The Advanced Tokamak Path to a Compact Demonstration Fusion Pilot Plant

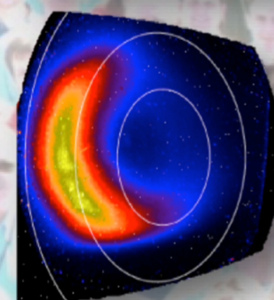
By

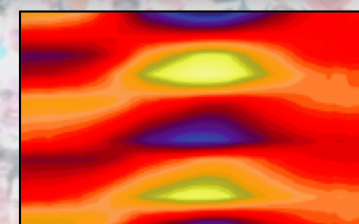
RJ Buttery, JT McClenaghan, JM Park, D Weisberg, J Canik, J Ferron, A Garofalo, C Holcomb, PB Snyder and H Zohm

at the

PPPL (PAC talks)

Princeton, New Jersey





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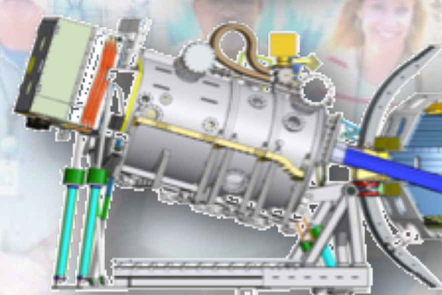

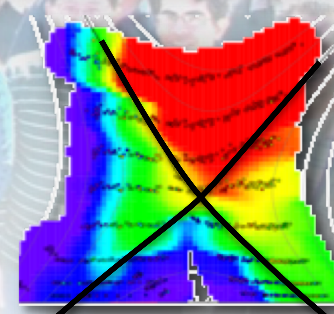

This work is supported by the US DOE under DE-FC02-04ER54698.

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GENERAL ATOMICS

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

- **Presently envisaged steps beyond ITER are largely based on the conventional aspect ratio Advanced Tokamak**
  - EU, Japan, Korea roadmaps to DEMO
  - CFETR & FNSF to test technologies
  - ARC MIT compact reactor
  - (EU stellarator: W7X→HELIAS-ITER→DEMO)

- **But conservative plasma assumptions make most proposals large and expensive**
  - *Low beta – requires driven current & heat*
  - *Huge fusion power to run H&CD systems*
  - *High neutrons & divertor challenge*

Typically 8m radius & 40% driven current !

The Advanced Tokamak Concept Offers a Much More Efficient Route To Fusion Energy

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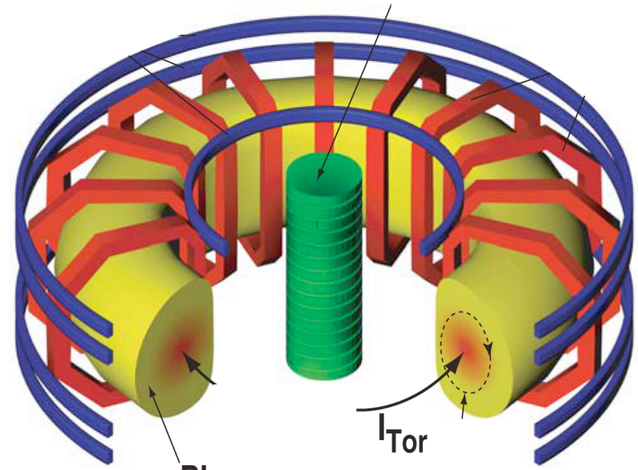
A Fusion Reactor Must Sustain its Current Non-inductively for Steady State Operation

- **Sources of current:**

~ 0 expensive

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



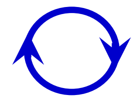
- **Goal: High pressure + High self-driven current**
  - Fusion power (High pressure)
  - Steady-state & high energy gain (High self-driven current)

- **The Advanced Tokamak naturally generates a high self-driven current**
  - **"Bootstrap current"** – arises at high plasma pressure
  - Avoids the need for expensive current drive

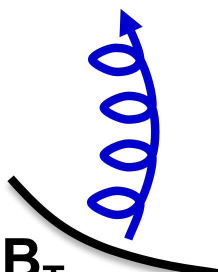
Baron von Münchhausen

High Pressure Gradients Lead to a Net 'Bootstrap' Current

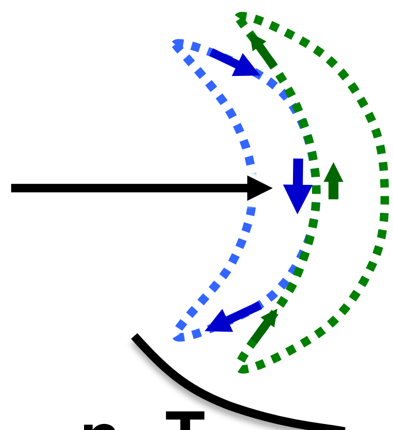
1. Ions execute gyro-orbits about toroidal field

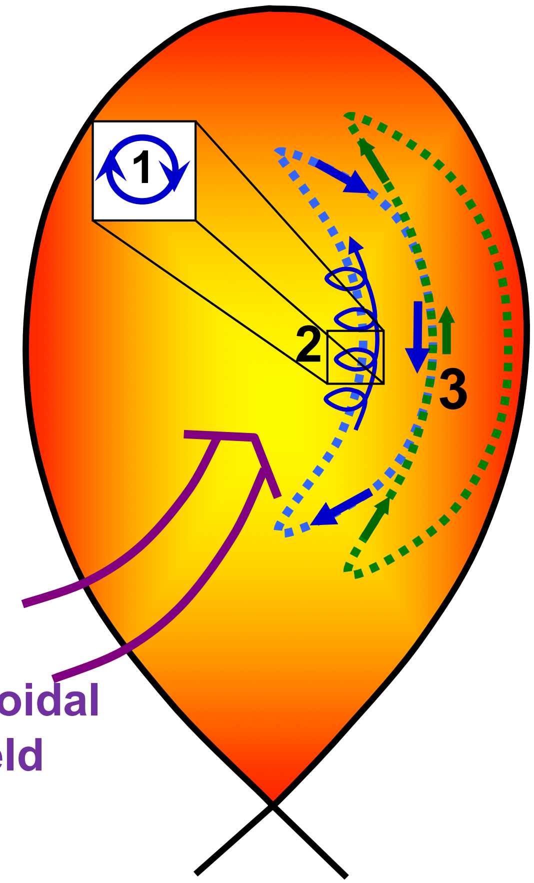


2. Gyro-orbits drift due to non-uniformity of magnetic field, tracing out "banana" orbits



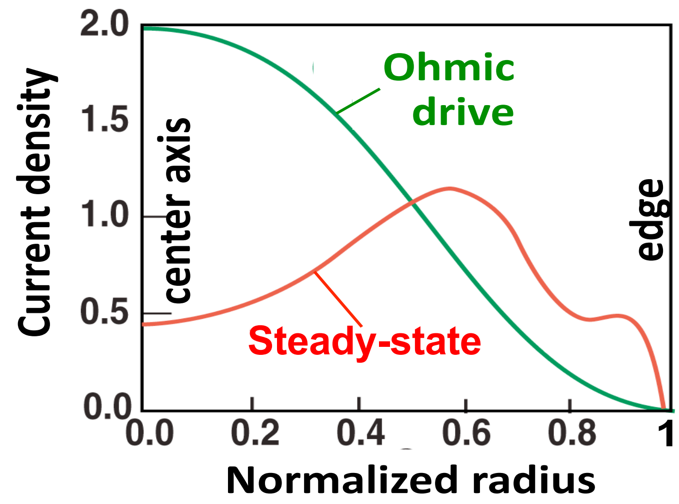
3. Higher densities and velocities on orbits nearer the core lead to a net current





Tokamak steady state exploits a natural synergy between off-axis profiles and high β operation

- **Pressure gradients drive bootstrap currents off axis**



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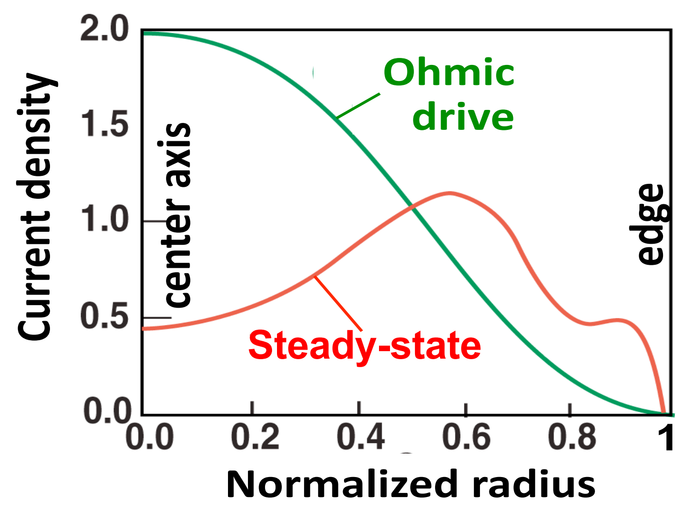
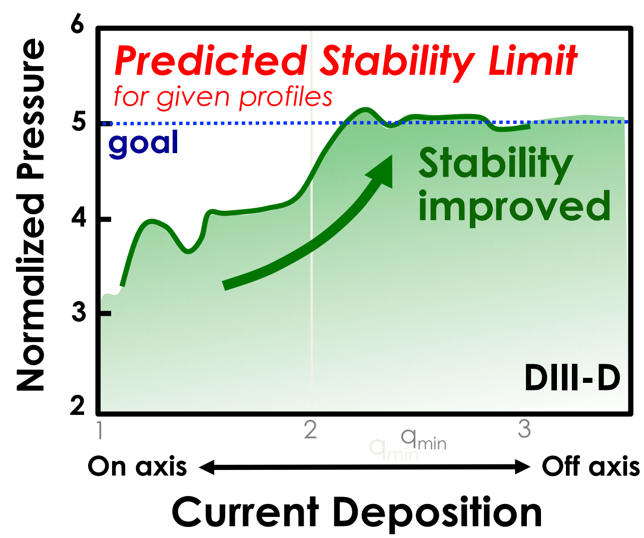
  - As eigenmode interacts with wall more





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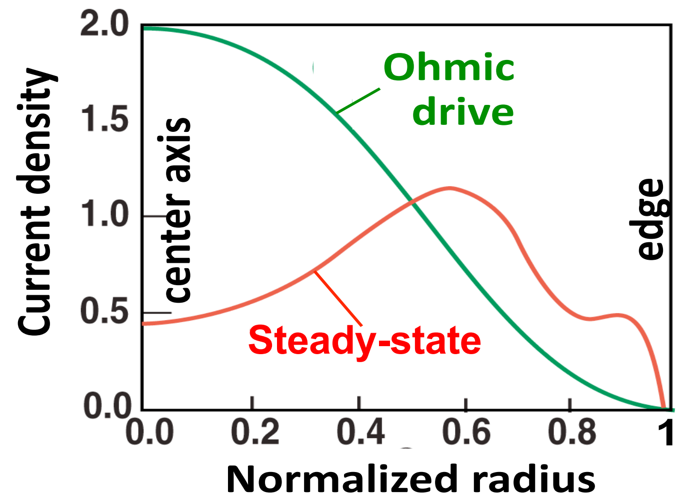
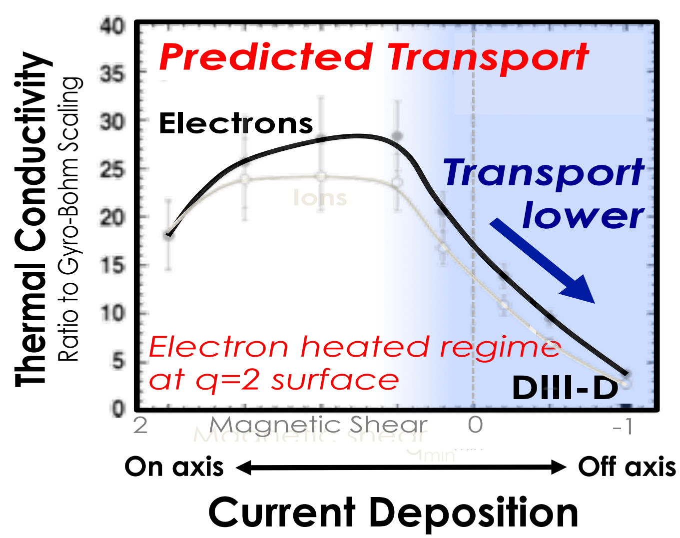
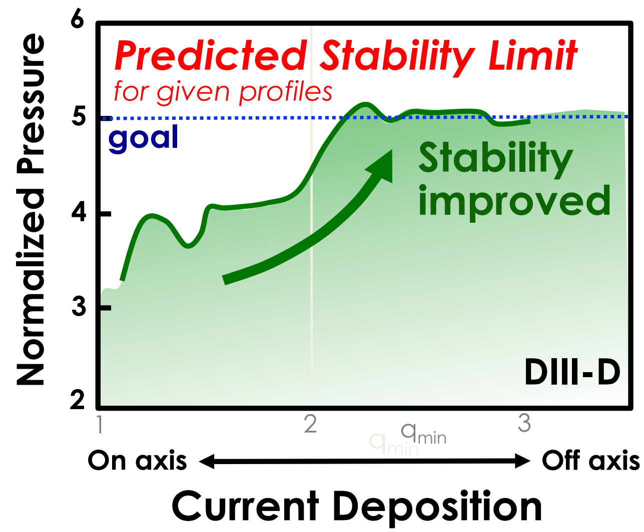
- **Pressure gradients drive bootstrap currents off axis**
- **Off-axis current distribution leads to higher pressure stability limit**
  - As eigenmode interacts with wall more
  - **And reduced transport**







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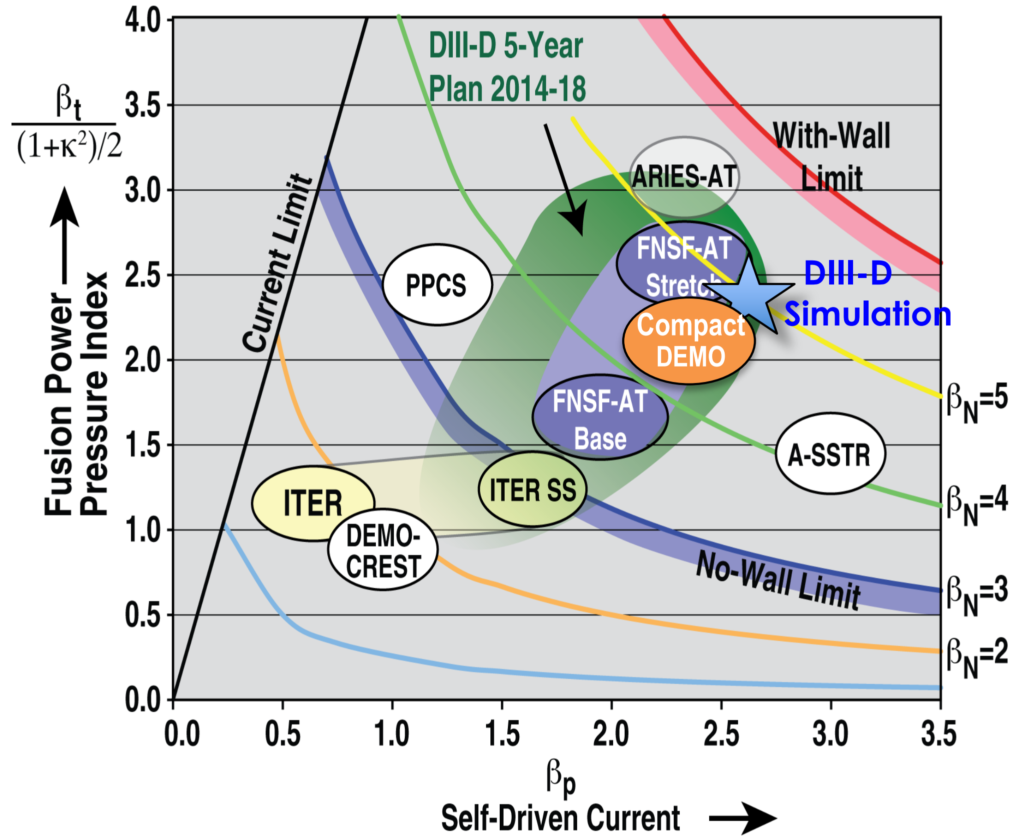
Future Fusion Reactors Require Both High Plasma Pressure and Self-Driven Plasma Current

- **Fusion power**
  - $\beta_T \sim P / B_T^2$
- **Bootstrap fraction**
  - $\beta_P \sim P / I_P^2$

➔ **High β_N is needed**

Range to be explored:



This is the physics range DIII-D aims to explore
But what devices do we need to get there?

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Present Paths to Fusion Energy Are Not Optimized For a Speedy or Politically Acceptable Approach

- **EU, Japan, Korea argue a 2 step approach after ITER**
  - ITER → DEMO → Fusion Power Plant (FPP)
    - *DEMO integrates material, breeding development, and power plant potential*
  - ***But these DEMOs are very large and expensive – program killers?***
    - ***Does DEMO need to be this big to fulfill its demonstration mission?***
- **US has argued 3 step approach after ITER**
  - ITER → FNSF → DEMO → FPP
    - *FNSF resolves materials and breeding*
    - *DEMO prepares for FPP, but will still not be efficient*
  - ***This adds a generation timescale to fusion energy and seeks a machine that does not generate electricity! Is this credible?***

A more compact DEMO could achieve materials and breeding mission while still providing proof of the power plant concept

– ***Must learn enough that we could follow up with a competitive FPP***

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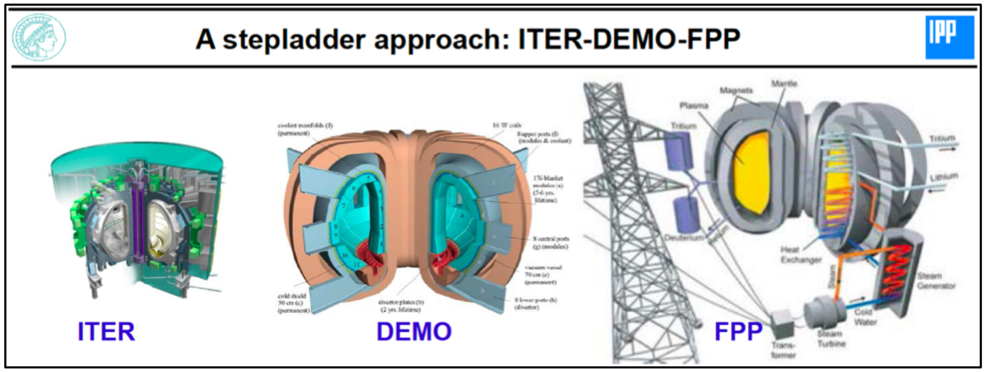
Next Step ‘Advanced Tokamaks’ Are Too Pessimistic on Plasma Physics

- **EU DEMO studies based on pragmatic “*what can we do now?*”**
  - **Smaller scale & lower net electric than a power plant**
  - 5.6T, ~8m, ~0.5GWe, β_N~3.5, q_{95}~4.5, f_{BS}~62%
  - **Still significant size & cost**



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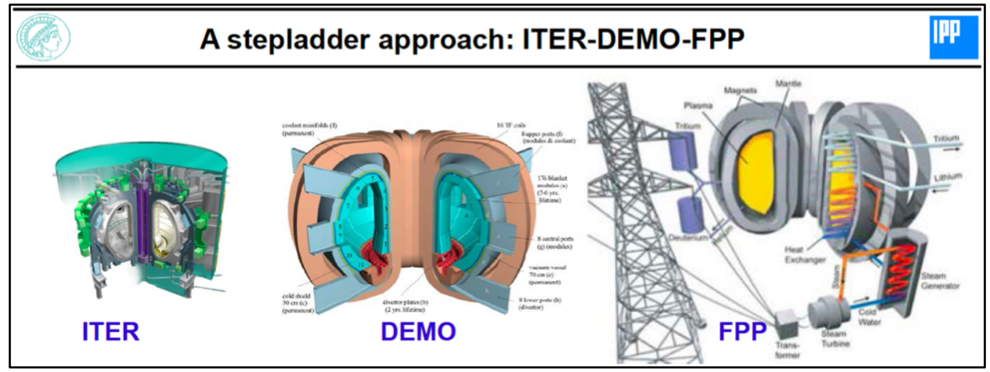
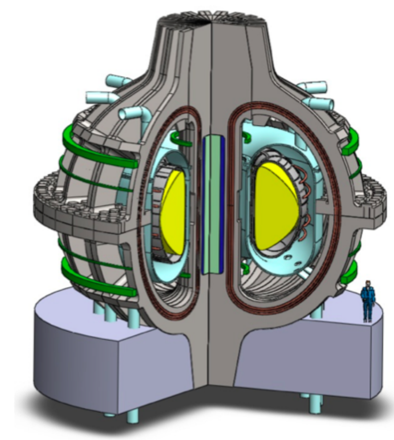


- **MIT's ARC, a compact higher B device**
  - Based on advances in superconducting technologies
  - 9T, ~3.3m, ~200MWe, β_N~2.6, q_{95}~7, f_{BS}~63%
  - **Significant technology assumptions**



- **Required current drive raises recirculating power**
  - Drives up size, cost, neutrons, heat load

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  - S
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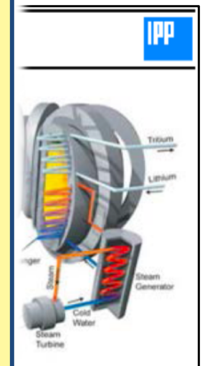

