The First DT Experiments in TFTR: Planning and Operational Perspectives

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PPPL Experimental Seminar
May 23, 2014
Status of Tokamak Physics in 1983

- Reliable operation at current <1MA with pulse lengths up to 1s
- Gas and frozen pellet fueling
  - Empirical density limits: Murakami → Hugill (later → Greenwald)
- Neutral beam heating up to ~8MW, RF heating up to ~5MW (ion cyclotron, electron cyclotron, lower hybrid)
  - High ion temperatures, ~ 7keV, with NBI; first studies of $\beta$-limits
- Compressional heating (transient benefit)
- Global confinement scalings:
  - “Alcator” scaling for ohmic heating ($\propto$ density)
  - L-mode scaling for NB heating ($\tau_E \propto I_p P^{-1/2}$) (ISX-B, PDX, DITE ...)
    - Poor predictions for TFTR, JET (“Goldston catastrophe”)
  - First TFTR NBI heating experiments in 1985 confirmed fears
- H-mode discovered (ASDEX) in divertor plasmas with improved confinement ($\sim 2 \times$ L-mode)
In 1986, the L-mode Deadlock Was Broken When "Supershots" Were Discovered in TFTR

- High power NBI applied to low-current plasmas after "conditioning" to reduce hydrogen influx from limiter
  - Pioneered by Jim Strachan based on experience in PLT
- Fueled by NBI ⇒ density peaked, sawteeth suppressed, confinement improved

\[ P_{\text{NBI}} = 22 \text{MW}, \quad I_p = 1.4 \text{MA}, \quad B_T = 4.7 \text{T} \]

\[ n_e(0) T_i(0) \tau_E \text{ increased by factor 30!} \]

- Subsequently developed additional techniques, including Li wall coating, to reduce influx from limiter ⇒ eventually pushed supershots to 2.5MA, 40MW

- Supershots were excellent vehicles for studying high-temperature plasma phenomena and fusion physics but they had to be handled with care
Supershots Did Not Follow L-mode Empirical Scaling

- Confinement almost independent of current and power
  - Unlike H-mode plasmas
- DD reactivity scaled very favorably with power
  - TRANSP simulations suggested DT fusion power of 8MW possible, \textit{but}
  - Need to increase the plasma current to avoid $\beta$-limit
  - Need to develop ways to reduce edge influxes at higher current and power
Supershots Limited by Pressure-Driven Instabilities Below Troyon-Scaling Limit

- Peaked profiles still beneficial for fusion-relevant $\beta^* = 2\mu_0^2 / (\int p^2 dV/V)/B_T^2$
- TFTR identified ballooning mode growing rapidly on underlying $n = 1$ mode before disruption \((Fredrickson, Nagayama and Janos)\)
  - Made possible by excellent spatial and time resolution of $T_e$ diagnostics (ECE)
- Spurred investigation of alternative modes, \textit{e.g.} high-$l_i$, H-mode
  - High-$l_i$ shots produced by current rampdown exceeded Troyon limit
The Burden of Supershots

• Extensive conditioning of the limiter was needed
  – TFTR inner “bumper” limiter contained about 2T of ATJ graphite
  – Bakeout limited to 150°C by concerns over thermal stresses in vessel
  – Followed this by days of Pulse Discharge Cleaning and Disruptive Discharge Cleaning
  • Provoke deliberate disruptions of OH plasmas at increasing currents
• Long sequences of OH helium shots were necessary to degas limiter
  – Developed empirical indicators to assess limiter “condition” e.g. \( H_\alpha: \text{CII} \) ratio
• High energy disruptions were extremely detrimental to limiter condition
  – Avoided them by backing off: ran hundreds of shots without disruption, but
  – Lure of peak fusion performance inevitably pushed us towards the limit
  – Took three days to recover from 7MJ disruption trying for 10MW in 1994
• Led us to increase toroidal field to 6T from 5.2T design during DT phase
In 1991, Developed Detailed Plan for DT Campaign

- Earlier plans (1985,7) scrapped after budget cuts
  - Development of tritium handling systems was essentially stopped
- DT projections based on supershot progress (1988-90) revived hope
- 1991 plan was for a final 2-year campaign starting mid-1993 to study
  - Plasma behavior near “breakeven conditions” (Q ~ 0.5) with E ~ 10MJ per pulse
  - Fusion alpha confinement and thermalization \( \Leftarrow \) diagnostic progress
  - Alpha heating \( \Leftarrow \) a stretch for Q < 1
  - Effects of alphas on stability & transport \( \Leftarrow \) burgeoning theoretical work
  - Effects of isotopic mix
  - ICRH in DT
  - Fueling with T pellets (in addition to NBI fueling) \( \Leftarrow \) prototype for BPX
  - Tritium retention
- Within limits of 5g T on-site, 1g T in-vessel, \(10^{21}\) neutrons/year
- All with assumption that TFTR would end operation at the end of FY94!
Experimental Plans Developed in 1992 - 3

