Progress in Modeling of FNSF-AT

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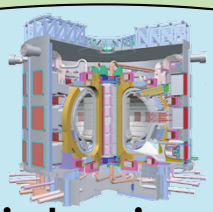
UC San Diego, Center for Magnetic Recording Research

GENERAL ATOMICS

US DOE: A Fusion Nuclear Science Facility to Provide, in Parallel with ITER, the Basis for DEMO

TODAY'S RESEARCH FACILITIES

ITER



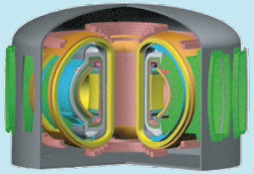
High energy gain burning plasma physics
Reactor scale superconducting technology

Fusion Nuclear Science Facility and Program

Burning Plasma Dynamics and Control

Materials in a Fusion Environment and Harnessing Fusion Power

DEMO



High gain, advanced physics, steady-state high duty factor fusion power

Options for the Fusion Nuclear Science Facility

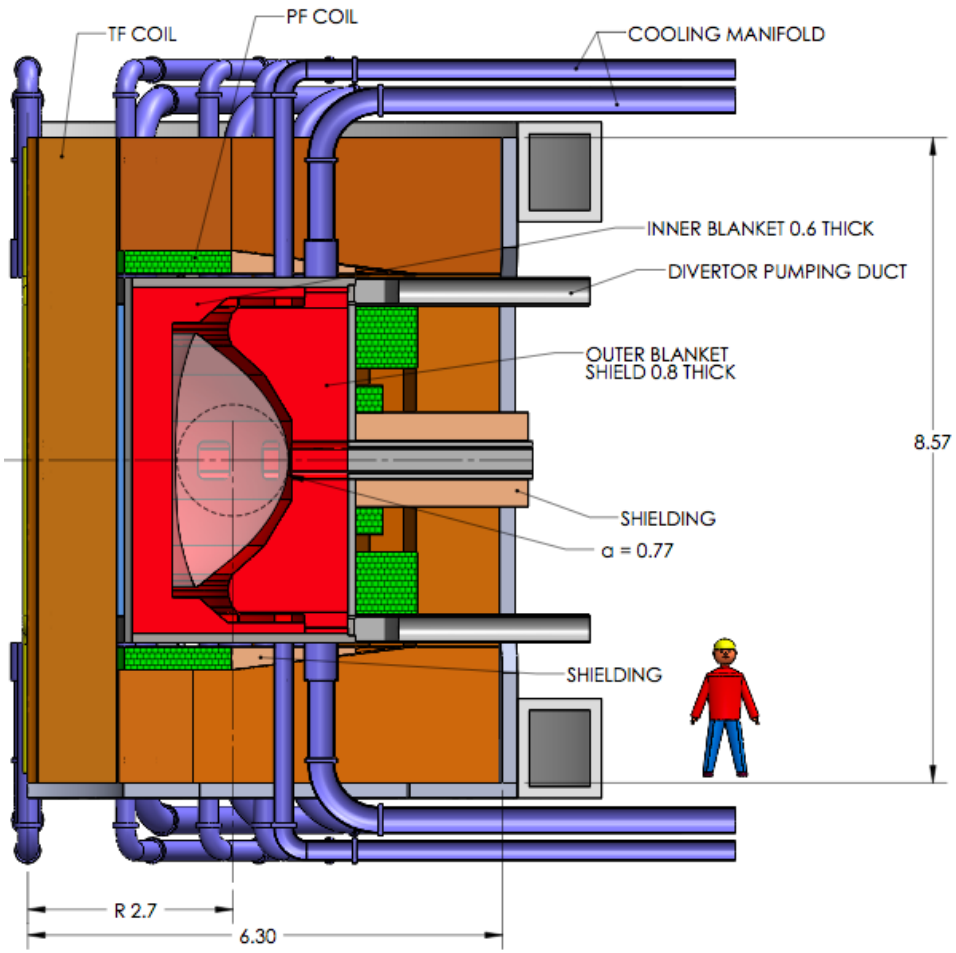
- **FNSF-ST** (larger step to DEMO)
  - Operate steady-state
  - High neutron fluence for component testing
  - Provide a materials irradiation facility to test/validate fusion materials
  - Demonstrate tritium breeding
  - Show fusion can produce high-grade process heat and electricity
- **FNSF-AT** *adds:*
  - Produce significant fusion power (100-300 MW)
  - Demonstrate tritium self-sufficiency
  - Further develop AT physics towards Demo regimes
- **Pilot Plant** (larger step from present program) *adds:*
  - Generate net electricity
  - Reactor maintenance schemes

What is the Appropriate Size and Scope of Next Step Forward?

- **Complements ITER**
  - Not necessary to duplicate main efforts of ITER
- **Addresses key identified gaps to DEMO**
- **Can be done now** [start design]
  - **Get us ready for DEMO construction triggered by Q=10 in ITER (~2030)**

FNSF-AT — a Facility with Dual Mission: Fusion's Nuclear Science and Advanced Tokamak with Burn

- **Produce significant fusion power (100-300 MW)**
- **Operate steady-state with:**
  - Modest energy gain (1<Q<7)
  - Duty factor of 0.3 a year with up to 2 weeks of continuous operation
  - High neutron fluence (3-6 MW-yr/m^2, 30-60 dpa lifetime)
- **Provide a materials irradiation facility to develop/qualify advanced fusion materials**
- **Demonstrate tritium self-sufficiency**
- **Show fusion can produce high-grade process heat and electricity**
- **Further push AT physics towards Demo regimes**



Why AT?

AT Physics Enables Nuclear Mission at Modest Size

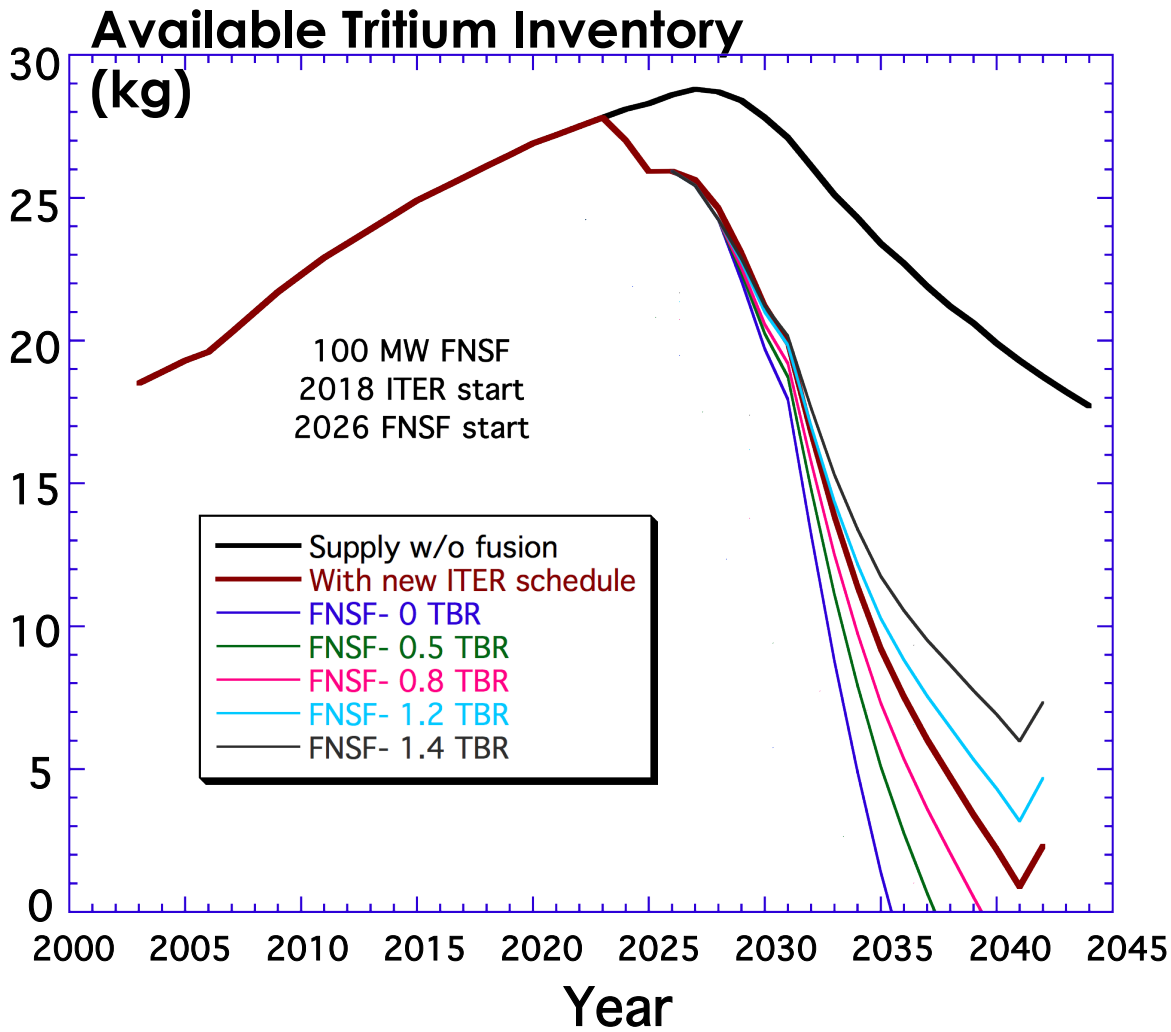
Demonstrate AT operation in steady-state with burn ⟷ Develop fusion's nuclear technology

