TFTR: What We Learned and Yet May Learn

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Topics

• Brief history of the TFTR project
• Developments in plasma diagnostics
• State of tokamak physics at the start of TFTR operation in 1983
• Progress in understanding transport and MHD stability
• Developments in controlling anomalous transport
• Optimizing D-T fusion reactivity in present scale experiments
• Alpha particle confinement, heating and loss and effects of isotopic mass on confinement in TFTR
• Toroidal Alfvén Eigenmodes excited by energetic alpha particles

This is not a comprehensive review - no one hour lecture can encompass the results from a worldwide effort at dozens of institutions.

It is intended to show you that high temperature plasma physics made progress in TFTR, and can continue to do so in the tokamak.
Brief History of TFTR Project

- Project approved in 1976 after discussion starting in 1973
  - *demonstrate D-T fusion energy production and study reactor grade plasmas*
- Began operation on December 24, 1982
- Produced more than 60,000 high-power shots
  - 23,500 shots with neutral beam injection (NBI) heating
  - 40MW peak NBI power; up to 3s heating with stacked beams
  - 6,300 shots with radio-frequency (RF) wave heating
  - 7MW peak ICRF power
- Began operation with deuterium-tritium plasmas in December 1993
  - 1,031 plasma shots either with tritium NBI or with tritium gas puff
- Completed its last series of experiments on April 4, 1997
Progress in Understanding Depended on Advances in Tokamak Diagnostics

**Profile Data**
- $T_e$
  - Multipoint Thomson Scattering (TVTS)
  - ECE Heterodyne Radiometer
  - ECE Fourier Transform Spectrometer
  - ECE Grating Polychromator
- $n_e$
  - Multipoint Thomson Scattering (TVTS)
  - Multichannel Far IR Interferometer (MIRI)
- $T_i$, $v_\phi$, $v_\theta$
  - Ch.-Exch. Recomb. Spectrometers (CHERS)
  - X-ray Crystal Spectrometer
- $q$
  - Motional Stark Effect Polarimeter (MSE)

**Comprehensive Magnetic Measurements**

**Fusion Neutrons**
- Epithermal Neutron Detectors
- Neutron Activation Detectors
- 14 MeV Neutron Detectors
- Collimated Neutron Spectrometer
- Multichannel Neutron Collimator Array
- Fast Neutron Scintillation Counters
- Gamma Spectrometer

**Alpha-particles**
- Lost Alpha/Triton Detector Array
- Alpha-Pellet Charge-Exchange Analyser (PCX)
- Alpha Ch.-Ex. Recomb. Spectrom. ($\alpha$-CHERS)

**Impurity Concentration**
- Visible Bremsstrahlung Array
- VUV Survey Spectrometer (SPRED)
- Multichannel Visible Spectrometer
- X-ray Pulse Height Analyzer (PHA)

**Radiated Power**
- Tangential Bolometers
- Bolometer Arrays
- Wide-Angle Bolometers

**Fluctuations/Wave Activities**
- Microwave Scattering
- X-mode Microwave Reflectometer
- Beam Emission Spectrometer
- X-ray Imaging Camera
- ECE Grating Polychromator
- Neutron Fluctuation Detector
- Mirnov Coils
- ICE/RF Probes

**Plasma Edge/Wall**
- Filtered Photodiode Arrays (C-II,H-alpha)
- Fabry-Perot Spectrometer (H/D/T ratios)
- Sample Exposure Probe
- Plasma TV
- IR Camera
- Disruption Monitor (IR Detector)
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)
- Global confinement scalings:
  - “Alcator” scaling for ohmic heating ($\propto$ density)
  - L-mode scaling for NB heating ($\tau_E \propto I_p P_h^{-1/2}$): poor predictions for TFTR, JET
- 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

- Discovered when high power NBI applied to low-current plasmas after "conditioning" to reduce influx from limiter

- Subsequently developed additional techniques, including wall coating, to reduce influx from limiter ⇒ extended supershots to 2.7MA, 40MW

- Supershots are reliable, reproducible vehicles for studying high-temperature plasma phenomena and fusion physics
Supershots Had Dramatically Different Confinement

- Fixed External Tokamak Parameters: \( P_{NB} = 22 \text{ MW}, \ I_p = 1.4 \text{ MA}, \ B_T = 4.7 \text{ T} \)
- Limiter conditioning to reduce recycling changes L-Mode to Supershot

**L-mode:**
\[
\tau_E = 0.060 \text{ s} \\
ne(0)T_i(0)\tau_E = 0.15 \times 10^{20} \text{ m}^{-3} \text{ keV s}
\]

**Supershot:**
\[
\tau_E = 0.18 \text{ s} \\
ne(0)T_i(0)\tau_E = 4.3 \times 10^{20} \text{ m}^{-3} \text{ keV s}
\]
Supershots Did Not Follow L-mode Empirical Scaling

