Major Remaining Challenges and Solution Paths

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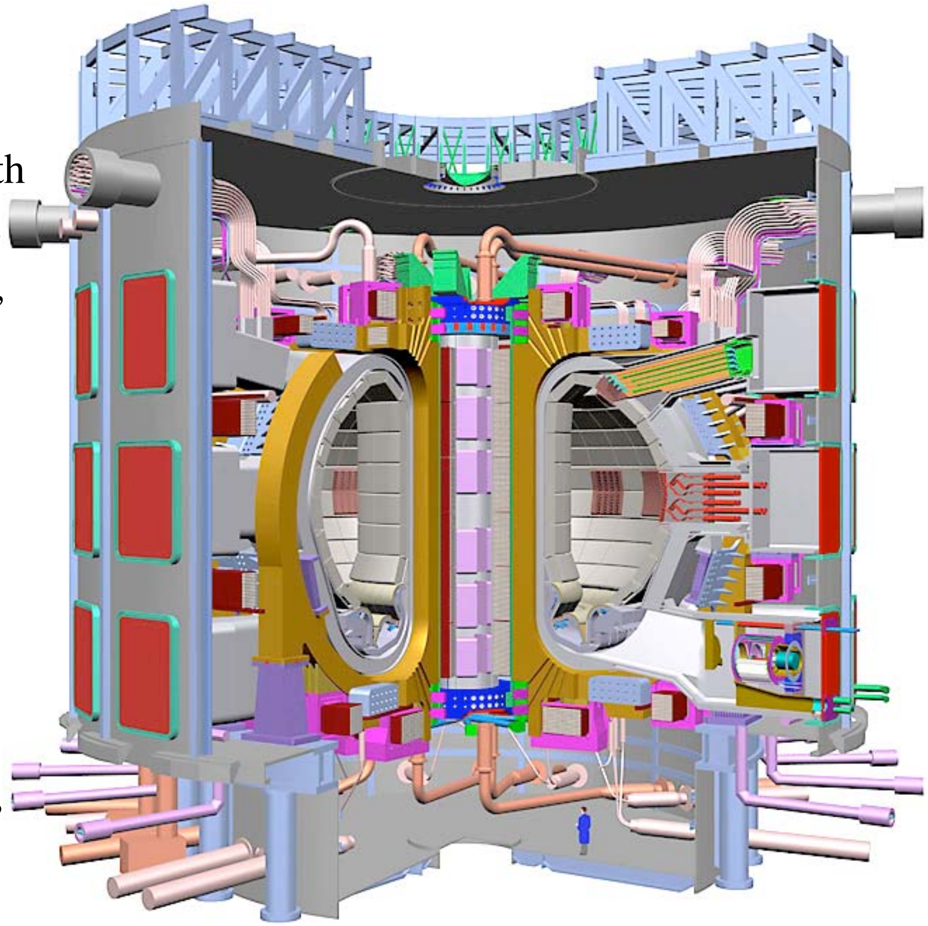
GENERAL ATOMICS

ITER Mission: To Demonstrate the Scientific and Technological Feasibility of Fusion Energy

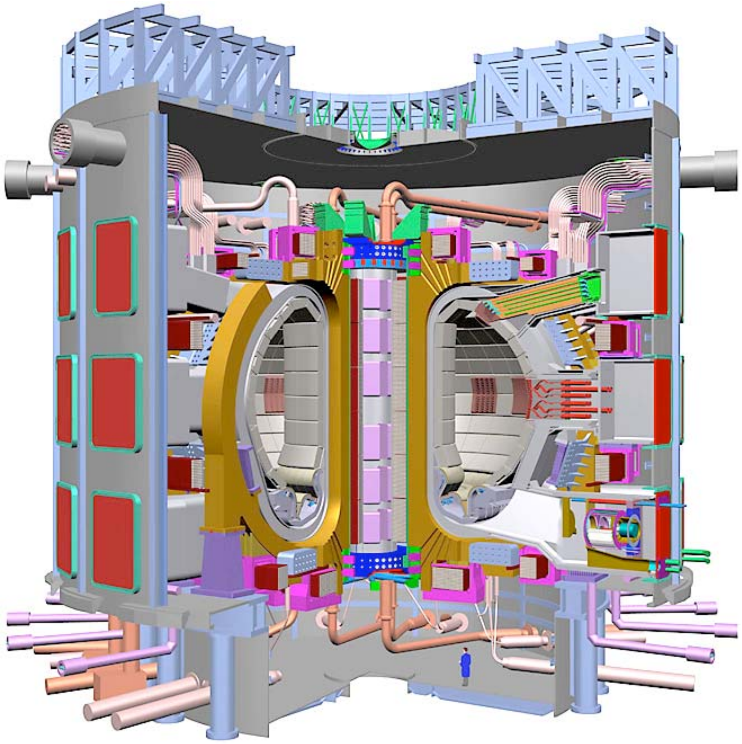
- "Achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power of at least 10 for a range of scenarios, and with a duration sufficient to achieve stationary conditions on the timescales characteristic of plasma processes, whilst not precluding the possibility of controlled ignition."
  - Q=10, 500 MW fusion power for 400 seconds.

- "Aim at demonstrating steady-state operation using non-inductive current drive with the ratio of fusion power to input power for current drive of at least 5."
  - Q>5, 350 MW for 1000 to 3000 seconds



ITER is the Power Plant Scale, All Superconducting Machine, the MFE High Energy Gain Burning Plasma Experiment

- ITER will develop power plant technologies
  - Large superconducting magnets
  - Plasma Heating and Current Drive systems
  - Plasma Measurement systems
  - Tritium handling, fueling systems
  - High stored energy in plasma
  - High power exhaust to surfaces
  - Remote handling
  - Test blanket modules
- ITER will allow study of high energy gain plasmas in which most of the plasma heating and electrical current flowing in the plasma is produced by the plasma – the “self-organized plasma state.”



- ITER is a joint project of the EU, Japan, US, Russia, China, South Korea, India
  - Half the population of the earth, the organizing principle of the world MFE Program
  - The International Tokamak Physics Activity has allowed 1000 scientists world wide to contribute to ITER

ITER Has a Clear Path to Construction

- **Baseline Design Approved**
- **Osamu Motojima New Director General**

Looking northeast over the ITER construction site.

Bulldozers and scrapers are busy leveling the 14,000 square-meter area that will host the huge PF Coils Assembly Building.

Operations and Safety on the ITER Platform are being carefully coordinated by the Engage Consortium and the French company APAVE.

A power shovel removes the first of some 230,000 cubic meters from the Tokamak Pit.

In Addition to What We Learn in ITER, What Else Do We Need to Learn to Build an Electricity Producing DEMO?

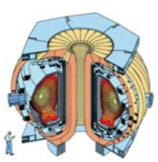
- **Fusion Nuclear/Material Science: Learning to Use and Deal With the Products of Fusion Reactions**
  - How to produce significant fusion power in true steady-state
  - How fusion can make its own fuel
  - How high grade process heat can be made from fusion reactions
  - How to make electricity from the process heat
  - How fusion chambers and blankets can survive high plasma and neutron fluences with low activation
  - How to measure plasma properties in the face of a high neutron fluence

Challenges mainly connected with high fluence,
high fluxes x time, and high operating temperatures.
Fluence: ITER (1x), DEMO (100x)
On time per year: Today's tokamaks (10^4 sec), DEMO (10^7 sec)

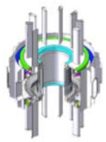
Path to Fusion Power Plant: Role of Major Facilities

Current Tokamak Program

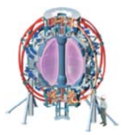
US Tokamaks



DIII-D



Alcator Cmod



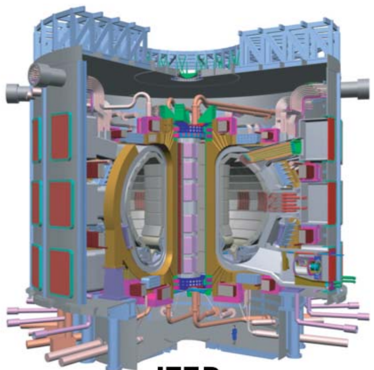
NSTX

International tokamaks

Key roles

- Develop operating regimes
- Evaluate new physics
- Develop control techniques

ITER Program



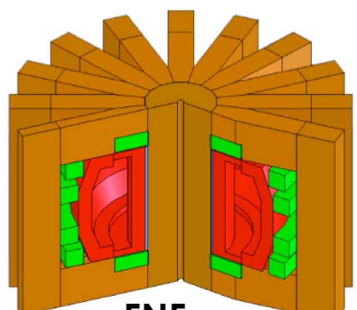
ITER

Viability of a burning plasma, high gain

Behavior of plasma and plant at near reactor scale

Integrated solution with necessary control technologies

Fusion Nuclear Science /Materials Program



FNF

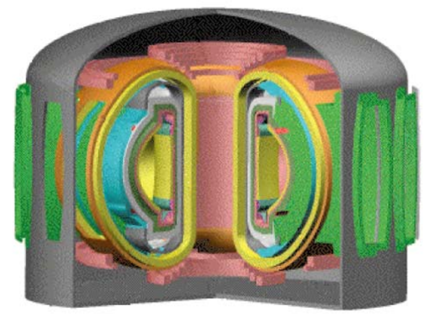
Continuous steady state operation

Make fusion fuel

Extract fusion power

Resolve nuclear & high fluence materials issues

GWe Power Plant



Power Plant

Characteristics

- High fusion power in steady-state
- Net tritium production
- Makes net electricity with high duty factor
- Plasma facing and blanket materials survive a long time

