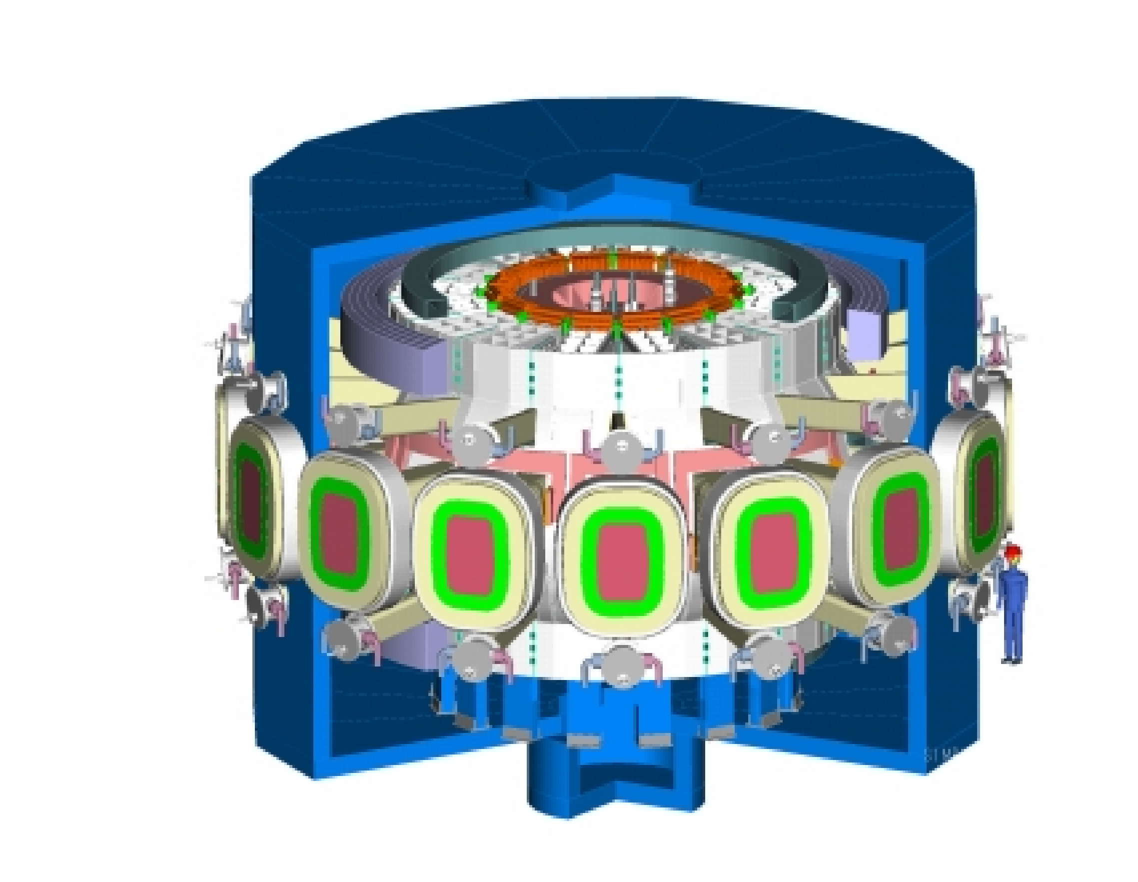
FIRE
Engineering Status Summary



Richard J. Thome
for the National FIRE Team

July 20, 2000

The FIRE Design effort has addressed all major subsystems & issues:

TF Coils & Global Structure
Central Solenoid & Poloidal Field Coils
Vacuum Vessel
Plasma Facing Components
Thermal Shield
Ion Cyclotron Heating
Fueling & Pumping
Tritium Systems
Neutronics & Shielding
Activation, Decay Heat & Radiation Exposure
Remote Maintenance
Magnet Power Systems
Cryoplant
Facilities & Siting
Safety

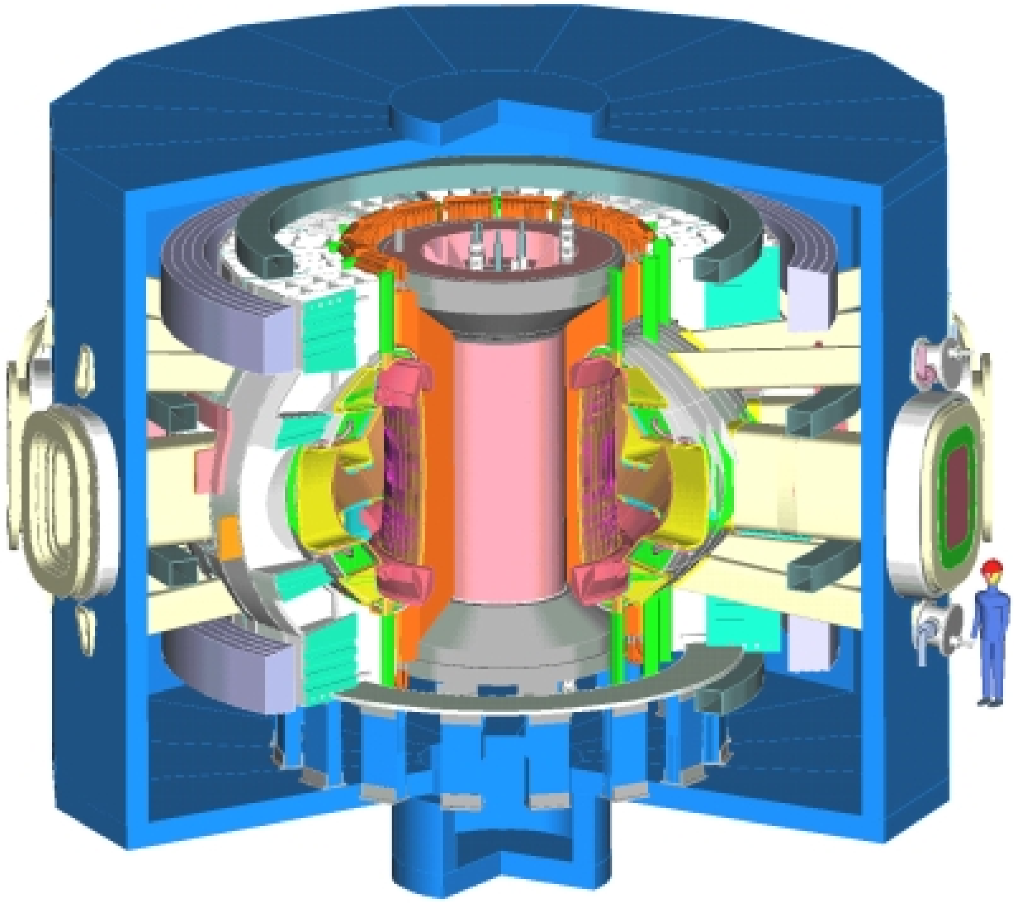
Design goals have been met or exceeded.

Several options and issues have been identified for further evaluation.

Cost estimates are underway.

Cutaway Through Thermal Shield

- **16 Large Midplane Ports**
- **32 Angled Ports**
- **32 Vertical Ports**
- **Thermal Shield:**
  - **SS Frame with SS skin**
  - **Insulated Exterior**
  - **Provides 80-90 °K Inside**



FEATURES of FIRE

- **16 Wedged TF Coils**
- **Two Pairs of External Divertor Coils**
- **Two Pairs of External Ring Coils**
- **Free-standing, Segmented Central Solenoid**
- **Vacuum Vessel Filled with Steel/Water for Shielding**
- **Plasma Facing Components:**
    - **-Be coated Cu 1st Wall**
    - **-W pin-type Inner Divertor, Baffle, & Outer Divertor**
- **2 Outboard Poloidal Limiters**
- **Internal Passive & Active Stabilization Coils**

FIRE General Requirements

Parameter	***Value***
R, major radius, m	**2.0**
a, Minor radius, m	**0.525**
B_t, Tesla	**10 (12)***
No. TF coils	**16**
Fusion power, MW	**200 (250)***
Max. TF ripple	**0.3% (edge)**
Time Between Pulses, hr.	**< 3 at full power**
TF and PF coil type	**LN_2 cooled copper or copper alloy**
Plasma current	**~6.5 MA (7.7 MA)***
Flat top, s	**$\geq$18.5 (12)***
Triangularity, δ_{95} **Triangularity, δ_x**	**~0.4** **~0.8**
Elongation, κ_{95} , **Elongation, κ_x**	**~1.8** **~2.0**
Neutral beam Power	**None planned**
ICRF Power, MW	**30**
FWCD	**None in baseline-possible later option.**
LHCD	**None in baseline-possible later option.**
Vacuum level	**10^{-8} torr**
Bake out temp.	**350 °C**
Life pulses at full power	**3000 (min)**