AT physics enables steady-state burning plasmas with

- **>10x ITER neutron fluence**
  - High fluence is required for FNSF's nuclear science development objective
- **in compact device**
  - Moderate size is required to demonstrate TBR>1 using only a moderate quantity of limited supply of tritium fuel

FNSF Must Have Tritium Breeding Ratio > 1 to Build a Supply to Start Up DEMO

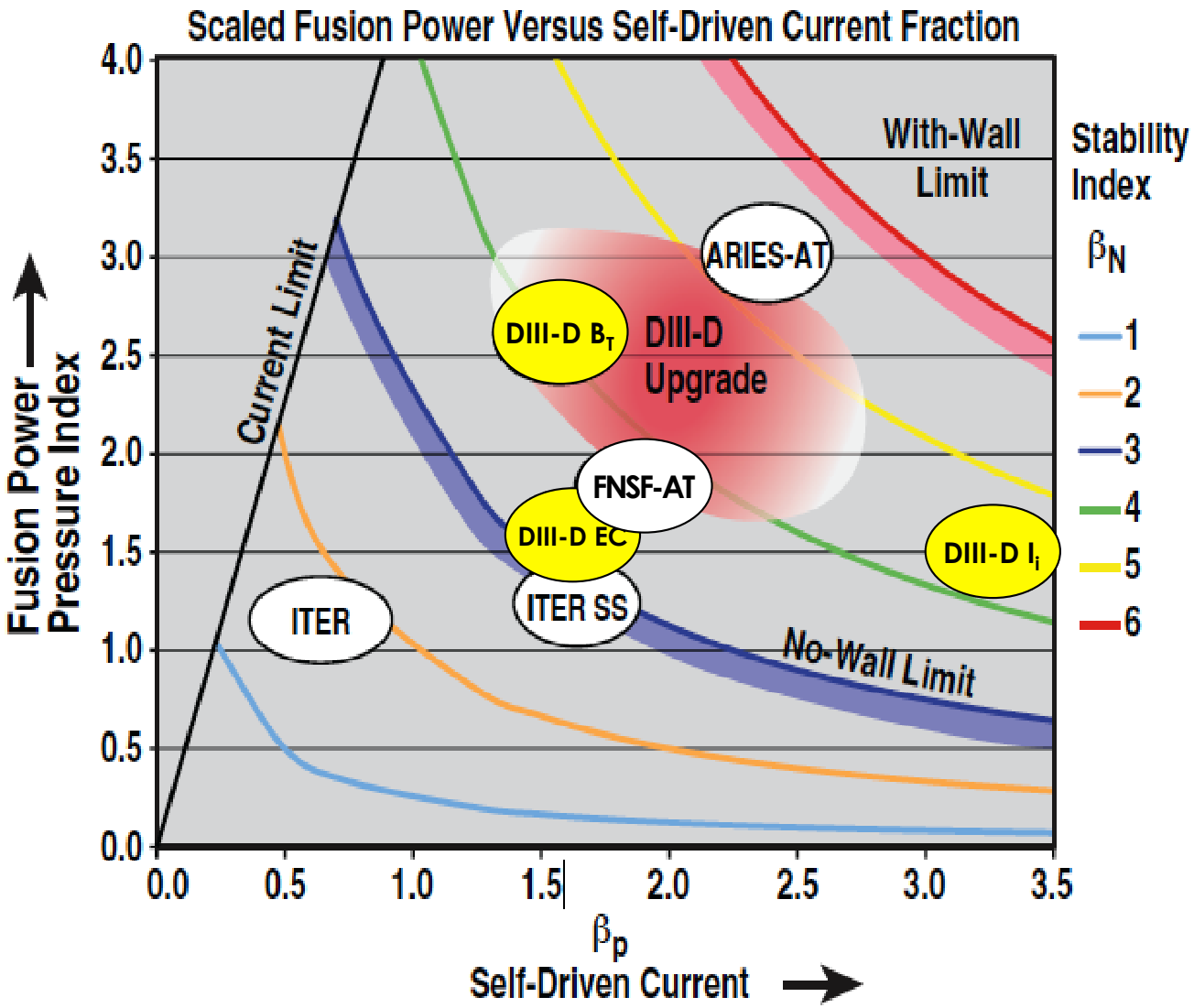
- A 1000 MWe DEMO will burn 12 kg Tritium per month
- Tritium inventory available for DEMO at end of ITER and FNSF operation depends strongly on TBR in FNSF



[M.E. Sawan, TOFE (2010)]

Is AT realistic?

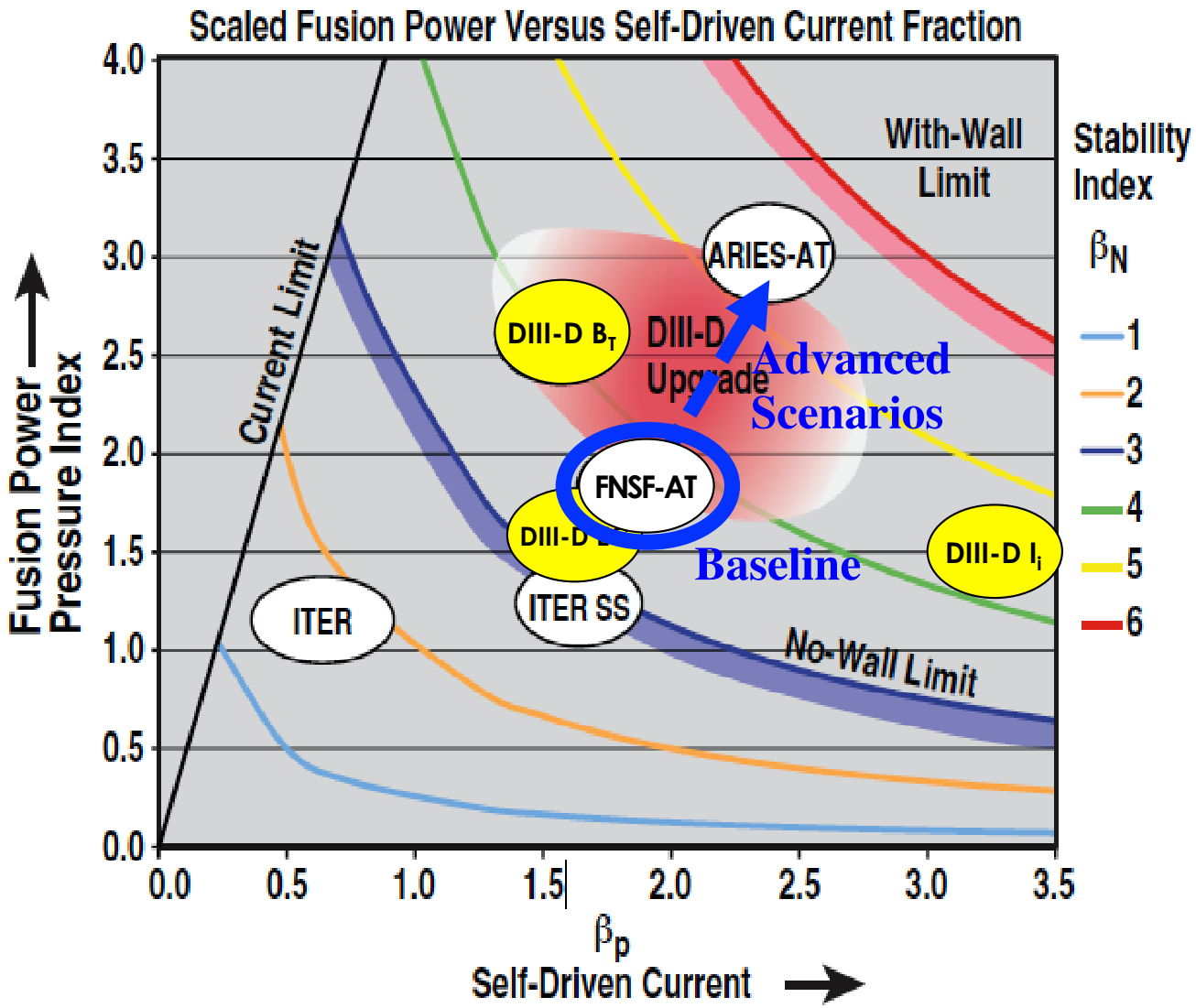
FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO



- **100% noninductive modes developed on DIII-D bracket FNSF-AT baseline**
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles

Pulse length extension in next few years

FNSF-AT Can Be Designed Using Proven AT Physics, Can Develop More Advanced Physics Towards DEMO



