Options for a Component Test Facility (ST, Tokamak, GDT)

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CTF Is a User Facility for Technology Developers – What Are the Options and Issues?

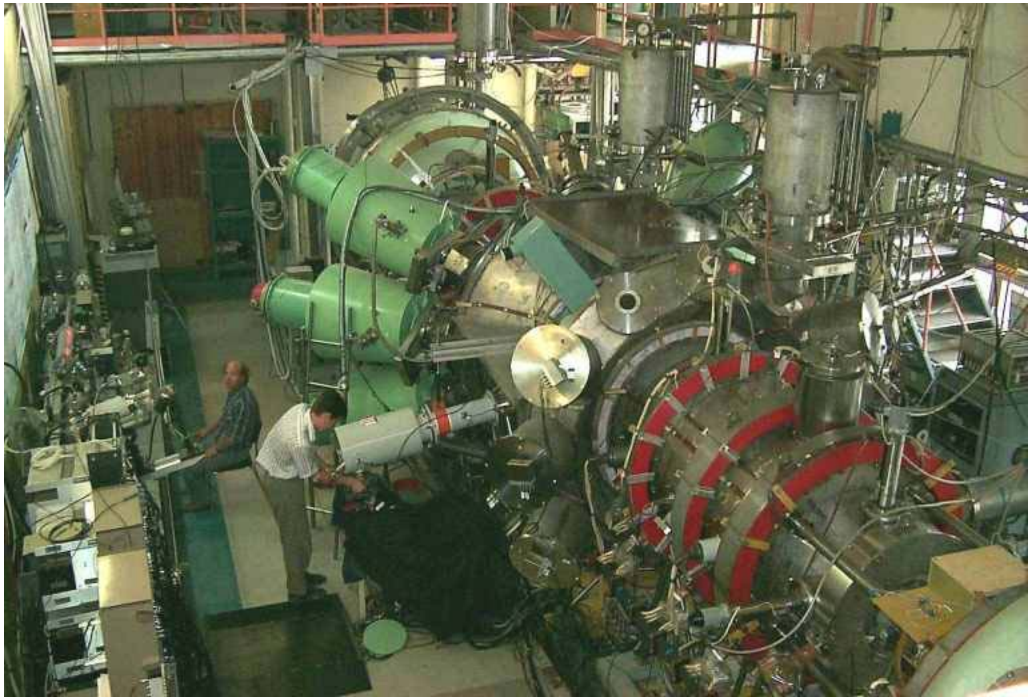
- “The CTF facility will provide the necessary integrated *(fusion nuclear technology)* testing environment of high neutron and surface fluxes, steady state plasma (or long pulse with duty cycle >80% per pulse), electromagnetic fields, large test area and volume, and high neutron fluence.”
- Required performance:
  - 14 MeV $W_L > 1$ MW/m^2
  - Testing area > 10 m^2
  - Fluence > 0.3 MW-yr/m^2 per year
- Options:
  - Gas Dynamic Trap (brief summary first)
  - Conventional A (AT)
  - Small A (ST)

  } (current results of assessment)
- What are the physics, engineering, and technology issues of CTF?
- Can CTF support fusion development effectively?

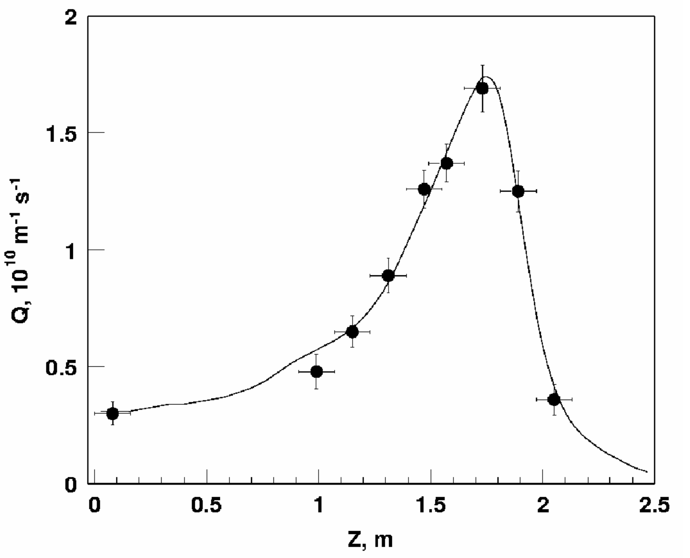
Gas Dynamic Trap (GDT)

Budker Institute of Nuclear Physics, Novosibirsk, Russia

(IAEA-CN-94/EX/C1-4Rb, FEC 2002, Lyon, France)



