JP1.004

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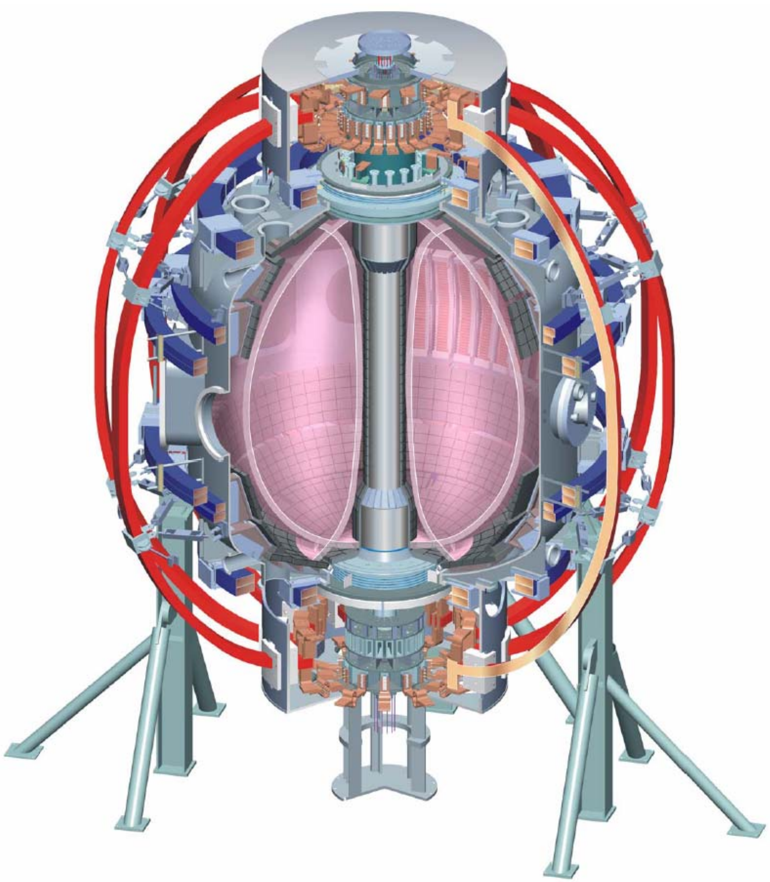
# NSTX Physics Progress toward Sustained High-Performance Plasmas of CTF



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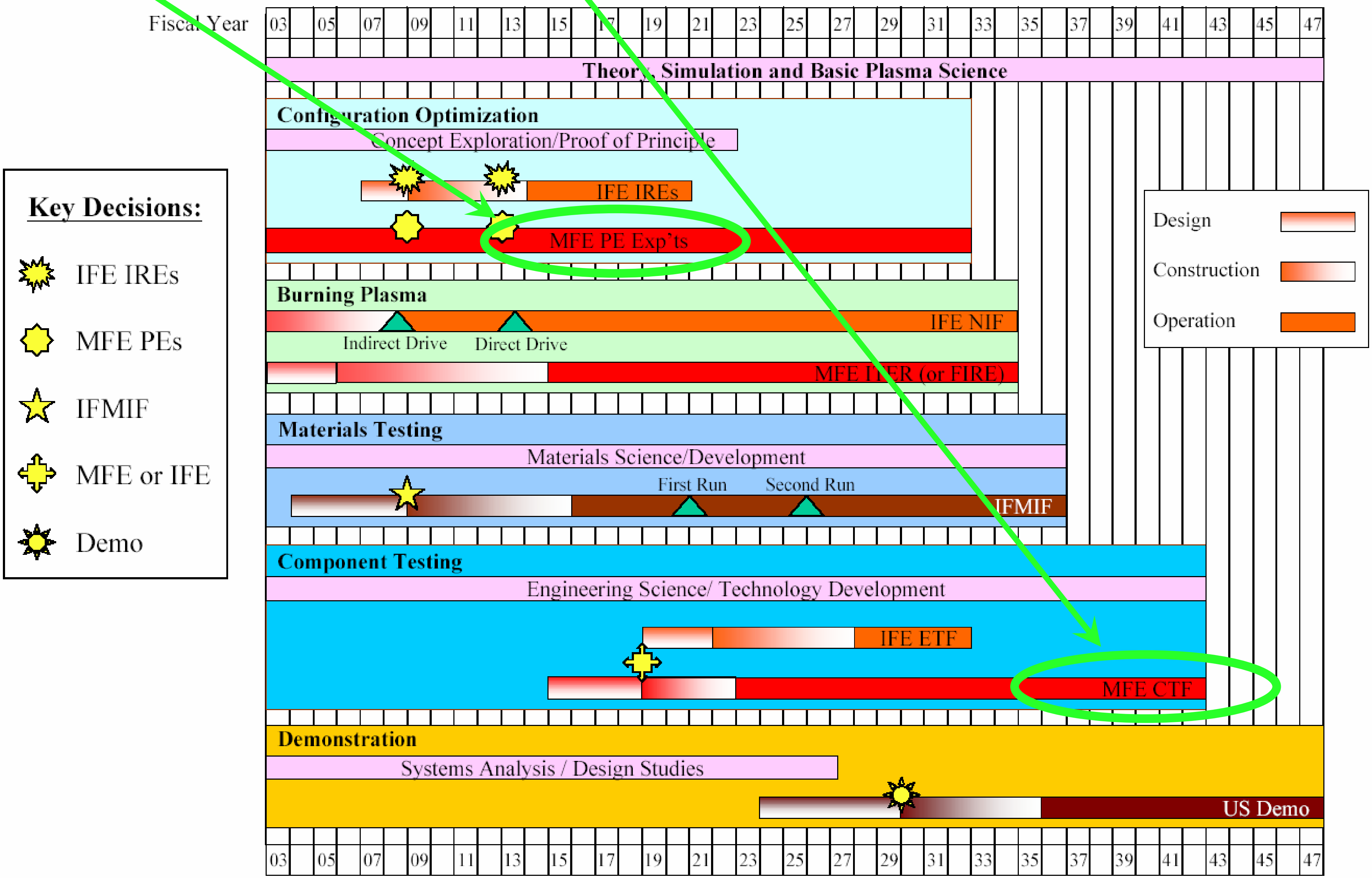
Savannah, GA

# 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 $MW\text{-}yr/m^2$ per year
  - 30% duty factor, > 6 $MW\text{-}yr/m^2$ total capability
  - Test tritium self-sufficiency – goal: net consumption ~ 10's g/yr
- **This presentation:**
  - Programmatic importance
  - Required engineering features
  - Plasma and device parameters based on latest phys understanding
  - Database needs in physics, engineering, & technology

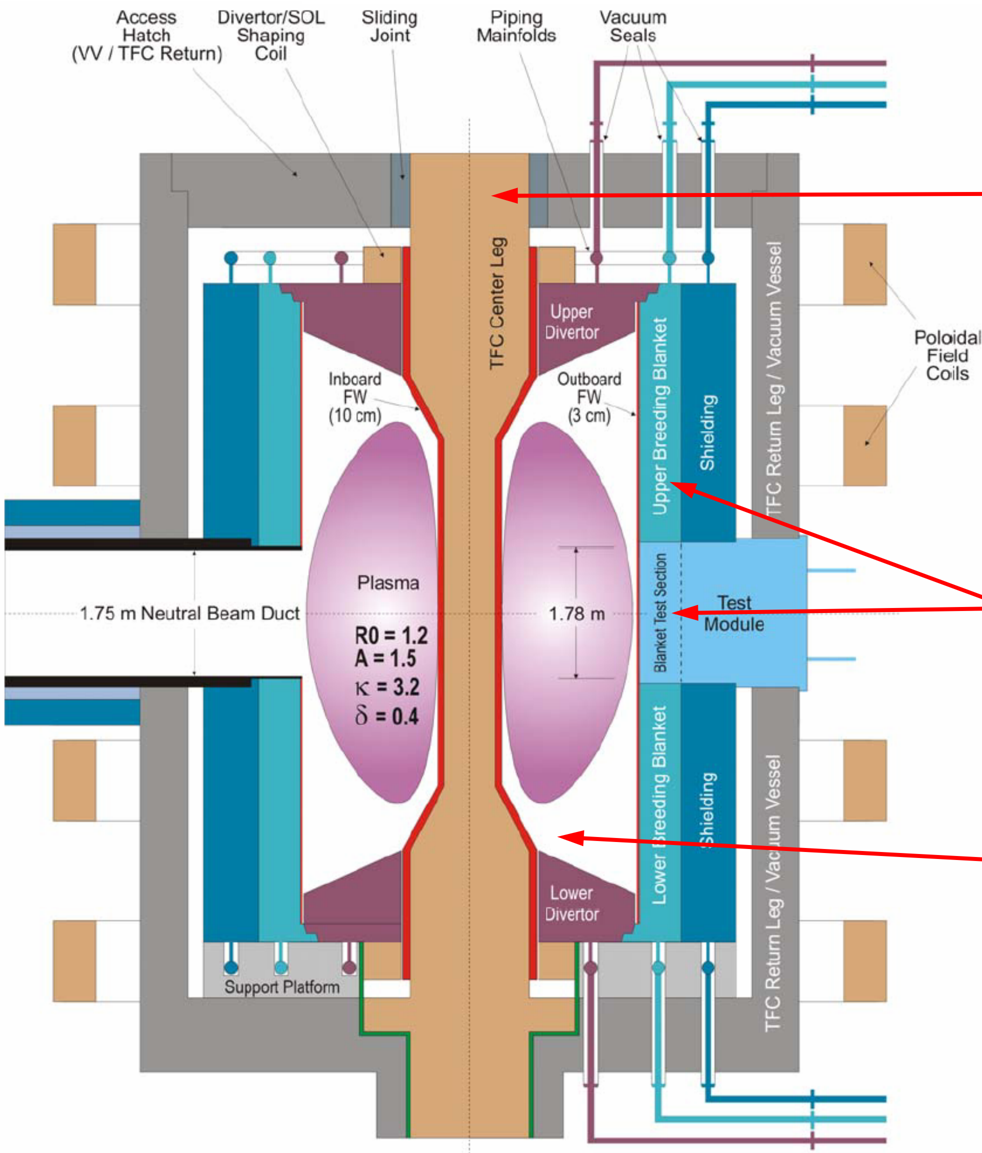
# ST Offers Strong Candidate for MFE Performance Extension (PE) Experiment and CTF (FESAC Panel – Goldston, 2003)



