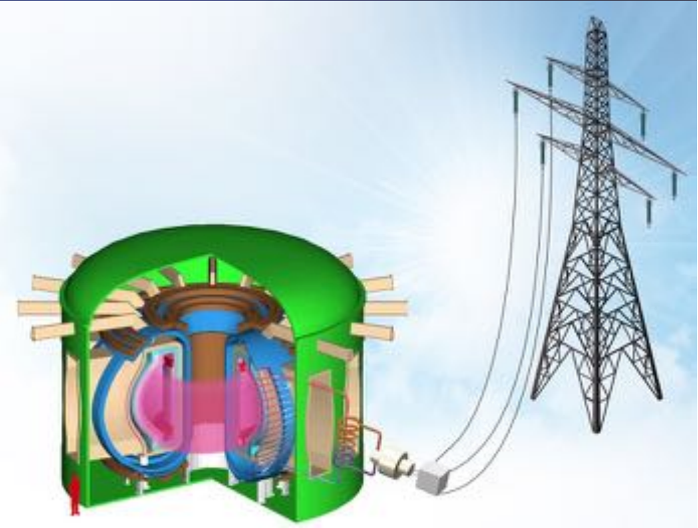
The Steady State Approach to a Fusion Pilot Plant

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**



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USBPO Webinar Series on Burning Plasma Concepts

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GENERAL ATOMICS

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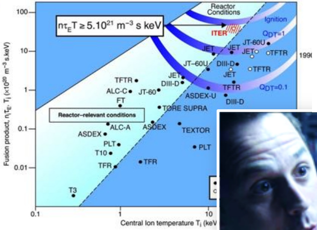
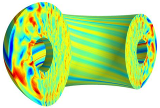
It's Time to Get Serious about Fusion Energy

- **We've made a lot of progress**
  - Physics issues, new solutions, ITER on track
  - Need to apply to develop a power plant concept
- **Should not wait around for 'unobtanium' solutions**
  - Base on what we know or will know soon
  - Can't wait for perfect answer





- **Aggressive plan must accept some risk & figure out as we go**
  - Staggered decision making & design integration

Main parameters ◆ | Engineering design: coils, vessel, forces, neutronics ◆ | Long lead fabrications: vessel, TF, PF ◆ | Assembly ◆

Heating & CD ◆ | RF system design ◆ | RF fabrication ◆ | RF install ◆

Divertor config ◆ | Divertor design ◆

Materials ◆ | PFC design ◆ | PFC fabrication ◆ | PFC install ◆

Quench choice ◆ | Quench system design ◆ | Quench fabrication ◆ | Quench install ◆

Core-edge solution ◆ | Operating scenarios & control preparation ◆

Primary elements: Safety, licensing, breeding, remote handling, power extraction, plant → ongoing research, prototyping, design, integration, fabrication, installation ◆

Mid 2030s

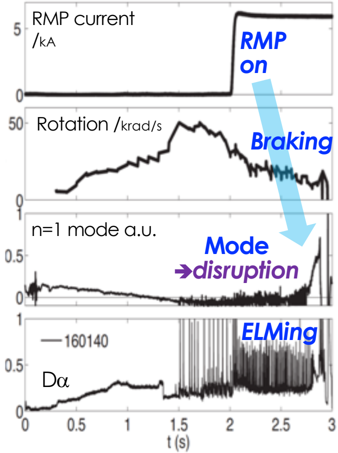
FPP

ARC, CAT STPP, etc.

- **Ambitious research program needed ← CPP plan**
  - Technology development
  - **Plasma solutions** *← Focus of this talk*

Plasma Solutions for FPP Still Face Significant Challenges

- Critical issues
  - At low torque & safety factor plasma subject to disruptions
  - ELMs hard to control



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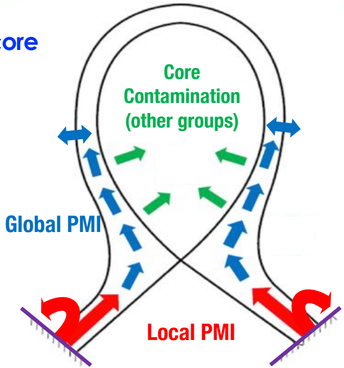

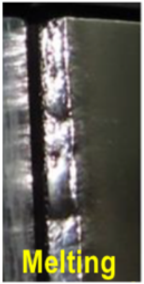

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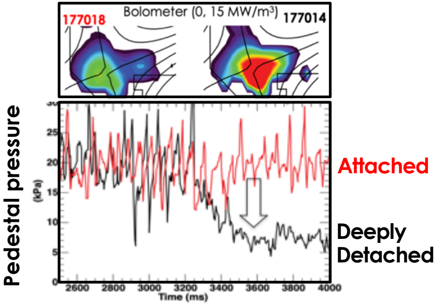

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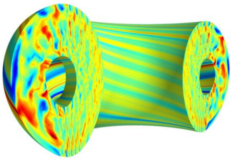
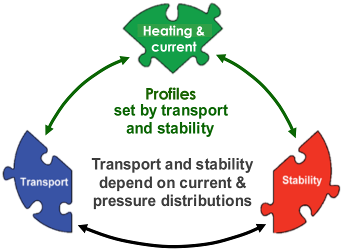
    - ***Transport, stability, fast ions, pedestal, dissipation, divertor***





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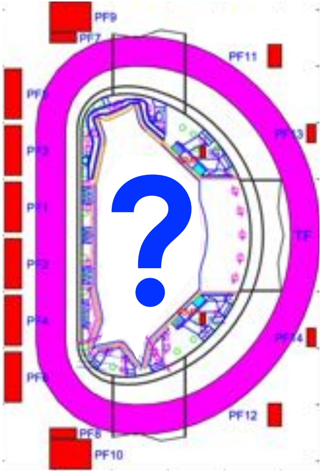
- **Choice of plasma operating scenario has primary impact on the challenge and the solutions to meet the FPP goal**
  - **Key questions on where to operate:**
    - ***Current, q, pressure, field, size, shape, etc.***



Plasma Solutions for FPP Still Face Significant Challenges

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- **Pulsed & Steady State concepts offer promising solutions**
  - Strengths and challenges for both