FIRE General Requirements

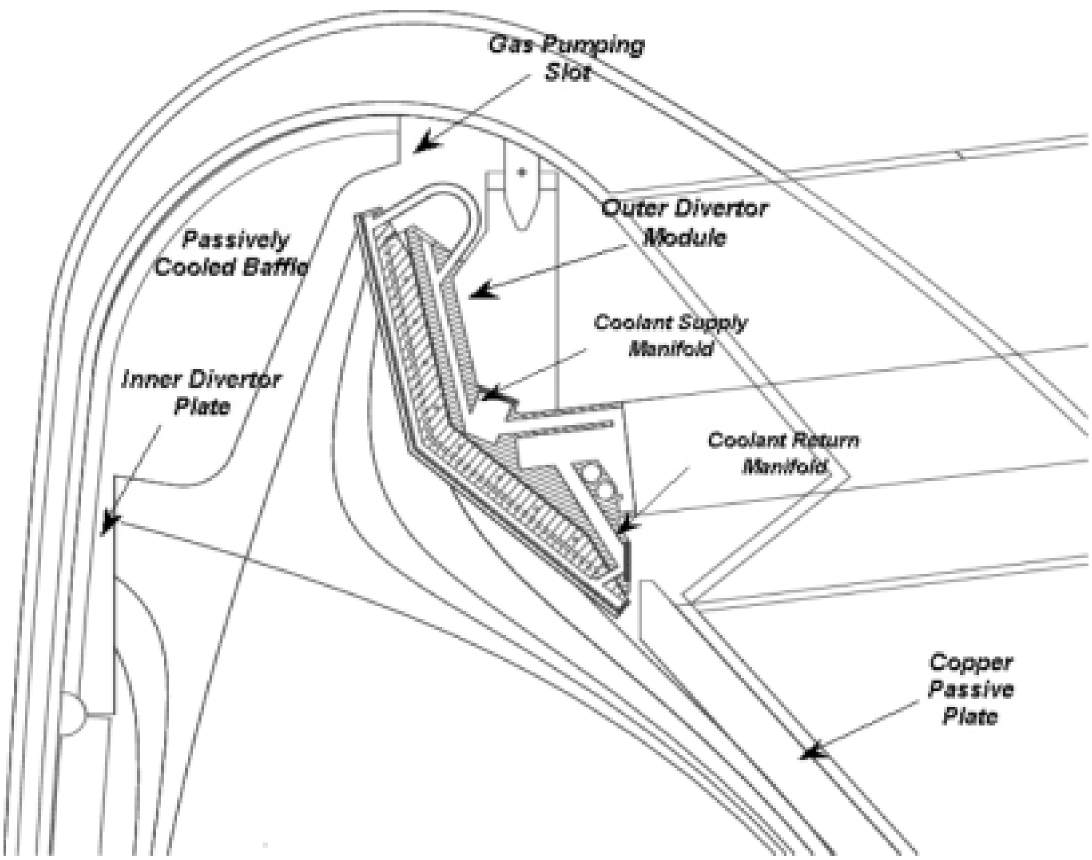
Parameter	*Value*
Coil init. temp.	**80 °K**
Coil max. temp.	**373 °K**
First wall materials	**Beryllium**
First wall replacement/maint. times	**Single unit: 3wks; limiter: 6wks.; entire system 12 mos.**
Total Fusion Energy	**5 TJ - DT + 0.5 TJ - DD**
Limiters	**For start up**
First wall life	**Machine lifetime**
VV pressure suppression system	**No**
FW heat flux	**TBD**
First wall cooling	**Inertial**
VV operating temp.	**100 °C**
Divertors	**Double null; actively cooled outer W plate, inertially cooled elsewhere**
In-vessel RH reqmts.	**Must be able to replace/repair all components**
Ex-vessel RH requirements	**Classification system & maintenance similar to ITER.**
TF support arrangement	**Wedged with compression rings**

( )* = values for operation at 12 T

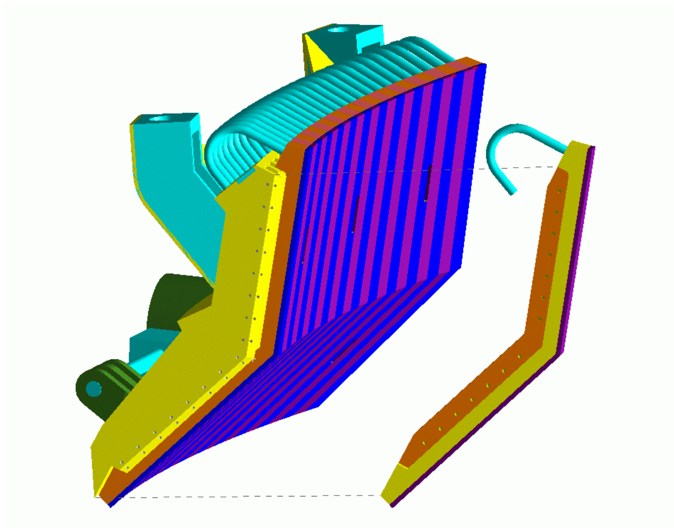
Divertor & Plasma Facing Components

-The divertor design is open due to the short distances from the x-point to the plate and the spreading of the field lines.

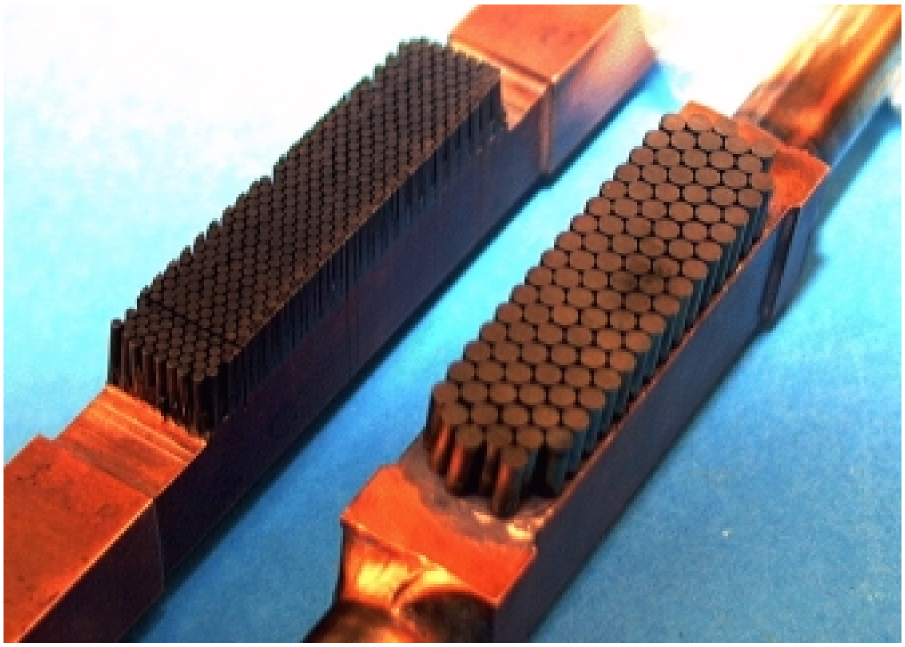
- **Outer divertor plate and baffle will be actively cooled.**
- **Inner divertor plate and first wall will be conduction cooled to the copper clad vacuum vessel wall, which is actively cooled.**



Cross-section Through Actively Cooled Divertor Module & Baffle



Finger Plate for Outer Divertor Module



Two Tungsten Brush Armor Configurations
Tested at 25 MW/m^2

TF Coils-Baseline

- **Baseline TF design:**
  - **wedged and inertially cooled using LN2**
  - **Inner legs: C17510 BeCu (68% IACS)**
  - **Outer legs: C10200 OFHC (100% IACS)**

Pulse Flat Top Time Based on TF Coils

initial temperature=80°K

peak allowable temperature = 373°K

Field	DT Operation	DD Operation
12T	12 s	15 s
10 T	18.5 s	26 s
8 T	31 s	46 s
4 T	-----	214 s

TF Coils-Stresses

- **Peak conductor Von Mises stresses of 469 MPa for 10T and 689 MPa for 12T (7.7 MA) are within the static allowable stress of 724 MPa.**

- **Stress limits for a mission of 3000 cycles at full field & 30000 cycles at 2/3 field are expected to be acceptable since the loading in the peak stress areas is primarily compressive, which inhibits crack growth.**

- **Support for the overturning moment on the inner coil leg:**
  -This moment causes shear stresses in the insulation between the turns in the inner legs as they are twisted

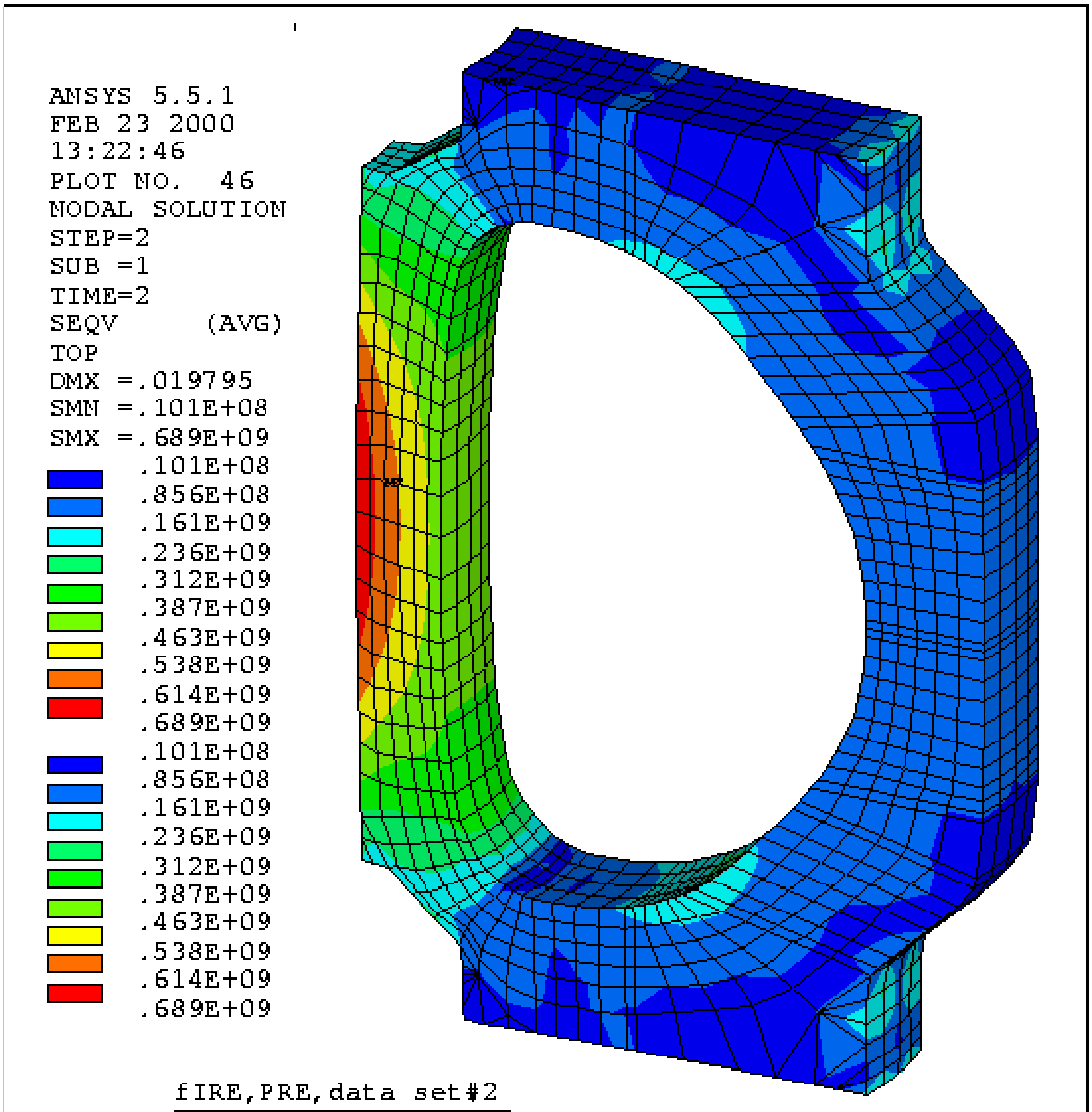
  -The maximum shear is ~50 MPa. Using a coefficient of friction of 0.3 and the calculated wedging pressure of ~200 MPa, the allowable stress would be 60 Mpa