# 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 $\beta_0$~1 and A~1
  - New data challenge the conventional-A physics basis $\rightarrow$ 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"

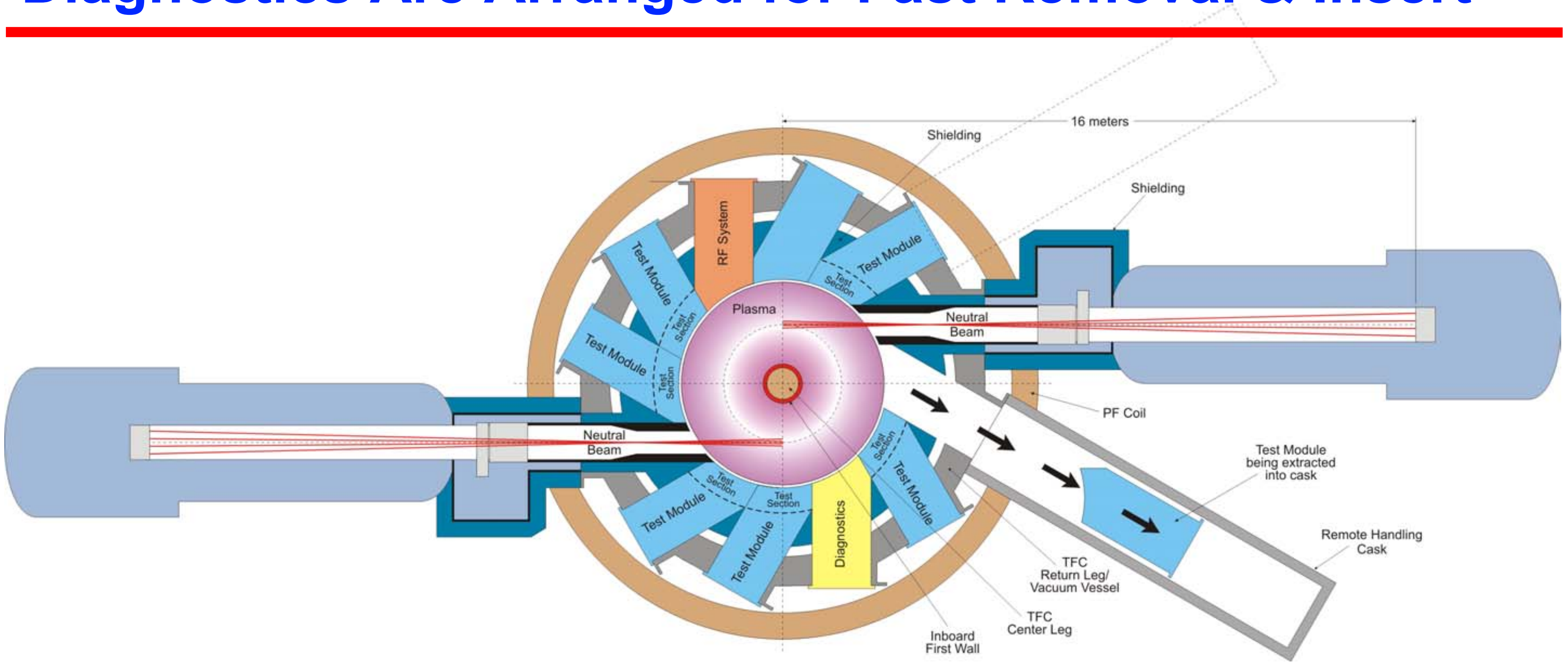
# Optimized Device Configuration Features of ST Also Fulfill the CTF Mission Effectively




## 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.

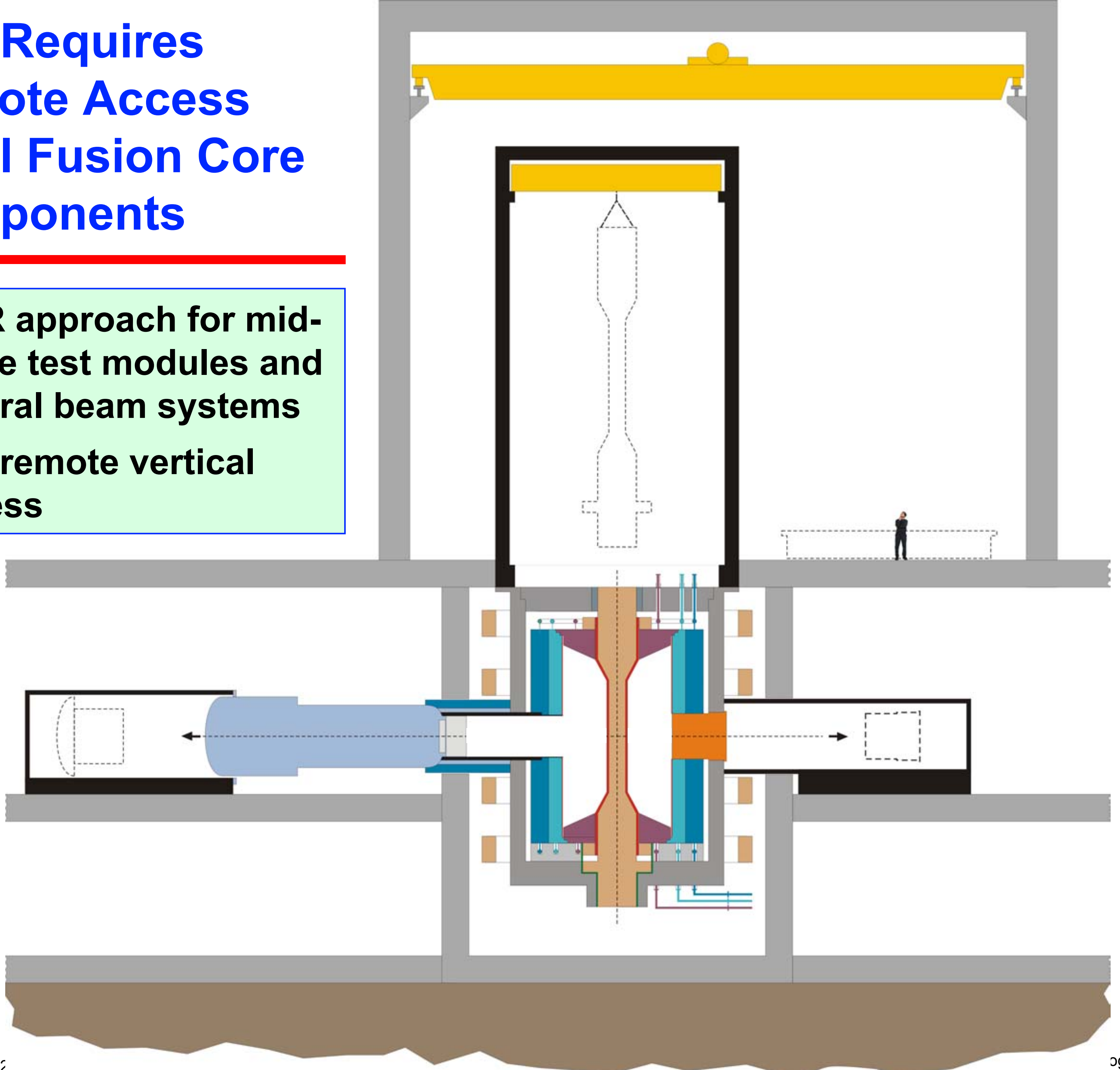
# Mid-Plane Test Modules, Neutral Beam Injection, RF, Diagnostics Are Arranged for Fast Removal & Insert



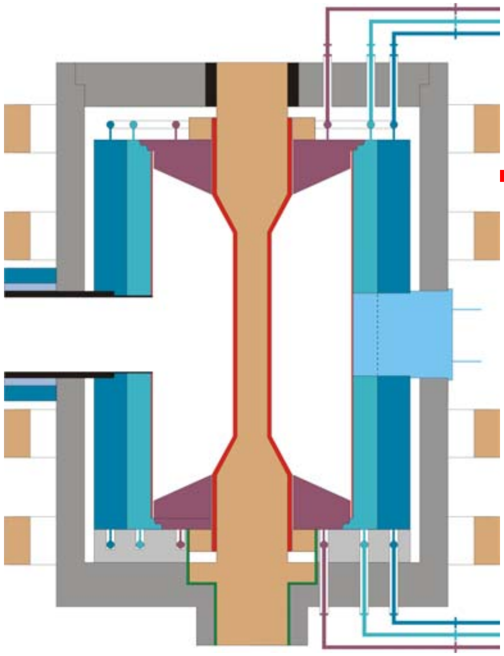

- 8 mid-plane blanket test modules provides ~ 15 m$^2$ at maximum flux
  - Additional cylindrical blanket test area > 50 m$^2$ at reduced flux
- 3 m$^2$ mid-plane access for neutral beam injection of 30 MW
- 2 m$^2$ mid-plane access for RF (10 MW) and diagnostics
- All modules accessible through remote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