Exciting research in coming years will resolve the path

Plasma Solutions for FPP Still Face Significant Challenges

- **Critical issues**
  - At low torque & safety factor plasma subject to disruptions
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    challenge it face
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    - *Transport, stab*
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  on the challenge c
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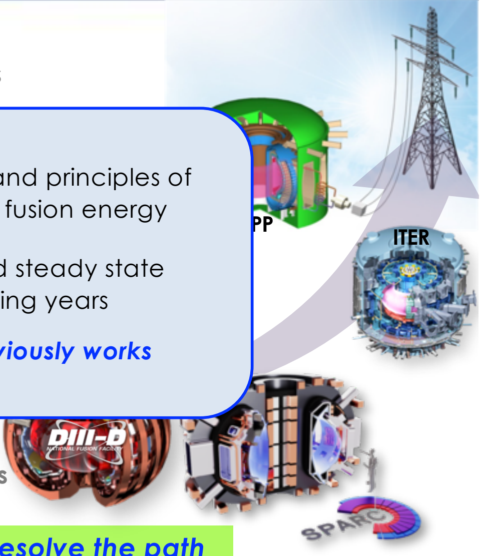
This talk sets out the motivation and principles of the Steady State approach to fusion energy

A choice between pulsed and steady state will become clear in coming years

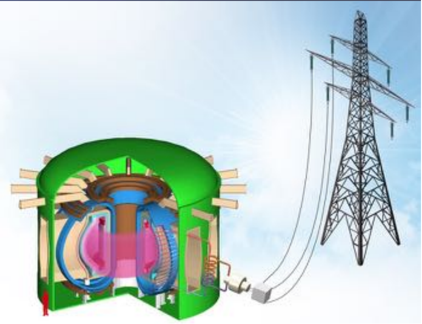
We will all embrace what obviously works



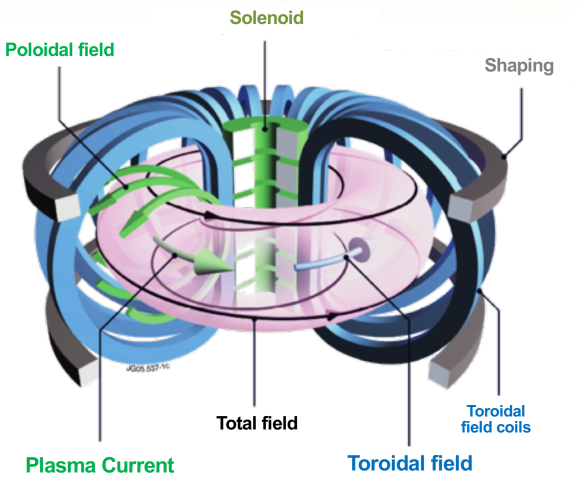
Exciting research in coming years will resolve the path

Talk Outline – Path to a Compact Fusion Pilot Plant

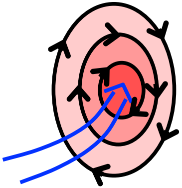
- **Paths to an efficient & compact fusion tokamak**
  - Plasma configurations, limits, pulsed & steady state
- **The Steady State optimization**
  - Shaping, broad profiles & high β raise performance
- **Pilot power plant projection and benefits**
  - Key trends in optimization & attractive solutions
- **Research needs**



Tokamak Concept Meets Fusion Challenge with Flux Surface Structure



- **Plasma current + toroidal field generates flux surfaces**
  - Confines hot plasma for fusion conditions
  - Confines α's to heat plasma



- **Requires sustainment with**
  - **Sufficient heating**
  - **Sufficient current drive**

  } P_{aux}

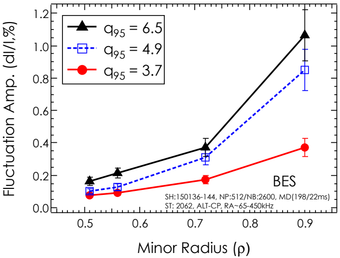
- **Leads to efficiency metric**

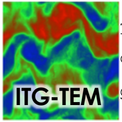
Fusion Gain, $Q = \frac{P_{fus}}{P_{aux}}$

Need to minimize auxiliary power for efficient fusion solution

Tokamak Must Confine Heat

- **Energy confinement governed transport and turbulence**
  - **Neoclassical transport depends on poloidal ion Larmor radius** ← Current dependent
    - *Sets base level of transport*
  - **Turbulence driven by pressure gradients**
    - *Introduces more complex dependencies: B, I, …*
    - *Eddy size ~ toroidal Larmor radius*





[Gyro, Candy]

Amplitude decreases as current ↑

- **Characterize energy confinement by a timescale**

$$\tau = \textbf{Thermal Energy} / P_{heat} \propto Current$$ ← *empirical*

- **Leads to overall thermal gain**

$$Q_{th} = \frac{P_{fus}}{P_{heat}} = \frac{P^2V}{PV/\tau} \propto Pressure\,.\,Current\,.\,H$$

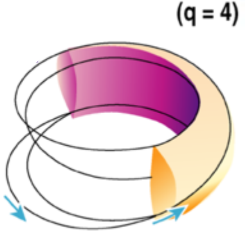
Confinement efficiency (τ/I)

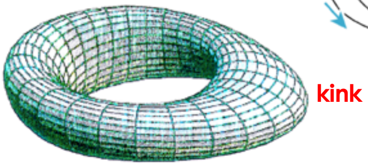
What is the best path? High pressure, current or confinement efficiency?

