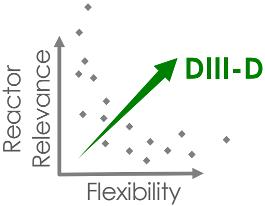
Key physics



- Aspect ratio
- Divertor magnetic geometry
- Super Alfvénic ions & high β
- Bulk W wall & high Z behavior



- **Flexibility:** Pioneer innovative exhaust & core solutions. Marry them together
- **Relevance:** Discover physics basis & techniques to project to future fusion reactors



An Attractive Compact Pilot Plant is Possible
when Advanced Tokamak Physics Principles are Applied

Integrated physics simulation model show:

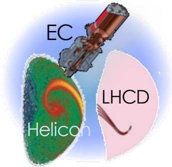
- **High β_N permits high bootstrap to reduce recirculating power**
  - Mitigates divertor heat flux challenge and neutron wall loading
- **High density highly levering in reducing auxiliary power needs and alleviating divertor challenge**
  - Permits operation at safety factor levels where disruptions are avoided
- **Research needed to resolve this (or any) concept**
  - **Validate AT physics – high β_N high density transient free scenario**
  - **Efficient current drive and steady state divertor solution**
  - **High temperature superconductors, reactor materials & engineering**

A challenging but tractable mission for research to enable a fusion pilot plant

Cool CAT

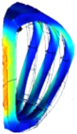
Bonus Slides

With Key Upgrades DIII-D Can Meet The Challenges



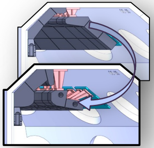
RF rise for core
Explore FPP profiles, confinement, stability & edge compatibility in reactor-relevant physics regimes
Higher pressure & density

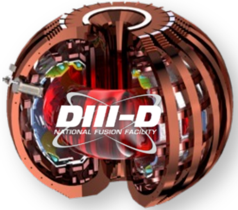
B_T rise
Low ν^*

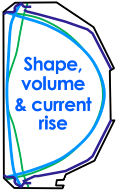


Pressure

Modular Divertor Series to isolate & understand dissipation
Higher local density



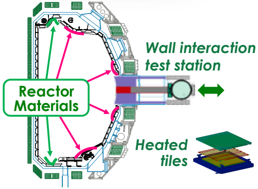




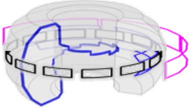
Higher pressure & density

Shape rise
Explore path to raise pressure & density

Wall tests
Qualify materials & interaction with core
New materials & test facilities

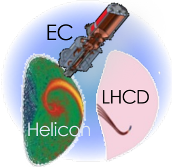


3D rise
Control transients and runaways



With Key Upgrades DIII-D Can Meet The Challenges

These work synergistically to close physics gaps & resolve compatibility



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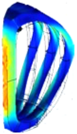
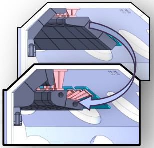
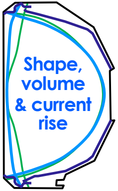


Pressure

Modular Divertor Series to isolate & understand dissipation

Higher local density





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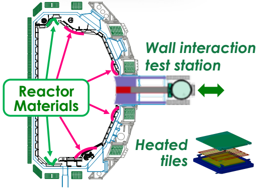

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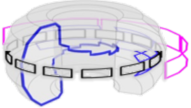
Control transients and runaways



Synergy:
Test high dissipation with high performance & close remaining gaps on reactor physics regimes

Unique capability to prepare for FPP and ITER

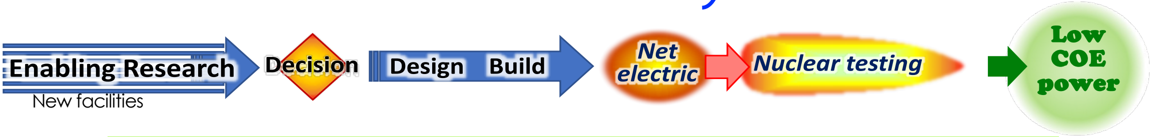
"Enabling Research" Required in Seven Areas for Pilot Plant Decision & Design

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

"Enabling Research:"