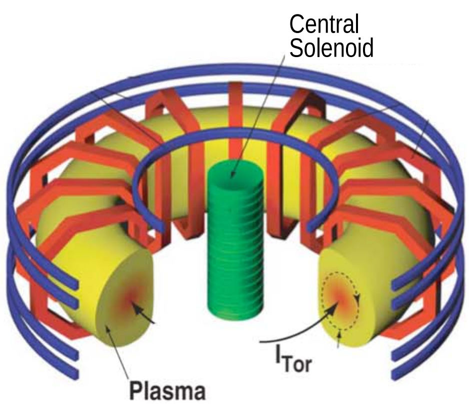
Controlling Current Distribution is Key to Steady State High Performance Plasma

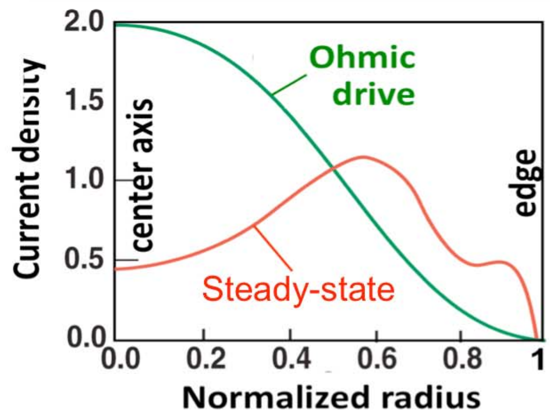
- Goal: $\underbrace{\text{High pressure}}_{\text{Fusion power}} + \underbrace{\text{High self-driven current}}_{\text{Steady-state \& high energy gain}}$

- Theory & experiment show current must be distributed off-axis to achieve optimized high pressure steady-state solutions

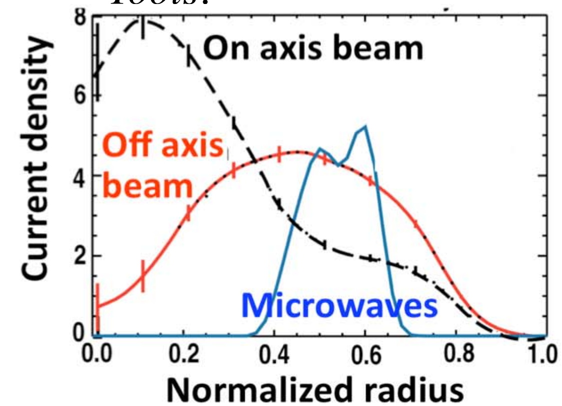
$$I_{steady\ state} = \overset{0}{\cancel{I_{CS}}} + I_{self\text{-}driven} + (I_{NBI} + I_{waves})$$

DIII-D examples





Tools:



Off-axis current sources are Lower Hybrid Current Drive (LHCD, neutral beams (NBCD) & microwave driven currents (ECCD)

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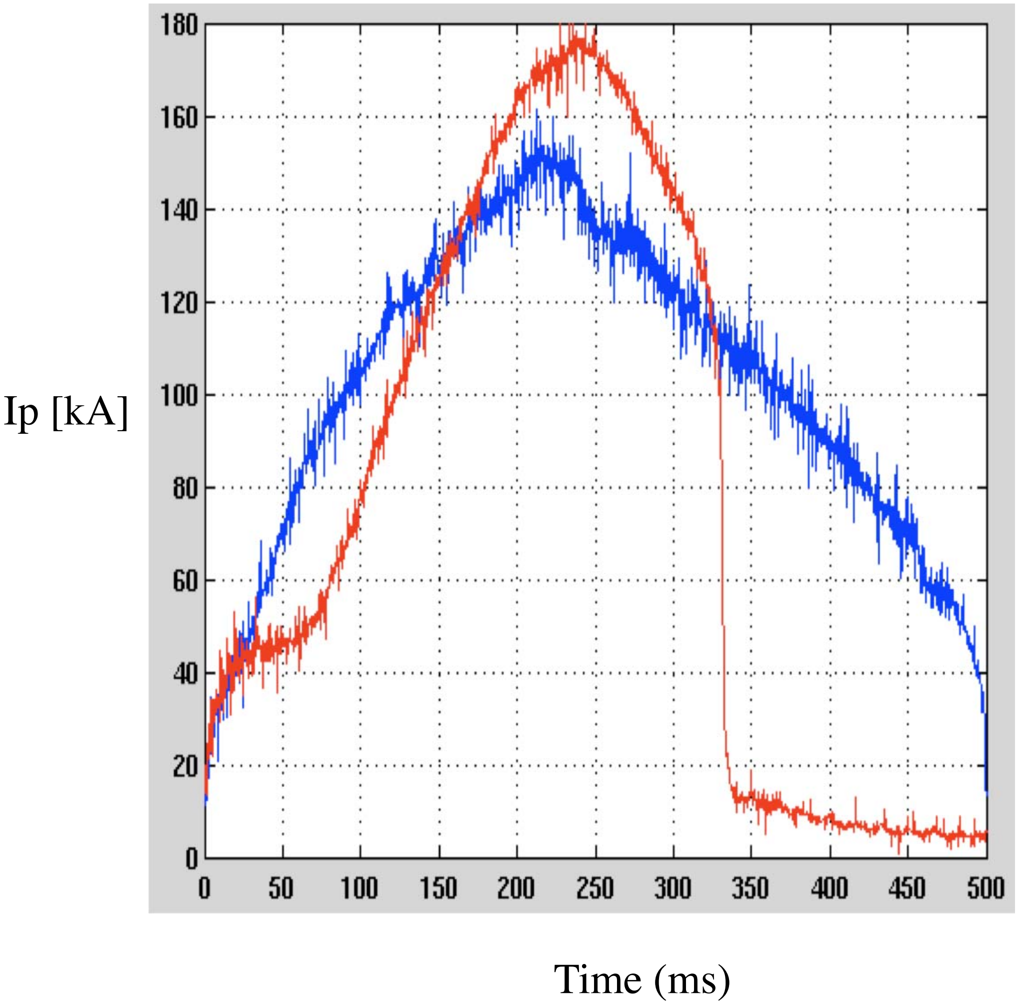
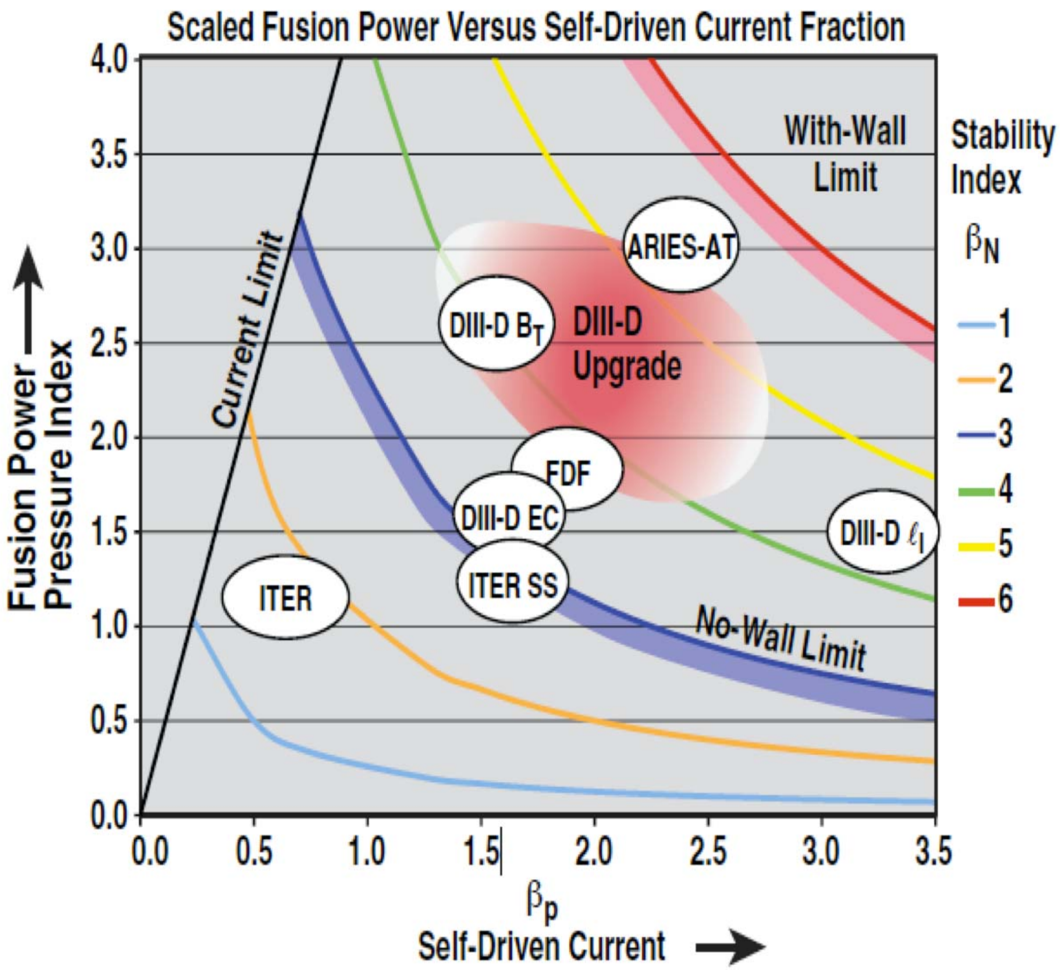
Startup Without an Ohmic Heating Transformer is a Feasibility Issue for the FNF-ST