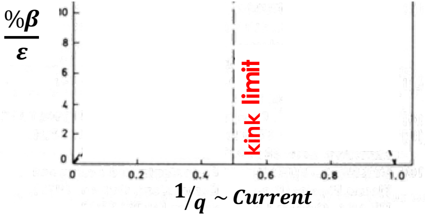
Tokamak is Limited in Current and Pressure by Global MHD Modes

- **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**

$$q = \frac{\text{toroidal turns}}{\text{poloidal turns}} \propto \frac{RB}{I}$$







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

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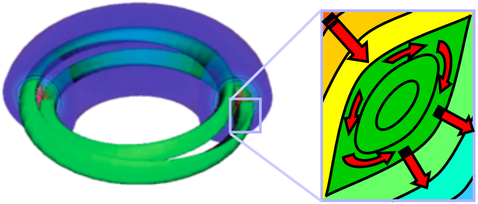
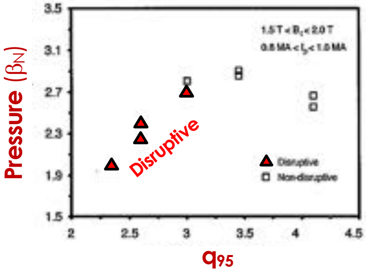
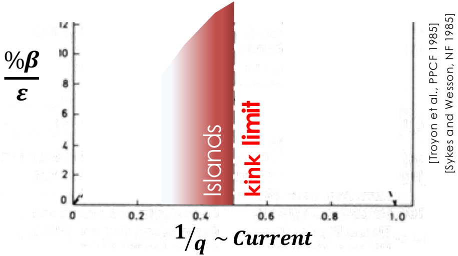


- **Magnetic islands also emerge at modest q** – *additional free energy as flux surfaces split*



[ZOHM PPCF 1995]

⇒



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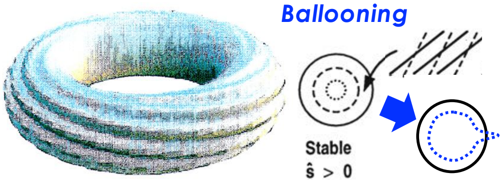
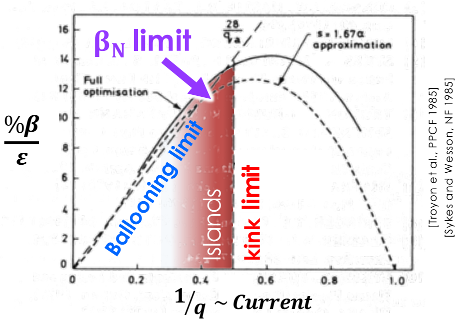
- **Magnetic islands also emerge at modest q**
- **'*Ballooning*' limit to pressure is stabilized by increased twist (current, I)**
- **Leads to Pressure limit ~ BI/R**

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

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



Pressure pushes field line through surface

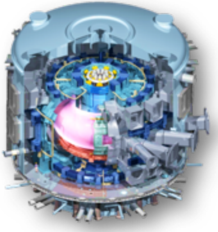


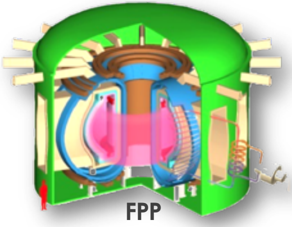
Discussion: How Best to Optimize in β, q and Confinement?

- **Pulsed tokamaks optimize to high current & low q**
  - Current a primary driver of confinement → maximizes performance
  - Sustainment not a concern for performance and burning plasma proof
    - ✓ *Potential to yield very high performance & self-heating*
    - *Q. High current poses a challenge for disruptions, heat loads, and device stresses*

- **Steady state optimizes to high β & high confinement efficiency**
  - Improved plasma properties at reduced absolute parameters
  - Lower current (higher q) desirable to reduce required non-inductive current drive & recirculating power
    - ✓ *Reduced disruptivity, heat loads and devices stresses*
    - *Q. Can these benefits be realized?*

ITER





FPP

A Steady State Tokamak Sustains Current Non-Inductively with Improved Confinement and Stability at Lower Current

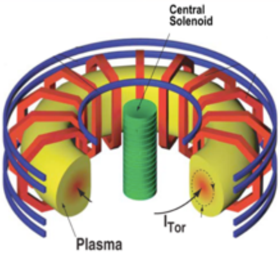
- **Sources of current:**

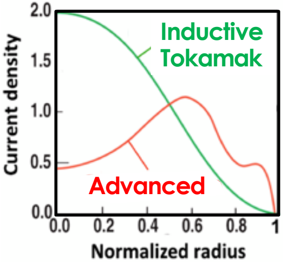
~ 0 expensive

$$I_{steady\ state} = I_{CS} + I_{self\text{-}driven} + (I_{NBI} + I_{waves})$$

- **Goal: High pressure + High self-driven current**

Fusion power — Steady-state & high gain





- **The Advanced Tokamak optimizes profiles to improve stability & performance**
  - Naturally generates a high self-driven **"Bootstrap current"** at high pressure
  - ***Reduces the need for expensive current drive***

bootstrap

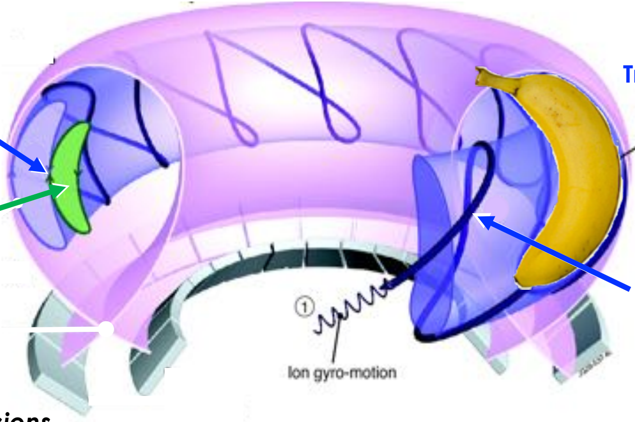
Baron von Münchhausen

High Pressure Gradient Leads to a Net 'Bootstrap' Current

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

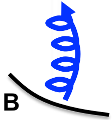
2. Currents due to neighbouring banana orbits largely cancel

3: More & faster particles nearer the core lead to net "banana current"
$\propto \nabla Pressure/Current$



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

1. Orbits tighter where field stronger



4: *Transferred to helical bootstrap current by collisions*

Utilize bootstrap to provide the plasma current

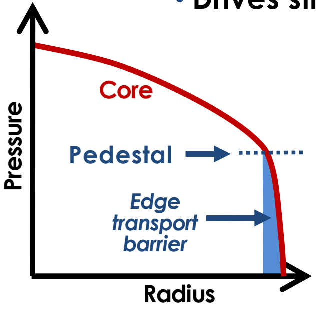
[Galeev, Sov. Phys. JETP 1968]

