ST Questions 1, 3b

1) What are the essential features of the device that would fulfill the ST goal?

3b) How does the program envision reaching solutions for the technological issues associated with the goal – especially those particular to the ST approach – NBI, magnets, etc.?

Brad Nelson, Tom Burgess, Charles Neumeyer,
Dave Rasmussen, Paul Fogarty, Adam Carroll,
Roger Stoller

FESAC TAP meeting
June 30 – July 2, 2008, DFW Airport

What is the ST goal?

Long Term ST Mission:

To develop compact, high-beta burning plasma capability for use-inspired R&D

(example: to simplify energy source configuration; make it smaller and cheaper)

ITER - Era Goal:

To produce a sustained plasma fusion environment of high heat flux and high neutron fluence to enable the R&D that establishes the knowledge base for an attractive fusion energy source.

ST goal - continued

Address Themes B (PMI) and C (Power) issues defined in the Greenwald Panel report, using

A sustained plasma fusion environment (Q4c):

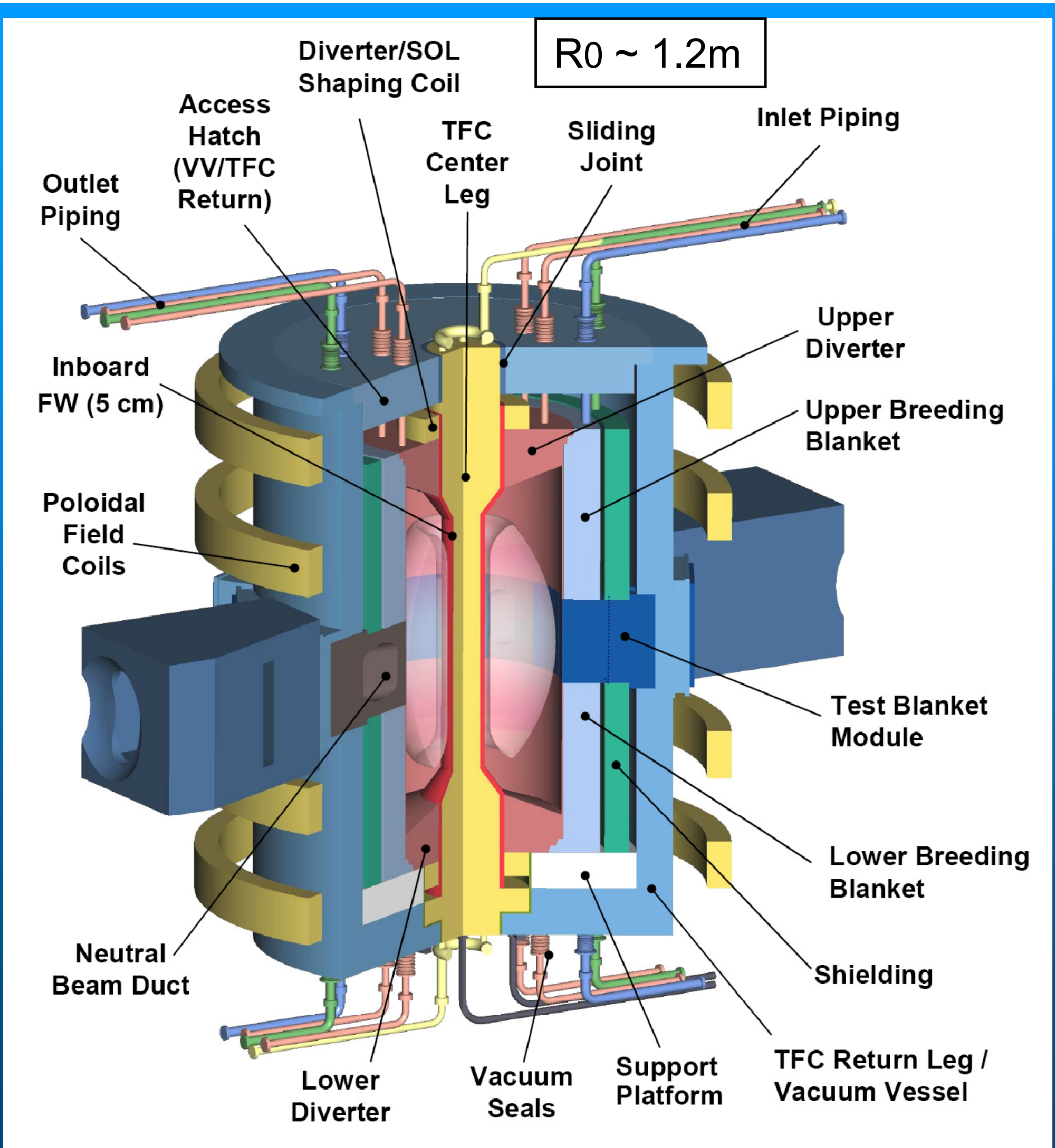
Wall load: ~1 MW/m^2

Fluence: ~ 3 MW-a/m^2 (for ITER era)

This can be done in parallel with ITER

Vision: ST CTF working example –
a compact, high duty factor Volume Neutron Source

Essential features are driven by high duty factor – high reliability & maintainability



- Cu TF magnet post
- MIC startup solenoid
- Continuous NBI
- Super-X divertor
- Minimizing disruptions
- Extensive modularity
- Remote handling
- Ex-shield boundary hands-on access
- Large design margins
- Tradeoffs plus R&D leverage

Fluence determined by duty factor

How to progress toward high Duty Factor (30%)?

$$\text{Duty Factor} \sim \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})}$$