• Great increase in formality of reviews and operation following visits by “Tiger Team” (1990) and several DOE committees of experts

• Preparation of Experiment Proposals organized by Task Forces
  - Fusion Power (led by Jim Strachan) - responsibility for Day-1 XPs
  - D-T Technology (Kingston Owens)
  - D-T Transport and Advanced Physics (Mike Zarnstorff)

• Tension between desire for performance and reliability of operation
  – Wanted reliable, reproducible shot conditions for DT vs D-only comparisons
  – Higher DT power (⇒ more alphas) would increase likelihood of disruption

• Analyzed recent TFTR D supershots and JET PTE experience
  – Substituting 50:50 DT in TRANSP model gave \( \frac{P_{DT}}{P_{DD}} \approx 162 \pm 10 \)
  – With 30MW NBI, we had about an even chance of reaching 7MW

• Settled on a goal of \( P_{DT} = 5 \text{MW} \) for Day 1
  – Straightforward to explain to media - but not just a walk in the park either
Many Diagnostics Installed and Others Modified to Measure Fusion Alpha Particles

<table>
<thead>
<tr>
<th>Alpha birth profile</th>
<th>10-Channel Neutron Collimator</th>
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<tbody>
<tr>
<td>Alpha loss rate</td>
<td>Poloidal array of detectors</td>
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<td></td>
<td>Movable probes</td>
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<tr>
<td>Confined alphas</td>
<td>Alpha CHERS (U Wisc)</td>
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<td>Alpha-Li pellet charge exchange (GA, Ioffe)</td>
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<td>Spectroscopy with Li pellet (NIFS, LANL)</td>
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<td>Alpha gyrotron scattering (MIT, Lodestar)</td>
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<tr>
<td>Alpha transport and ash</td>
<td>He CHERS</td>
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</table>

- Some needed setup and calibration with 14MeV neutrons and 3.5MeV alphas
Rehearsed Scenarios Many Times Before Day 1

- TFTR outage from November 92 through May 93
  - Tritium system commissioning: started handling trace T in May
- PDC, DDC, NB checkout and conditioning through June 93
- June 21 – 25, 93: DOE *Operational Readiness Review* for DT and *Operational Readiness Evaluation* (review of the review!)
- In July, rehearsed shots for main Day 1 XP, DT-7 or 607 (9 days), and continued development of Li pellet conditioning and 2.5MA shots
  - Operational reliability was not good at this stage – many technical faults
- Break for month of August for vacations – techs were run ragged
- Stand-down for almost a week at beginning of September for “self-assessment” after 3 safety-related occurrences: *close call for T program*
  - Even more scrutiny of operations and insistence on procedures
- Resumed operation in October then broke for DPP meeting (Nov 1-5)
- After final checks of systems, diagnostics, ready for Trace-T on Nov 12
“Trace Tritium” Phase Used to Check Tritium System, Experimental Methods and Diagnostics

- Used mixture of ~2% $T_2$ in $D_2$ delivered through T system
- Three experiments planned and performed
  - DT-6: Trace tritium NBI (Jassby)
  - DT-16: Trace tritium gas puffing (Efthimion)
  - DT-23: Tritium accounting and cleanup (Owens)
- First trace-T NBI occurred on Friday November 12, 1993

<table>
<thead>
<tr>
<th>Shot</th>
<th>$P_{NB}$</th>
<th>$S_n$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>72611</td>
<td>16.4</td>
<td>1.5</td>
<td>T-1 (in D) All diagnostics OK</td>
</tr>
<tr>
<td>72612</td>
<td>16.3</td>
<td>1.4</td>
<td>T-1, but trace-T beam failed to fire</td>
</tr>
<tr>
<td>72613</td>
<td>13.8</td>
<td>1.9</td>
<td>T-1 for real !! Low Pb-- source 5A faulted</td>
</tr>
<tr>
<td>72614</td>
<td>16.3</td>
<td>2.3</td>
<td>T-1 better. All sources fired. [T-2 now cancelled- large $\tau_E$]</td>
</tr>
</tbody>
</table>

- Effect of T (in 1 of 7 NB sources) on neutron rate (indicator only!) obvious
- Injected trace-T from 8 NB sources by end of day – increased neutrons $\times 6$