Neoclassical Theory of Bootstrap Current Validated in Tokamak Edge 'Pedestal' Region

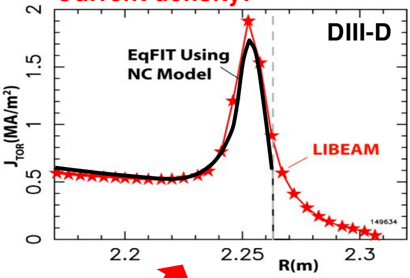
- **Strong pressure gradients arise near edge of tokamak plasma → 'pedestal'**
  – Magnetic & rotational shear suppress turbulence

- **Drives strong bootstrap current**

$$j_b \propto \frac{dp/dr}{B_\theta\left(1+0.9\sqrt{\nu_e^*}\right)}$$



Current density:



[H. Stoschus, 2012]

Experimental validation on DIII-D

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*

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

Radio Frequency Current Drive

Wave accelerates electrons preferentially decreasing their collisionality

Collisional asymmetry drives most current, not momentum from wave!

v

[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

Recap: Higher Beta or Higher Current?

- **Efficient fusion requires high Q**
- **Both heating and current sustainment have two optimization paths**
  - **Heating power** ← $Q_{th} \propto \frac{\beta_N H B^3 R^3}{q^2}$ → **through High β_N H or High I_P** (low q)
  - **Current drive power** ← Q_{CD} → **High β or High I_P directions**

High bootstrap path

Efficient current drive path

Challenges

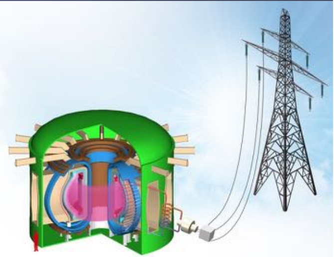
- **High β stability?**
- **Confinement?**

Challenges

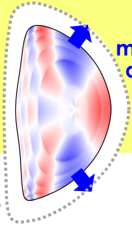
- **Low safety factor stability?**
- **Current drive technique?**

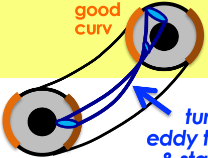
What is the best path? High pressure, current or confinement efficiency?

Talk Outline – Path to a Compact Fusion Pilot Plant



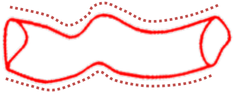
- **Paths to an efficient & compact fusion tokamak**
  - Plasma configurations, limits, pulsed & steady state
- **The Steady State optimization**
  - Shaping, broad profiles & high β raise performance
    - ***Stability***
    - *Transport*
    - *Pedestal*
    - *Energetic particles*



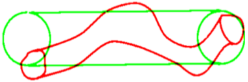


- **Pilot power plant projection and benefits**
- **Research needs**

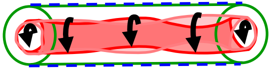
β_N Limiting Global MHD Modes Can Be Stabilized by Device Wall



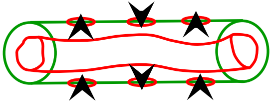
- **Pressure driven kink displaces magnetic flux about the plasma**



- **Conducting wall permits <u>slow</u> kink growth as flux diffuses through it**

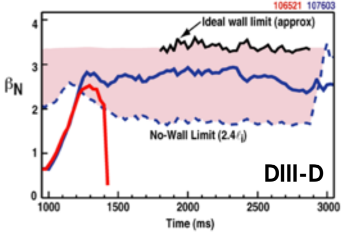


- **Rotating mode sees ideal wall**
  – Also mode gives energy to particles with rotational orbit resonances



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

Enables stable operation above no-wall limit



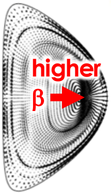
[Garofalo PoP 2006]

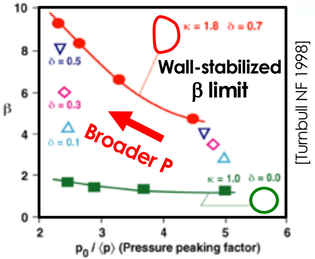
How do we increase wall stabilization of this pressure limit?

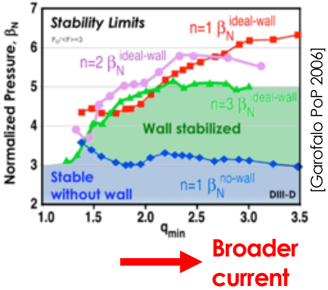
Advanced Tokamak Benefits from Synergy of Shaping and Broad Profiles at High β_N

- **Shaping raises ideal MHD limits**
  - Increases current carrying capacity
  - Extends eigen-structure into wall
- **Broader pressure profile places pressure gradients in strong magnetic shear region**
- **Broader current displaces mode further into the wall**
  - Effectively current perturbation gets closer to wall
  - Greater than additive benefit
- **Higher β increases Shafranov shift** (axis moves outward)
  - Moves mode further to wall & raises shear

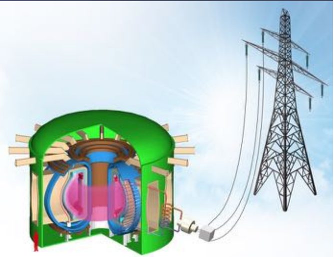
Effects combine to raise pressure in core by factor 5
- *Self-consistently generates bootstrap current aligned with required profiles for stability*







Talk Outline – Path to a Compact Fusion Pilot Plant



- **Paths to an efficient & compact fusion tokamak**
  - Plasma configurations, limits, pulsed & steady state
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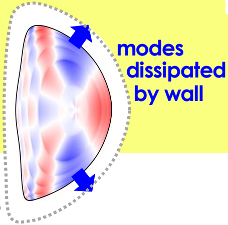
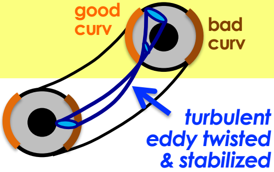
  - Shaping, broad profiles & high β raise performance
    - *Stability*
    - ***Transport***
    - *Pedestal*
    - *Energetic particles*