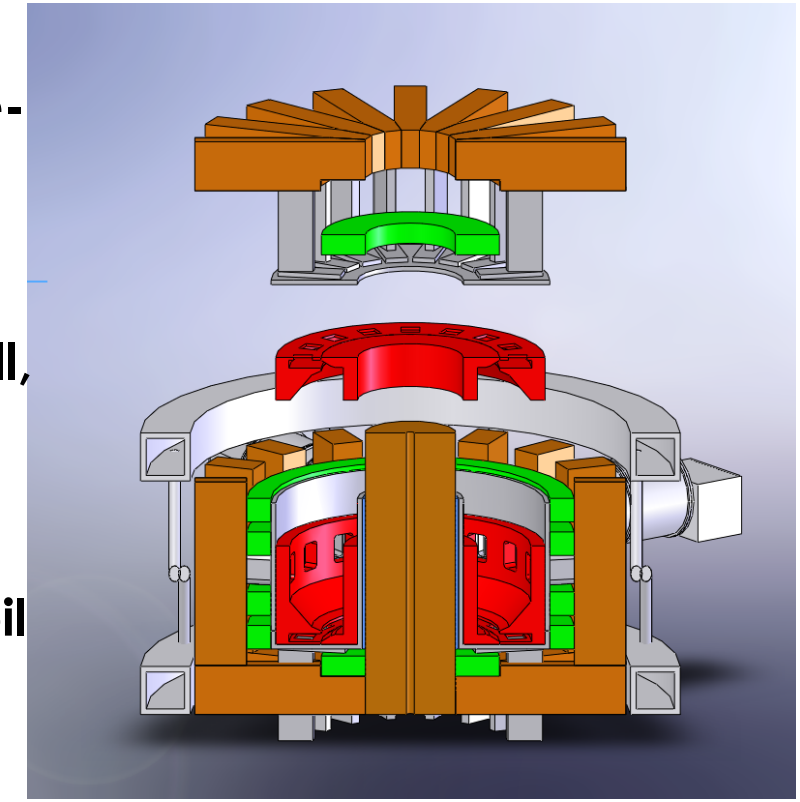
- **100% noninductive modes developed on DIII-D bracket FNSF-AT baseline**
  - Negative central magnetic shear
  - High bootstrap fraction
  - Near-stationary profiles

  Pulse length extension in next few years
- **Baseline FNSF-AT to meet nuclear science mission**
- **More advanced scenarios to close physics gaps to DEMO**

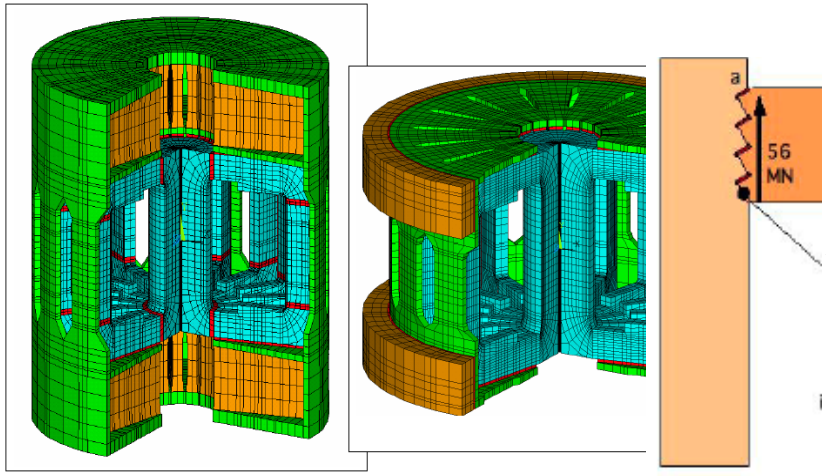
Why copper coils?

Demountable Copper Coils Enable Effective Nuclear Science Progress

- **A Fusion Nuclear Science Facility must be a research device, maintainable, accessible, re-configurable**
  - Change device components as understanding evolves
- **Jointed copper coil enables changeouts of wall, blanket, divertor**
  - Constructed as toroidally continuous ring structures
- **Other devices will address superconducting coil issues**



Sliding Joint (C-mod)



Sawtooth Joint (Rebut)

Titus et al. SOFE (2009)

A Staged Approach to Learn and Improve Nuclear Components, Diagnostics, Operating Scenario

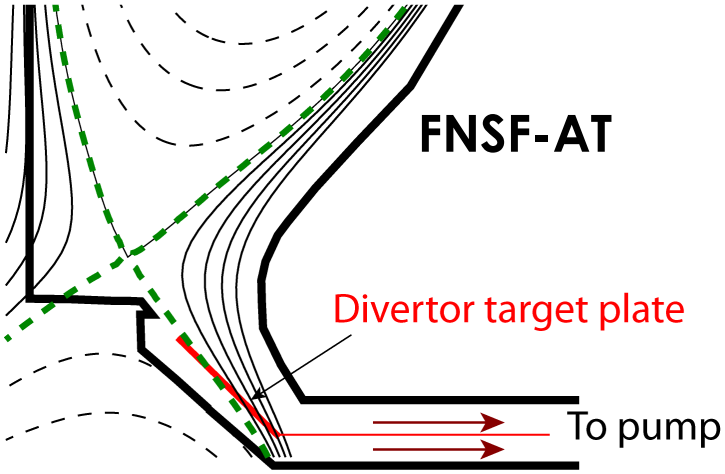
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	← START UP →				FIRST MAIN BLANKET							SECOND MAIN BLANKET							THIRD MAIN BLANKET				
	H	D	DT																				
Fusion Power (MW)	0	0	125		125				250			250			250				250				400
P_N/A_{WALL} (MW/m^2)			1		1				2			2			2				2				3.2
Pulse Length (Min)	1		10		SS				SS			SS			SS				SS				SS
Duty Factor	0.01		0.04		0.1				0.2			0.2			0.3				0.3				0.3
T Burned/Year (kG)			0.28		0.7				2.8			2.8			4.2				4.2				5
Net Produced/Year (kG)					–0.14				0.56			0.56			0.84				0.84				1
Main Blanket	He Cooled Solid Breeder Ferritic Steel											Dual Coolant Pb-Li Ferritic Steel							Best of TBMs RAFS?				
TBR					0.8				1.2			1.2			1.2				1.2				1.2
Test Blankets							1,2					3,4		5,6					7,8		9,10		
Accumulated Fluence (MW-yr/m^2)			0.06						1.2						3.7								7.6

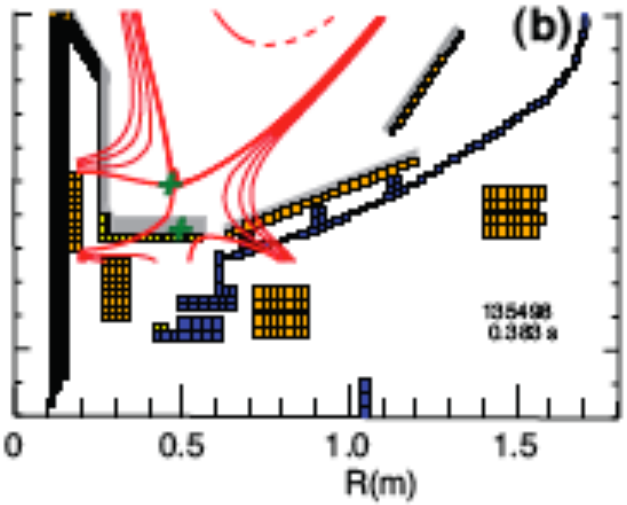
Radiation damage survival strategy:

Nuclear facing structures do not see more than 2 MW-yr/m^2 (20 dpa) before removal

Can Start FNSF-AT Design Now

- Shovel-ready
  - Standard coils
  - Standard NBI
  - Standard divertor
  - Proven AT physics
  - Proven materials
- Concept is open to new advances
  - Demountable superconducting coils
  - Snowflake, SX divertor
  - Negative NBI technology
  - Advanced materials





NSTX Snowflake Divertor experiment achieves large reduction of peak heat flux

Soukhanovskii, et al., IAEA 2010

Achieving the Baseline AT Performance of FDF Requires Resolving Some Outstanding Challenges

- Integration of high performance, steady-state, burning plasmas
- Compatibility of auxiliary systems with tritium self-sufficiency
- Maintenance and controlling of high-performance burning plasmas
- Heat and particle management
- Avoidance and mitigation of off-normal events

Nuclear Science Mission Can Be Accomplished by FNSF-AT Baseline Mode with Operating Margin

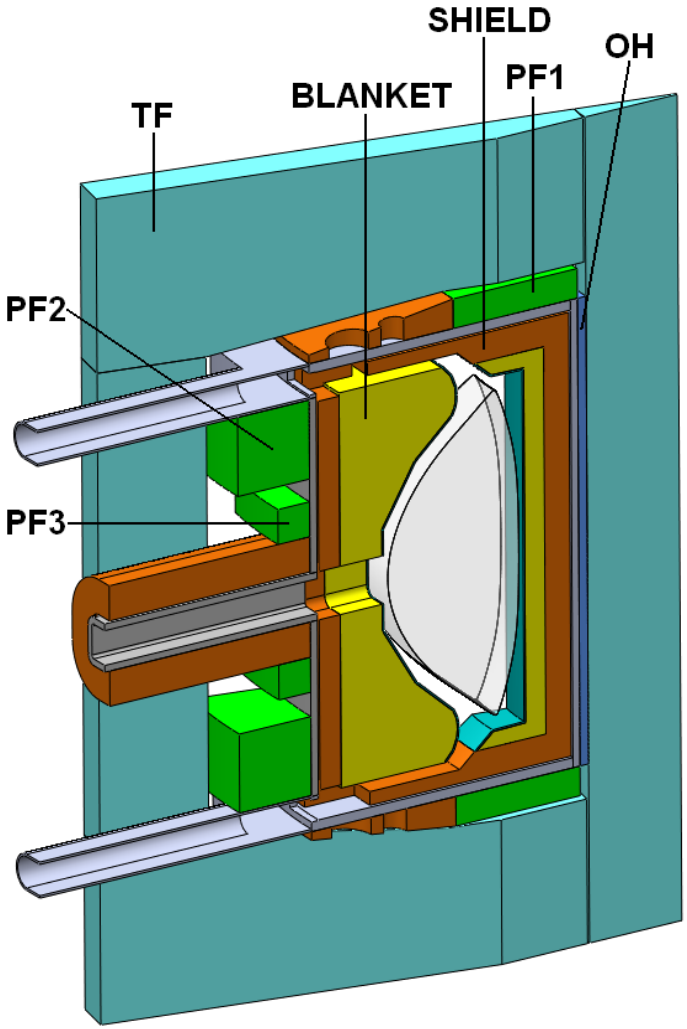
- Baseline FNSF-AT: 4x neutron flux of ITER and annual duty factor of 30%
  - 10x neutron fluence of ITER
  - Materials/components qualification for first few years of DEMO

