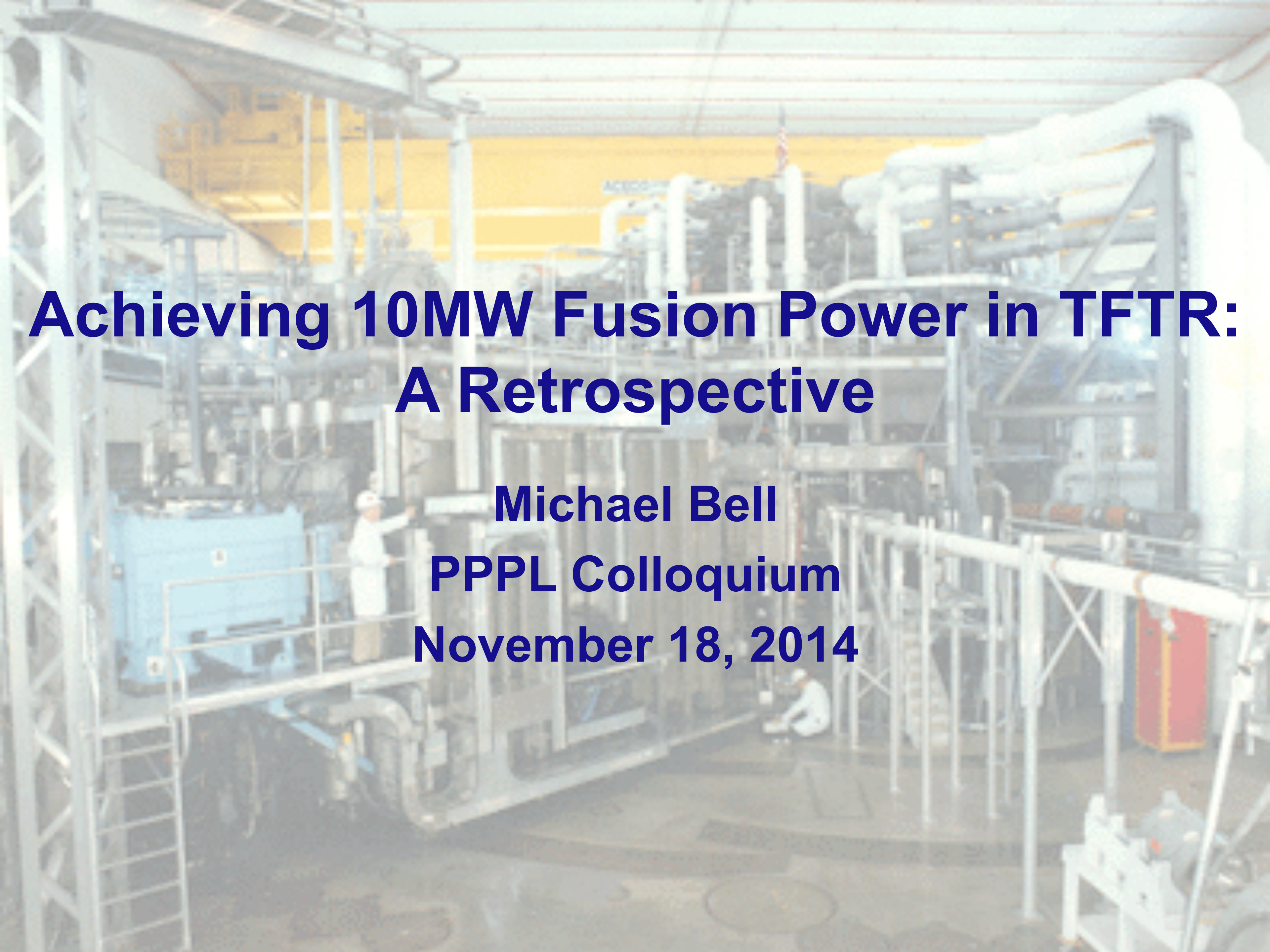


Achieving 10MW Fusion Power in TFTR: A Retrospective

Michael Bell

PPPL Colloquium

November 18, 2014

TFTR Began in 1973

- Following reports of record temperatures in the Russian tokamak T-3 in 1968, tokamaks of all sizes were being built worldwide in the 70s

1973 July: Bob Hirsch (Head of Fusion at AEC) called for a DT burning tokamak to be built at Oak Ridge National Laboratory

1973 Dec: At meeting to review nascent plans for this, Harold Furth stated

"If all you want is neutrons, here is how to do it"

and proposed Two Component Tokamak using Neutral Beam Injection

1974: PPPL (Gottlieb, Furth, Rutherford & Jassby) and Westinghouse developed TCT concept

– Smaller and less ambitious step than the ORNL project

1974 July: Fusion Power Coordinating Committee (FPCC) recommended building the Tokamak Fusion Test Reactor (TFTR) at PPPL

– Later that month, Hirsch approved the project and the site, *and*

– also approved PDX at PPPL *and* DIII at GA

TFTR Objectives Originally Quite Modest

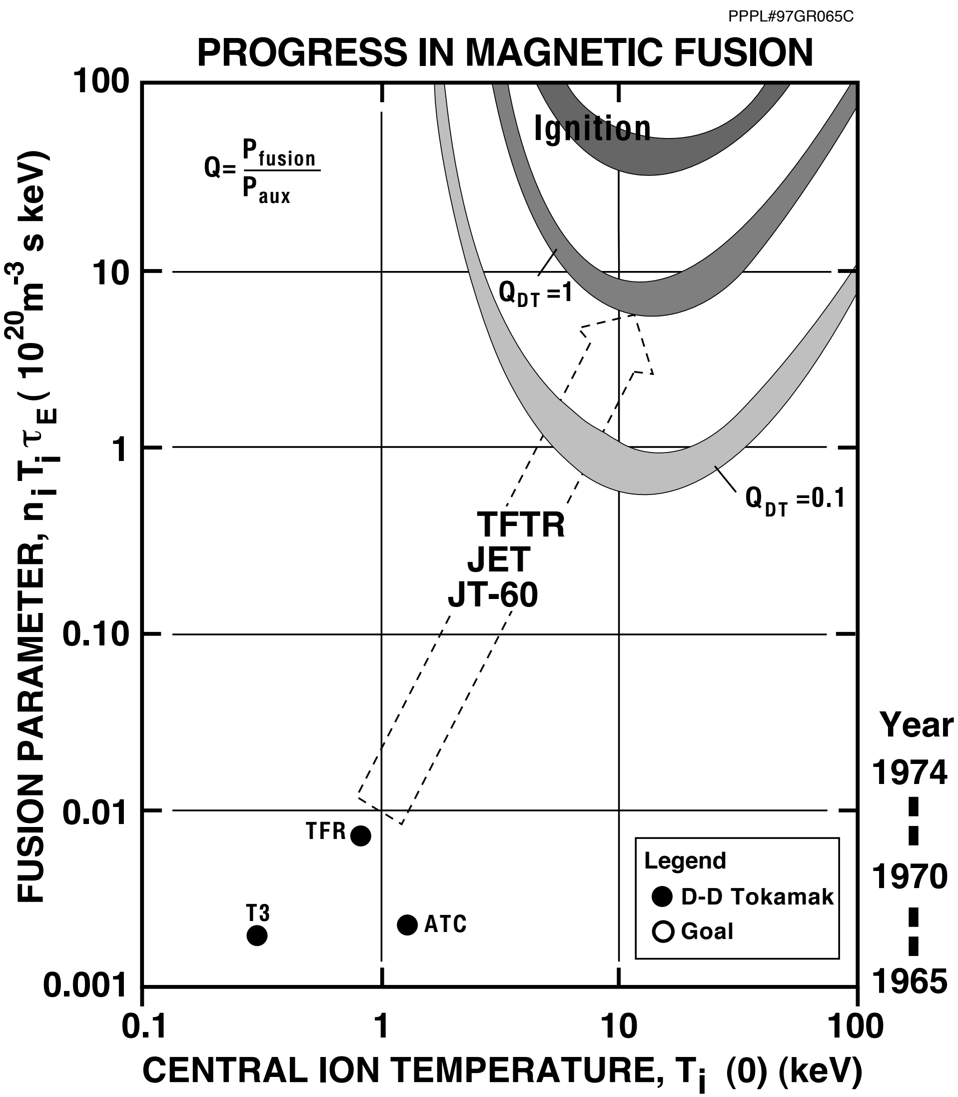
- Produce 1 – 10 MegaJoules of thermonuclear energy per pulse … with neutral beam injection in order to:

  1. Demonstrate fusion energy production from the burning, on a pulsed basis, of deuterium and tritium;
  2. Study the plasma physics of large tokamaks;
  3. Gain experience in the solution of engineering problems associated with large fusion systems.

- This was expected to require:

  1. Achieving a “Lawson parameter” $n\tau_E \sim 10^{19}\,m^{-3}.s$;
  2. 20MW of 120keV neutral beam injection;
  3. Toroidal magnetic field $B_T = 5T$ and
     Toroidal plasma current $I_p = 2.5MA$

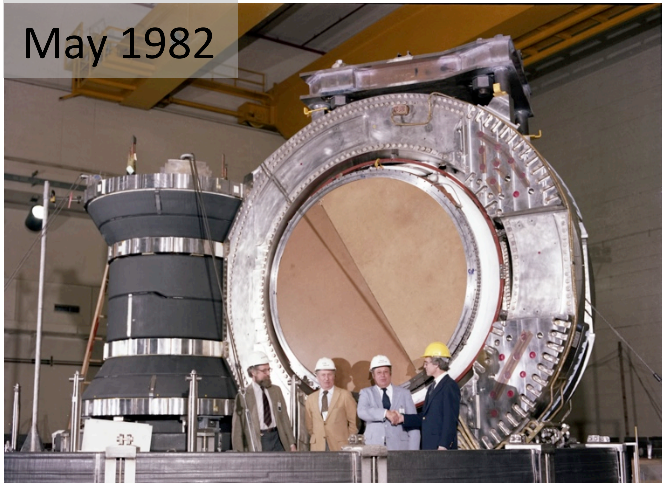
A Huge Step From Where We Were in 1974



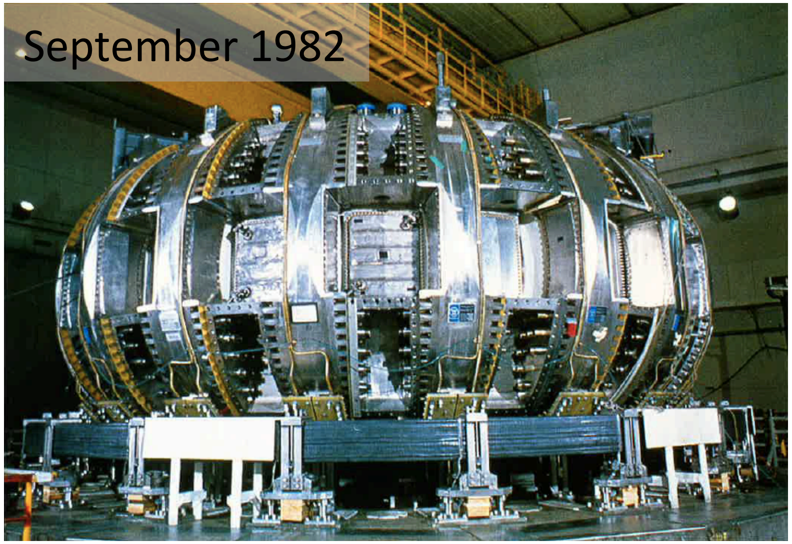
<u>Extrapolation factors from operating tokamaks</u>