Axial profile of D-D neutron flux 4MW neutral beam injection



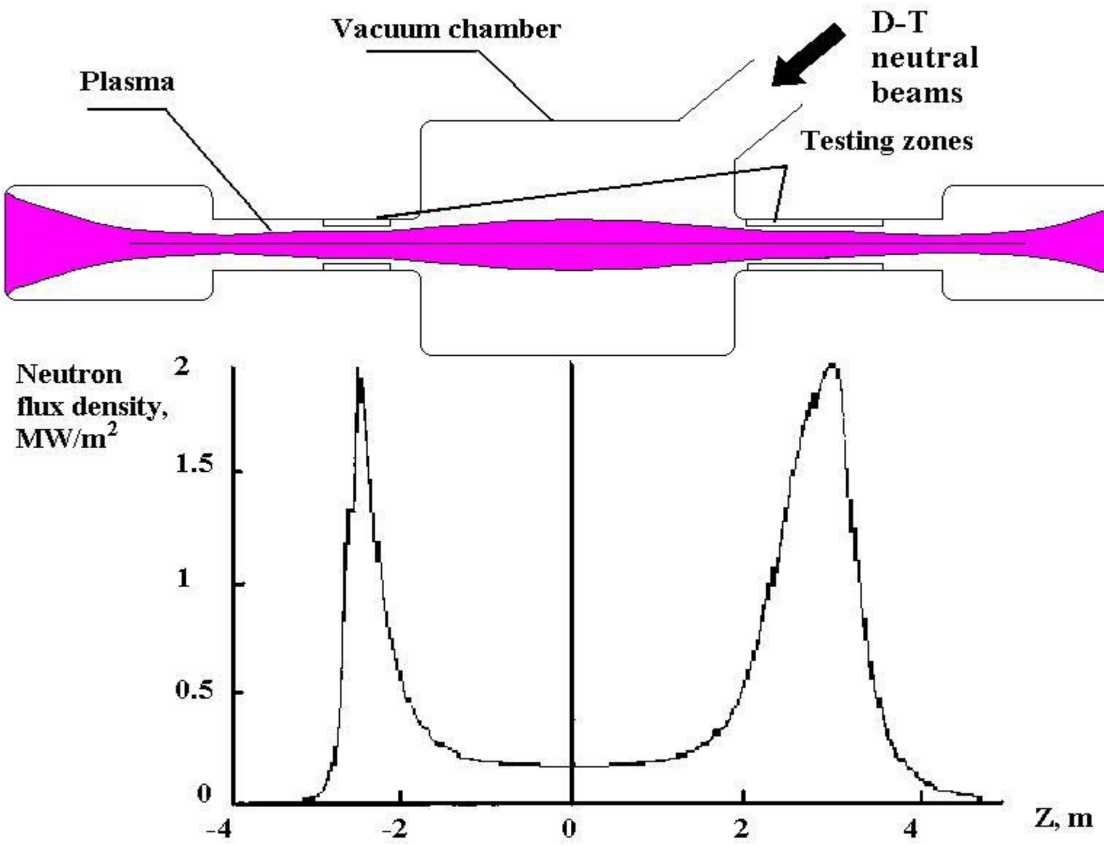
Recent Physics Progress

- MHD stability of simple mirror geometry (β ~ 40% at turning points)
- Modeled sloshing ion confinement
- Suppression of longitudinal electron thermal conductivity via very large B expansion ratio ~ $(M/m)^{1/2}$

Layout of GDT NS & Neutron Flux Density Distribution Along the Trap

(Courtesy of E. P. Kruglyakov)

- Testing Zone = 1 m², WL = 2 MW/m², Tritium Consumption ~ 0.15 kg/yr
- Could provide large material testing volume (~ 0.3 m³ for > 0.5 MW/m²)



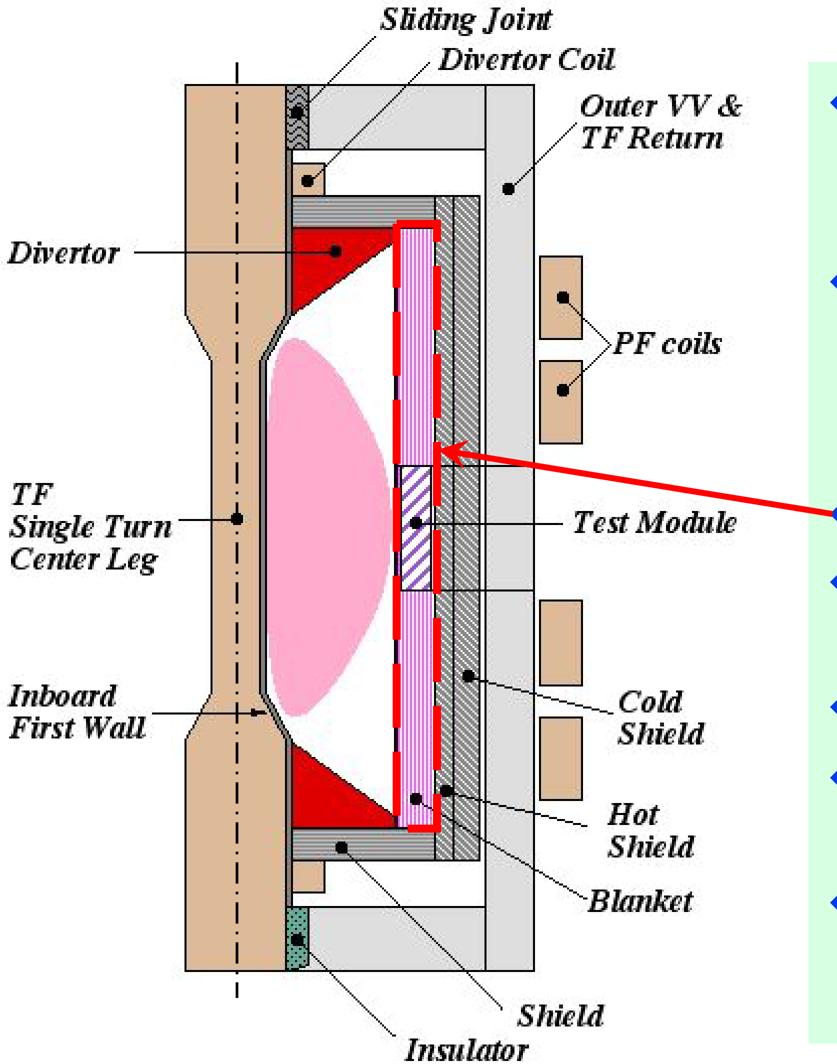
Main Parameters OF GDT, GDT-U, GDT-NS

(Courtesy of E. P. Kruglyakov)

