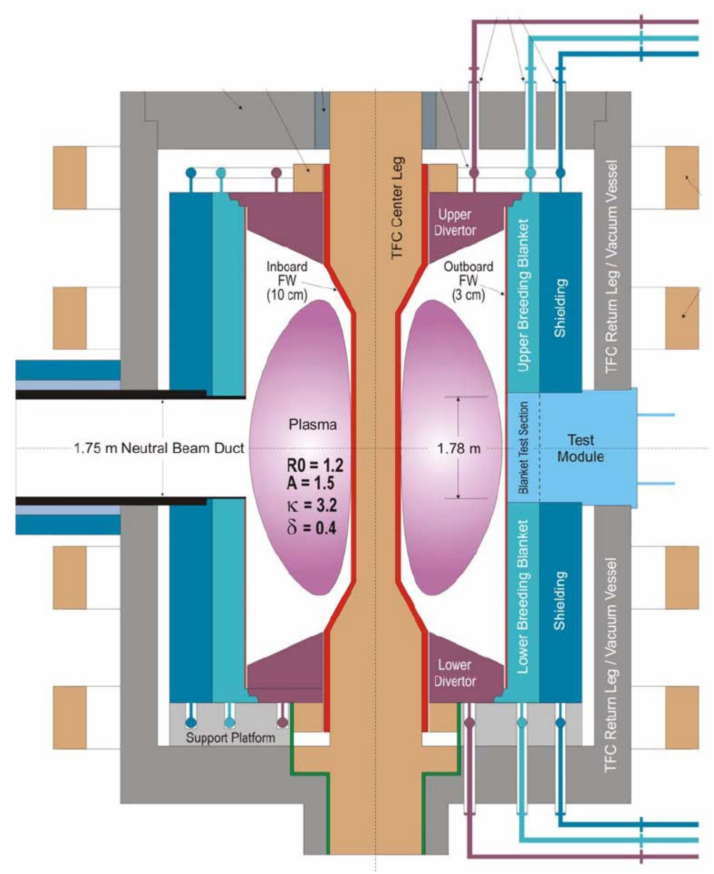
Engineering Assessment and Physics Basis of Spherical Torus Component Test Facility



Y-K Martin Peng, P J Fogarty, D J Strickler,
T W Burgess, J Tsai, B E Nelson
Oak Ridge National Laboratory – UT Battelle

C Neumeyer, C Kessel, D Mikkelsen, J Schmidt,
P Rutherford, J Menard, D Gates,
E Synakowski, L Grisham
Princeton Plasma Physics Laboratory

S Sabbagh
Columbia University

16th ANS Topical Meeting on the Technology of Fusion Energy
Madison, Wisconsin
September 14-16, 2004

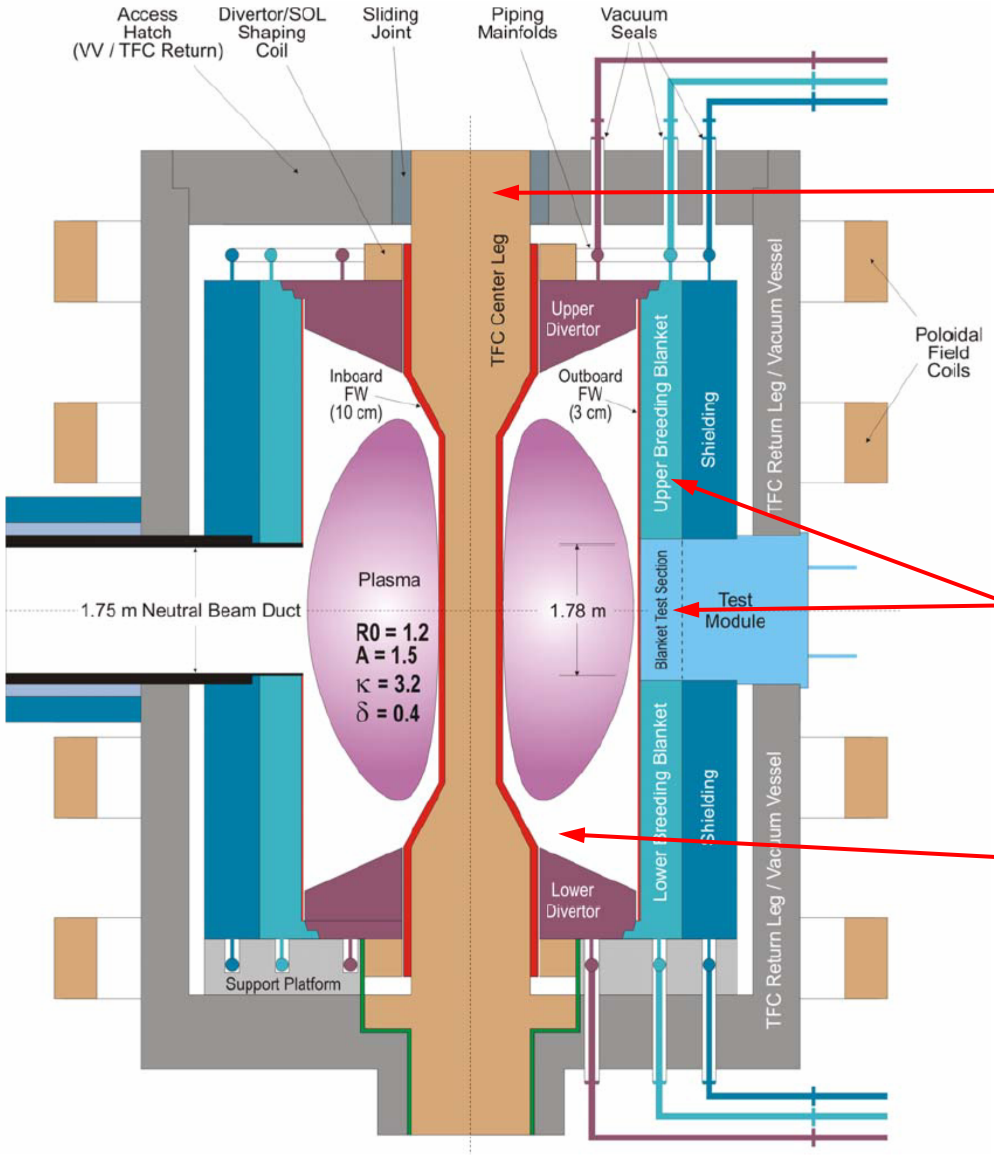
CTF – A Facility for Developing Fusion Engineering Science with Stringent Performance Goals

