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

Martin Peng
Oak Ridge National Laboratory
&
National Spherical Torus Experiment
Princeton Plasma Physics Laboratory

Meeting of FESAC Sub-Panel on “DEMO in 35 Years”

October 28 – 30, 2002
Livermore, CA
“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 $W_L > 1 \text{ MW/m}^2$
  - Testing area $> 10 \text{ m}^2$
  - Fluence $> 0.3 \text{ MW-yr/m}^2$ per year

- Options:
  - Gas Dynamic Trap (brief summary first)
  - Conventional A (AT)
  - Small A (ST)

- 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)

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

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>GDT (Achieved)</th>
<th>GDT-U (Projected)</th>
<th>GDT-NS (Projected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGNETIC FIELD AT MID-PLANE (T)</td>
<td>0.22</td>
<td>0.35</td>
<td>1.3</td>
</tr>
<tr>
<td>MIRROR RATIO</td>
<td>~70</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>NBI PARAMETERS:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INJECTION ANGLE</td>
<td>45°</td>
<td>45°</td>
<td>30°</td>
</tr>
<tr>
<td>BEAM ENERGY (keV)</td>
<td>15-17</td>
<td>25-30</td>
<td>65</td>
</tr>
<tr>
<td>POWER (MW)</td>
<td>4</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>DURATION (ms)</td>
<td>1</td>
<td>4-5</td>
<td>Steady state</td>
</tr>
<tr>
<td>PLASMA PARAMETERS:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DENSITY (10^{13} cm^{-3})</td>
<td>8</td>
<td>4.4</td>
<td>~10</td>
</tr>
<tr>
<td>ELECTRON TEMP (keV)</td>
<td>0.1</td>
<td>0.3</td>
<td>0.75</td>
</tr>
<tr>
<td>FAST IONS DENSITY AT TURNING POINTS (10^{13} cm^{-3})</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>D-T NEUTRON FLUX DENSITY (MW/m^2)</td>
<td>(equivalent)</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>TEST ZONE AREA (m^2)</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Key Engineering Design Features to Support the Component Test Mission Are Being Explored

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** $\propto (R+a)\kappa_a$ 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

**Common Physics Design Bases**

- **Start with “low-Q”**
  - “No-wall” plasma for $W_L = 1 \text{ MW/m}^2$
  - $H(98H) \leq 1.4$, $\beta_N \sim 3 - 4.5$, $q_{cyl} \geq 2$
- **Capable of “high Q”**
  - “Stabilized” high performance plasma
  - $H(98H) \leq 1.8$, $\beta_N \sim 5 - 8$, $q_{cyl} \geq 2.5$
  - Push to maximum $B_T$, $I_{TFC}$
  - Goal: $W_L = 5 \text{ MW/m}^2$
- **Achievable shape via far away coils**
  - Blanket shield (d/a) grows with A
  - Dependent on internal inductance, $\xi$
- **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.

**Achievable Shape:**

- $A = 1.5$
- $\kappa = 3$
- $\delta \sim 0.4-0.5$
- $\xi = 0.2$

- $A = 2.5$
- $\kappa = 2.5$
- $\delta \sim 0.2-0.5$
- $\xi = 0.2$

(Kessel, PPPL)
Initial CTF Parameters Are Being Estimated for Low and Conventional A Using Common Bases

<table>
<thead>
<tr>
<th>A</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>n wall load (MW/m²)</td>
<td>1-5</td>
<td>1-5</td>
<td>1-5</td>
</tr>
<tr>
<td>H(98H)</td>
<td>1.4-1.8</td>
<td>1.4-1.8</td>
<td>1.4-1.8</td>
</tr>
<tr>
<td>$A_{test} \sim 2\pi(R_0+a)\kappa a$ (m²)</td>
<td>47</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>$R_0$ (m)</td>
<td>1.5</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>$B_{tr}$ (T)</td>
<td>2.0-2.5</td>
<td>4.5</td>
<td>5.6</td>
</tr>
<tr>
<td>$I_{tr}$ (MA)</td>
<td>15-19</td>
<td>43</td>
<td>64</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>13-15</td>
<td>16-13</td>
<td>13-11</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>3.00</td>
<td>2.75</td>
<td>2.50</td>
</tr>
<tr>
<td>$\beta_T$ (%)</td>
<td>24-38</td>
<td>7-13</td>
<td>4-9</td>
</tr>
<tr>
<td>$\beta_N$ (%)</td>
<td>3.8-6.5</td>
<td>1.8-4.5</td>
<td>1.7-4.3</td>
</tr>
<tr>
<td>$P_{fusion}$ (MW)</td>
<td>105-523</td>
<td>123-614</td>
<td>140-700</td>
</tr>
<tr>
<td>Q</td>
<td>1.9-17</td>
<td>3.2-28</td>
<td>3.5-33</td>
</tr>
<tr>
<td>$P_{NBI(H&amp;CD)}$ (MW)</td>
<td>54-31</td>
<td>39-22</td>
<td>41-21</td>
</tr>
<tr>
<td>$(P_{heat}-P_{rad})/R_0$ (MW/m)</td>
<td>39-62</td>
<td>31-56</td>
<td>27-52</td>
</tr>
<tr>
<td>$T_{consumption}$/yr (gm)</td>
<td>9-45</td>
<td>111-556</td>
<td>199-996</td>
</tr>
<tr>
<td>$P_{elec_input}$ (MW)</td>
<td>293-306</td>
<td>413-361</td>
<td>484-432</td>
</tr>
</tbody>
</table>

