# 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

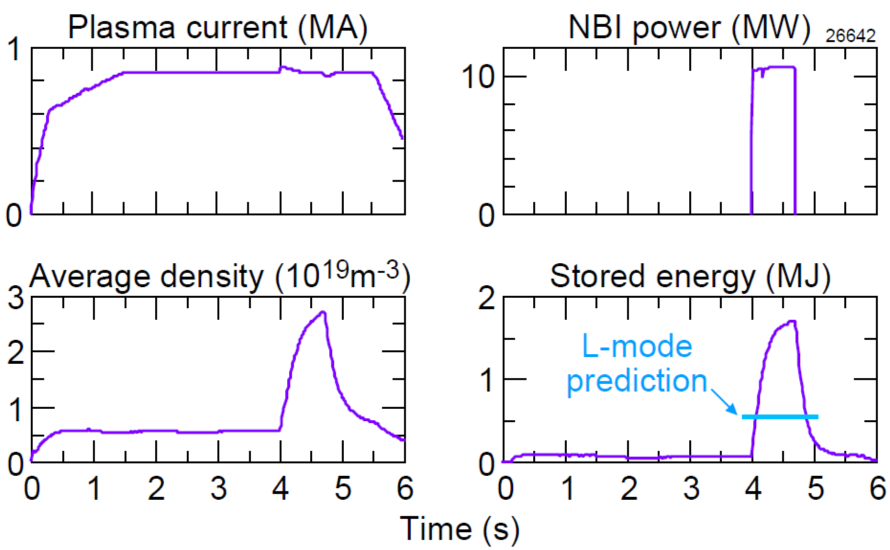


- Reliable operation at current <1MA with pulse lengths up to 1s
- Gas and frozen pellet fueling
  - Empirical density limits: Murakami → Hugill (later → Greenwald)
- Neutral beam heating up to ~8MW, RF heating up to ~5MW (ion cyclotron, electron cyclotron, lower hybrid)
  - High ion temperatures, ~ 7keV, with NBI; first studies of β-limits
- Compressional heating (transient benefit)
- Global confinement scalings:
  - "Alcator" scaling for ohmic heating (∝ 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 (~2 × L-mode)

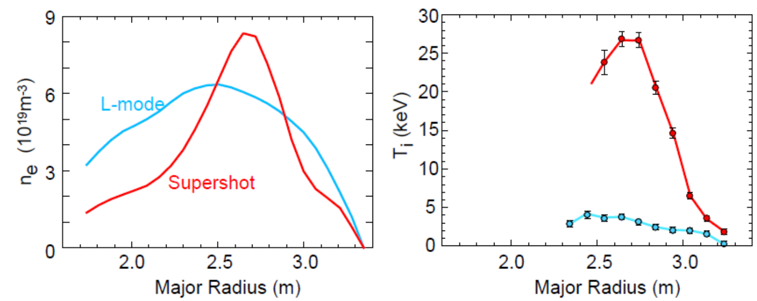
# In 1986, the L-mode Deadlock Was Broken When "Supershots" Were Discovered in TFTR