PARAMETER	GDT (Achieved)	GDT-U (Projected)	GDT-NS (Projected)
MAGNETIC FIELD AT MID-PLANE (T) MIRROR RATIO	 0.22 ~70	 0.35 45	 1.3 10
NBI PARAMETERS: INJECTION ANGLE BEAM ENERGY (keV) POWER (MW) DURATION (ms)	 45^o 15-17 4 1	 45^o 25-30 10 4-5	 30^o 65 35 Steady state
PLASMA PARAMETERS: DENSITY (10^{13} cm^{-3}) ELECTRON TEMP (keV)	 8 0.1	 4.4 0.3	 ~10 0.75
FAST IONS DENSITY AT TURNING POINTS (10^{13} cm^{-3})	1	5	10
D-T NEUTRON FLUX DENSITY (MW/m^2)		(equivalent) 0.5	2
TEST ZONE AREA (m^2)			1

Key Engineering Design Features to Support the Component Test Mission Are Being Explored

Basic Configuration



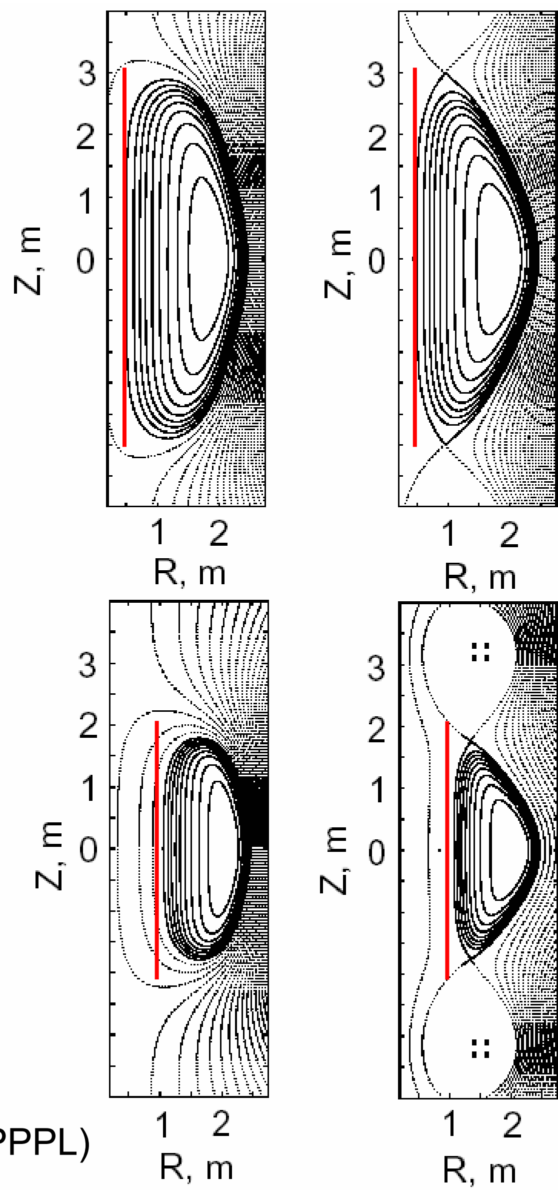
Features Required by Small Size & High Neutron Fluence

- **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 neutron fluence.
- **Blanket test area** $\propto$ (R+a)κa outboard.
- Adequate **tritium breeding ratio** **required** for long term fuel sufficiency.
- Accommodate **high heat fluxes** on PFC.
- **15-60 MA power supply** for Single-turn TF.
- Initial core components could use **DEMO-relevant technologies** (such as from ITER and long-pulse tokamaks).

Initial CTF Parameters Are Being Estimated for Low and Conventional A Using Common Bases

Achievable Shape:
A = 1.5
κ = 3
δ ~ 0.4-0.5
$\ddot{U}_i$ = 0.2

A = 2.5
κ = 2.5
δ~ 0.2-0.5
$\ddot{U}_i$ = 0.2



(Kessel, PPPL)

Common Physics Design Bases

- **Start with "low-Q"**
  - "No-wall" plasma for **W_L = 1 MW/m^2**
  - H(98H) ≤ 1.4, β_N ~ 3 – 4.5, $q_{cyl} \geq 2$
- **Capable of "high Q"**
  - "Stabilized" high performance plasma
  - H(98H) ≤ 1.8, β_N ~ 5 – 8, $q_{cyl} \geq 2.5$
  - Push to maximum B_T, I_{TFC}
  - Goal: **W_L = 5 MW/m^2**
- **Achievable shape via far away coils**
  - Blanket shield (d/a) grows with A
  - Dependent on internal inductance, $\ddot{U}_i$
- **NBI, RF heating and current drive**
- **Physics-technology heat flux solutions**
  - Large P/R → big challenge
  - Low A SOL → new physics?
  - Tungsten (ITER, Tore Supra), Li, etc.