  -In wedged TF coils, the wedging pressure tends to decrease at the top and bottom of the inner leg so the allowable shear stress on insulation decreases. In FIRE, large rings add compression in these corners and compensates for this effect.

TF Coils-Optional Configuration
(Preliminary results in FY00-study in FY01)

An all OFHC, Bucked and Wedged, TF configuration is an option:

- **Max Field is 11.5T to remain within the OFHC copper allowable stress limit**
- **Longer pulses may be possible at a given field level**
- **Lower power requirements may increase number of possible sites**
- **TF material costs will be reduced and R&D for a BeCu to OFHC joint in TF plates will not be required**
- **TF fabrication & assembly will be more complex to assure proper bucking & wedging**



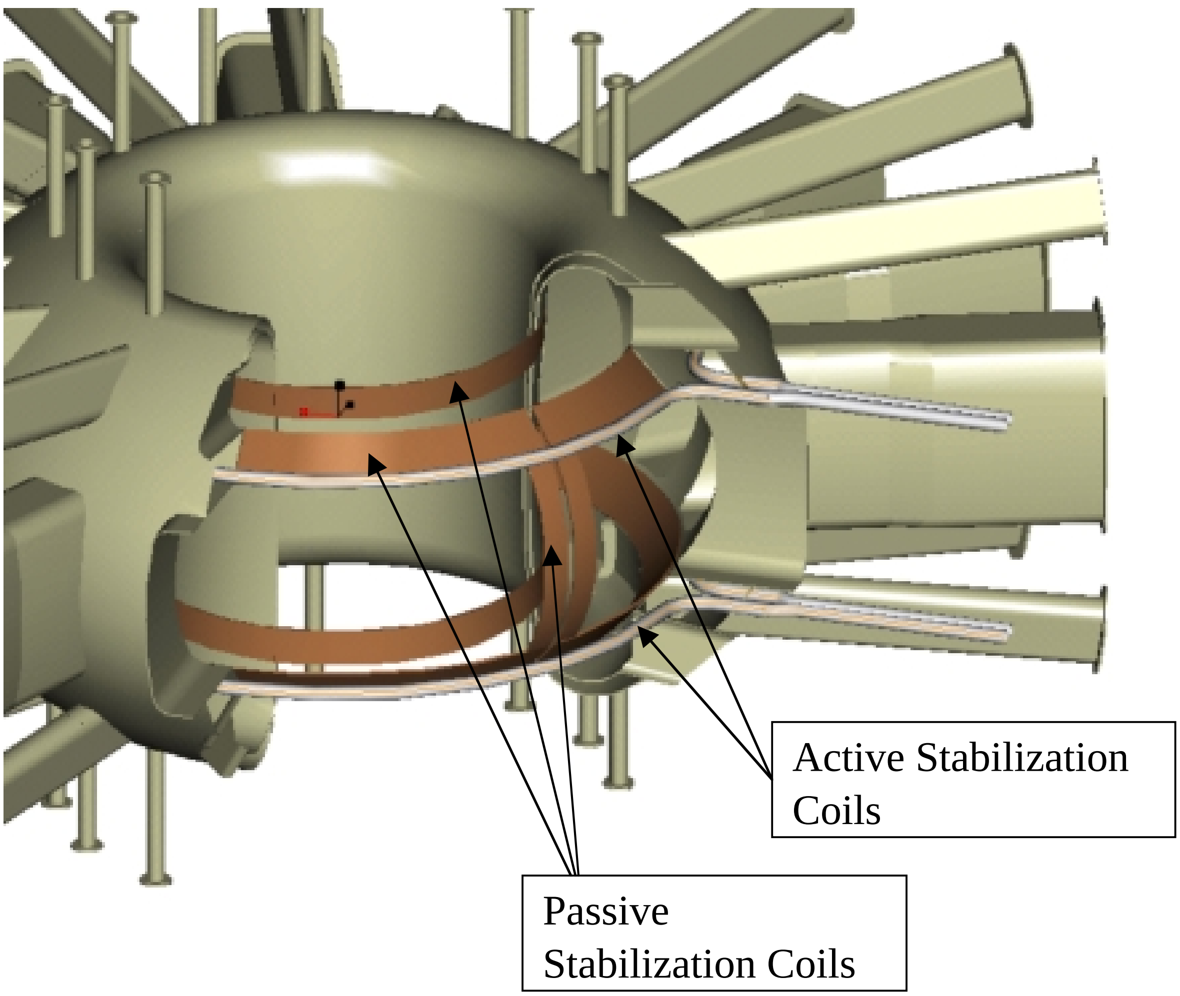
FIRE TF Precharge Von Mises Stress (MPa)(EOF is less) With Tierod Removed

TF Coil Von Mises Stress Contours at 12 T for Baseline

Peak conductor Von Mises stress of 689 MPa for 12T (7.7 MA) is within the static allowable stress of 724 MPa

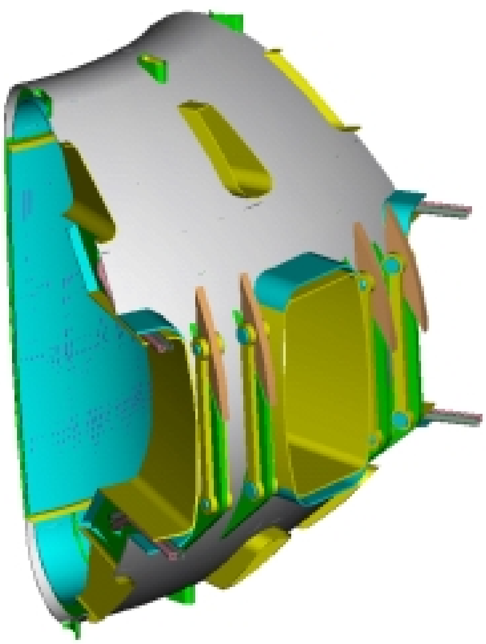
Vacuum Vessel

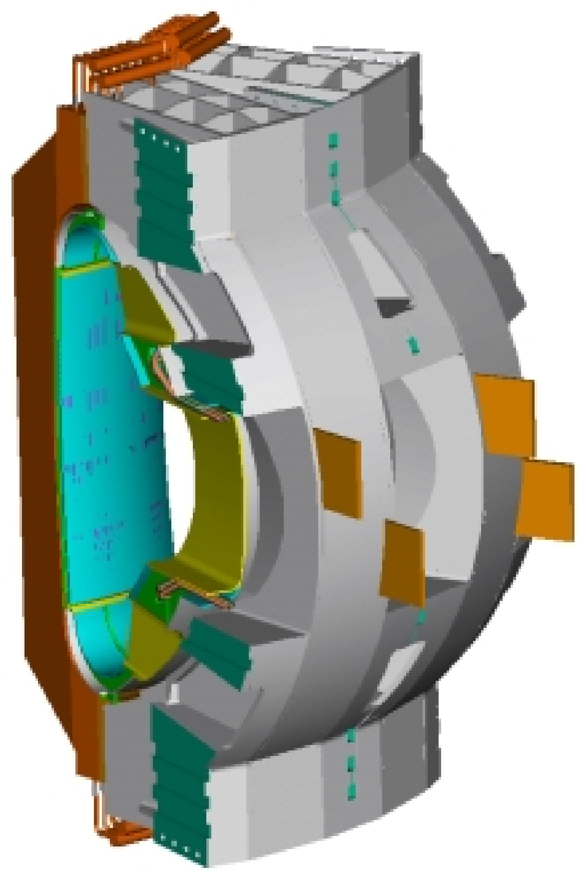
- A double walled vacuum vessel with integral water and steel shielding is used for FIRE.
  - Benefits: Reduced nuclear heating; reduced insulator dose; reduced machine activation to permit "hands on" external maintenance; greater vessel stiffness**.**
- Active and Passive Stabilization Coils are integrated with the Vacuum Vessel



Vacuum Vessel is Fabricated in Octants and Assembled into TF & Structure in Octants