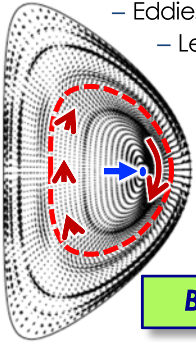


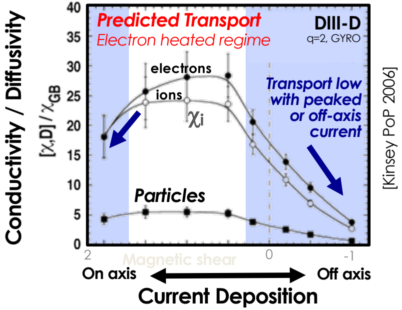


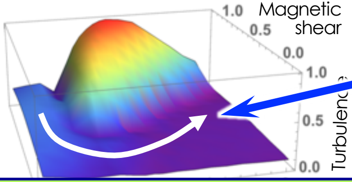
- **Pilot power plant projection and benefits**
- **Research needs**

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
- **Broad current profile drives negative local shear**
  - Even though weak average shear
    - Eddies twist into good curvature region
      - Leads to turbulence stabilization
        - ***Accentuated by Shafranov shift:***
          - *Pressure further raises local shear*



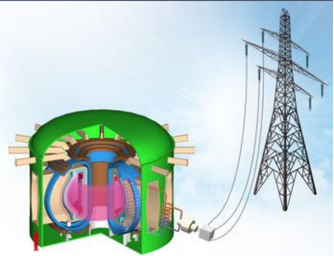




Bifurcation to high pressure state

Broad profiles and high β play key role in stabilizing turbulence

Talk Outline – Path to a Compact Fusion Pilot Plant



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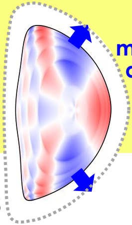
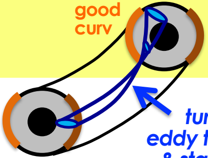
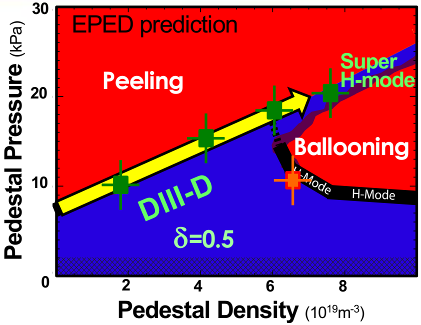




- **Pilot power plant projection and benefits**
- **Research needs**

Pedestal Model Projects Strong Shaping Raises Performance

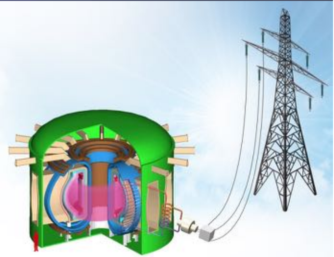
- **Peeling-ballooning instability couples**
  - Fine scale ripple-like interchange
  - Low order peel off of edge
- **Modes well coupled at low shape**
- **High shaping see drives separate in parameter space**
  - Opens valley in pedestal stability
  - **Sweet spots at higher pressure & density**
    - *More elongation moves nose right*
- **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]

Talk Outline – Path to a Compact Fusion Pilot Plant



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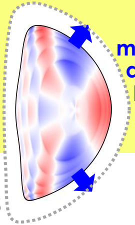
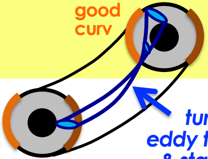
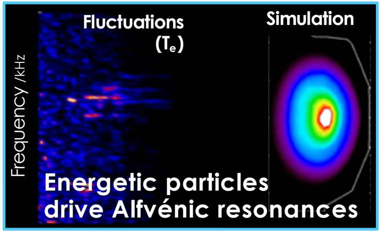


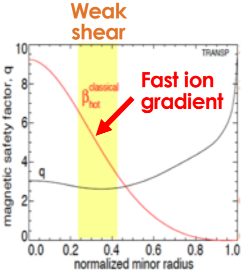


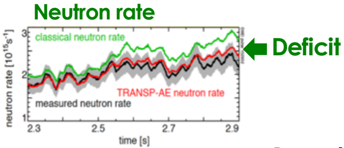
- Pilot power plant projection and benefits
- Research needs

Broad Current Profile Ensures Fusion Products Stay Confined

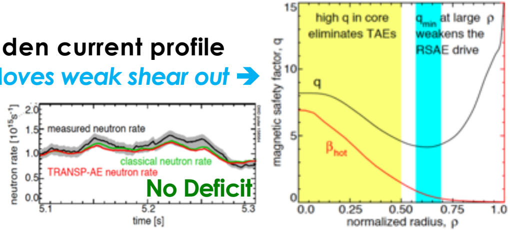
- **Potential for Alfvénic resonances in weak magnetic shear regions**
  – Overlapping modes lead to transport







- **Broaden current profile**
  – *Moves weak shear out* ➔

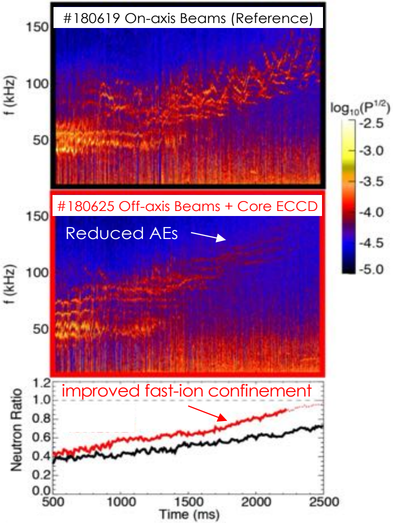


[Kramer 2018]

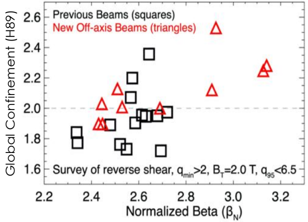
Current Broadening Demonstrated to Lead to Improved H and β_N in DIII-D with Off Axis Beams