Plasma current:	10
Toroidal field:	2
Magnetic energy:	10^2
Pulse length	10^3
Auxiliary heating:	10^2
Ion temperature:	10
$nT\tau$:	10^3
Fuel:	DT
Fusion power:	10^8

TFTR Constructed 1976 - 1982

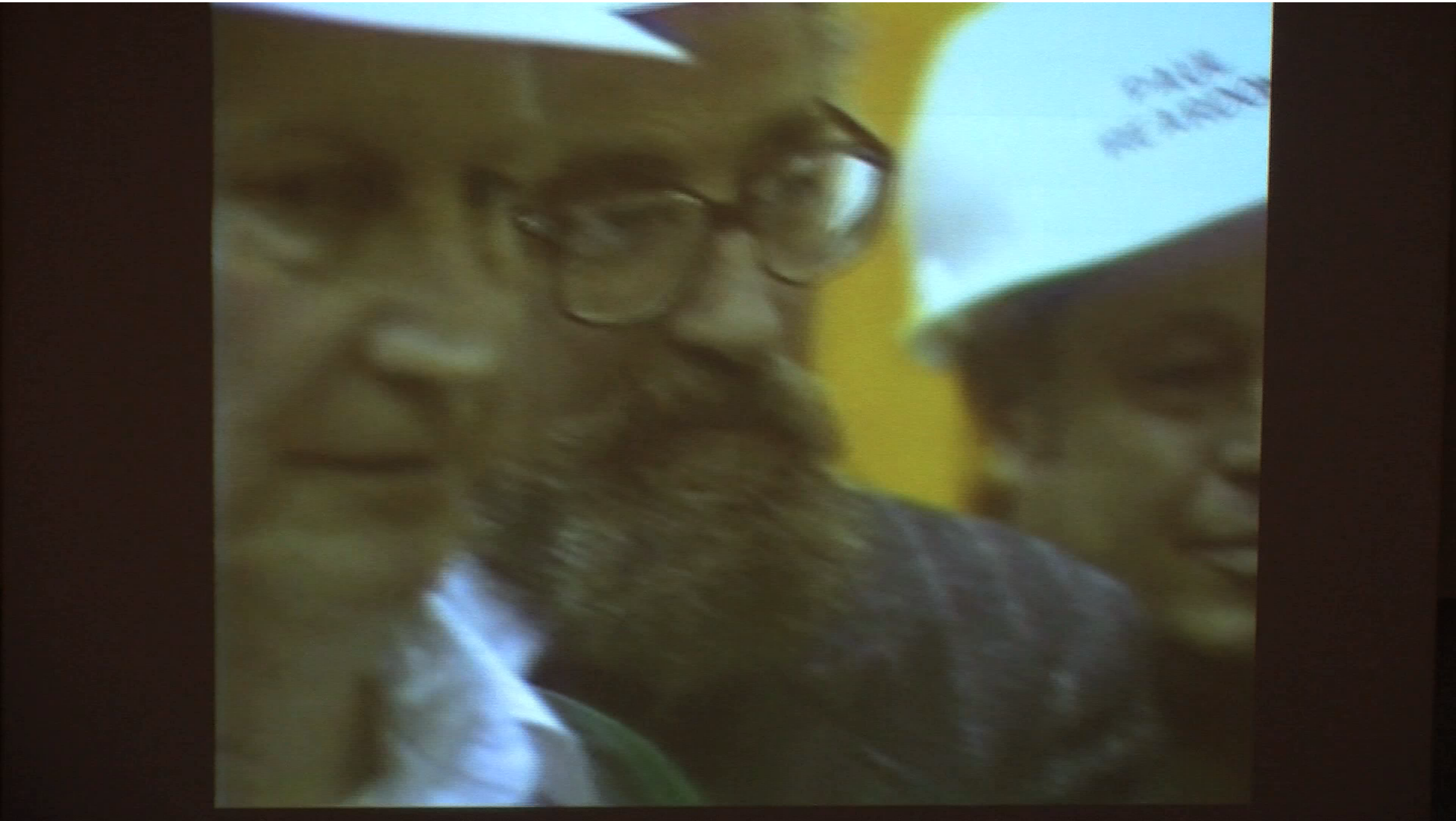


Harold Furth, Don Grove, Paul Reardon, Milt Johnson



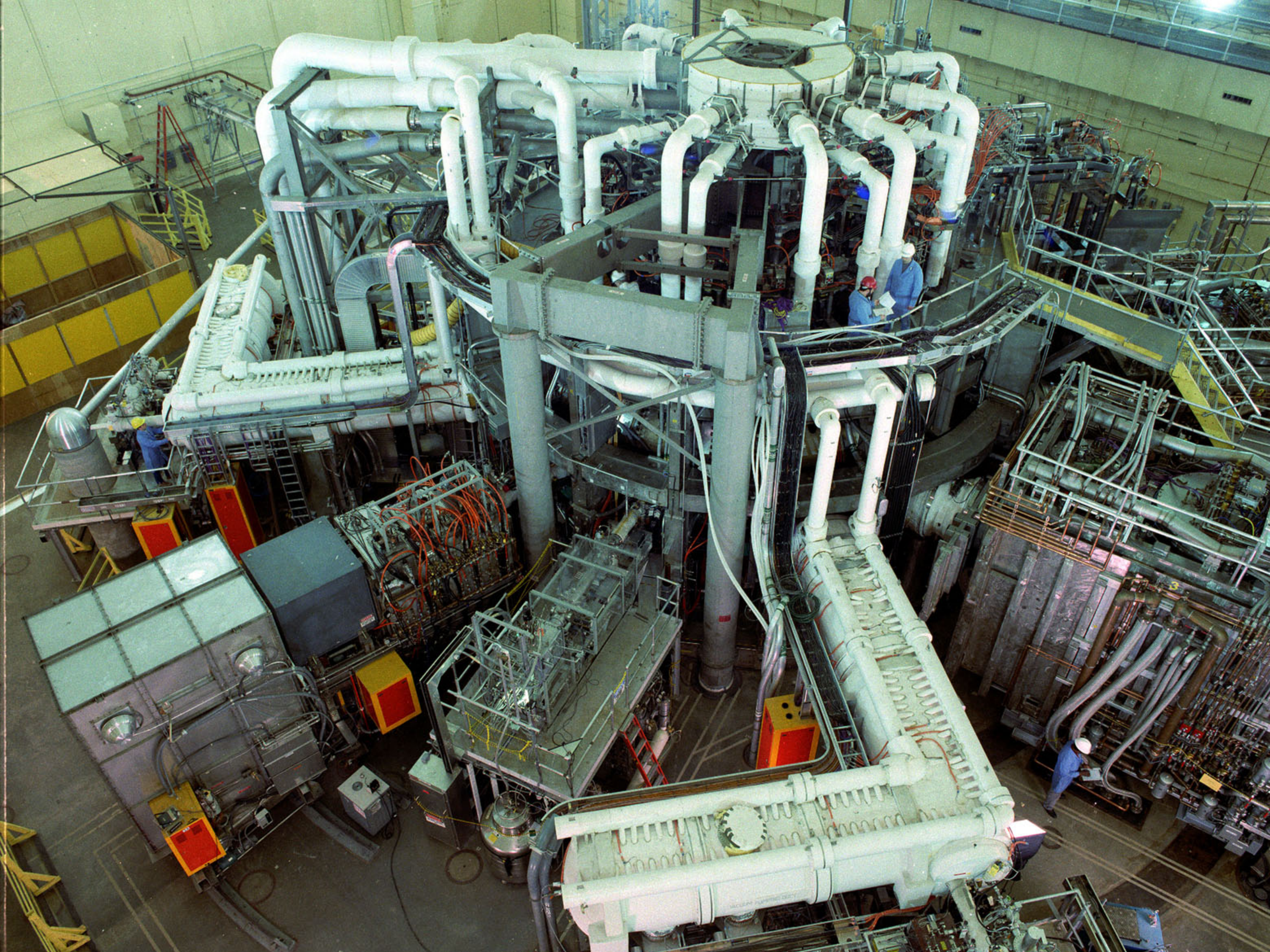
First Plasma on December 24, 1983

- Harold Furth had told us to stop at 2am *but*
- *The wall clock mysteriously stopped at 1:55am for about an hour*



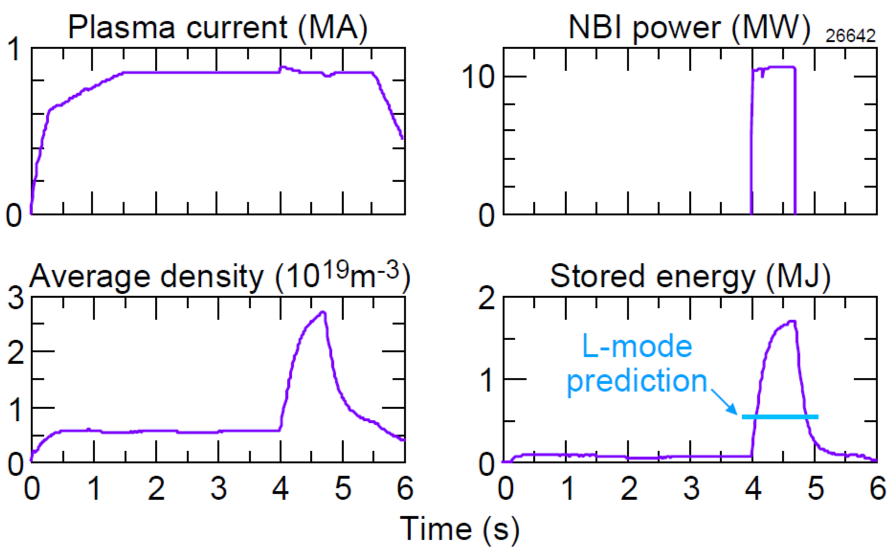
Status of Tokamak Physics in 1983

- 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 in PLT; first studies of β-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 ...)
    $\Rightarrow$ 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 $\times$ L-mode)