Vacuum Vessel Octant

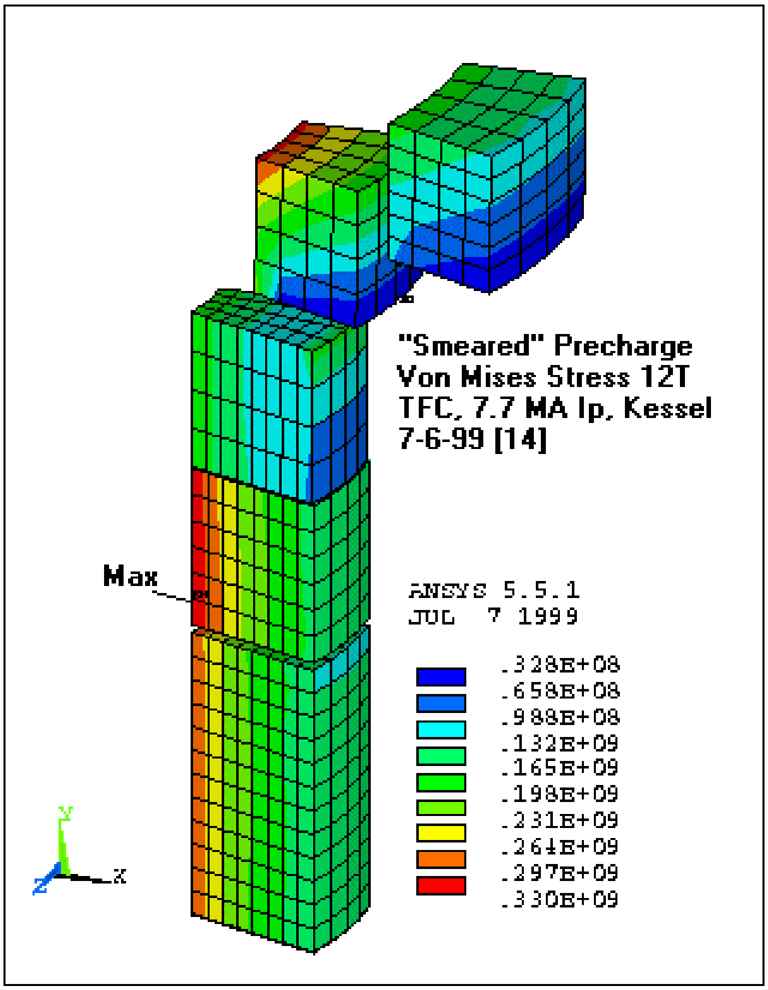




VV Sector Rotated into TF Assembly

Central Solenoid & PF Coils

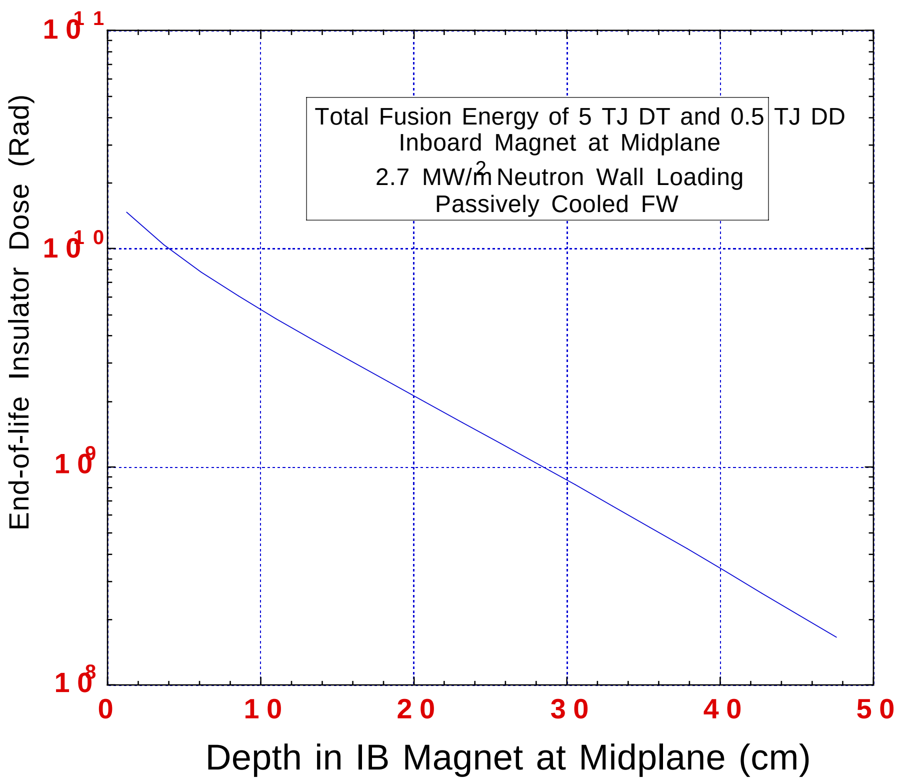
- All of the CS and PF coils use LN2 cooled OFHC copper conductor
- The max temperature in a CS or PF coil occurs for the 12 T, 7.7 MA scenario: 161 K in CS1, and 183 K for PF2
- For the baseline 10T or 12 T pulses, the pulse length is limited by the temperature rise of the TF coils.
- Pulse length is limited by the TF and the temperature related reduction in the stress allowable for the CS and PF coils.
- All specified scenarios will meet stress and temperature limits, but the higher field scenario (12 T & 7.7 MA) needs adjustment



Neutronics and Shielding

- **Nuclear heating has been computed for the major components (eg- magnets, vacuum vessel and PFC's) and can be accommodated.**

- **Neutronics analyses indicate that the insulation must withstand 1.47 x 10^{10} rads for a cumulative fusion energy of 5 TJ DT and 0.5 TJ DD. This is the peak, end of life value and occurs at the magnet surface at the inboard mid-plane.**
  It is expected that insulation materials can be identified that can meet the exposure limits.



Radial variation of insulator dose in inboard leg of TF coil

Activation & Radiation Exposure

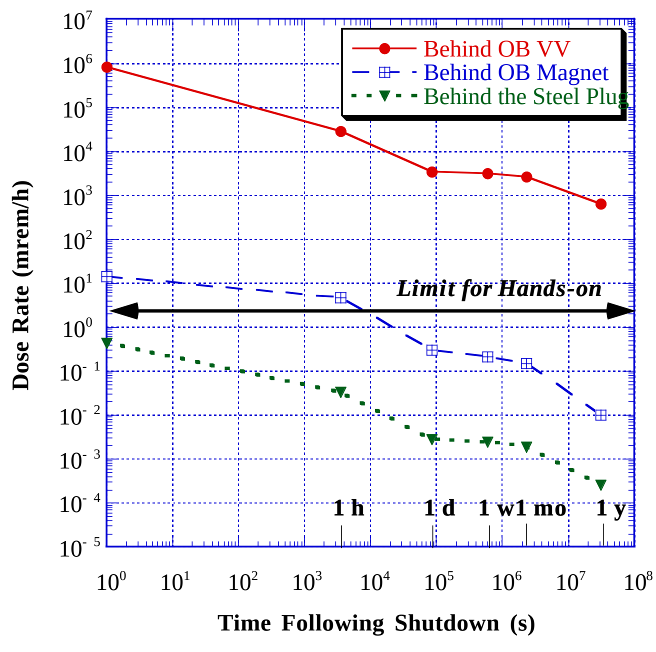
- **The PFC's produce the highest levels of specific activity and decay heat.** ***However, the favorable operational schedule allows for the decay of short-lived radionuclides between pulses resulting in low levels of activity and decay heat at shutdown*.**

- **The biological dose rates behind the vacuum vessel and the divertor remain high during the first year following shutdown**

  - **The vacuum vessel jacket/shield thickness, in conjunction with the shielding provided by the TF coils and port plugs, is such that "hands on" ex-vessel maintenance will be permitted within a few hours after shutdown.**

  - **At the end of the machine life, all components qualify for disposal as Class C low level waste.**

Biological dose rates at the midplane as a function of time following shutdown.