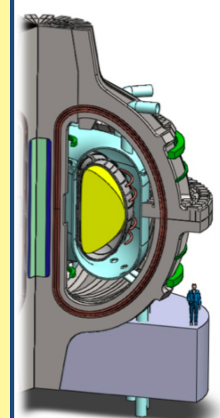

Basis for improved approach

- **Back off further on net electric power**
  - Enough to show viability of FPP? Chose 200MW
- **Low recirculating power → higher β_N**
  - **The true AT path – high bootstrap & self heating**
  - Avoid wasting lots of fusion energy in H&CD systems that challenges wall and divertor
- **Compact size, but provide margin in B_T, η_{th}, η_{CD} & reduce aggressive assumptions**
  - Affordable, enable several testing devices
- **Some optimism: Pose tractable research challenge**
  - Set some things to progress on to enable go ahead
  - Some optimism beyond "*what can we do now?*"

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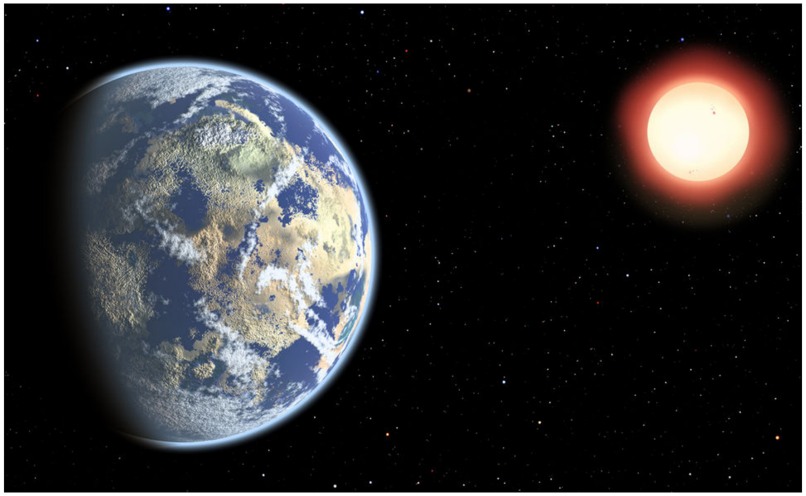
Mission of A Compact Pilot Plant Should Be To Bridge To Fusion Power Plant in One Step, Alongside ITER

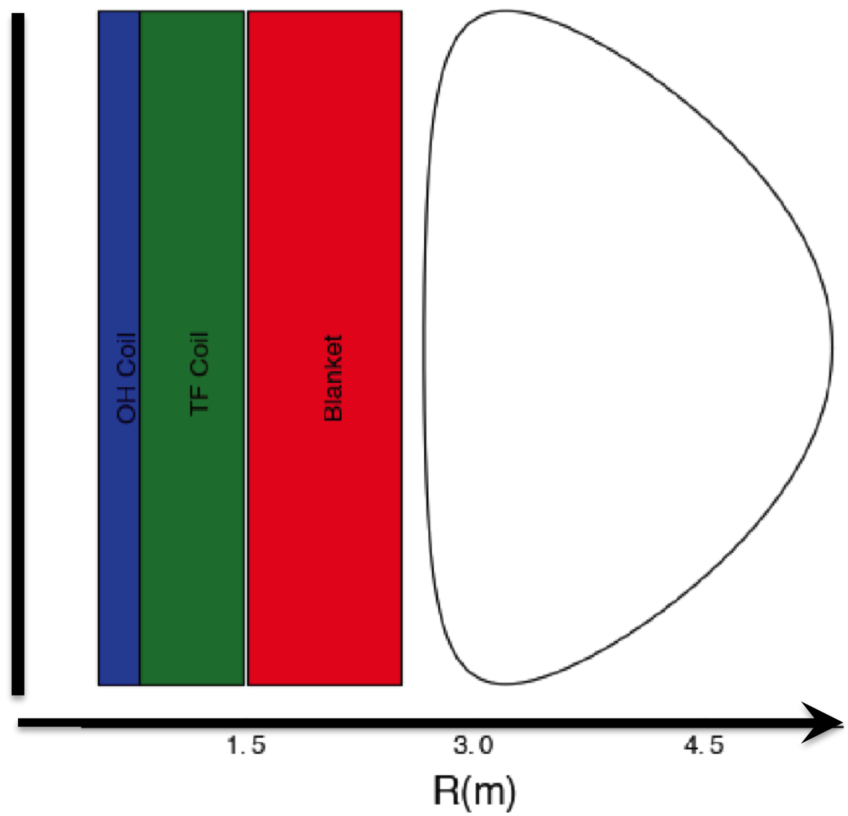


- **Demonstrate net electricity production**
  - Integration of heat → electricity generation with reactor core
  - Proof of potential – device can power itself and make electricity (performance + efficient systems)
- **Test nuclear materials in fusion reactor environment**
  - Require neutron loading and change-outs for rapid testing at rate that still leaves time for healing properties to emerge
- **Demonstrate and optimize breeding technology**
- **Show configuration can be sustained in truly long pulse conditions (months)**

A Compact Pilot Plant could be started soon, make energy, and lay the groundwork for low COE successors

Considerations for a Compact AT Pilot Plant

- **World context and need for a Compact AT Pilot Plant**
- **Approach, Tools, Targets and Assumptions**
- **Integrated transport simulation to resolve design optimization**
- **Heat Load, H mode, Force Requirements**
- **Conclusions**



EU-DEMO Analytics Shows More Attractive Path is Possible

- **Fusion power scales with β_N, B, R and I_P**

Stepladder approach in 0-D

For fixed β_N, H, q, A, f_{rec}, n, we can determine sets of (B_t, R) pairs **[Zohm APS 2016]**

- $P_{fus} = c_{fus} \frac{{\beta_N}^2 B^4 R^3}{A^4 q^2}$ will increase with B and R
- $n = f_{GW} n_{GW} \propto f_{GW} \frac{B}{qR}$, so constant n and n_{GW} means constant B/R
- R (and B) scale with $(P_{fus})^{1/7}$ from device to device
- $P_{CD} = c_{CD} \frac{B}{q^2} \frac{{f_{GW}}^2}{\beta_N} \left(5 + c_{exh} \left(\frac{P_{fus}}{5R} + \frac{P_{CD}}{R} - \frac{P_{sep}}{R}\right)\right)\left(1 - c_{bs}\sqrt{A} q \beta_N\right)$ varies surprisingly little

⇒ at constant physics parameters, f_{rec} will drop substantially from DEMO to FPP ☺

EU-DEMO Analytics Shows More Attractive Path is Possible

- **DEMO should credibly challenge our research program**
  - EU DEMO based on what we know now - still large (and expensive)
  - Some confidence that we may make progress: higher B and β_N

*

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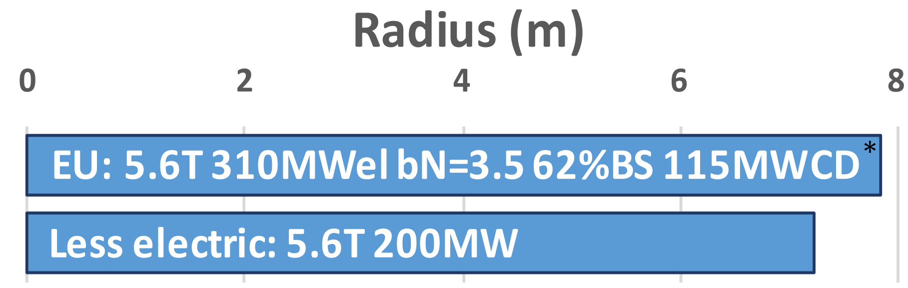
- **Extension of EU DEMO indicates cheaper devices within reach***
  - Rapid decrease in device size possible… **lower P_{elec}**



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*Based on Zohm analytic model, APS 2016

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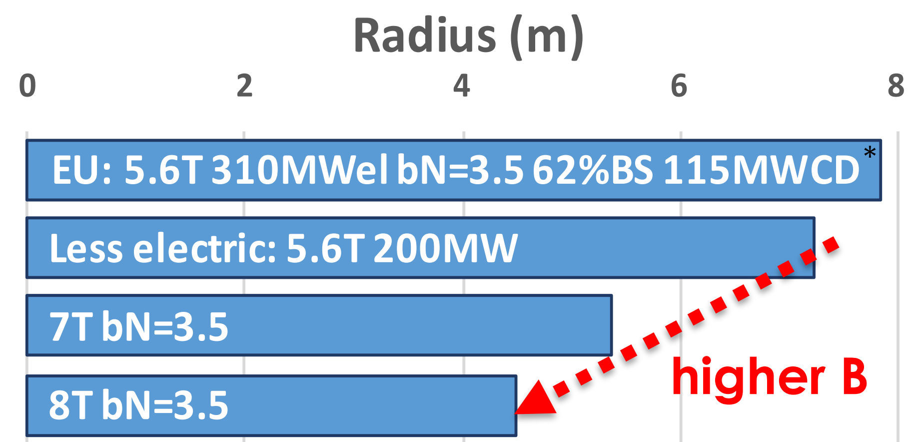

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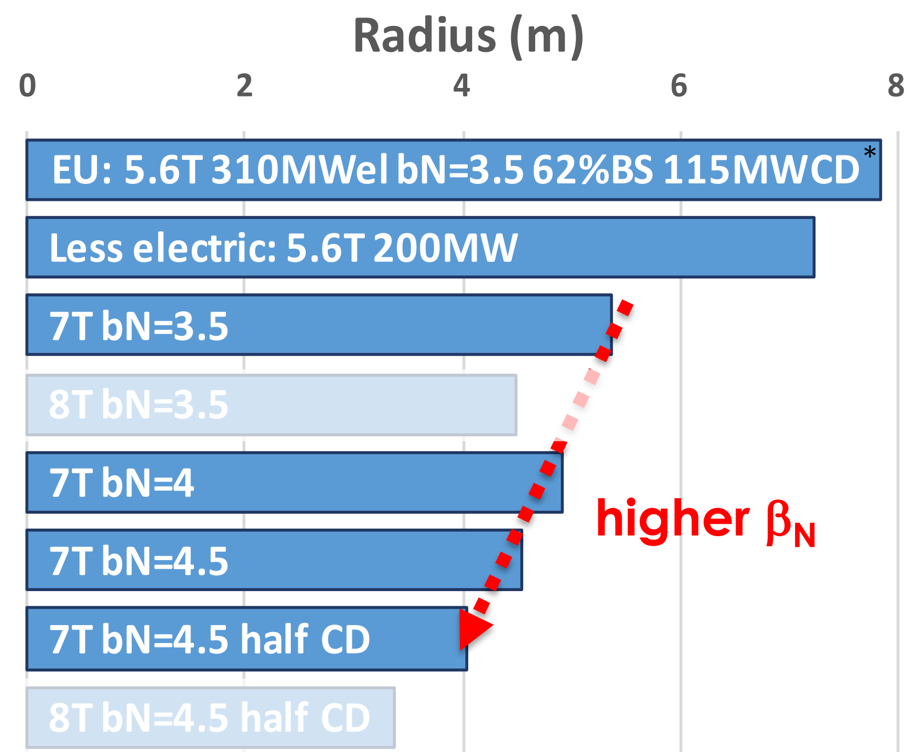

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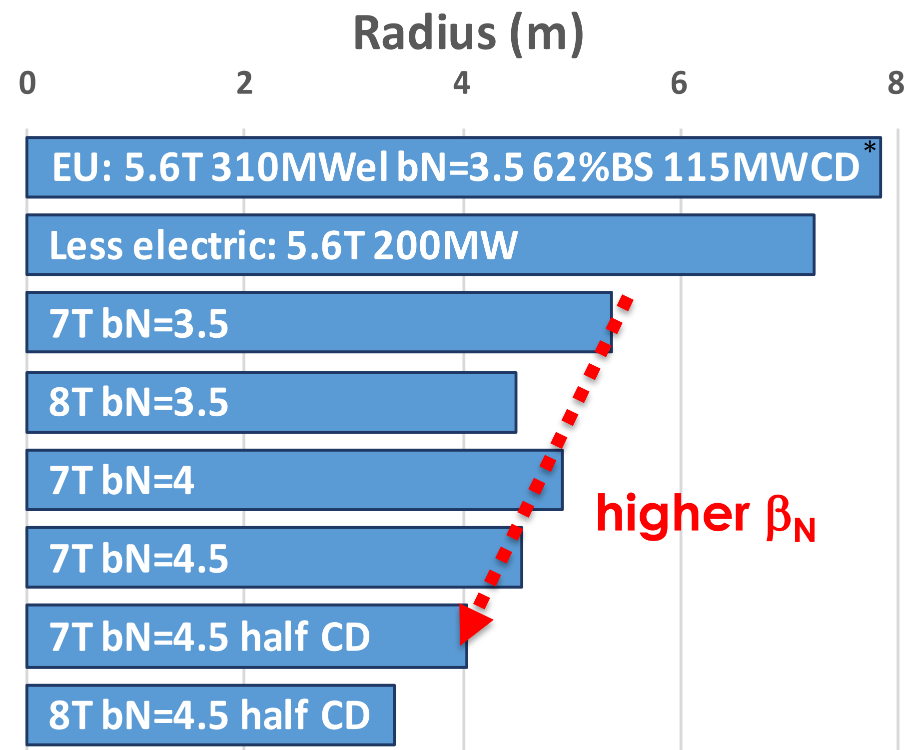
- **Sets challenge for research**
  - AT performance & control
  - Divertor-PMI solution
  - Materials. Superconductors. Breeding.



Is such a device possible?

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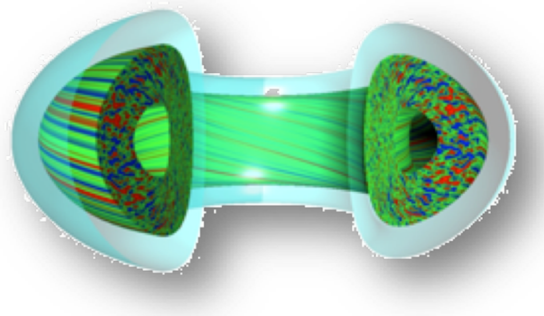
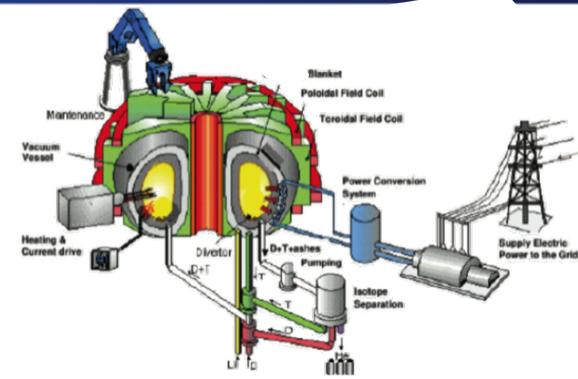
Study Launched to Determine if Compact AT Pilot Plant Is Viable, and to Understand Dependencies





FASTRAN full physics suite#

- **Integrated transport, pedestal, stability, H&CD solution**
  - Latest physics models+
  - Starting point to identify realistic physics challenge

GA Systems Code (GASC)*

- **Empirical known requirements**
  - Rapid exploration of space
  - Initial engineering constraints and compatibility
  - Shows required performance

Analyses & Consultation on Key Topics

- **Divertor challenge**
- **H mode access**
- **Neutron Load**
- **CD**
  - *Obviously many more topics to follow up later*

#TGLF, EPED1, NUBEAM ESC equilibrium

+may need validation for reactor parameters

GASC matches EU-DEMO when inputs matched

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Parameter Constraints and Goals For Compact AT Pilot Plant

- **~200MW net electric ← prove integrated solution can work**
  - Make enough energy & plant efficiency to close the loop
- **Compact size ← must be affordable & enable a testing mission**
  - Permit 3 – 6m (<=ITER), and 5 – 9T
- **Low recycling power → 90% bootstrap, modest auxiliary heating**
  - Implies high β_P + high performance→β_T, ➔ high β_N
- **Tolerable divertor challenge ←→ H mode access**
  - Trade off between these through core radiation assumption
- **Tolerable neutron load for wall testing mission ← 2-4MW/m^2**
  - Not so high that self-healing properties are lost

Device could set some challenges on issues we expect to progress in the next few years

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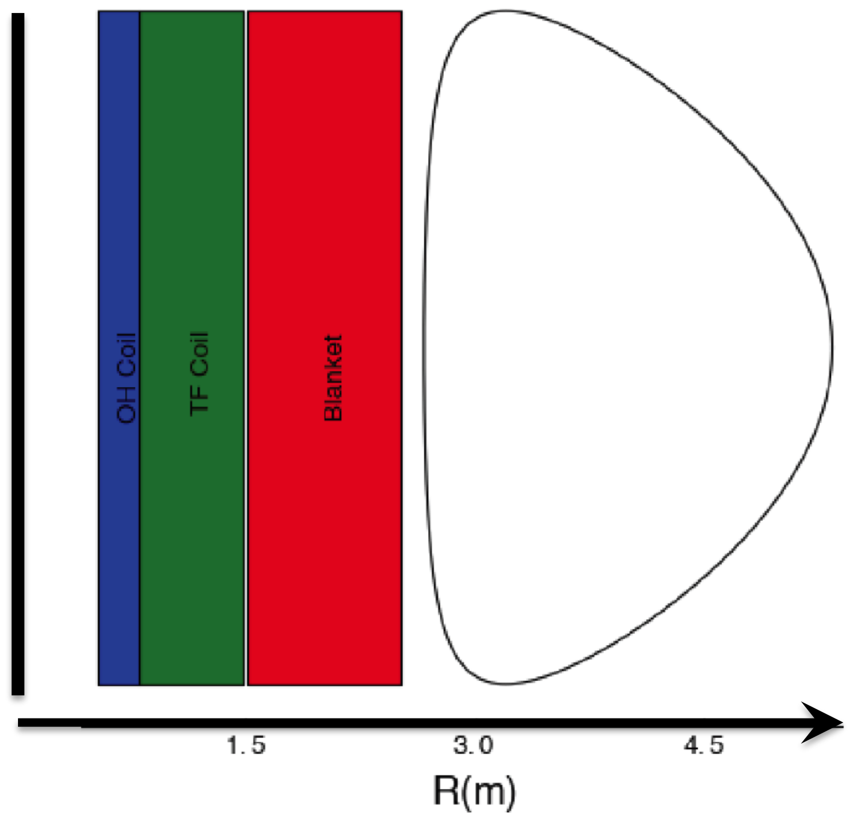
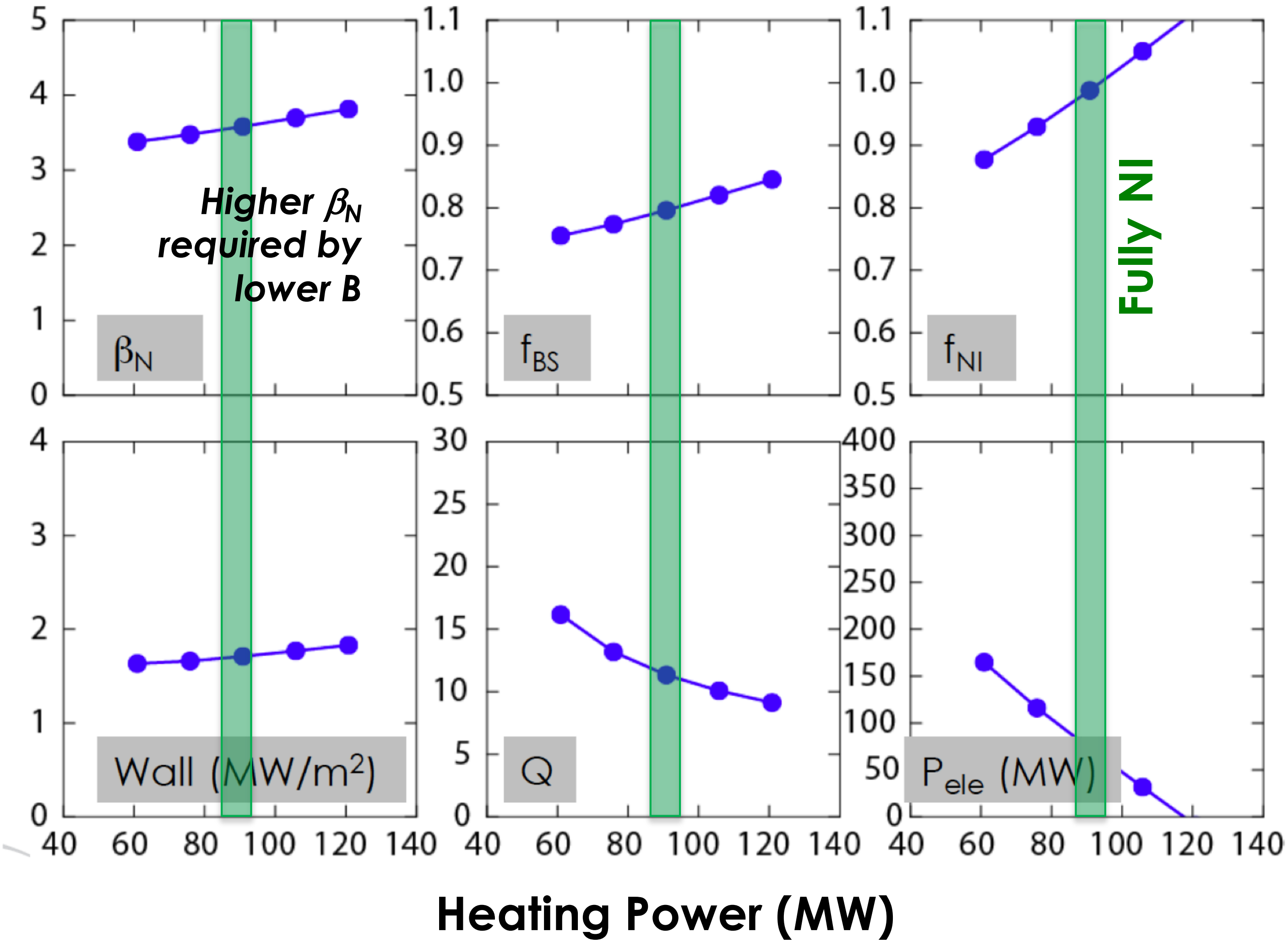


Initial FASTRAN Scan at 5m 5.3T Predicts Low β_N and Significant Recirculating Power !