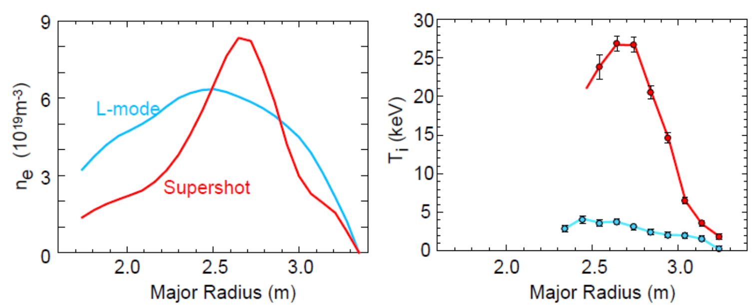


In 1986, the L-mode Deadlock Was Broken When "Supershots" Were Discovered in TFTR

- 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, confinement improved



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

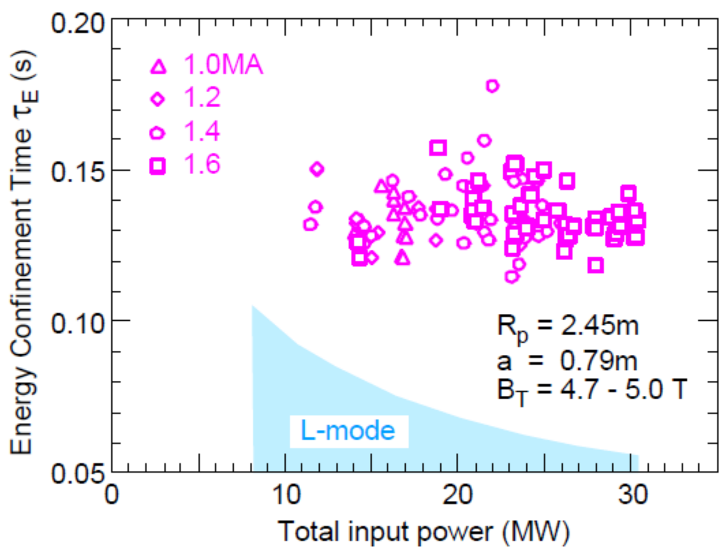


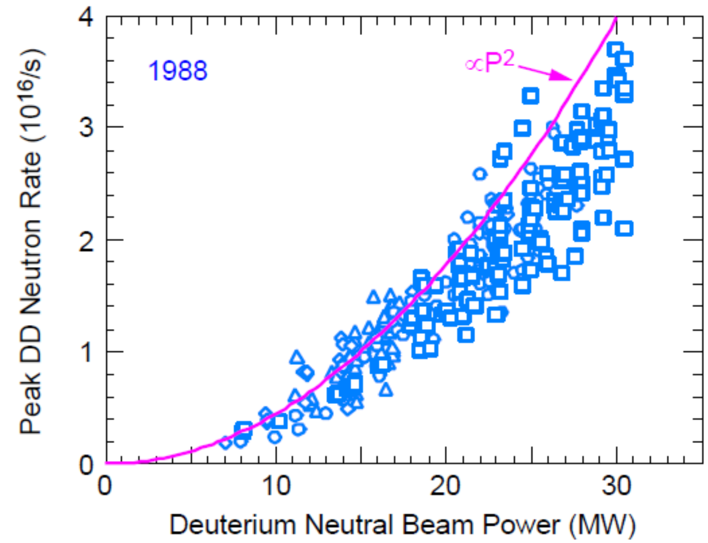
$n_e(0)\ T_i(0)\ \tau_E$ increased by factor 30!

- Subsequently developed techniques, including Li wall coating, to reduce influx from limiter ⇒ eventually pushed super shots to 2.5MA, 40MW
- *Supershots were excellent vehicles for studying high-temperature plasmas and fusion physics but they had to be handled with care*

Supershots Did Not Follow L-mode Empirical Scaling

TFTR





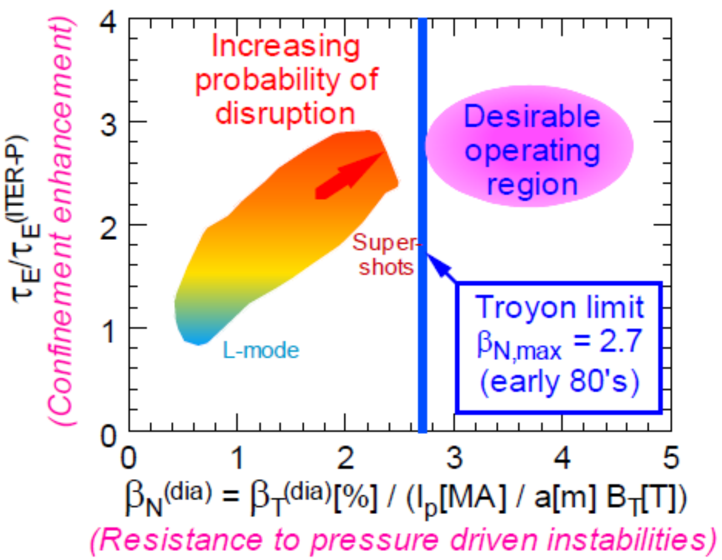
- Confinement almost independent of current and power
  - Unlike H-mode plasmas
- DD reactivity scaled very favorably with power

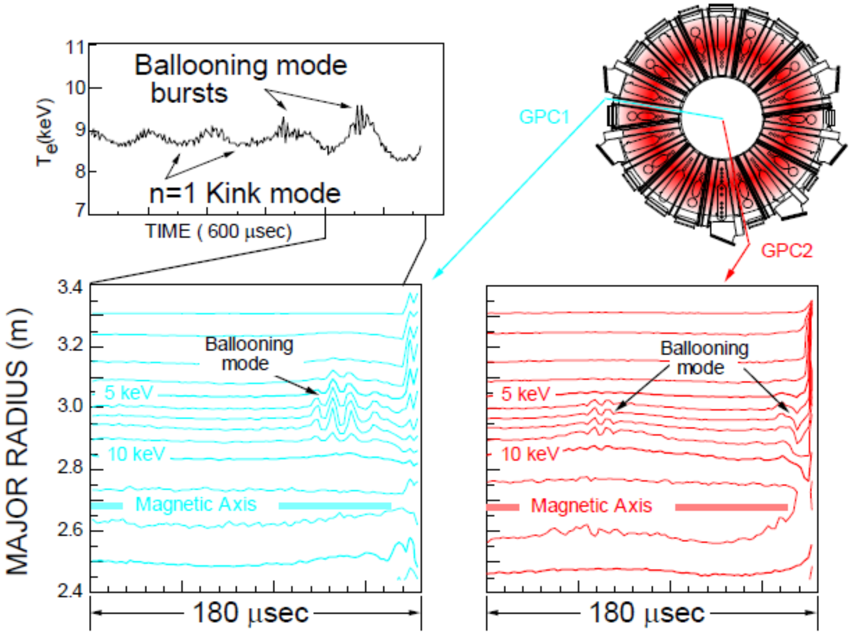
– TRANSP simulations suggested DT fusion power of 8MW possible, *but*

– 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





- Peaked profiles still beneficial for fusion-relevant β^* [$= 2\mu_0\sqrt{(\int p^2 dV/V)}/B_T^2$]
- 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

In 1991, Developed Detailed Plan for DT Campaign

- Earlier plans delayed then abandoned 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" (Q ~ 0.5) with E ~ 10MJ 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
  - Tritium retention
  - Fueling with T pellets (injector dropped in 1993)

  ⇐ 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!*

Preparing for D-T Involved Many Elements

- Commissioning tritium handling systems
  - Operator training and certification
  - Tritium and radiation monitoring
- Modifying vacuum & gas injection systems
- Modifying HVAC for negative pressure
- Seismic qualification of critical systems
- Flourinert system to cool TF coils
- Modifying and upgrading diagnostics
  - Increased shielding
  - Alpha-particle physics diagnostics
- Modifying Neutral Beam system for tritium
- In 2014 dollars ~$95M project
  - >80% done in 2 years
  - ***While continuing to operate TFTR!***

Tritium Receiving Glove Box

Approval to Operate TFTR with Tritium Required Large Increase in Formality and Rigor

- TFTR became classified as a Category 3 nuclear facility
- Instituted formal training, qualification and certification programs for Tritium Operators and Chief Operating Engineers
- DOE increased emphasis on safety and environmental concerns just as we were preparing for D-T
  - Environmental and safety problems in DOE defense facilities
  - Tritium release occurred at BNL
- DOE, under Secretary Watkins, sent its “Tiger Teams” in 1990
  - Wake up call for us on expectations for a nuclear facility
- Successfully implemented DOE Conduct of Operations requirements
- Despite the increased formality, TFTR produced a record number of PRLs during its DT phase!

Could We Do the TFTR D-T Program Without a Major Machine Failure?

- Plan was to operate in D-T for less than a year
  - By 1993, PPPL was proposing to build TPX to succeed TFTR
- Did not have remote maintenance other than long handled tools
- Eventually operated TFTR for three years in DT without breaking vacuum
  - Surmounted unexpected problems such as repairing a vacuum leak
  - Abandoning the “igloo” shield preserved access to the vacuum vessel
- We qualified the neutral beam source repair facility for handling tritium contaminated sources
- Flourinert cooling enabled us to live with the leaks in the TF coils
- In 1996, vented the machine and installed new diagnostics and a launcher for IBW RF heating
- Demonstrated to our sponsors and **to the world** that we can operate and maintain a DT facility!