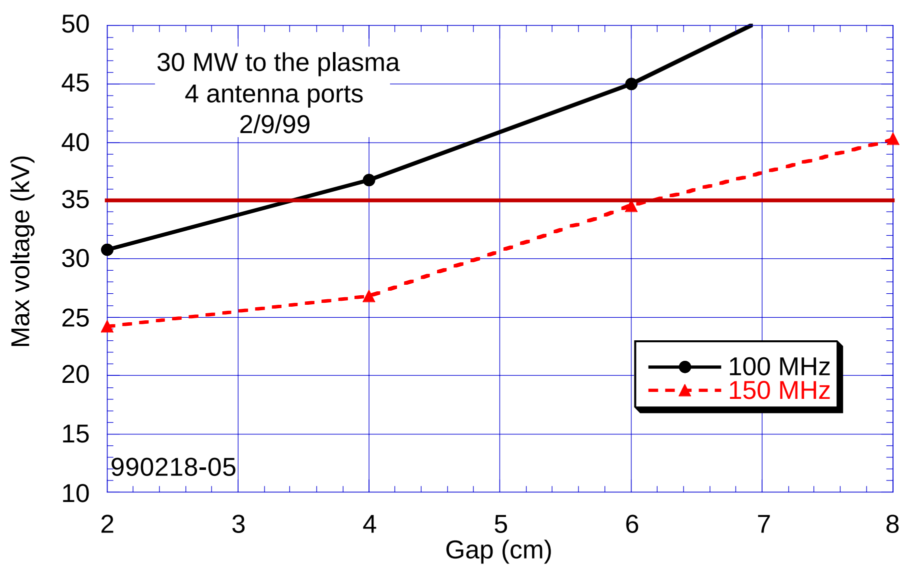


Ion Cyclotron Heating

- **Plasma transport calculations indicate the need for 30 MW of ICRH**

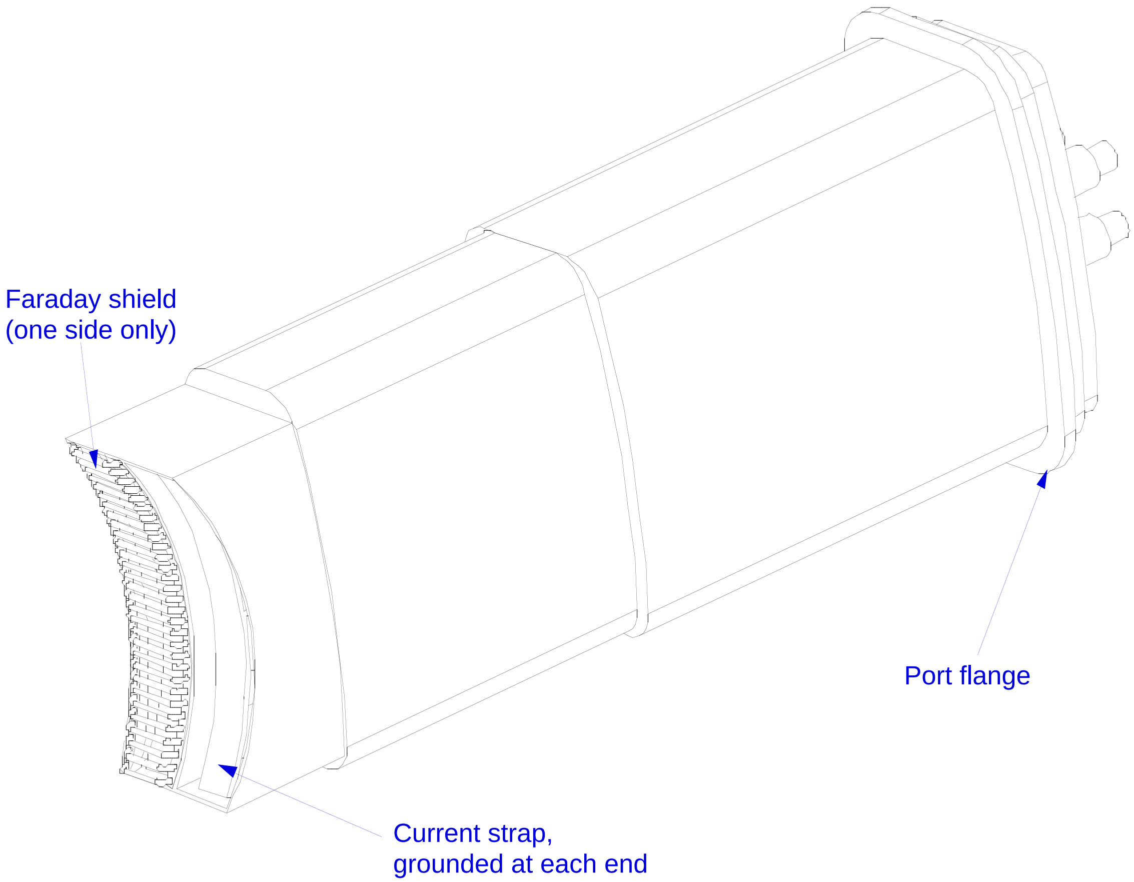
- **The design calls for a 4 port system with 2 antennae per port.**

- **With a 6 cm gap to the plasma, the 30 MW can be delivered at 150 MHz using 35 kV. The design value for the gap is 3-4 cm and calculations indicate that 30 MW can be delivered at 100 MHz with a 3.5 cm gap.**



Ion Cyclotron 2-Strap Antenna Design

- **Two strap antennas will be located at four midplane ports.**



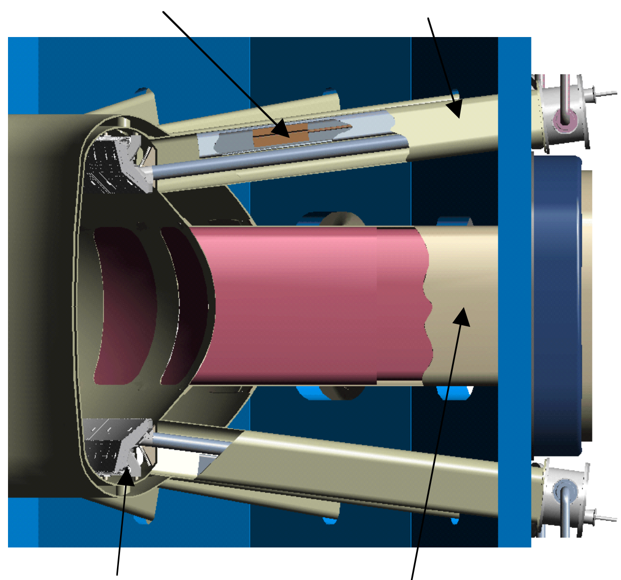
Fueling & Vacuum Pumping

- **Pellet injection is being considered from the outside mid-plane, vertically and from the inside lower quadrant aimed towards the plasma center.**

- **A tritium-rich pellet source will be used for core fueling and a deuterium-rich gas source for edge fueling.**
  - conventional gas puffing system with all-metal electromagnetic valves (four toroidal stations at two poloidal locations at each divertor level)
  - pellet injection system with two identical (redundant) injectors.

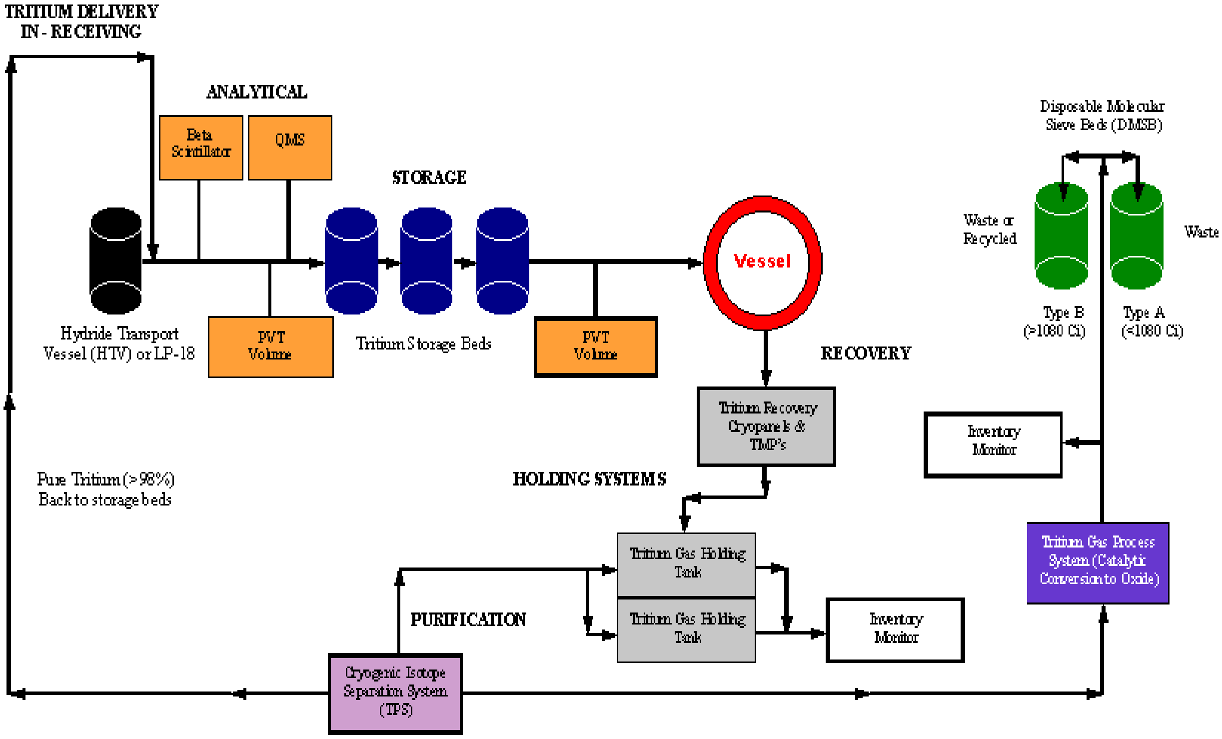
- **The design vacuum pumping speed is 200 torr-liter/s for a 20s pulse length. The base pressure is 10^{-7} torr for fuel gases (H, D, T) and 10^{-9} torr for impurities; operating pressure is~10^{-4} to 10^{-3} torr.**
  - **16 cryopumps are used (8 each top and bottom at alternate divertor ports) close coupled to the torus in the pumping duct directly from the double null divertor.**

Cryopump Divertor duct



Divertor Midplane port

PPPL
Tritiuim Delivery and Process System



- **The on-site tritium inventory has been set at 30 g to allow sufficient operational flexibility without introducing additional restrictions.**

- **The inventory can be reduced if a tritium reprocessing system is added to recycle the working tritium daily.**

Cryoplant

- **FIRE magnets obtain nitrogen from a specially built, “leased” LN2 production facility**
  - **No upfront plant installation costs**
  - **~10M$/year nitrogen cost**
- **FIRE uses the Alcator C-Mod method of one pump and individual regulator valves for each flow circuit.**
- **A subcooler is used to provide 80 °K liquid nitrogen to the coils.**

- **The magnets are kept cold overnight and weekends, and only warmed up to room temperature during maintenance periods**

- **The storage requirements are higher than they were in the CIT design:**
  -The energy dissipated is higher than in CIT (18.7 GJ vs. 12 GJ)
  -The number of pulses is higher than in CIT (40/week vs. 20/week)
  -note: if 7,000 gallon trucks are used, this would require 60 trucks/day

The amount of radioactive nitrogen-13 generated is small and would be within allowables for most site boundaries.