# CTF Requires Remote Access to All Fusion Core Components

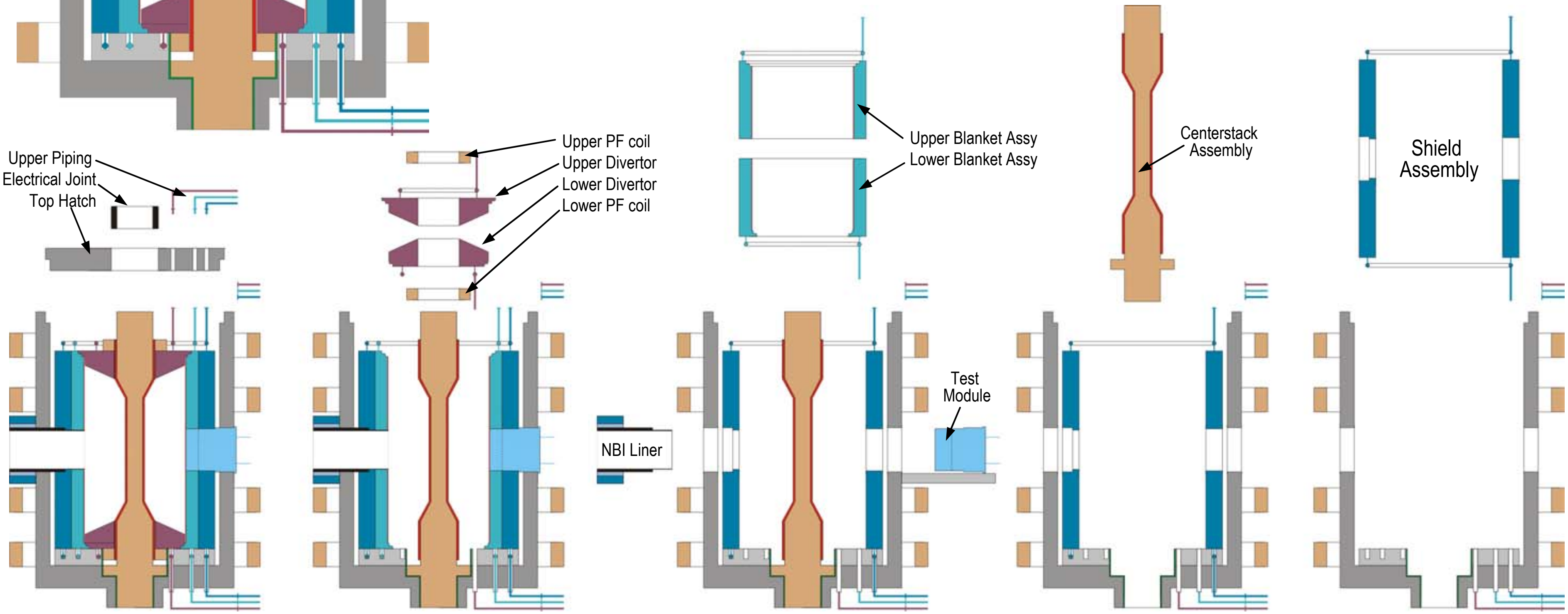
- ITER approach for mid-plane test modules and neutral beam systems
- Full-remote vertical access



# 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

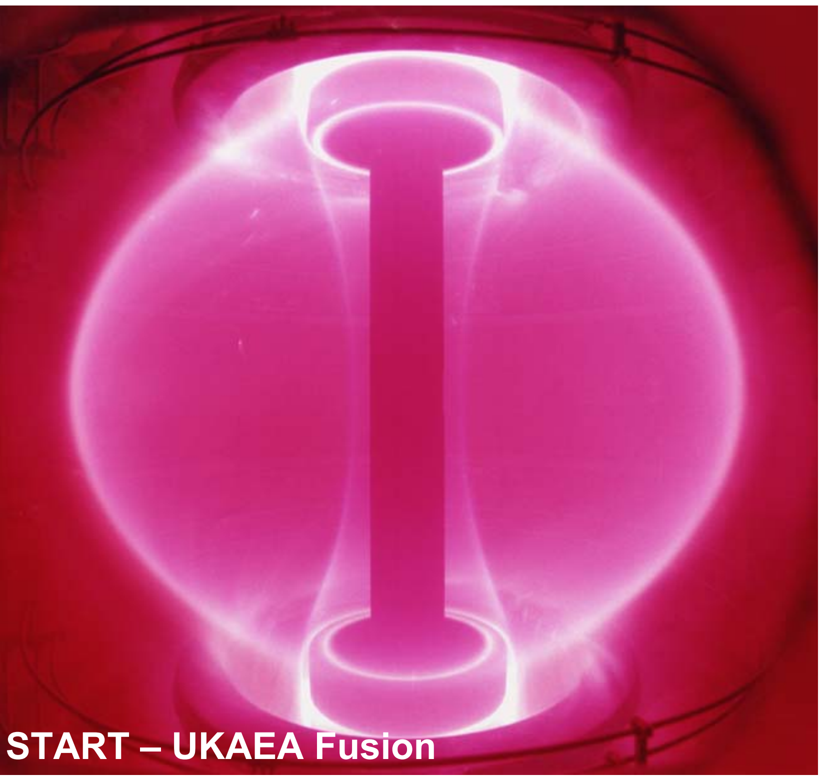
- Extract NBI liner
- Extract test modules
- Remove upper blanket assembly
- Remove lower blanket assembly

- Remove centerstack assembly

- Remove shield assembly

# ST Physics Delivers the Required CTF Performance

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




**Highly efficient utilization of applied field**

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

**Contains plasma energy efficiently**

- Small plasma size relative to gyro-radius ($a/\rho_i$~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**

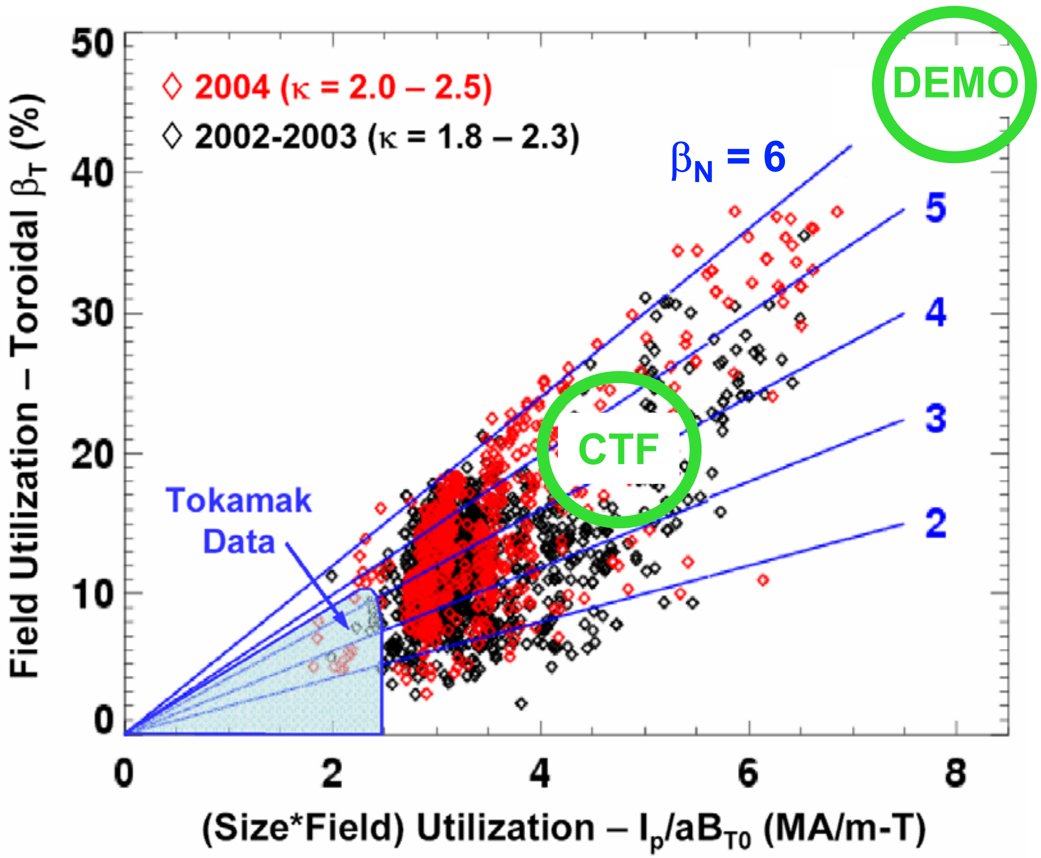
- Large mirror ratio in edge B field ($f_T \rightarrow 1$)
- Strong field line expansion

**Allows effective solenoid-free operation**

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

# 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




VO/2-3, Kaye et al

- **Verified very high beta prediction** ⇒ new physics:

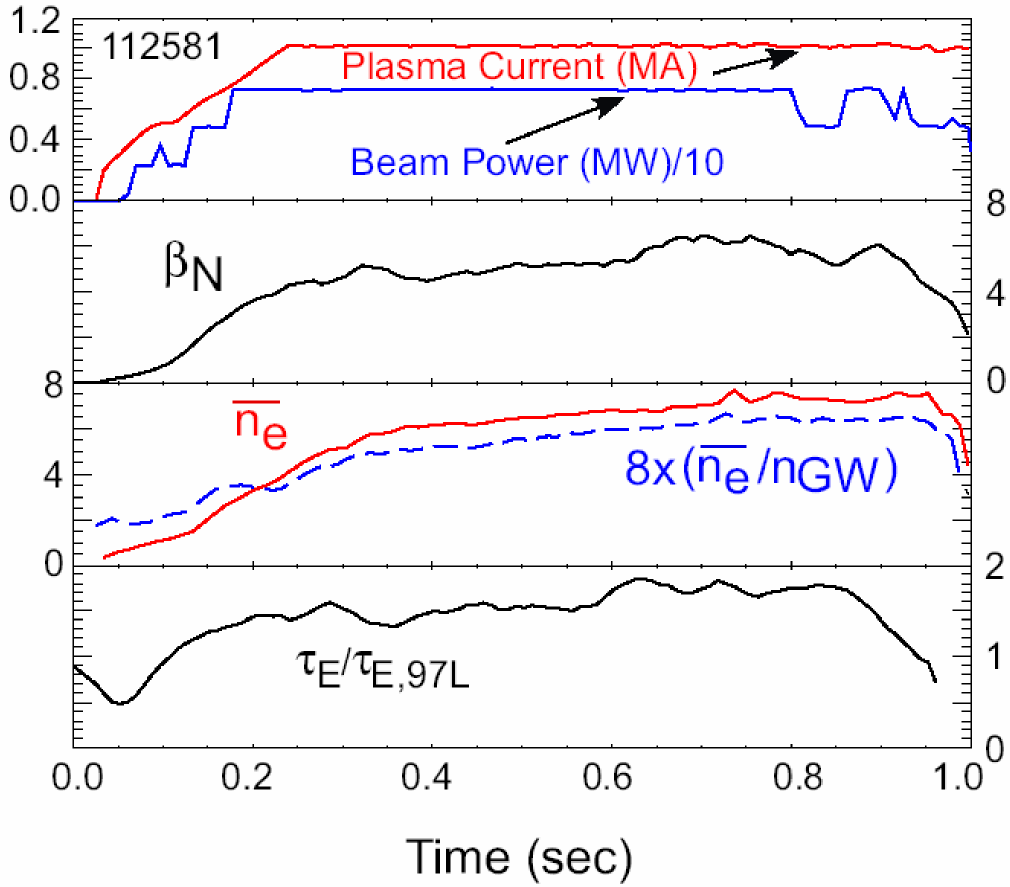
  $\beta_T = 2\mu_0\langle p\rangle / B_{T0}^2 \leq 38\%$

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

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

- Approaching 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**

# NSTX Has Made Significant Progress Towards Goal of High-$\beta_T$, Non-Inductive Operation

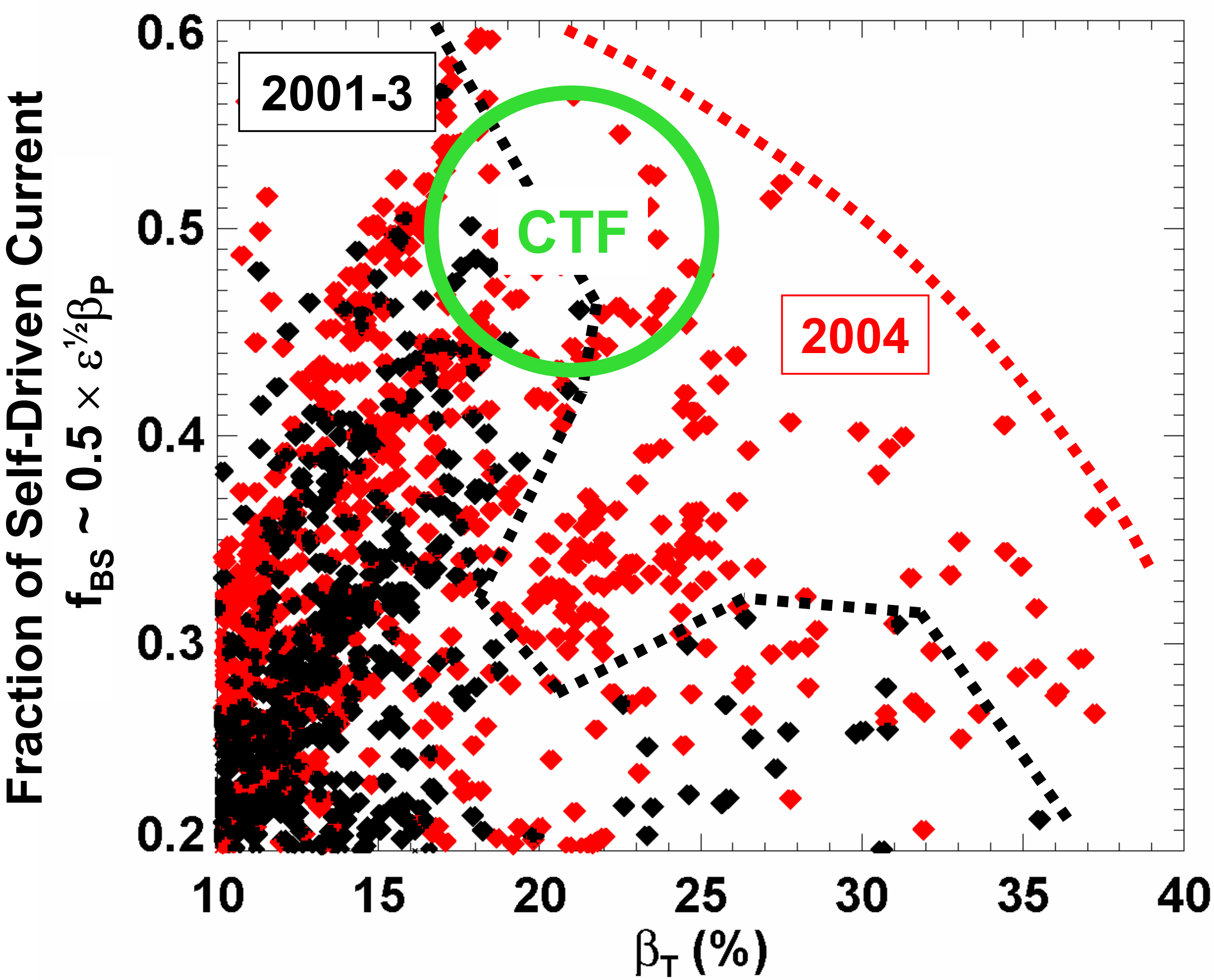



- $\tau_{Ip\ flattop} \sim 3.5\tau_{skin}$
- $\tau_{W\ flattop} \sim 10\ \tau_E$
- $\beta_T$>20%, $\beta_N$>5
- $\tau_E/\tau_{E,L}$>1.5 for ~10 $\tau_E$