- **Vary power…**
- **Fully non-inductive point at 90MW**

12MA n_e^{ped}/n_{GW}= 0.85 (f_{GW}~1.1)



FASTRAN simulations at 5m, 12MA 5.3T, q=5.2, η_{th}=0.33 η_{CD}=0.25*, f_{GW}=1.1(ped=0.85)

(*Overly pessimistic He ash model: $10\tau_E$)

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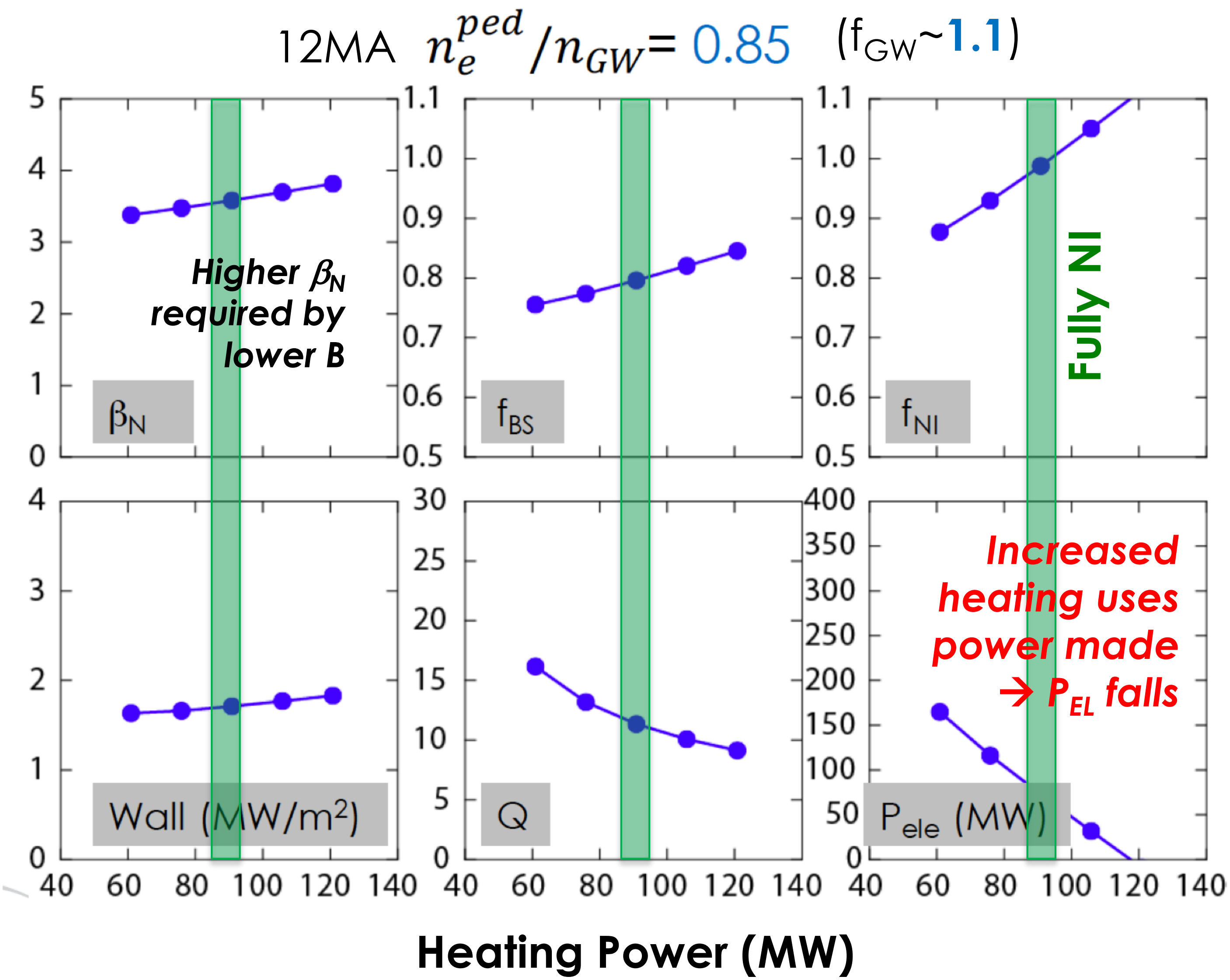
  - AT gives no win



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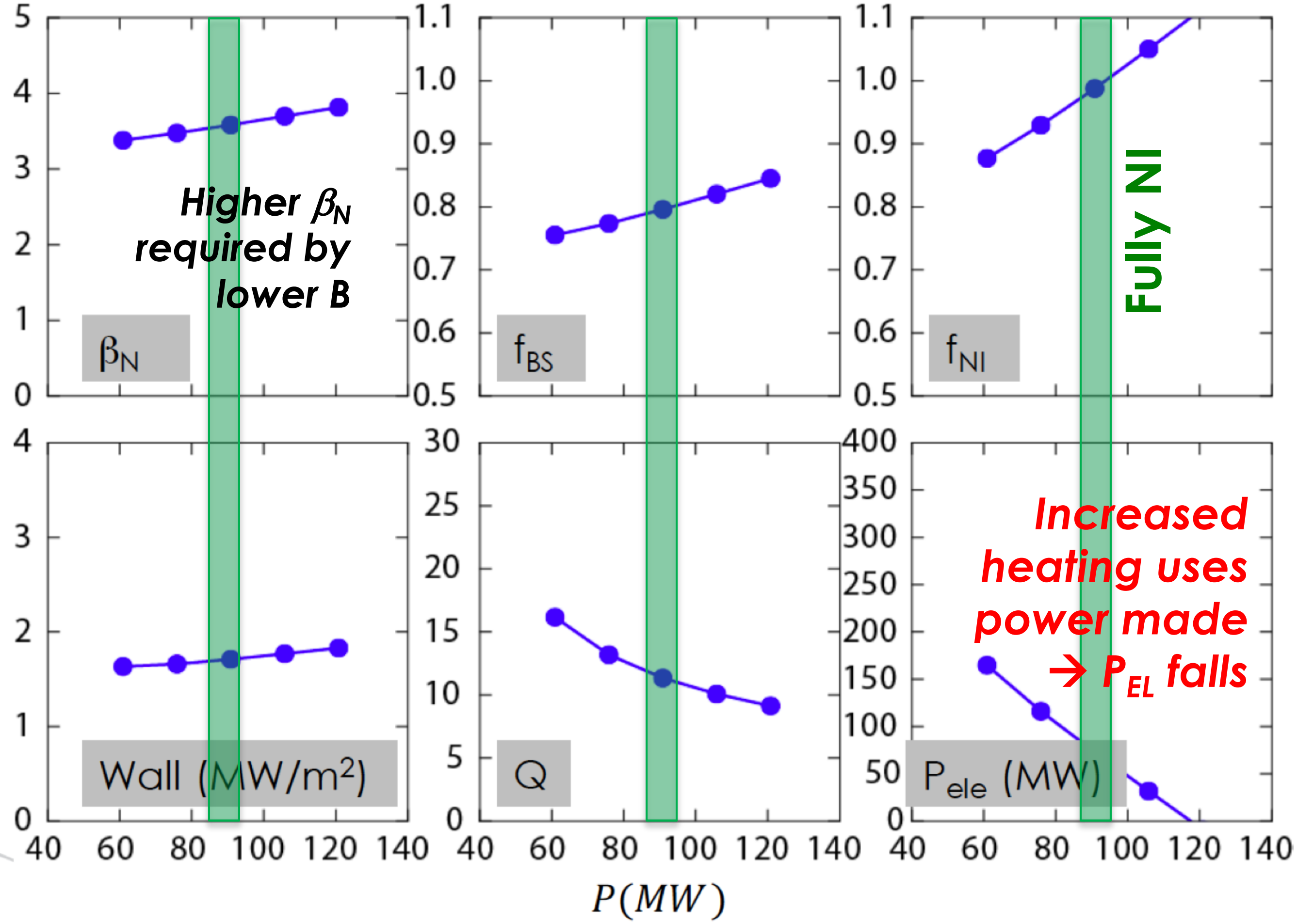

Need to raise performance !

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Explore Range of Fully Non-Inductive Solutions at 4.5m ...*But Confinement Limited*

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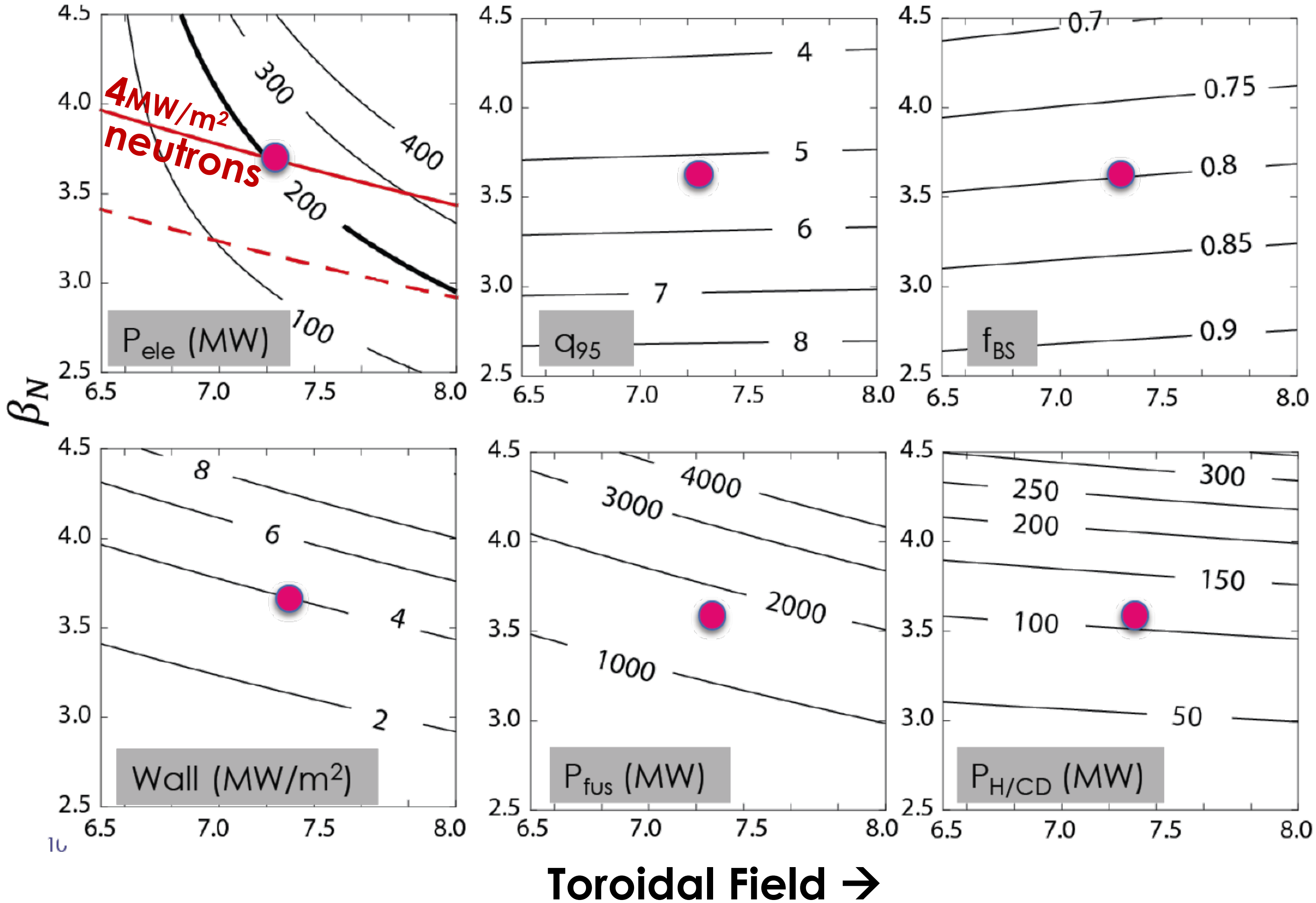

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**η's from EU-DEMO, cf ARC η_{th}=0.4 η_{CD}=0.43*

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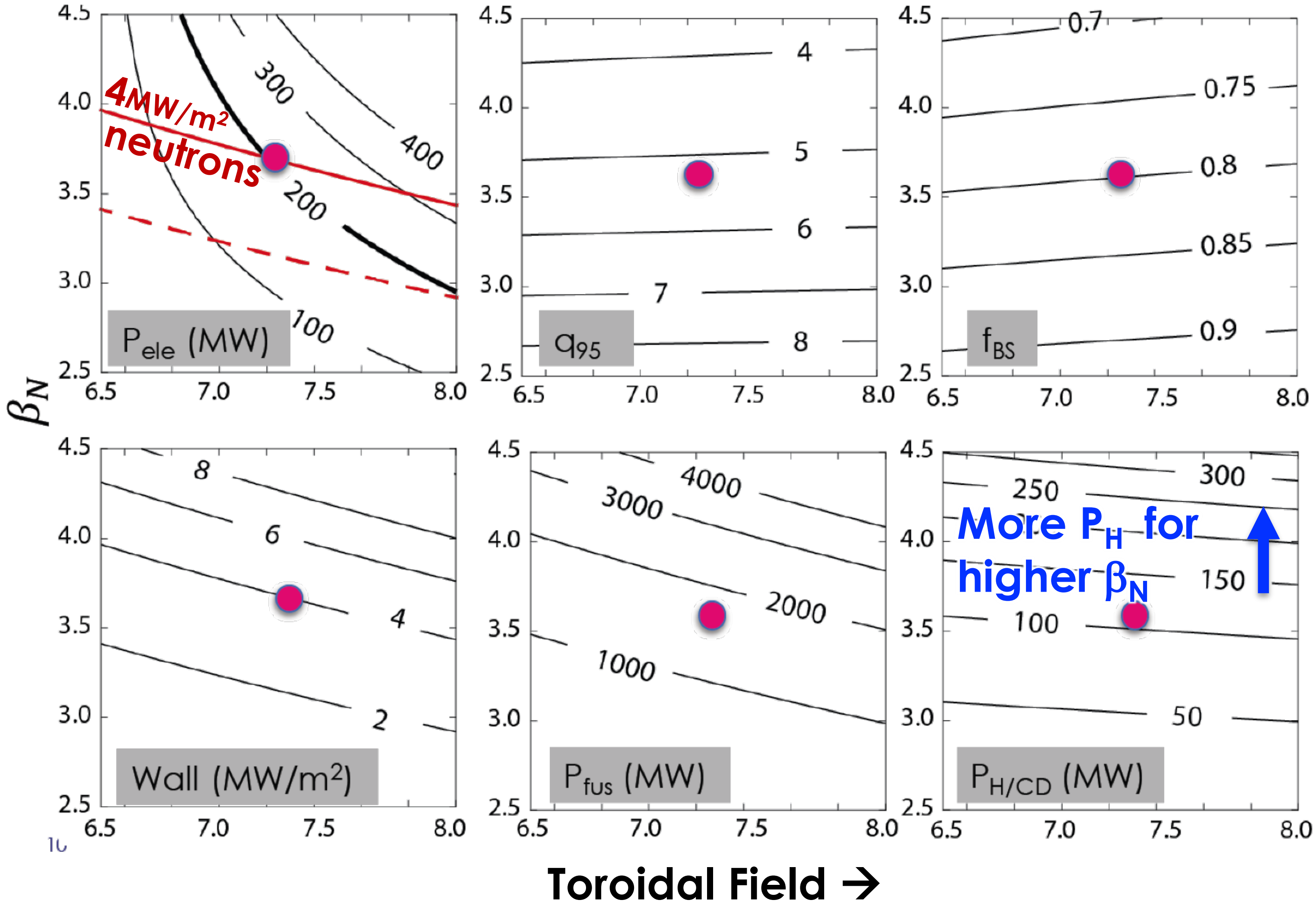

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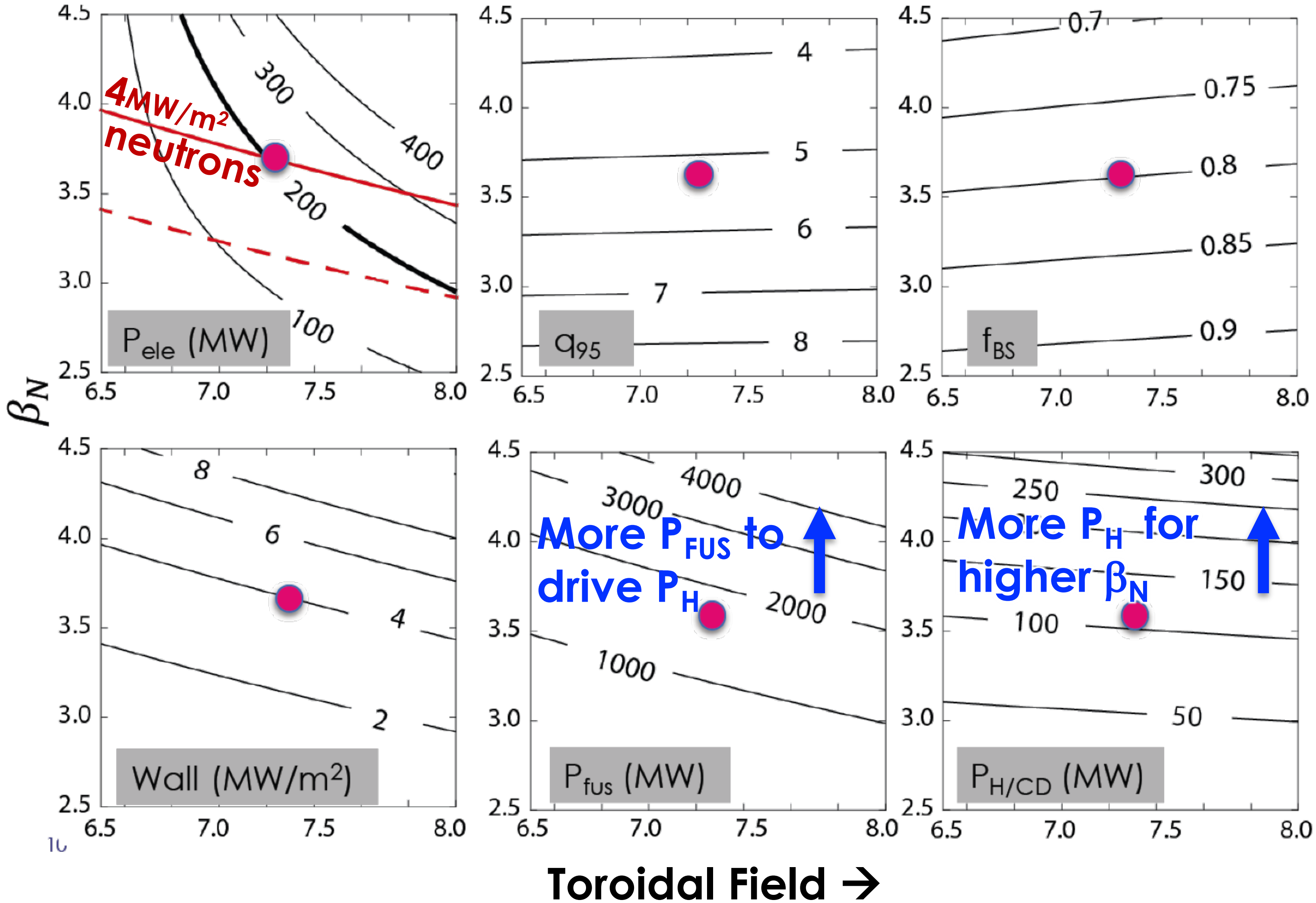

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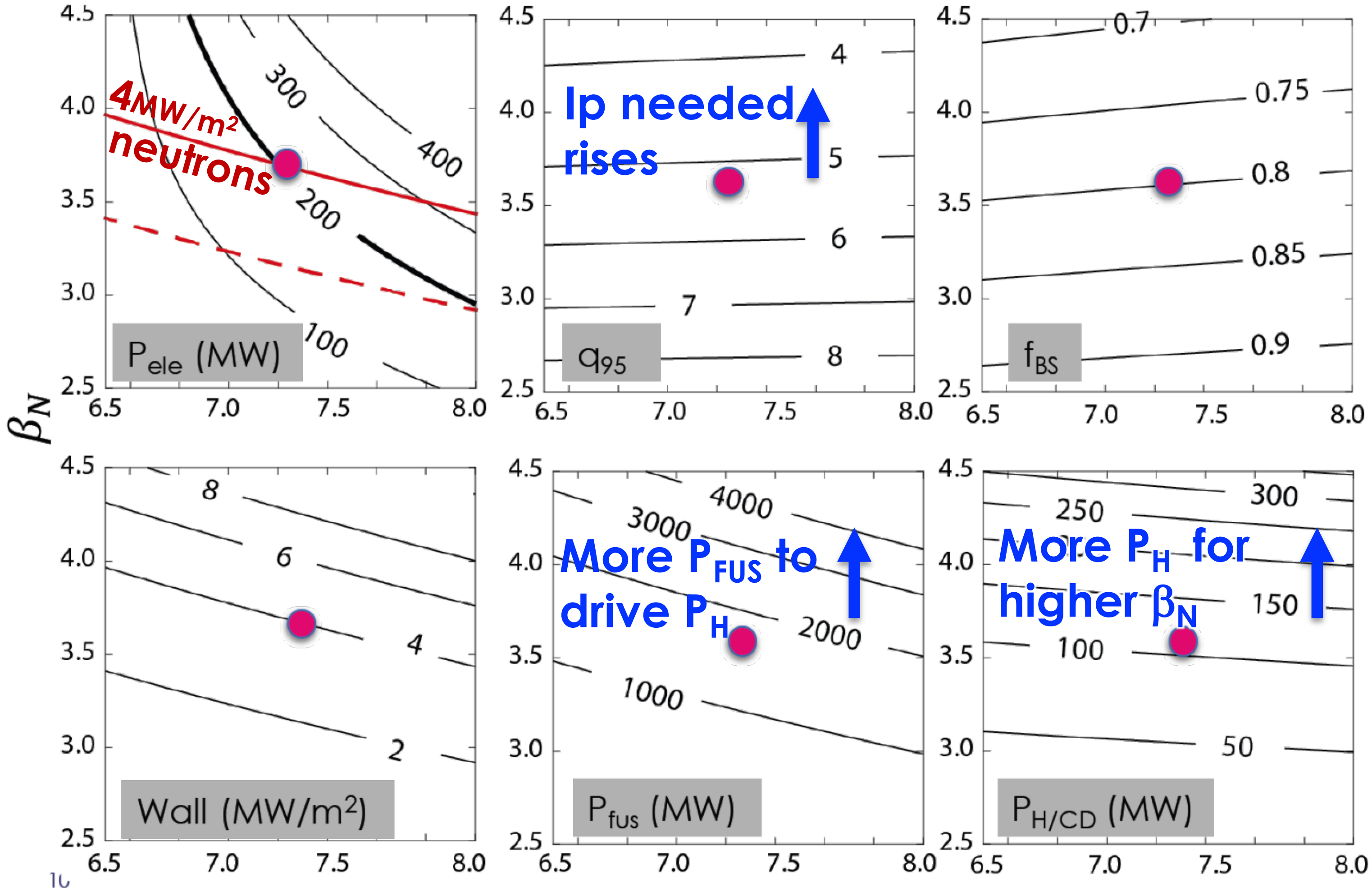