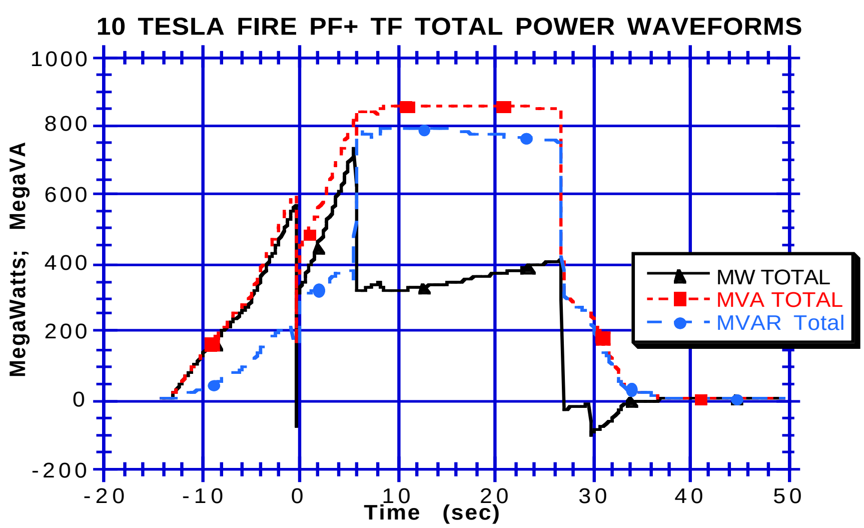
- **One day hold-up of N13 unnecessary**
- **One hour hold-up ok with nitrogen flush**
- **Eliminate hold-up if use helium flush**

Power Supplies

- **A 10 T pulse will require 14 Gigajoules for the TF system and 2 Gigajoules for the CS/PF magnets; the Peak power is 542 MVA and 412 MVA, respectively.**

- **Power equipment for TF and CS/PF magnets includes thyristor rectifiers, resistor banks, and switching-interrupter circuits.**
  -The total pulse rating of the rectifiers is approximately 1000 MVA for the 10 Tesla pulse.
  -For a long-pulse option (eg- 4 Tesla, 2 MA), the total 214 second long-pulse rectifier rating is 345 MVA.

- **For the 12 Tesla 7.7 MA case:**
  -An additional 200 MVA of thyristor rectifiers would provide a short-pulse 12 Tesla 7.7 MA capability
  -An extended flattop at 12 Tesla could be obtained by inserting additional TF rectifiers in series to boost the TF charging voltage, bringing the total rectifier rating to 1850 MVA. An option would be to power the additional 650 MVA from a local MG storing at least 1.7 Gigajoules of energy.



Note: Power Requirements could be reduced significantly if all Cu TF coils are used

POWER REQUIREMENTS FOR FIRE

(BeCu vs OFHC Cu TF)

BeCu TF Coil Inner Legs

	10T (20s)		12T (12s)	
	Peak Power (MW)	Peak Energy (GJ)	Peak Power (MW)	Peak Energy (GJ)
TF	490	11.5	815	11.5
PF	250	2.2	360	3.7
RF	60	1	60	0.6
$\sum$	800	14.7	1235	15.8
Grid	550 (TF&RF)	12.5	600 (TFbase)	10.9
MG	250 (PF)	2.2	635 (TFsupp &PF&RF)	4.9

All Cu TF Coils

	10T (45s)		12T (25s)	
	Peak Power (MW)	Peak Energy (GJ)	Peak Power (MW)	Peak Energy (GJ)
TF	267	12.6	345	13.2
PF	250	5	360	4.6
RF	60	2.3	60	1.3
$\sum$	577	19.9	765	19.1
Grid	577 (All Systems)	19.9	404 (TF&RF)	14.5
MG	0	0	360 (PF)	4.6

The OFHC ("All Cu") option will be studied further in FY01

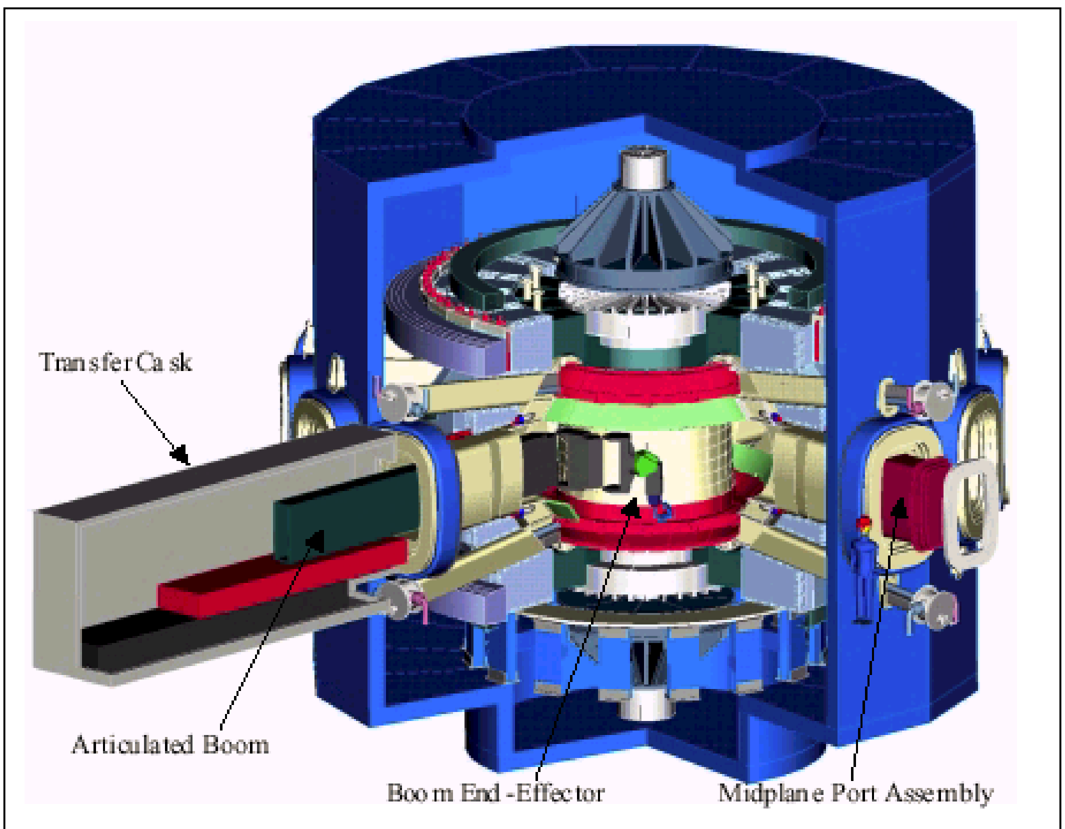
Remote Maintenance

- **The strategy is to employ hands-on maintenance to the fullest extent possible.** ***The activation levels outside the thermal shield are low enough to permit hands-on maintenance; temporary local shielding will be necessary when the duct shield plugs are removed*.**

- **In-vessel components will generally be removed as integral assemblies and transferred to the hot cell for repair or processing as waste.**

- **In situ operations will be limited to inspection, vacuum window replacement, leak testing and, if necessary, dust removal.**

- ***Remote maintenance will continue to be a driver for design of interfaces. Components have been given a classification and preliminary requirements are being accommodated in the layout of facilities and the site.***



Safety

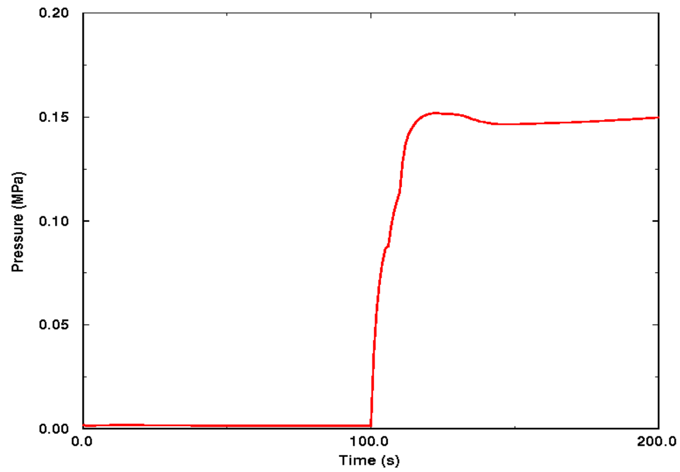
- ***Release targets for tritium, and activated tungsten, air and nitrogen have been established.***

- **A goal is to keep the total on-site tritium inventory below 30 g**
  -Site can be classified as a low hazard nuclear facility

- **Confinement barriers:**
  -double-walled vacuum vessel is a highly reliable primary barrier
  -thermal shield will serve as a moderately reliable 2nd barrier
  -double confinement will be implemented in all penetrations attached to the vacuum vessel

- ***Examination of the potential safety concerns associated with the energy sources has not yet revealed any events that pose a serious challenge to the radiological confinement function.*** **A preliminary analysis has been done for:**
  - **Long term thermal response and passive decay heat removal under a complete loss of coolant condition for the divertor and VV --** ***decay heat is not a serious concern and oxidation of the activated PFC surfaces will not be significant.***
  - **Break in the divertor or VV cooling lines inside of the VV—*pressure does not rise to a level expected to compromise the VV radiological confinement integrity. Furthermore the chemical energy from Be-steam and W-steam interactions does not threaten the radiological confinement function of the VV.***
  - **Deflagration and/or detonation of hydrogen upon mixing with air-- From the accident perspective, hydrogen from Be/steam and W/steam reactions was not of concern, *however the tritium on the cryopumps must be controlled.* The deflagration limit of 30 g- moles translates into a deflagration limit of ~ 300 g DT. Regeneration will be scheduled frequently enough to stay well below this limit.**

- ***The control of plasma energy, magnet energy, loss of vacuum events, or potential cryogen/water interactions have not yet been analyzed.***