- The CTF facility will provide the necessary integrated environment to develop fusion engineering science
  - High neutron and surface fluxes (new materials, chamber systems)
  - Steady state burning plasma (plasma control support)
  - Large test area and volume (chamber systems)
  - High neutron fluence (new fusion materials)
- Required performance:
  - 14 MeV $W_L > 1$ MW/m^2, over testing area > 10 m^2 & volume > 5 m^3
  - Fluence > 0.3 MW-yr/m^2 per year
  - 30% duty factor, > 6 MW-yr/m^2 total capability
  - Tolerable net tritium consumption – as small as 10's gm/yr
- This presentation:
  - Programmatic importance
  - Required engineering features
  - Plasma and device parameters based on latest understanding
  - Database needs in physics, engineering, & technology

ST CTF Provides Optimized Configuration to Fulfill Fusion Energy Sciences Program Strategies

- **DOE Office of Science Strategic Plan for Fusion Energy Sciences Program (http://www.science.doe.gov/sub/Mission/Mission_Strategic.htm)**
  - **CTF identified as "Fusion Energy Contingency" in the next decade**
  - **CTF is key tool to achieve Strategic Goal:**
    - **"Develop new materials, components, and components necessary …"**
  - **Preparation in this decade for CTF (NSTX, NSST) addresses additional Strategic Goals:**
    - **"Determine the most promising approaches and configurations …"**
    - **"Develop a fundamental understanding of plasma behavior sufficient …"**
- **ST extends fusion plasma parameters to β_0~1 and A~1**
  - **New data challenge the conventional-A physics basis → ITER**
  - **New physics discoveries Address Overarching Scientific Themes**
    - **"Understand the dynamics of matter and fields …"**
    - **"Create and understand … starfire on earth"**
    - **"Make fusion power practical"**

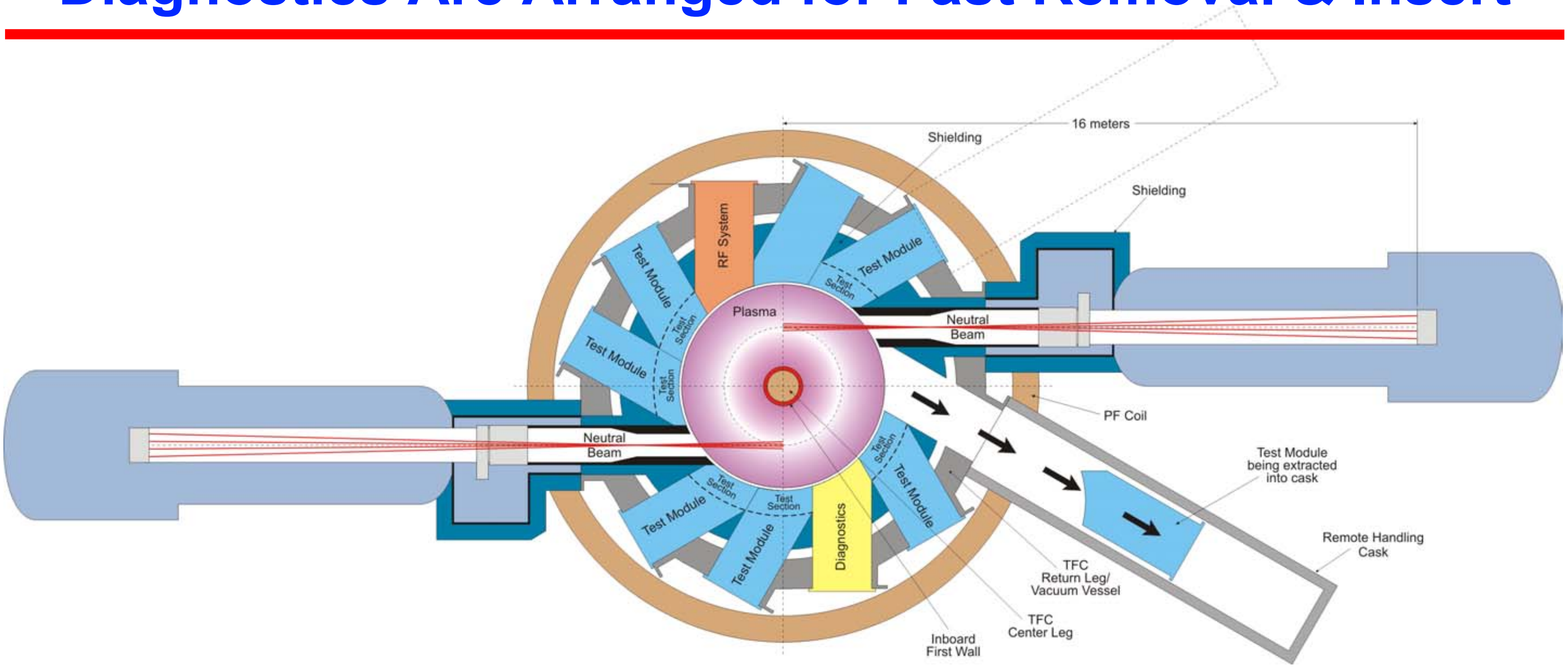
Optimized Device Configuration Features of ST Also Fulfill the CTF Mission Effectively



Features Required by High Duty Factor & Neutron Fluence

- **Single-turn demountable center leg** for toroidal field coil **required** to achieve small size and simplified design.
- **Fast remote replacement** of all fusion nuclear test components (blanket, FW, PFC) & center post **required** to permit high duty factor & neutron fluence.
- **Large blanket test areas** $\propto (R+a)\kappa a$.
- Adequate **tritium breeding ratio** & **small fusion power** from low A **required** for long term fuel sufficiency.
- **High heat fluxes** on PFC.
- Initial core components could use **DEMO-relevant technologies** (such as from ITER and long-pulse tokamaks).
- **12-MA power supply** – Single-turn TF.

