Confinement and Heating of Deuterium-Tritium Plasmas in TFTR*

M. G. Bell and the TFTR Group

Plasma Physics Laboratory,
Princeton University

Abstract

The Tokamak Fusion Test Reactor was authorized for construction in 1976 with the mission to produce significant fusion power from a magnetically confined D-T plasma heated by beams of energetic neutral atoms (NB). After construction began, results from the smaller tokamaks then operating with NB heating suggested that the confinement and performance of TFTR would be less than originally projected. In physics experiments conducted in deuterium plasmas through the 1980s, regimes of improved confinement were discovered and developed to the point where projections of TFTR performance justified proceeding to D-T fuel in 1993.

TFTR operated with D-T for over 3 years, achieving a peak fusion power of 10.7 MW, producing over 1 GJ of fusion energy and providing a demonstration of the feasibility of operating a fusion power plant. Detailed experiments were conducted to study the physics of the energetic alpha-particles produced by D-T fusion reactions and the confinement and heating of the thermal plasma in their presence. The progress both in plasma performance and in understanding transport and stability achieved during the life of TFTR suggest that fusion research is ready to advance to the study of burning plasmas, where the plasma heating by the alpha particles dominates the losses.

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Brief History of TFTR Project

- Project approved in 1976 after discussion starting in 1973
  - *demonstrate D-T fusion energy production*
  - *study reactor grade plasmas*
- Began operation on December 24, 1982
- Produced more than 60,000 high-power plasma shots
  - 24,000 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 fueling
- Completed its last series of experiments on April 4, 1997

Requirements for Deuterium-Tritium Fusion

- DT reaction has the highest cross-section:

  $D + T \rightarrow He^4\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV})$

- For thermalized plasma near the optimum temperature (~15keV)

  $<\sigma v> \sim T^2 \qquad P_{fusion} = E_{DT} \int n_D\, n_T <\sigma v> dV \qquad \int n^2 T^2 dV \qquad \int p^2 dV$

- $P_\alpha << P_{aux}$ (no self heating by fusion alphas)

  $P_{aux} = P_{loss} = 3 <nT>/\tau_E$

  $\mathbf{Q \equiv P_{fusion}/P_{aux} \qquad [<n^2T^2>/<nT>]\,\tau_E}$

  This is often approximated as **$Q \qquad n_e(0) \cdot T_i(0) \cdot \tau_E$**

- $P_\alpha = P_{loss}$ (ignited plasma)

  $<n^2T^2> \qquad <nT>/\tau_E$

  $n_e(0) \cdot T_i(0) \cdot \tau_E = 6 \times 10^{21}\ \mathrm{m}^{-3} \cdot \mathrm{keV} \cdot \mathrm{s}$ *(with same approximation)*

- Need high pressure and good confinement

- At optimum temperature, DT reactions produce about 200 times the fusion power of DD reactions for the same plasma conditions

Heating Plasmas to Fusion Relevant Temperatures

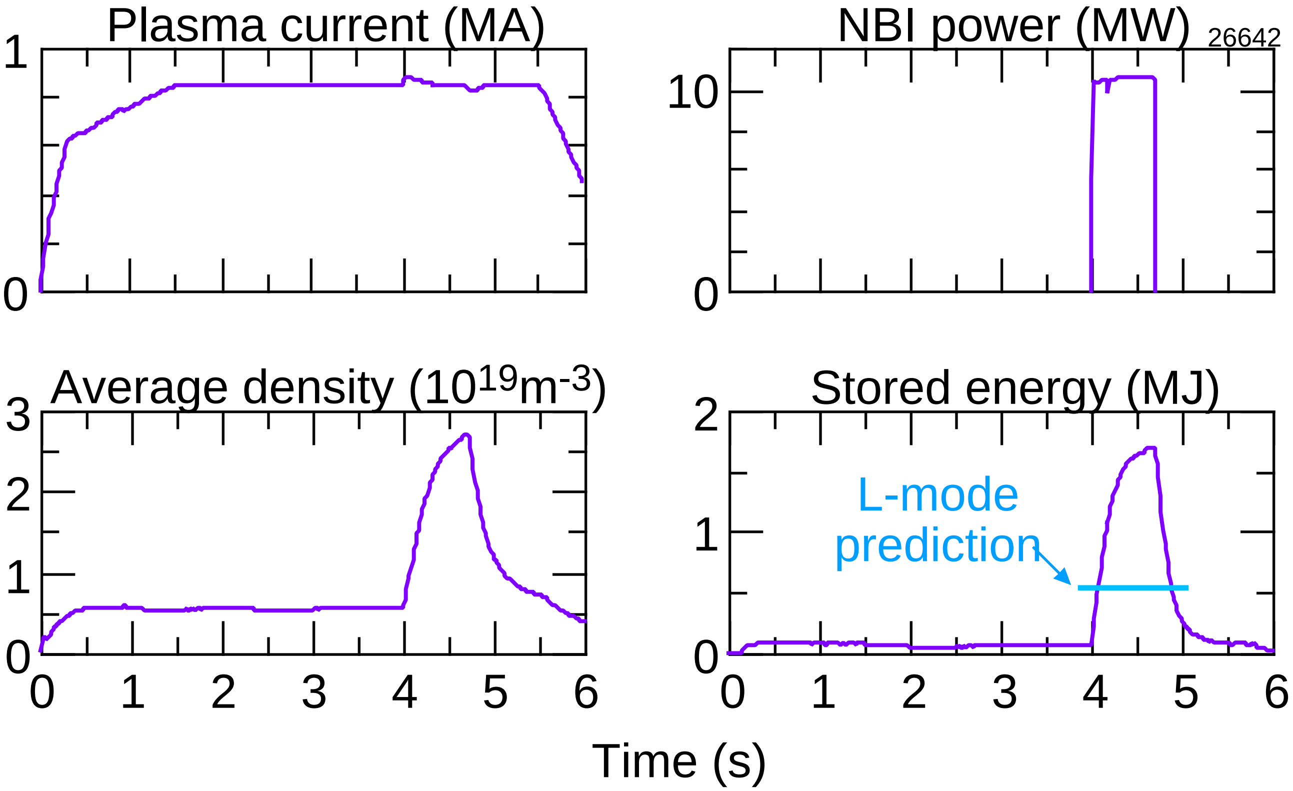
- Electrical resistance (Ohmic) heating
  - efficient and always present in a tokamak due to plasma current
  - limited to about 5 keV by increasing conductivity with temperature
- Neutral Beam Injection heating
  - energetic neutrals can enter the plasma across the magnetic field
  - ionize in the plasma and thermalize with the ions and electrons
- Electromagnetic (RF) wave heating
  - waves absorbed in plasma by resonance or Landau damping
  - can heat specific plasma components separately
- Adiabatic compression of plasma
  - Transient and can perturb magnetic configuration
- Alpha-particle heating in DT plasma
  - thermalize 3.5MeV energy of alphas confined by magnetic field
  - goal of fusion research - required for self-sustaining reaction