Fast ion confinement raised 25%

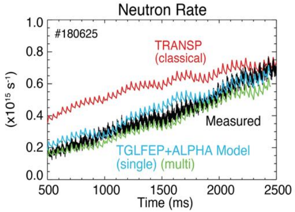
Key: Raise ρ_{qmin} to region of reduced EP gradient



Accessed new regimes with 15% higher β_N



Improved fast-ion transport modeling



[Collins IAEA 2020]

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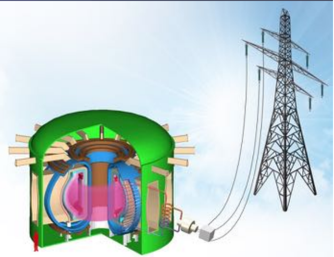
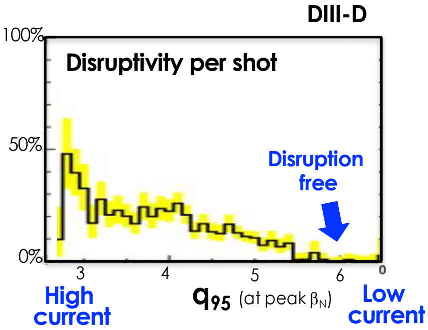
  Enables high performance at lower current, reducing heat loads, recirculating power & device stress



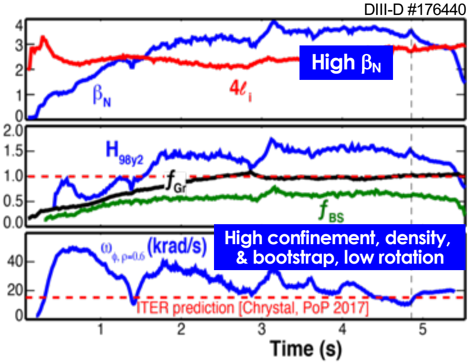
- Pilot power plant projection and benefits
- Research needs

Potential of Advanced Tokamak Approach to Steady State Demonstrated in DIII-D

- **Lower current dramatically improves stability**
  - Key: safety factor
  - No dependence on β_N



- **Broad current profile delivers high stability & confinement**
  - Density at Greenwald value with high bootstrap fraction



[Garofalo FED 2014]

[Huang NF 2020]

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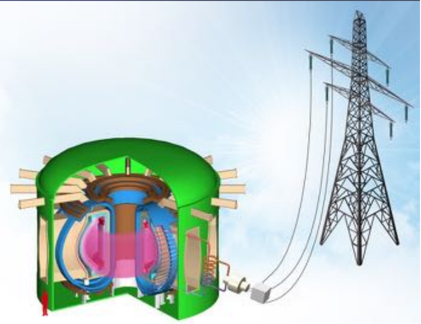


Based on Steady State Concepts Reactor Analytics Show a More Efficient & Robust Path is Possible

- **Recall fusion power:**

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

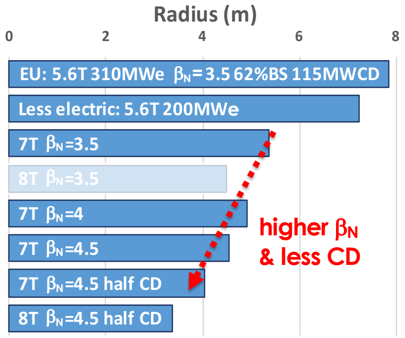
  – Raising β_N & B will reduce required device size, R, and still leave net electric

- **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, **higher β_N** & **less CD**

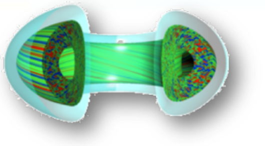
Smaller cheaper devices within reach



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

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

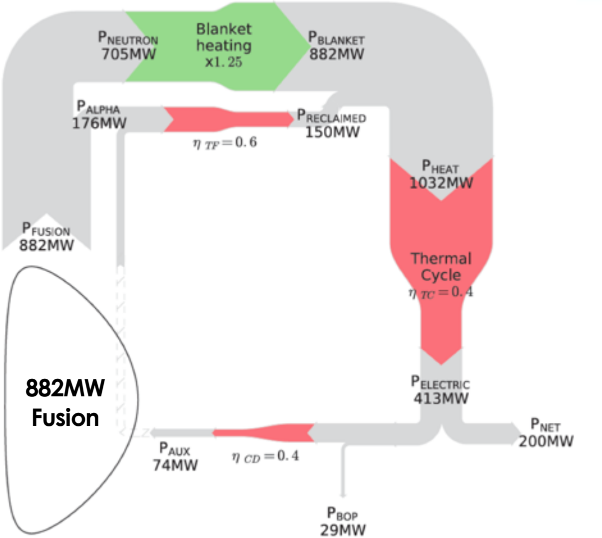
First predictive approach to reactor design!

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

6T, GA Systems Code

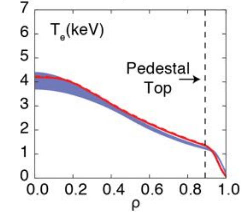
- **Large devices make plenty of fusion to heat plasma & power current drive**
- **Smaller devices must minimize ➔ losses at every step**
  - Otherwise no electricity left
  - *Or they might melt!*
- **Key is to minimize recirculating power**
  - Steady State approach
  - Efficient technology

Simulations explored how…
…with full physics models

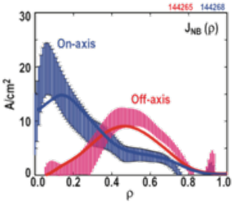


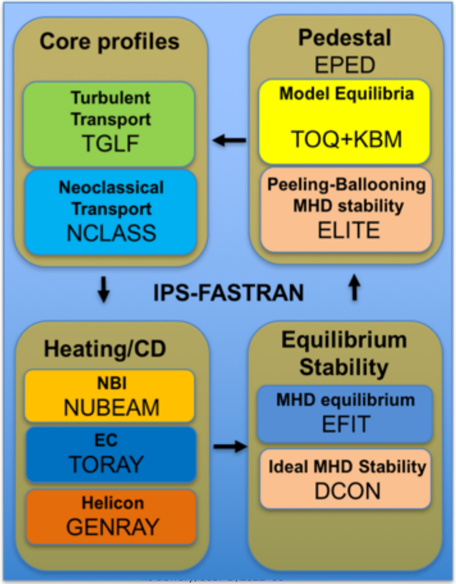
FASTRAN Integrated Simulation Suite Provides Tool To Validate Physics Models & Project Performance