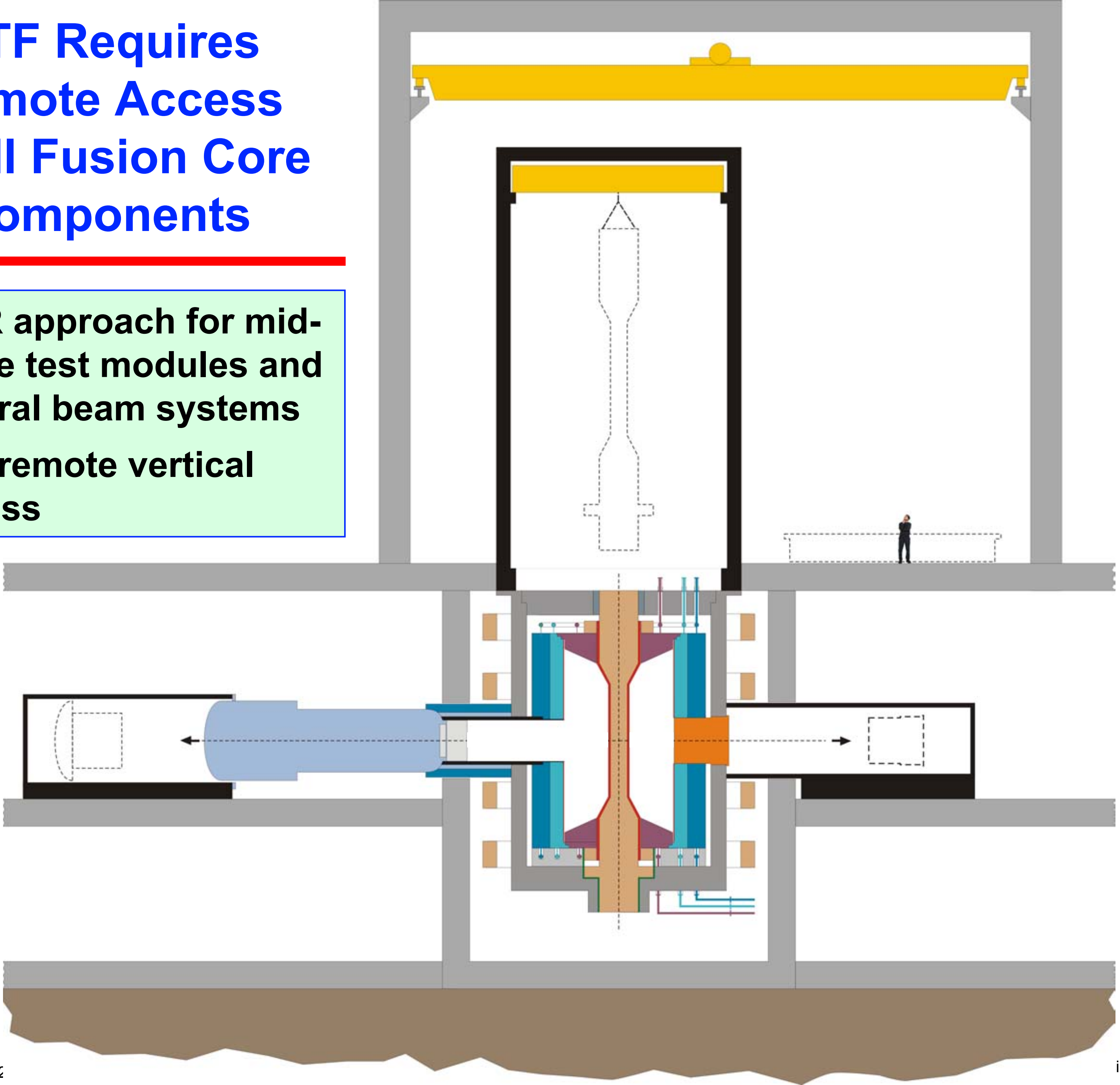
Mid-Plane Test Modules, Neutral Beam Injection, RF, Diagnostics Are Arranged for Fast Removal & Insert



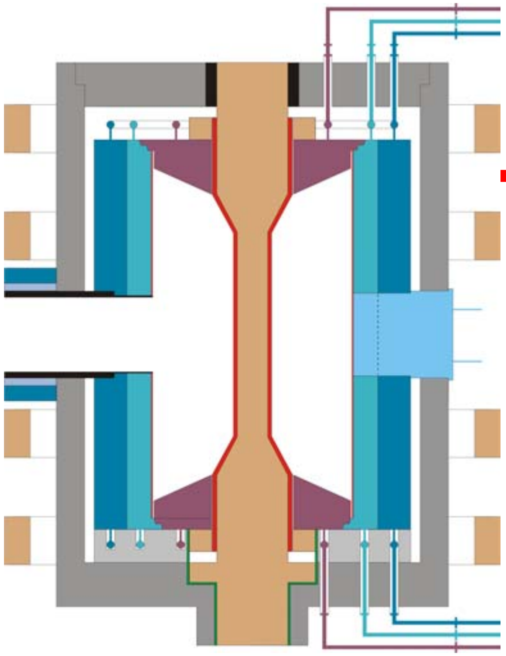
- 8 mid-plane blanket test modules provides ~ 15 m^2 at maximum flux
  - Additional cylindrical blanket test area > 50 m^2 at reduced flux
- 3 m^2 mid-plane access for neutral beam injection of 30 MW
- 2 m^2 mid-plane access for RF (10 MW) and diagnostics
- All modules accessible through remote handling casks (~ITER)

CTF Requires Remote Access to All Fusion Core Components

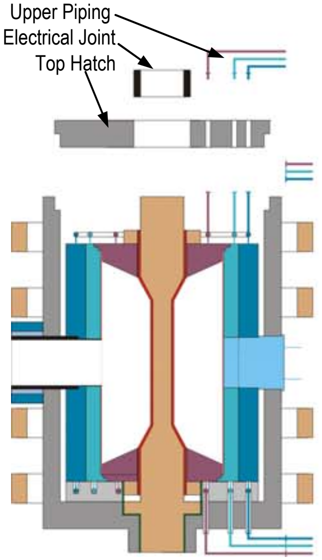
- ITER approach for mid-plane test modules and neutral beam systems
- Full-remote vertical access