*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




$P_{NBI}$ = 22MW, $I_p$ = 1.4MA, $B_T$ = 4.7T

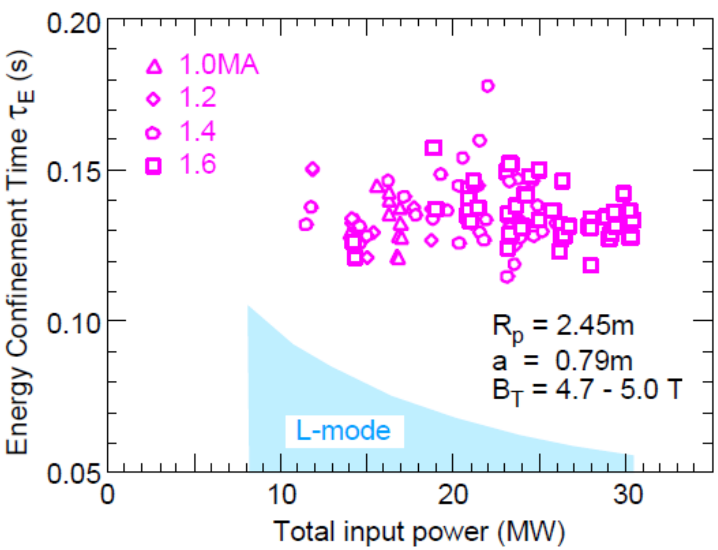


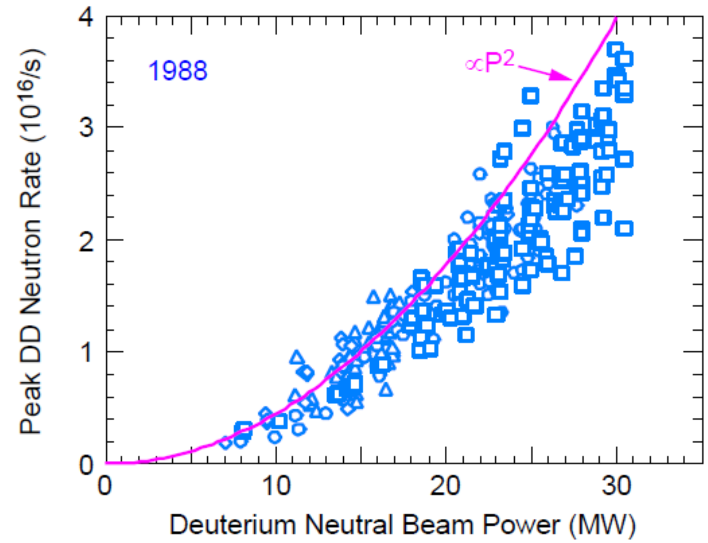

**$n_e(0)\ T_i(0)\ \tau_E$ increased by factor 30!**

- 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

*TFTR*




- Confinement almost independent of current and power
  - Unlike H-mode plasmas
- DD reactivity scaled very favorably with power

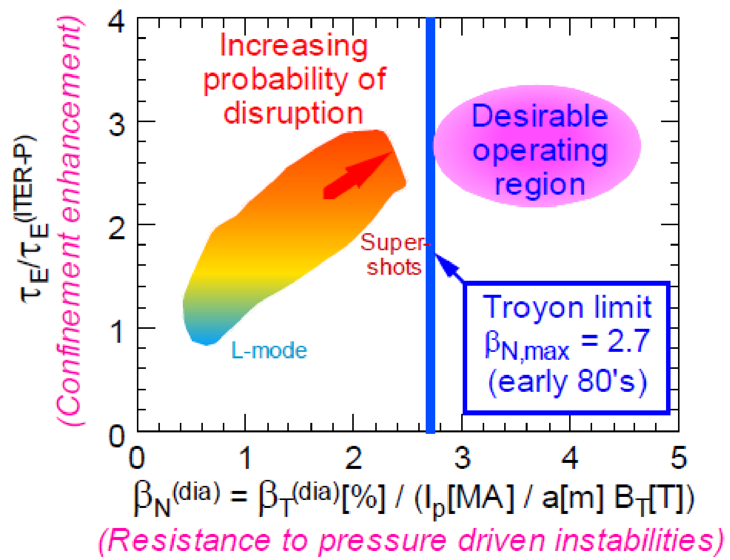
– TRANSP simulations suggested DT fusion power of 8MW possible, *but*