Initial CTF Parameters Are Being Estimated for Low and Conventional A Using Common Bases

A	1.5	2.0	2.5
n wall load (MW/m^2)	1-5	1-5	1-5
H(98H)	1.4-1.8	1.4-1.8	1.4-1.8
A_{test}~$2\pi(R_0+a)\kappa a$ (m^2)	47	47	47
R_0 (m)	1.5	1.9	2.3
B_{tf}(T)	2.0-2.5	4.5	5.6
I_{tf}(MA)	15-19	43	64
I_p(MA)	13-15	16-13	13-11
κ	3.00	2.75	2.50
β_T(%)	24-38	7-13	4-9
β_N(%)	3.8-6.5	1.8-4.5	1.7-4.3
P_{fusion}(MW)	105-523	123-614	140-700
Q	1.9-17	3.2-28	3.5-33
$P_{NBI(H\&CD)}$(MW)	54-31	39-22	41-21
(P_{heat}-P_{rad})/R0 (MW/m)	39-62	31-56	27-52
$T_{consumption}$/yr (gm)*	9-45	111-556	199-996
P_{elec_input}(MW)	293-306	413-361	484-432

(Beam-plasma fusion not included)

Common Engineering Design Bases

- **Equal outboard testing area**, initially
- **One-turn TF, (VNS, ARIES-ST)**
  - Water cooled (T≤ 150°C, f_W=20%)
  - Glidcop Cu alloy (σ ≤ 100MPA)
  - Current return via aluminum VV shell
- **Component efficiencies**
  - TF power supply η=95%
  - NBI η=45%
  - Balance of plant 20MW
- ***Neutronics, blanket assumptions**
  - Line-of-sight fusion neutron absorption on TF center leg
  - 90% neutron capture & breeding by outboard blanket
  - Need neutronics calculations

(Neumeyer, PPPL)

As a Technology Test Facility, CTF Requires Well-Established Physics Database

- **Solenoid-free initiation to ~ 1 MA & ramp up further to ~ 10 MA**
  - Initiation: **ECH-EBH, LHCD, bootstrap, CHI**, etc.
  - Ramp-up: ECW-EBW CD, LHCD, bootstrap, **FW, NBI, current hole**?
- **Non-inductive sustainment with f_{BS} = 0.5 → 0.9 (W_L = 1 → 5 MW/m^2)**

	"No-Wall"	**"Stabilized"**
MHD Equilibrium & Stability	• β_N = 3 – 4.5, β_T = 5 – 25% • Field error & large plasma flow • Tearing modes vs. low & hi q • Disruptions, ELM's, pedestal	• β_N → 4.5 – 8, β_T → 10 – 50% • J-profile control, aligned J_{BS} • Plus resistive wall modes • **A dependence?**
Transport & Turbulence	• Close to neoclassical ions • Large flow shearing, ρ_i^*	• χ control → ∇p, J_{BS} control • Effects of β_0 ~ 1
Wave-Plasma-Fast Particles	• Beam ion phys in good shape • RF needs phys-tech solutions	• ECW in good shape at high A • FW, EBW under test at low A
Boundary Physics	• **A-dependence observed** • L-mode or inboard limited? • Requires DND at low A?	• Requires DND at low A • Higher P/R! • Needs phys-tech solutions
Burning Plasma	• Low Q (~2-3)	• High Q (~10-20)

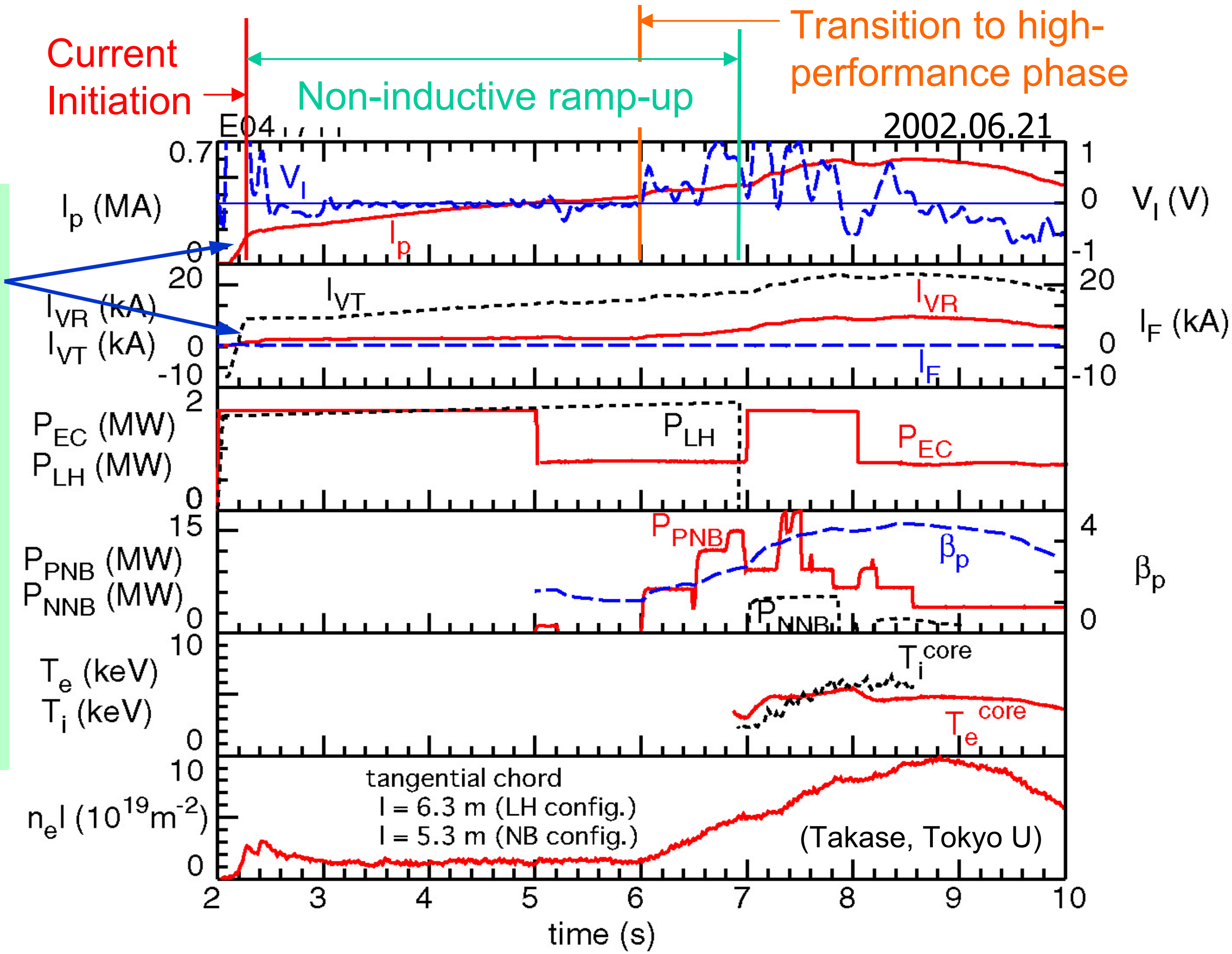
Solenoid-less Formation of High-Performance Plasma Nearly Demonstrated on JT60U