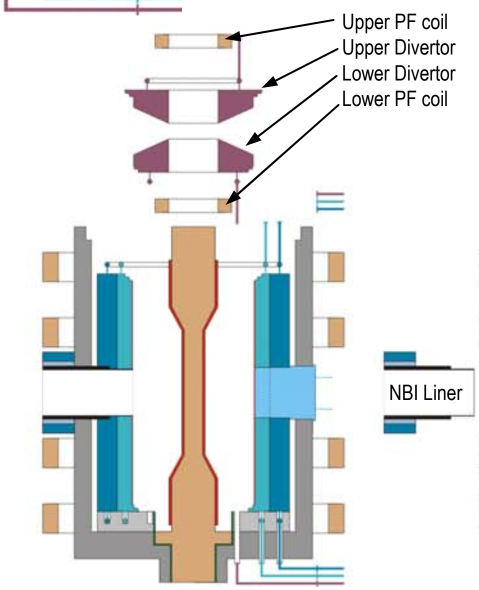
Machine Assembly/Disassembly Sequence Are Made Manageable



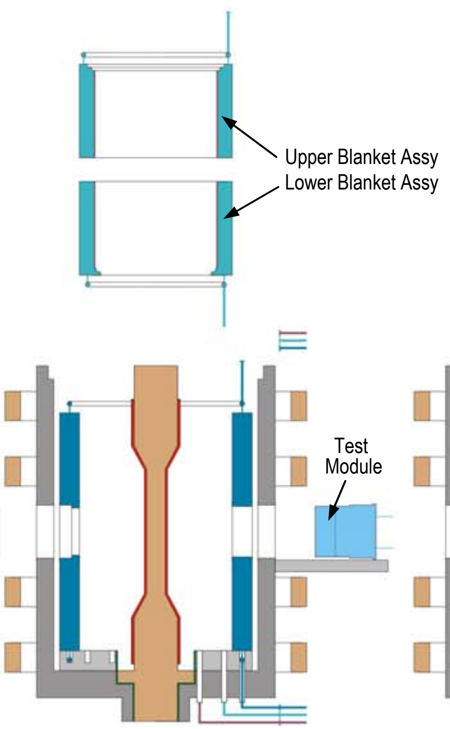
- **Hands-on connect and disconnect service lines outside of shielding and vacuum boundaries**
- **Divertor, cylindrical blanket, TF center leg, and shield assembly removed/installed vertically**



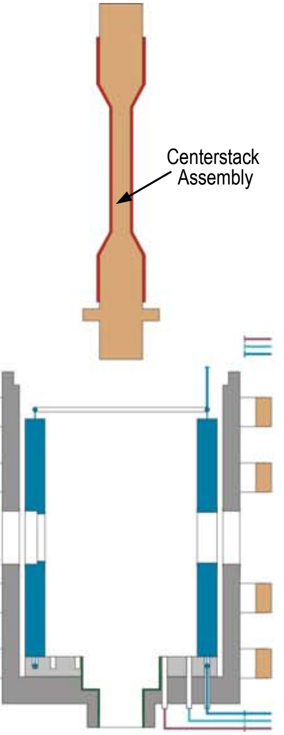
- Disconnect upper piping
- Remove sliding electrical joint
- Remove top hatch



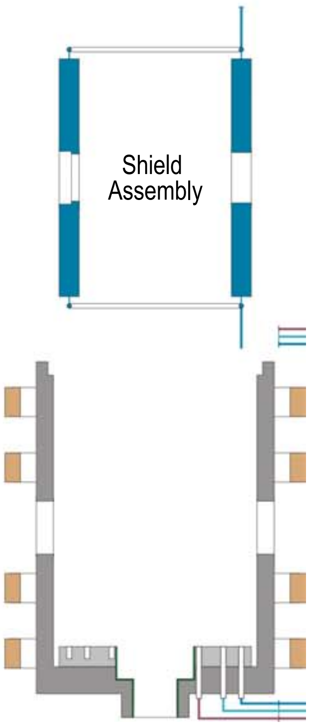
- Remove upper PF coil
- Remove upper divertor
- Remove lower divertor
- Remove lower PF coil



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



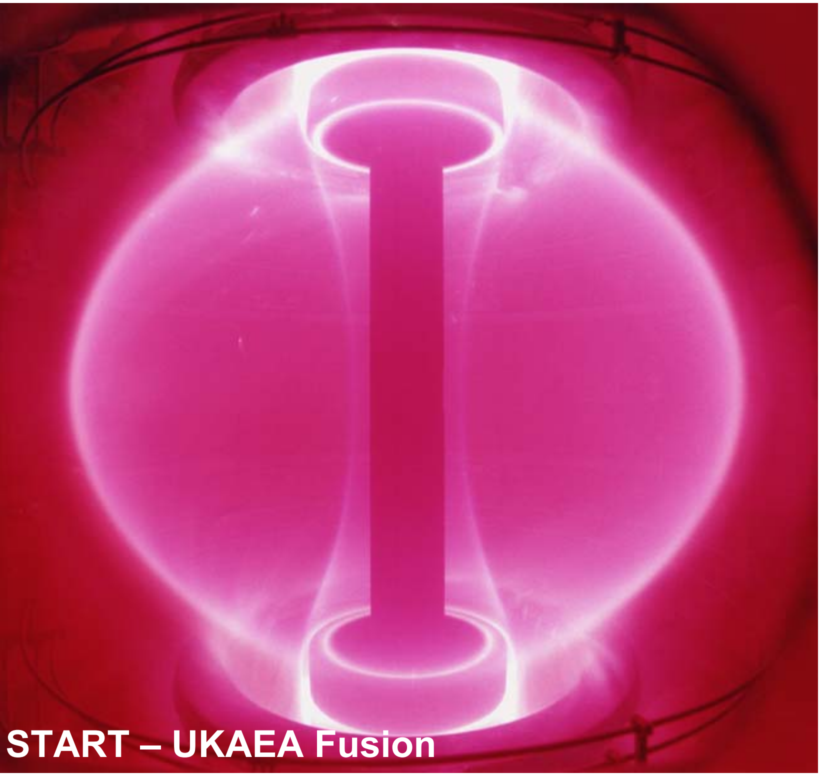
- Remove centerstack assembly



- Remove shield assembly

ST Offers Extended Parameters That Drives Plasma Science and Delivers the Required CTF Performance

New discoveries in extended parameter space challenge and strengthen scientific basis for fusion energy.



