Progress in Tokamak Physics during the TFTR Project

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Topics

- The state of tokamak physics at the start of TFTR operation in 1983
- Developments in plasma diagnostics
- Progress in understanding neoclassical and anomalous 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 has progressed, and can continue to do so, in the tokamak.
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 with NBI in PLT: ~7keV
- 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 ($\sim 2 \times$ 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
Progress in Understanding Depended on Advances in Tokamak Diagnostics

**Profile Data**
- $T_e(r)$
  - Multipoint Thomson Scattering (TVTS)
  - ECE Heterodyne Radiometer
  - ECE Fourier Transform Spectrometer
  - ECE Grating Polychromator
- $n_e(r)$
  - Multipoint Thomson Scattering (TVTS)
  - Multichannel Far Infra-Red Interferometer (MIRI)
- $T_i(r)$
  - Ch.-Exch. Recomb. Spectroscopy (CHERS)
  - X-ray Crystal Spectrometer
- $q(r)$
  - Motional Stark Effect Polarimeter

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

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

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

**Comprehensive Magnetic Measurements**

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

**Plasma Edge/Wall**
- Plasma TV
- IR Camera
- Filtered Diodes (C-II)
- Filtered Diodes (H-alpha)
- Sample Exposure Probe
- Disruption Monitor (IR Detector)
- Fabry-Perot (H/D/T ratios)

**Alpha-particles**
- Lost Alpha/Triton Array
- Alpha-Charge-Exchange Analyser
- Alpha-Ch.-Exch. Recomb. Spectros. ($\alpha$-CHERS)
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:**
\[
\tau_E = 0.18 \text{ s} \\
\ne(0)T_i(0)\tau_E = 4.3 \times 10^{20} \text{ m}^{-3} \text{ keV s}
\]
• $B \propto 1/R$ dependence of toroidal magnetic field creates magnetic mirror which can reflect particles with large perpendicular velocity component
  ⇒ "trapped" particles on "banana" orbits with large radial excursions

• Trapped particles dominate transport when collision frequency < bounce frequency

• Collisions between trapped and "passing" particles in presence of a pressure gradient drives net current
  ⇒ bootstrap current is zero on axis and becomes small in the cool, collisional edge
Supershots Provided Ideal Vehicle to Investigate the Bootstrap Current in a Tokamak

- Hot, collisionless plasma without sawtooth instabilities
- Good confinement at low current produced high poloidal beta: $l_{bs} \propto \beta_p$
- Balanced co- and counter-directed NBI allowed separation of NB driven current

\[ \beta_p (= \frac{2\mu_0 <p>/B_p(a)^2}{\mu_0 <p>/B_p(a)^2}) \]

\[ I_p = 0.8 - 1.0 \text{ MA} \]
Plasma Surface Voltage is Well Modeled by Including Beam-Driven and Bootstrap Currents

- Negative surface voltage early in NB pulse with resistive model arises from flux-conserving changes in equilibrium during rise in plasma pressure

![Graph showing plasma surface voltage and currents](image-url)
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

Graph:
- Energy Confinement Time $\tau_E$ (s) vs. Total input power (MW)
- Points for different current levels: 1.0 MA, 1.2, 1.4, 1.6
- Parameters: $R_p = 2.45m$, $a = 0.79m$, $B_T = 4.7 - 5.0$ T

L-mode area is shaded in cyan.
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

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

- 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
Ballooning Mode Grows Rapidly Before High-\(\beta\) Disruption

- Identification made possible by excellent spatial and time resolution of \(T_e\) diagnostics

Fredrickson, Nagayama, Janos
Magnetic islands with low poloidal and toroidal mode numbers (m/n) can reduce the sustainable beta and fusion performance ⇒ "Soft" $\beta$-limit

These instabilities grow on slow resistive timescale
– Growth is influenced by perturbed bootstrap current

Z. Chang
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"
Turbulent Fluctuations Are Suppressed During ERS Phase and Return After Back Transition

- Fluctuations measured by microwave reflectometer
- Turbulence suppressed by generation of flow shear between flux surfaces
  - flow driven by pressure gradient itself and external momentum sources (NBI, RF waves)
- Stimulating expansion of theory to cover other regimes of enhanced confinement: supershots, H-modes
Externally Driven Ion-Bernstein-Waves Produced Poloidal Velocity Shear in Absorption Region

- Small poloidal velocity, < 0.5km/s, apparent in companion shot without IBW

R. Bell
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 have been 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
DT Fusion

- DT reaction has the highest cross-section:
  \[ \text{D} + \text{T} \rightarrow \text{He}^4 \ (3.5 \text{ MeV}) + \text{n} \ (14.1 \text{ MeV}) \]

- For thermalized plasma near the optimum temperature (~15keV)
  \[ \langle \sigma v \rangle \sim T^2 \Rightarrow P_{\text{fusion}} = E_{\text{DT}} \int n_D n_T \langle \sigma v \rangle \text{dV} \propto \int n^2 T^2 \text{dV} \propto \int p^2 \text{dV} \]

- \( P_\alpha \ll P_{\text{aux}} \) (no self heating by fusion alphas)
  \[ P_{\text{aux}} = P_{\text{loss}} = 3 \langle nT \rangle / \tau_E \]
  \[ \Rightarrow Q \equiv P_{\text{fusion}} / P_{\text{aux}} \propto [\langle n^2 T^2 \rangle / \langle nT \rangle] \tau_E \]
  *This is often approximated as* \( Q \propto n_e(0) \cdot T_i(0) \cdot \tau_E \)

- \( P_\alpha = P_{\text{loss}} \) (ignited plasma)
  \[ \langle n^2 T^2 \rangle \propto \langle nT \rangle / \tau_E \]
  \[ \Rightarrow n_e(0) \cdot T_i(0) \cdot \tau_E = 6 \times 10^{21} \text{ m}^{-3} \cdot \text{keV} \cdot \text{s} \] *with same approximation*

- Need high pressure and good confinement

- At the optimum temperature, DT reactions produce about 200 times the fusion power of DD reactions for the same plasma conditions
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; $Q \approx 0.27$
- 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
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.
- 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 was under vacuum for >3 years of continuous operation to Aug ‘96
  - ICRF launchers and new diagnostics installed during opening Aug - Oct ‘96
  - Resumed operation for final run Dec ‘96 through April 4, ‘97
- A credit to the scientific, engineering and technical staff of PPPL and of our collaborators
Supershots Produced High DT Fusion Power, as Expected

- Shot producing 10.7MW of fusion power met TFTR goal established in 1975:
  \( n_e(0) = 1.0 \times 10^{20}\text{m}^{-3} \), \( T_e(0) = 13.5\text{keV} \), \( T_i(0) = 40\text{keV} \)
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
Global Confinement Increases With Tritium NBI

- 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 Particle Orbits in Tokamaks

- Alpha particles from DT fusion reactions are born with energy of 3.5MeV
  \[ \Rightarrow \] Larmor radius up to 5cm in TFTR
  \[ \Rightarrow \] 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 TRANSPP 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
In Matched D and D-T Plasmas, Change in $T_e$ Consistent with Alpha Particle Heating

- Alpha heating $\sim10\%$ of power through electron channel
- TRANSP prediction shown includes alpha particle heating
  - shaded region indicates uncertainty range of prediction
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 $\beta_\alpha(0)$

\[ \frac{V_{beam}}{1/3 V_{Alfvén}} \]

\[ \gamma_{growth} \]

\[ \gamma_{damping} \]

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

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

DT NBI

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; \( Q = 0.27 \) (\( P_{\text{NB}} \) 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!*