ITER aims for ≤ 3%; Demo needs ≥ 60%

Reliability increases Mean-Time Between Failure (MTBF, “up-time”); Maintainability reduces Mean-Time To Repair/Replace (MTTR, “down-time”)

Reliability

Reliability in this design is enhanced by:

- Simplifying design solutions
- Performing adequate R&D, testing, and prototyping of those solutions
- Including adequate margins in performance – robustness

High maintainability enables fast reliability improvement

Single-turn Cu magnet reliability

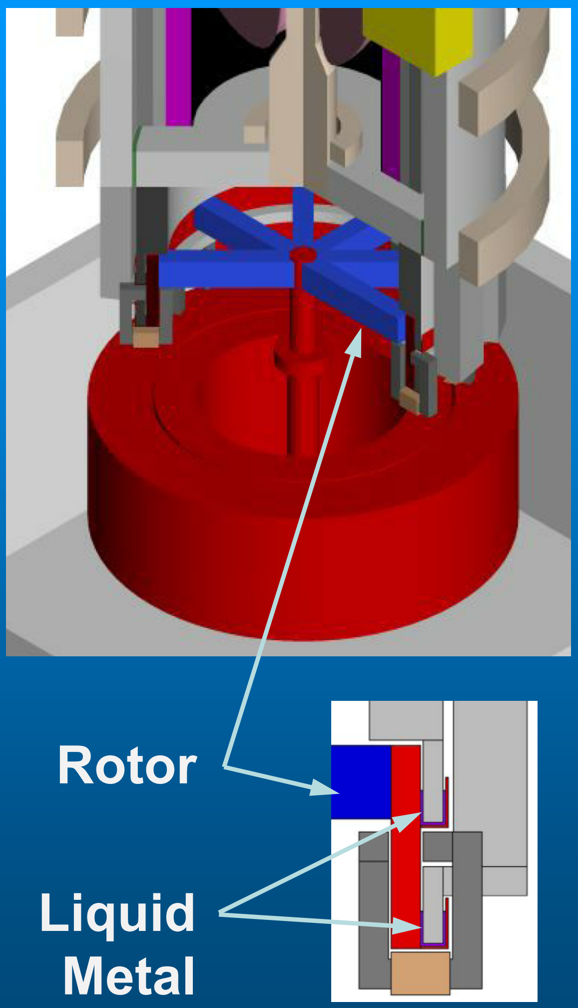
- Conventional multi-turn coil set reliability is problematic and replacement of a TF or PF is extremely difficult.
  - Failures are usually electrical and S/C coils have high quench voltages (some kVs)
  - Significant shielding (1+ meters) is required to protect insulation and limit nuclear heating of S/C coils
- Single-turn Cu allows much lower voltages (10-15 V)
- Issues include:
  - High current, low voltage power supply system and bus (10 MA vs. 75 kA in ITER)
  - High current electrical joints/insulation
  - High current density (resistive heating)
  - Radiation damage (essentially no shielding)

High current power supply and feeder

High current (~ 10 MA) power supplies and feeder bus system expected to be more expensive

- To balance multiple supplies, current control and feedback (instead of voltage) is needed
- Dissipation in feeds must be minimized – short distance, HTSC? (0.6- GW, 140-kV line in Long Island)
- R&D: homopolar generator
  - Cheaper, works better at low voltage

ST-CTF Example



10-MA electrical joints at end of center core

Due to thermal and structural expansion of the center core, sliding joints may be needed.

Mechanical sliding joint – standard approach

- Average current densities need to be reasonable (<1 kA/cm^2), cooling is important

Liquid metal joint is intriguing possibility

- Need adequate seals
- Configure Lorentz (JxB) forces to retain liquid instead of expelling it
- Need rigorous prototyping & testing at full parameters

Central Cu core cooling and radiation damage

- Current density is expected to be high for compact device (5.3 kA/cm^2, ~ 150 W/cm^3 in Glidcop)
- Nuclear heating adds ~20 W/cm^3 at surface
- Will require careful optimization of cooling passages
- Must consider corrosion, radiation hardening
- Glidcop life 0.5 MW-a/m^2 (~ 5 dpa) measured (fission)
- CTF example – 2 calendar year under full performance
- R&D: How to build? Life under 14-MeV neutrons?

Startup: solenoid option

- Multi-turn MIC design
- 1-cm solenoid (9% of CS cross section, 30% Cu) → 0.4 Wb (0.5 MA) in 0.5-s operation
- Relatively high voltage compared to TF, only used during startup, avoiding radiation induced conductivity
- Ceramic powder (MgO) measured to retain insulating capability up to ~10 dpa (fission)
- Will require proper design for cooling and protection during DT burn
- Helium may be the best coolant (e.g., ~50% volume fraction)
- R&D: life under 14-MeV neutrons