START – UKAEA Fusion

Highly efficient utilization of applied field?

- Strong plasma shaping & self fields (vertical elongation ~ 3, $B_p/B_t \sim 1$)
- Very high β_T (~ 40%) & bootstrap current

Contains plasma energy efficiently?

- Small plasma size relative to gyro-radius ($a/\rho_i \sim 30–50$)
- Large plasma flow ($M_A = V_{rotation}/V_A \leq 0.3$)
- Large flow shearing rate ($\gamma_{ExB} \leq 10^6$/s)

Efficient Heating and Current Drive?

- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4–5$)
- High dielectric constant ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$)

Disperses plasma fluxes effectively?

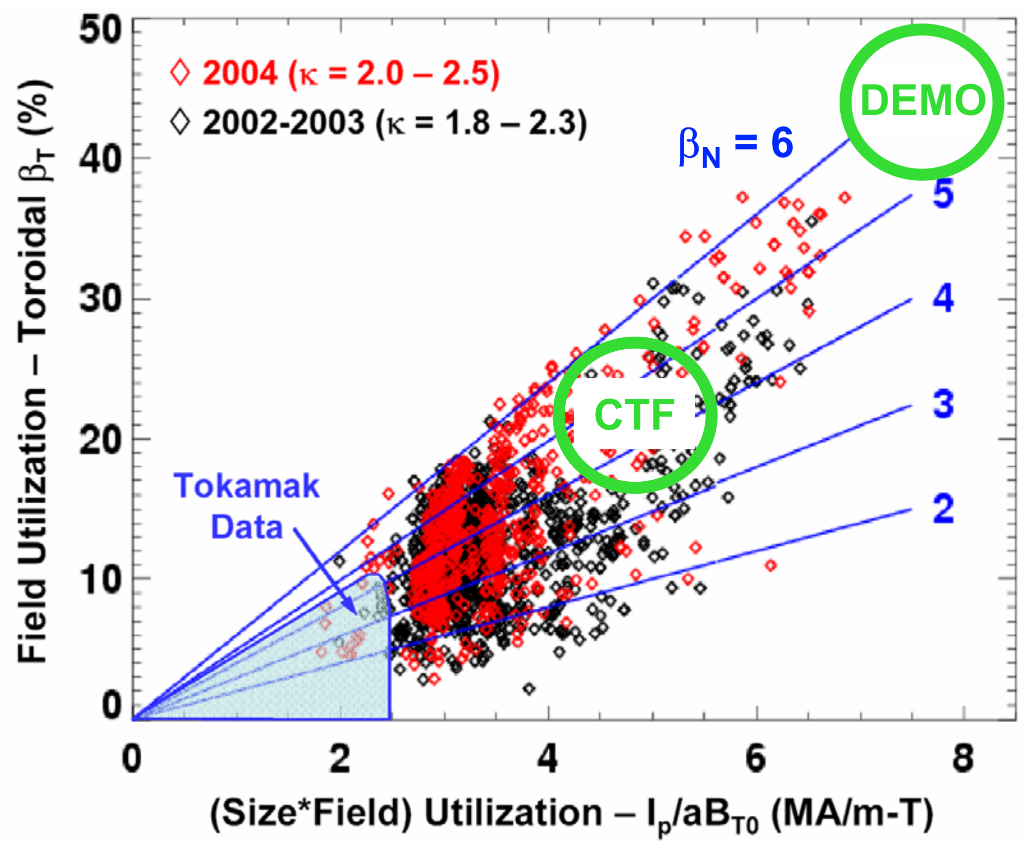
- Large mirror ratio in edge B field ($f_T \rightarrow 1$)
- Strong field line expansion

Allows effective solenoid-free operation?

- Small magnetic flux content ($\sim \ell_i R_0 I_p$)

NSTX Exceeded Standard Scaling & Reached Higher I_p/aB_T, Indicating Better Field and Size Utilization

CTF β requirement well within stability Limits, without using active control



- **Verified very high beta prediction** $\Rightarrow$ new physics:

  $\beta_T = 2\mu_0\langle p\rangle / B_{T0}^2 \leq 38\%$

  $\beta_N = \beta_T / (I_p/aB_{T0}) \leq 6.4$

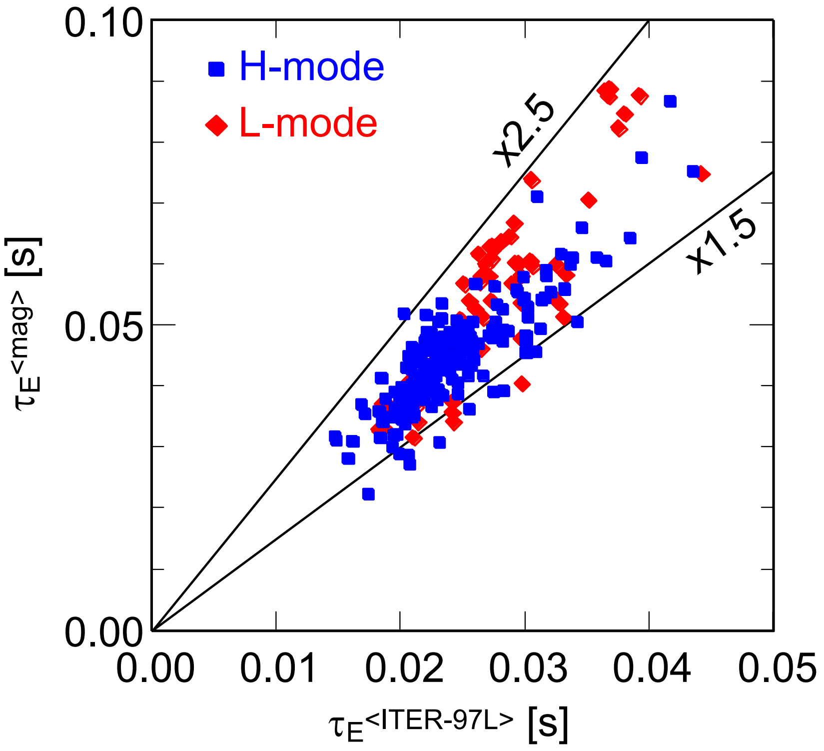
  $\langle\beta\rangle = 2\mu_0\langle p\rangle / \langle B^2\rangle \leq 20\%$