- Confinement time calculated from magnetic measurements of plasma energy (includes unthermalized beam-injected ions)
- Confinement essentially independent of heating power or plasma current
- H-mode plasmas did show adverse power and favorable current dependences but were about twice L-mode levels

TFTR

1988 IAEA Conference

- $a = 0.79m$
- $B_T = 4.7 - 5.0 \, T$
- $R_p = 2.45m$
Supershots Exhibited Decreasing Ion Thermal Diffusivity with Temperature

- L-mode plasmas showed adverse dependence of $\chi_i$ with temperature
- Estimates of diffusivity of energetic beam ions continued supershot trend
• TRANSP code suggested DT fusion power of about 8MW might be possible
• Two related obstacles to higher performance:
  - Stability of plasmas ⇒ increase plasma current
  - Difficulty of obtaining low edge influxes at higher current
Supershots Were Limited by Pressure-Driven Disruptions Below the Troyon-Scaling Limit

\[ \beta_{N,\text{max}} = 2.7 \] (early 80's)

- Improving confinement by peaking pressure profile reduced plasma stability
  \[ \Rightarrow \text{fast } \beta\text{-limit disruptions at high field (ideal MHD modes)} \]
- Stimulated search for methods to increase \( \beta \)-limit

\[ \beta_{N,\text{(dia)}} = \beta_{T,\text{(dia)}}\% / (I_p[M\text{A}] / a[m] B_T[T]) \] (Resistance to pressure driven instabilities)
Ballooning Mode Grows Rapidly Before High-β Disruption

- Identification made possible by excellent spatial and time resolution of $T_e$ diagnostics
Advances in Diagnostic Techniques Paved Way for Investigating New Regimes with Good Confinement

**Reversed-shear**

\[ \tau_E = 0.23 \text{s} \]

*NBI heating during current ramp in large plasma*

**High-\(l_i\)**

\[ \tau_E = 0.23 \text{s} \]

*Low-q startup in small plasma followed by expansion*

- Both regimes have NBI fueling, low edge recycling, peaked profiles and \(T_i > T_e\)
Reversed-Shear Plasmas can Transition to Another Regime of Enhanced Confinement: ERS

- RS - Similar to supershots: low $\chi_e, \chi_i$
- ERS - Reduced $D_e, D_i, \chi_i$
  - turbulent fluctuations suppressed within "transport barrier"
• Flux balance effective $\chi$, $D$: $q = -n \chi \nabla T$ and $\Gamma = -D \nabla n$
• Neoclassical calculation includes off-diagonal contributions
• Orbit squeezing effects from Shaing et al. [Phys. Plasmas 1, 3365 (1994)]
• Analysis of density profile evolution assuming D and $v_r$ functions of space only
• In ERS case, T and He data are best fitted with $|v_r| < 3\text{m/s}$ for $r/a < 0.5$
• Tritium diffusivity is ~20 times larger than electron diffusivity from particle balance
• Neoclassical values calculated by NCLASS code

P. Efthimion
W. Houlberg (ORNL)
Gyrokinetic Simulations

- Turbulent eddies disrupted by strongly sheared plasma flow

Experiment

- Bursts of fluctuations are suppressed when $E \times B$ shearing rate exceeds growth rate of most unstable mode
Large Transient Excursion in Poloidal Velocity Measured Prior to ERS Transition

- Occurs in most *but not all* plasmas which make transition to ERS
- Excursion precedes signs of ERS in pressure profile by ~50ms
Narrow Poloidal Velocity Shear Layer Develops Inside $q_{\text{min}}$ Surface Prior to ERS Transition

- Chordal measurements inverted to produce local poloidal velocity
- Shear layer narrower than sightline separation $\Rightarrow$ creates artifact inside
- Located between maximum pressure gradient and shear reversal surface

R. Bell, E. Synakowski
Suppression of Turbulence by Sheared Flow
Important in Other Confinement Regimes

- Majority of TFTR operation in “Supershot” regime with NBI
  - transitionless: develops smoothly from L-mode
  - shear is positive throughout and $q(0) < 1$
  - sawteeth suppressed
  - minimal degradation of confinement with power up to $\beta$-limit

- Measured changes in poloidal flow shear as supershots degraded to L-mode

- Model with turbulence suppressed by velocity shear reproduces many features and trends of supershot confinement
Model with Turbulence Suppressed by Velocity Shear Reproduces Ion Temperature Profiles in Supershots

- Based on suppression of ITG turbulent ion thermal diffusivity when \( \omega_{E \times B} \approx (I_{FS-PPL}) \) with self-consistent calculation of neoclassical plasma flow.