In Planning D-T Experiments, There was Tension Between Performance and Reliability of Operation

- Wanted reliable, reproducible conditions to compare DT vs. D-only
  - Higher DT power (⇒ more alpha particles) would increase likelihood of disruption
- Preparation of Experiment Proposals (XPs) organized by Task Forces

  Fusion Power (led by Jim Strachan)

  D-T Technology (Kingston Owens)

  D-T Transport and Advanced Physics (Mike Zarnstorff)
- Analyzed recent TFTR D super shots 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 a pushover either

Rehearsed Scenarios Many Times Before Day 1

- TFTR outage from November 92 through May 93 for D-T preparation
  - Tritium system commissioning: started handling trace T in May
- Restarted tokamak and NB operation and conditioned in June
- 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 (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!*
  - Even more scrutiny of operations and insistence on procedures
- Resumed operation in October then broke for APS meeting (Nov 1-5)
- After final checks of all systems, ready for Trace-Tritium experiments

Many Diagnostics Installed and Others Modified to Measure Fusion Alpha Particles

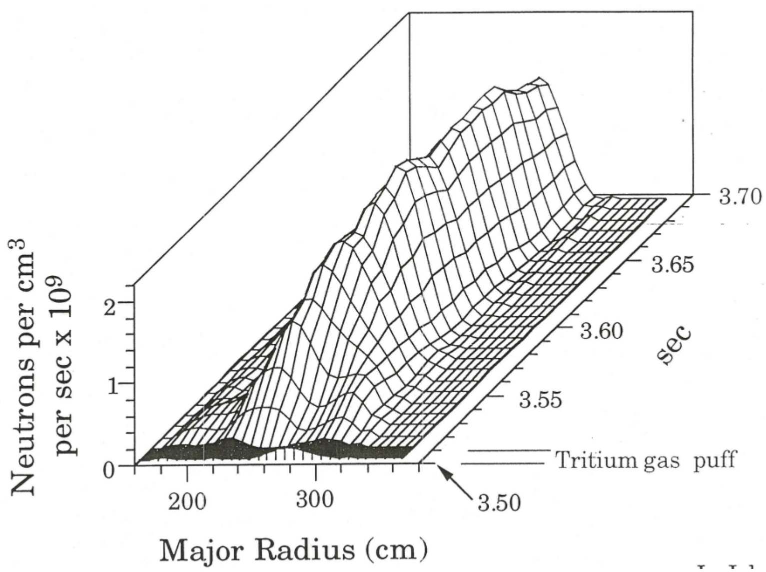
Alpha birth profile	10-Channel Neutron Collimator
Alpha loss rate	Poloidal array of detectors Movable probes
Confined alphas	Alpha CHERS (U Wisc) Alpha-Li pellet charge exchange (GA, Ioffe) Spectroscopy with Li pellet (NIFS, LANL) Alpha gyrotron scattering (MIT, Lodestar)
Alpha transport and ash	He CHERS

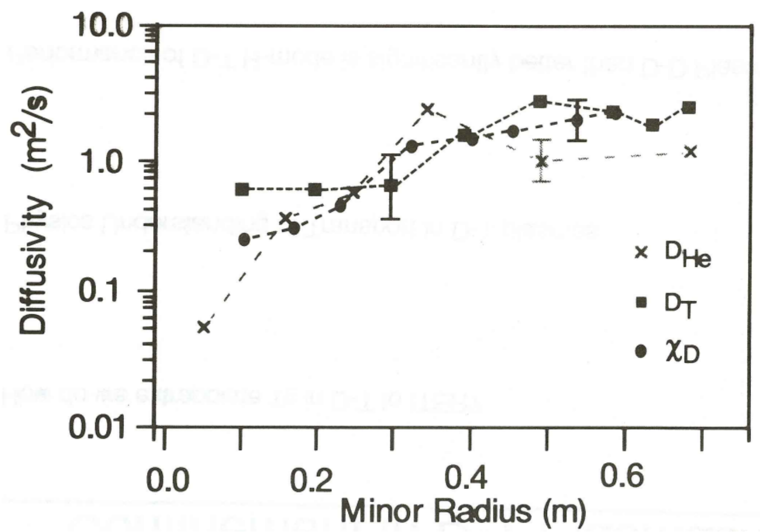
- Some needed setup and calibration with 14MeV neutrons and 3.5MeV alphas

“Trace Tritium” Phase Used to Check Tritium System, Experimental Methods and Diagnostics

- ~2% T_2 in D_2 mixture delivered to gas injectors and NB sources
- First trace-T NBI on Friday November 12, 1993
- Ran 3 Trace-T experiments over 10 days – 71 shots total with T
- All systems worked well, calibrated diagnostics and obtained new data

Measured Tritium Diffusion with Trace-T Gas Puff





- *But this was just the warm-up act for the main event …*

Larry Johnson, Phil Efthimion

Day 1 of Full DT – Dec 9, 1993: 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 Meade held the media gathered in the MBG Auditorium at bay
- Ended shift with a D-only prototype of the first low-power DT shot for XP DT-1 (Escaping Alpha Diagnostic Baseline and Checkout)
- First TFTR shot (73222) with full T in source 2a (counter) at 4:47pm
  - About 3×10^{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)
  - Made small adjustments to conditions
- 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
  - **6.5×10^{17} DT neutrons/s ⇒ $P_{DT} \approx$ 1.8MW** (equalling JET PTE)
  - Audio from the Test Cell began to "snarl" with neutron-induced shot noise and the TV camera images were blanketed by "snow"
  - The "Fusion Power" indicator (TV image of a scintillator) 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!**

  - **1.4×10^{18} DT neutrons/s ⇒ $P_{DT} \approx$ 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

Countdown to the First High-Power DT Shot

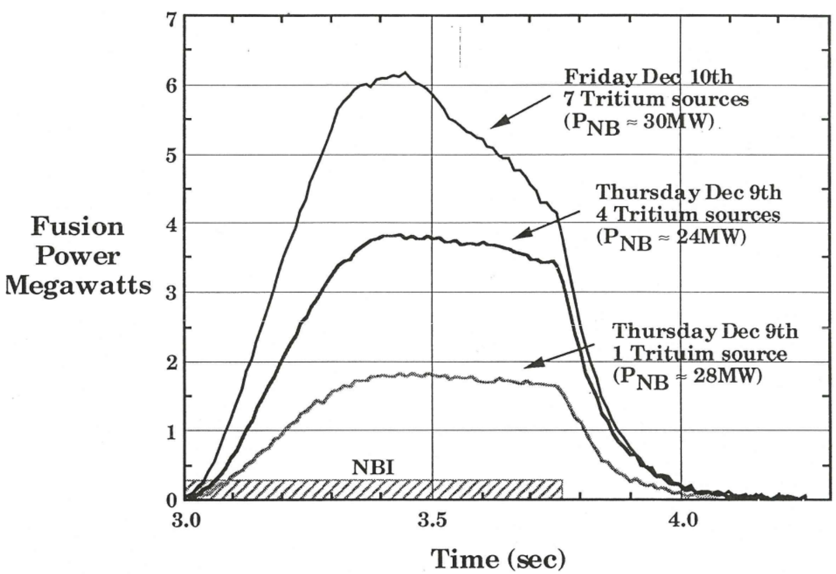
The Reaction to the Reactions

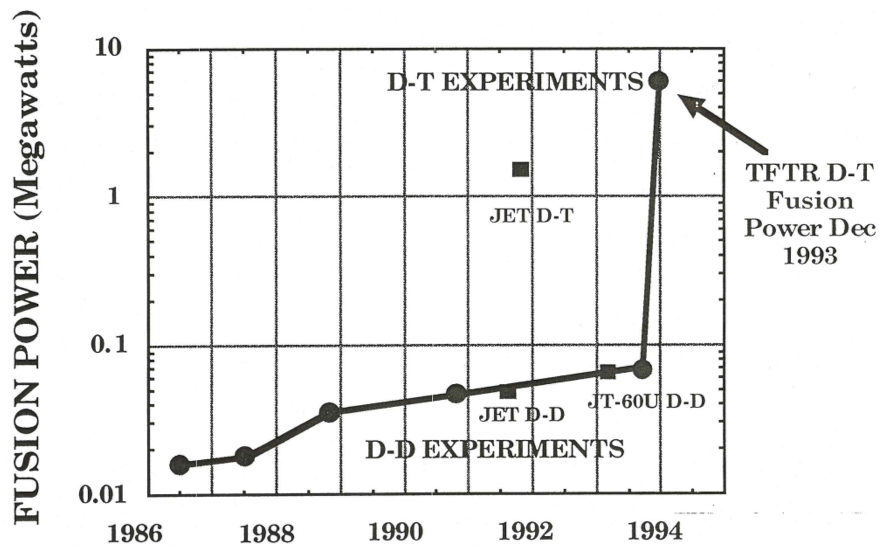
DT Day 2: Stick to the Plan or Go For It?

- 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

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



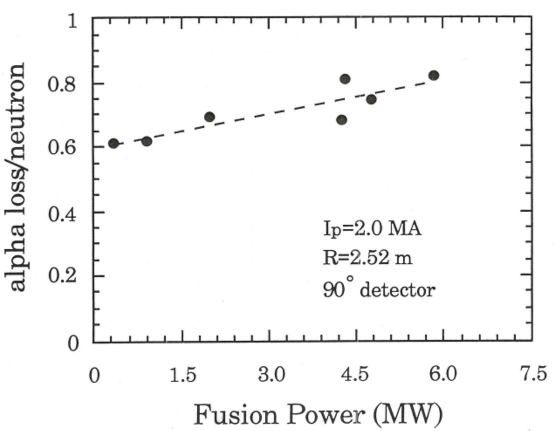


- “All hands” meeting on Wed 12/15 to congratulate and thank the Lab staff
  - PU President Harold Shapiro visited to convey the university’s appreciation

Alpha Particle Physics from Days 1 & 2

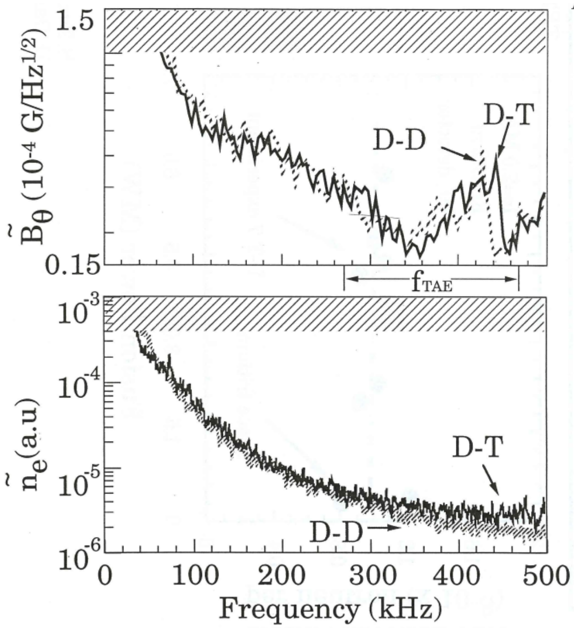
TFTR

Alpha loss rate did not increase strongly with fusion power



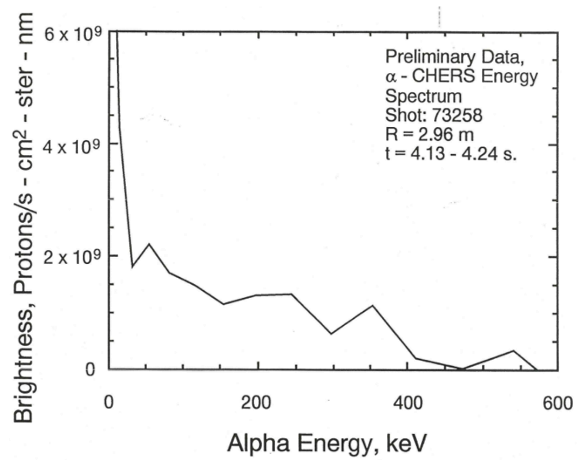
- Lost-alpha detectors were ready for planned current scans starting in the following week