Several Approaches to Solenoidless Startup Are Showing Promise

- DIII-D: I_p = 170 kA with induction from divertor coils
- JT60U: I_p= 100kA with outer PF coils
- NSTX: I_p= 160kA with CHI
- Pegasus: I_p = 160 kA with helicity injection



Economical Fusion Power Requires Both High Plasma Pressure and Self-Driven Plasma Current Fraction

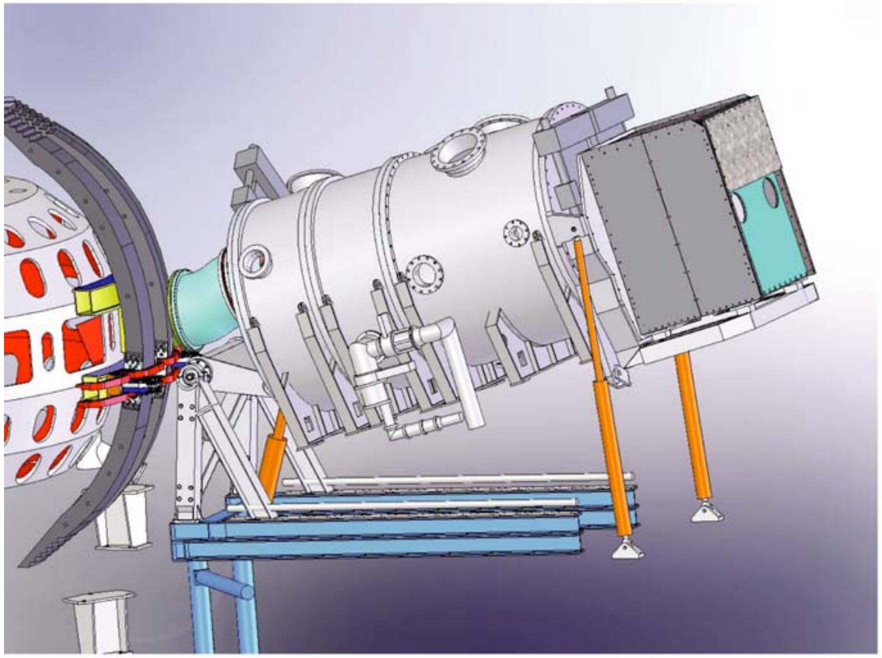


- Simultaneous achievement of high pressure and high self driven current requires high stability index

- Optimization requires:
  - Shape ✓
  - Active control ✓
  - Rotation ✓
  - Current profile

Off-axis Neutral Beam and Increased Microwave Power Equip DIII-D to Address Steady State Issues for Fusion Energy

- Microwaves provide precise localized currents
  - Adjust profile
  - Physics of electron heating



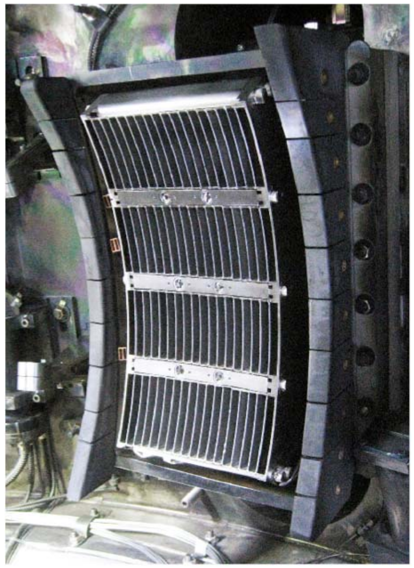
- Off axis beam provides bulk current drive capability
  - Avoids peaking up in the core

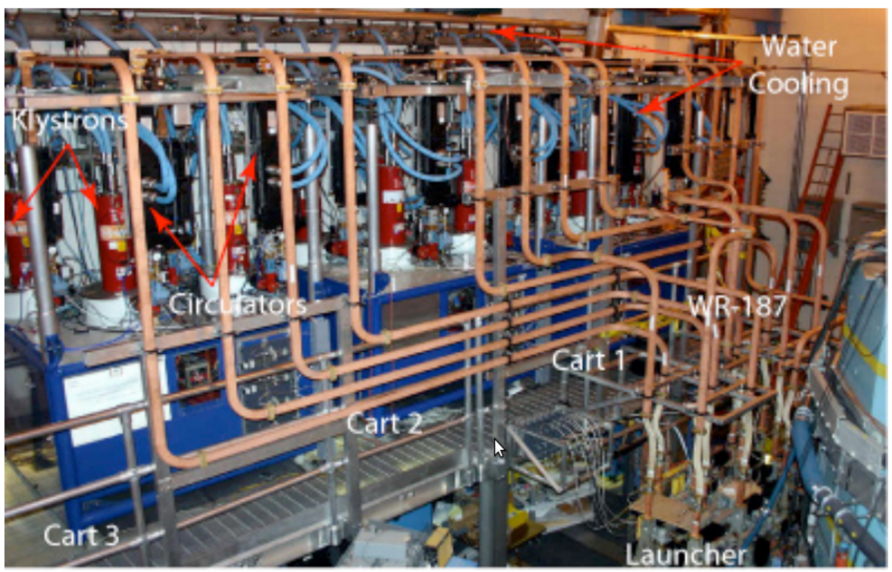
Provides unique capability to address important issues for ITER, FNF and Demo

Off-axis Current Drive by Lower Hybrid Waves is Key to Operation of Advanced Modes

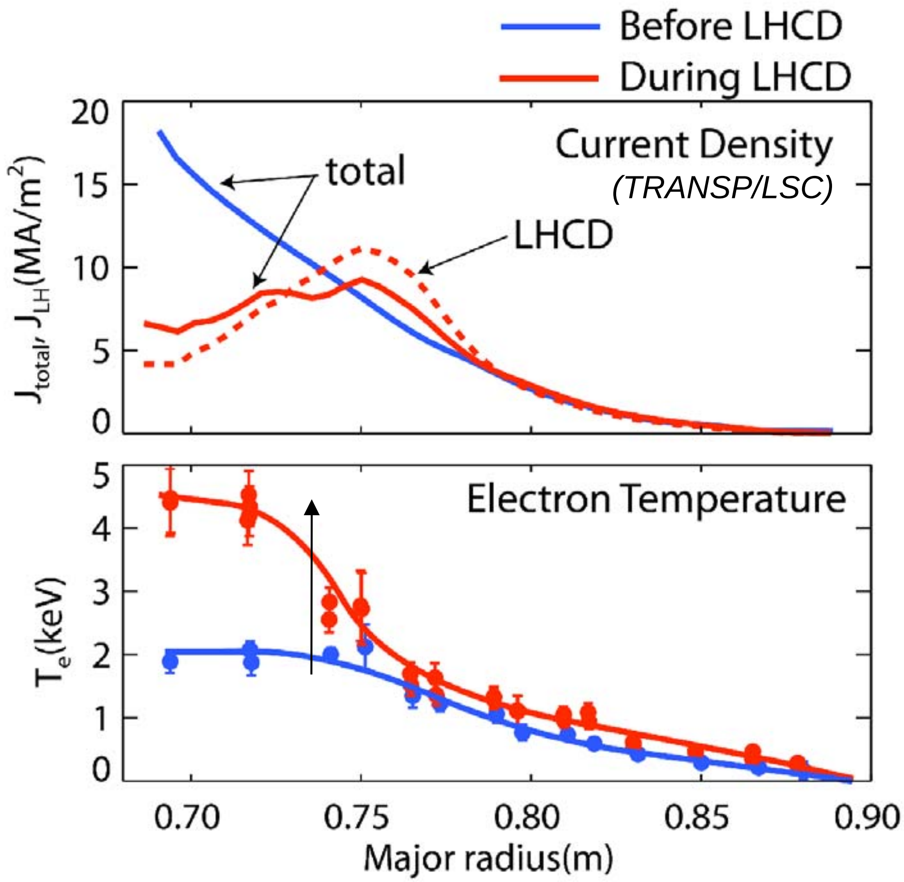
Alcator C-Mod

- New LHCD launcher installed in 2010, driving > 500kA plasma current. Additional launcher is planned in 2012-3 for total 1MA class LHCD