Toroidal Field →

All points here are fully non-inductive

*η's from EU-DEMO, cf ARC η_{th}=0.4 η_{CD}=0.43

Explore Range of Fully Non-Inductive Solutions at 4.5m …*But Confinement Limited*

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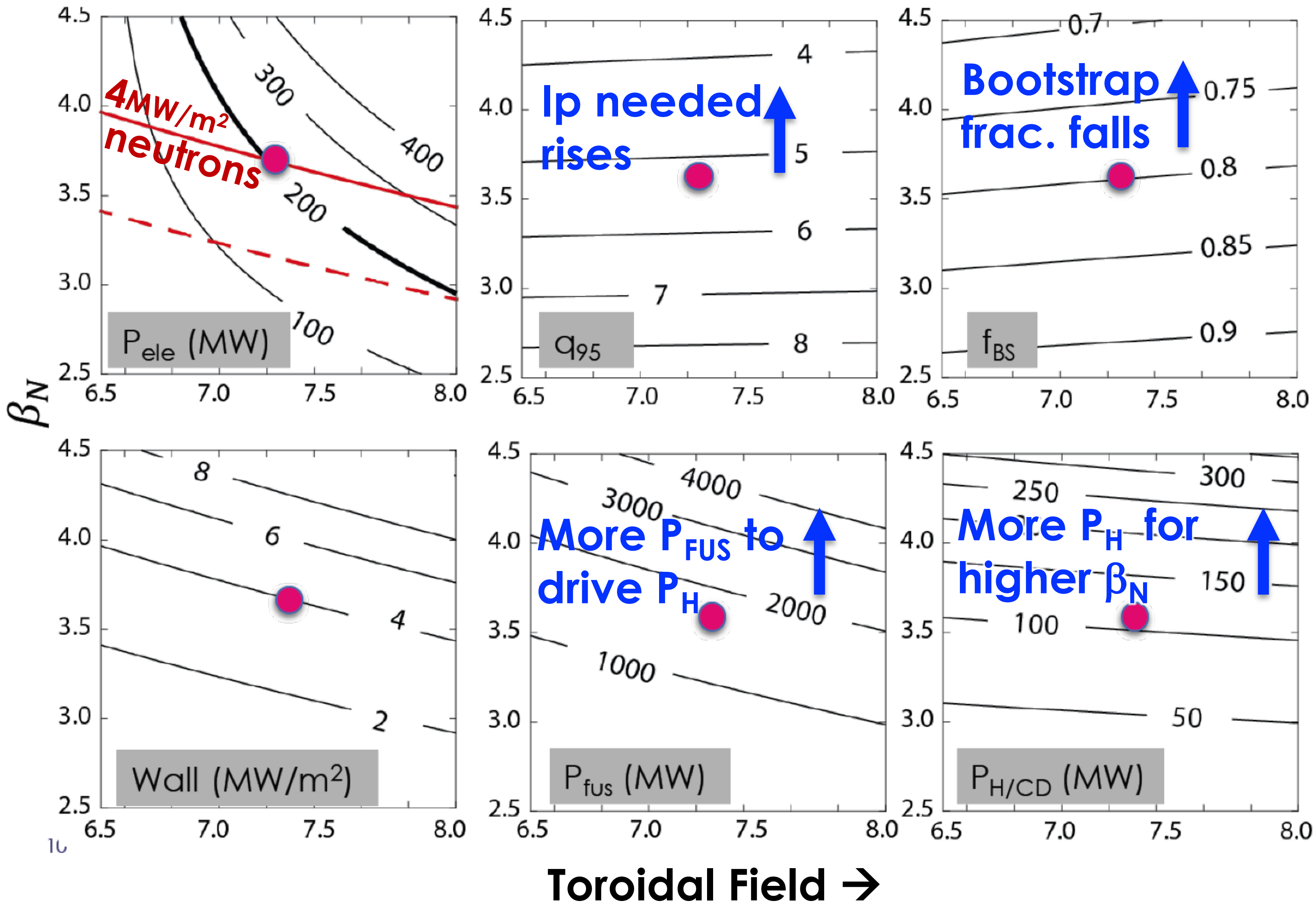

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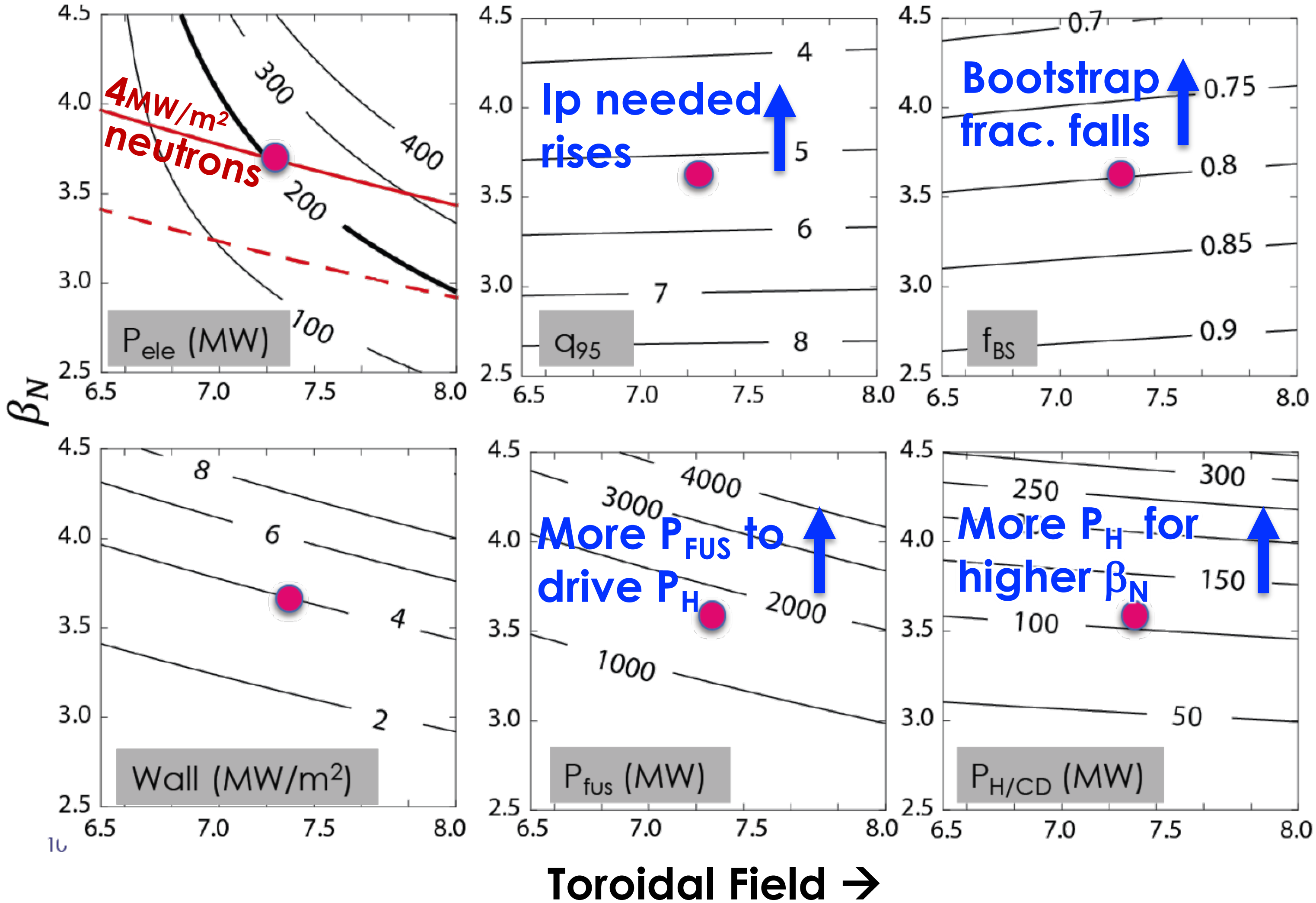


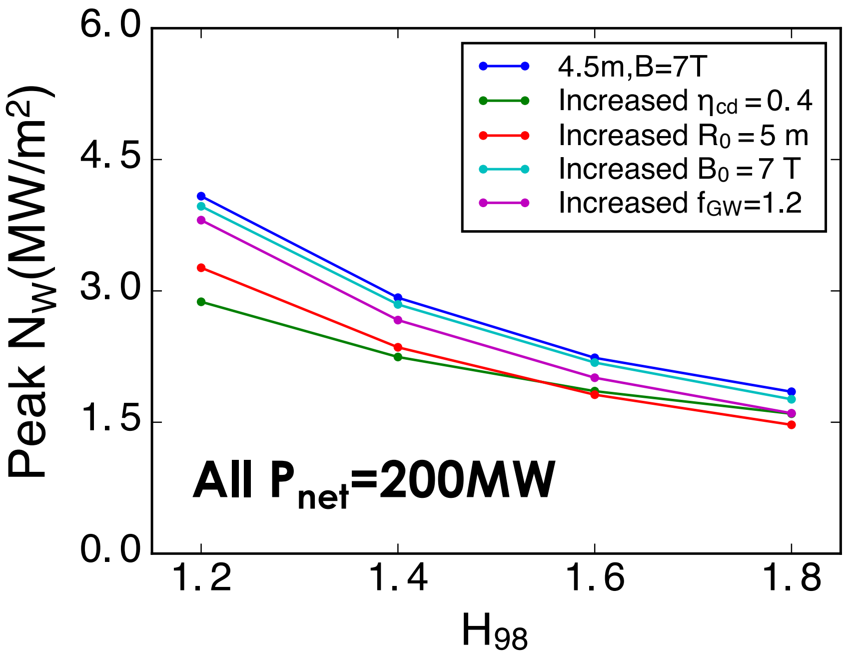
Float I_P for f_{NI}=1:

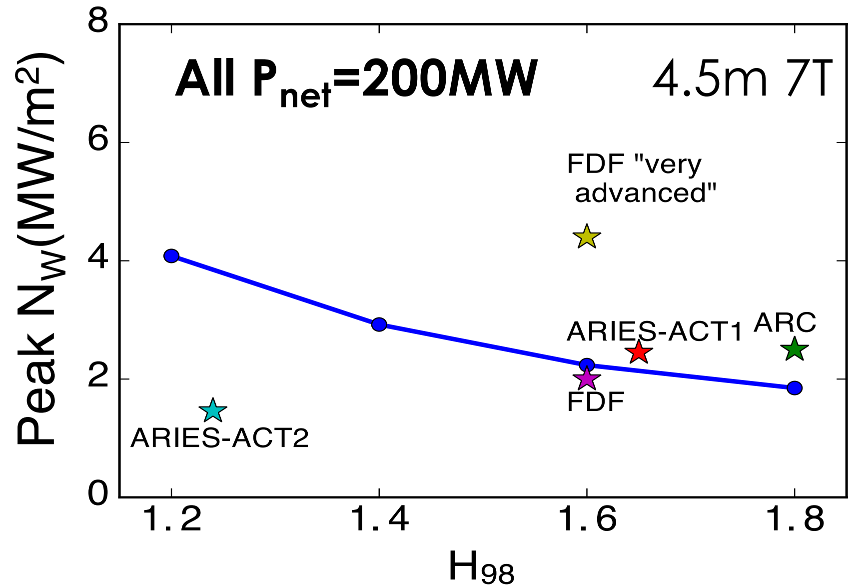
- **Optimizes to low β_N *!***
  - Confinement limited; *need heating to reach high β*
  - Drives up required P_{fus}
- **Neutron rate limited**
- **Recirculating power is high**
- *Note conservative efficiencies here**

Making a lot of fusion to drive auxiliary heating !

GA Systems Code Analysis Shows Rapid Decrease in Required Fusion Power and Neutrons as H_{98} Rises

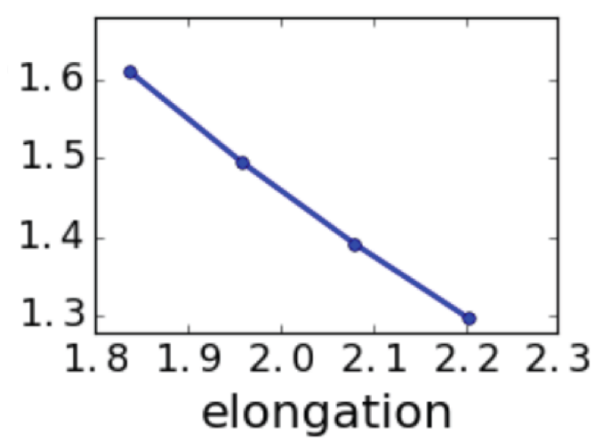
- **Higher H_{98} reduces → recirculating power**





← ***Higher R, B, f_{GW} & η_{CD} reduce required fusion power***

- **Elongation reduces required → H_{98} at constant P_{net}**

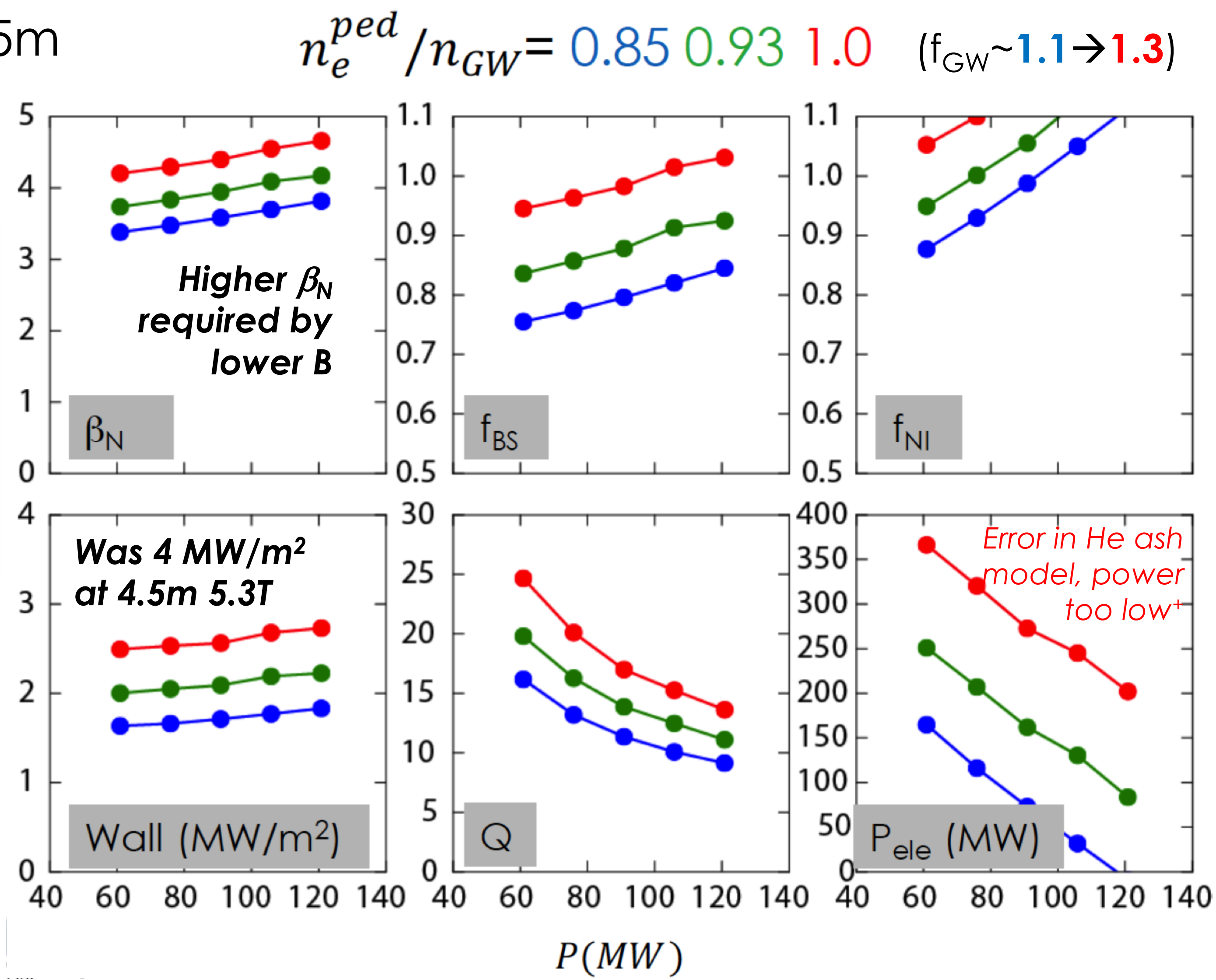


GASC **fully non-inductive** simulations at 4.5m 7T, η_{th}=0.4 η_{CD}=0.25, f_{GW}=1.1, H_{98}=1.6, P_{el}=200MW

5m Scan Shows Density to be a Key Levering Parameter

- FASTRAN: 12MA 5.3T 5m
  - Vary heating to explore tradeoffs
- **Increasing density**
  - Raises P_{fus}
  - Raises bootstrap
  - Decreases P_{CD}
  - Raises P_{el} & Q
- **200MWe attainable at lower P_H and N_{wall}**

Is there a 4m solution?



FASTRAN simulations at 5m, 12MA 5.3T, q=5.2, η_{th}=0.33 η_{CD}=0.25*, f_{GW}=1.1(ped=0.85)

(+Overly pessimistic He ash model: $10\tau_E$)

We Were Being a Bit Conservative with Efficiencies

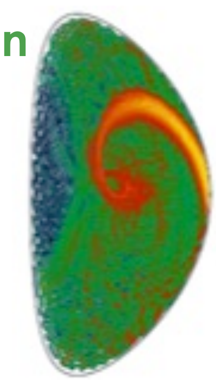
- **FASTRAN studies started with EU-DEMO η's ➔**
  - Well below other device designs as based on what we can do now…

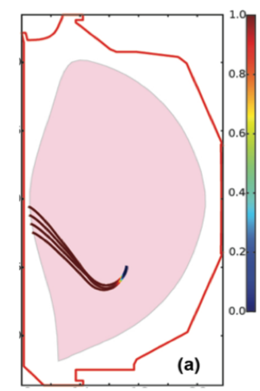
	η_{th}	η_{cd}	$\eta_{th} \cdot \eta_{cd}$
EU DEMO	0.33	0.25	**0.08**
C-AT DEMO	0.33–0.4	0.25–0.4	**0.08–0.16**
ARC	0.4	0.43	**0.28**
ARIES ACT1	0.575	0.4	**0.23**
ARIES ACT2	0.45	0.4	**0.18**

- **More efficient current drive technologies being explored ➔**
  - Design and build commencing on DIII-D tokamak

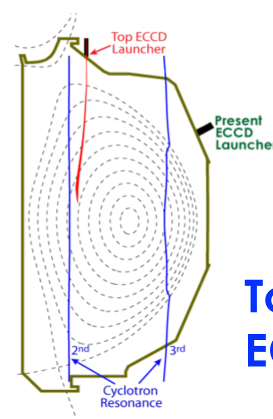
Move to: η_{th}=0.4 η_{CD}=0.4 for further analyses

Helicon





HFS LHCD



Top launch ECCD

GASC Finds 4m Pilot Possible if H_{98} is Good Enough

- **Constrain GASC to 90% bootstrap & no further heating**
  - We required H_{98} floats to meet this target. Density scanned.