			Baseline	Lower BetaN, fbs, H98	Lower BT, fbs	Advanced
A	aspect ratio		3.5	3.5	3.5	3.5
k	plasma elongation		2.31	2.31	2.31	2.31
Pf	fusion power	MW	290.07	159.07	144.65	476.44
Pinternal	power to run plant	MW	499.75	526.57	348.22	500.35
Qplasma	Pfusion/Paux		6.88	2.93	3.52	12.37
Pn/Awall	Neutron Power at Blanket	MW/m2	2.00	1.10	1.00	3.28
BetaN	normalized beta	mT/MA	3.69	2.65	3.69	4.50
fbs	bootstrap fraction		0.75	0.54	0.56	0.85
Ip	plasma current	MA	6.60	6.56	6.39	7.09
Bo	field on axis	T	5.44	5.44	3.90	5.44
Paux	Total Auxiliary Power	MW	42.16	54.22	41.11	38.53
Peak Heat Flux	Peak Heat Flux to Outer Divertor	MW/m2	6.70	6.83	5.19	7.26

Nominal parameters for some of the operating modes evaluated from a 0-D system optimizer model [Chan, Stambaugh, et al., FS&T (2010)]

Tritium Breeding Ratio in FNSF-AT Is ≥1 for Two Blanket Concepts Considered: DCLL and HCCB

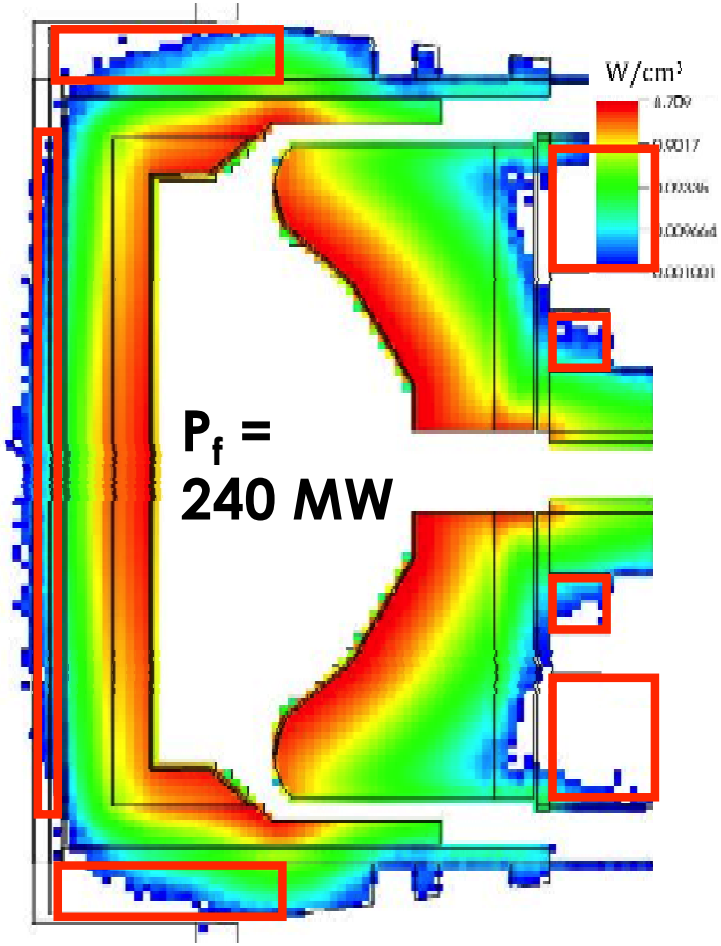
- **DCLL = Dual Coolant Lead Lithium**
- **HCCB = Helium Cooled Ceramic Breeder**
- **3-D neutronics analysis using the DAG-MCNP code and FENDL-2.1 nuclear data library**
- **TBR = 1.09 (HCCB), 1.0 (DCLL)**
  - Lost coverage in 16 midplane ports accounts to ~6% in TBR



[M.E. Sawan, TOFE 2010 (to be published in FS&T)]

Compatibility of FNSF-AT Layout Supported by Detailed 3-D Neutronics Calculations

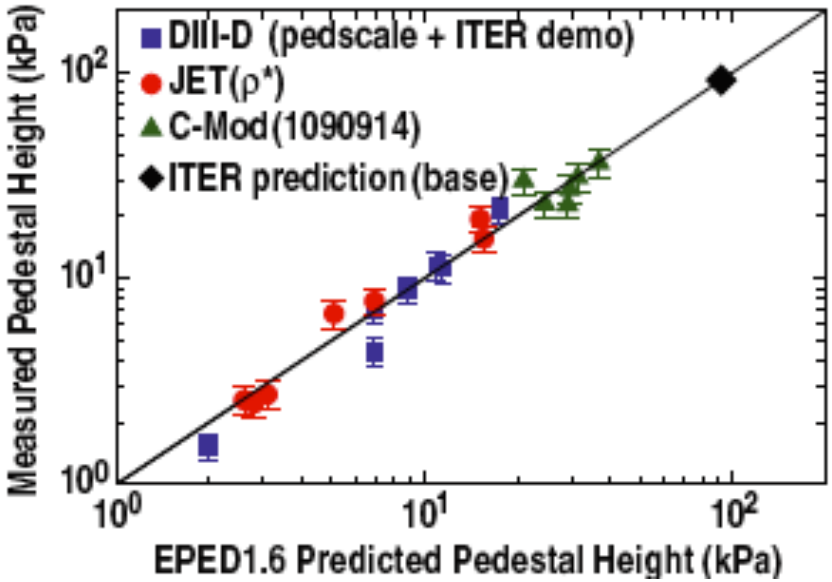
- Acceptable cumulative end-of-life organic insulator dose levels in TF, OH, and most PF coils
- Minor configuration change needed for PF coil in divertor region

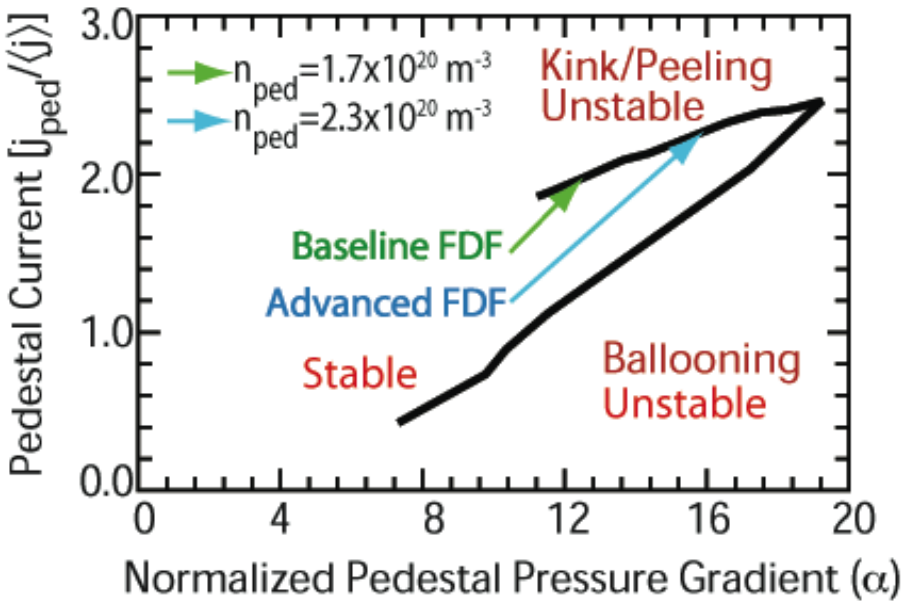


[M.E. Sawan, TOFE 2010 (to be published in FS&T)]