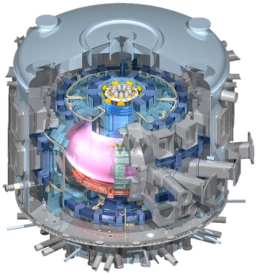
Tokamak research enables ITER & pilot plant missions

Work on engineering & technologies to advance pilot plant approach



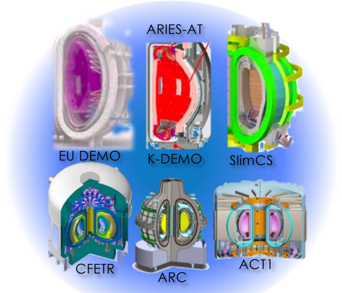
Will provide opportunities for breakthroughs in understanding & performance that transform prospects for all fusion paths!

ITER Provides Vital Learning for Path to a Fusion Reactor



ITER

- Exploration of the burning plasma concept !
- Testing physics & techniques at reactor scale & physics regimes
- Development of validated predicted models
- Understand how to build and operate a large scale nuclear fusion facility



Steady State

ITER participation is vital if the U.S. is serious about fusion energy and building its own reactors

- *Crucially informs U.S. approach to a D-T reactor*
- *Know-how you just don't get from reading the papers*

Simulations Provided Key Insights over Basic AT Logic

- **Density levers high β approach by enhancing current drive**
  - *And helps maintain temperature close to optimum for fusion cross-section*
- **Toroidal field improves confinement by reducing turbulence,**
  - *In addition to (known) improvements in stability margins β (kink) and q (safety factor) limits*
- **Compatibility of plasma solution with heating & current drive systems**
- **Prediction of confinement and fusion performance, required scale, field etc.**
  - *Rather than choice in a systems code or flawed H_{98} scaling*

Identifies limits of configuration as we optimize to a more compact scale to find design points and set required scale and field

Shows trade-offs between various target parameters are possible

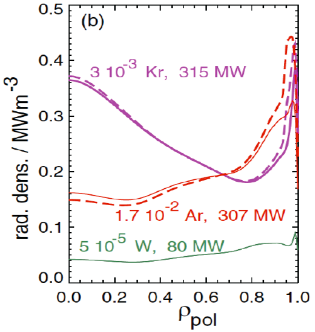
Fuel dilution due to core radiation remains a challenge for all DEMO concepts

- **As core impurity fraction is increased, higher Z_{eff} drives down fuel ion fraction**

$$f_i = 1 - 2f_{He} - Z_{imp}f_{imp}, \qquad P_{fus} \propto f_i^2 n^2 T^2 V_p$$

  - even a small change in f_i dramatically reduces fusion power

- **Kallenbach et. al. have predicted impurity profiles for a R = 9m, a = 2.25m DEMO**
  - scaling to C-AT DEMO parameters results in a 60% reduction in fusion power, 2x more than the 33% assumed in this study
  - $f_{Kr} = 1{\times}10^{-2}$ needed for 172 MW of core radiation
- **a radiative model is needed in GASC to ensure self-consistancy**



Kallenbach *et al* 2013 PPCF **55**

DIII-D NATIONAL FUSION FACILITY

The World is Focused on the Advanced Tokamak Path to Fusion Power

But Not Advanced Enough !

- **Presently envisaged steps beyond ITER are largely based on the conventional aspect ratio Advanced Tokamak**

- **But not very 'advanced' – high recirculating power:**
  - **EU-DEMO:** 5.2T, **~9m**, ~500MWe, **β_N~2.6**, q_{95}~3, H=1.1, **f_{BS}~34%**
    - ***Based on "what we can do now" technologies & pulsed***
  - **ARC: 9T**, ~3.3m, ~200MWe, **β_N~2.6**, q_{95}~7, **H=1.8**, **f_{BS}~63%**
    - ***Exploits high temperature superconductors, but optimistic confinement assumptions***
  - **Many devices proposed are large size & high fusion power**
    - ***Does next step need to be so big?***

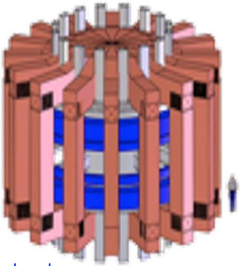
Can Advanced Tokamak principles & different constraints be applied to enable a more cost attractive next step device?
- *Reduce recirculating power to reduce required scale*
- *Combine required missions into single generation*
- *Minimum size for research mission*