- **GASC solution at f_{GW}=1.3 and heating only for CD requires H_{98}=1.6**
  - 7T, q_{95}~6.5, β_N~3.5 N_W~2.3MW/m^2, P_{fus}~700MW ← much better!
  - ***High β_P plasma have reached this H_{98} and q…***
  - (GASC shows f_{GW}~1.0 requires H_{98}~2.2)

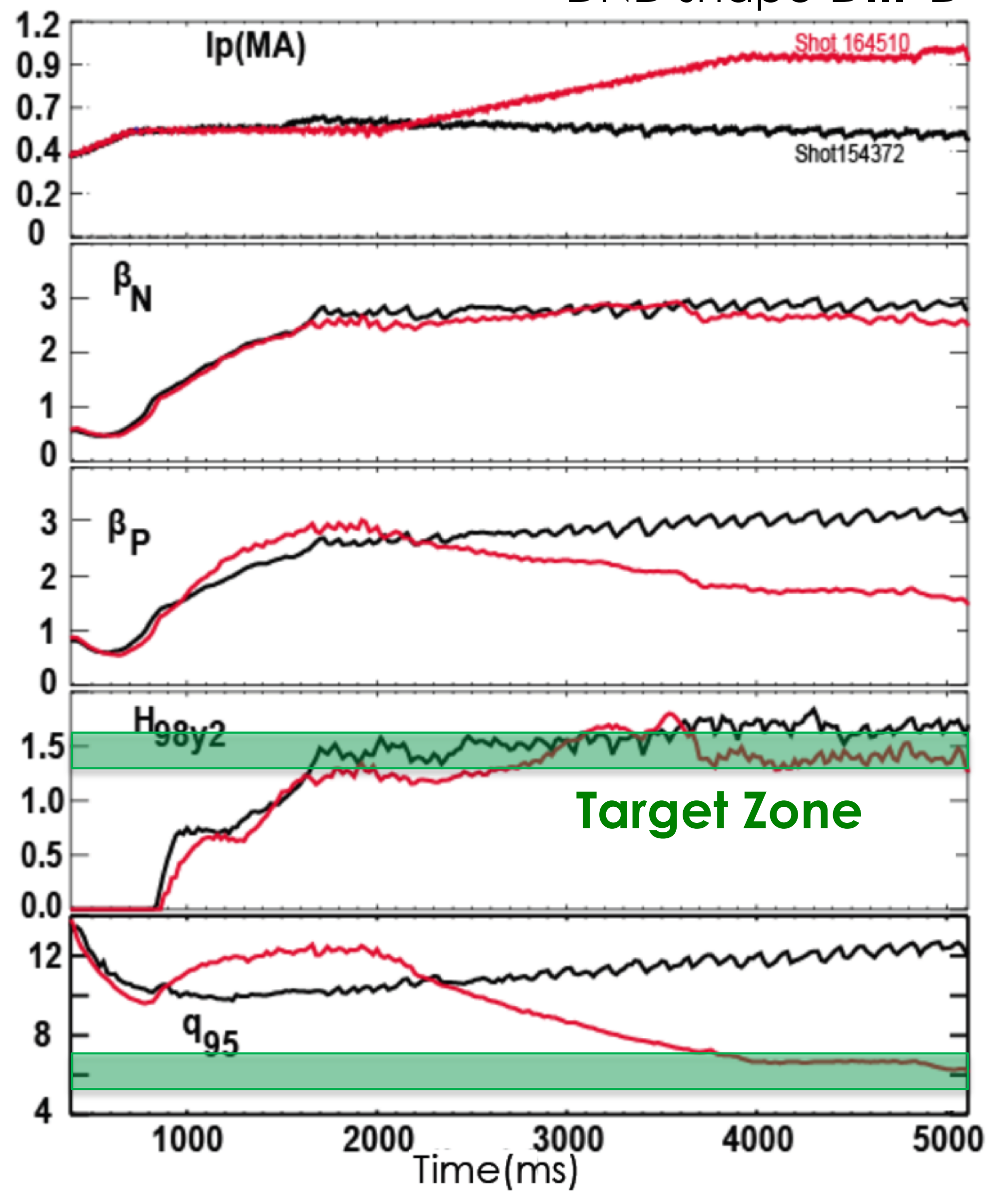
GASC **fully non-inductive** simulations at 4m,
η_{th}=0.4 η_{CD}=0.4, f_{GW}=1.1, H_{98}=1.6, P_{el}=200MW

DIII-D NATIONAL FUSION FACILITY

DIII-D Experiments Suggest High H_{98} with Good Performance (low q) Plausible *(H=1 not a rule!)*

- **High H_{98} region accessed with ITBs**
  - ITB sustained in high β_P solution by strong Shafranov shift
    - Validates TGLF

DND shape **DIII-D**



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- **High H_{98} region accessed with ITBs**
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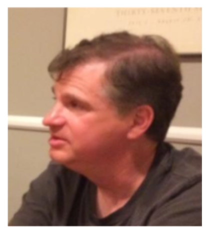
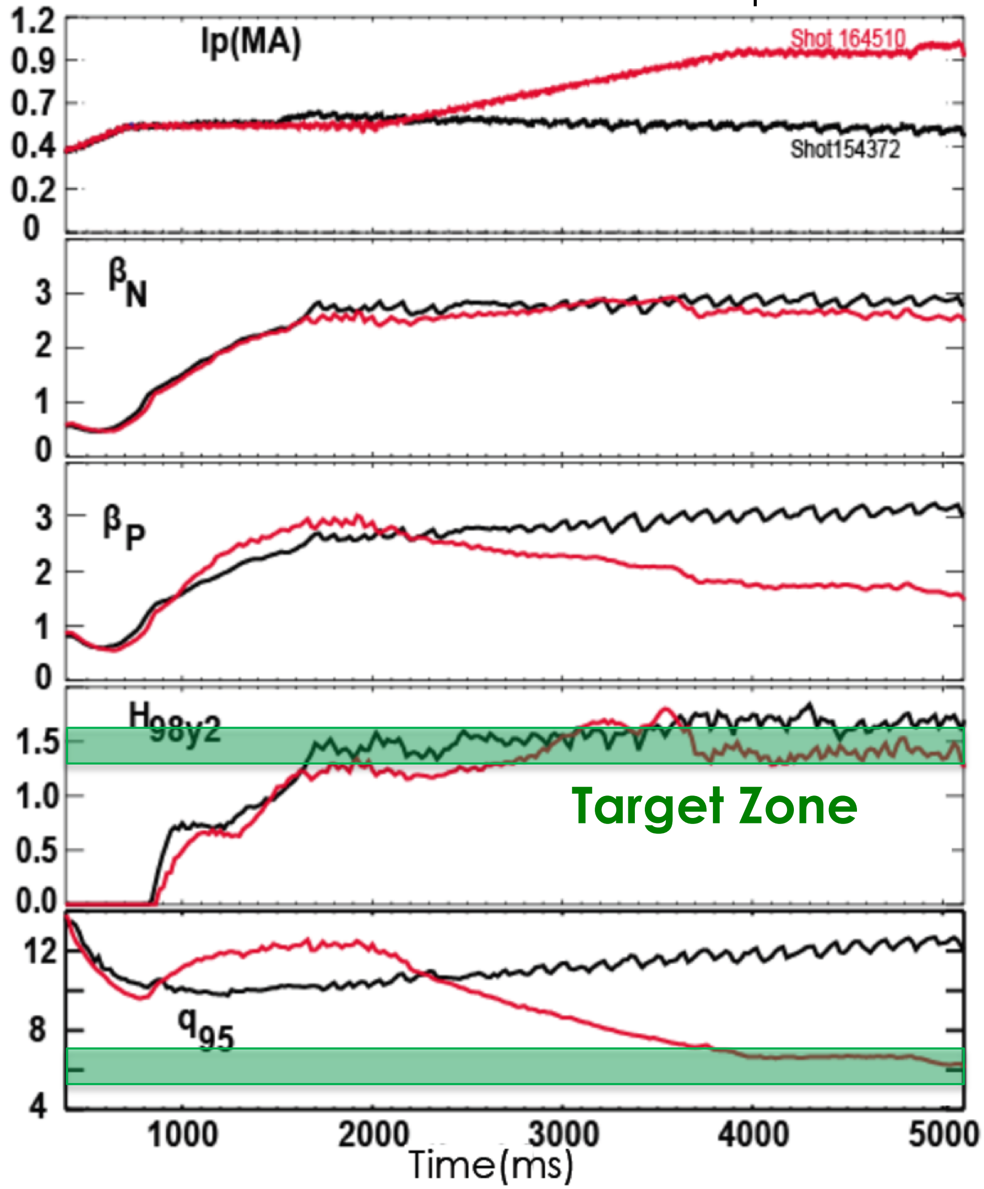
    - Validates TGLF

- ***H scaling not necessarily valid for AT & reactor!!!***
  (PS not happy with using H)



- ***Simulations project good transport & ITBs more easily sustained with broad J profile and shaping***

DND shape **DIII-D**



DIII-D NATIONAL FUSION FACILITY

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  - ***High β_P plasma have reached this H_{98} and q…***
  - (GASC shows f_{GW}~1.0 requires H_{98}~2.2)

- **Is this Greenwald fraction realistic?**
  - **Pedestal density** may be key limiting physics
    - *Limit to ~ Greenwald fraction* → **Research challenge**
  - Core density can rise with peaking **✔yes f_{GW}=1.3 is reasonable**

A low recycling solution through the AT high β concept

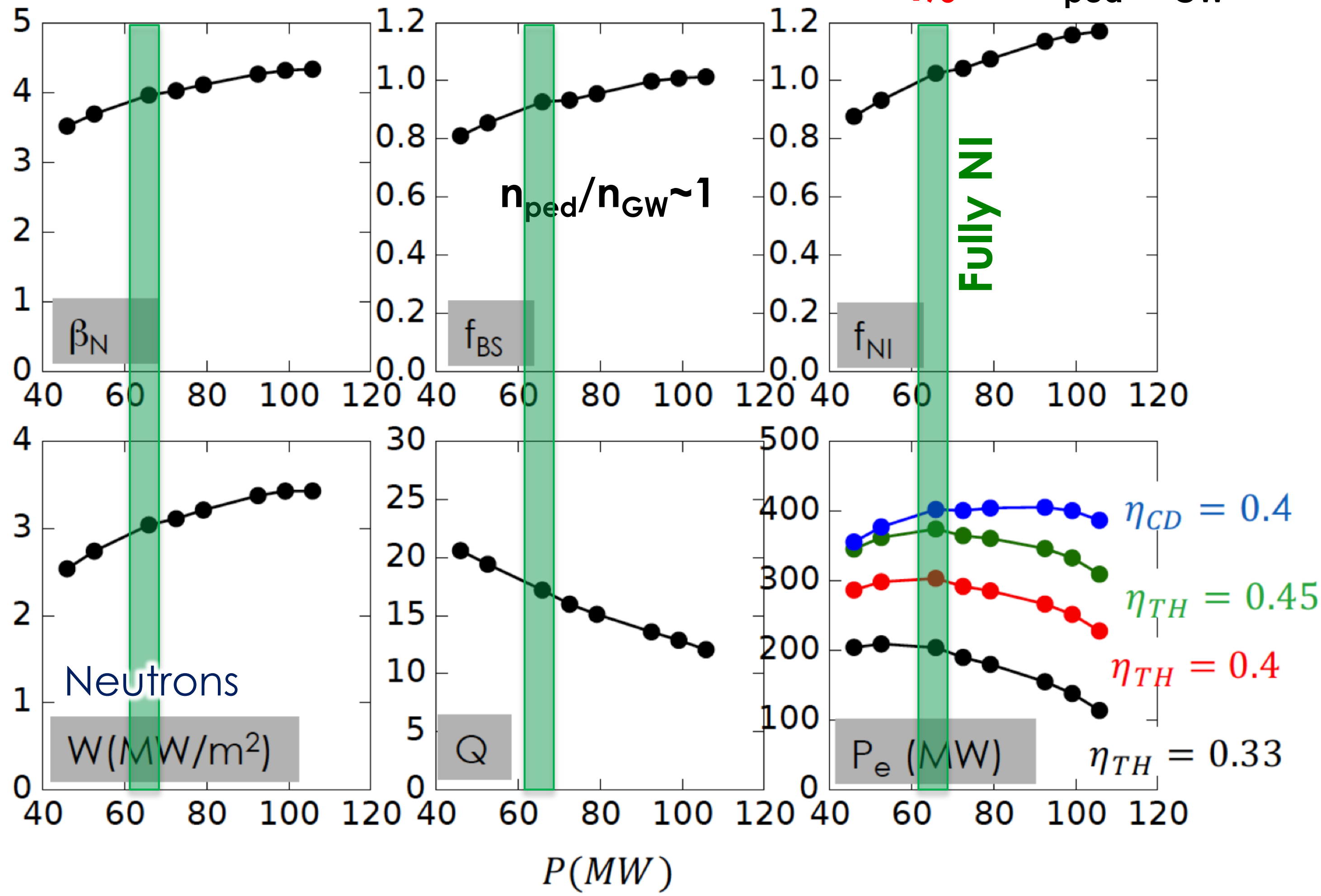
GASC **fully non-inductive** simulations at 4m, η_{th}=0.4 η_{CD}=0.4, f_{GW}=1.1, H_{98}=1.6, P_{el}=200MW

DIII-D NATIONAL FUSION FACILITY

At n_{ped}/n_{GW}~1, FASTRAN Predicts Transport Good Enough for a 4m Pilot Plant

- **Modest heating leads to f_{NI}~1**
  - 65MW inc. CD
  - β_N~4, 92%BS
  - Conservative η_{th}=0.33 η_{CD}=0.25
  - Tolerable neutrons
- ***Increase in η offers further potential***
  - *200MWe with conservative EU DEMO η values*

4m 11MA 6T q_{95}~4 n_{ped}/n_{GW}~1



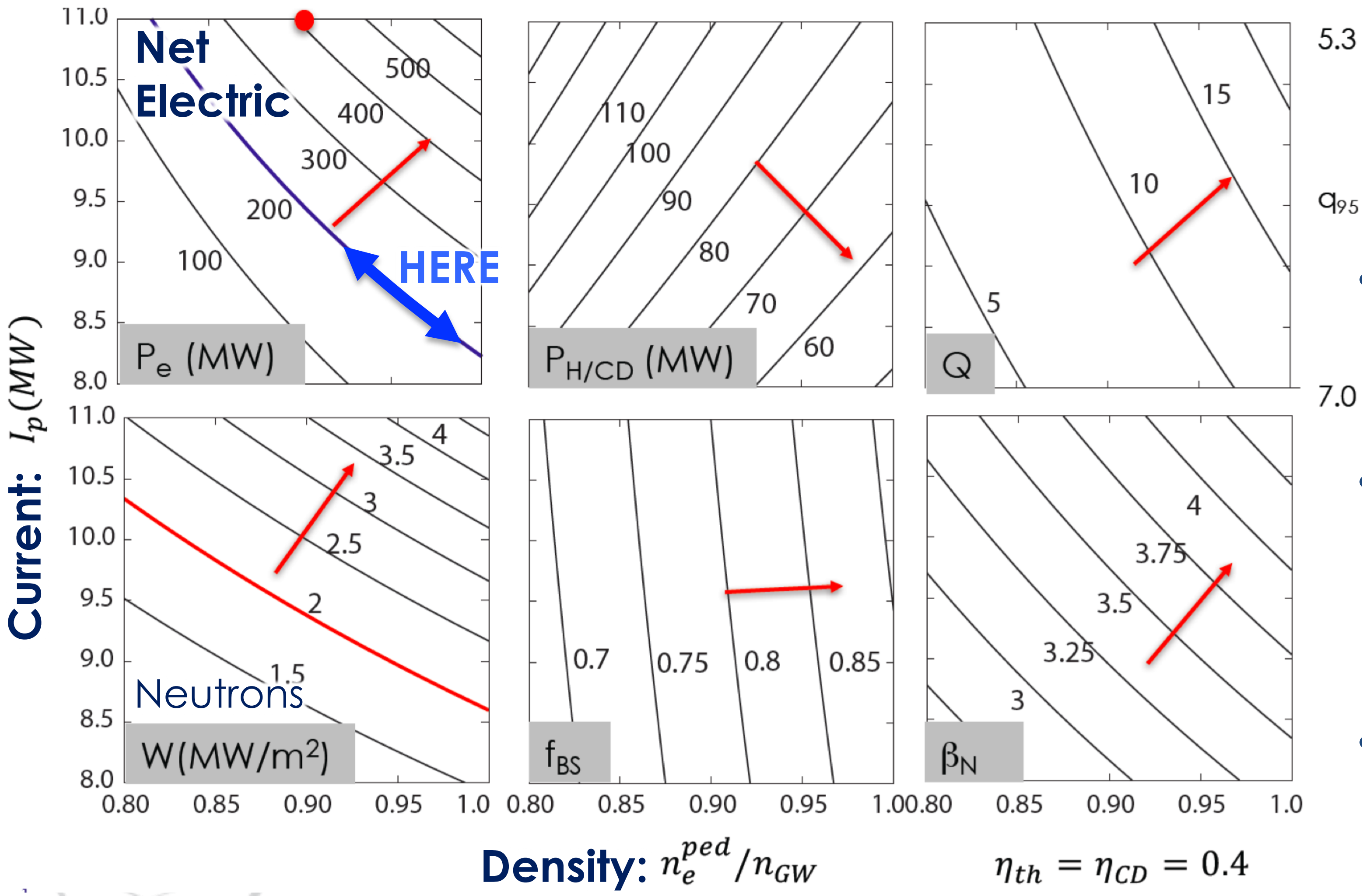
H_{98}=1.23 – lower than GASC → high current needed (q_{95}~4) → Disruption risk

FASTRAN simulations at 4m, 11MA 6T,
η_{th}=0.33 η_{CD}=0.25, n_{ped}/n_{GW}~1, f_{GW}~1.3, He ash fixed

Increased B_T (7T) Enables Considerable Margin

Vary Plasma Current and Greenwald Fraction:

All fully non-inductive (P_H floats)

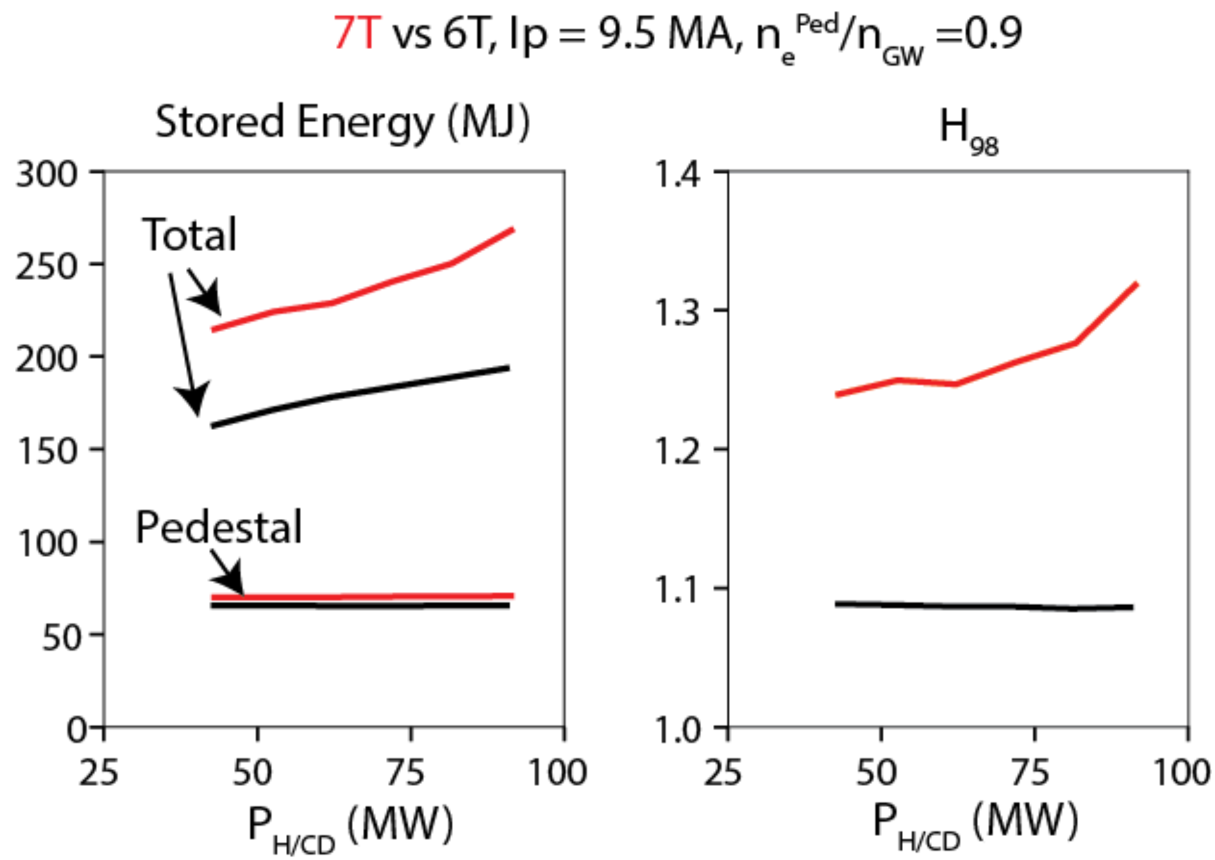


- **Higher safety factor**
  - Expect low disruptivity
- **Now optimizes to high β_N**
- **Space to back off in density or other metrics**
- **Tolerable neutrons**

DIII-D NATIONAL FUSION FACILITY

Higher Toroidal Field Improves Core Confinement!

- **Core confinement rises**
  - Puzzling pedestal dependence
- **Not reflected in H_{98} scaling**
  - Reflects higher field devices have been underpowered?