Turbulent Transport
TGLF

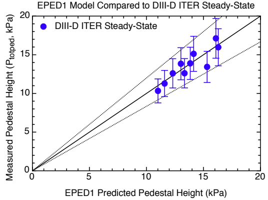


Off-axis Current Drive
NUBEAM

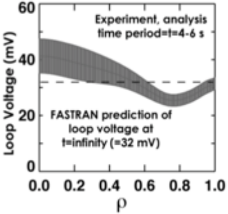




Edge Pedestal
EPED



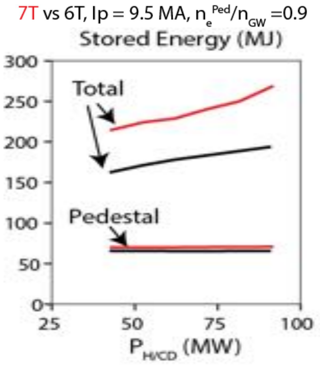
Equilibrium/Loop Voltage
EFIT



[Park Comp Phys Com 2017]

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

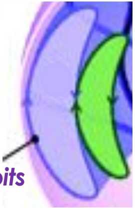
[Buttery NF 2021]

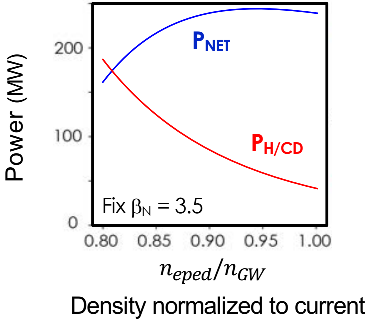
Increasing Density Enables More Bootstrap & Less CD Power

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

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

***Temperature effect depends on flows & orbits**

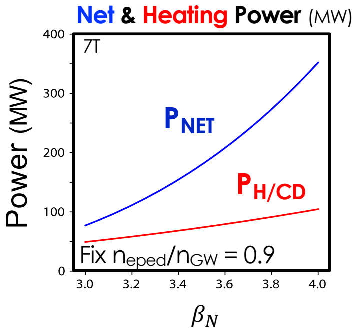


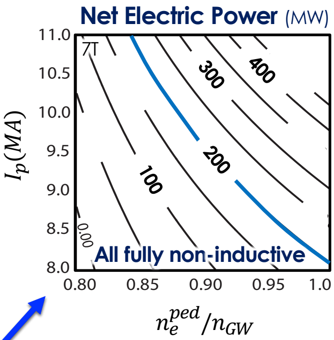


[Buttery NF 2021]

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**





	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

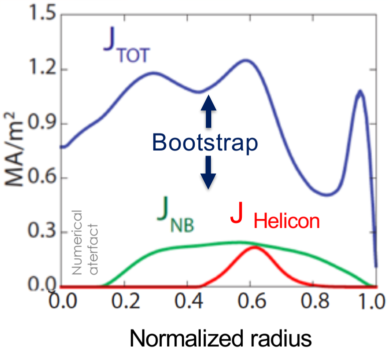
- *Family of fully non-inductive solutions at 4m radius*

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

[Buttery NF 2021]

Broad Profiles, Shaping & High β Lead to Improved Stability & Heat Loads

- **Broad profiles and higher field raise energy confinement**
  - Enables more compact and lower current approach
- **Higher pressure & density increase bootstrap**
  - **80-90% bootstrap current – reduce recirculating power**



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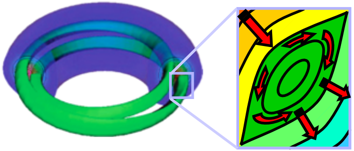
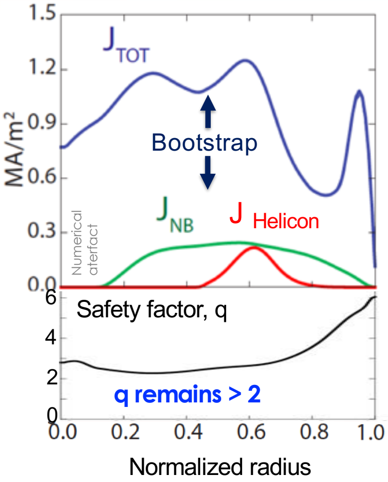
  - **Removes low order surfaces that tear and disrupt**





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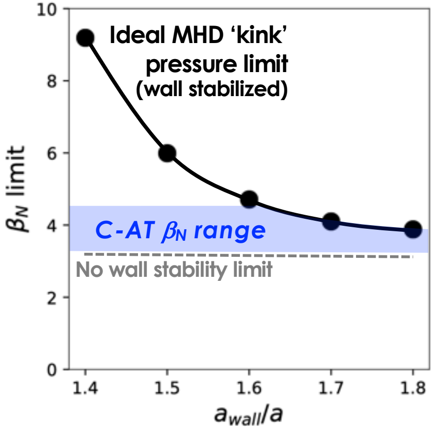
  - ***High β wall-stabilized even with high wall distance***



Wall : Plasma distance ratio

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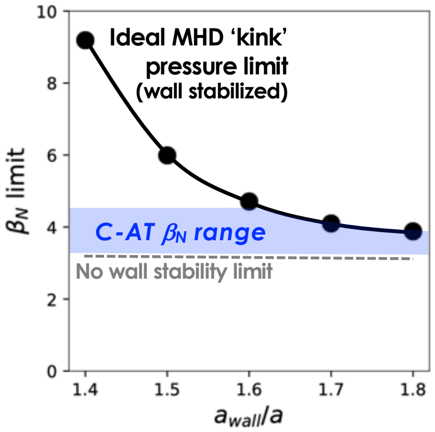
    - ➢ ***Reduced disruptivity, stresses and device risk***