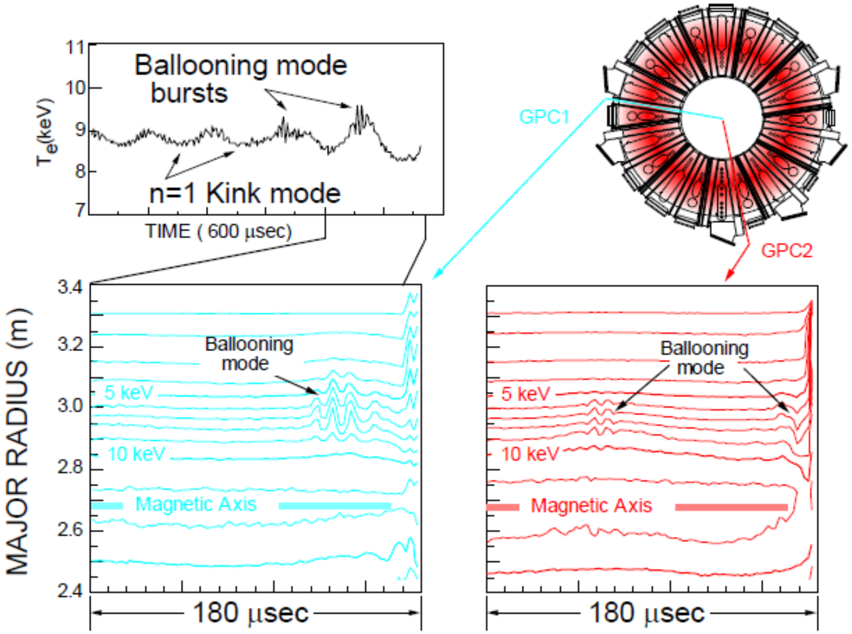
– Need to increase the plasma current to avoid β-limit

– Need to develop ways to reduce edge influxes at higher current and power

# Supershots Limited by Pressure-Driven Instabilities Below Troyon-Scaling Limit

*TFTR*




- Peaked profiles still beneficial for fusion-relevant $\beta^*$ [$= 2\mu_0\sqrt{(\int p^2 dV/V)}/B_T^2$]
- 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, *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.* $H_{\alpha}$: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" ($Q \sim 0.5$) with $E \sim 10$MJ per pulse
  - Fusion alpha confinement and thermalization ⇐ diagnostic progress
  - Alpha heating ⇐ a stretch for $Q < 1$
  - Effects of alphas on stability & transport ⇐ burgeoning theoretical work
  - Effects of isotopic mix
  - ICRH in DT
  - Fueling with T pellets (in addition to NBI fueling)
  - Tritium retention

  (ICRH in DT, Fueling with T pellets, Tritium retention) ⇐ prototype for BPX
- 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 ($\Rightarrow$ more alphas) would increase likelihood of disruption
- Analyzed recent TFTR D supershots and JET PTE experience
  – Substituting 50:50 DT in TRANSP model gave $P_{DT}/P_{DD} \approx 162 \pm 10$
  – With 30MW NBI, we had about an even chance of reaching 7MW
- Settled on a goal of $P_{DT}$ = 5MW 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



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

- 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

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

  – Effect of T (in 1 of 7 NB sources) on neutron rate (indicator only!) obvious

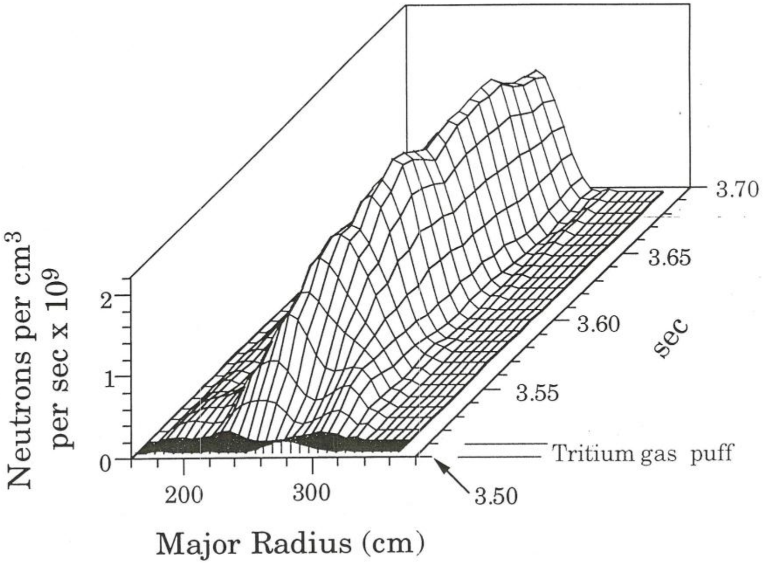
  – Injected trace-T from 8 NB sources by end of day – increased neutrons $\times 6$