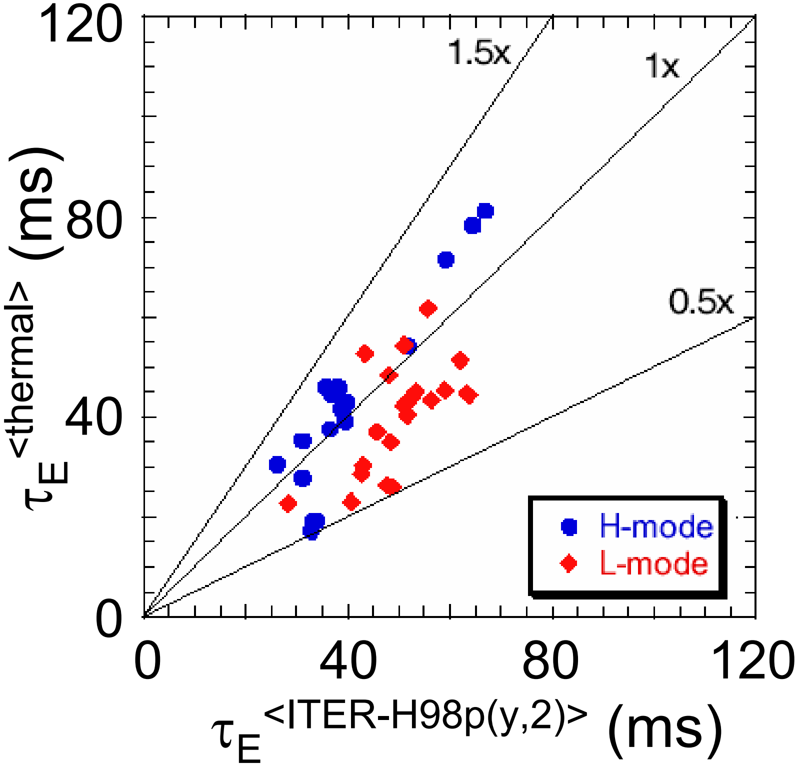
- Obtained nearly sustained plasmas with neutral beam and bootstrap current alone
  - Basis for neutral beam sustained ST **CTF** at Q~2
  - Relevant to **ITER** hybrid mode optimization
- To produce and study full non-inductive sustained plasmas
  - Relevant to **DEMO**

Columbia U, LANL, PPPL

Global and Thermal Energy Confinement Times, τ_E's, Compare Favorably with Conventional-A Database

NSTX



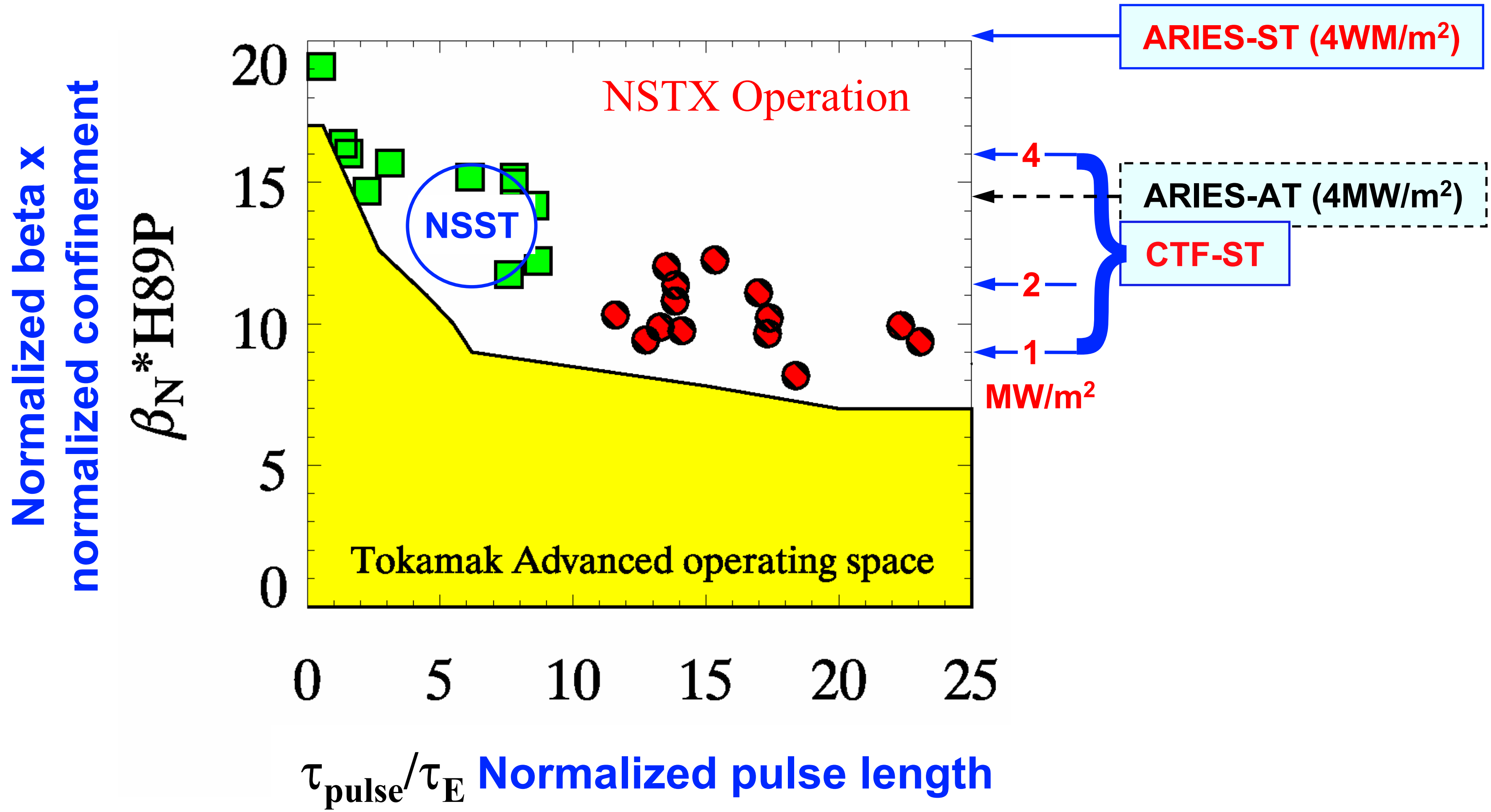


- Compare with ITER scaling for total confinement, including fast ions
- TRANSP analysis for thermal confinement

Discovery: L-mode nearly as good as H-mode

Strong low-A effects challenge the physics basis of conventional-A scaling.