Continuous NBI

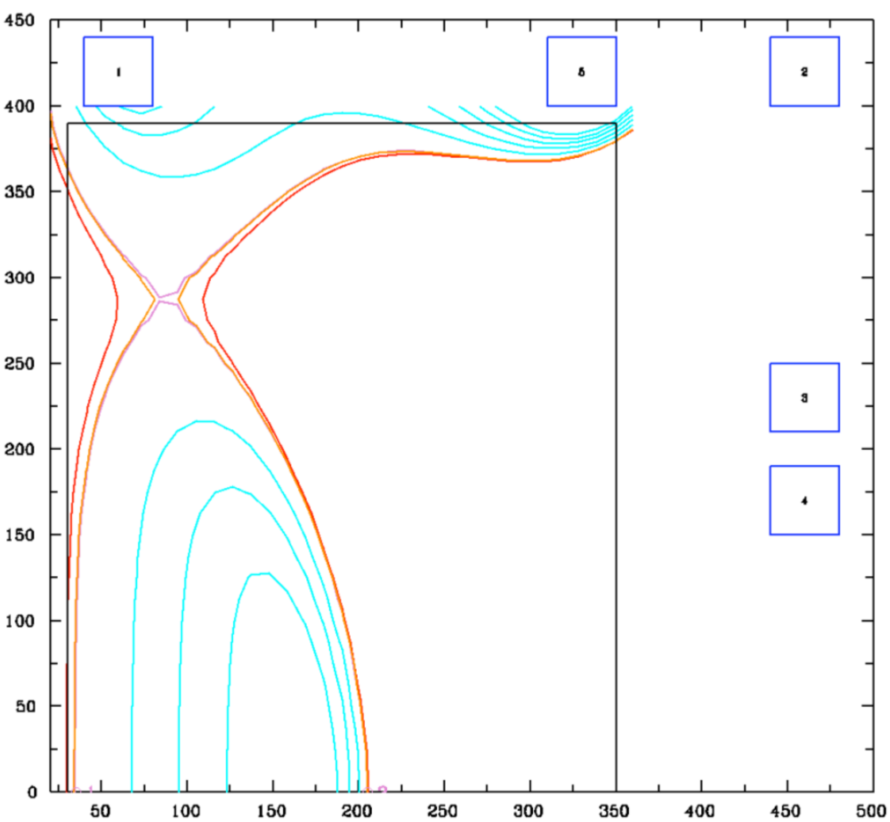
- ITER NBI system allows cryogenic condensation of D,T in neutralizer in batch mode
- Need to extend operation to weeks
  - Will require continuously cryogenic condensation and regeneration
  - R&D for potentially improved solutions: lithium vapor jet neutralizer and particle pumping
- Lower energy (0.25 MeV) → higher beam-let divergence
  - Increased divergence for given <u>source</u> and <u>accelerator</u> configuration – assume ~40A/m^2 (JAEA)
  - R&D to improve both

Divertor solutions

- Conventional divertor has very high heat (~40 MW/m^2, Δ = 0.5 cm) and neutron fluxes
    - Major ITER R&D (~10 MW/m^2) will benefit ST goal

- “Super-X” Divertor lowers heat flux by > 5-6x
    - Expanded SOL area
    - Longer connection length; increased radiation loss
    - More nuclear shielding

- Another R&D: power & particle control using liquid metal in lower single null



Minimizing disruptions in CTF

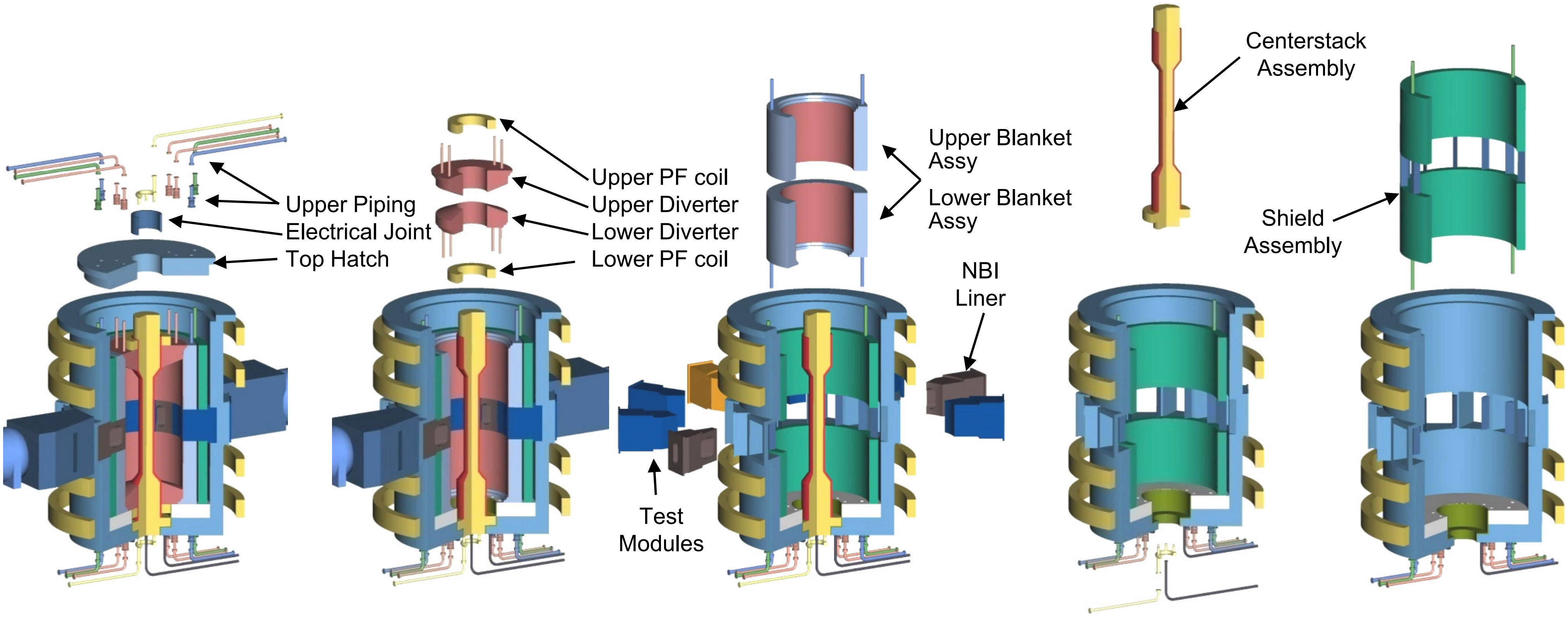
Biggest issue with current carrying devices, but:

- ST-CTF configuration has high ideal with-wall beta limit (β_T ~ 35-40%)
- Possible to reduce disruption frequency by operating well below ideal limit (e.g., β_T ~ 18%, β_N ~ 3.8, q_{cyl} ~ 3.7)
- Halo currents measured (MAST) to be much lower and more symmetric than normal A tokamak – lower mechanical loading and peaking of heat deposition
- R&D: stability control to minimize disruptions with substantial stability margins (Q4b)

High Maintainability via Modularity

Extensive modularity expedites remote handling:

- Large components with linear motion
- All welds external to shield boundary
- Parallel mid-plane/vertical RH operation



Disconnect upper piping
Remove sliding electrical joint
Remove top hatch

Remove upper PF coil
Remove upper diverter
Remove lower diverter
Remove lower PF coil

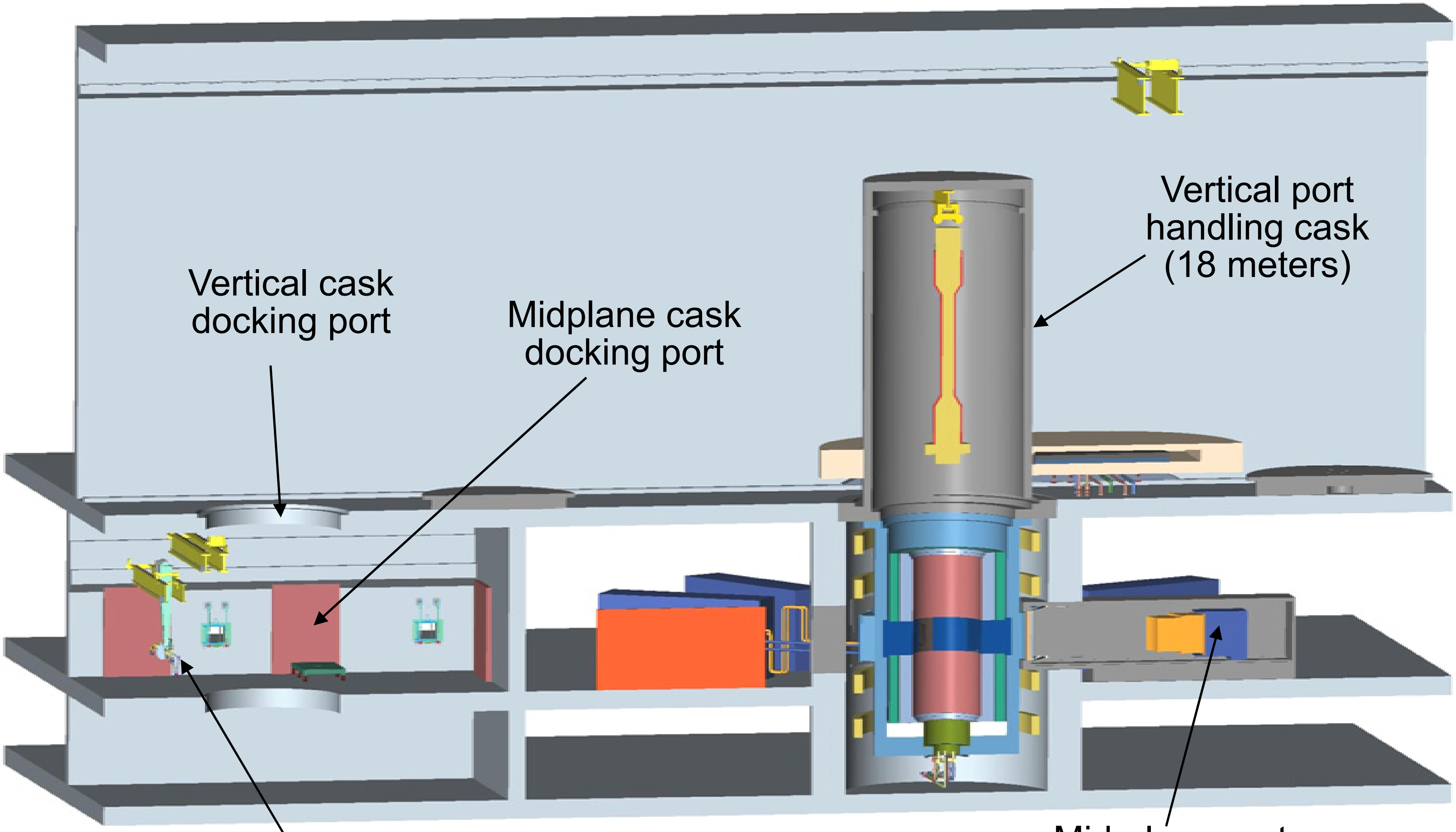
Extract NBI liner
Extract test modules
Remove upper blanket assembly
Remove lower blanket assembly