Physics-Based Integrated Modeling Needs to Treat Realistic Edge Pedestal

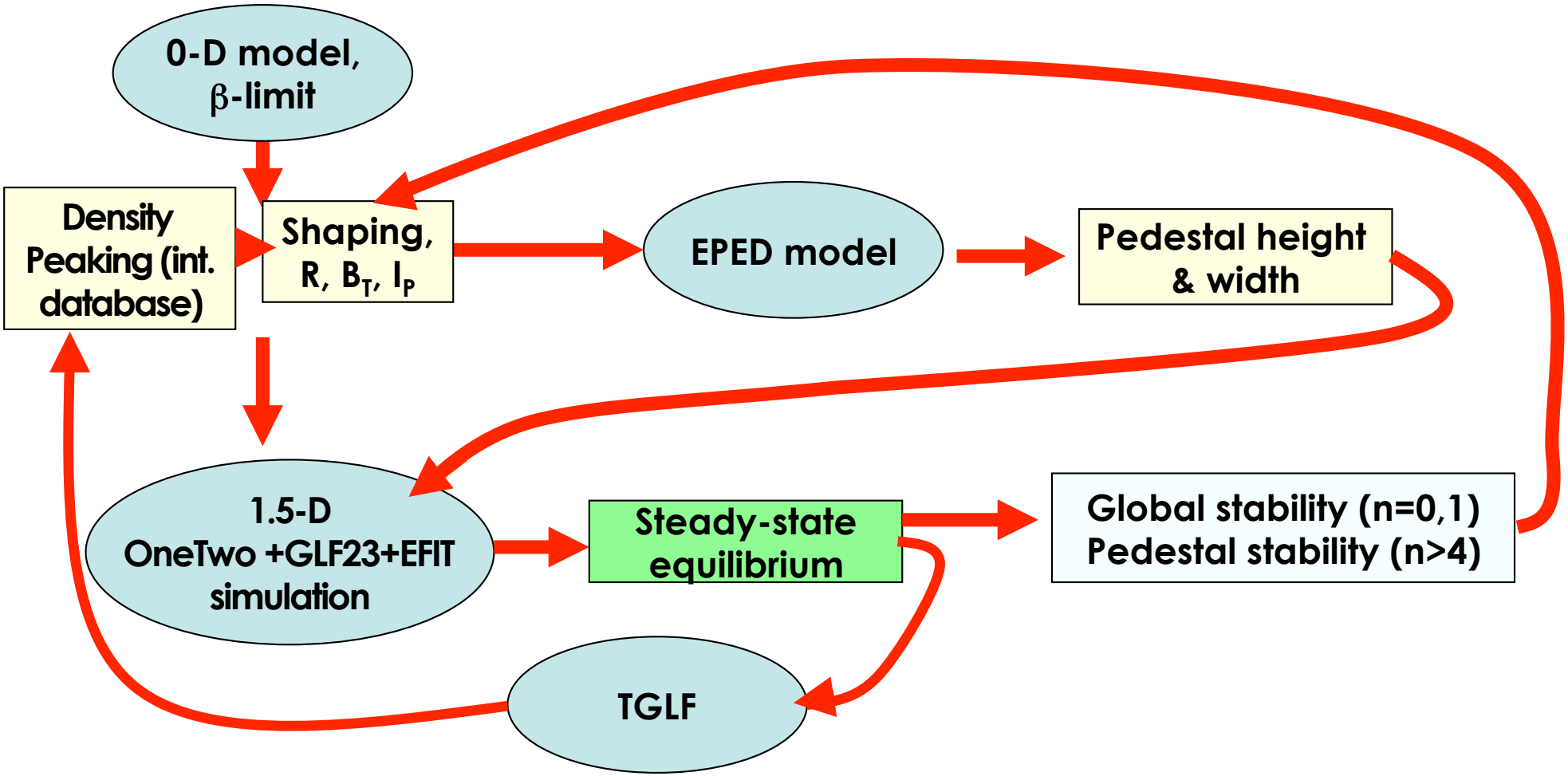
- **Pedestal height and width predicted by EPED model, successfully validated against several experiments [Snyder, et al. Nucl. Fusion (2011)]**
  - Constraints based on intermediate wavelength peeling-ballooning modes and kinetic ballooning turbulence





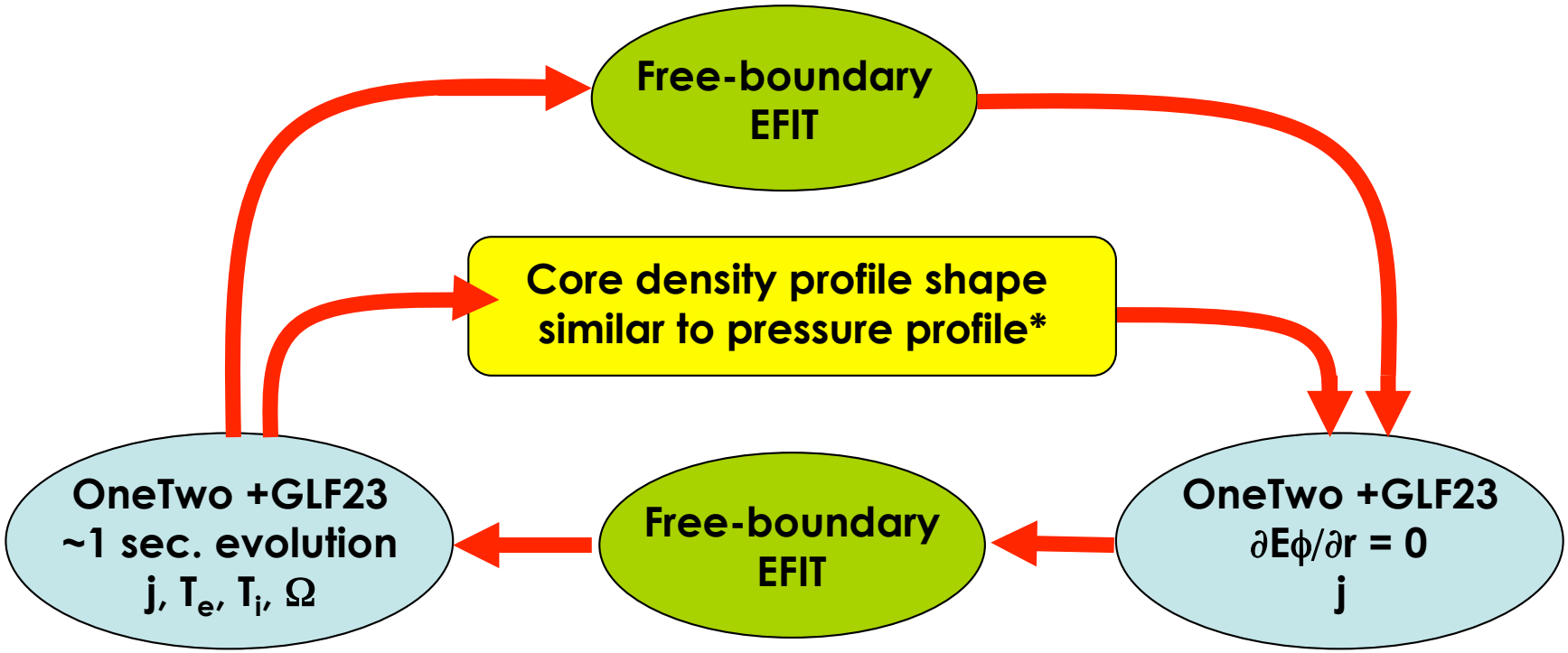
- **Peeling ballooning stability calculations predict that FNSF-AT pedestal will operate on peeling boundary, where QH-mode can exist**

Steady-State Scenario Development - Iterative Process toward Self-consistent Physics Solution



Start-up scenario not yet developed

Steady-state Is Found via Iteration of Alternating Temperature Profiles and Current Profile Evolution



* **Density pedestal fixed at EPED value, density peaking fixed at international database value [**Angioni, et al., Nucl. Fusion (2007)]

FDF Modeling Yields Full Noninductive Current Drive and High Fusion Power with Combination of EC and LH

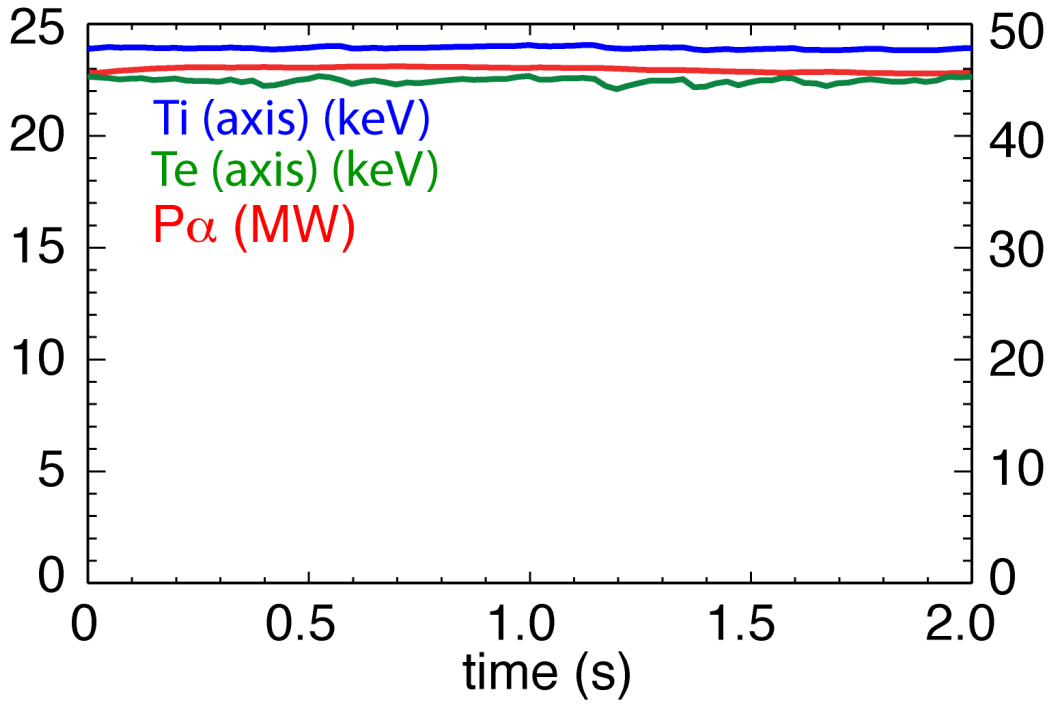
No NBI → Most challenging scenario, but →
- Simplifies tritium containment
- Increases area for tritium breeding
- Negative-ion NBI technology uncertain