# 2004 Progress on NSTX Also Covered CTF Level of Sustained Plasmas

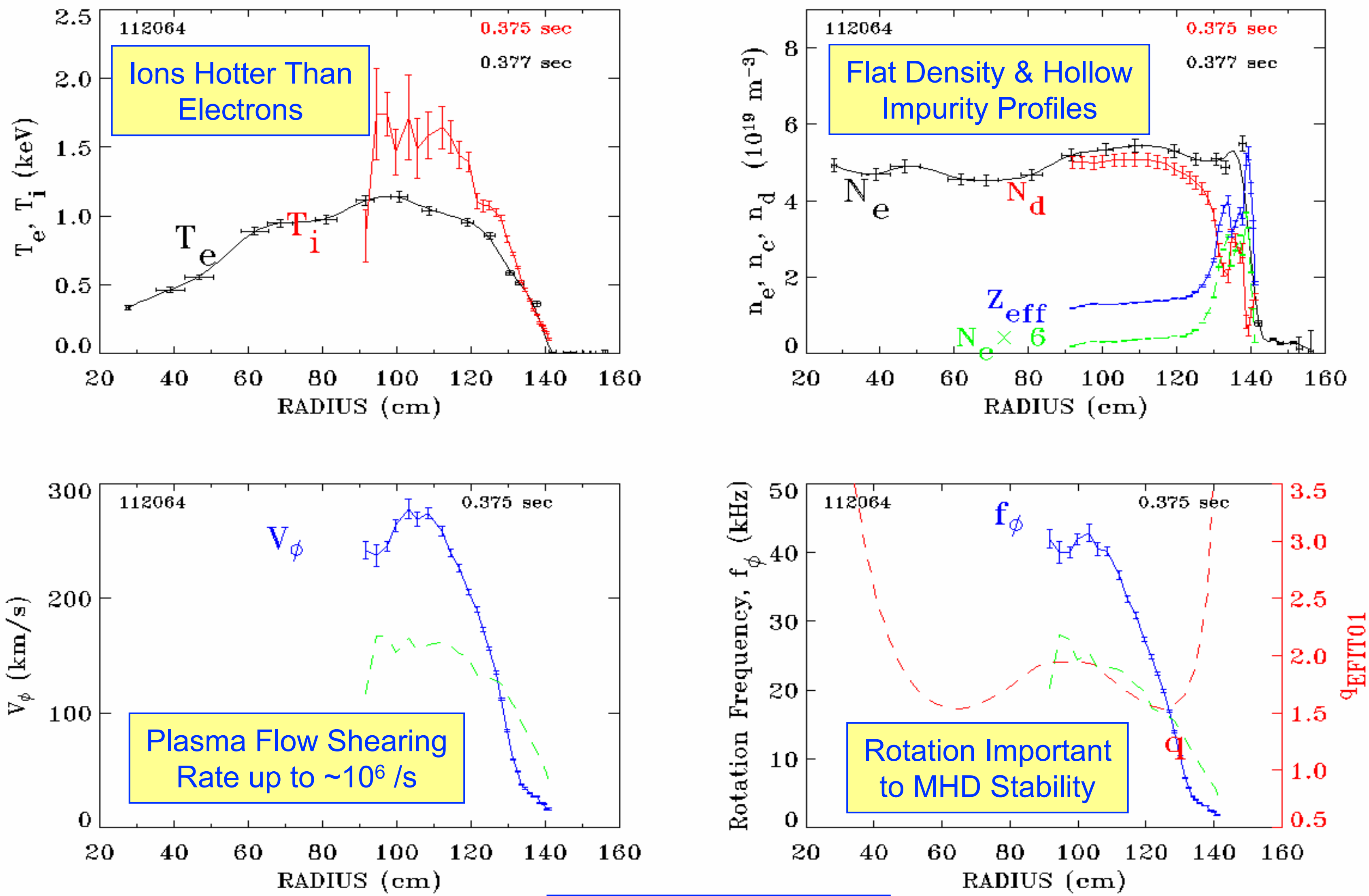
DEMO

NSTX



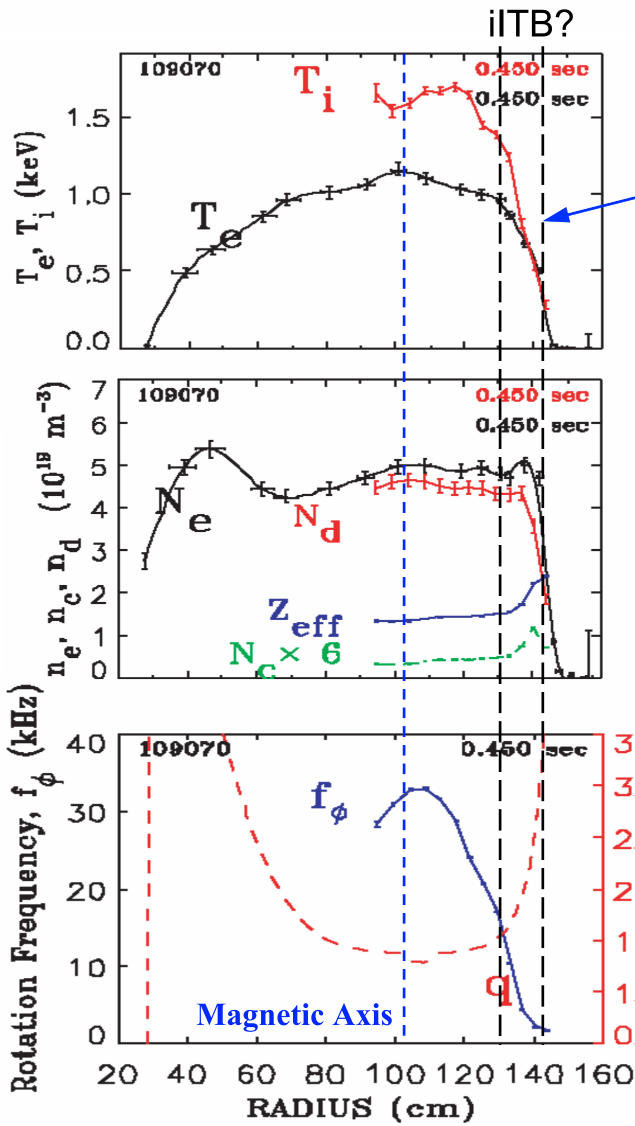

- EFIT02
- Peak $\beta_T$
- **All shapes**

# Measurements & Analysis of Plasma Profiles Provide Basis for Projections



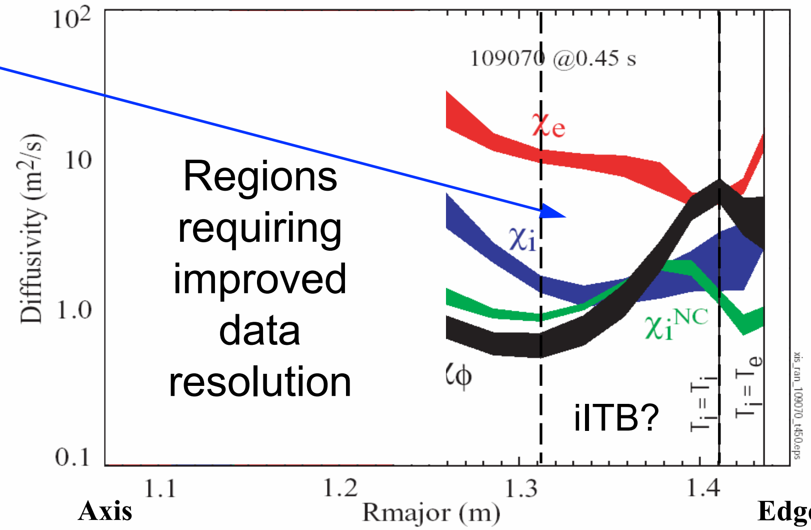

**_EX/P2-26, Menard et al_**

# Ion ITB in NBI-Heated H-Mode Contrasts with Improved Electron Confinement in L-Mode

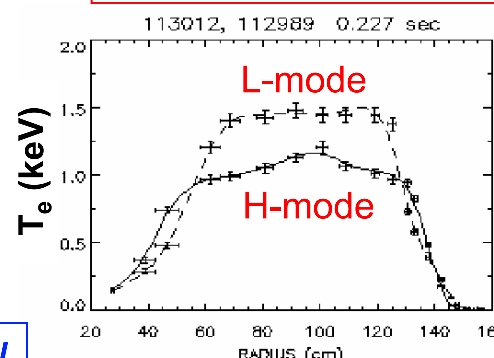


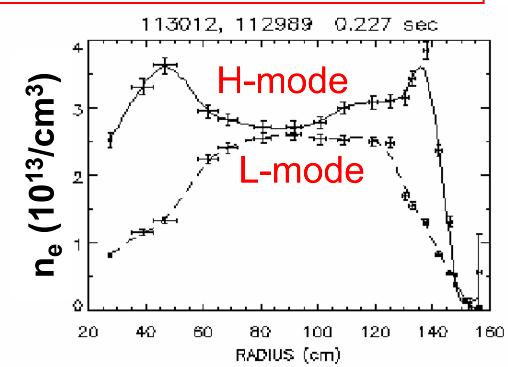

**Transport Barrier region where $\chi_i \sim \chi_i^{NC}$ and $\chi_e >> \chi_i$**

Kinetic Profile Local Error Sampling




**But Low $n_e$ L-mode plasmas show improved electron confinement! Why?**

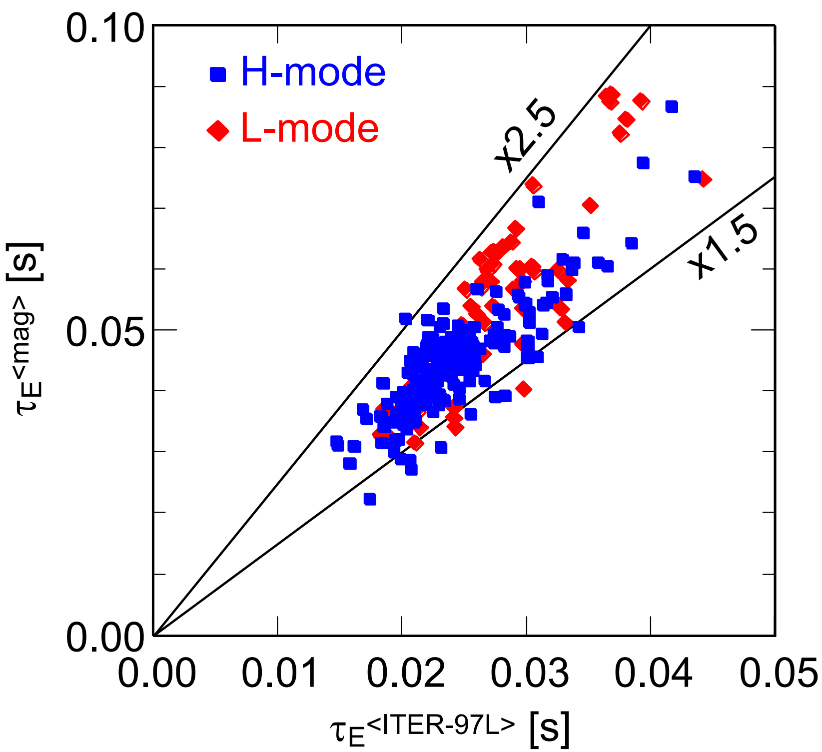


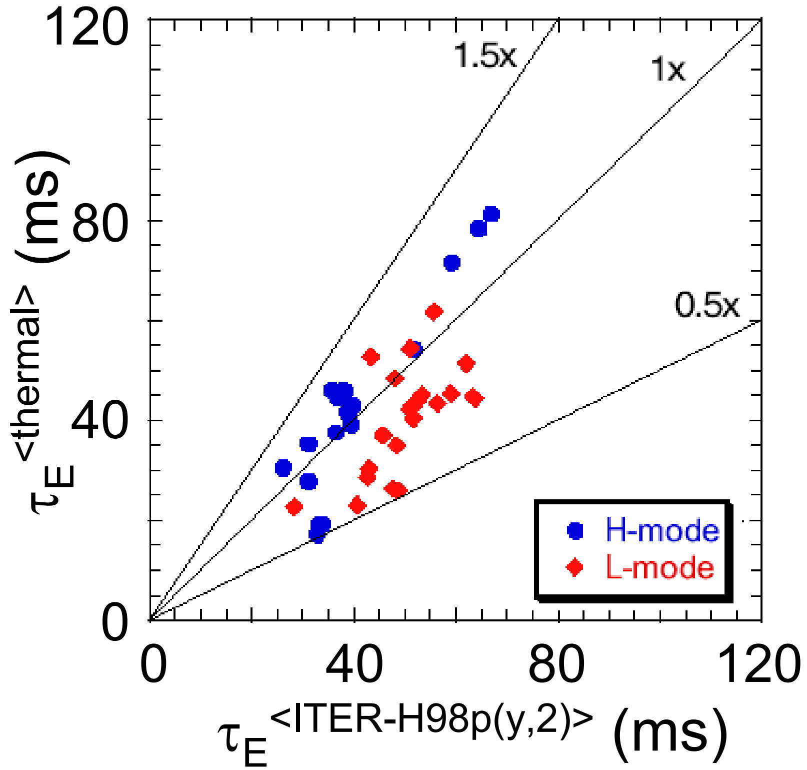






*EX/P2-8, Stutman et al*

# Global and Thermal $\tau_E$'s Compare Favorably with Higher A Database




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

L-modes have higher non-thermal component and comparable $\tau_E$! Why?