Remove
centerstack assembly

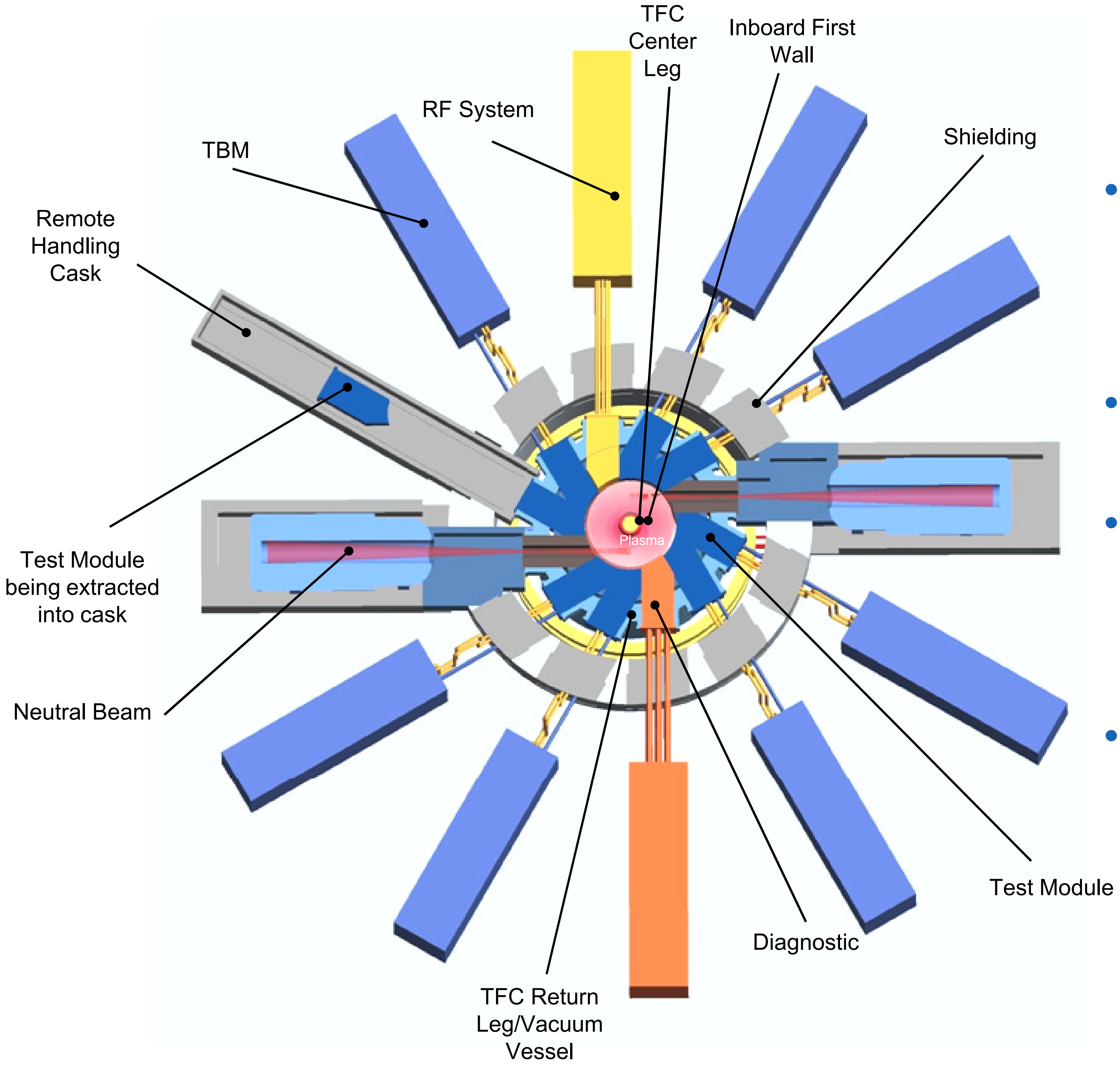
Remove
shield assembly

Extensive hot cell laboratories

Remote handling equipment includes hot cell laboratories for accompanying fusion nuclear sciences R&D



Compact design allows close-fitting shielding and ex-shield hands-on access, reducing MTTR



Mid-plane ports

- Minimize interference during remote handling (RH) operation
- Minimize MTTR for test modules
- Allow parallel operation among test modules and with vertical RH
- Allow flexible use & number of mid-plane ports for test blankets, NBI, RF and diagnostics

Minimizing module replacement times drives performance of remote handling equipment

Component	**RH Class**	**Expected Frequency**	**RH Operation Time Estimate* (very preliminary, improvable by practicing)**
Divertor Module	1	~ At least annually ~ Parallel operation	Upper module: ~ **4 weeks** Upper and lower**: ~ 6 weeks (assuming center stack not removed)**
Mid-plane Port Assemblies			**~ 3 weeks** per port assembly
Neutral Beam Ion Source			**~ 1 week** per NBI
In-vessel Inspection (viewing/metrology probe)	1	Frequent deployment	Single shift **(8-hr)** time target (deployed between plasma shots, at vacuum & temp.)
Upper and Lower Breeder Blanket (to approach tritium self-sufficiency)	2	~ Several times in life of machine ~ In parallel with mid-plane operation	Upper: ~ **6 weeks** Upper and Lower: **~ 9 weeks** (**need to retract mid-plane modules)**
Center Stack			**~ 6 weeks**
Neutral Beam Internal Components			**~ 2 to 4 weeks**
Vacuum Vessel Sector / TF Coil Return Conductor	3	Replacement not expected	Replacement must be possible and would require extended shutdown period
Shield			

* Includes active remote maintenance time only. Actual machine shutdown period will be longer. Time estimates are rough approximations based on similar operations estimated for ITER and FIRE.