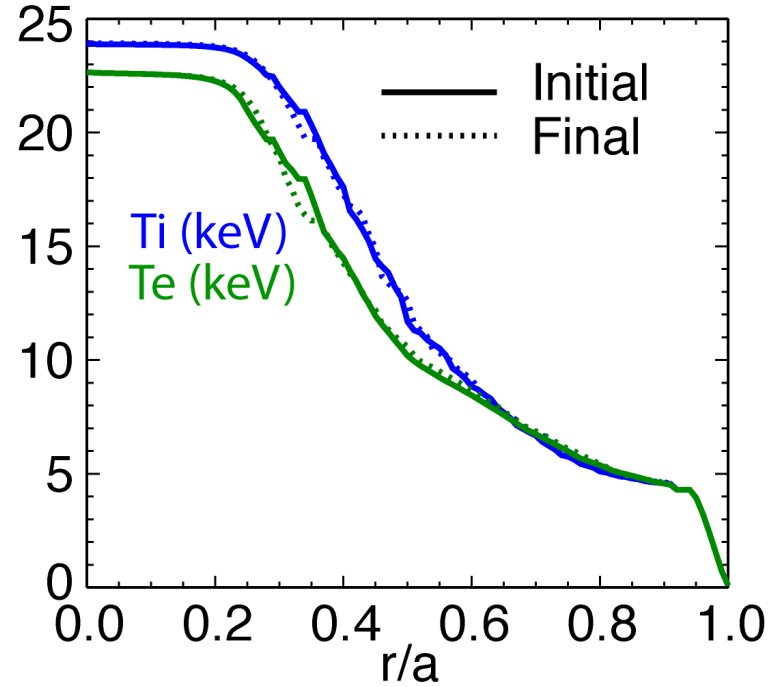
1.5-D OneTwo+GLF23+EFIT simulation

→ ECH/ECCD only → Too much ECCD power required for steady-state baseline scenario (β_N~3.7)

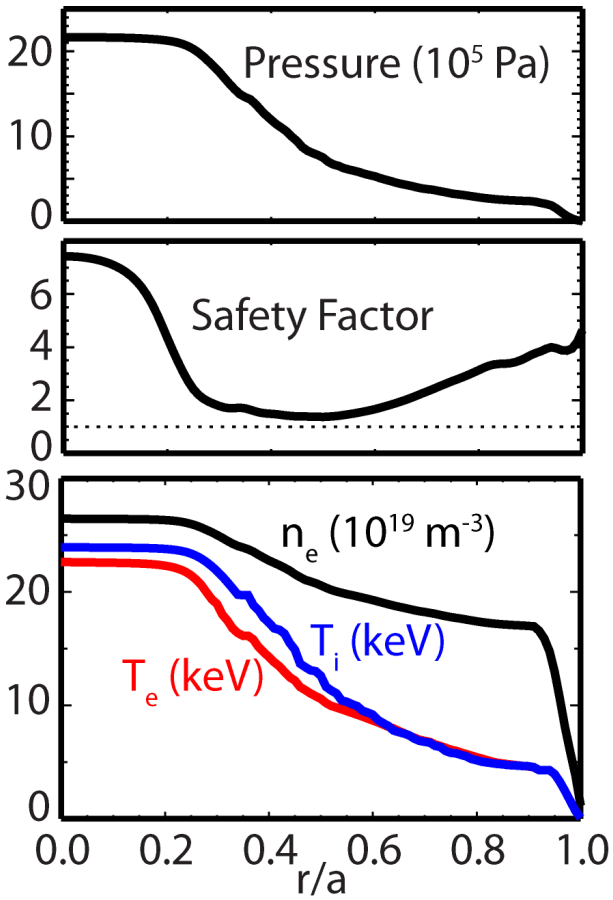
→ ECH/ECCD + LHCD → Steady-state baseline equilibrium:
Q~3, P_{fus}~230 MW,
P_{EC}=55 MW, P_{LH}=25 MW,
H_{98y2}~1.2, f_{BS}~70%

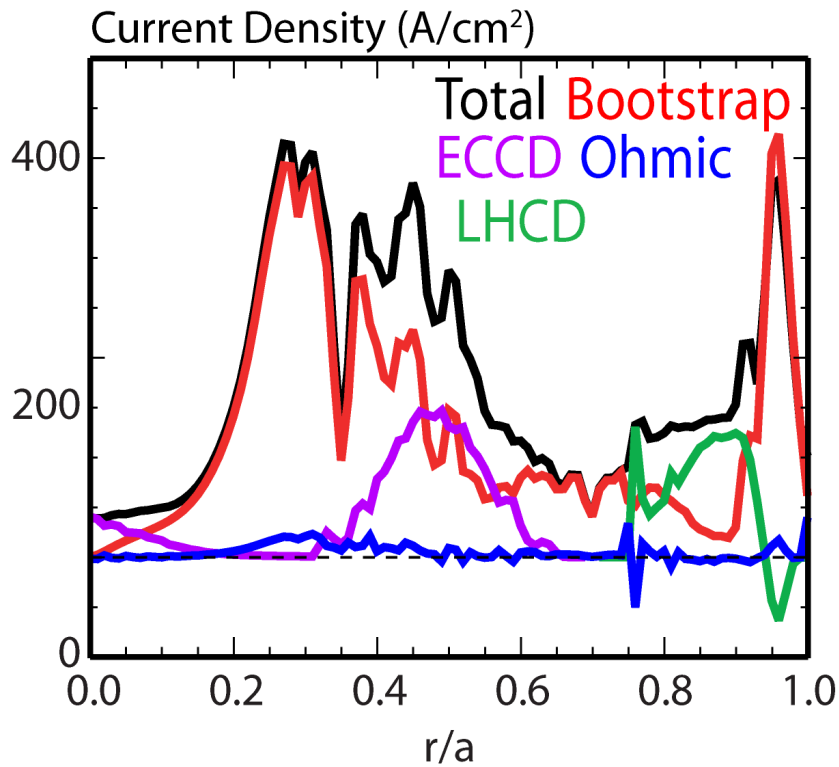
Evolution Has Reached Steady-state Equilibrium (or Very Close to It)