- Total 3MW high power klystrons for LHCD. Additional klystrons have been purchased to raise the power to 4MW



- Monotonic current profile became peaked off-axis by LHCD, triggers formation of an internal transport barrier

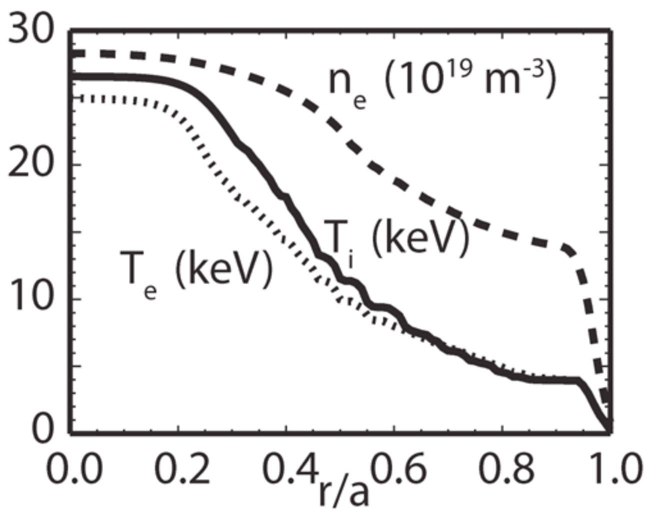
- Increasing the LHCD power allows for further off-axis current in high density regime

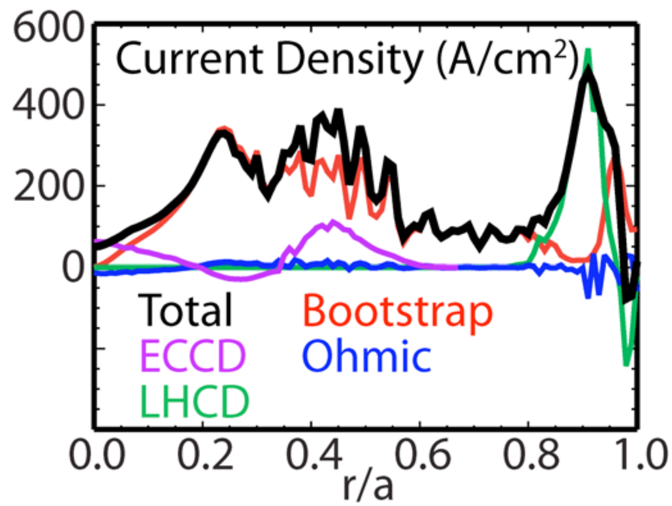
FNF-AT Modeling Yields Full Non-Inductive Current Drive and High Fusion Power with EC and LH

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~4, H_{98y2}~1.2, f_{BS}~70%, P_{fus}~260 MW, P_{EC}=35 MW, P_{LH}=21 MW)**





We Have to Make Tritium from Lithium

- **T is made from Energetic neutrons on Li7 and thermal neutron capture by Li6**

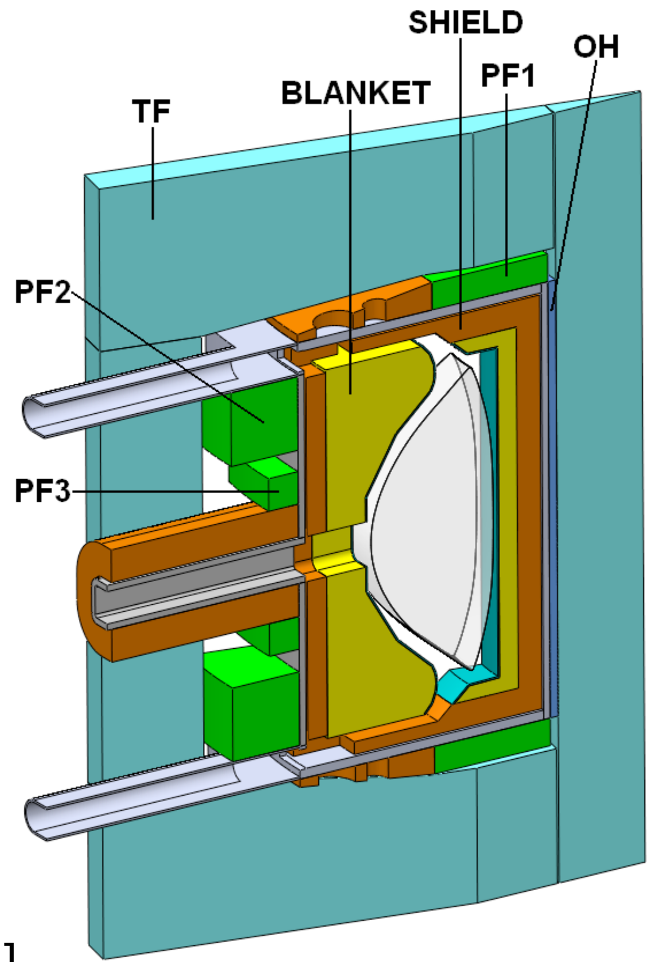
- **The Tritium Breeding Ratio (TBR= ratio of tritons produced/burned) must be > 1.0**
  - A 1000 MWe fusion plant burns 12 kg T per month.
  - FNSF should have TBR >1.2 to build up a supply to startup DEMO.
  - Almost any TBR>1 does not restrict the growth of fusion reactors.
  - Theoretical maximum in an optimized homogeneous medium is ~ 2.5.
  - But realistic aspects of design result in TBR predictions ~1.0 – 1.2.

- **Ways to lose TBR and/or sources of uncertainty**
  - Non-breeding structural materials
  - Non-breeding coolants
  - Non-blanket structures embedded in blanket, e.g. passive stabilizers
  - Limited blanket coverage, e.g. ports, penetrations, divertors, inboard
  - Finite blanket thickness
  - Uncertainties in nuclear data
  - Tritium retention inside the fusion chamber
  - Tritium holdup in elements of the processing system
  - Tritium permeation from one part of processing system to another

FNF must show Tritium Breeding Ratio > 1 is possible

Calculated Tritium Breeding Ratio in FNF-AT Is >1 for Both Blanket Concepts Considered : DCLL and HCCB

- **3-D neutronics analysis using the DAG-MCNP code and FENDL-2.1 nuclear data library**
- **DCLL = Dual Coolant Lead Lithium**
- **HCCB = Helium Cooled Ceramic Breeder**
- **TBR = 1.09 (HCCB), 1.0 (DCLL)**
  - Assumes that no Tritium breeding blanket modules are inserted in all of the 16 mid-plane ports
  - TBR could be 6% higher except for lost coverage in the 16 mid-plane ports
  - Several of these ports will be utilized for advanced breeding blanket testing



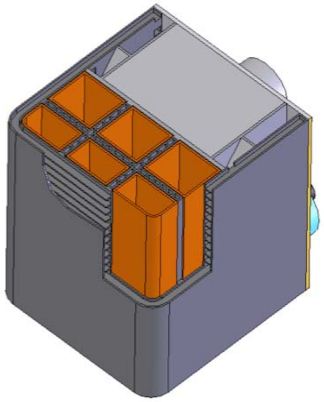
[M.E. Sawan, TOFE 2010 (to be published in FS&T)]

How Will We Choose What Blanket Type to Build Into DEMO?

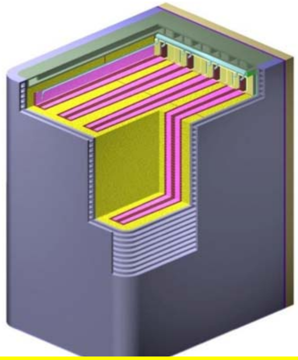
- **Fusion has yet to capture its first neutron in a blanket.**
  - No fusion blanket has ever been built.
  - Over 30 years of blanket studies for MFE and IFE fusion reactors, 24 blanket designs were considered.