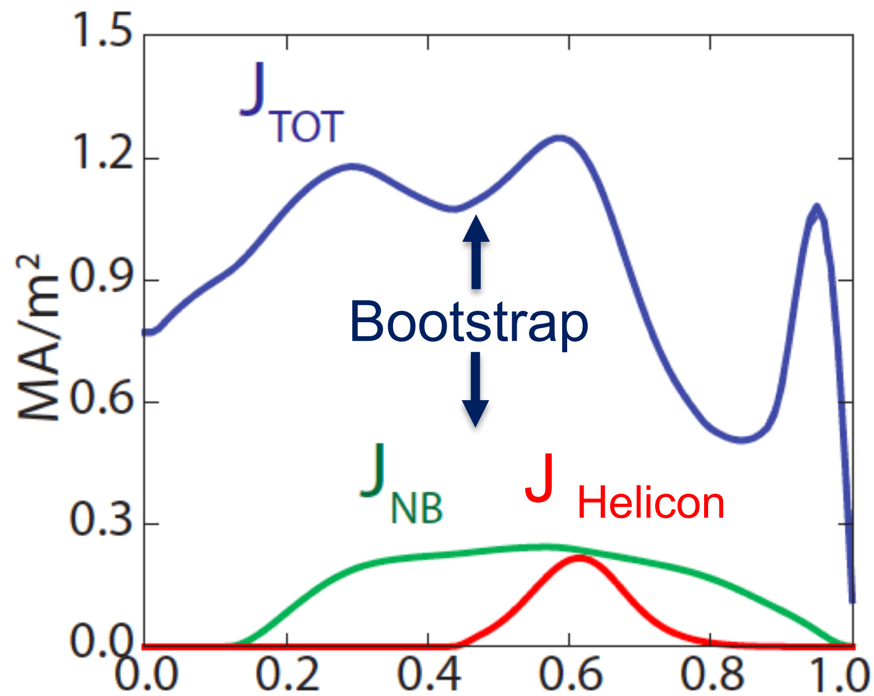


[From FASTRAN solutions]

Equilibria Dominantly Bootstrap Driven with Residual Current Consistent with Realistic Current Drive Sources

- **80-90% Bootstrap**
- **750kV off axis NBI**
- **1.2GHz Helicon**

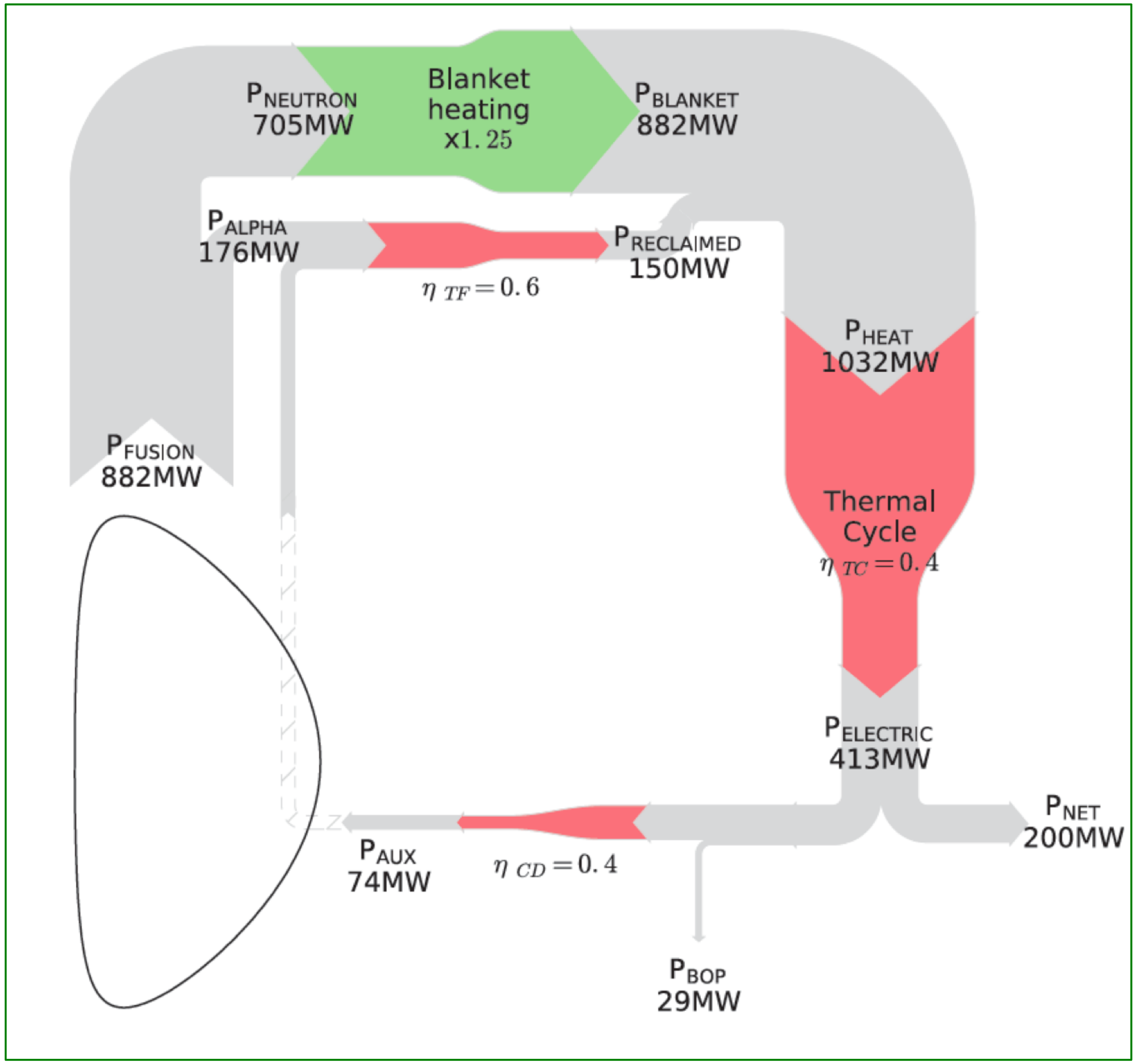
Discharges also well suited to 230GHz top-launch ECH (not used here)



Promising self-consistent solution

Low Recirculating Power is Needed in a Compact Device

- **Power gains from**
  - Nuclear heating in blanket
  - Reclaimed power from radiation & divertor
  - Small B.O.P. from HTS
  - Efficient thermal cycle & current drive



DIII-D NATIONAL FUSION FACILITY

6T version, GASC

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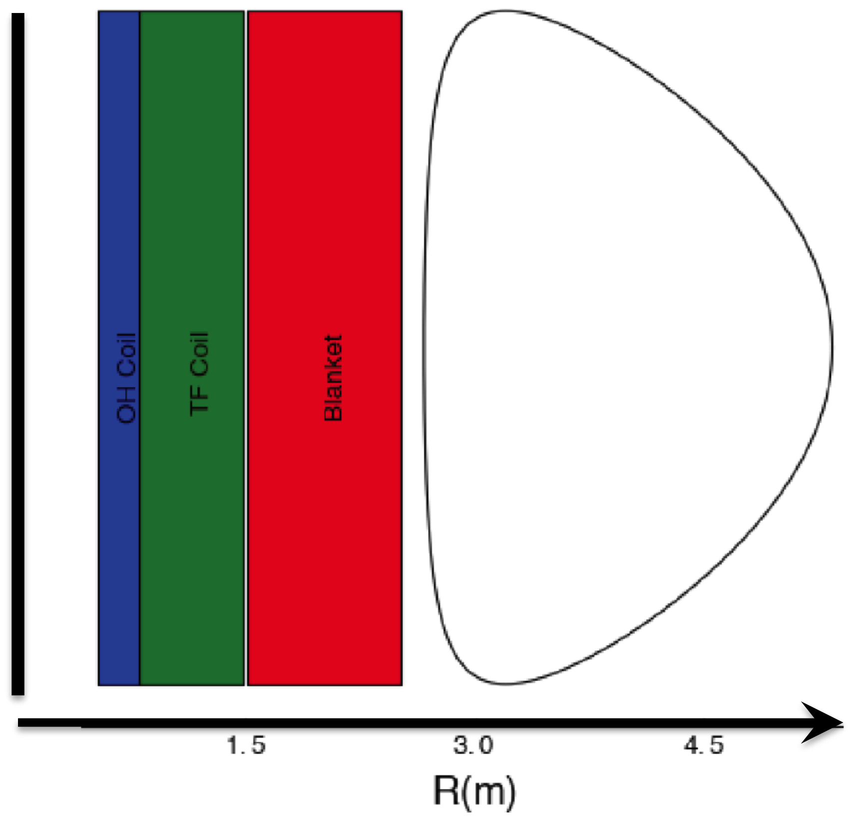
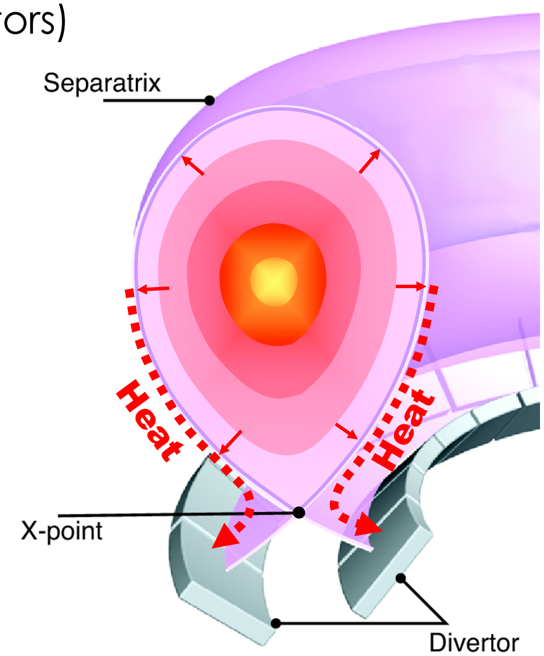


DIII-D NATIONAL FUSION FACILITY

Divertor Challenge Metrics

- **Power into SOL: $P_{SOL} = P_{alpha\ heat} + P_{H\&CD} - P_{brems/synch/line\ radn}$**
  - Ways to deal with this: core radiation, divertor radiation, spreading
- **Divide P_{SOL} by midplane SOL area: Poloidal heat flux**, $q_\theta \sim P_{SOL} / N\ R\ \lambda_q$
  - Plug in Eich scaling: $q_\theta \sim P_{SOL}\ B_\theta / N\ R$ (N=1 or 2 divertors)



Ip drops out of q_{div} because poloidal field plays a role in divertor incidence angle as well as SOL width; and parallel flux expansion drops α

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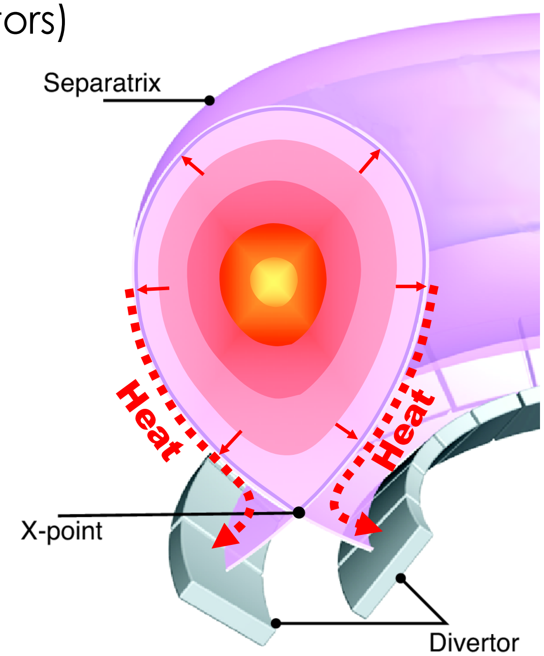
- **But heat flux down flux tube must allows for field pitch at midplane**
  - Parallel heat flux: $q_{||} \sim q_\theta B / B_\theta, \sim P_{SOL} B / N R$
  - Heat flux to divertor: $q_{div} \sim q_{||} \sin\alpha$ (intersect angle)



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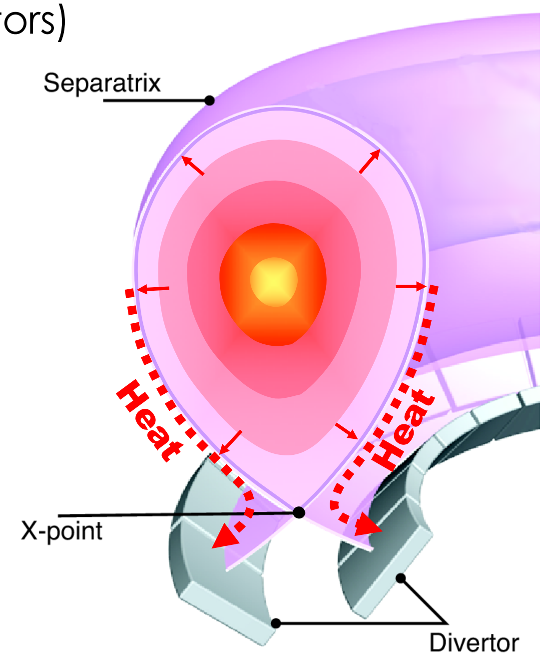
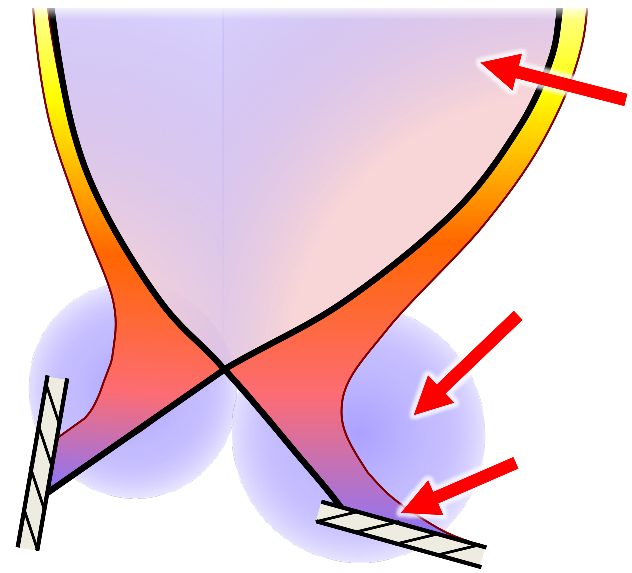
  - Heat flux to divertor: $q_{div} \sim q_{||}\ \sin\alpha$ (intersect angle)
- **Choice of metric depends on mechanism**
  - Power to target: $q_{div} \sim P_{SOL}\ B / N\ R$
  - Detached radiative solution : $q_{div} \sim P_{SOL}\ B_\theta\ / N\ R$
- ***This has caused a lot of debate, we are looking at both, but consider radiative metric more relevant***



Ip drops out of q_{div} because poloidal field plays a role in divertor incidence angle as well as SOL width; and parallel flux expansion drops α

Core Radiation an Important Factor Trading Off Divertor Challenge and H mode Quality

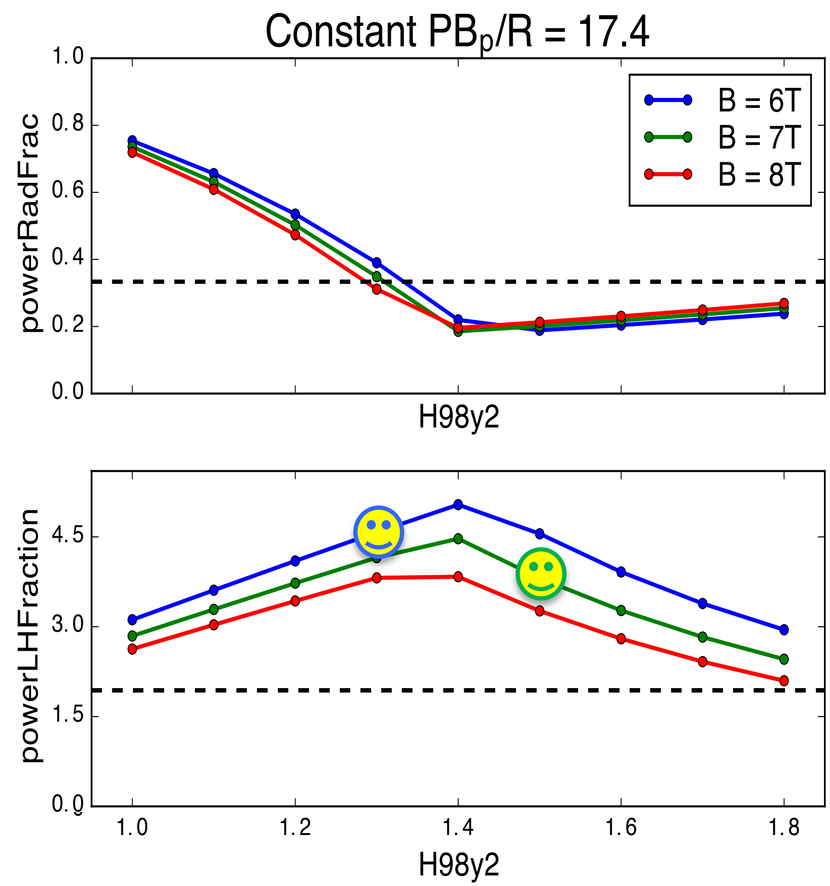
- **Adding impurities to radiate in core/pedestal reduces heat load into divertor**
  - Alleviates level of divertor radiation required or heat flux spreading
  - **But may drop P_{SOL} below L-H threshold**
    - *Factor 2 margin considered desirable to avoid confinement degradation*
- **So need to add core radiation to drop $P_{SOL}\ B_{\theta}\ /\ N\ R$ while ensuring $P_{SOL}/P_{L\text{-}H} > 2$**



Divertor Challenge Can Be Lower Than ITER with Good H-mode Access Maintained

- **Match ITER divertor challenge by adjusting core radiation**
  - ITER 33% core radiation
  - At expected H, C-AT requires 20-40% core radiation
  - Good H mode access margin
- **Further increasing radiation eases divertor challenge and maintains good H-mode access**
  - f_{rad} = 67%, f_{LH} = 2.5
  - PB/RN = 63, q_{div} = 7.3 MW/m^2
- **Benefits from two divertors & low fusion/recycling power**

Adjust core radiation to match poloidal field metric



η_{th}=0.4 n_{ped}/n_{GW}~1

Divertor Challenge Can Be Lower Than ITER with Good H-mode Access Maintained

- **Match ITER divertor challenge by adjusting core radiation**
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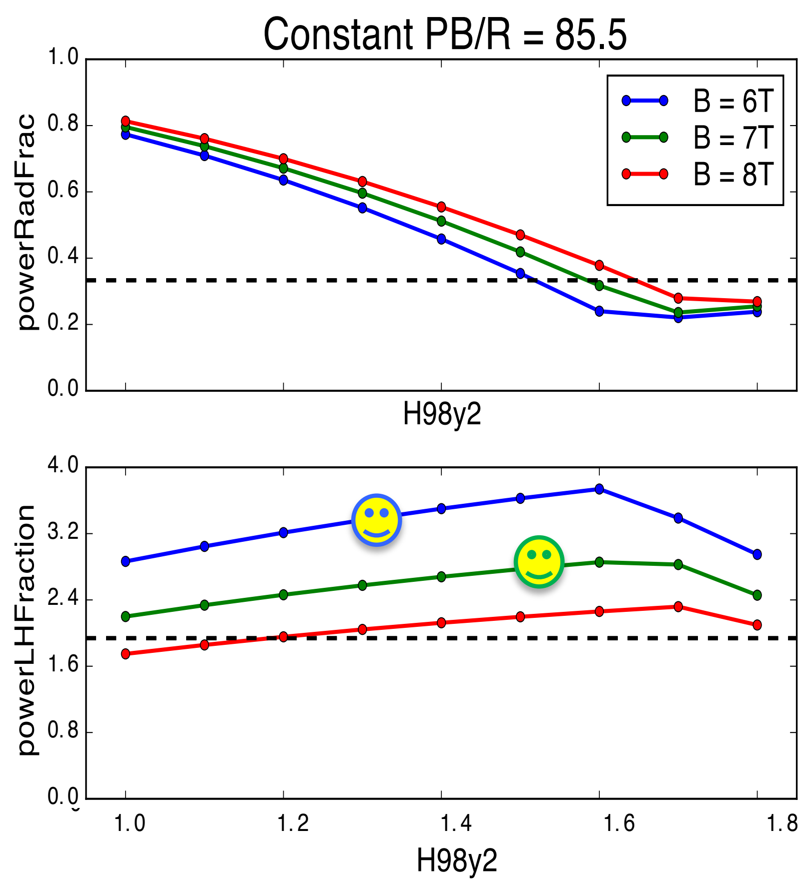
Adjust core radiation to match toroidal field metric



η_{th}=0.4 n_{ped}/n_{GW}~1

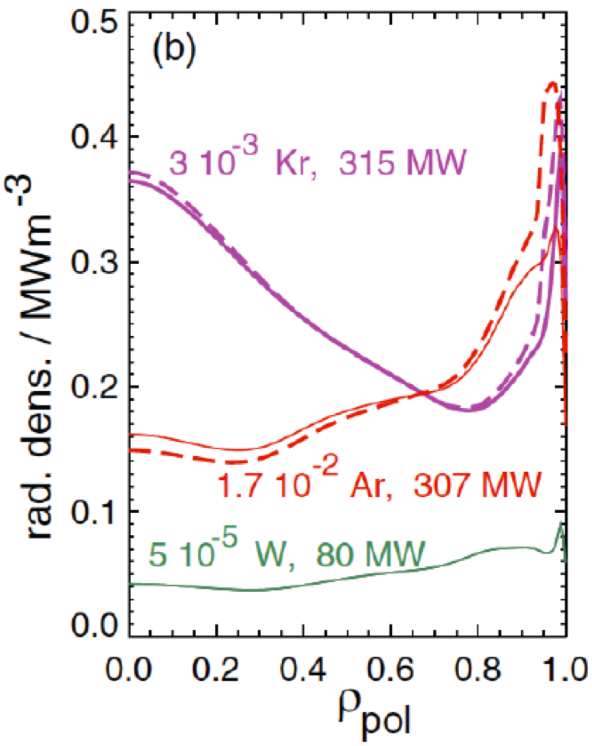
Fuel dilution due to core radiation remains a challenge for all DEMO concepts