TAE range fluctuations did not increase in DT plasmas



- Spurred refinement of TAE theory

Thermalizing alphas detected by CHERS

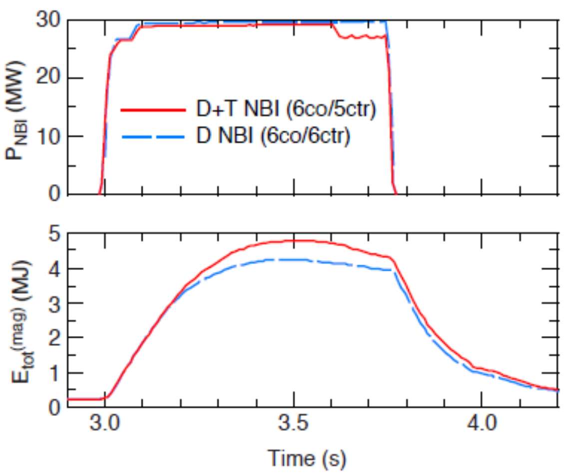


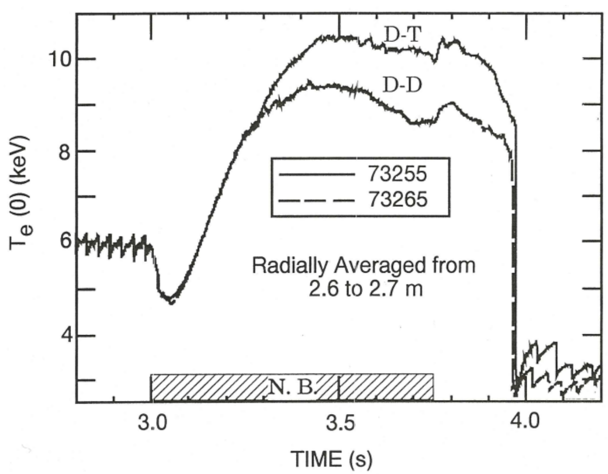
- Later detected by pellet-alpha charge-exchange
- CHERS also measured thermal helium ash

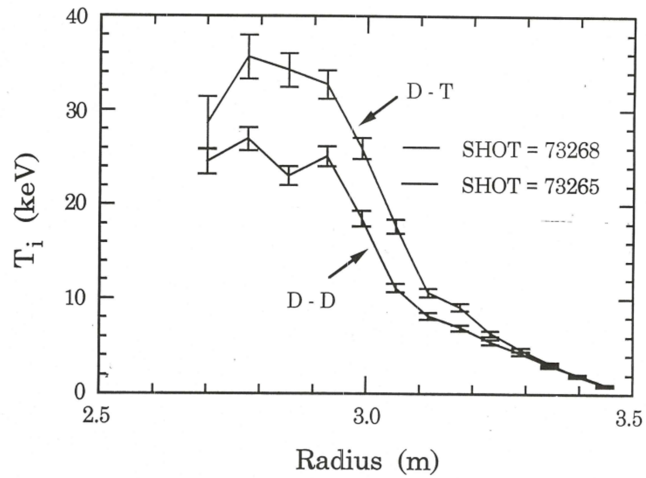
Significant Isotope Effect Apparent from Day 1

TFTR

- The neutral beams worked *better* in T: higher voltage and power
- There was still considerable D influx from the walls, despite our efforts to condition them to reduce that influx
  - We needed to run T-NBI rich to achieve optimum reactivity





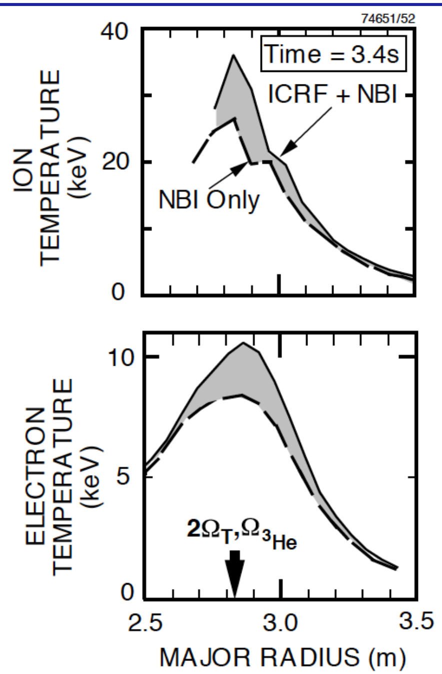


- TRANSP calculated ~50% of increase in T_e could have been alpha heating
- Ion thermal diffusivity decreased by ~2 in DT plasma
  - Increase in T_i not entirely welcome: too high for optimum reactivity
- Initial indications of isotope scaling later evolved into an intriguing mystery

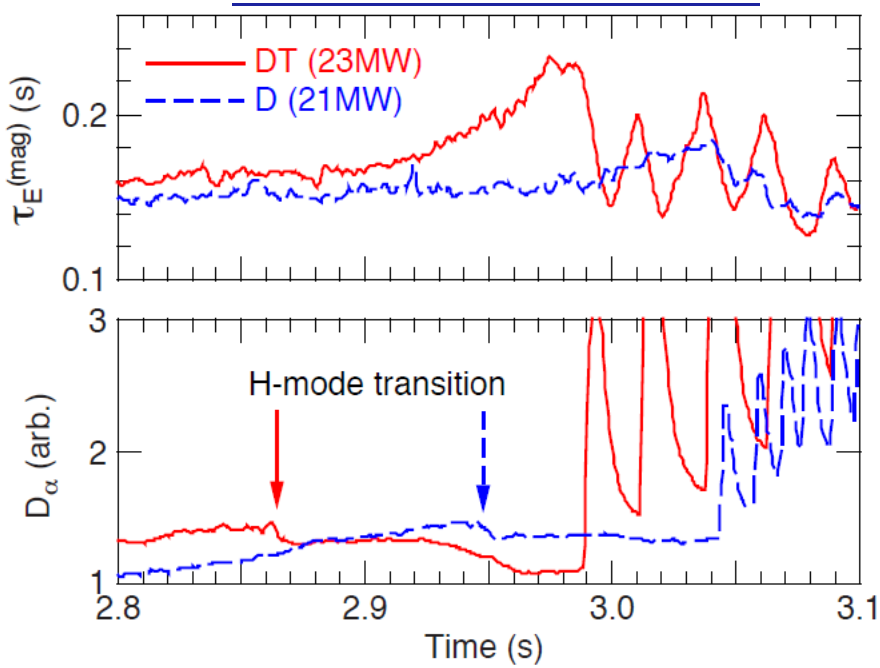
Still Under Threat of TFTR Termination, We Continued with the DT Plan into the New Year

- We continued experiments in the following week, including
  - Alpha loss *vs* plasma current
  - Alpha heating investigation
  - Tritium accounting
  - ICRF with trace tritium
- Resumed full DT operation Feb - Apr 1994 with experiments on
  - ICRF heating
  - high-l_i regime
  - H-mode plasmas

5.5MW ICRF heated both ions & electrons in 24MW DT-NBI plasma



Confinement & ELM size increased in D-T H-modes



- **DT operation became routine**

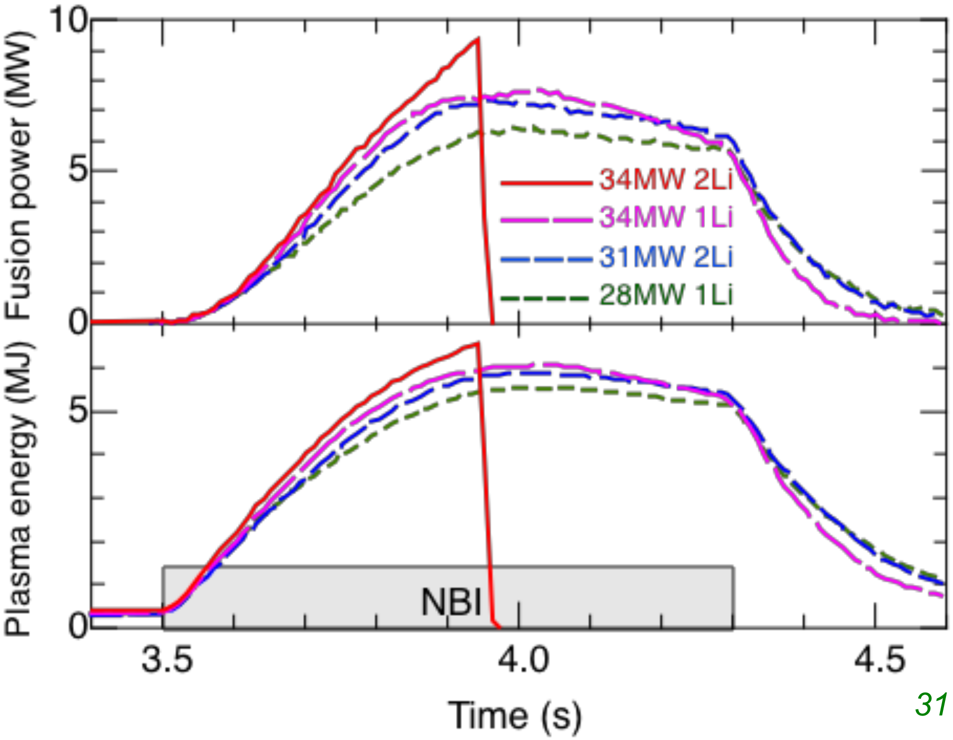
We Then Began a Push to Higher DT Power

- Improve the chances of observing alpha-particle phenomena
  - We had promised our sponsor that TFTR would achieve 10MW
- The challenge:
  - Higher fusion power would require higher plasma energy
  - This would exceed the beta limit unless we could increase
    - Plasma current and/or
    - Toroidal field – already at “nameplate rating” 5.1T
  - Increasing the plasma energy would entail
    - Higher neutral beam power and/or
    - Higher plasma confinement
  - Increasing confinement by *e.g.* aggressive lithium conditioning tended to reduce the stability limit
  - More current alone would reduce the MHD “safety factor” q

In May, We Made Our First Attempt at 10MW

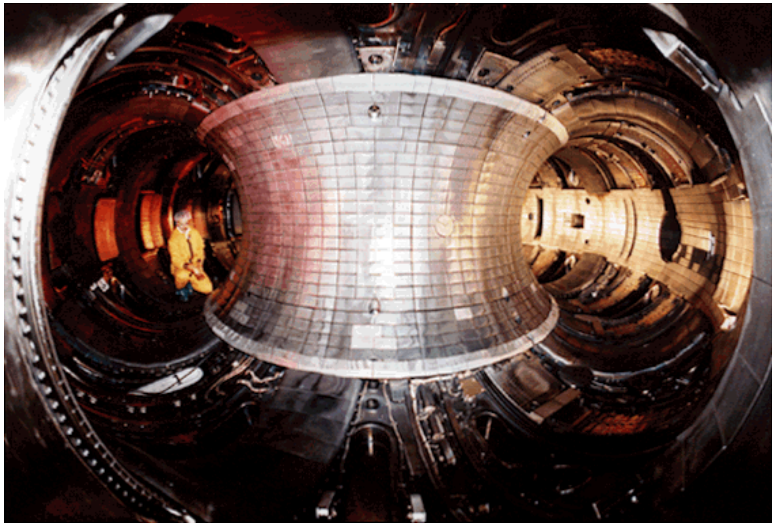
- Experimental proposal DT-8 ran on 4 days
- One NB source failed so we had to rely on improving confinement
  - We knew this would involve the risk of a major disruption
- NB system gave us 34MW peak power with 6 T, 5 D sources
  - Source 5c operated at 116kV and injected 3.8MW of T-NBI
- On Friday 5/27, had invited DOE people to witness the attempt