(IAEA-CN-94/PD/T-2, FEC 2002, Lyon, France)

Inboard I_{VT} provided ~10% induction flux.

LH initiation to ~100 kA already Demonstrated in PLT.

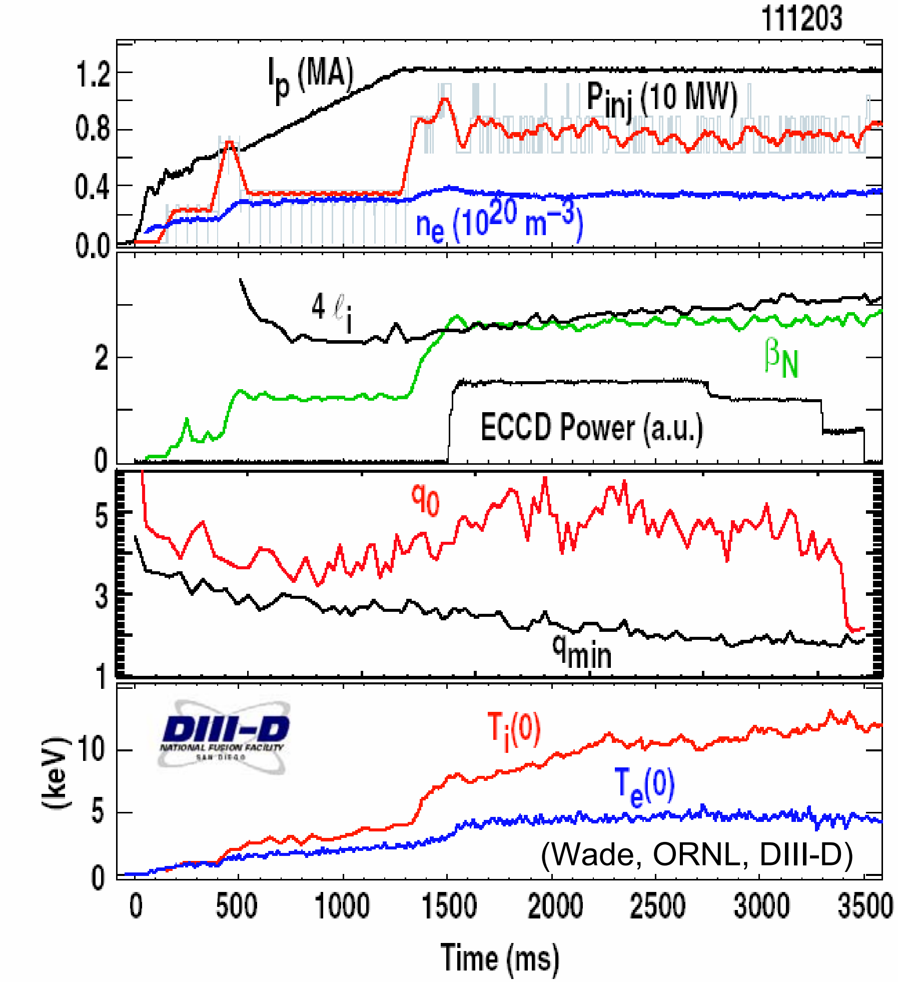
CHI, ECH, LHCD will require more tests.



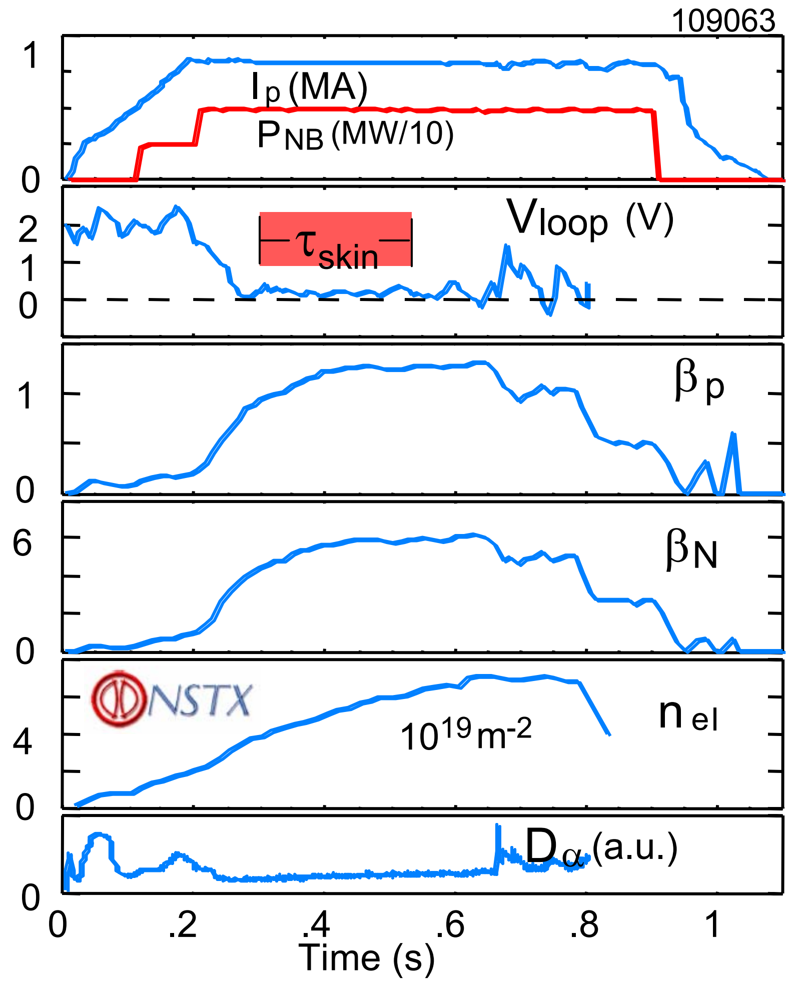
Database needed at ~10x plasma current.