Plasma and engineering design allows substantial margins to increase operational reliability and MTBF

Physics Assumptions - Menard *et al* PPPL- 3779 (2003)

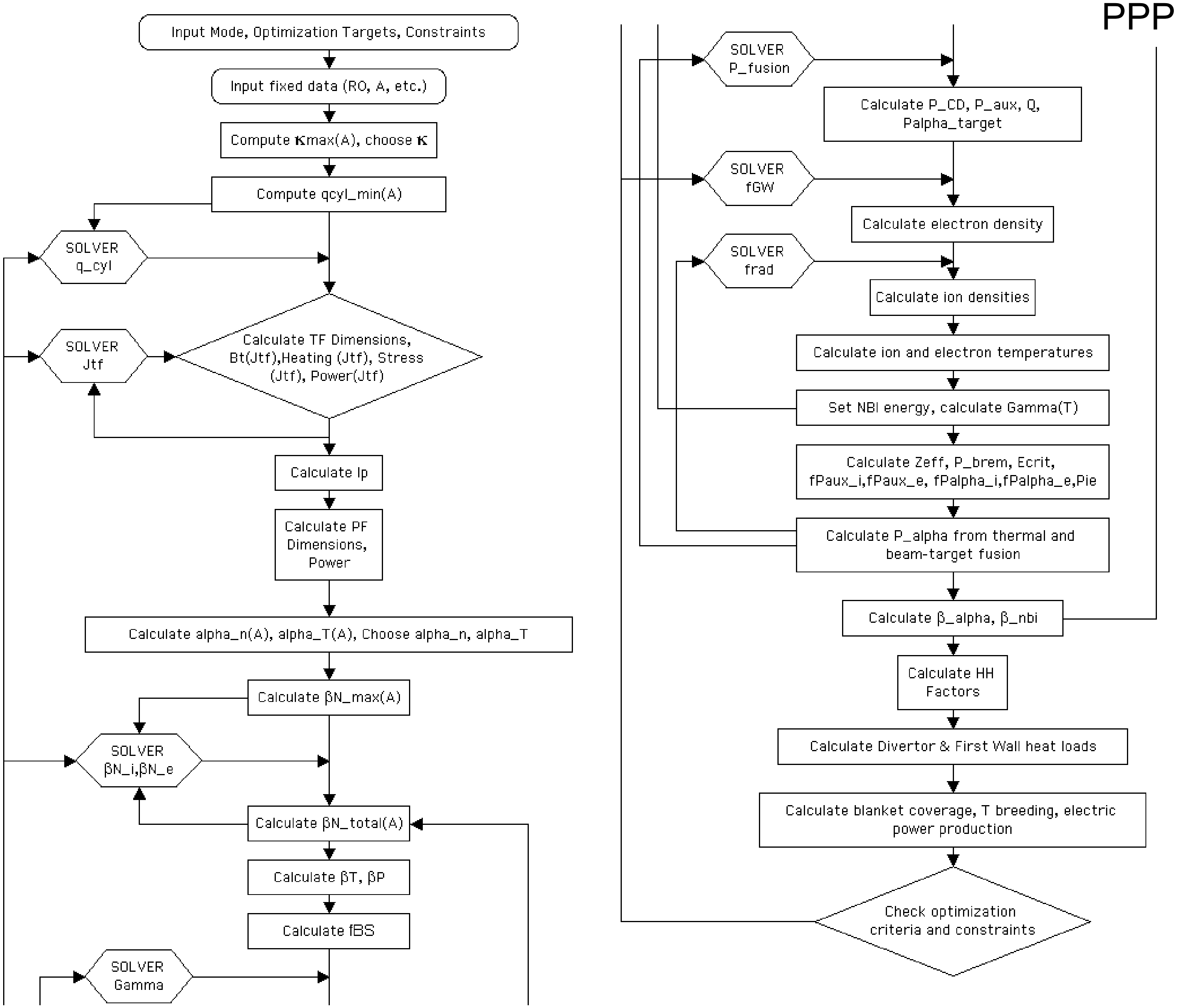
Shape	$\kappa = 3.674A^{-1/2} \quad \delta = 0.4$
MHD Safety Factor	$\mathrm{q}_{\mathrm{cyl\_min}} = 1.19 + 7.8\mathrm{A}^{-1} - 16.2\mathrm{A}^{-2} + 12.2\mathrm{A}^{-3}$
Normalized Pressure	$\beta_{N\_\max} = 6.43 - 1.02\mathrm{A}$ (no-wall limit)
Bootstrap Fraction	$f_{BS} = \dfrac{\beta_P K_{BS} pf^{0.25}}{\sqrt{A}} \quad K_{BS} = 0.344 + 0.195A$ $pf = \int \left[1-\left(\dfrac{r}{a}\right)^2\right]^{\alpha_N} \left[1-\left(\dfrac{r}{a}\right)^2\right]^{\alpha_T} \quad \alpha_N = \alpha_T = \dfrac{0.64 - 0.3A^{-1}}{2}$
Confinement	$HHi \le 0.7[neoclassical] \;\; HHe \le 0.7[ITER_{98} - H] \;\; HH_{global} \le 1.5$

Engineering Assumptions - Neumeyer *et al* PPPL- 4165 (2006)

Center Stack Build	4cm inboard SOL + 10cm first wall
TF Inner Leg	Glidcop 87% IACS, water cooled 10m/s, T≤150°C,σ ≤130MPA
OH Solenoid	Glidcop 87% IACS, MIC, 10-20% center stack area, 30% fill factor, T ≤ 200°C,σ ≤130MPA, single swing flux ~ 0.4-0.8Wb to ramp Ip ~ 0.5-1.0MA in 0.5s, He cooled during DT operation
NBI	PINBI E ≤ 120keV, J=144A/m²,NINBI E > 120keV, J=40A/m²
Neutron Flux Distribution	ARIES-ST model

Non-Linear Optimizer help to clarify tradeoffs, sensitivities, and leverages of near-term R&D

PPPL-4165 (Neumeyer et al)



Input Mode, Optimization Targets, Constraints

Input fixed data (R0, A, etc.)