- **ITER plans to test at least 7 blanket types in test blanket modules**
  - Helium-cooled Lithium-Lead blanket (1)
  - Dual-Coolant (He and LiPb) type Lithium-Lead (DFLL and DCLL) blankets (2)
  - Dual-Coolant (He and LiPb) Lithium-Lead Ceramic Breeder (LLCB) blanket (1)
  - Helium-cooled Ceramic/Beryllium blanket (3)
  - Water-cooled Ceramic/Beryllium blanket (1)

U.S. blanket experts prefer two blanket types



Dual Coolant
Lead-Lithium

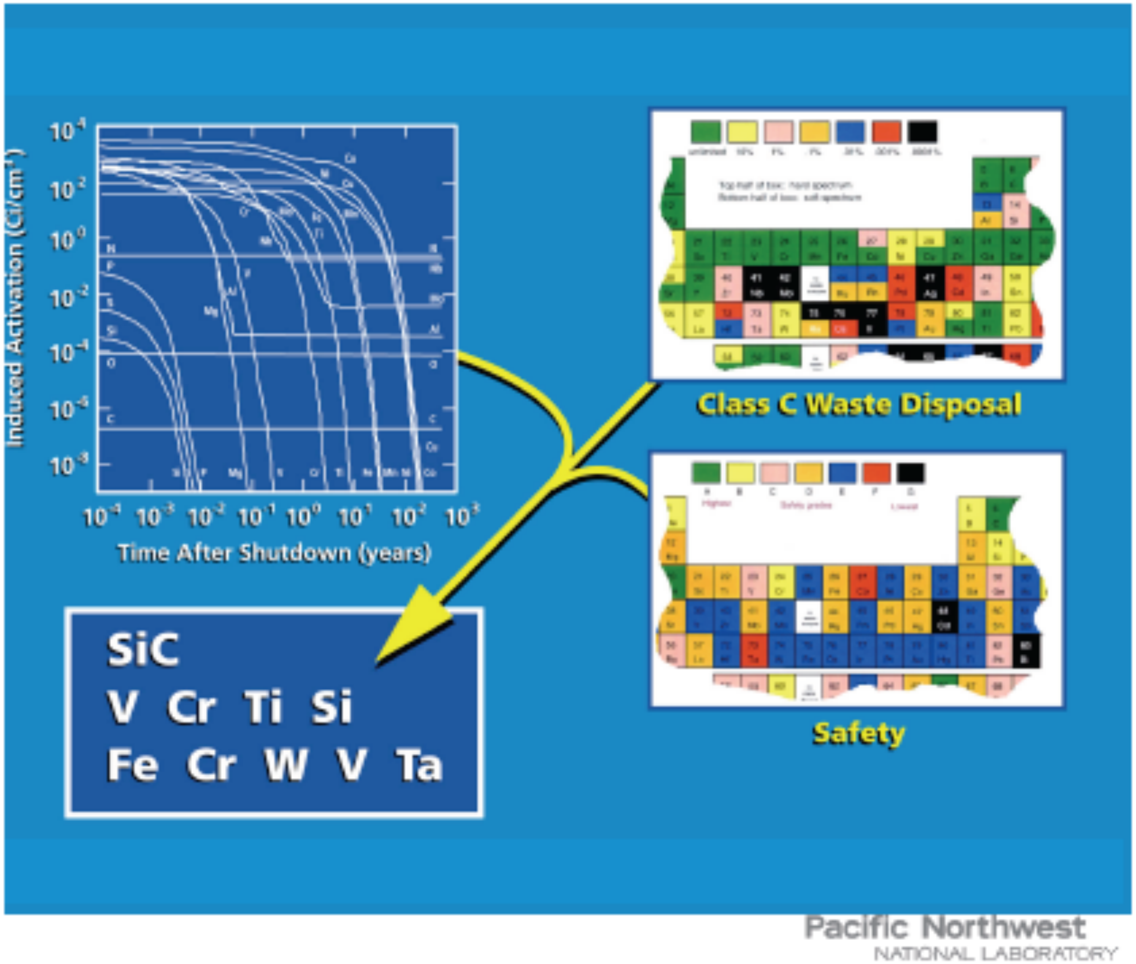


Helium cooled
Ceramic breeder

A Fusion Nuclear Facility will test/validate various blanket types for long durations

What Will We Make the DEMO Blanket Out Of? Structural Materials for Fusion Are Limited

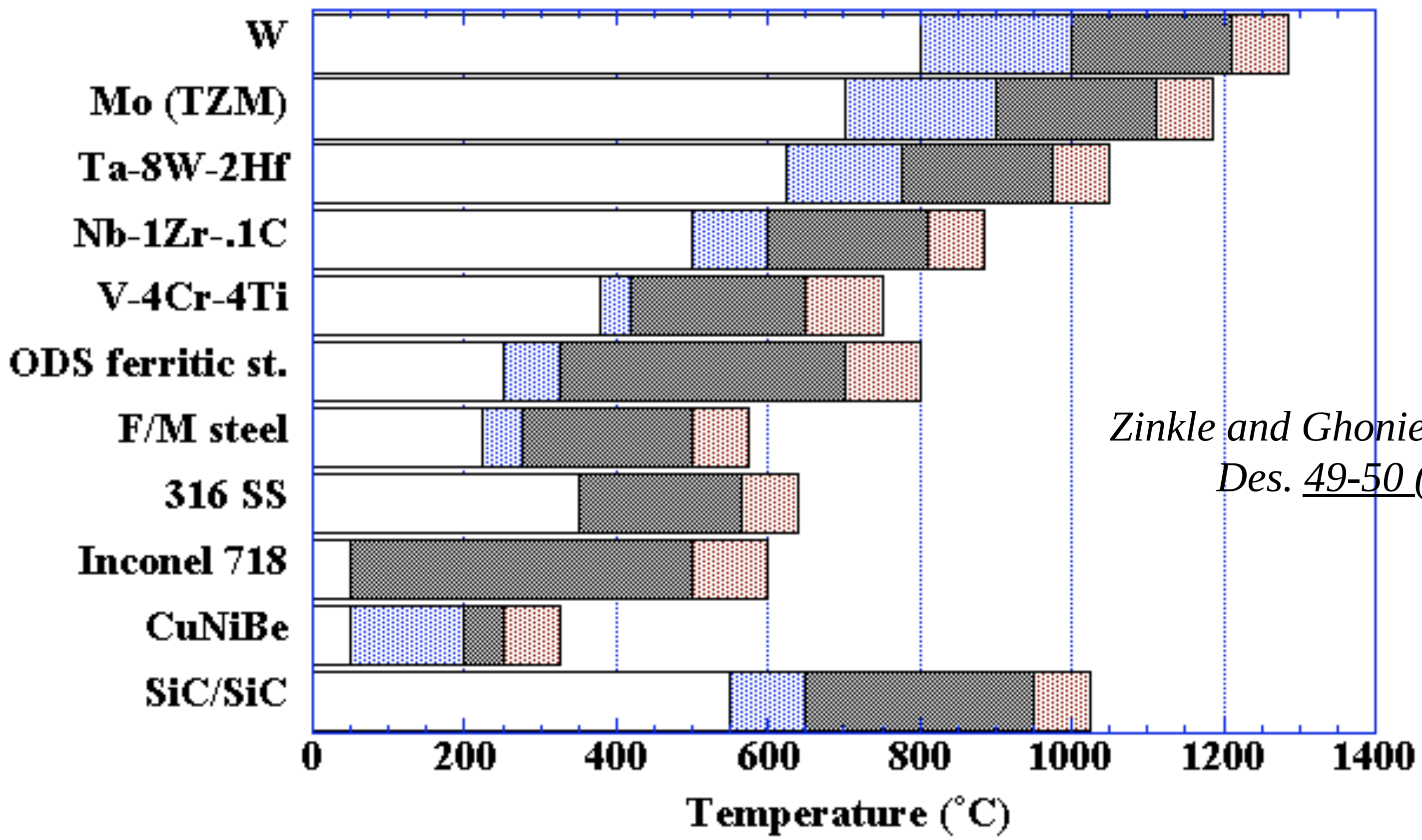
- Structural materials most strongly impact economic and environmental attractiveness of fusion power.
- Key issues: thermal stress, compatibility, safety, waste disposal, radiation damage, safe lifetime limits.
- Ti alloys, Ni base superalloys, and most refractory alloys are unacceptable for various technical reasons.
- Based on safety, waste disposal and performance considerations, the 3 leading candidates:
  - Ferritic/martensitic steels
  - Vanadium alloys
  - SiC composites