Near Sustainment Are Achieved with High β_N & β_T Values at ~ 1MA Level in High and Low A

A = 2.5, β_N = 2.8, β_T = 4.2%, $\Delta t \sim 0.5\tau_{skin}$



A = 1.4, β_N = 6, β_T = 17%, $\Delta t \geq \tau_{skin}$

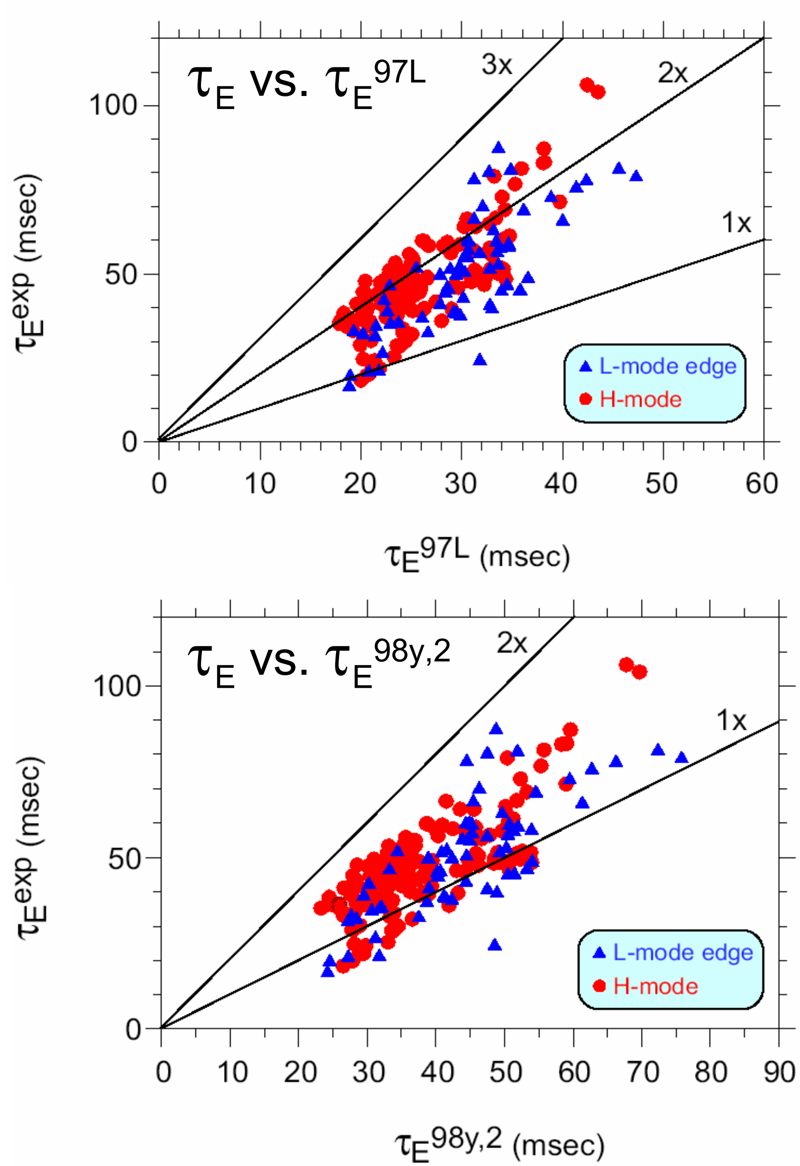


Database needed at ~10x current and >> τ_{skin}, for "no-wall" and "stabilized" β's.

Low-A Global Confinement Has Reached (& Exceeded?) High-A Levels, Relative to Scaling Laws

- **A ~ 1.3 – 1.5, similar to A = 2.5 – 3.0 results**
- H(97L) → 2.6

  H(98H) → 1.7
- True for both H-mode and L-mode edge plasmas! Assume H(98H) = 1.4 – 1.8
- Understanding underlying physics important for next-step device
- ***Database needed at 5 – 10 MA level for CTF***