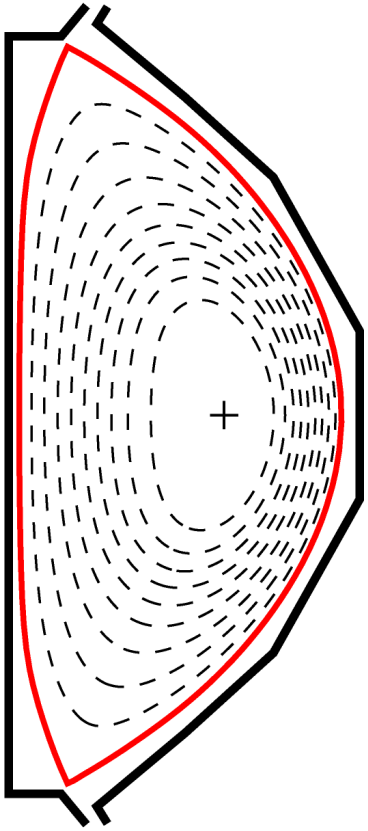




Steady-State Equilibrium for Baseline FDF Mode Has Desirable AT Features

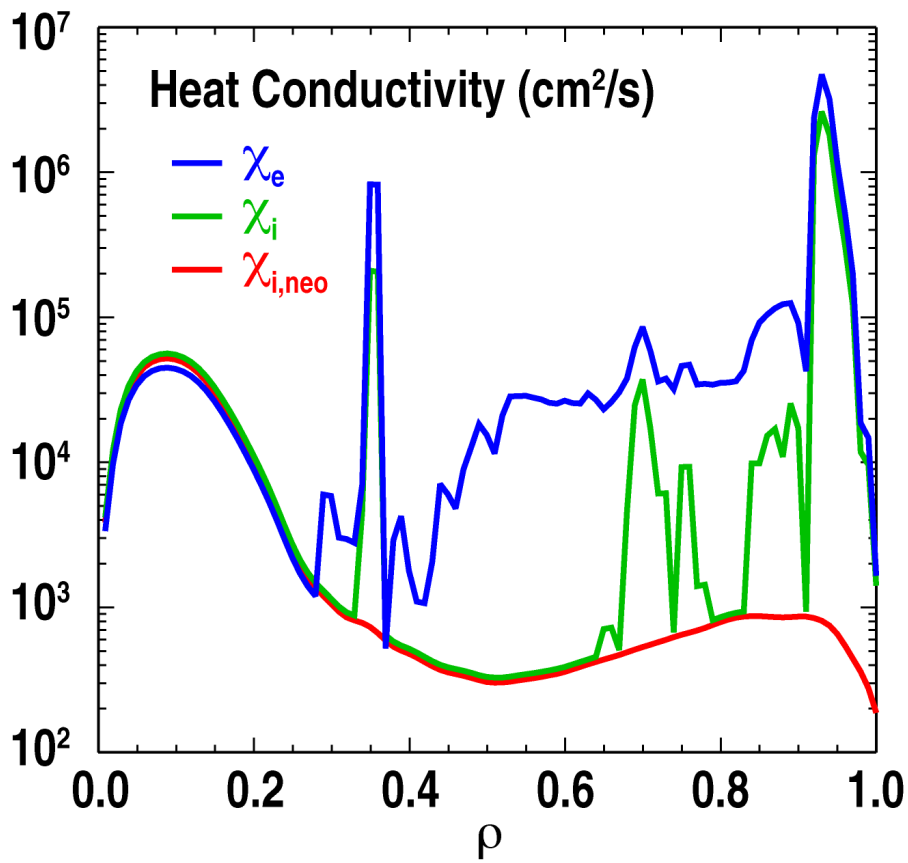






ITB Formation Explained by Turbulent Transport Profiles

Transport Model – GLF23

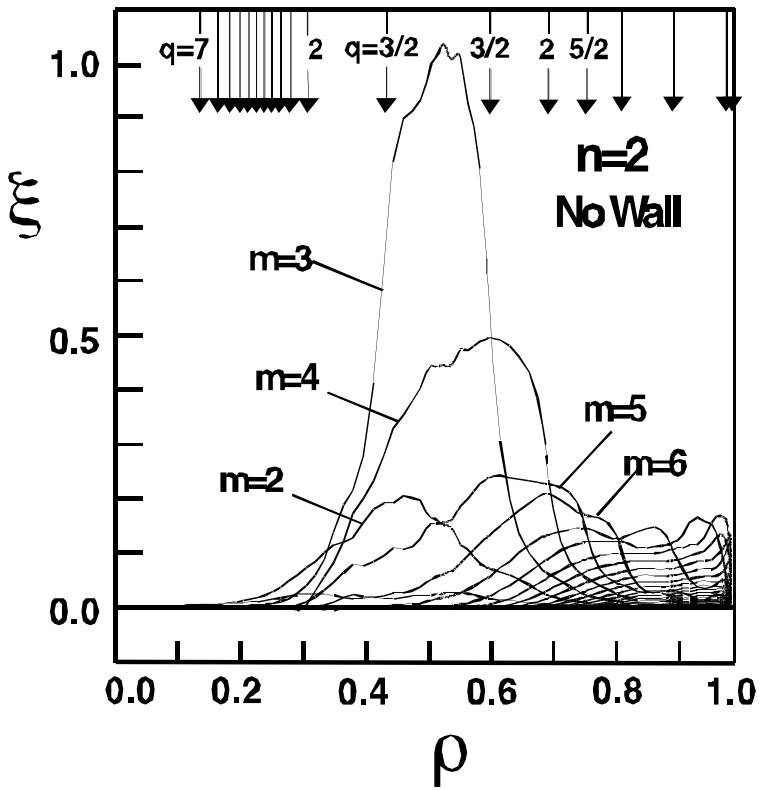


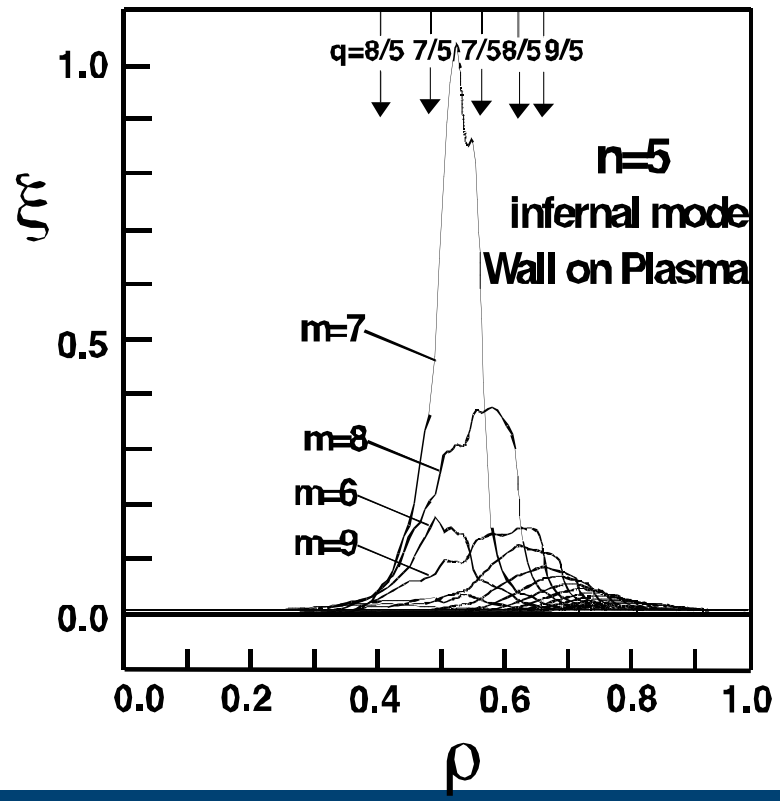
Summary Chart:
Comparison of 0D and 1.5D Modeling

Parameter		Unit	Baseline 0-D	Baseline 1.5-D
A	aspect ratio		3.5	3.5
k	plasma elongation		2.31	2.28
δ	Plasma triangularity		0.7	0.7
Pf	fusion power	MW	290	230
Qplasma	Pfusion/Paux		6.88	2.93
BetaT	toroidal beta		5.79%	5.84%
BetaN	normalized beta	mT/MA	3.69	3.7
fbs	bootstrap fraction		0.75	0.7
Ip	plasma current	MA	6.60	6.60
Bo	field on axis	T	5.44	5.44
Zeff			2.0	1.6
Ti(0)	Ion Temperature	keV	16.41	23.9
<TI>	Volume Averaged Ion Temp	keV	9.38	10.1
n(0)	Electron Density	E20/m3	3.14	2.64
<n>	Volume Averaged Elec Density	E20/m3	2.09	1.88
Paux	Total Auxiliary Power	MW	42.16	80
HITER98Y2	H factor over ELMY H		1.60	1.2

Ideal MHD Stability Analysis Shows Configuration Stable to Global Modes

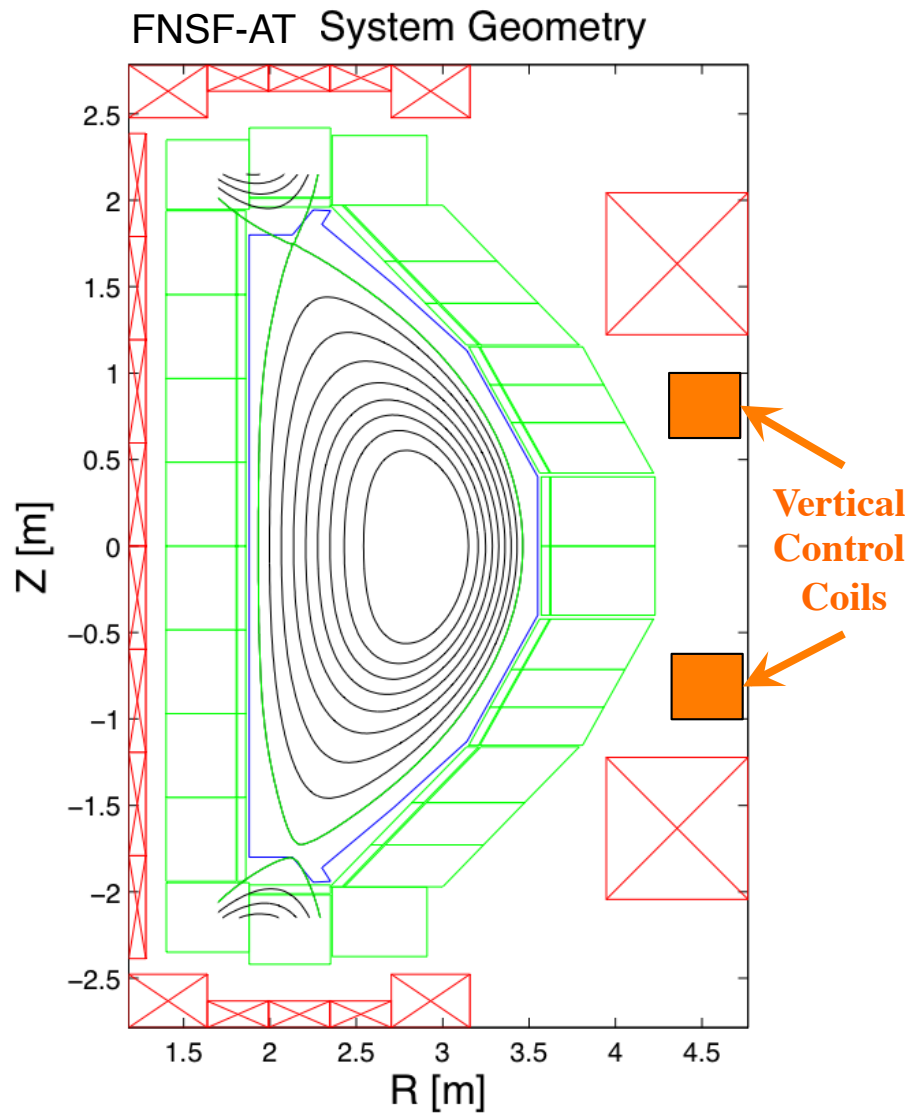
- **All n < 5 modes stabilized by conformal wall at 1.15 times minor radius**
  - All these modes are infernal modes with n = 2 least stable
  - n = 5 infernal mode remains unstable with wall on plasma
- **High n weak infernal modes stabilized by slightly reduced pressure gradient in low shear region and likely self stabilize and saturate**