# Increased SOL Mirror Ratio ($M_R$) ⇒ Increased Footprint & Decreased Peak of Divertor Heat Flux

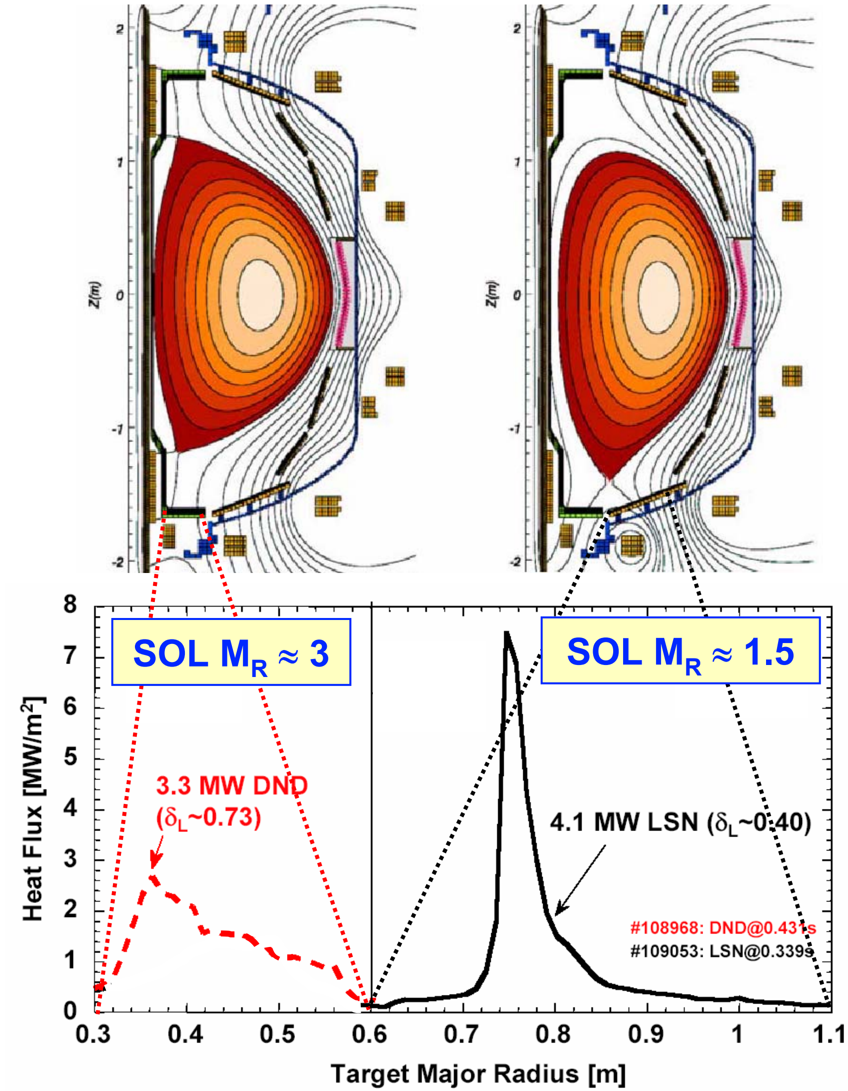
NSTX

**Factor of ~2 in $R_{div}$ and $M_R$**

**⇓**

**Factor of ~3 in $\Delta_{div}$**

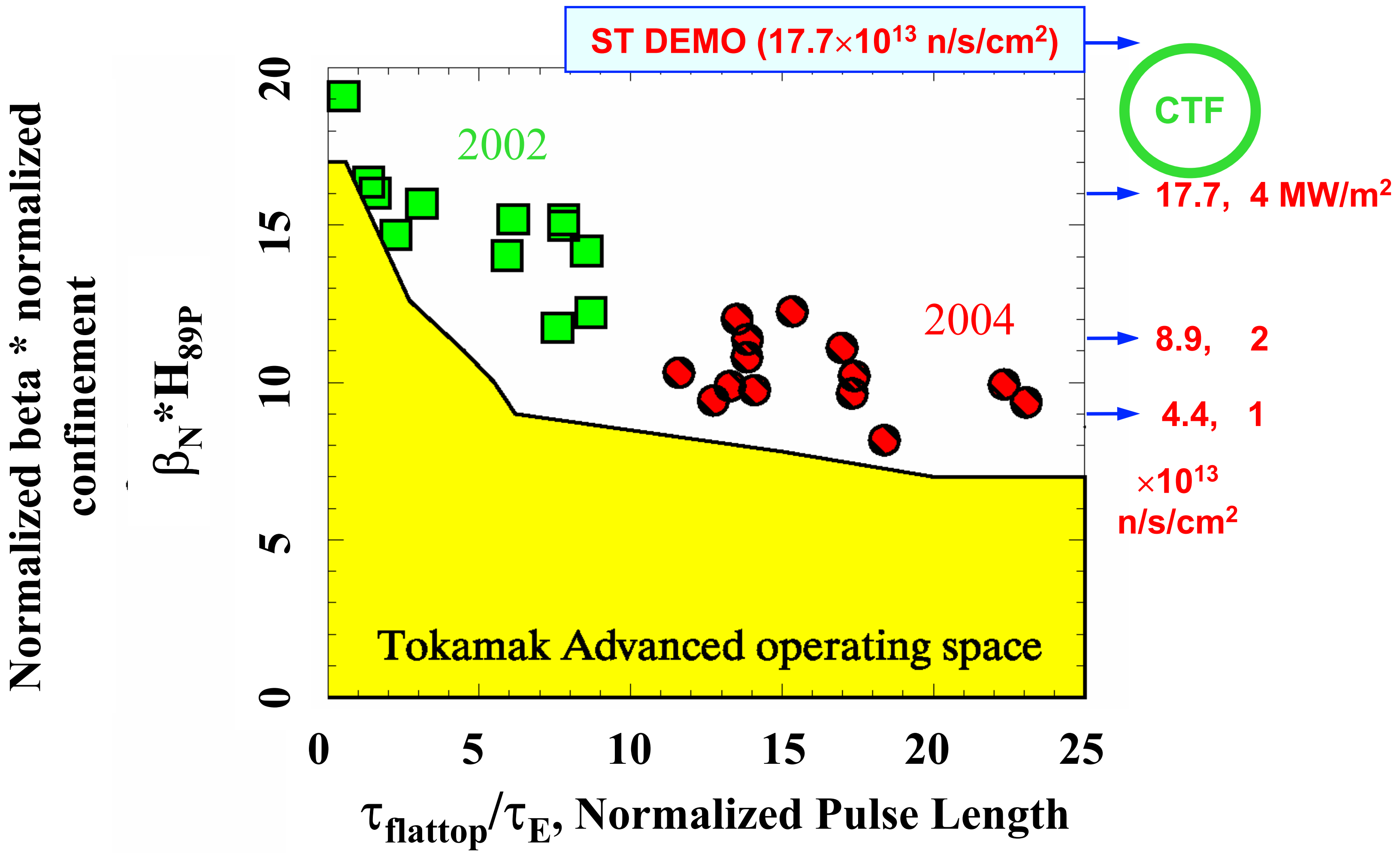
**Why?**




**High & Low δ Divertor Bolometer Measurements**

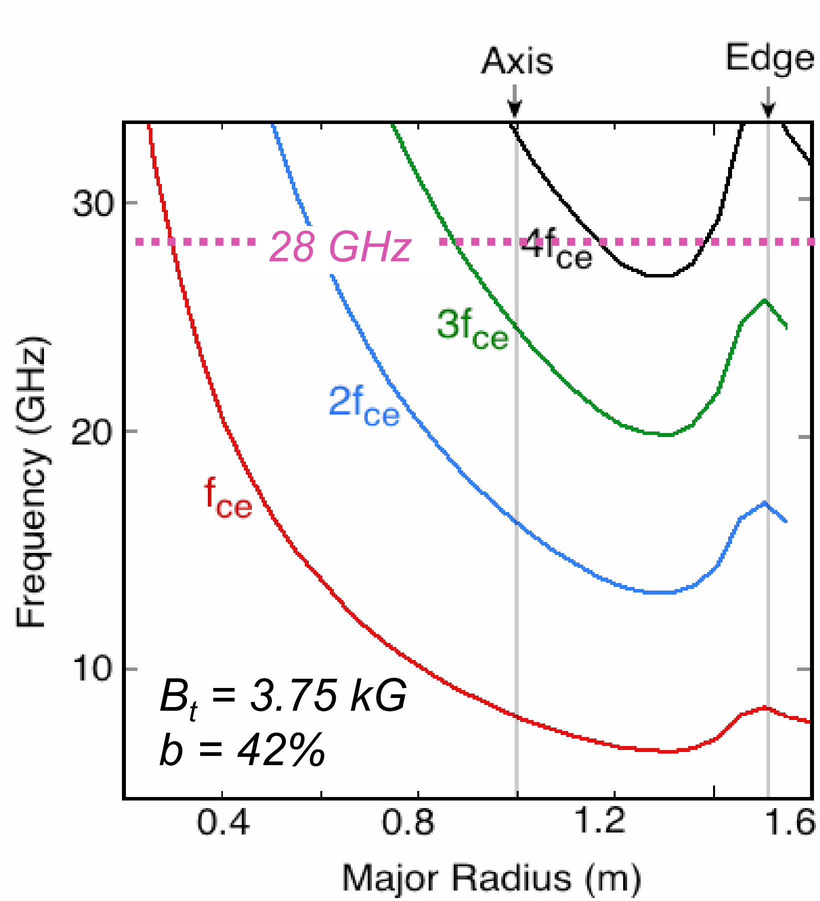
| | | |
|---|---|---|
| $R_{div}$ (m) | 0.36 | 0.75 |
| SOL $M_R$ | ~ 3 | ~ 1.5 |
| $\Delta_{div}$ (m) | ~ 0.3 | ~ 0.12 |