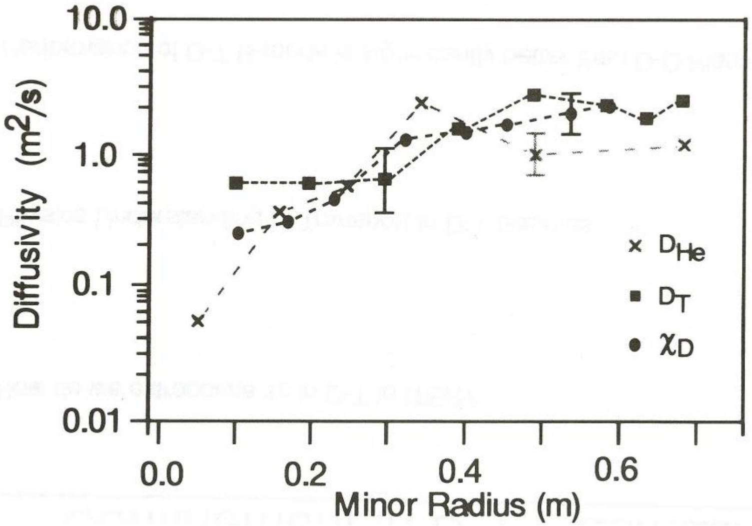
- All systems worked well
- Ran Trace-T experiments on 10 days – 71 shots total with T
- Finished with a final rehearsal of DT-7 (high $P_{DT}$) on December 6

# 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, $v_{pinch}$ 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 $\Rightarrow P_{DT} \approx 0.8$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 $\Rightarrow$ $P_{DT} \approx$ 1.8MW** (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 $\Rightarrow$ $P_{DT} \approx$ 3.9MW 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?