R.J. Kurtz PNNL

Operating Ranges for Irradiated Structural Materials Are Limited

Structural Material Operating Temperature Windows: 10-50 dpa



Zinkle and Ghoniem, Fusion Engr. Des. 49-50 (2000) 709

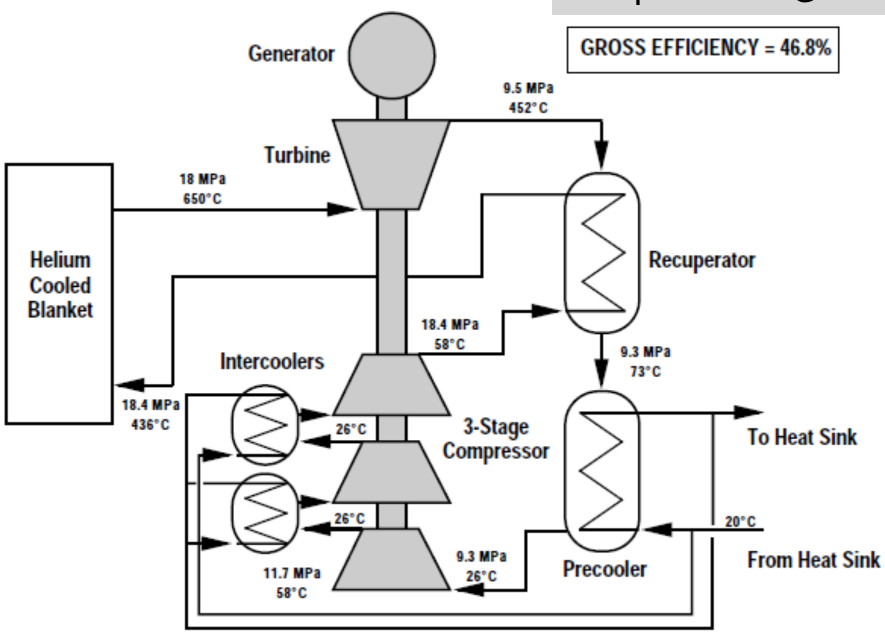
Hot walls will be an entirely new operating regime for fusion devices

We Know How to Make Electricity from Process Heat. But Making Some Electricity is Important.

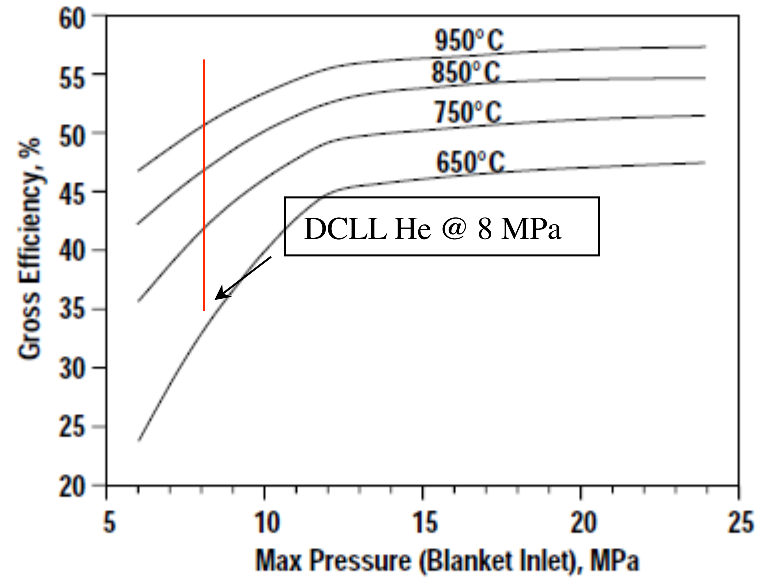
Options are:

1. Use a port blanket module in FNF to make 300 kW electric from 1 MW neutrons
2. From main blanket in FNF, make 100 MW electric from 300 MW neutrons
3. Build a pilot plant device to make 50 MW net electric.

For comparison: Fort St. Vrain HTGR (1981-1989),
He pressure @ 4.8 MPa, Tin/Tout: 405ºC/775ºC, Steam Rankine cycle



Simplified Brayton Cycle (CCGT) at He pressure of 18 MPa



Gross η_{th} versus He pressure and Tout

Another motivation for hot walls

GENERAL ATOMICS

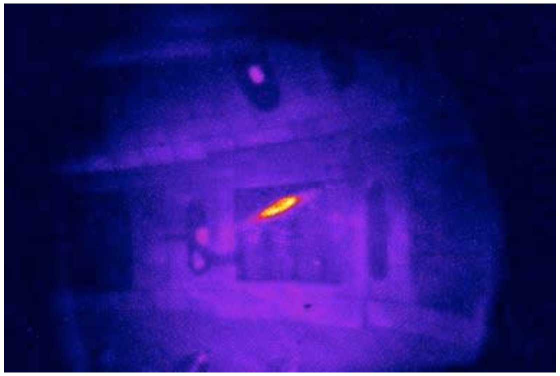
The Critical Issues of Plasma Wall Interactions and Plasma Facing Components Must Be Squarely Addressed

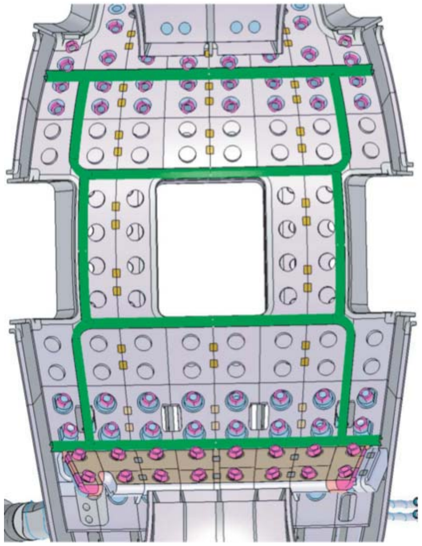
- **Hot wall operation**, above 400^0C at least, will be an entirely new regime.

- **Erosion**
  - Biggest step is in on time, 10^7 seconds per year, and hence neutron and particle fluence. (100 times ITER).
  - Tons of material per year will erode and redeposit. Properties?
- **Tritium Retention**
  - Cannot be allowed to prevent TBR > 1
  - Hot walls will help limit codeposition. Removal methods being developed
- **Heat Flux Handling**
  - Need precision toroidal alignment of surfaces to hide edges and allow maximal use of flux expansion. New divertor ideas being tested.
  - High density promotes radiation
- **Other issues**
  - Fast plasma shutdowns, first wall heat fluxes in fault conditions, EM forces

Dealing With Off-Normal EventsWill Be a Necessary Progress Step to DEMO

- **Goals for FNF**
  - Operate for 10^7 seconds per year, duty factor 0.3.
  - Run two weeks straight without disruption
  - Only one unmitigated disruption per year
- **Disruption Strategy**
  - Real-time stability calculations in the control loop.
  - Active instability avoidance and suppression - RWMs, NTMs
  - Control system good enough to initiate soft shutdowns and limit firing the disruption mitigation system more than 20 times per year.
  - Disruption mitigation system 99% reliable.
- **ELM Suppression**
  - Resonant magnetic perturbation coils
  - QH-mode