- All systems worked well
- Ran Trace-T experiments on 10 days – 71 shots total with T
- Finished with a final rehearsal of DT-7 (high $P_{DT}$) on December 6
Measured T Diffusion with Trace-T Gas Puff

- Effect of scattering of 14MeV neutrons on collimated detectors measured by moving plasma with trace-T NBI radially
- Followed time evolution of DT neutron emission from ohmically heated D plasma as T puffed at edge diffused to center
- Modelled radial diffusion with combinations of $D$, $v_{\text{pinch}}$ to match

Larry Johnson
Phil Efthimion
Dec 9, 1993 - Day 1 of Full DT: Technical Difficulties and Halting Steps

• After the standard “fiducial” shot around 9 am, we had to break for a technical problem for about 3 hours
• When we resumed conditioning shots with lithium pellets, second one disrupted immediately after the pellet!
• After recovering, we had to break again to fix a neutron detector problem
  – Dale held the crowd in the MBG Auditorium at bay
• Ended first shift with a D-only prototype of the first shot for XP DT-1 (Escaping Alpha Diagnostic Baseline and Checkout), making way for ...
• First TFTR shot (73222) with full T in source 2a (counter) at 4:47pm
  – About $3 \times 10^{17}$ DT neutrons/s ⇒ $P_{DT} \approx 0.8$MW
• After the D-only comparison and several failures of source 5c to inject T, next T shot wasn’t until about 8pm
• Ran one more shot with T to finish first part of DT-1 around 8:30pm
• There was a lot of excitement and tension building in the control room ...
DT Day 1: The Control Room Scene

Only people with a special red badge were allowed in (including a TV crew) ... but there were also a few faces we hadn’t seen in a long time in the room!
Started High Fusion Power Experiment (DT-1) Around 9pm on 12/9/93

- Began with four D-only reference shots (2MA, 28MW) to check conditions
  - Beam fault on first, evidence of slideaways on the third (too much Li) so added small gas puff to maintain density
- At 10:50pm we ran shot T-1 of the plan (73234) with one T source (3MW!) but dropped total power to 28MW out of concern for stability
  - $6.5 \times 10^{17}$ DT neutrons/s $\Rightarrow P_{DT} \approx 1.8$MW (equalling JET PTE)
  - During the NBI, the microphones in the Test Cell began to “snarl” with neutron-induced shot noise and the TV camera images were blanketed by “snow”
  - Dale’s “Fusion Power” diagnostic (TV image of a scintillator behind a mask) lit up
- At 11:07 we ran shot T-2 with 4 T, 5 D sources (original XP had 5 T, 7 D)
- From the Task Force Leader’s logbook:
  - 73235 T-2 (5co/4ctr, T in 1a,2a,4c,5a) EEYAH!
    - $1.4 \times 10^{18}$ DT neutrons/s $\Rightarrow P_{DT} \approx 3.9$MW with 24.3MW NBI ($Q = 0.16$)
- Although we had not quite reached our 5MW goal, it was decided to stick with the plan and take the D-only comparison shot to finish off a long day
The Reaction to the Reactions
DT Day 2: Stick to the Plan or Go For It?

- After 3 OH shots with Li and several D-only setup shots with ~25MW NBI, first DT shot didn’t come until after 1pm
- Worked our way through shots T-3 and T-4 (5 T sources) by 3pm
  - Increased NBI to 5T, 6D sources (73255)
  - $2.0 \times 10^{18}$ DT neutrons/s $\Rightarrow P_{DT} \approx 5.5$MW with 29.2MW NBI ($Q = 0.19$)
- We had followed the XP and reached our goal, but more seemed possible ...
- Serious discussion ensued in the control room: we went for it!
- Ran several 30MW D-only shots to prepare for a 7 T source shot
  - Progress delayed for an hour by a mysterious TF fault
- Finally took a 7 T, 4 D source shot (73268) at 8:02pm
  - $2.2 \times 10^{18}$ DT neutrons/s $\Rightarrow P_{DT} \approx 6.2$MW with 29.6MW NBI ($Q = 0.21$)
- After more argument and a 2 hour delay to fix the TF problem, we boldly headed into terra incognita by running a shot (73273) with 8 T sources only
  - $0.8 \times 10^{18}$ DT neutrons/s $\Rightarrow P_{DT} \approx 2.2$MW with 22.5MW NBI ($Q = 0.10$)
  - We had gone “over the top” in the DT mixture
Serious Analysis (and Celebration) Now Began

- First discussion of results was at Physics Meeting on Monday 12/13/93
- Lots of work over the weekend by Data Analysis and Diagnostic physicists
  - Larry Johnson was tasked to assess the fusion power we achieved
  - Neutron rates spanned more than $10^5$: showed good consistency between methods