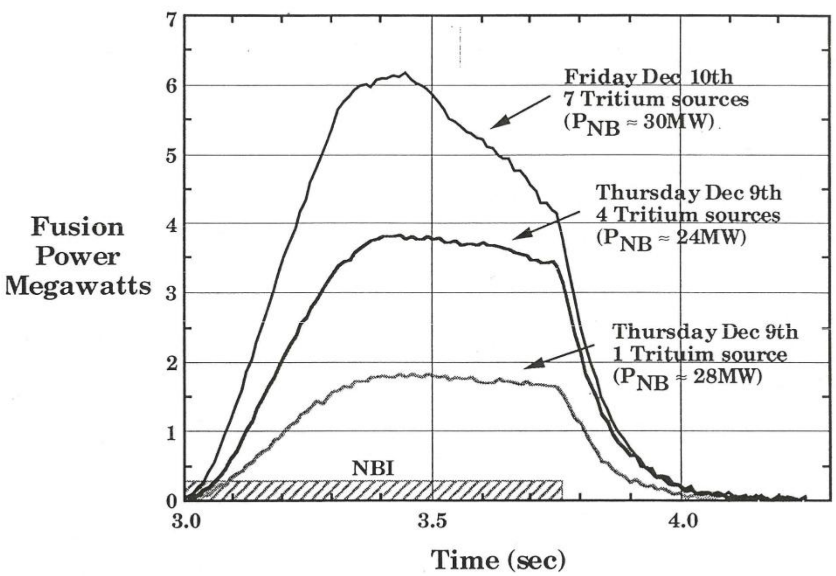


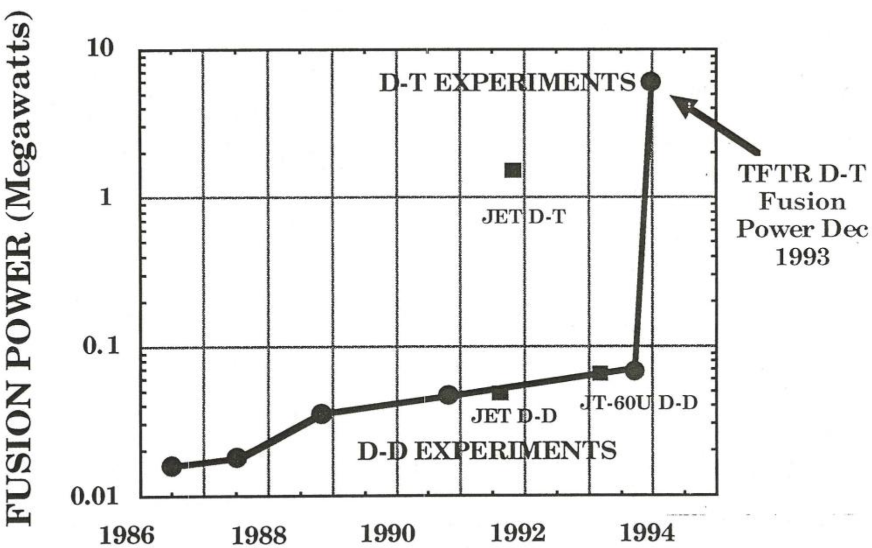
- After 3 OH shots with Li and several D-only setup shots with ~25MW NBI, first DT shot didn't come until after 1pm
- Worked our way through shots T-3 and T-4 (5 T sources) by 3pm
  - Increased NBI to 5T, 6D sources (73255)
  - **2.0 $\times 10^{18}$ DT neutrons/s $\Rightarrow P_{DT} \approx$ 5.5MW with 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 $\Rightarrow P_{DT} \approx$ 6.2MW 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 $\Rightarrow P_{DT} \approx$ 2.2MW with 22.5MW NBI (Q = 0.10)**
  - We had gone "over the top" in the DT mixture

# Serious Analysis (and Celebration) Now Began

*TFTR*

- 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



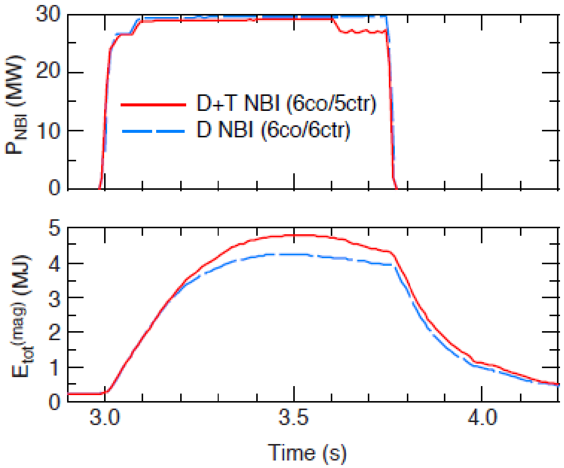



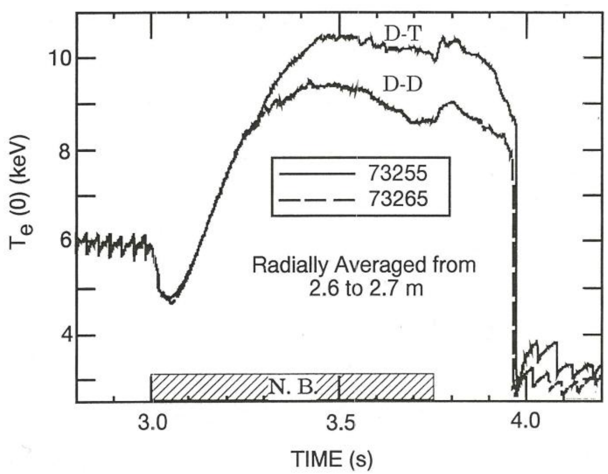

- "All hands" meeting on Wed 12/15 to congratulate and thank the Lab staff
  - PU President Harold Shapiro visited to convey the university's appreciation