- Leads to apparent \( \chi_i \propto 1/T_i \) scaling at fixed radius.

- Enhanced confinement zone expands with heating power.

- Supershot behavior resembles ERS, NCS, JT-60 ITB, etc.

D. R. Ernst
Summary of Progress in Tokamak Physics

• We have made major strides in understanding the physics of plasmas in the tokamak:
  - Neoclassical transport phenomena
  - Anomalous transport, including link to plasma fluctuations
  - MHD stability

• New regimes of improved performance were developed and exploited

• There is a complex interaction between transport and stability in regimes of high reactivity

• Precise control of the plasma in a tokamak will be required to take advantage of “advanced” confinement regimes
  - We are developing the necessary diagnostic and control tools
History of D-T Experiments 1991-7

JET, November 1991 (“PTE”)
- First DT experiments with low concentrations of tritium: $P_{\text{fus}} = 1.7\text{MW}$

TFTR, December 1993 - April 1994
- High fusion reactivity: $P_{\text{fus}} = 10.7\text{MW}$ peak; $Q = 0.27$
- Extensive studies of fusion alpha particle heating, confinement and loss
- Isotope effects on plasma confinement in several regimes
- ICRF physics in D-T plasmas
- Tritium technology in a tokamak

JET, May 1997 - November 1997 (“DTE1”)
- High reactivity: $P_{\text{fus}} = 16\text{MW}$ peak; $Q \approx 0.6$
- Prototype operating regimes for ITER
- ICRF physics in D-T plasmas
Supershots Produced High DT Fusion Power, as Expected

• Shot producing 10.7MW of fusion power met TFTR goal established in 1975:
  \[ n_e(0) = 1.0 \times 10^{20} \text{m}^{-3}, \quad T_e(0) = 13.5\text{keV}, \quad T_i(0) = 40\text{keV} \]
TRANSP Code Can Successfully Model DT Reactivity

- Use measurements of $n_e$, $T_e$, $T_i$ profiles, $Z_{\text{eff}}$ and NBI parameters
- Models atomic physics, classical orbits and thermalization of injected particles, DT reactivity from nuclear cross-sections
• Tritium concentration limited by D influx from limiter, even with pure T-NBI
• Strong $\tau_E$ increase in supershot and H-mode regimes $\langle A \rangle^{0.8}$, weaker in ICRF heated D-T plasmas $\langle A \rangle^{0.5}$ (no supra-thermal tritons present)
  - ITER global scaling: $\tau_E \propto \langle A \rangle^{0.5}$
• Contrast with JET where no isotope scaling observed in D-T plasmas
• Favorable scaling of ion thermal transport with temperature and mass appear to contradict Bohm and gyro-Bohm scalings of L-mode (and H-mode) plasmas
• Alpha particles from DT fusion reactions are born with energy of 3.5MeV
  ⇒ Larmor radius up to 5cm in TFTR
  ⇒ Radial excursions of trapped alphas are much larger
• Good confinement of alpha particles necessary for D-T ignition
 Flux of $\alpha$-Particles to 90° Detector Agrees with Calculated Loss for Unconfined Orbits

- Shaded region shows result from an orbit-following code based on TRANSP calculations of alpha-particle birth and current profiles.
- At 2.5 MA, ~3% of alphas are lost on first orbit after birth
Alpha Loss Fraction does not Increase with Fusion Power

- Data for MHD-quiescent phases of D-T supershots
- No indication of loss processes driven by alpha-particles themselves
Measurements Confirm Classical Slowing Down of DT Fusion Alpha Particles

- Detect energetic helium atoms produced by double charge-exchange of alpha-particle with neutral cloud surrounding ablating boron pellet

- Calculation with TRANSP/FPPT code based on classical Coulomb collisions using measured plasma parameters
  - alpha-particle velocity slowing time typically 0.5 - 1 s
- High ion temperature and presence of unthermalized NB injected ions results in broadening of alpha spectrum above birth energy

GAT, IOFFE, PPPL Collaboration
Rapid Transport of Thermal Helium Ash from Center to Edge

- Charge-exchange spectrometry calibrated against He gas puff
- Data consistent with modelling based on He transport deduced from gas puff experiments
- $D_{\text{He}} / \chi_{D} \sim 1$
- Consistent with $\tau_{p}^{*}(\text{He}) / \tau_{E} \approx 8$: acceptable for reactors
Alpha-Driven Toroidal Alfvén Eigenmodes

- Toroidal Alfvén Eigenmodes (TAEs) are a threat to alpha confinement
- TAEs not seen in D-T supershots for $P_{DT}$ up to 10.7MW

Theory

- Ways to excite $\alpha$-TAEs:
  - Increase drive by reducing shear;
  - Wait until damping by beam ions is reduced after NBI