- **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**

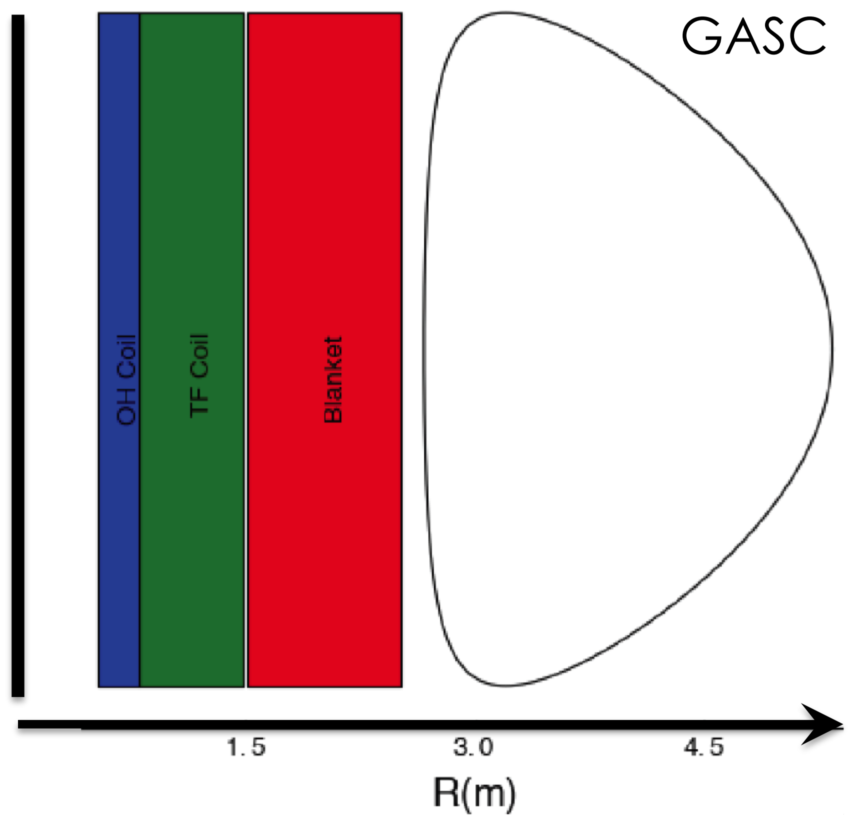


Kallenbach *et al* 2013 PPCF **55**

DIII-D NATIONAL FUSION FACILITY

Structure Appears Viable Though Requires Advanced Approach for Stress Handling

- **GASC uses "realistic" models for required thicknesses**
  – Needs investigation…
- **Forces are high in GASC model, at 1500MPa,**
  – But < ARC's 1900MPa (GASC conv. Tech estimate)
- **ARC argues use of bucking and whole TF/OH material to react the load**
  – Reduces stress to 660MPa in ARC… ***do same for C-AT DEMO?***

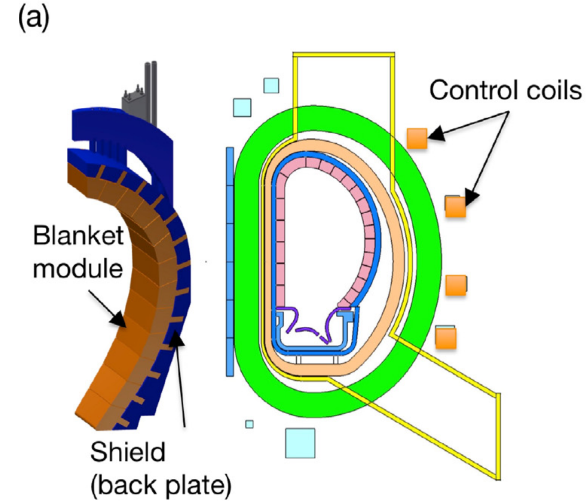


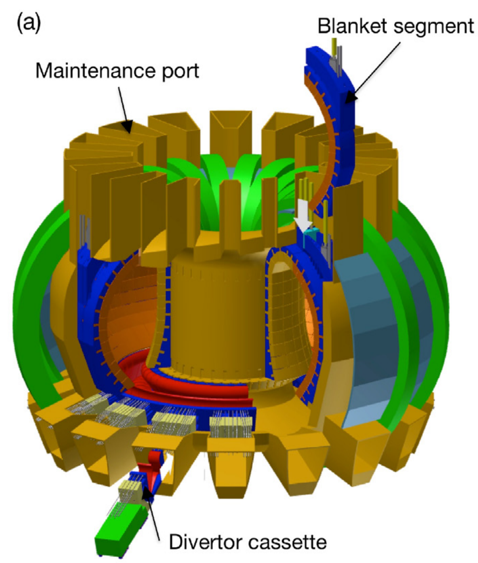
Clearly this needs much more in depth thought

Higher Field High T_C Superconductors Offer Advantages for Maintenance & Testing Program

- **HTS may enable demountability**
  - Greatly accelerates maintenance, improving duty cycle and thus device overall efficiency
- **Staged approach:** qualify materials & breeding, then net electric
- **We are working on PF arrangements and vertical control**
  - Place PF inside TF for better shaping
  - Use copper vertical control coil placed closer to the plasma (less shielding)

Vertical change out scheme in Japanese SN design





[Utoh, Fus. Eng. Des. 2017]

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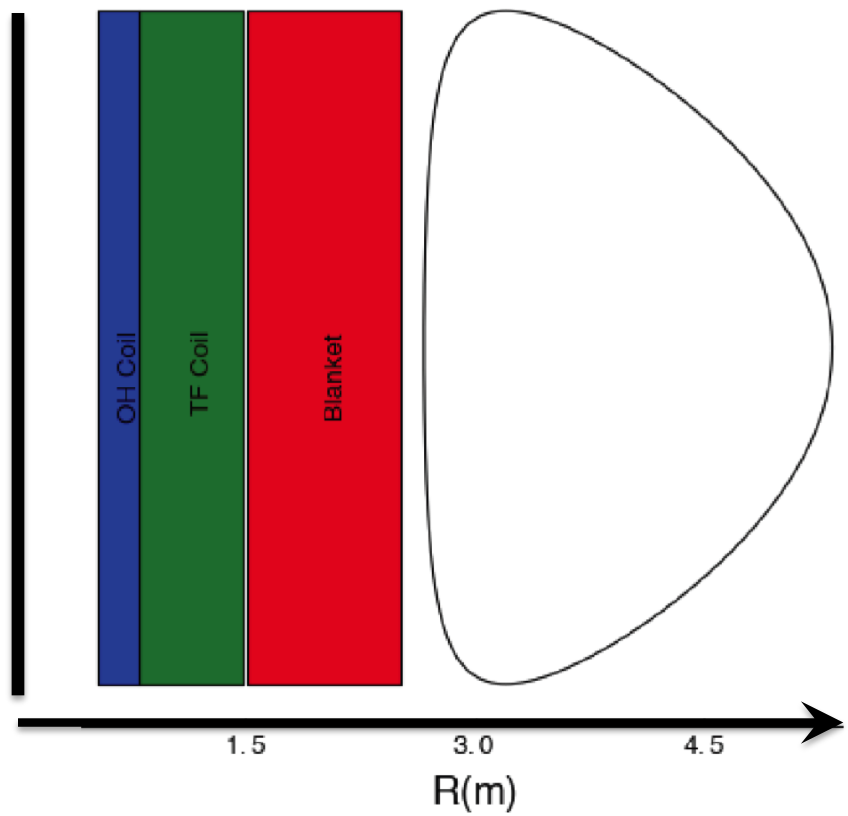


Compact-AT Compares Well with Other AT Reactors – Just Smaller and Cheaper

- **6 & 7T C-AT PPs**
  - Lower efficiency
  - Higher efficiency
- **Broadly consistent with other devices:**
  - H_{98}, f_{BS}, f_{GW}, f_{Rad}
  - N_W, q_{div}, $P_{sep}B/R$

But C-AT PP smaller and lower P_{EL}

- **7T C-AT: scope to lower f_{GW}, I_P, $P_{H\&CD}$**

	CATD FTRN	CATD FTRN	CATD FTRN	CATD FTRN	CATD FTRN	EU-DEMO	ARC	ACT1	ACT2	ITER
R	4	4	4	4	4	7.85	3.3	6.25	9.75	6.2
B	6	6	7	7	7	5.6	9.2	6	8.75	5.3
I_P	11	9.5	8.2	9.5	9.6	14	7.8	11	14	9
η_{th}	0.33	0.4	0.4	0.4	0.33	0.33	0.4	0.575	0.44	0.33
η_{CD}	0.25	0.4	0.4	0.4	0.25	0.25	0.43	0.4	0.4	0.25
q_{95}	4	5.7	7.1	6.2	6.1	4.5	7.2	4.5	8	5
f_{GW}	1.3	1.3	1.28	1.15	1.31	1.21	0.67	1	1.3	1
f_{RAD}	83%	77%	80%	80%	80%	72%	80%	90%	90%	*50%*
β_N	4	4.2	3.5	3.4	4	3.5	2.6	5.6	2.6	2.9
H_{98}	1.23	1.31	1.49	1.31	1.42	1.2	1.8	1.65	1.22	1.4
f_{BS}	92%	83%	90%	80%	90%	62%	63%	91%	77%	80%
P_{fus}	1280	746	636	775	1095	1960	525	1800	2600	400
$P_{H\&CD}$	73	74	51	82	63	115	38	42	105	130
P_{EL}	200	200	200	200	200	400	190	1000	1000	0
Q	17	10.1	12.6	9.5	17.3	17	13	42	25	7
NW	3.9	1.93	1.71	2.1	2.95	?	2.5	2.45	1.46	?
$P_{sep}B/R$	85	76	62	83	99	101	80	39	56	90
q_{div}	9	7	~ITER	~ITER	~ITER	?	?	13	10	10

Lwr n_e Lwr η

*with GASC analysis of loads

Compact-AT Compares Well with Other AT Reactors – Just Smaller and Cheaper

- **6 & 7T C-AT PPs**
  - Lower efficiency
  - Higher ef
- **Broadly co with other d**
  - H_{98}, f_{BS}, f_{G}
  - N_W, q_{div},

But C-AT PP and lower P

- **7T C-AT: sc lower f_{GW}, I_P**

	CATD FTRN	CATD FTRN	CATD FTRN	CATD FTRN	CATD FTRN	EU-DEMO	ARC	ACT1	ACT2	ITER
R	4	4	4	4	4	7.85	3.3	6.25	9.75	6.2
								6	8.75	5.3
								11	14	9
								.575	0.44	0.33
								0.4	0.4	0.25
								4.5	8	5
								1	1.3	1
								90%	90%	*50%*
								5.6	2.6	2.9
								1.65	1.22	1.4
								91%	77%	80%
								1800	2600	400
								42	105	130
								1000	1000	0
								42	25	7
NW	3.9	1.93	1.71	2.1	2.95	?	2.5	2.45	1.46	?
$P_{sep}B/R$	85	76	62	83	99	101	80	39	56	90
q_{div}	9	7	~ITER	~ITER	~ITER	?	?	13	10	10

Lwr n_e Lwr η

These are encouraging parameters that merit further investigation.

Point is not to argue for a particular parameter set, but point out the direction & benefits of an AT optimization

A facility that developed key elements of fusion technology with modest scale and cost would be a compelling proposition

*with GASC analysis of loads

AT Approach Offers Benefits in the Development of a Compact Net Electric Fusion Facility

- **First integrated transport/pedestal/CD/profile reactor simulations show converged steady state solutions possible**
  - High density and high β_N reduce recirculating power
  - *Could this approach improve margins in ARC on assumed field, current drive efficiency, confinement or recirculating power?*
  - Higher field improves performance, design margins & safety
  - Leads to tolerable divertor challenge, good H mode access and acceptable neutron loading
  - Compatible with predicted current drive
- **These factors should be considered in the optimization of a US net electric facility**

A compact net electric facility poses a tractable research challenge we should use to motivate our work, so we can start an engineering design and construction in the US asap.

DIII-D NATIONAL FUSION FACILITY

Compact AT Analysis Identifies Key Research Challenges U.S. Program Should Pursue

- Validate high β_N high density transient free scenario
- Proof advanced current drive technologies
- Develop divertor solution for long pulse erosion-free operation
- Develop high T_C demountable super-conductors
- Qualify candidate materials for nuclear environment

These issues are common to many concepts; advancing them benefits all → should be US focus

Compact Pilot Plant Poses Tractable Research Challenge

High β_N & density core without transients
Fully NI high perf. Low rotn $Q_{DT\text{-}equiv}$~1
3D & control e^- dominant Higher field
Disrupt mit'n High density → integrated solutions
QS stellarator

Efficient current drive heating & fueling
Test new tech at MW… Develop reactor implementation
Helicon HFS LHCD
Top EC Pellets
Apply at large scale in integrated scenarios

HTS demountable superconductors
Proof HTS… Demountable… Large scale
Coils… Joints… escalating prototypes
Manufacturing efficiency

Non-eroding divertor
Advanced concepts → Validated models
Closure Simulation High power tests Integration
Magnetic Diagnosis Relevant materials ($Q_{DT\text{-}equiv}$~1)

Materials
Assess compatibility, mitigation, new materials
Sample irradiation (many) New wall tests
Plasma interaction Phoenix IFMIF GDT… (increasing scale)
Simulation Blanket design

Reactor Development
Systems designs
Critical design issues:
stress, neutronics, diagnostics,
remote handling, breeding, etc.
Integration
Decide concept
Engineering Design
Construction

Use existing facilities & upgrades:
Performance, current drive, divertors, PMI (eg ADX, D3, NSTXU)
New Testbeds:
For range of issues, particularly materials & HTS
$Q_{DT\text{-}equiv}$~1 D-D facility:
Resolve behavior at reactor parameters for simultaneous core-edge without extrapolation (separation of nu & GW, high bootstrap, H&CD actuator tests relevant FI content, Te~Ti, WDM validation
(eg major upgrade / intl)

PILOT: Phased operation
Short pulse Long pulse
High Q steady st.
Divertor, PMI
Breeding Tests
Material
Upgrade & Relicensing
10 dpa testing
Full Breeding
200MWe
Increasing performance
PRIVATE SECTOR REACTOR
Successor concept design

2017 2027 2037 2047

DIII-D NATIONAL FUSION FACILITY

A Compact Pilot Plant/FNSF Provides a Compelling Focus for U.S. That Complements ITER Participation

- **ITER provides foundations for pilot plant and projection to FPP**
  - Already proving technology and engineering at reactor scale
  - Reactor diagnostic and control solutions
  - Proof of the burning plasma concept
  - Projection of physics to larger scales
- **Compact pilot plant proves the steady state potential**
  - Net-electric with high performance core & efficient auxiliaries
  - Reactor hard materials for continuous operation
  - Breeding solution to make its own fuel
  - Sustainment of configuration in continuous operation

A Compact AT Pilot Plant is attractive as a modest scale energy generator, & would combine with ITER learning to project large scale fusion energy

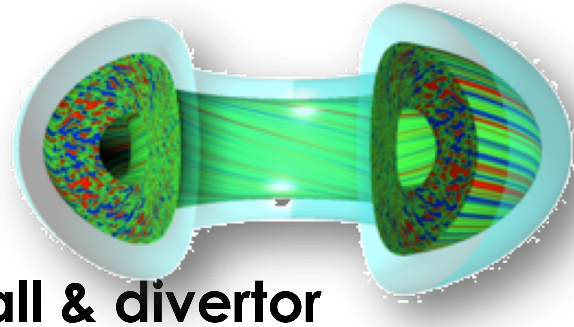
Bonus slides…

Compact AT Analysis Identifies Research Challenges for the Fusion Community

Some aspects to look into soon for this concept:

- **PF coil configuration and demountability**
- **Stress analysis – started bucking calculations**
- **Nuclear materials and loading, change out strategy**
- **Device structure & shielding**
- **Refine physics analysis**

Compact DEMO Concept Motivates Research To Prepare for a Decision to Proceed



- **Relevant performance core plasma**
  - Confinement, self-driven, stability
- **Erosion free divertor solution**
- **Promising candidate materials for wall & divertor**
- **High Tc superconductors with demountable technology**
- **Current drive approach for residual drive & control**

Strong research mission for the U.S. community

- **A Compact DEMO would:**
  - Learn from ITER technologies to develop its engineering solutions
  - Combine ITER learning to project larger future fusion power plants
  - Put U.S. at the forefront of the development of fusion energy

The U.S. has the leading scientific and engineering capability to progress a fusion reactor. It should focus its effort on the earliest possible commencement of a U.S. Compact DEMO Reactor.

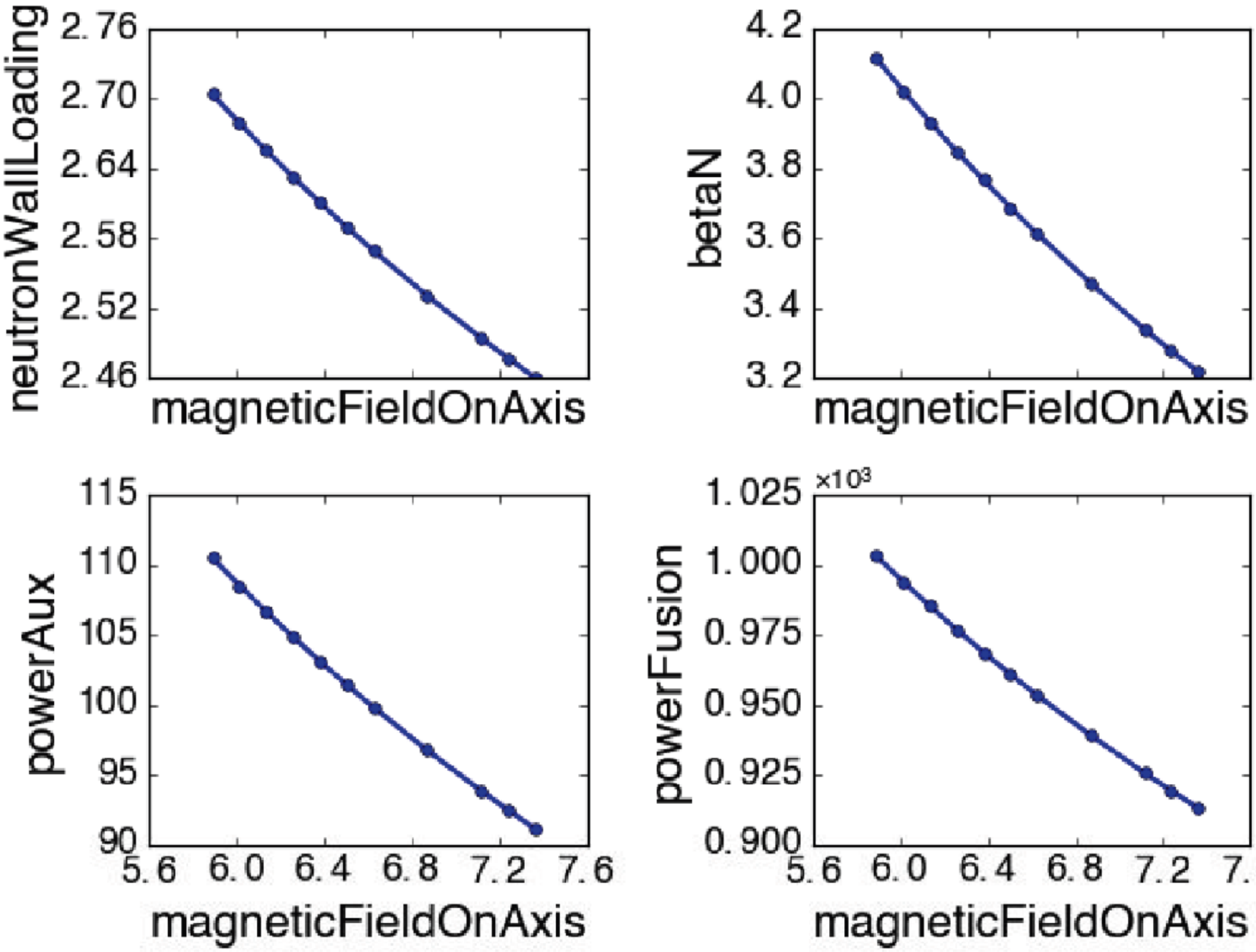
DIII-D NATIONAL FUSION FACILITY

GASC Reveals There is a Trade off in B_T and β_N

$\eta_{th}=0.4$,
$\eta_{cd}=0.4$
$P_{net}=200MW$

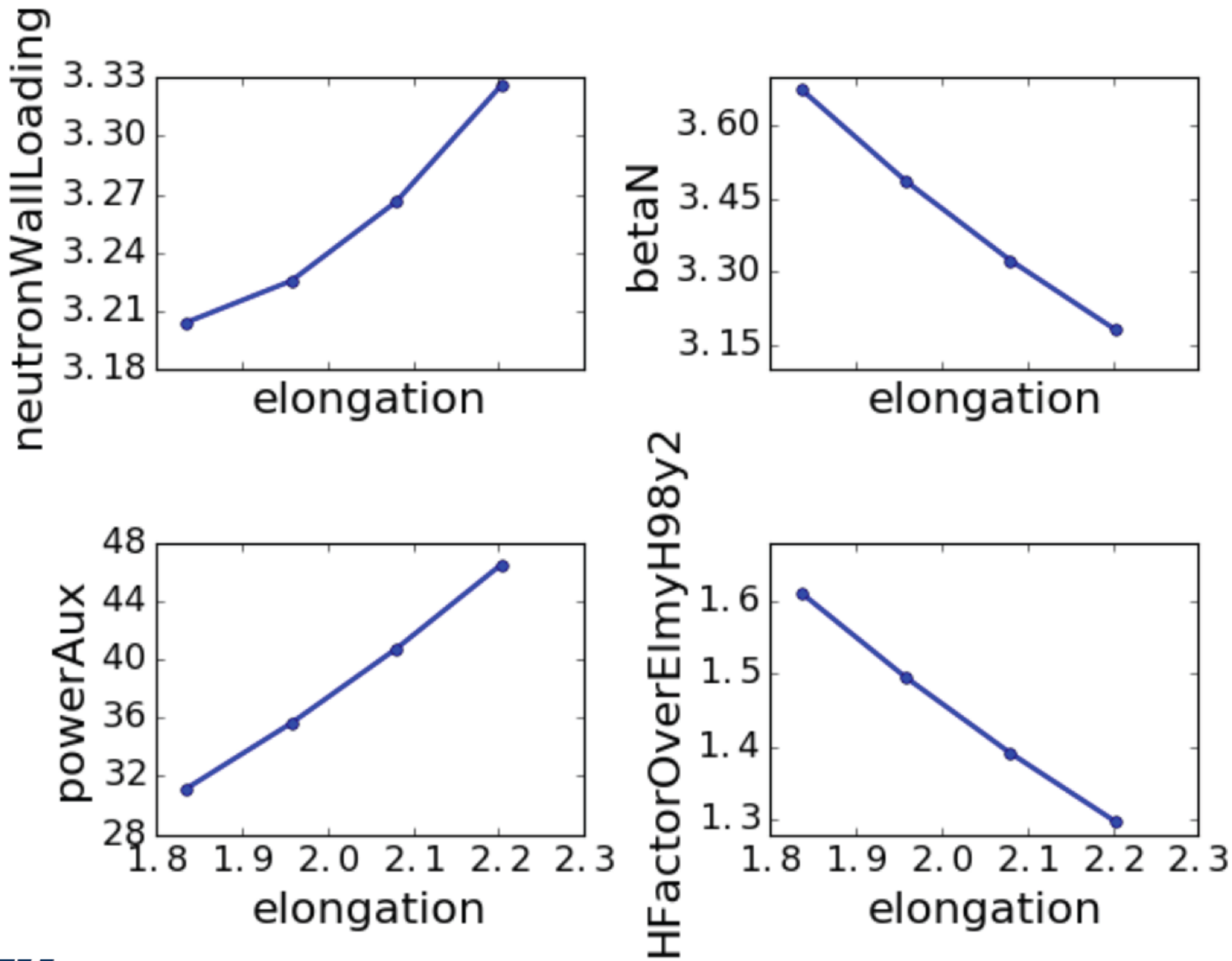
- **Note y axis ranges!**
- **Add fastran???**
- **H98=1.3, fGW=1.33**