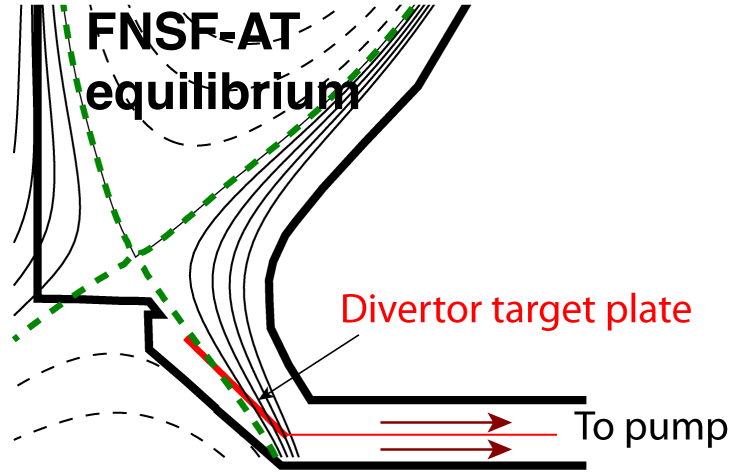
FNSF-AT Has Comparable Level of Controllability to DIII-D, with Conservative Coil Design Assumptions

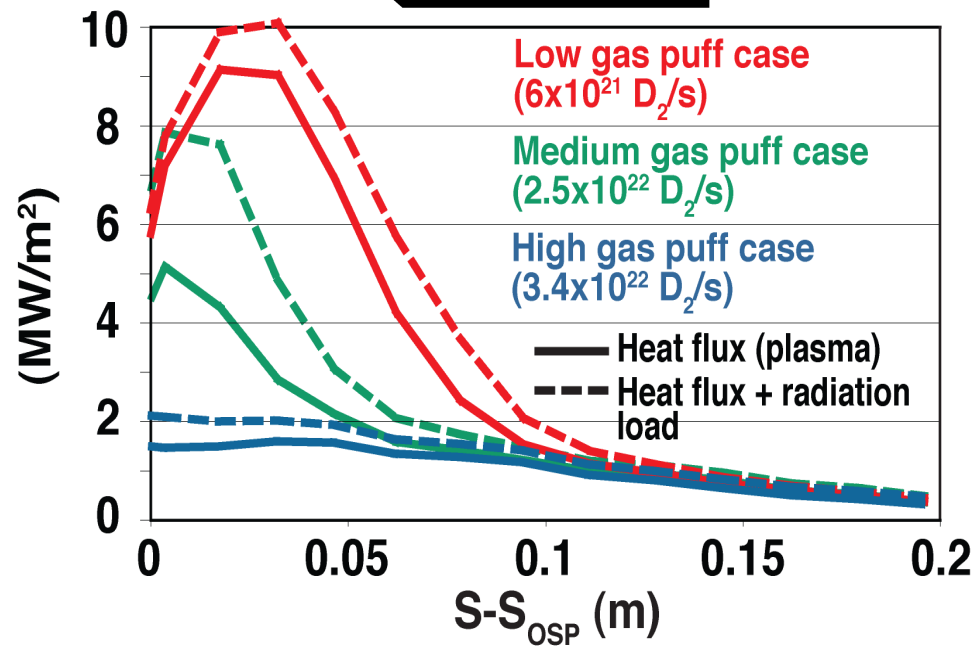
- **Toroidally continuous vessel and blanket produce very low vertical growth rate**
  - $\gamma\tau_w \sim 0.67$ ($\ll \gamma\tau_w|_{DIII\text{-}D} \sim 2.5$)
- **Achievable control coil engineering assumptions**
  - Maximum voltage 6 kV (in 50 turns
  - Maximum cross-section current density 1.5 kA/cm^2
- **Maximum controllable displacement comparable to DIII-D**
  - $\Delta Z_{MAX}/a \sim 12\%$
  - DIII-D typ. $\Delta Z_{MAX}/a \sim 10\%$ with no VDE



Axisymmetric Divertor Structures Allow Precision Tile Alignment, Enable Strong Divertor Plate Tilting

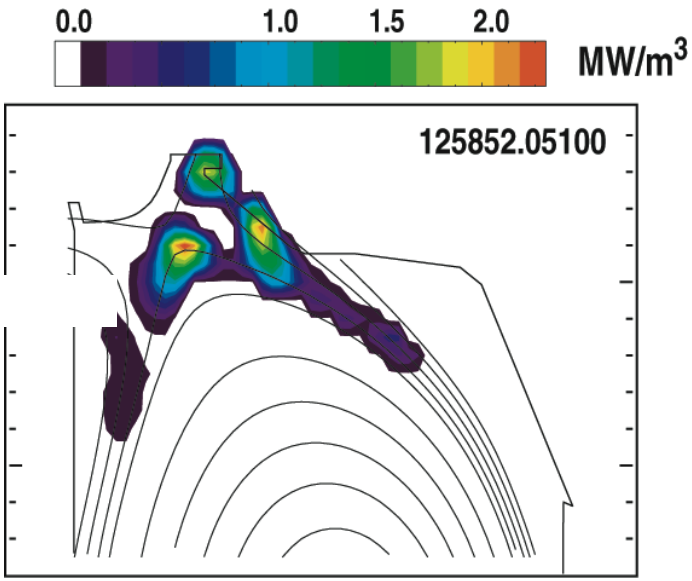
- **2-D analysis (SOLPS, J. Canik, ORNL) predict peak heat flux <10 MW/m^2**
  - Strong plate tilting
  - DND configuration
  - ~50% core radiation fraction
- **Several approaches can be used in parallel to further reduce peak heat flux**
  - SOL and divertor radiative dissipation
  - Flux expansion (X divertor, SX divertor, Snowflake divertor are being tested in experiments)



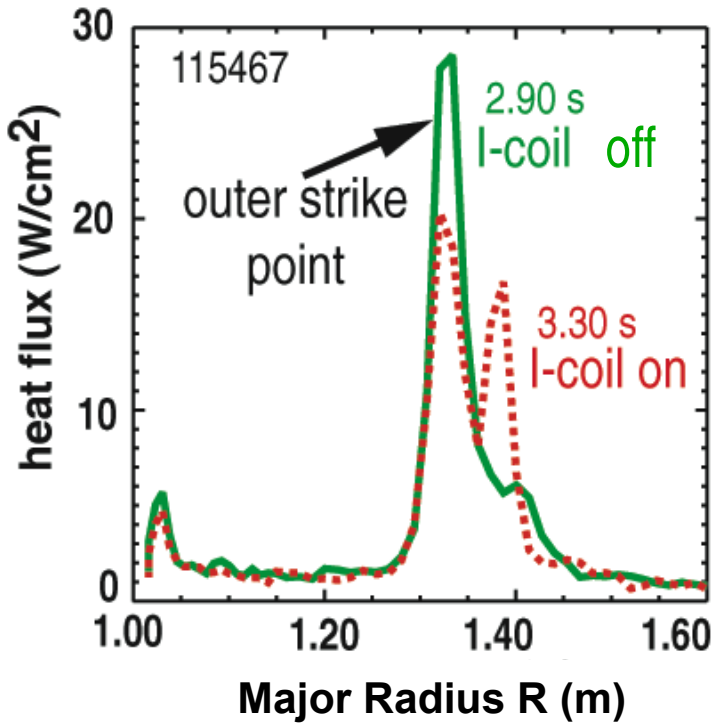


DIII-D Shows Radiative Dissipation and 3D Fields Are Viable Approaches to Reducing Peak Heat Flux

- **Divertor radiation preferentially enhanced using puff and pump technique**



- **P_{rad}/P_{NBI} ~ 60% with Z_{eff}~2.0**
  - Argon and D_2 injection
- **β_N=2.6, H_{89}=2.0, G=0.4 maintained**
  - Experiments thus far focused on puff and pump studies, not fusion performance



- **n=3 magnetic field used for ELM control also splits strike points**
- **Angular rotation of the 3D field will result in a time averaged broadening of the OSP footprint**

Summary (1)

- **Steady-state scenario development of FNSF-AT carried out using iterative process of alternating kinetic profiles (GLF23) and current profile evolution toward a self-consistent solution**
  - No NBI to simplify tritium containment, increase area for tritium breeding, and avoid costly negative-ion NBI technology
  - Desired SS baseline equilibrium found using ECCD and LHCD
- **Equilibrium ideal MHD stable for n<5, with pedestal height against predicted (EPED) ELM threshold**
- **Vertical controllability achievable with conservative coil design assumptions**
- **Peak divertor heat flux (SOLPS) comparable to ITER**
- **TBR>1 possible, neutron damage of coils acceptable using organic insulators (DAG-MCNP)**

Summary (2)

- Some key physics models are still missing - disruption, ELM dynamics
- Modeling of the plasma edge and PFC is preliminary – recycling, material erosion
- Whole Device Modeling is limited by speed of codes – hardware and software development required
- Extensive verification and validation effort remains

FNSF-AT Will Get Us Ready For DEMO Construction Triggered By Q=10 in ITER

Key features of the FNSF-AT approach:

- **FNSF-AT is on direct path towards attractive DEMO**
- **FNSF-AT plus ITER fill gaps to DEMO**
- **Ready to start design of FNSF-AT**
  - Proven materials, proven physics for first stage of operation