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 ($\sigma \leq 100\text{MPA}$)
  - Current return via aluminum VV shell
- **Component efficiencies**
  - TF power supply $\eta=95\%$
  - NBI $\eta=45\%$
  - 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

(Beam-plasma fusion not included) (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 $f_{BS} = 0.5 \rightarrow 0.9$ ($W_L = 1 \rightarrow 5 \text{ MW/m}^2$)

<table>
<thead>
<tr>
<th></th>
<th>“No-Wall”</th>
<th>“Stabilized”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MHD Equilibrium</strong></td>
<td>• $\beta_N = 3 - 4.5$, $\beta_T = 5 - 25%$</td>
<td>• $\beta_N \rightarrow 4.5 - 8$, $\beta_T \rightarrow 10 - 50%$</td>
</tr>
<tr>
<td>&amp; Stability</td>
<td>• Field error &amp; large plasma flow</td>
<td>• J-profile control, aligned $J_{BS}$</td>
</tr>
<tr>
<td></td>
<td>• Tearing modes vs. low &amp; hi q</td>
<td>• Plus resistive wall modes</td>
</tr>
<tr>
<td></td>
<td>• Disruptions, ELM’s, pedestal</td>
<td>• $A$ dependence?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transport &amp;</strong></td>
<td>• Close to neoclassical ions</td>
<td>• $\chi$ control $\rightarrow \nabla p$, $J_{BS}$ control</td>
</tr>
<tr>
<td><strong>Turbulence</strong></td>
<td>• Large flow shearing, $\rho_i^*$</td>
<td>• Effects of $\beta_0 \sim 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wave-Plasma</strong></td>
<td>• Beam ion phys in good shape</td>
<td>• ECW in good shape at high $A$</td>
</tr>
<tr>
<td><strong>Fast Particles</strong></td>
<td>• RF needs phys-tech solutions</td>
<td>• FW, EBW under test at low $A$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Boundary Physics</strong></td>
<td>• A-dependence observed</td>
<td>• Requires DND at low $A$</td>
</tr>
<tr>
<td></td>
<td>• L-mode or inboard limited?</td>
<td>• Higher P/R!</td>
</tr>
<tr>
<td></td>
<td>• Requires DND at low $A$</td>
<td>• Needs phys-tech solutions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Burning Plasma</strong></td>
<td>• Low Q ($\sim$2-3)</td>
<td>• High Q ($\sim$10-20)</td>
</tr>
</tbody>
</table>
Solenoid-less Formation of High-Performance Plasma Nearly Demonstrated on JT60U

(Database needed at ~10x plasma current.)

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

LH initiation to ~100 kA already Demonstrated in PLT.

CHI, ECH, LHCD will require more tests.

Current Initiation

Non-inductive ramp-up

Transition to high-performance phase

(Takase, Tokyo U)
Near Sustainment Are Achieved with High $\beta_N$ & $\beta_T$ Values at $\sim 1$MA Level in High and Low $A$

**A = 2.5, $\beta_N = 2.8$, $\beta_T = 4.2\%$, $\Delta t \sim 0.5\tau_{\text{skin}}$**

**A = 1.4, $\beta_N = 6$, $\beta_T = 17\%$, $\Delta t \geq \tau_{\text{skin}}$**

*Database needed at $\sim 10x$ current and $\gg \tau_{\text{skin}}$, for “no-wall” and “stabilized” $\beta$’s.*
Low-A Global Confinement Has Reached (& Exceeded?) High-A Levels, Relative to Scaling Laws

• $A \sim 1.3 - 1.5$, similar to $A = 2.5 - 3.0$ results
• $H(97L) \rightarrow 2.6$
  $H(98H) \rightarrow 1.7$
• 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
• \textit{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/m²
Compact CTF with Simplified Configuration Can Make Major Contributions to DEMO Availability

- Demountable single-turn TF center leg allows smaller simplified toroidal devices ($R \sim 1 – 2$ m) with potential RM advantages
- Range in $A$ and $R$ can provide $W_L \sim 1$ 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 $W_L \sim 5$ 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

The diagram shows variations in aspect ratio with values of A=1.5 and A=2.5. The graph illustrates how different parameters such as Itf, Bt, Pelec_input, and FBR change with variations in A.