- On shot 76778, things worked perhaps a bit too well …
- Confinement better than expected
- Achieved 9.3MW fusion power *but*
- Shot ended in a jaw-dropping disruption with over 6MJ of energy
- Went with this result to the IAEA conference in Seville 9/26-10/1/94



The Burden of Supershots

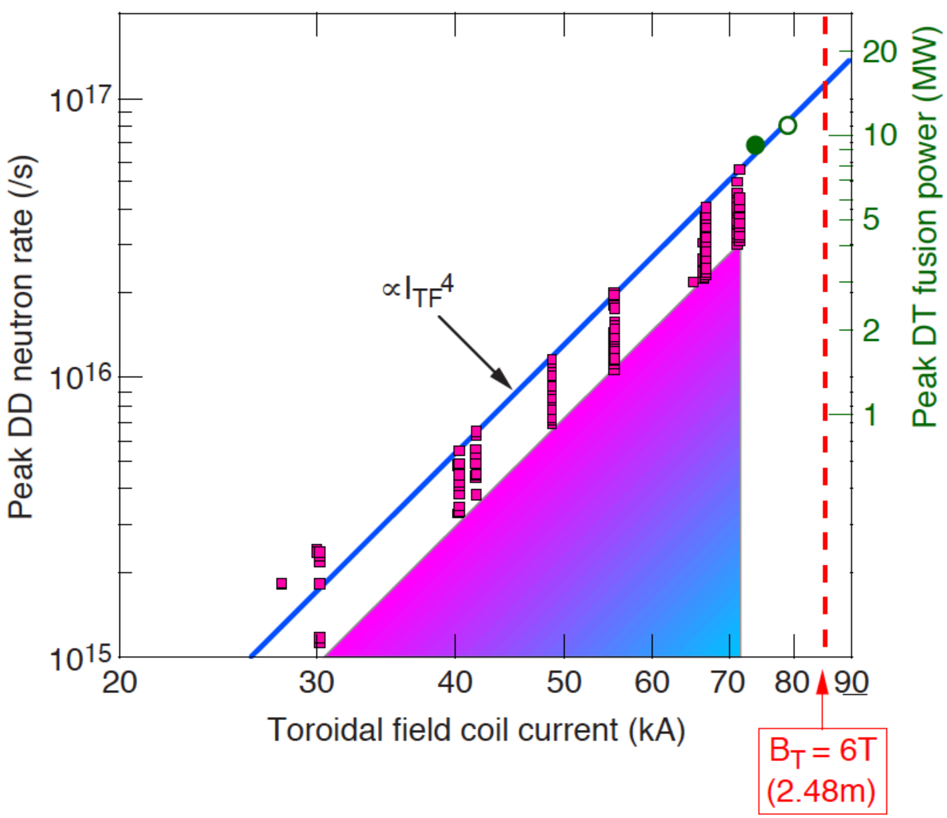
TFTR



- Extensive "conditioning" of the limiter was needed
  - TFTR inner "bumper" limiter contained about 2 Tons of ATJ graphite
  - Bakeout limited to 150°C
  - Days of Pulse Discharge Cleaning *and* "Disruptive Discharge Cleaning"
- Long sequences of ohmically heated helium shots to degas limiter
- Achieving super shots at higher plasma current necessitated even more thorough cleaning and degassing
- After degassing, coating with lithium could further improve super shots
- High energy disruptions extremely detrimental to limiter condition
  - Avoided by backing off: ran hundreds of shots without disruption, *but*
  - Lure of peak fusion performance inevitably pushed us towards the limit
  - Took several days to recover from the disruption of the 9.3MW shot

Increasing the Toroidal Field Might Allow Us to Achieve our 10MW Goal

- Experience in D phase had confirmed expected scaling of fusion rate with toroidal field



- $S_{DD} \propto W_{tot}^2$ (TFTR observation)
- $W_{tot(max)} \propto I_p B_T \propto B_T^2/q_a$ (β-limit)

$\Rightarrow S_{DD(max)} \propto B_T^4 / q_{a(min)}^2$

- Points are top 10% at each field

Engineering Division Analyzed Capabilities of Coils, Structure and Power Systems for 6 Tesla

- Tremendous effort by many people
- Analysis was complicated by discovery of loose bolts on TF coil cases in 1986 and water leaks in coils
  - Had tightened all the bolts we could (>1000) with long-handled wrenches
- Achieving a reasonable flattop time on the TF pulse required significant changes to the power supplies
  - New circuit breakers and current limiting reactors
  - Manage power demand on the Motor-Generators by sharing power feeds between the TF and NB supplies
- Final Design Review on July 5, 1994
  - No "showstoppers" identified but there were "unknown unknowns"
  - Revealed a range of (strongly held) opinions on the wisdom of using 6 Tesla
- Extension to 6 Tesla operation was finally approved by management
- Ultimately, TFTR ran about 600 shots above the original 5.1T
  - Most at 5.6T and a few at 6T

Neutral Beam System was a Great Success

- Neutral Beams were originally not expected to inject tritium
  - Concern that tritium would compromise epoxy insulators
  - Worked with Sandia and Lawrence Berkeley to qualify insulators
  - Needed to install and qualify T gas supply and controls
- Abandoned plans for automated changeover from D to T
  - Operators needed to change many settings to switch to T
- Initial operation showed NB sources worked better in T!
  - Reliable T-NB operation depended on continuous 3-shift schedule
- After success in first D-T experiments (including 9MW shot) a problem was discovered with all NB sources in June 1994
  - Just as we were negotiating an extension of TFTR with DOE!
- Necessitated rebuilding all 12 T-contaminated sources
  - Accomplished in just 13 days in July!

Before We Could Try for High Power Again, We had to Recover from the RF-Induced Vacuum Leak

- After the NB source repair, DT experiments resumed in July and continued through early September
  - High-β_P, H-modes, Isotope scaling, Helium ash, TAE search
- On Sep 7, while conditioning the RF system antenna, a large vacuum leak developed, halting operation
- RF-generated energetic ions were escaping onto the vacuum vessel wall where they melted welds on a port
  - Ions became trapped in magnetic field ripples
- This presented a major problem to repair
- Installed a sealed cuff around damaged area to provide “guard vacuum”
  - Required “hands-on” maintenance of the activated vessel
  - Accomplished well within regulatory exposure guidelines
- We resumed operation on October 12 but machine was not then ready for a high power experiment for another week

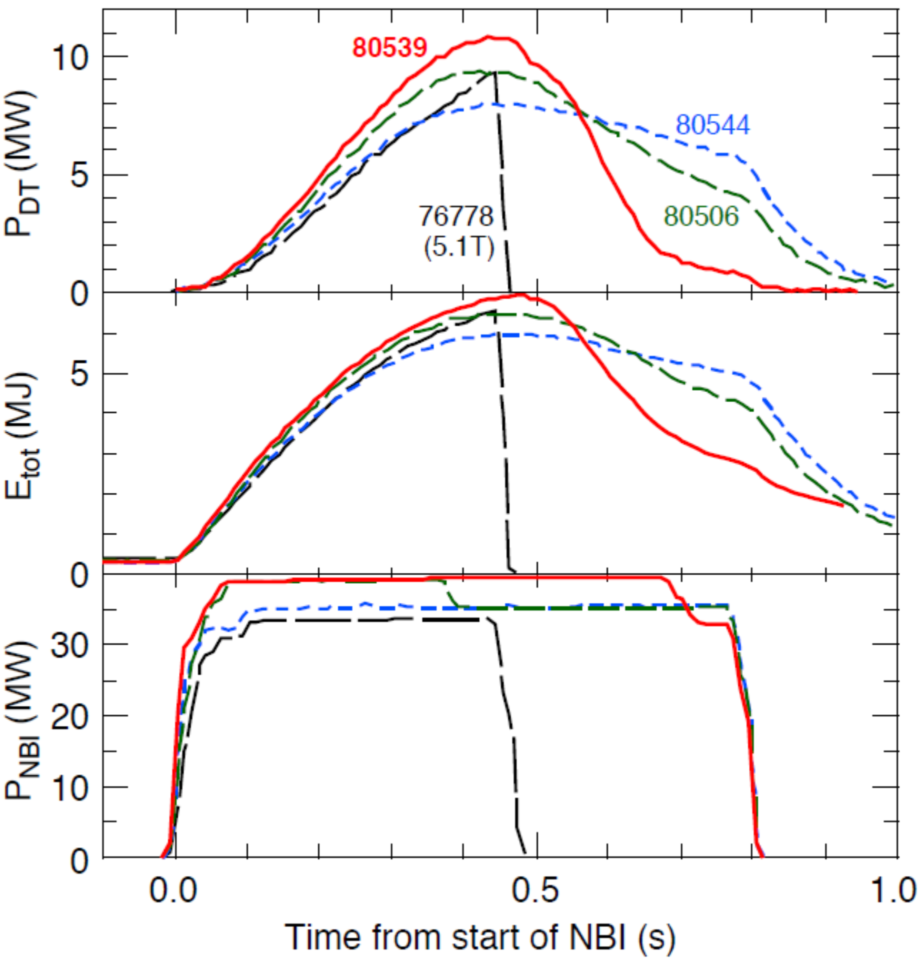
It Took 10 Days of Operation to Reach 10MW

- Needed to develop discharge scenarios to utilize higher TF, plasma current and expected NB power
  - Engineers and physicists wrestled with details of waveforms and timing
  - Despite proceeding cautiously, we bumped against various operational limits which caused disruptions and set us back
- NB team was conditioning sources and inching up in power
  - Jim Strachan was against making another 10MW attempt unless the beams could deliver substantially more power than the 34MW achieved in May
- Needed to condition limiter to obtain good super shots at high current
- On Friday Oct 28, NB team achieved record power in D: 34MW
- Switched to T on next shot: MG tripped → disruption → start over!
- Tried again on Monday: NBs made 39MW, P_{DT} reached 8MW
- Tuesday: Slow start but conditions improved, 9.2MW without disruption
- Wednesday 11/2: After slow start, everything came together finally
- **Beams delivered 39.5MW, plasma took it (just) and …**

nature did the rest!