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  - Decreases neutron loads at wall

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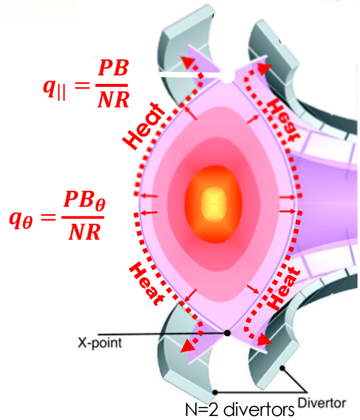
  - Decreases neutron loads at wall
- **Lower fusion power and current reduce heat fluxes**
  - **Modest core radiation needed to reach ITER-like heat fluxes**
    - *Still enough power through plasma edge to maintain 'H-mode'*
  - **A 24/7 fusion power plant will need to go further**

But key challenges remain…



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

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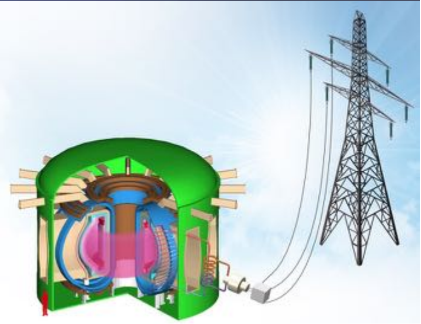
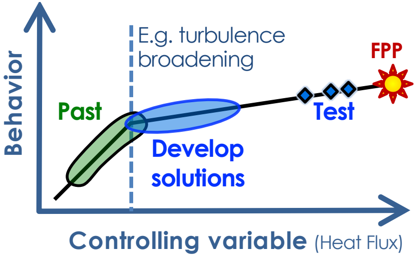
- **Research needs**



Key Plasma Physics Challenges Remain

- **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 all future concepts***

Position facilities above physics phase transitions to project FPP:

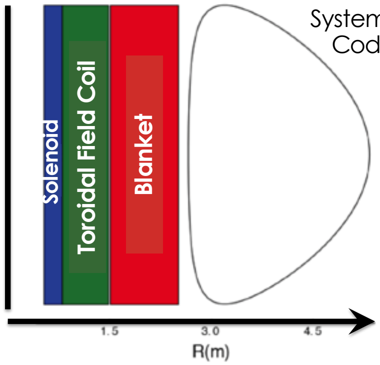


- **Requires exploration in relevant physics regimes**
  - Upgrade and exploit flexibility of present facilities to rapidly deliver answers
  - Execute key tests at high field (ITER, SPARC, DTT, BEST)
  - Theory advances and model based understanding critical to path

DIII-D, SPARC & NSTX-U will confront these challenges

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%



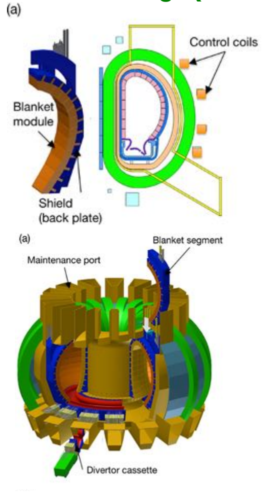
[*Stambaugh FST 2011]

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]

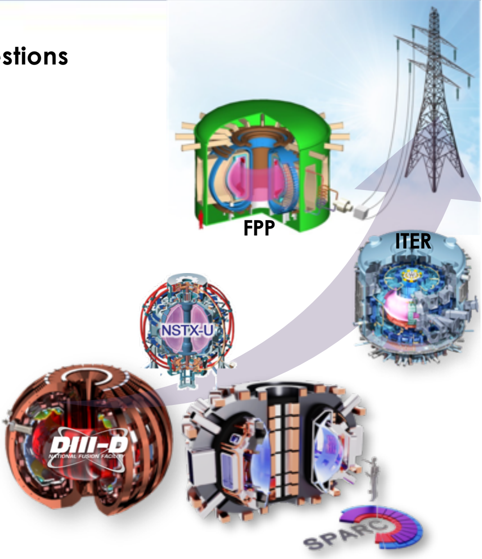
Time is of the Essence

- **Need to rapidly address science and technology questions**
  - *"what we'll know soon"* – don't wait for fantasy solutions
  - Target research programs for near term answers
- **Resolution of the confinement concept will emerge from forthcoming research on near term facilities**
  - Partnership, complementarity, goal-orientation
  - Innovation, scientific foundation & models are key

I would say…

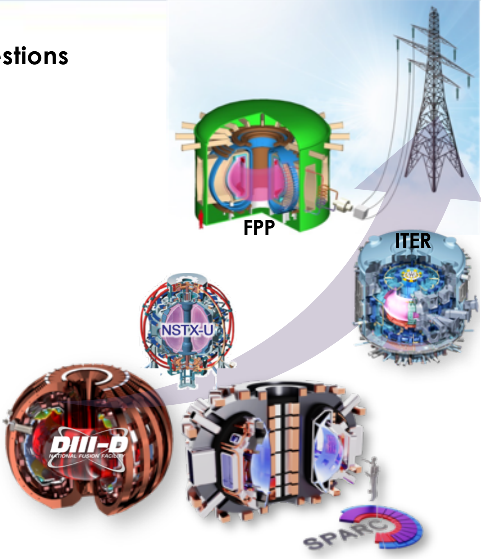
"Steady state concept confers key advantages in lowering required performance, disruptivity, heat flux and device stress."

…but we will all embrace what obviously works



Time is of the Essence

- **Need to rapidly address science and technology questions**
  - *"what we'll know soon"* – don't wait for fantasy solutions
  - Target research programs for near term answers
- **Resolution of the confinement concept will emerge from forthcoming research on near term facilities**
  - Partnership, complementarity, goal-orientation
  - Innovation, scientific foundation & models are key
- **Vital to invest in required technology programs and start serious reactor design studies**
  - Critical to engage private sector, government too slow for major new facilities
  - Staggered decision making design process



An exciting time – our research can resolve critical solutions to make fusion energy happen