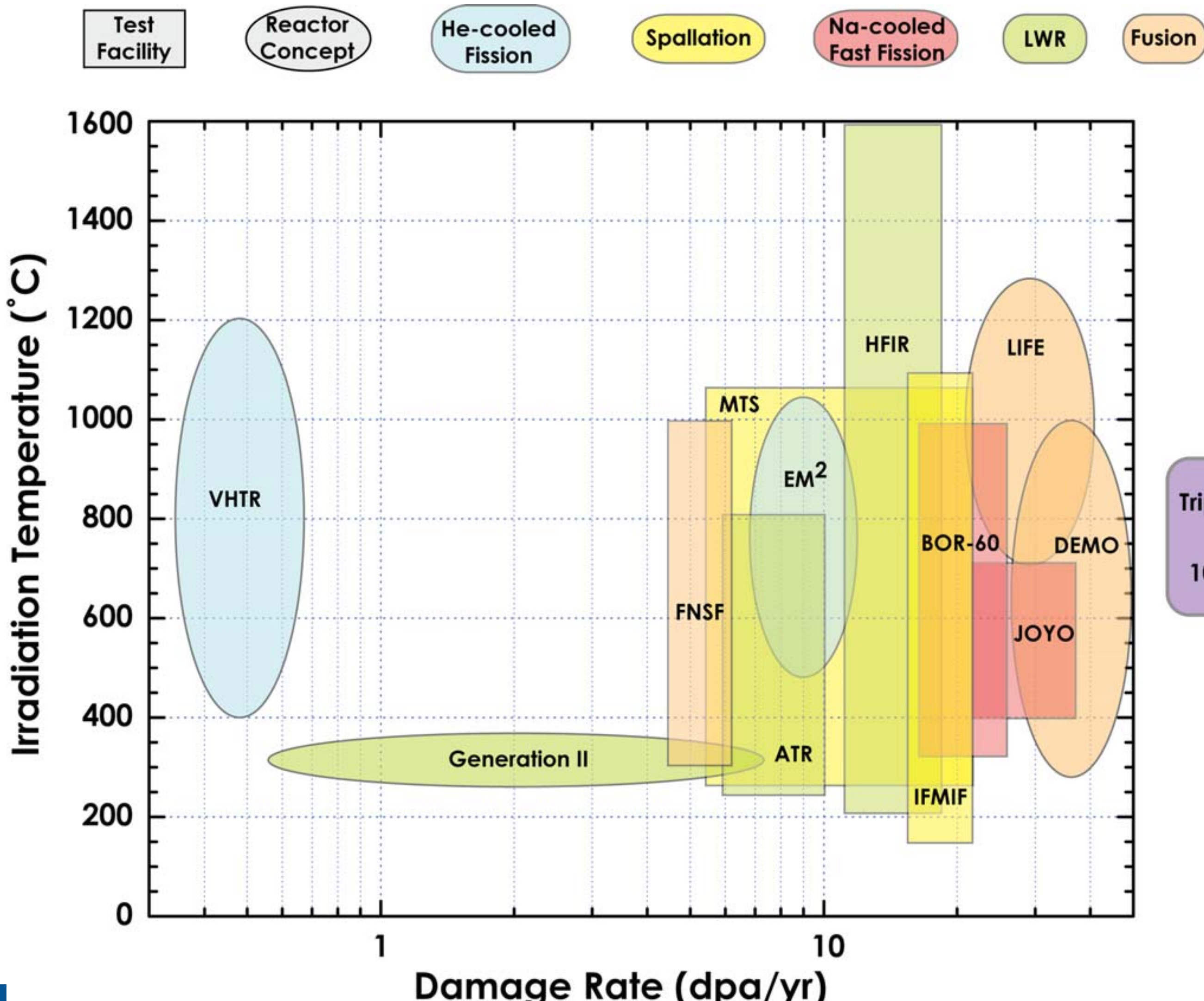




Targets for Disruption Handling

Device	ITER	FNF	DEMO
Pulse length (s)	400	$1x10^6$	$3x10^7$
Number of pulses per year	1000	10	1
Fast shutdowns per year	100	20	5
Time between fast shutdowns (s)	$4x10^3$	$5x10^5$	$6x10^6$
Unmitigated disruptions per year	5	1	0.3

How To Get the High Fluence (50-300 dpa) neutron irradiation date needed?



Triple Ion Beam up to 100 dpa/day

Strategy Elements to Obtain High Fluence Fusion Materials Irradiation Data

- **DT Fusion has a special problem with neutrons above 5 MeV making large amounts of helium and hydrogen, besides the dpa problem shared with fission.**

- **Use fission reactors to produce dpa rates up to 30 dpa/year**
  - Load the damaged material with He and H using ion beams, but 20-200 micron thick samples

- **Use FNF as a broad survey instrument (2 m^3 volume of samples)**
  - Irradiate samples, welds, subassemblies, larger assemblies, 40,000 samples to 20 dpa in 3 years

- **Use Triple Ion Beam Facilities for fast high dpa surveys**
  - 100 dpa per day! But only 20-200 microns thick samples, not neutrons, dpa rate too high

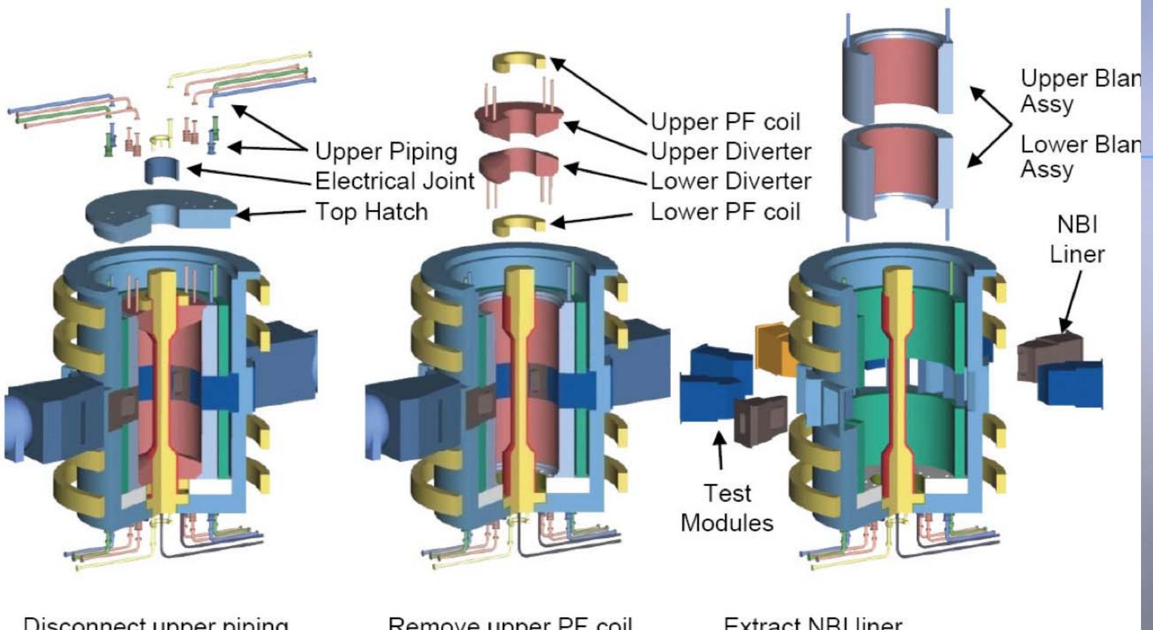
- **Modify U.S. Spallation Neutron Sources for neutron irradiation purpose**
  - Modest cost option. Possibly 6-20 dpa per year
  - Drawback may be neutron spectrum extends to too high energy, makes too much He

- **Participate in international construction and operation of IFMIF accelerator neutron source**
  - Best but not perfect neutron spectrum, sample volume just 0.5 liters
  - Possibly 20 dpa per year

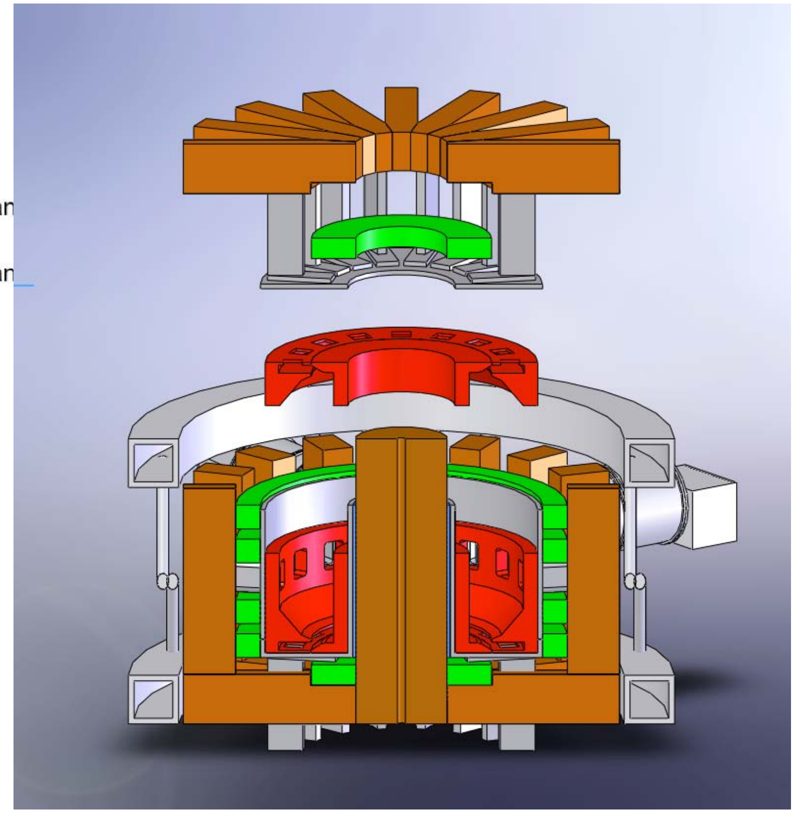
- **Knit all the above together with a computation program on predicting neutron damage**

We can obtain the necessary irradiation data in time for DEMO

A Fusion Nuclear Facility Will Be a Research Device, Maintainable, Flexible, Re-configurable