- “All hands” meeting on Wed 12/15 to congratulate and thank the Lab staff
  - PU President Harold Shapiro visited to convey the university’s appreciation
Significant Isotope Effect Apparent from Day 1

- The neutral beams worked better in T: higher voltage and power
- We learned immediately that there was still considerable D influx from the walls, despite our efforts to condition them to reduce the influx
  - We needed to run T-NBI rich to achieve optimum reactivity
- TRANSP calculated ~50% of increase in $T_e$ could have been alpha heating
- $\chi_i$ decreased by ~2 in DT plasma
  - Increase in $T_i$ not entirely welcome: too high for optimum reactivity
  - Decreasing $T_i$, at constant pressure would have improved DT/DD reactivity ratio
- These initial indications of isotope scaling held up in later experiments
Alpha loss rate did not increase strongly with fusion power

- Lost-alpha detectors were ready for planned current scans starting in the following week
- Spurred refinement of TAE theory

TAE range fluctuations did not increase in DT plasmas

- Later detected by pellet-alpha charge-exchange
- CHERS also measured thermal helium ash

Thermalizing alphas detected by CHERS
Still Under Threat of TFTR Termination, We Pushed on with the DT Plan into the New Year

- We continued experiments in the following week, including
  - Alpha loss vs plasma current
  - Alpha heating investigation
  - Tritium accounting
  - ICRF with trace tritium

- After the holiday break, we resumed operation in Feb 1994 and spent the first month on ICRH experiments in DT

- More DT experiments on high-\(l_i\) plasmas and limiter H-modes followed

- In April, we began preparation for a push to 10MW fusion power (DT-8)
  - This meant higher current and more power from the NBI system
  - We began analysis and review of increasing the toroidal field to 6T (from 5.2T)

- DT operation became routine
By the APS-DPP Meeting in November 1994, TFTR Had Completed an *Annus Mirabilis*

- On May 27, reached $P_{DT} \approx 9.3\text{MW}$ with $29.2\text{MW NBI}$ transiently ($Q^* = 0.35$!): shot 76778 with 6.5MJ stored energy disrupted with a jaw-dropping bang
  - This was our “best shot” at the time of the IAEA FEC in Seville
- In mid October, resumed the power push using higher TF (5.5T at 2.52m) and unleashing the NBI system
- On Nov 2, reached $P_{DT} \approx 10.7\text{MW}$ for $\sim 0.05\text{s}$ with $39.5\text{MW NBI}$ (80539)

- Meanwhile, the Lab had won a reprieve for TFTR which was funded for continuation of the DT program in 1995
  - In 1995, we prepared a proposal for the TFTR “Advanced Performance” project
    - Exploit new regimes, *e.g.* “reversed shear”
    - Favorably reviewed and started but the funding was not available to complete it
TFTR Achieved More than Three Years of Safe and Successful D-T Operation

- 1031 D-T shots and >23000 high-power shots after the start of D-T
  - Machine availability comparable to that during operation in deuterium
  - We proved that it was possible to conduct productive and innovative research despite the strictures of operating a nuclear facility
- 952 kCi (99g) of tritium were processed
  - Tritium Purification System operated in a closed cycle during final run
- Successful maintenance and operation of an activated and tritium contaminated facility was demonstrated.
  - Machine under vacuum for >3 years of continuous operation May 93 – Jul 96
  - ICRF launchers and new diagnostics installed during opening Aug - Oct ‘96
  - Resumed operation for final run Dec ‘96 through April 4, ‘97
- A wealth of scientific data about DT plasmas and alpha particles was gathered: some of it remains to be analyzed
- A credit to the scientific, engineering and technical staff of PPPL and of our collaborators
TFTR Achieved Many of the Parameters Expected to be Produced in ITER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TFTR</th>
<th>ITER</th>
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<tbody>
<tr>
<td>Central pressure $\beta(0)$ %</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Collision frequency $\nu_e^* (10^{-2})$</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Electron density $(10^{20} \text{ m}^{-3})$</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$T_i$/keV)/$T_e$ (keV)</td>
<td>36/13</td>
<td>18/20</td>
</tr>
<tr>
<td>Fuel mixture D/T</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Toroidal field $B_T$ (T)</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Fusion Power Density (MWm$^{-3}$)</td>
<td>2.8</td>
<td>1</td>
</tr>
</tbody>
</table>

• Confinement was the outstanding issue *and remains so*
  Confinement time (s)                0.2        2.5

• Most reliable solution: *bigger device with higher current*
  Normalized gyro-radius $\rho_i/a (10^{-3})$ 6.5        2

Ref: http://www.iter.org/a/index_use_5.htm