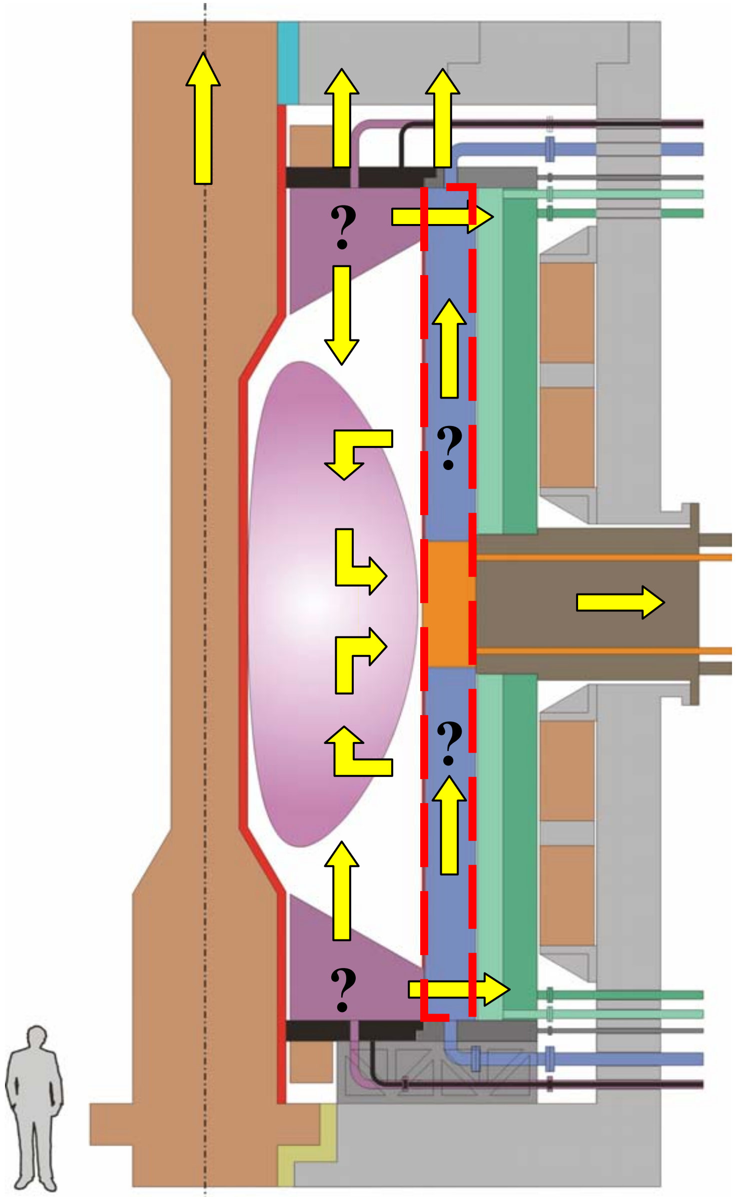


CTF Enabling Technology and Engineering Requirements Need Assessment

- **TF System Engineering**
  - TF center leg optimization and fabrication technology
  - Multi-MA, high efficiency TF power supply
- **Plasma facing components**
  - **Highly reliable and remotely replaceable divertor components (large MTBF and small MTTR)**
  - Take advantage of DEMO-relevant ITER designs
- **Heating, current drive, and fueling**
  - 300 kV negative ion beam under development by LHD, JT60U
  - **Highly reliable and remotely replaceable RF launchers**
  - FW at 30-100 MHz available, EBW at 50-100 GHz nearly available
- ***Requires database from long-pulse high performance tests (Tore Supra, KStar, LHD, ITER, test stands, etc.) to raise MTBF***
- ***Requires efficient Remote Maintenance (RM) to reduce MTTR***

How to Take Advantage of Single-Turn TF Coil and Reduced Device Size?

- **TF center leg**
  - Replaced vertically from above
- **Blanket test modules**
  - Integrated port assemblies replaced at port interface
  - Similarly for heating modules
- **Test blankets**
  - Integrated assembly(s) removed vertically or as modules through mid-plane ports?
- **Divertor**
  - Integrated assemblies removed vertically, or as port assemblies, or as modules through mid-plane ports?
- **Permanent and/or hands-on**
  - Shield
  - VV/TF coil outer leg
  - PF coils