Experiment:

- Make plasmas with $q(0) > 1$ and weak or reversed shear in core
- Optimize D-T performance to maximize $\beta_\alpha(0)$

\[
\gamma_{\text{growth}} \quad \gamma_{\text{damping}} \quad \frac{V_{\text{beam}}}{1/3 V_{\text{Alfvén}}}
\]

\[
\tilde{B}_\theta [\text{mG}]
\]

\[
\approx 25 \text{ MW}
\]

\[
T \text{AE activity}
\]

G-Y. Fu, D. Spong, R. Nazikian
Observed $\alpha$-Driven TAEs Consistent with Full Linear Theory

- Calculations with NOVA-K code
- Weak shear and high $q(0)$ are destabilizing
- Weak or reverse shear plasmas in a reactor may be unstable to high-n TAEs

G. Fu, R. Nazikian
Summary of Results from the TFTR DT Experiments

- High fusion reactivity in 50:50 D:T with NBI heating and fueling
  - 10.7MW peak D-T power; \( Q = 0.27 \) (\( P_{NB} \) increased to 40MW, \( B_T \) to 5.6T)
  - Confirmation of modeling capabilities for fusion performance
  - First indications of alpha heating

- Alpha particle confinement and loss
  - Detected alphas lost by classical and MHD-induced processes
  - Confined alphas measured spectroscopically and by pellet charge-exchange

- Isotope scaling in OH, supershots, L-mode, H-mode, high-\( l_i \) plasmas
  - Transport of T introduced at edge
Summary (continued)

- ICRF physics in D-T plasmas (*not covered in talk*)
  - $2\omega_T$ heating
  - interactions of ICRF waves with energetic fusion products

- Studied physics of Toroidal Alfvén Eigenmode instabilities driven by fusion alpha particles
  - excellent example of the interaction of experiment and theory to develop a predictive capability for designing future reactors

*Tritium operation in TFTR provided new insights and tests of physics understanding. Only the surface of the data has yet been touched!*
Hot Ion Ignition

- Relax confinement requirements for “traditional ignition” by allowing Ti > Te
  (J.F. Clarke, N.F. 20 (1980) 563)
  - $\frac{1}{4}$ of alpha energy thermalizes to ions at $T_e \approx 20\text{keV}$
  - reactivity at fixed $\beta$ optimizes at higher $T_i$

- **Ignition**: $T_i = 30\text{keV}$, $T_e = 25\text{keV}$, $n_e = 1.1 \times 10^{20}\text{m}^{-3}$, $\tau_E = 2.1\text{s}$ *in a realistic plasma* ($p \approx 1\text{MPa}$) for $\chi_i / \chi_e = 1/4$

- Tokamaks confine energetic ions extremely well
  - *e.g.* Meade IAEA, IAEA, Washington (1990)
  - $q_{\text{conv},i} < \frac{5}{2} \cdot \Gamma \cdot T_i$ implies transport is predominantly of lower energy ions
  - sawteeth stabilized: essential for peaked density
  - operation with $q(0) > 1$: $\chi_i$ reduced to neoclassical

- In TFTR, hot-ion confinement *did not degrade with power* (but did not show the benefit of current scaling either)
  - factors other than “traditional” scaling parameters of tokamak confinement had the biggest effect
Apparent Ion Diffusivity Decreases with Ion Energy

- Consistent with behavior of ion thermal diffusivity in various TFTR regimes
- Suggests that orbits of energetic ions can "average" over turbulence causing anomalous transport

S. Zweben
Hot-Ion Ignited Plasmas Possible with Good Ion Confinement

• Assume classical alpha-particle slowing with perfect confinement
• Composition typical of center of TFTR supershot with lithium wall-conditioning, plus nominal helium ash and self-consistent alpha population
  - $n_{DT} : n_H : n_{He} : n_C = 0.80 : 0.05 : 0.05 : 0.01$
Hot Ion Ignition - Issues

• Need to devote experimental time in large tokamaks and theoretical and analysis effort to studying hot-ion regimes
  - mechanism: sheared flow, $T_i/T_e > 1$, $L_n$ ← theory
  - size scaling in comparable regimes ← experiment/theory
  - is central fueling necessary? ← reduced D regimes
  - put effort into controlling what matters ← edge control
  - investigate alpha channeling ← improves prospects
  - alpha-driven instabilities ← potential problem

• Improved core confinement is associated with lower $\beta$-limit
  - feature of all regimes with high fusion reactivity (TFTR, JET, JT-60U; supershots, HIHM, ERS, “optimized shear” etc.)
  - $\beta$-limit is a result of local, not global, stability violation
  - the devil is in the details of transport and stability considered together

• Study alternative regimes for improved core stability