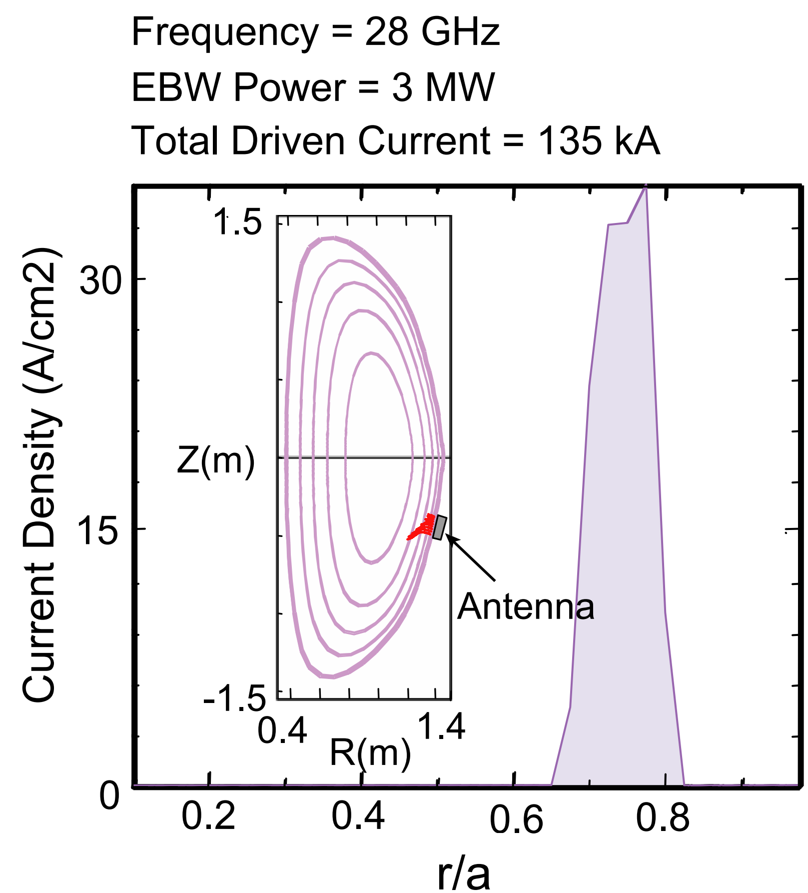
# Normalized Pulse Lengths of High Performance Plasmas on NSTX Also Reached CTF Level




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

# Modeling Predicts that 28 GHz EBW Can Drive Efficient Off-Axis Current at Plasma β ~ 40%



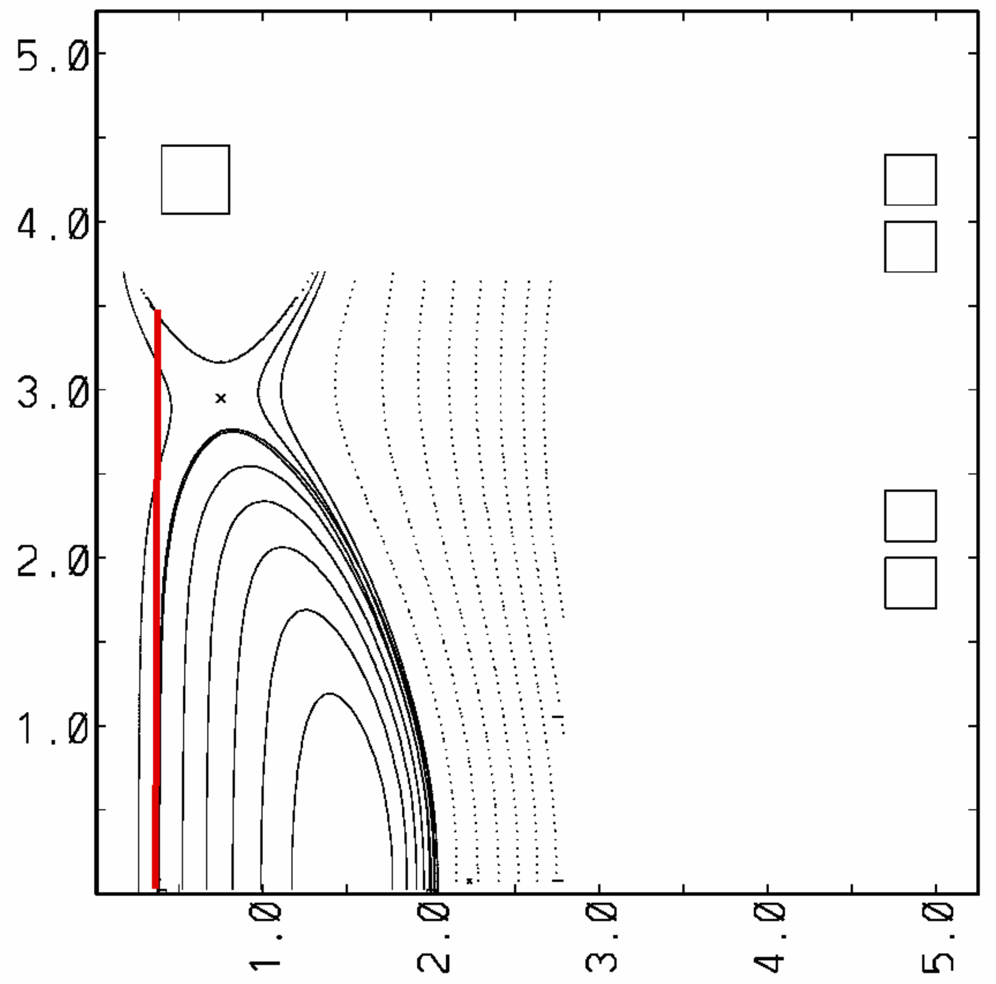




- EBW ray tracing, deposition and CD efficiency being studied with GENRAY & CQL3D for frequencies between 14 to 28 GHz