Compute κmax(A), choose κ

Compute qcyl_min(A)

SOLVER q_cyl

SOLVER Jtf

Calculate TF Dimensions, Bt(Jtf),Heating (Jtf), Stress (Jtf), Power(Jtf)

Calculate Ip

Calculate PF Dimensions, Power

Calculate alpha_n(A), alpha_T(A), Choose alpha_n, alpha_T

Calculate βN_max(A)

SOLVER βN_i,βN_e

Calculate βN_total(A)

Calculate βT, βP

Calculate fBS

SOLVER Gamma

SOLVER P_fusion

Calculate P_CD, P_aux, Q, Palpha_target

SOLVER fGW

Calculate electron density

SOLVER frad

Calculate ion densities

Calculate ion and electron temperatures

Set NBI energy, calculate Gamma(T)

Calculate Zeff, P_brem, Ecrit, fPaux_i,fPaux_e, fPalpha_i,fPalpha_e,Pie

Calculate P_alpha from thermal and beam-target fusion

Calculate β_alpha, β_nbi

Calculate HH Factors

Calculate Divertor & First Wall heat loads

Calculate blanket coverage, T breeding, electric power production

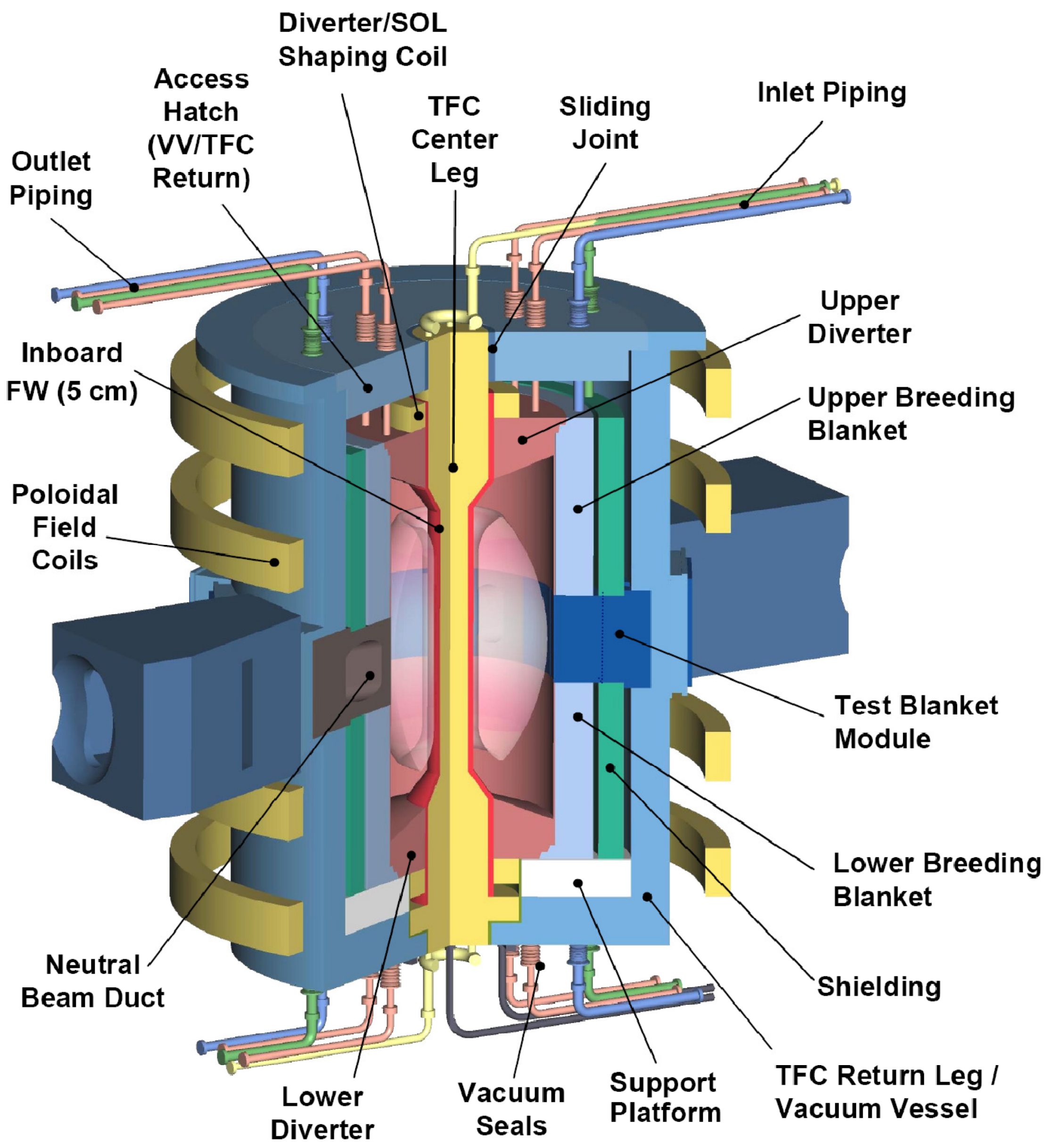
Check optimization criteria and constraints

Solver finds solution that optimizes an objective function within equality and non-equality constraints, by adjusting variables in ⬡

Tradeoffs:

- Any assumption
- A = 1.4 – 4.3
- 0.8 – 1.2x $\beta_{N(\text{no-wall})}$
- q_{cyl} = 2.4 – 4.5
- H_{98e} = 1 – 2
- MIC solenoid/iron core = 10-20% of CS cross section

Device example has moderate parameters including tritium consumption (Q4c)