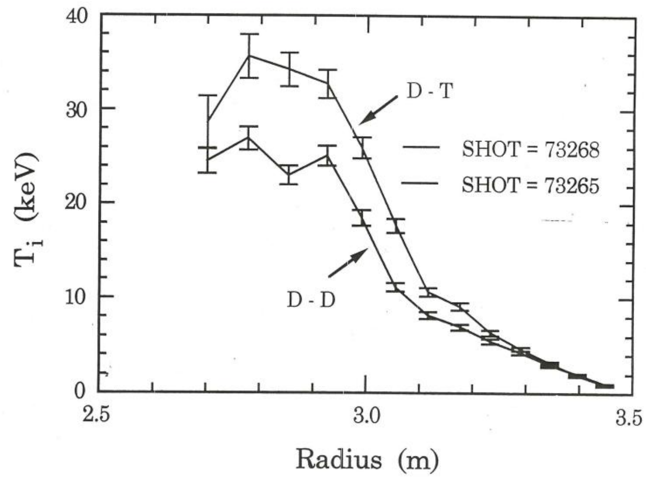
# Significant Isotope Effect Apparent from Day 1

*TFTR*

- 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



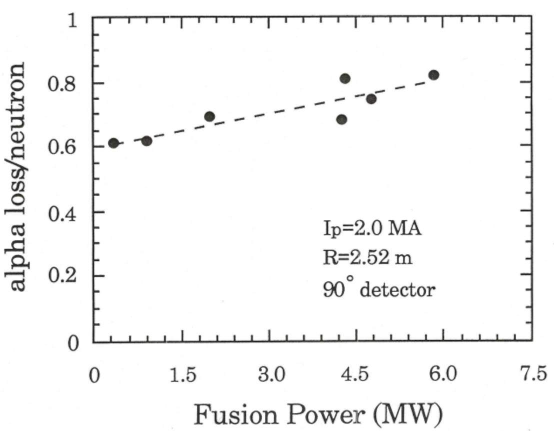




- TRANSP calculated ~50% of increase in $T_e$ could have been alpha heating
- $\chi_i$ decreased by ~2 in DT plasma
  - Increase in $T_i$ not entirely welcome: too high for optimum reactivity
  - Decreasing $T_i$, at constant pressure would have improved DT/DD reactivity ratio
- These initial indications of isotope scaling held up in later experiments