Pressure in FIRE plasma chamber resulting from an in-vessel break of the vacuum vessel cooling system

Radiological Release Targets for FIRE

	Normal Operation[a]	No-evacuation Limit	
Dose Limit	0.1 mSv/yr (10 mrem/yr)	10 mSv (1 rem) per off normal event	
Meteorology	Yearly average	Best-estimate or Average Weather	
Site Boundary	1 km	1 km	1 km
Release Point	Elevated via 100 m stack	Ground	Elevated via 100 m stack
Tritium as HTO	8 g/a	150 g	1.3 kg
Activated W dust	5 kg/a	5 Mg	53 Mg
Ar-41	5 Ci/hr	b	b
N-13	8 Ci/hr	b	b
C-14	0.1 Ci/hr	b	b

- Release targets have been reduced by a factor of ~ 10 relative to regulatory limits as an implementation of the ALARA principle.
- Not considered an accident hazard because of low inventory in FIRE

Facilities & Siting

- **A conceptual layout has been developed for the safety and non-safety related buildings based on a "green field" site. It may also be possible to adapt an existing facility to the FIRE project.**

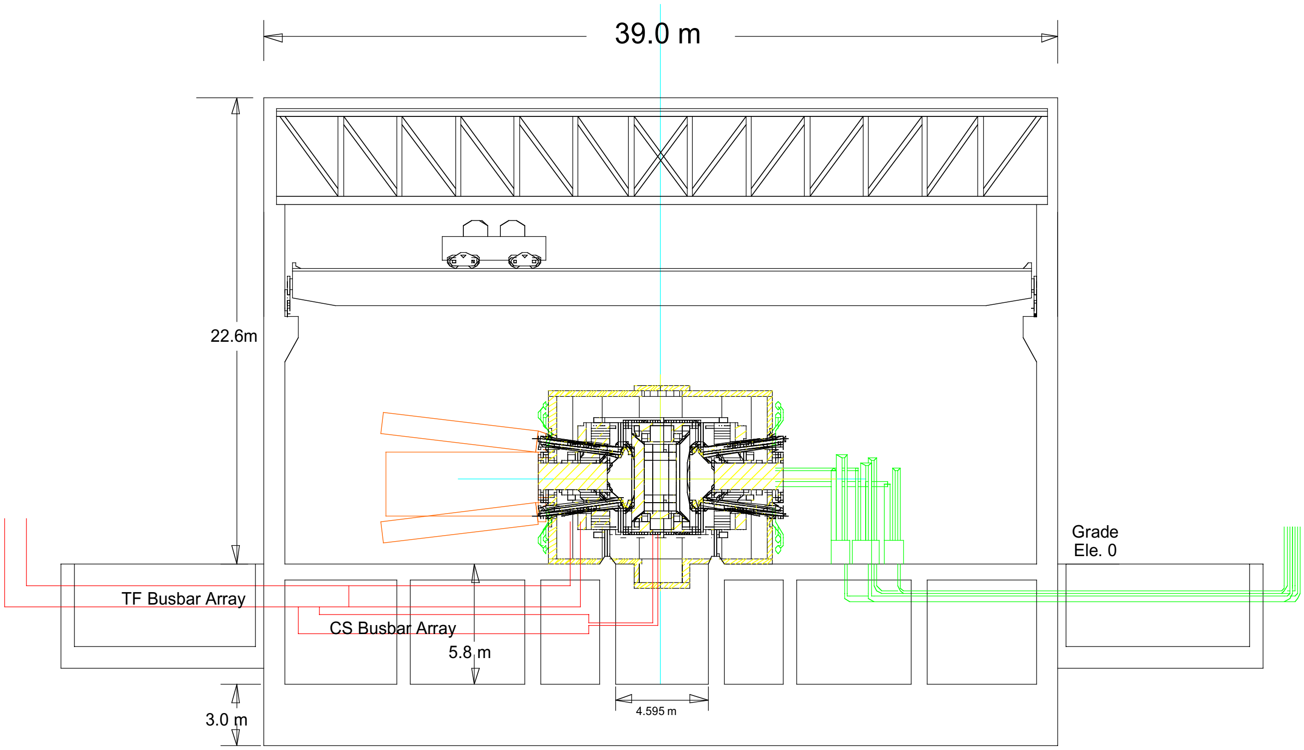
- **The test cell size is determined by the size of the cryostat and space required for remote handling casks at ports (casks are 8 m in length and about 1.9 m in width). *Several strategies are under consideration for the design of RH cask vehicles. A tentative routing for the vehicles to other parts of the facility has been selected.***

- **FIRE will take advantage of the shielding provided by the thick outer wall of the vacuum vessel and the magnet system. Port objects will provide equivalent shielding, making them both long and heavy, but with the result that the outboard end of the port objects will not become radioactive. The plasma facing end will be a strong radiation source, however the size and spacing of the ports make it impractical to include shielding in the casks. *The remote handling requirements on the facility for routing and storage of these items is being evaluated.***

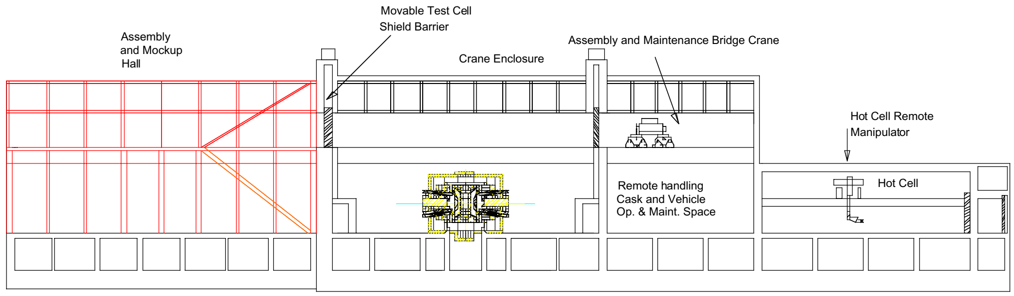
- **The hot cell concept assumes that some port mounted objects can be repaired. *The extent and nature of these processes are not yet well developed*, but it is expected that they will include replacement of divertor strike plates, and repair of diagnostic and plasma heating devices. Radioactive materials which cannot be returned to the tokamak will be processed in the hot cell to recover tritium from beryllium and will then be size reduced by sawing or cutting, and encapsulated for subsequent shipment to a waste repository.**

- ***Some building requirements are not yet well developed, but a preliminary allowance has been made*. For example, the cryogenics systems building is used to house indoor parts of the liquid nitrogen system. It also houses a liquid helium refrigerator for the cryopumps in the vacuum vessel and in the diagnostic neutral beam.**

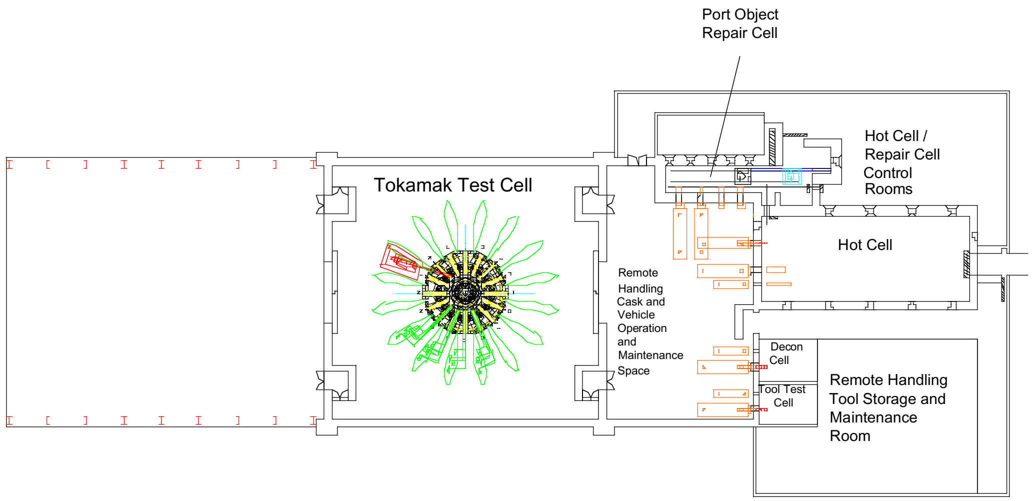
- **Magnets will be cooled before each operating pulse, using liquid nitrogen, supplied commercially.**