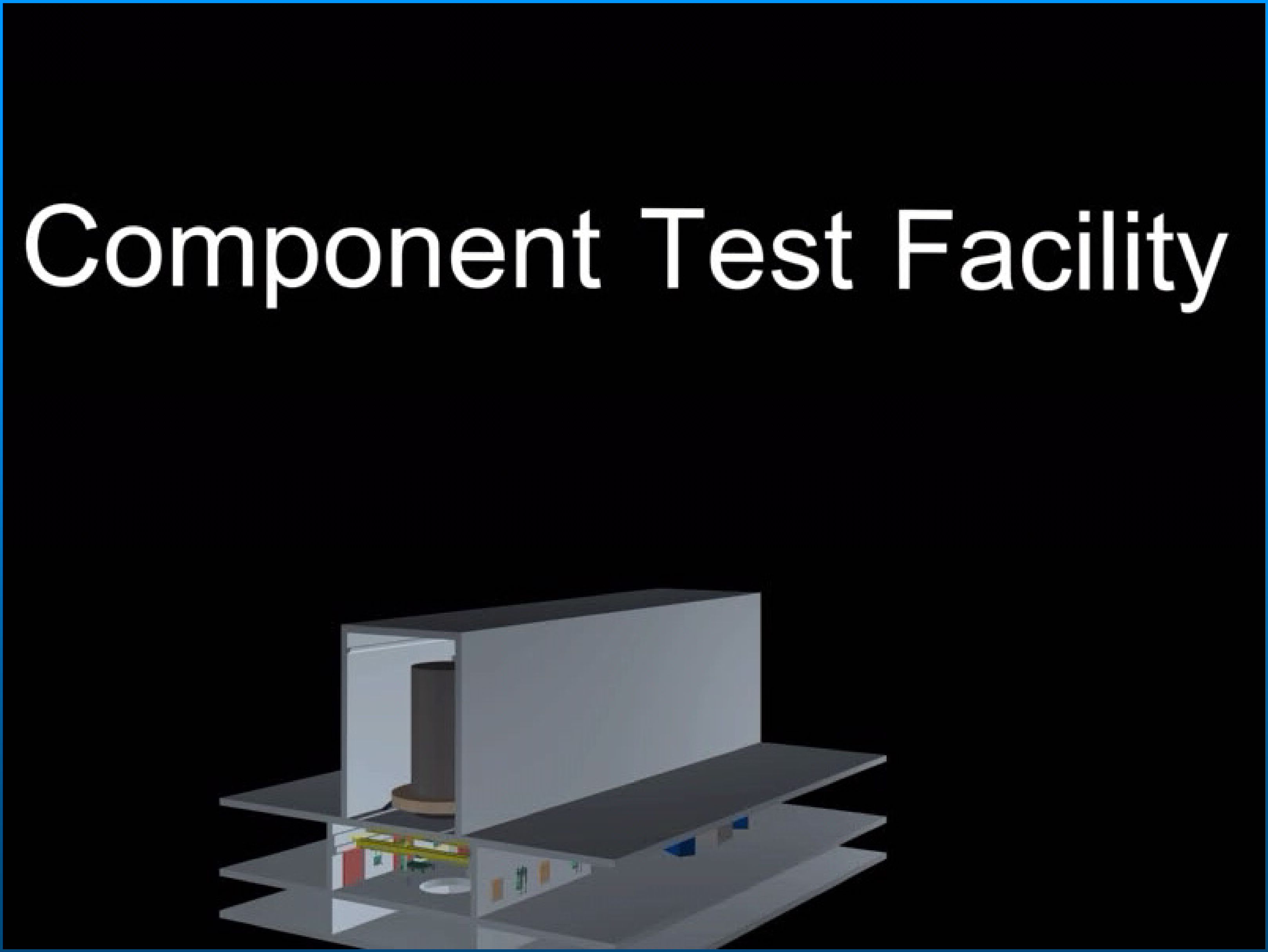
W_L [MW/m^2]	0.1	**1.0**	2.0
R0 [m]	**1.20**		
A	**1.50**		
kappa	**3.07**		
qcyl	4.6	**3.7**	3.0
Bt [T]	1.13	**2.18**	
Ip [MA]	3.4	**8.2**	10.1
Beta_N	**3.8**		5.9
Beta_T	0.14	**0.18**	0.28
n_e [10^{20}/m^3]	0.43	**1.05**	1.28
f_{BS}	0.58	**0.49**	0.50
T_{avgi} [keV]	5.4	**10.3**	13.3
T_{avge} [keV]	3.1	**6.8**	8.1
HH98	**1.5**		
Q	0.50	**2.5**	3.5
P_{aux-CD} [MW]	15	**31**	43
E_{NB} [keV]	100	**239**	294
P_{Fusion} [MW]	7.5	**75**	150
T M height [m]	**1.64**		
T M area [m^2]	**14**		
Blanket A [m^2]	**66**		
$F_{n-capture}$	**0.76**		

ST goal for ITER era requires high duty factor, which drives enduring device features

Features to maximize up-time and minimize down-time

- Cu TF magnet post – has high leverage (simplified, compact, reduced tritium use, modular, highly maintainable, etc.) but requires R&D
- MIC startup solenoid – MgO radiation life under 14-MeV n?
- Continuous NBI –neutralizer particle control, divergence?
- Super-X divertor – 5-6 times lower heat flux
- Minimizing disruptions – how much stability margin?
- Extensive modularity – extendable to normal A?
- Remote handling – large modules, parallel straight motion
- Ex-shield boundary welds & hands on – remains crucial
- Large design margins – tradeoffs in size, cost, reliability
- R&D leverage – which have more benefits to ST goal?

Machine Assembly Animation



Test Blanket Replacement Animation