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

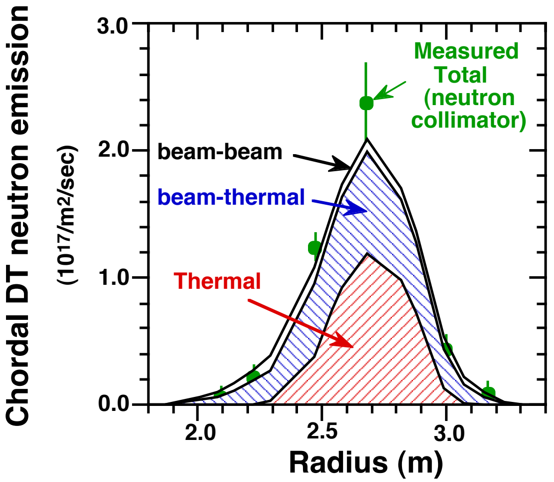
The steps leading to 10MW

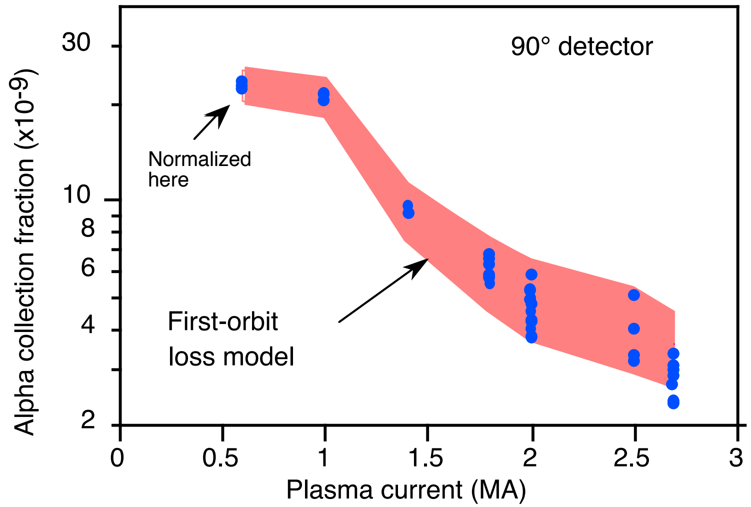


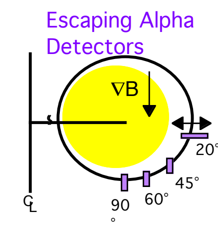
- **Also produced 7.6MJ of DT energy in a single pulse**

- Kevin McGuire delivered an invited talk highlighting the wealth of results we had already obtained
  - The DT experiments had been a resounding success so far
  - More than 200 shots with T-NBI
  - Much physics had been learned
- Meanwhile, PPPL 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
  - Project favorably reviewed and started but funding was not available to complete it

Classical Alpha Particle Behavior was Confirmed for Supershot Discharges







- Alpha particle birth rate and profile agreed with modeling
  - Neutron flux agreed well with calculations based on measured plasma profiles

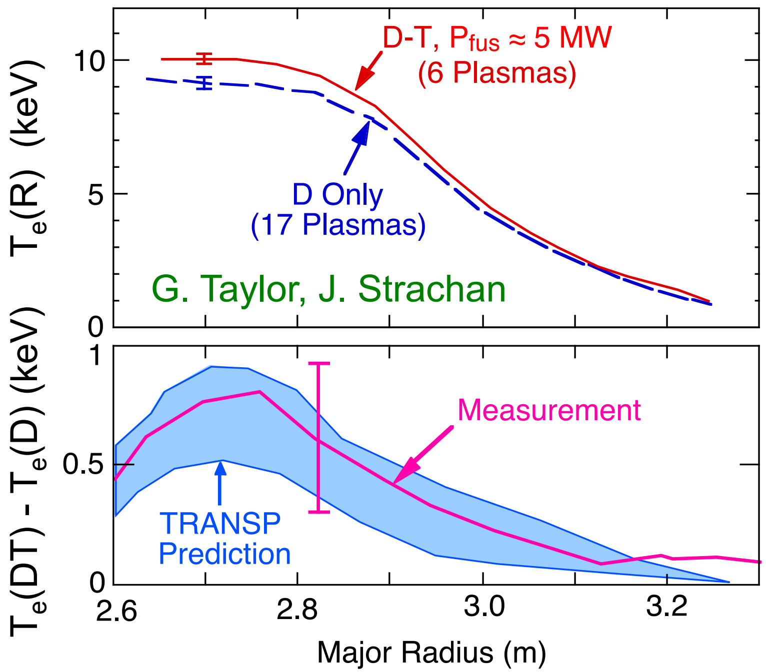
- Flux of alpha particles arriving at 90° detector was consistent with classical first orbit losses
  - Alpha particles born on "trapped orbits" can drift out of plasma

R. Budny, L. Johnson

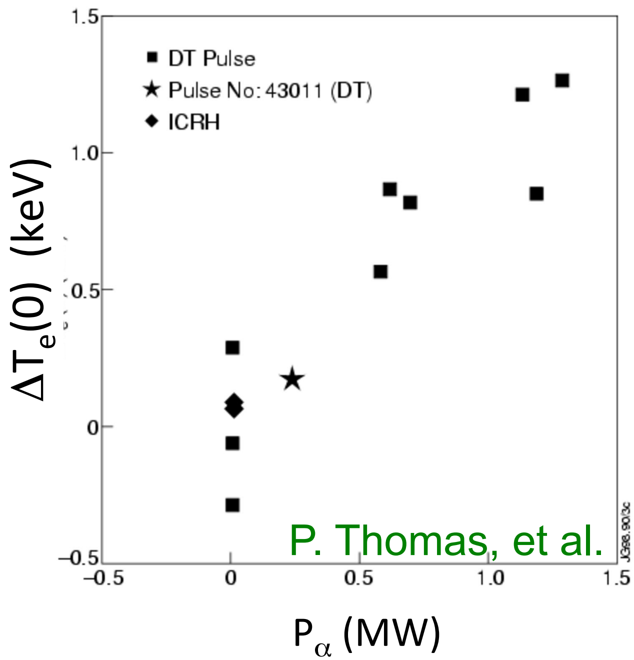
S. Zweben, D. Darrow

TFTR and Later JET Provided Evidence for Alpha-particle Heating of Electrons

TFTR



JET



- TRANSP calculation includes alpha heating
  - ~15% of total electron heating power from alphas

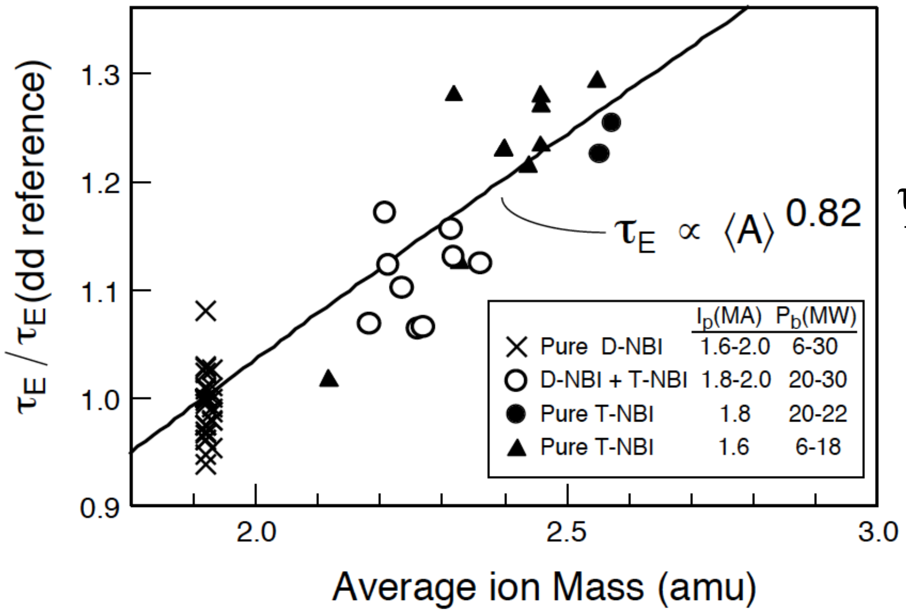
- P_{alpha}/P_{heat} ~12%
  - 30-40% flowed through the electron channel

- Definitive demonstration of alpha heating requires higher values of P_{alpha}/P_{heat} ➔ ITER

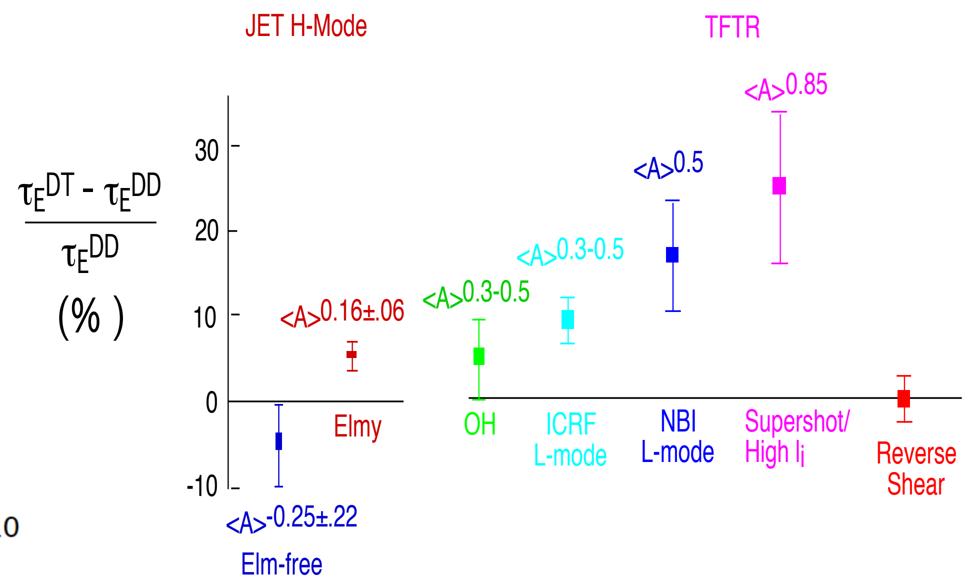
Isotope Effect on Confinement was Strong in Supershots but Weaker in Other Regimes

TFTR

Analysis of thermal energy confinement time in super shots with varying fractions of tritium



Data from other TFTR plasma regimes and JET show *weaker* scaling with average mass



- Diversity of confinement scaling with mass challenges theory
  – gyro-Bohm scaling: $\tau_E^{thermal} \propto \langle A \rangle^{-0.2}$
- ITER scaling for ELMy H-mode: $\tau_E^{thermal} \propto \langle A \rangle^{+0.19}$

By April 4, 1997, TFTR Had Achieved More than Three Years of Safe and Productive 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, technical and regulatory staff of PPPL and of our collaborators***

The DT Phase was Extraordinarily Productive: 28 Physical Review Letters Published 1994-7