Power plants	ACT1	SlimCS	Korea DEMO	EU DEMO
R (m)	6.3	5.5	6.8	9
I_P (MA)	11	17	17	20
P_{Fus} (GW)	1.8	3	2.9	1.8
P_{Net} (GW)	1	1	0.5	0.5

[Kessel FST 2015, Tobita NF 2009, Kim NF 2015, Feredici FED 2014]

Target: Low Capital Cost Pilot Plant To Close Gap on Future Power Plant

- **Key challenges for self-sustaining reactor:**
  - **Breeding**
  - **Nuclear materials**
  - **Net electricity**

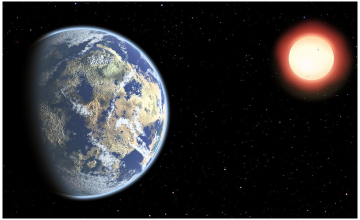


- **Address these in a single compact 'pilot plant' test facility**
  - Combine missions to remove a generation
  - Low capital cost → affordable

- **U.S. proposals for ARC, Compact-AT and ST-pilot at similar scales**
  - *100-200MWe, R~3-4m, A~2-3 & benefit from high temperature superconductors*
  - *Build on expertise being developed in ITER*
  - *May require additional research in parallel to ITER*

Pilot to address critical issues prior to low COE power plant

A Compact Pilot Plant Could Work Alongside & Beyond ITER to Bridge The Gap To Large Scale Fusion Power



- **Demonstrate net electricity production**
  - Integration of heat → electricity generation
  - Proof of potential – device can power itself
- **Test nuclear materials in fusion reactor environment**
- **Demonstrate and optimize breeding technology**
  - Ability to change out materials with demountable HTS
- **Configuration sustained in truly long pulse conditions (months)**

Lay the groundwork for low COE successors

Radiative Techniques to Meet Heat Flux Challenge

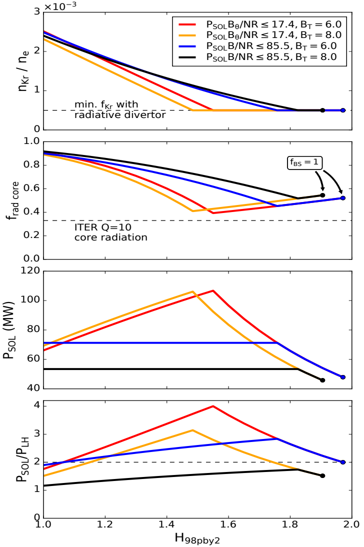
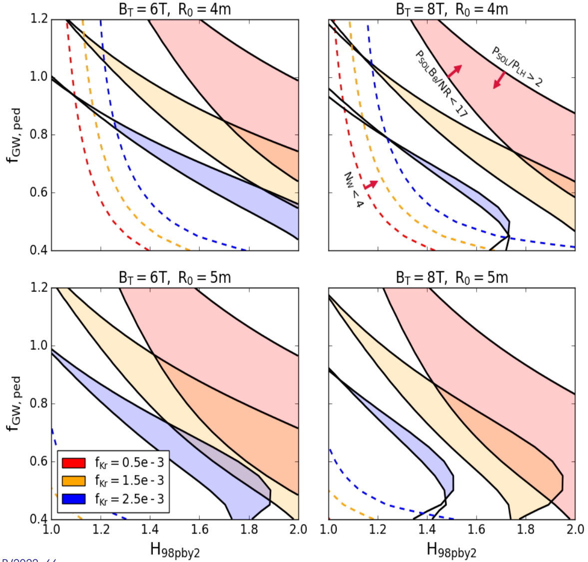


Fig 14: Self-consistent GASC solutions using krypton impurity seeding to limit divertor heat load below two variations of the ITER divertor metric. Impurity fraction, total core radiated power fraction, power into the scrape-off layer, and L-H power threshold fraction are shown for $B_T = 6T$ and $8T$ design points ($f_{GW}^{ped}=1$, $P_{net}=200MWe$, $R_0=4m$).

Fig 15: GASC parameter scans in confinement and density for four different design points. Contours of limits in L-H threshold power fraction and poloidal heat flux metric constrain the solution space for three levels of krypton impurity seeding. The neutron wall loading limit $N_W<4MW/m^2$ is also shown, but only constrains operation in a few cases. $f_{BS}<1$ for every shaded operational space.