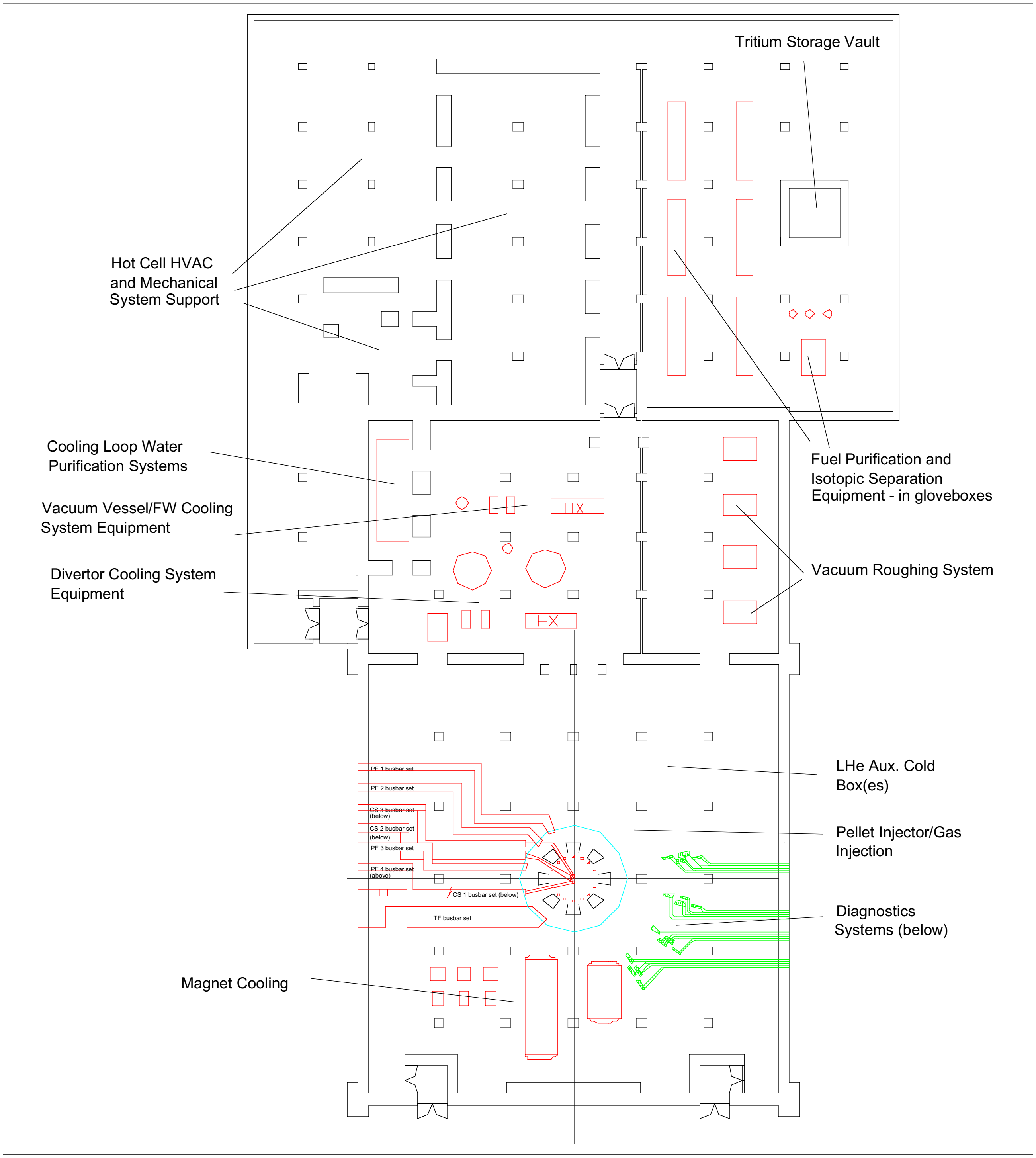
Building 11 - Tokamak and Hot Cell Building

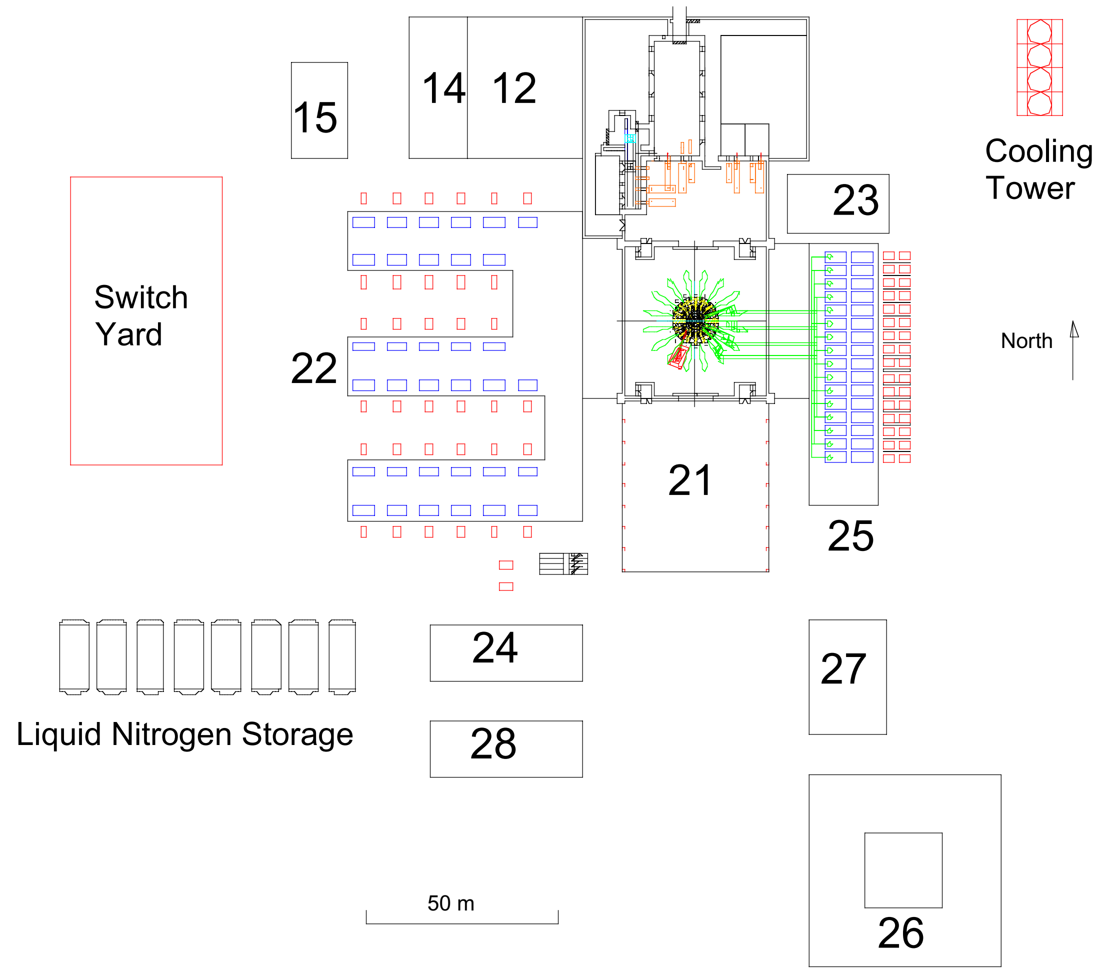


Assembly Hall, Tokamak Building, and Hot Cell - NS Section



Assembly Hall, Tokamak Building, and Hot Cell - Plan View


Tritium Storage Vault
Hot Cell HVAC
and Mechanical
System Support
Cooling Loop Water
Purification Systems
Vacuum Vessel/FW Cooling
System Equipment
Divertor Cooling System
Equipment
HX
HX
Fuel Purification and
Isotopic Separation
Equipment - in gloveboxes
Vacuum Roughing System
LHe Aux. Cold
Box(es)
Pellet Injector/Gas
Injection
Diagnostics
Systems (below)
Magnet Cooling
PF 1 busbar set
PF 2 busbar set
CS 3 busbar set
(below)
CS 2 busbar set
(below)
PF 3 busbar set
PF 4 busbar set
(above)
CS 1 busbar set (below)
TF busbar set



Legend:

Safety Related Buildings
11 - Tokamak and Hot Cell Building
12 - Radioactive System Support Building
14 - Radwaste Systems Building
15 - Emergency Power Supply Building

Non-Safety Related Buildings
21 - Assembly and Mock-up Hall
22 - Magnet Power Conversion Building
23 - Cooling Systems Building
24 - Cryogenic System Building
25 - ICRH Power Supply Building
26 - Laboratory Office Building
27 - Control and Operations Building
28 - Utility Services Building

Preliminary Site Layout

FIRE Baseline Operation Summary

Operating Mode	TF Coils :	CS Coils	PF Coils	PFCs
I. Baseline : **10 T / 6.44 MA** DT Fusion Power ~200 MW P_{ext}=20 MW	**BeCu , 68% IACS IL; rest OFHC.** 18 s flat top w/D-T; 26 s w/D-D	**OFHC (C10200);** Tmax 152 °K	**OFHC (C10200);** Tmax 173°K	**Actively cooled divertor outer plate & baffle. Divertor inner plate & FW cond. Cooled to Cu clad VV**
II . Higher Field Mode 12 T / 7.7 MA P_{fusion}=250 MW P_{ext}=25 MW	**Same as (I)** 12 s w/ D-T; 15 s w/ D-D	**Same as (I)** Tmax 161 °K	**Same as (I)** Tmax 183 °K	**Same as (I)**
III. TPX-like Mode 4T / 2 MA P_{fusion}=5 MW P_{ext}=15 MW	**Same as (I)** ~214 s pulse duration.	**Same as (I)** Tmax 144°K	Same as (I) Tmax 124°K	**Same as (I)..**
IV. AT/BP Mode 8T / 5 MA P_{fusion}=150 MW P_{ext}=15 MW	**Same as (I)** ~31 s w/ DT; ~46 s w/ DD.	**Same as** (I); Tmax TBD	**Same as (I)** Tmax TBD	**Same as (I)**

***note: for B limited to 10 T, cross-section of compression rings could be reduced**

CONCLUSIONS

- **Design has addressed all major systems, facilities and safety**
  - **FY99 Report available**
  - **FY00 Interim Report available now**

- **Baseline design meets or exceeds initial requirements for 10 T, 6.4 MA, flat-top > 10 s**
- **Possibility exists for higher fields (eg 12 T, 7.7 MA) and longer pulses at lower fields (eg 8T, 5 MA, 46 s)**

- **Cost estimates underway**

Issue: Divertor and first wall cooling details will have to be refined as the hardware details evolve.

Issue: Preliminary divertor disruption analyses indicate high stresses in module / vessel attachments for the current design. More detailed analyses are planned to better quantify loads. Studies will also consider toroidal electrical connections between modules to reduce torques.

Issue: For B limited to 10 T, compression ring cross-section could be reduced; inner leg material could change to BeCu with 77% IACS and pulses could lengthen slightly

Issue: For a bucked and wedged design and B limited to 11.5 T, TF coils could be entirely OFHC copper; <u>this would reduce power and TF coil costs and will be explored in FY01</u>