Long-Pulse H-Mode Plasmas Made Large Progress in Physics Basis for Next-Term ST Science Facilities



Well positioned to address the science of sustained high-performance plasmas.

Initial CTF Parameters Are Estimated Based on Latest Understanding of Toroidal Plasma Physics

Plasma Parameters Determined:

- R_0 = 1.2 m, a = 0.8 m, b/a = 3
- B_T = 2.1 T, I_{TF} = 12.5 MA

14MeV neut. flux, MW/m²	**1.0**	**2.0**	**4.0**
Confinement H_{98pby} factor	1.64	1.50	1.35
β_T, %	19	34	**48**
$\beta_N H_{89P}$	9.0	11.3	16
Safety factor, q_{cyl}	3.5	**2.5**	**2.5**
Normal density, n_{GW}	0.16	0.17	0.28
Bootstrap current frac.	0.51	0.43	0.60
I_p, MA	8.8	12.5	12.5
P_{fusion}, MW	77	155	310
P_{NBI}, MW	30	37	72
Beam energy, kV	110	300	300
P_{RF}, MW	6	10	20
Fusion amplification Q	2.1	3.3	3.3
P_{rad} (for **P_{div} = 15 MW/m²**)	50	75	90
Net $T_{consumption}$/yr, gm	5.5	11	83

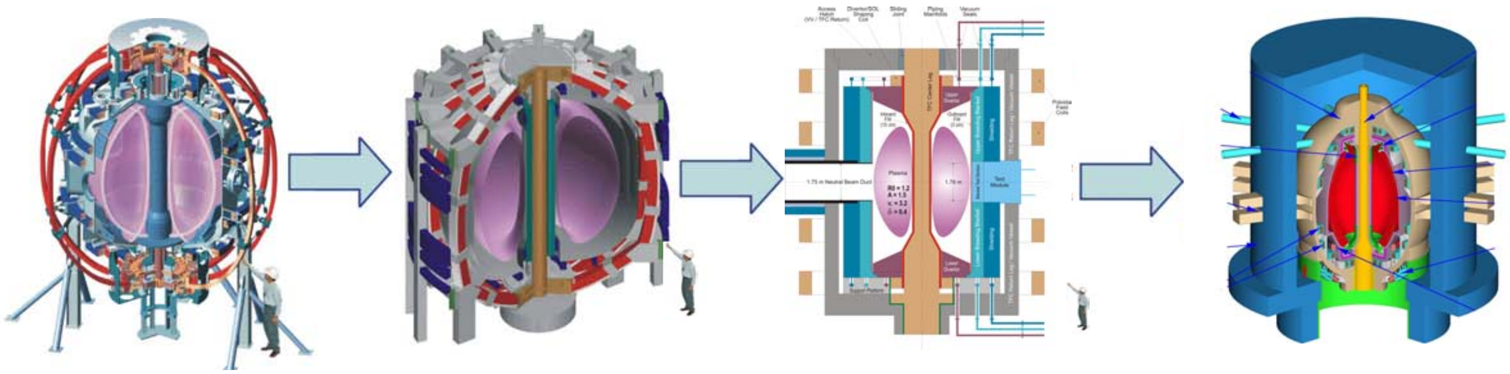
- **Baseline (1 W/m²) parameters well within ST plasma operation limits**
- **Higher neutron fluxes reach progressively more limits**
  - Limits only in β and safety factor
  - Assuming effective edge radiation
  - Requires moderate density << limit
- **Technology & physics of CTF can be advanced in synchrony**
  - 1 MW/m² – moderate ST physics, test beyond ITER technologies
  - 2-4 MW/m² – toward DEMO level
- **Low-A enables close approach to tritium self-sufficiency**
  - Line-of-sight fusion neutron absorption on TF center leg
  - ~80% neutron capture & breeding by outboard blanket, TBR = 1.2
  - 30% duty factor

As a Engineering Science Test Facility, CTF Requires Well-Established ST Physics at Multi-MA Current

- **How to introduce plasma magnetic flux without solenoid induction?**
  - How to initiation ~1 MA? (RF, CHI & outer magnetic coils)
  - How to ramp-up to multi-MA, and sustain current in overdense plasmas? (RF, NBI & Bootstrap)
- **How do plasma energy, particle, and momentum get lost from plasma?**
  - How to maintain large plasma spin, shown to be important?
  - How to ensure $T_i >> T_e$, for neutral beam dominated plasmas?
  - Does high β cause large differences for plasma turbulence & loss?
- **How do EM waves and supra-Alfvénic ions interact with plasmas?**
  - E_{beam}/T (NSTX) ~ E_{beam}/T (ITER) ~ 50
  - $V_{beam}/V_{Alfvén}$ (NSTX) ~ $V_{alpha}/V_{Alfvén}$ (CTF) ~ 4

  } new Alfvén modes?
  - Electron Bernstein Wave has great potential for ST; data needed.
- **How does large in/out asymmetry of edge help disperse plasma flux?**
  - Which edge configuration works best: double-null, single-null, inboard limited?