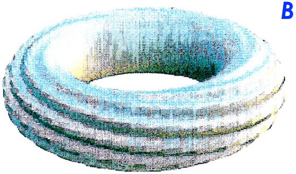
Tokamak is Limited in Current and Pressure by Global MHD Modes

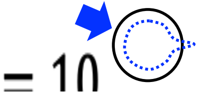
- **Current in tokamak drives a field line twist**
  - Measure through **safety factor**, **q** $\propto RB/I$
- **Twist in field drives global MHD 'kink' mode**
  - Leads to limit in current for given field
    - *Pressure also drives this distortion*
  - Increased field, B – tensions & stabilizes mode
- **Magnetic islands also emerge at modest q**
- **'*Ballooning*' limit to pressure is stabilized by increased twist (current, I)**
- **Leads to Pressure limit ~ BI/R**

$$\Rightarrow \beta_N = 100 \frac{2\mu_0 < P >}{B\ I\ /\ R\varepsilon}$$ *typically ~3-5*

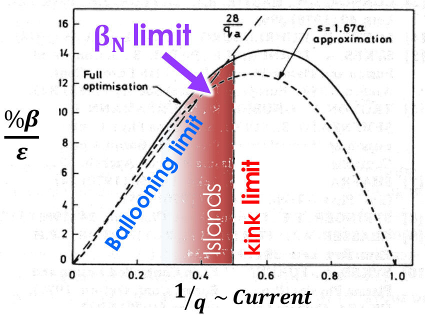
Q. *Where and how to optimize in β_N and q ?*

Ballooning





Pressure pushes field line through surface



[Troyon et al., PPCF 1985]
[Sykes and Wesson, NF 1985]

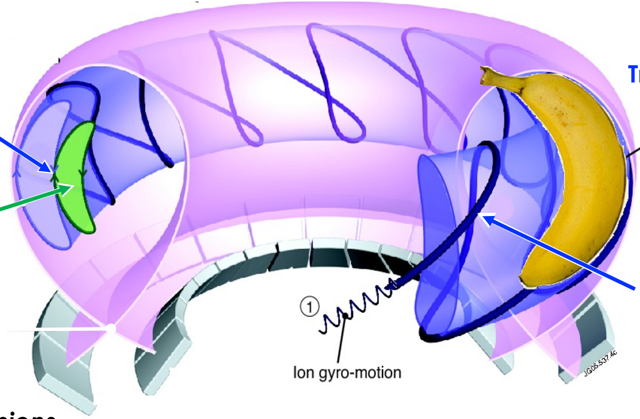
High Pressure Gradient Leads to a Net ‘Bootstrap’ Current

Gyro-orbits drift due to non-uniform field lead to banana orbits

2. Currents due to neighbouring banana orbits largely cancel

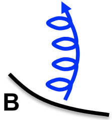
3: <u>More</u> & <u>faster</u> particles nearer the core lead to net “banana current”
$\propto \nabla Pressure/Current$

4: *Transferred to helical <u>bootstrap current</u> by collisions*



Traces out banana trajectory, width
$\propto {}^{1}/_{Current}$

1. Orbits tighter where field stronger



Utilize bootstrap to provide the plasma current

[Galeev, Sov. Phys. JETP 1968]

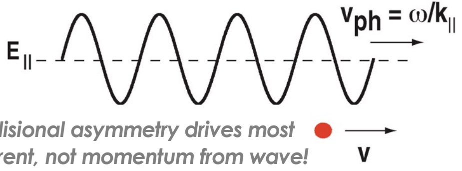
Combine Bootstrap with Auxiliary Current Drive in Steady State Tokamak

- **Bootstrap fraction:** $f_{BS} \propto p/I^2 \propto C_{BS}\beta_N q_{95}$
- **Additional current drive from RF heating**
  - Requires suitable population → *high T*
  - Collisions scatter electrons, reducing current
    - *Requires low density*

$$\Rightarrow f_{CD} \propto \frac{P_{CD}T}{nIR} \propto C_{CD}\frac{P_{CD}\beta_N B}{n^2}$$

<u>***Radio Frequency Current Drive***</u>

Wave accelerates electrons preferentially decreasing their collisionality



Collisional asymmetry drives most current, not momentum from wave!