*TH/P2-4, Kessel et al*

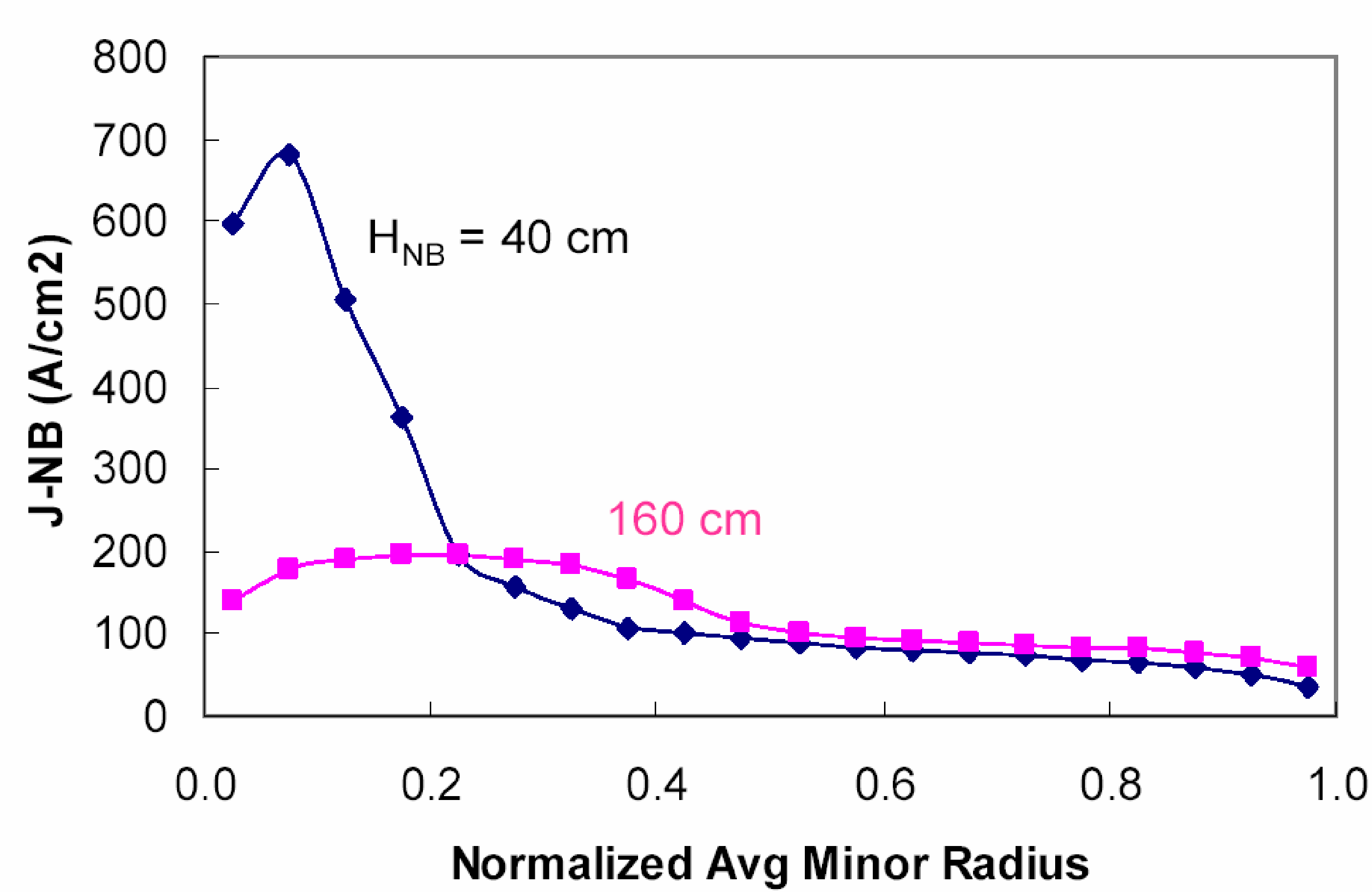
*GENRAY/CQL3D [Bob Harvey, CompX]*

# CTF Plasma With $\ell_i(1) = 0.25 – 0.5$, $\kappa = 3.2$, $\delta = 0.4$, $\beta_N = 4.0$, and $\beta_T = 20\%$ Using Far-Away PF Coils



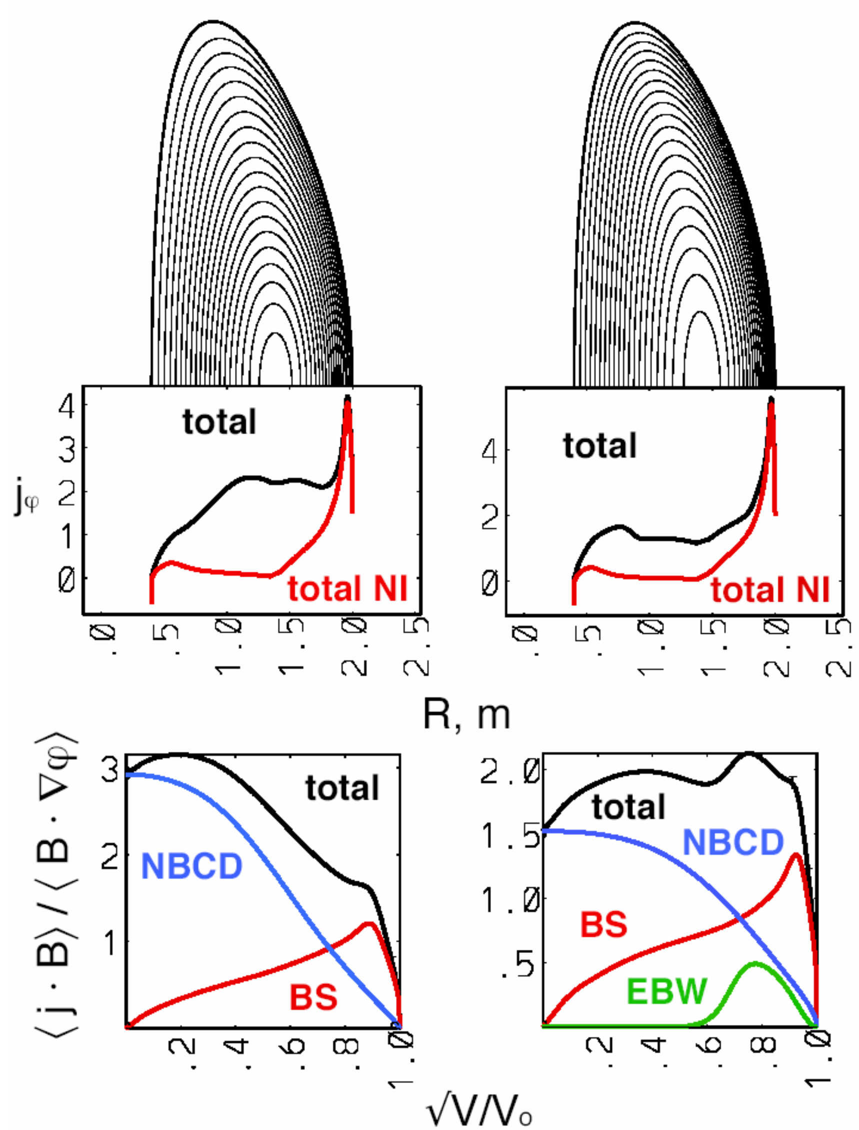

**Both Inboard Limited & Double Null Diverted Plasmas Can be Produced as Long as Low $\ell_i$ is maintained**

# Broad Driven Current Profile is Calculated for CTF With 160-cm Height ($H_{NB}$) Cross Section at NBI 110 keV




- **Positive Ion NBI Technology Would be Adequate for $\langle n_e \rangle \leq 10^{20}$ /m$^3$**
- **Broad NBI Current Profile Permits Low $\ell_i$**

# CTF Plasma Current Profiles Calculated by JSOLVER Code for Steady-State TSC Simulation.




- Profile with $\ell_i(1) = 0.5$ & $q_0 \sim 2$ maintained by $J_{NB}$ and $J_{BS}$ (left-hand side) using $P_{NB} = 36$ MW
- Adding $I_{EBW} = 1$ MA with $P_{NB} = 30$ MW would allow $\ell i(1) = 0.25$ & q0 ~ 4

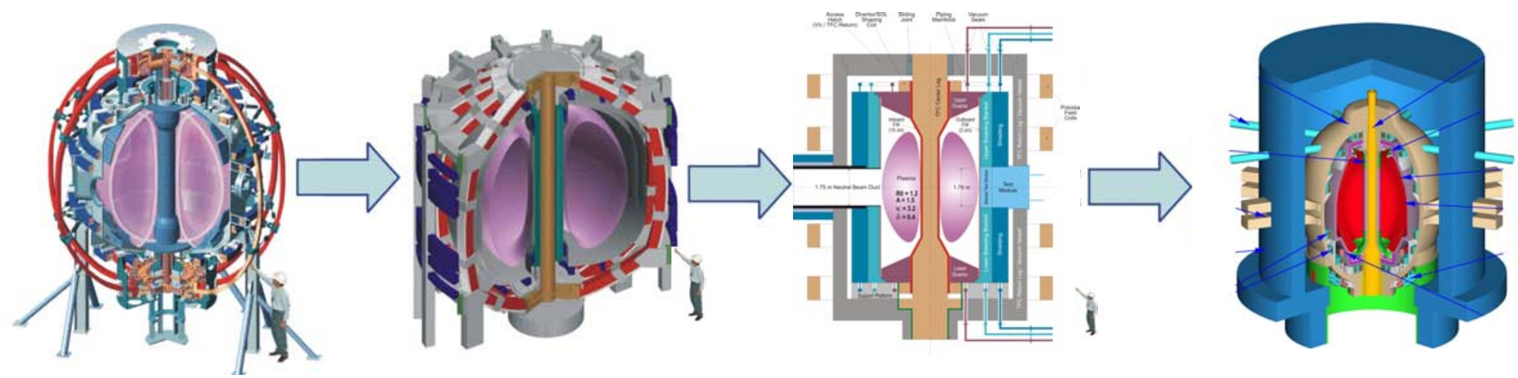
# Initial CTF Parameters Are Estimated Based on Latest Understanding of Toroidal Confinement Physics

- **$R_0$ = 1.2 m, a = 0.8 m, b/a = 3.2**
- **$B_T$ = 2.5 T, $I_{TF}$ = 15.3 MA**

| **14MeV neut. flux, MW/m²** | **1.0** | **2.0** | **4.0** |
|---|---|---|---|
| Combined $H_{98pby}$ factor | 1.61 | 1.48 | 1.38 |
| **$\beta_T$, %** | 14 | 24 | **39** |
| $\beta_N H_{89P}$ | 9.0 | 11.3 | 16 |
| **Safety factor, $q_{cyl}$** | 4.2 | 3.0 | **2.4** |
| **Normal density, $n_{GW}$** | 0.16 | 0.17 | 0.21 |
| Bootstrap current frac. | 0.53 | 0.43 | 0.44 |
| $I_p$, MA | 9.1 | 12.8 | 16.1 |
| $P_{fusion}$, MW | 72 | 144 | 288 |
| $P_{NBI}$, MW | 30 | 37 | 50 |
| Beam energy, kV | 110 | 160 | 250 |
| $P_{RF}$, MW | 6 | 10 | 15 |
| Fusion amplification Q | 2.3 | 3.6 | 5.2 |
| $P_{rad}$ (for **$P_{div}$ = 15 MW/m²**) | 50 | 75 | 90 |
| Net $T_{consumption}$/yr goal, gm | 7 | 14 | 180 |

- **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

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



| Device | NSTX | | NSST (DOE plan) | | CTF (DOE 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 |
| $\kappa$, $\delta$ | 2.5, 0.8 | | ~2.7, ~0.7 | | ~3, ~0.4 | | ~3.2, ~0.4 |
| $I_p$ (MA) | **1.5** | **1** | **~5** | **~10** | ~9 | ~16 | ~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** | **~72** | **~290** | ~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. |

# 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 $\beta$ 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 } new Alfvén modes?
  - $V_{beam}/V_{Alfvén}$ (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?

# CTF Control Technology Support Needs Defined; Some Satisfied by or Extend Present Fusion Program Plans

## To Achieve Baseline Performance (1-2 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 ~140 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<br>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