ORNL FNSF-ST

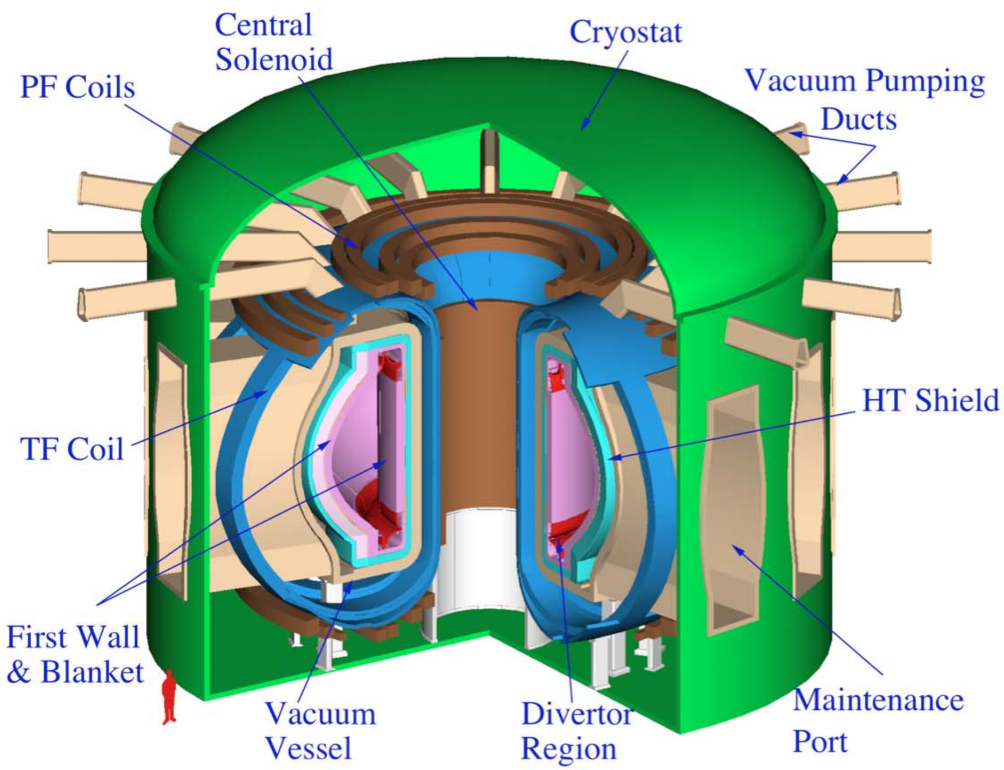


GA FNSF-AT (FDF)

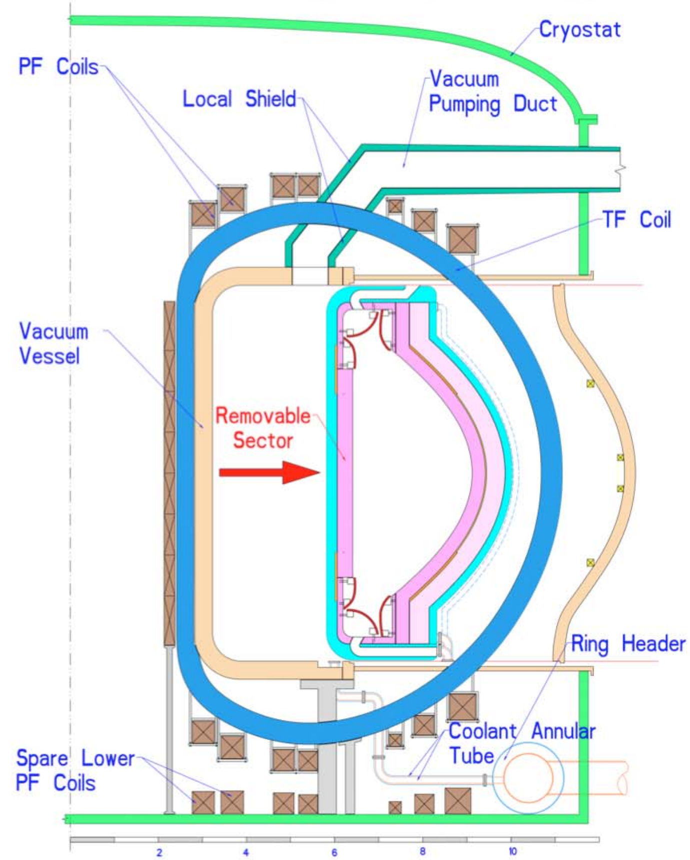
* A defining characteristic of device approaches

Maintainability of a Superconducting Fusion Reactor Is More Challenging

Cutaway of the ARIES-AT Fusion Power Core

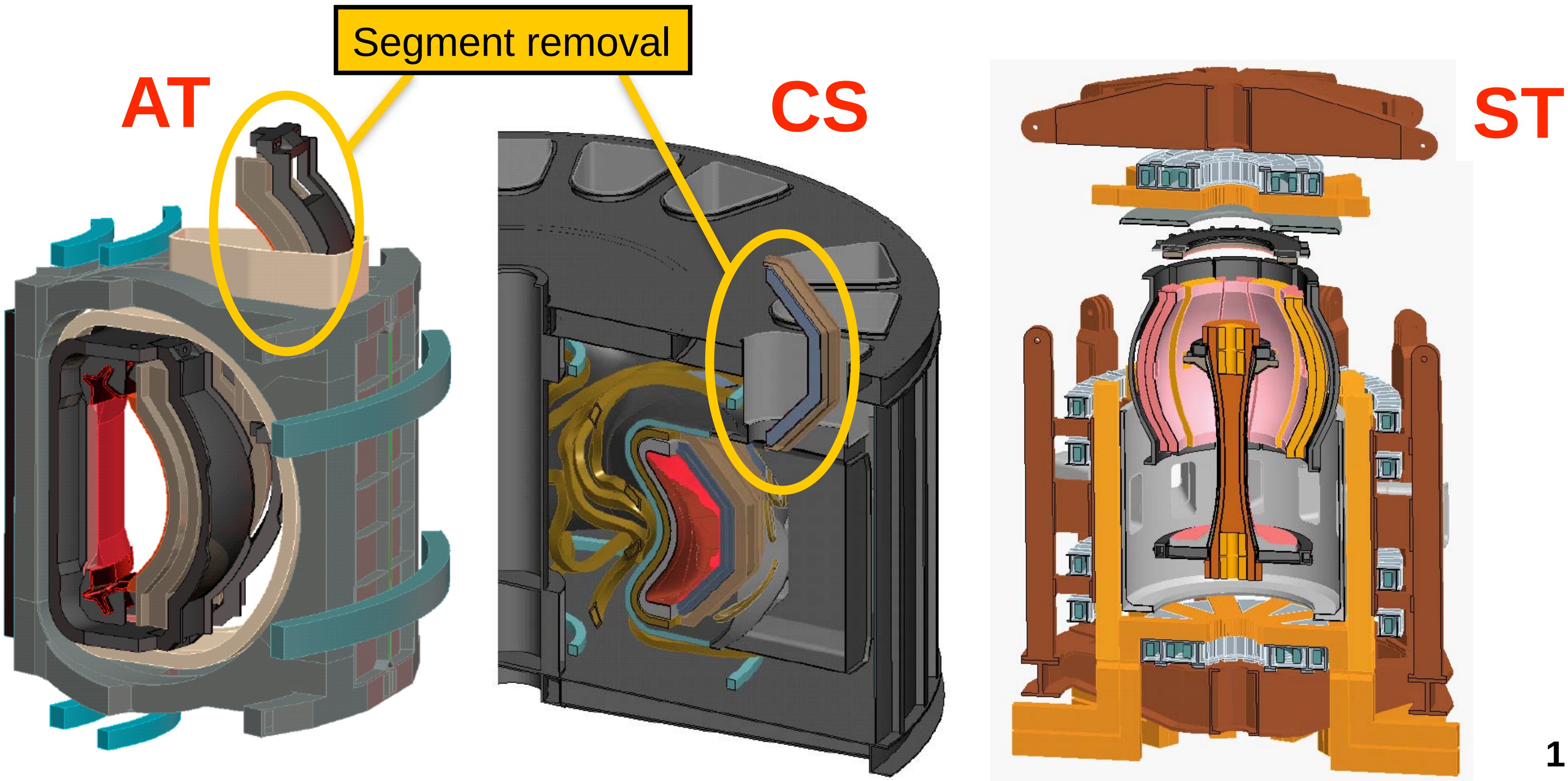


Cross Section of Showing the Maintenance Approach



Maintenance Schemes Are Being Investigated for Three Approaches to a Superconducting Pilot Plant

- AT and CS: segments translated radially, removed vertically
- ST: Top TF legs demountable, core/CS removed vertically
- Future work: maintenance schemes for smaller components



MFE Program Readiness Elements to Make a Steady-State Fusion Nuclear Facility

- **What we know now:**
  - How to keep tokamak plasmas **stable**
  - Three suitable **operating modes** exist (DIII-D)
  - **Confinement quality** achieved in DIII-D and confirmed by first principles plasma transport simulations
  - How to **heat** plasmas to fusion conditions
  - Hot walls will **retain little tritium**
  - We have **materials** to build the initial trial blankets

- **What we expect to know in the next few years**
  - **Operating Modes**, startup, rampup, current drive confirmed
  - **Erosion** of Plasma Facing Component(PFC) surfaces - significant but not defeating
  - **Maintenance** scheme is practical
  - **Jointed copper magnets** are feasible

- **What technology developments ITER will contribute during its construction**
  - Disruption **mitigation** system
  - **Auxiliary and diagnostic** systems
  - Power Plant Scale **superconducting magnets**
  - ITER **tritium** system
  - **PFC surfaces** that can handle 10 MW/m^2 heat loads