[Fisch FST 2014]

- **Solve for current drive** $f_{BS} + f_{CD} = 1$:

$$Q_{CD} \propto \frac{P_{fus}}{P_{CD}} \propto \frac{1}{(1 - C_{BS}\beta_N q_{95})} \frac{C_{CD}\,\beta_N^3 B^3}{(n/I)^2}$$

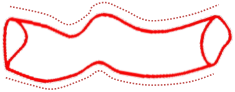
← β_N ***and B always help!***

More bootstrap removes need for current drive at high q_{95} (lower current)

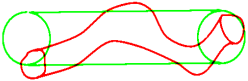
Lower density → higher f_{CD}
Higher current raises Q as $P_{fus} \sim \beta_N^2 I^2 B^2$

Alternate paths to steady state through bootstrap or current drive

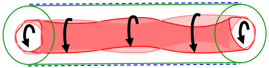
β_N Limiting Global MHD Modes Can Be Stabilized by Device Wall



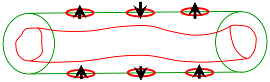
- **Pressure driven kink displaces magnetic flux about the plasma**



- **Conducting wall converts this slower Resistive Wall Mode**

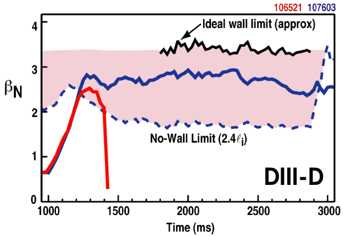


- **Mode gives energy to particles with rotational orbit resonances**



- **Magnetic feedback can control any residual mode**

Routine stable operation above no-wall limit



[Garofalo PoP 2006]

How do we increase wall stabilization of this pressure limit?

Compact Fusion Pilot Poses Critical Plasma Research and Integration Challenge

Compact scale requires higher power densities:

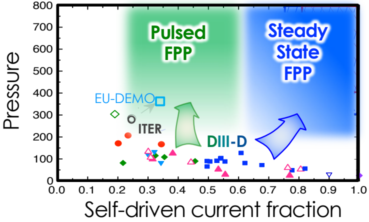
- **High pressure** and **energy confinement**
  – To fuse sufficiently in smaller volume & retain heat
- **Power handling** and **wall compatibility**
  – To mitigate hot plasma exhaust at high duty cycle
- **Plasma interacting technologies** and **control**
  – To resolve in plasma & fusion environment

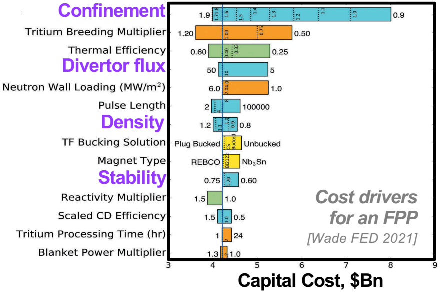
Each needs dramatically improved solutions over WWKN, requiring physics investigation

– & account for key cost drivers in an FPP →

Different elements trade off against each other

– Test together to resolve integration physics





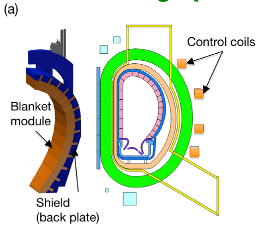
Plasma research vital to FPP design

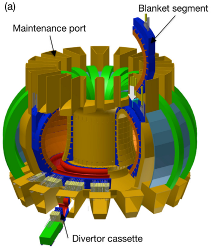
Compact Approach Requires Advanced Engineering & Technology

- **Requires advanced bucking approach to deal with forces**
  - ‘Bucks’ toroidal field coil forces off solenoid & central plug to cancel out stress by >50%
- **High Temperature Superconductors enables demountability**
  - Permits changes out for nuclear materials mission
  - Raises performance and increases duty cycle
- **Broad technology program (CPP plan)**
  - Materials, breeding, power extraction, RF, reactor design, licensing, safety, etc.
  - ITER plays key role in reactor scale expertise

Aggressive technology program required

Vertical change out scheme in Japanese SN design (C-AT is DN)





[Utoh, Fus. Eng. Des. 2017]