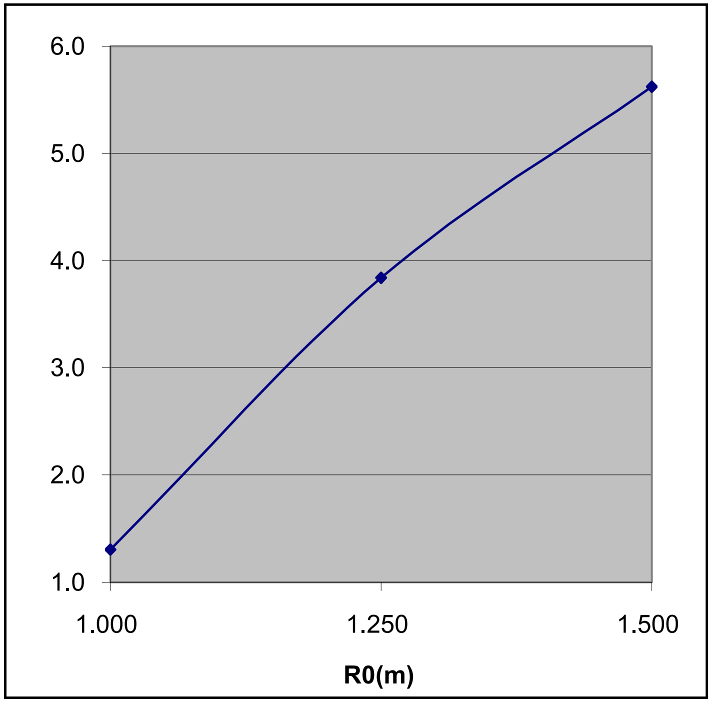


On-going Assessment Will Clarify Technical Characteristics of CTF Options

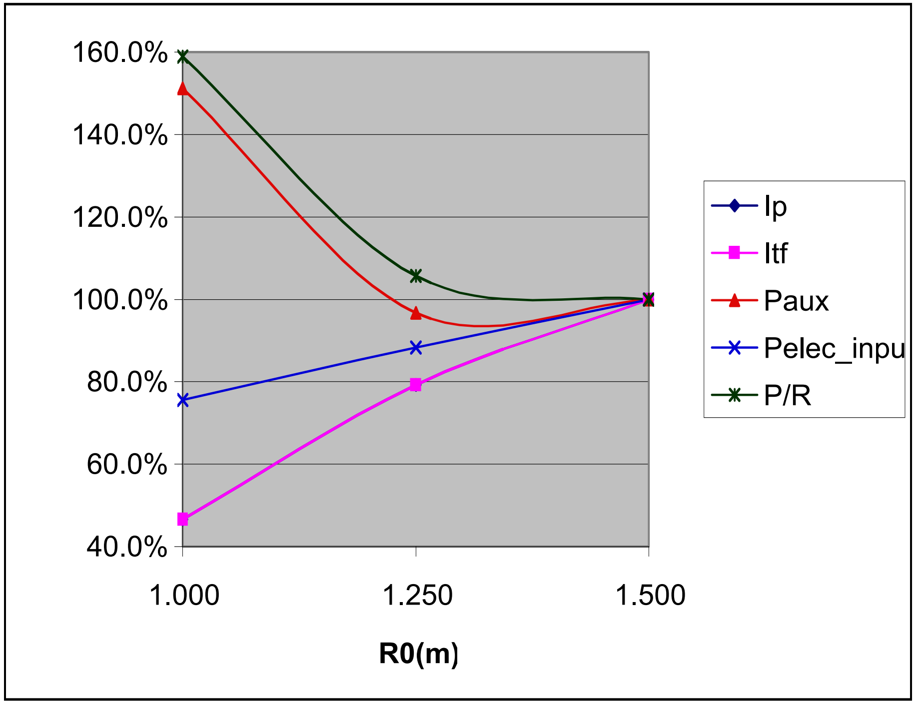
Performance Variation with R_0

(beam-plasma fusion not included)

Max. Achievable Wall Loading
Assuming "stabilized" plasma



Performance Relative to R_0=1.5 m
Assuming "no-wall" plasma, for 1MW/m^2

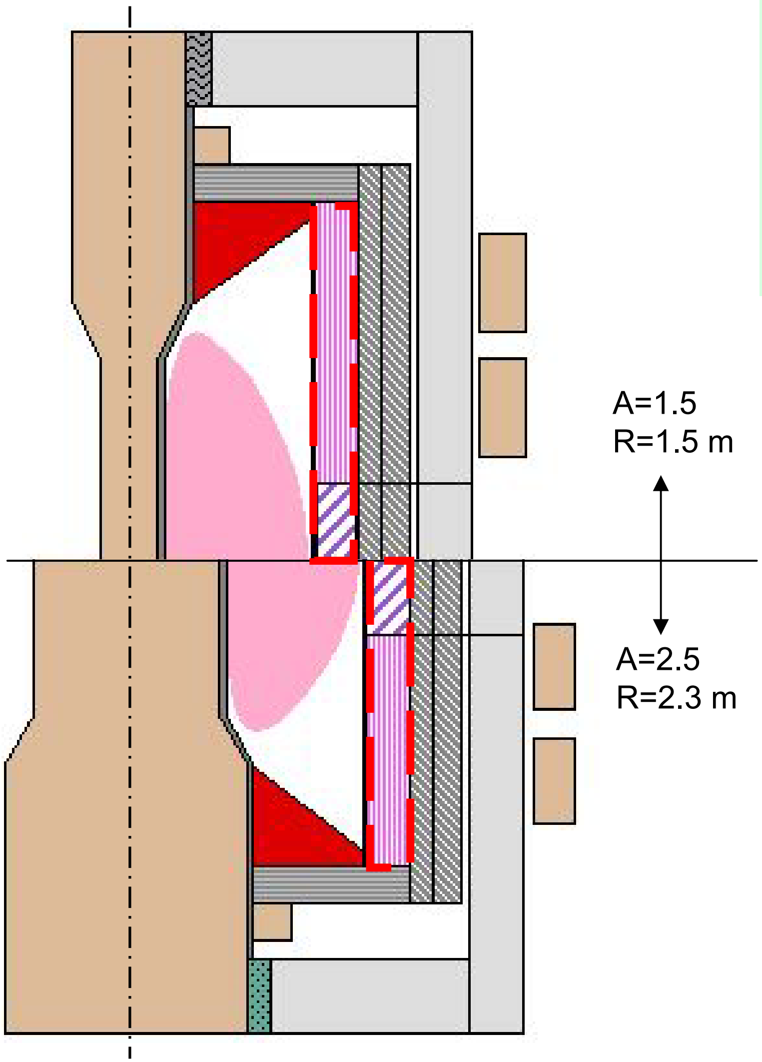


Compact CTF with Simplified Configuration Can Make Major Contributions to DEMO Availability

- Demountable single-turn TF center leg allows smaller simplified toroidal devices (R ~ 1 – 2 m) with potential RM advantages
- Range in A and R can provide W_L ~ 1 MW/m^2 in initial operation
- Plasma and enabling technology database already encouraging
- Need demonstrated long-pulse, high-performance physics data at 5 – 10 MA
- Continued physics and technology development raises the potential for achieving W_L ~ 5 MW/m^2 in CTF
- GDT neutron source provides an option between IFMIF and VNS
- Work is needed to determine the best candidates, involving physics researchers, technology developers and providers, and facility builders

Back Up

The Effects of Variations in Aspect Ratio Will be Identified and Quantified



Variations relative to A=1.5 for 1MW/m²

- TF Current
- TF Field
- Fusion Power
- Maximum breeding fraction
- Electric Power Input