# Alpha Particle Physics from Days 1 & 2

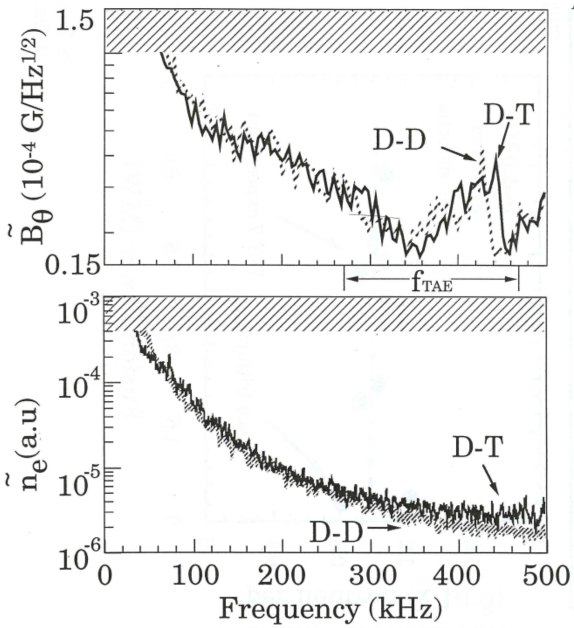
*TFTR*

Alpha loss rate did not increase strongly with fusion power



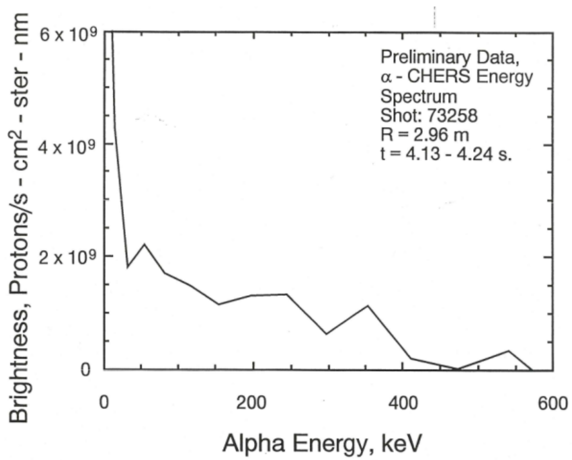

- Lost-alpha detectors were ready for planned current scans starting in the following week

TAE range fluctuations did not increase in DT plasmas




- Spurred refinement of TAE theory

Thermalizing alphas detected by CHERS



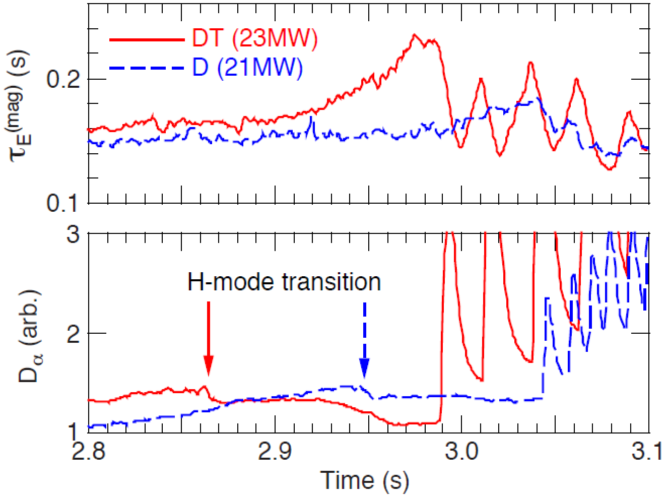

- Later detected by pellet-alpha charge-exchange
- CHERS also measured thermal helium ash

# 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

Both $\tau_E$ and ELM size increased in DT plasmas

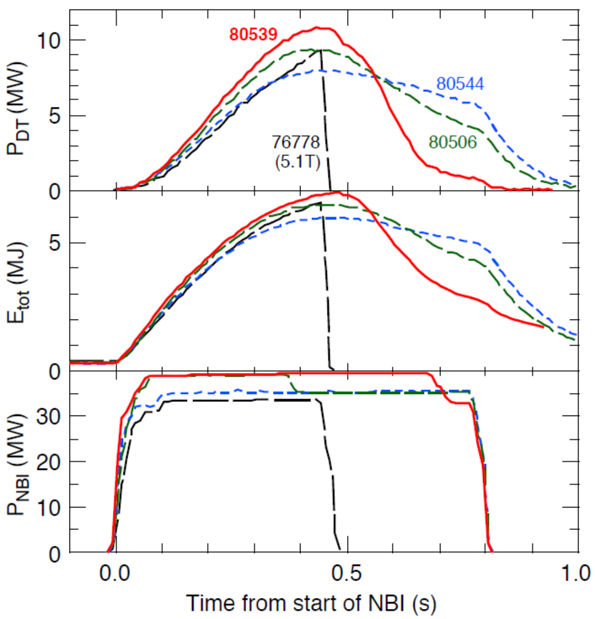



- In April, we began preparation for a push to 10MW fusion power (DT-8)
  - This meant higher current and more power from the NBI system
  - We began analysis and review of increasing the toroidal field to 6T (from 5.2T)
- **DT operation became routine**

# By the APS-DPP Meeting in November 1994, TFTR Had Completed an *Annus Mirabilis*



- On May 27, reached **$P_{DT}$ ≈ 9.3MW with 29.2MW 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 **$P_{DT}$ ≈ 10.7MW for ~0.05s with 39.5MW 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



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

- 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*