But not in P_{LH}



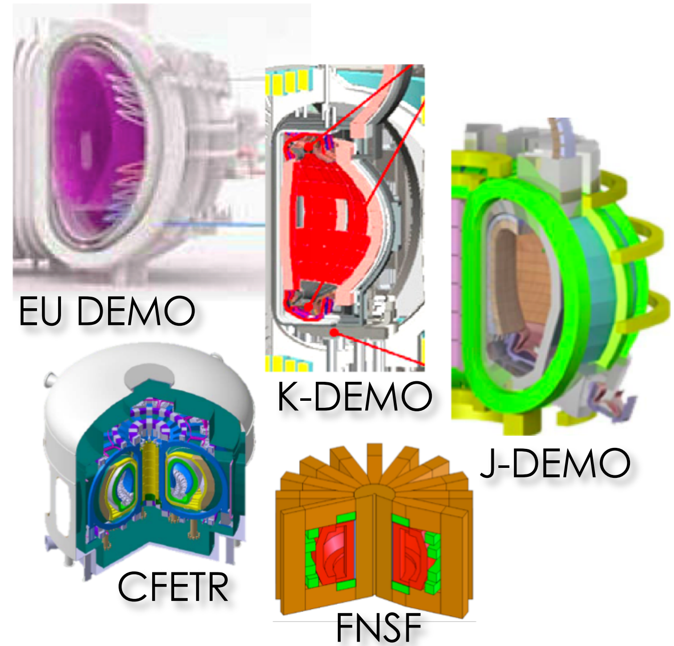
GASC **fully non-inductive** simulations at 4.5m,
η_{th}=0.4 η_{CD}=0.4, f_{GW}=1.33, 7T, H_{98}=1.3, P_{el}=200MW

Elongation Scan at fixed 200MWe



DIII-D Research Important to Resolve Future Advance Tokamak Reactor Concepts

- **Next step concepts based on AT,** *but:*
  - Modest β_N → high recirculating power, large size, divertor/neutron challenged
- **Simulations show efficient paths exploit the high β_N AT**
  - ARIES ACT1 1GWe: 6m, 6T, β_N~5.6*
  - More compact FNSF/DEMO possible:
    - 200MW net electric
    - Tolerable heat & neutron load with H access
- **Physics basis for all these solutions must be established → DIII-D**
  - Important to optimize (high β_N, f_{GW}…)

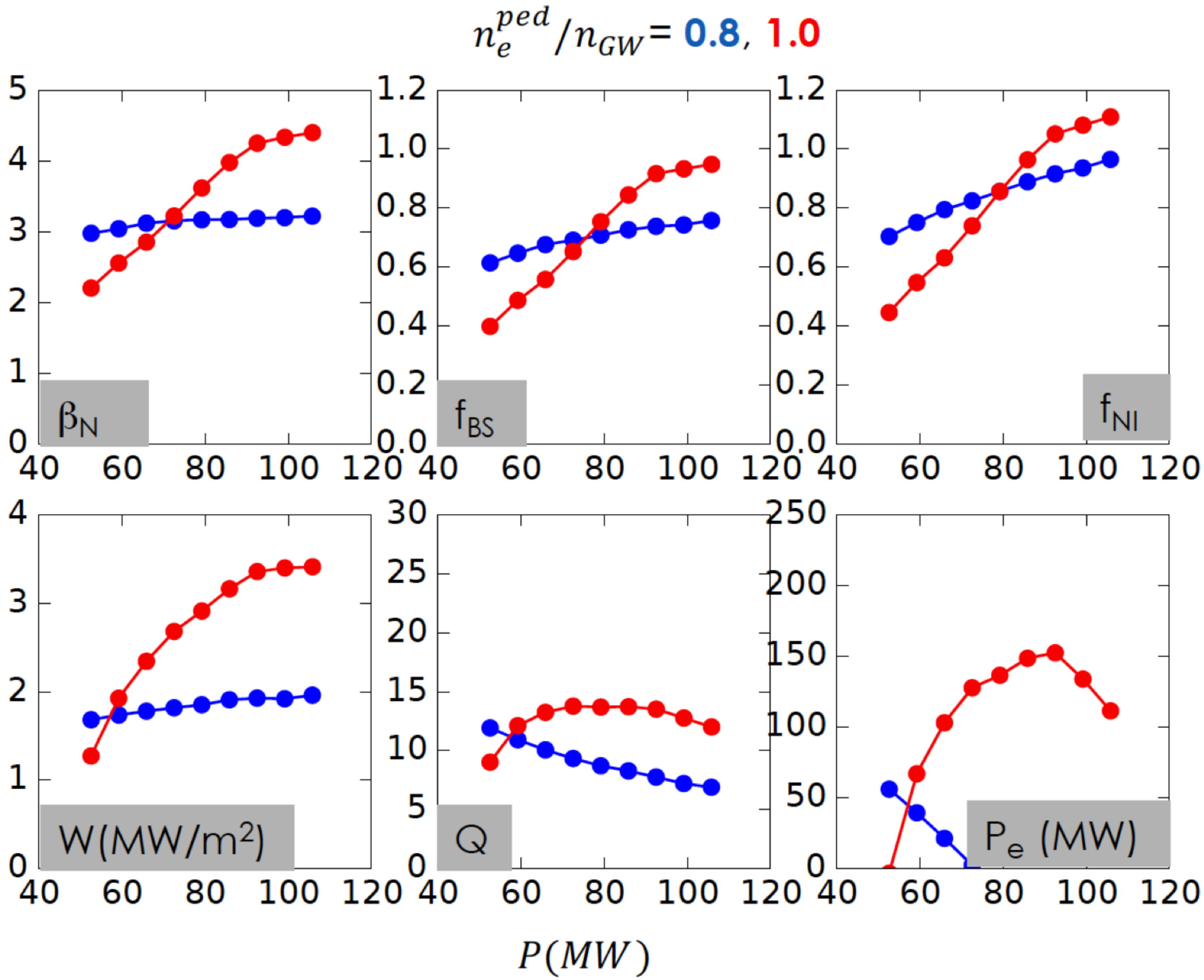


Compact AT DEMO: (GASC/FASTRAN TGLF/EPED)
4m 6T 9.4MA q~6 κ~2 β_N~4
f_{GW}=1.3 f_{BS}=0.9 f_{rad}=0.77
$\eta_{th}=\eta_{CD}$=0.4 H_{98}=1.3 Q=12
P_{aux}=78 P_{fus}=850 P_{el}=200 MW
N_W=2.6 q_{div}=8 MW/m^2

[*Kessel, FST, 2015]

Increased Pedestal Offers Considerably improves Optimization at R=4m, 6T

- **High density favors high β_N**
- **Inferior He ash model used here**
  - Explain
- **Improved pedestal offers further benefits**
  - (not shown)



FASTRAN simulations at 4m, η_{th}=0.33 η_{CD}=0.25*, f_{GW}=1.1(ped=0.85)

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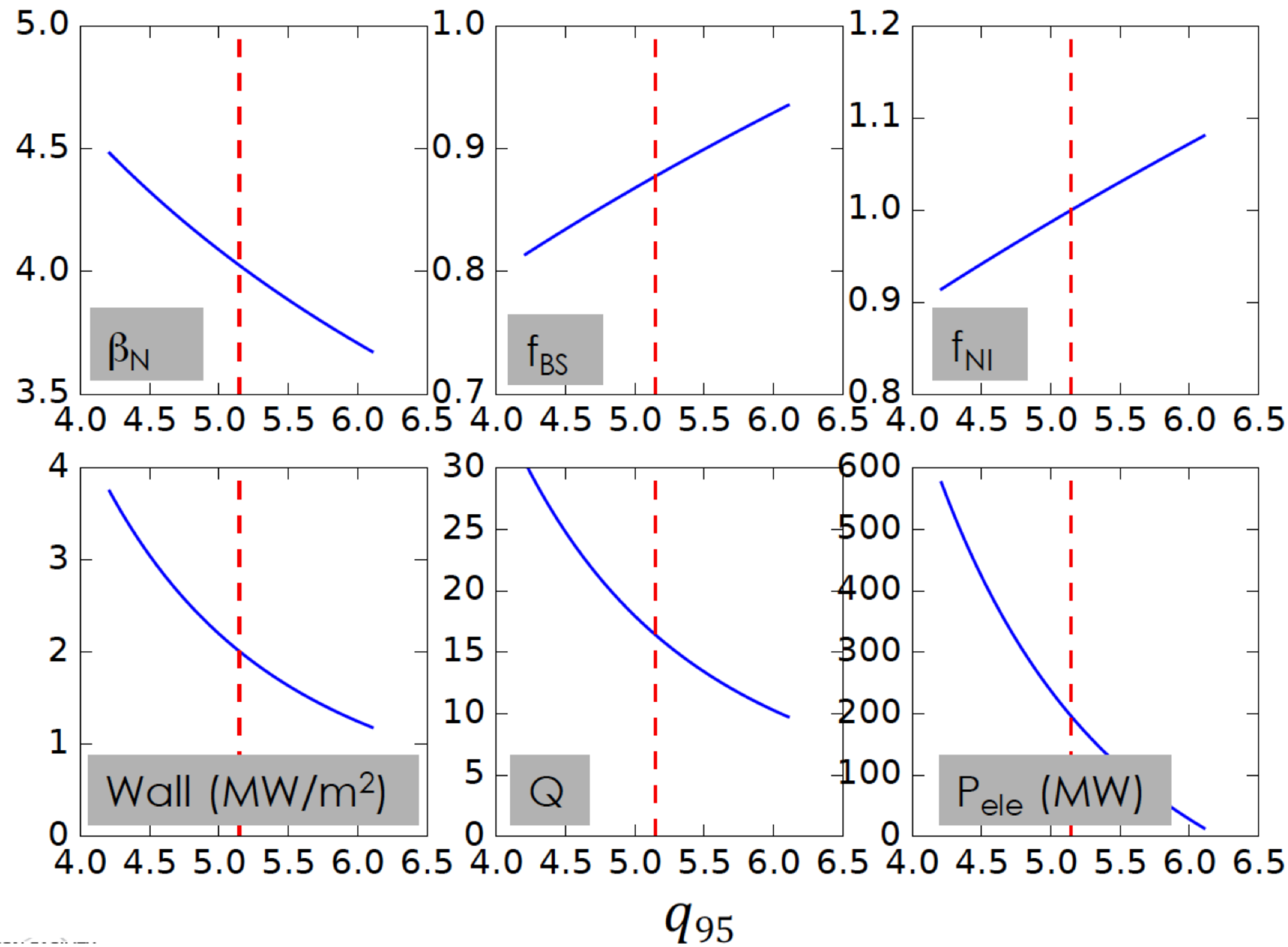
For reference: Performance optimizes to lower q95, but device becomes pulsed

- **Fully NI at q=5.2**

$$n_e^{ped}/n_{GW} = 1,\ P_{HCD} = 70\ MW$$



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Benchmark GASC to FASTRAN Shows Consistent Point at H_{98}~1.3

B_t =6 T, T_e =1.26, R_0 =4.0 m, κ=2.0, δ=0.6, β_N=4.24

	GASC	FASTRAN
I_p (MA)	10.99	11.0
Q	13.42	13.5
P_{aux} (MW/m²)	91.8	92.3
V (m³)	256	256
0.8*P_f/A	3.32	3.35
H_{98}	1.3	1.25
P_{net} (Zohm) (η_{th}=0.33, η_{CD}=0.25)		152
P_{net} (GASC) (η_{th}=0.33, η_{CD}=0.25)	116	

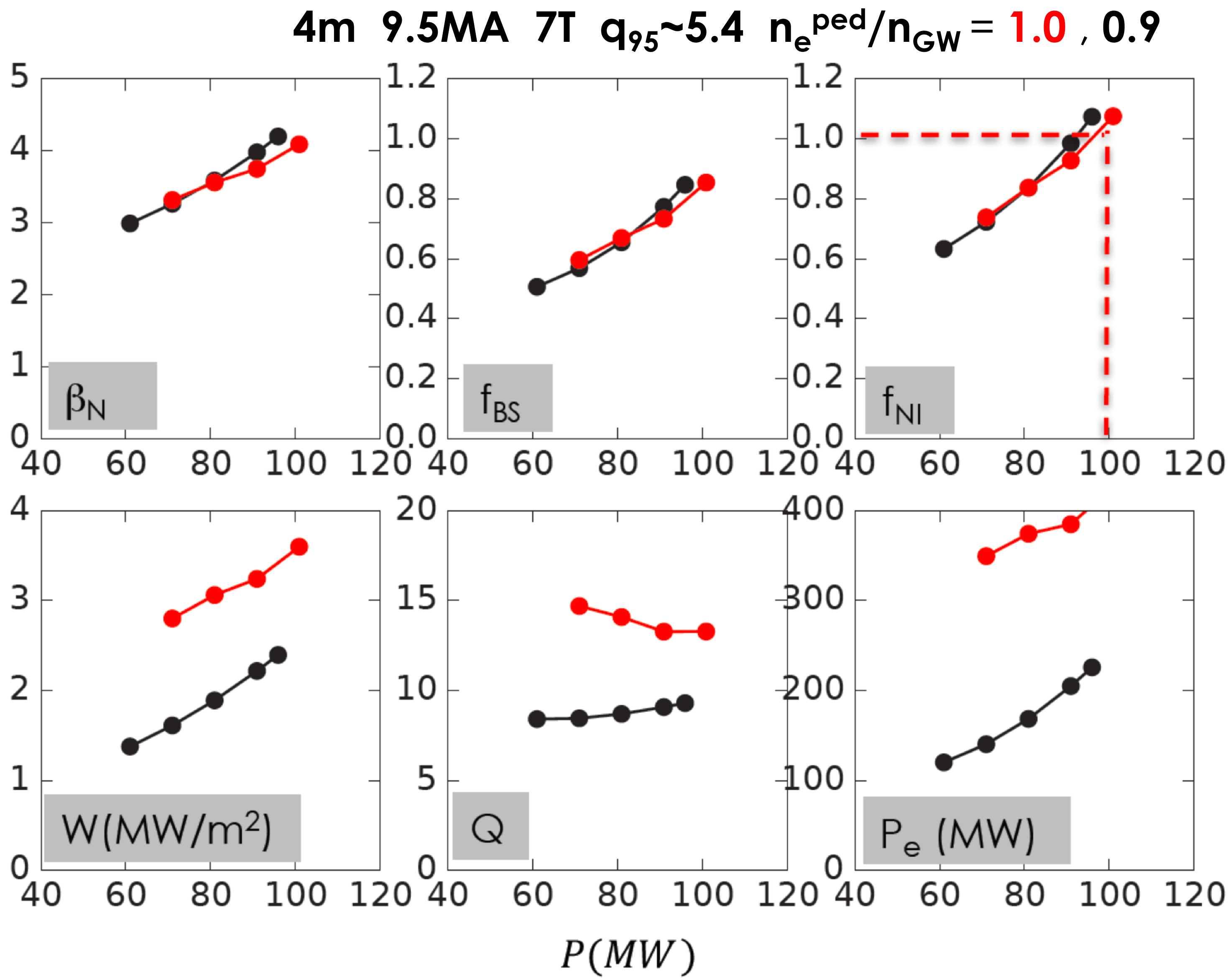
- ***Slight discrepancies in some parameter definitions account for slight differences***
  - *Radiation & H98*

Reasonable agreement between approaches

DIII-D NATIONAL FUSION FACILITY

FASTRAN TGLF/EPED Predicts 7T Provides Space to Reduce Density, Current or Auxiliary Power (to ~Zero?)

- **Performance rises cf 6T**
  - Challenges stability limit
  - And neutrons
- **A near zero heating & CD solution looks possible**
  - Being tested

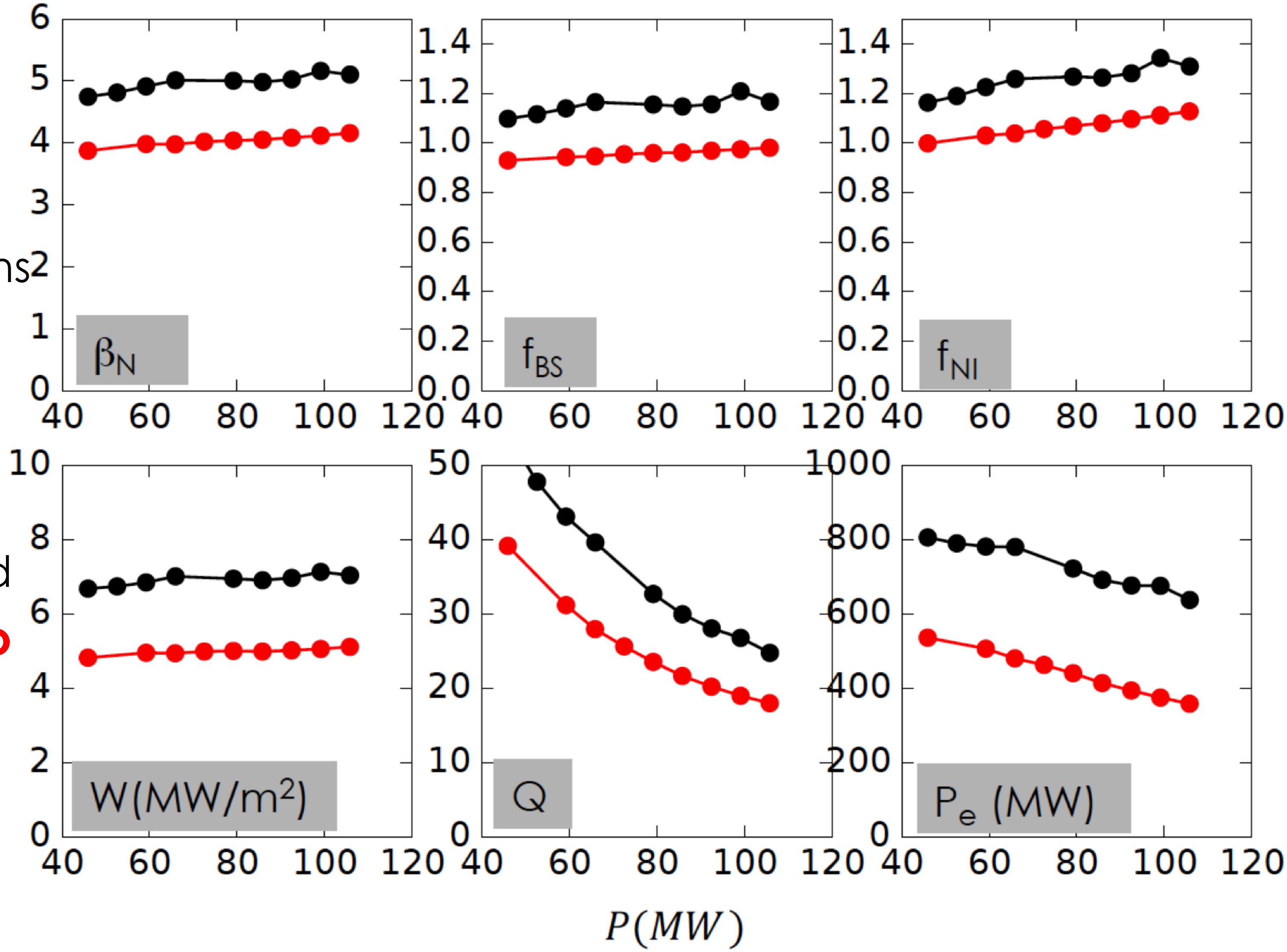


FASTRAN simulations at 4m, 9.5MA 7T, q~5.4, $\eta_{th}=\eta_{CD}=0.4$, n_{ped}/n_{GW}~1, f_{GW}~1.3

FASTRAN TGLF/EPED Predicts 7T Provides Space to Reduce Density, Current or Auxiliary Power (to ~Zero?)

- **Performance rises cf 6T**
  - Challenges stability limit
  - And neutrons
- **A near zero heating & CD solution looks possible**
  - Being tested
- **I_P probably too high at q~4**
- **DELETE TOO HIGH POWER**

4m 12.8MA 7T q_{95}~4 n_e^{ped}/n_{GW} = 1.0 , 0.9



FASTRAN simulations at 4m, 12.8MA 7T, q~4, η_{th}=0.33 η_{CD}=0.25, n_{ped}/n_{GW}~1, f_{GW}~1.3