Physics Data Needed by CTF Will Shape NSTX Research and Next Step Spherical Torus (NSST)



Device	**NSTX**		**NSST (SC plan)**		**CTF (SC plan)**		**DEMO**
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.4		~3.2, ~0.4
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~9	~12	~25
B_T (T)	**0.6**	**0.3**	**~1.1**	**~2.6**	~2.1		~1.8
Pulse (s)	**1**	**5**	**~50**	**~5**	**Steady state**		Steady state
P_{fusion} (MW)	–		**~10**	**~50**	**~77**	**~300**	~3100
W_L (MW/m^2)	–		–		**~1**	**~4**	~4
Duty factor (%)	~0.01		~0.01		**~30**	**30**	60
TFC; Solenoid	Multi-turn; Solenoid		Multi-turn; Solenoid		Single-turn; No-solen.		Single-turn; No-solen.

CTF Control Technology Support Are Defined – Some Satisfied within Present Fusion Program Plans

To Achieve Baseline Performance (1 MW/m^2)

- **TF system engineering**
  - TF center leg optimization and fabrication technology
  - Multi-MA, low-voltage TF power supply
- **Plasma facing components (~ITER)**
  - Highly reliable and remotely replaceable divertor components (large MTBF and small MTTR)
  - Take advantage of DEMO-relevant ITER designs
- **Heating, current drive, and fueling (~ITER)**
  - 300 kV negative ion beam under development by LHD, JT60U
  - EBW at ~110 GHz being developed and used
  - Highly reliable and remotely replaceable RF launchers
- ***Requires database from long-pulse high performance tests (Tore Supra, KStar, LHD, ITER, test stands, etc.) to raise MTBF***

ST CTF Has Attractive Physics and Engineering Features to Enable Cost-Effective Fusion Development

- **CTF, a user facility for fusion engineering science, demands stringent fusion plasma performance**
- **ST CTF provides optimized configuration to fulfill CTF mission and Fusion Energy Sciences Program Strategies**
- **ST extends the toroidal parameter space, challenges conventional-A science, and delivers the required CTF performance**
- **Recent discoveries in ST research already proved several estimated CTF plasma conditions**
- **Steady State ST CTF design concept with R_0 ~ 1.2 m is estimated to satisfy baseline performance goals (1 MW/m^2), with potential to reach DEMO-level testing (4 MW/m^2)**
- **Additional ST physics data needs are identified and will shape present and next step research agenda**
- **CTF control technology support are identified, some within present fusion program plans**

Costing for CTF (W_L=1 MW/m^2, $A_{test} \geq 10$ m^2) – I (in 2002 M\$)

SuperCode Costing Components	R_0=1.2m A= 1.5	Comments
1. Toroidal Device	**193**	
– TF magnets	38	
• *TFC center post*	*(12)*	$U_{TFcenter}$ = 0.075/ton (single-turn cooled GlidCop)
• *TFC outer magnet (VV)*	*(26)*	$U_{TFouter}$ = 0.03/ton (single-turn Al, combined with VV)
– PF magnets	50	U_{PF} = 0.058/ton (no OH solenoid)
– Device structure	11	U_{MS} = 0.052/ton
– Vacuum vessel	0	Combined with TFC outer conductor
– Blanket modules	10	ITER-FEAT: 220; FIRE (reflector): 19*; CTF: basic T-breeding blankets cost 1/3 of advanced test blankets**
– Device, penetration shielding	43	
– Divertor, PFCs	29	ITER-FEAT: 109; FIRE: 42; CTF: U_{Div} = 1.61/m^2
– Fueling	12	ITER-FEAT: 10; FIRE: 9
2. Device Ancillary Systems	**187**	
– Machine assembly tooling	29	ITER-FEAT: 72; FIRE: 0; CTF only: $\propto R^{3/4}$
– Remote handling equipment	152	ITER-FEAT: 145, FIRE: 101; CTF only: requires high duty factor RH operation, $\propto R^{1/2}$
– External cryostat	0	
– Primary heat transport	6	$U_{PHT} = \$72.3/W^{0.7}$
– Thermal shield	0	
3. Tokamak Gas & Coolant Systems	**88**	
– Vacuum	19	ITER-FEAT: 37; FIRE: 14; CTF only: $\propto R^{1/4}$
– Tritium (and fuel) handling	41	ITER-FEAT: 104; FIRE: 9; CTF only: $\propto P_F^{1/2}$
– Aux heat transport	8	$U_{AHT} = \$33.9/W^{0.7}$
– Cryogenic plant	0	
– Heat rejection	8	
– Chemical control	12	

* ITER-FEAT-FIRE Cost Comparison, Fusion Study 2002, Snowmass; ** Comments by M. Abdou, B. Nelson

Costing for CTF (WL=1 MW/m^2, $A_{test} \geq 10\ m^2$) – II (in 2002 M$)

SuperCode Costing Components	**R_0=1.2m** **A=1.5**	**Comments**
4. Power Supplies & Control	**120**	
– Magnet power supplies	63	
• *Resistive TFC*	*(52)*	U_{TFC} = 0.4/MW (4X conventional power supply)
• *Resistive PFC*	*(11)*	U_{PFC} = 0.13/MVA
– Heating system power supplies	0	Included in heating systems costs
– Site electric plant, transformers, etc.	21	ITER-FEAT: 38; FIRE: 18
– Device operational I&C	36	ITER-FEAT: 72; FIRE: 23
5. Heating, Current Drive, Diagnostics	**210**	
– ECH-EBW	40	8, 10 MW @ 100 GHz, 12 MW @ 200 GHz (ITER-FEAT: 111)*
– NBI	125	30, 33, 34 MW at ~ 400 kV (ITER-FEAT: 138)
– LH	0	
– Plasma operational I&C	45	ITER-FEAT: 214; FIRE: 29
6. Site, Facilities and Equipment	**252**	
– Land, site improvement	0	Government site
– Buildings	180	ITER-FEAT: 546; FIRE: 126
– Hot cell	0	Included in Buildings
– Radwaste management	38	ITER-FEAT:12; FIRE: 11 (CTF requires FNT testing at high duty factors, substantially increasing radwaste)
– Coolant supply and disposal	18	ITER-FEAT: ?; FIRE: 18
– General test and qualification	16	(CTF requires acceptance verification of all incoming test components.)
– Magnet fabrication tools	0	
Total Construction Cost, no Contingency	**1,050**	
with 40% Contingency	**1,470**	Included in the ST development cost

* Comments by D. Rasmussen, R. Temkin