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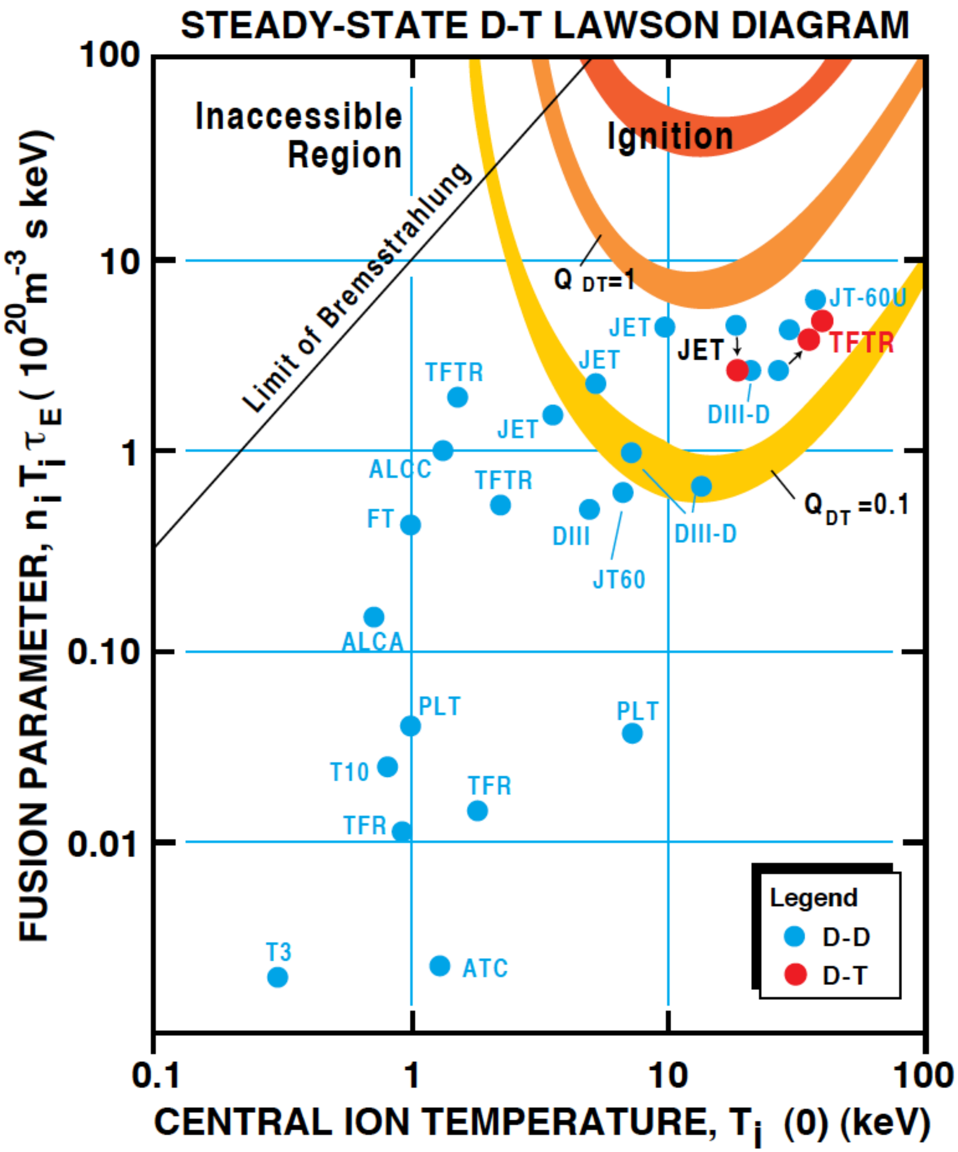
TFTR and the Other Large Tokamaks Crossed the Desert in the Lawson Diagram Facing Us in 70s



- Status in 1994 at the end of the first year of DT in TFTR
- JET and JT-60U produced slightly higher nTτ products subsequently
  - JET in DT

TFTR Achieved Many of the Parameters Expected to be Produced in ITER

	TFTR	**ITER**
Central pressure (MPa)	0.7	0.6
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
Collision frequency ν_e* (10^{-2})	1	0.8

- Confinement was the outstanding issue ***and remains so***

Confinement time (s)	0.2	2.5

- **Most reliable solution: *bigger device with higher current***

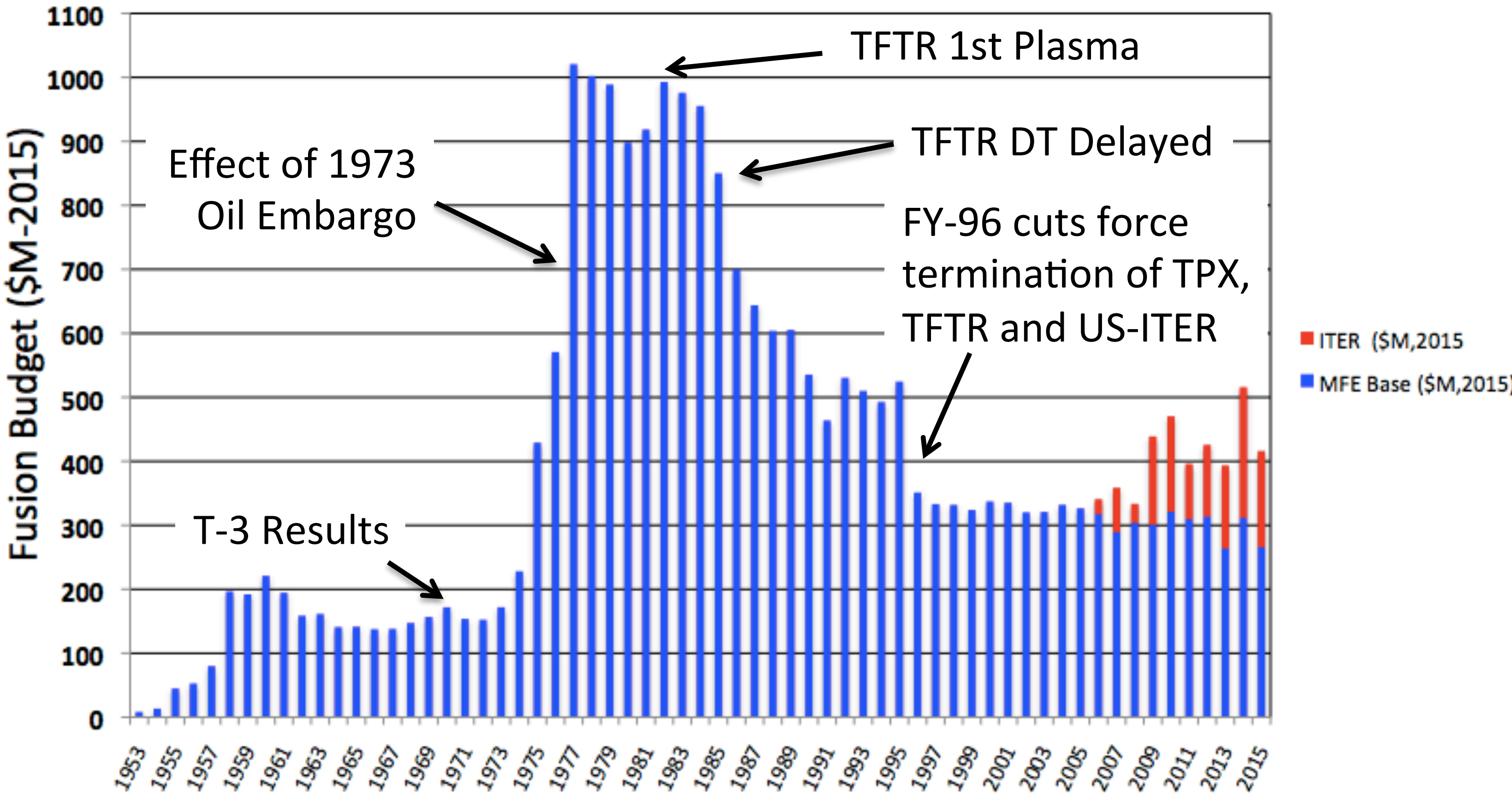
Normalized gyro-radius ρ_i/a (10^{-3})	6.5	2

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

Success of TFTR Made Possible by Generous Funding and Willingness to Take Bold Steps

- Big, high risk projects were started in the '70s: **TFTR, JET, JT-60**

U.S. Fusion Energy Sciences Funding (2015 $)



- Today's fusion program continues to benefit from that investment

What Really Propelled Our Success Was the Dedication and Effort of the Entire TFTR Team

- It took years of hard work to pull off D-T operation in TFTR
- Collaborators from 20 different institutions were on the author list of paper accompanying the TFTR lead talk at the 1994 APS-DPP Meeting
- Sergei Mirnov of TRINITI in Moscow, a long time collaborator with PPPL and TFTR, sent this tribute:

> *"Their great achievement lives on in ITER as well as in neutron sources (FNS).*
>
> *They managed to peek over the edge of the horizon!*
>
> *Not everybody understood them at the time, but such is the fate of great deeds."*

- The fusion research program and this laboratory is yet capable of more great deeds
- Achieving that will require vision, honest scientific debate, hard work and a willingness to take risks and coalesce around a major project

Acknowledgements

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Ken Young
Jim Strachan
Mike Williams
Bob Woolley
Tim Stevenson
Al vonHalle
Tom Carroll
Carl Scimeca
Charles Skinner

Thank you to all the TFTR Team for making this possible

Major TFTR Accomplishments 1983-1997

- Temperature of 200 million K (20 keV) (1986), and ultimately 510 million K (45keV). (1995)
- Record Lawson product $n\tau_E = 1.4 \times 10^{20}\ m^{-3}s$ at 1.4 keV with deuterium pellet injection. (1986)
- First observation of the self-generated "bootstrap current" in a tokamak. (1986)
- First direct measurements of long wavelength turbulence determining plasma transport. (1990)
- First magnetic fusion experiment to use 50:50 mixture of deuterium and 50% tritium. (1993)
- First magnetic fusion experiment to produce fusion power exceeding 10 million watts. (1994)
- Record peak plasma pressure of 6 atmospheres in a D-T plasma. (1994)
- Record fusion power densities of 3 million watts per cubic meter. (1994)
- First demonstration of RF wave heating plasma using second harmonic T resonance. (1994)
- First observation of the "enhanced reversed shear" confinement mode. (1995)
- First observation of neoclassical tearing modes that limit performance fusion plasmas. (1995)
- First measurements of self-heating by alpha particles in a DT fusion plasma. (1995)
- First demonstration of mode conversion RF wave heating in a D-T plasma. (1995)
- First measurements of instabilities excited by fusion alpha particles (1996).
- First to measure the retention of tritium in graphite plasma facing components. (1995)
- First closed cycle processing of tritium on a fusion experiment. (1997)
- Operated above the design ratings for toroidal field and neutral beam power.
- About 1 million curies of tritium was handled safely over a three year period.
- Total cost of TFTR (design, construction, operation, decommissioning) was $1.65 B.