Tokamak Physics in 1983

- Reliable operation at current <1MA with pulse lengths up to 1s
- Plasma fueling by gas puffing and injection of frozen D_2 pellets
  - MHD limits on plasma current; empirical density limits
- 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)
- Global confinement scalings:
  - "Alcator" scaling for ohmic heating (τ_E density)
  - "L-mode" scaling for NB heating (τ_E $I_p P_h^{-1/2}$): *poor prognosis for TFTR, JET*
- H-mode discovered (ASDEX) in divertor plasmas with improved confinement (~2 × L-mode): *promise of better performance!*

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

- 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

TFTR

Profile Data

$T_e(r)$

- Mutipoint 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

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

Alpha-particles

- Lost Alpha/Triton Array
- Alpha-Charge-Exchange Analyser
- Alpha -Ch.-Exch. Recomb. Spectros. (α-CHERS)

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

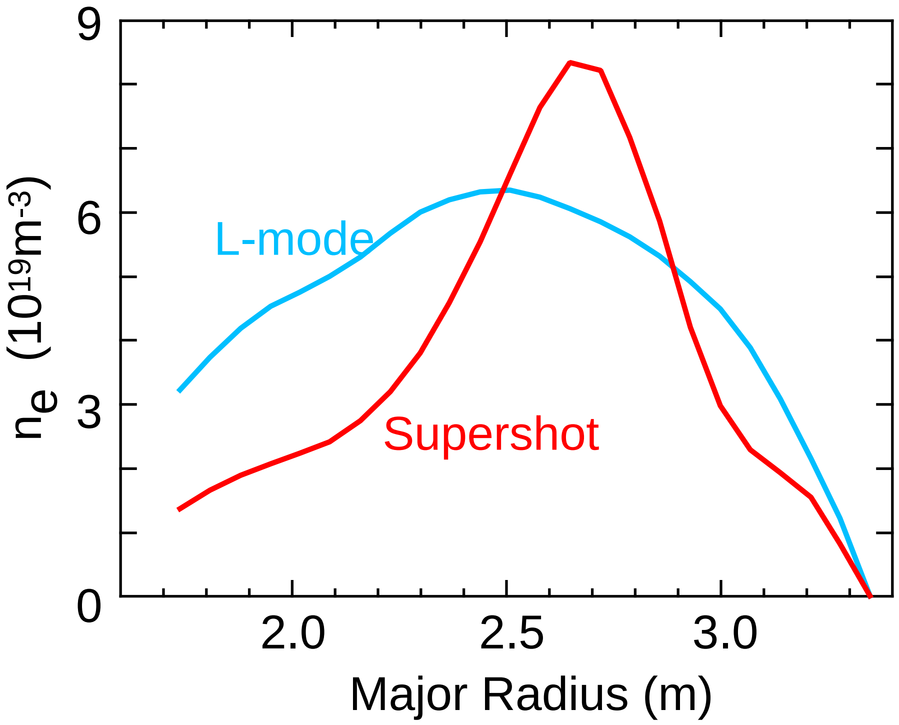
Plasma Edge/Wall

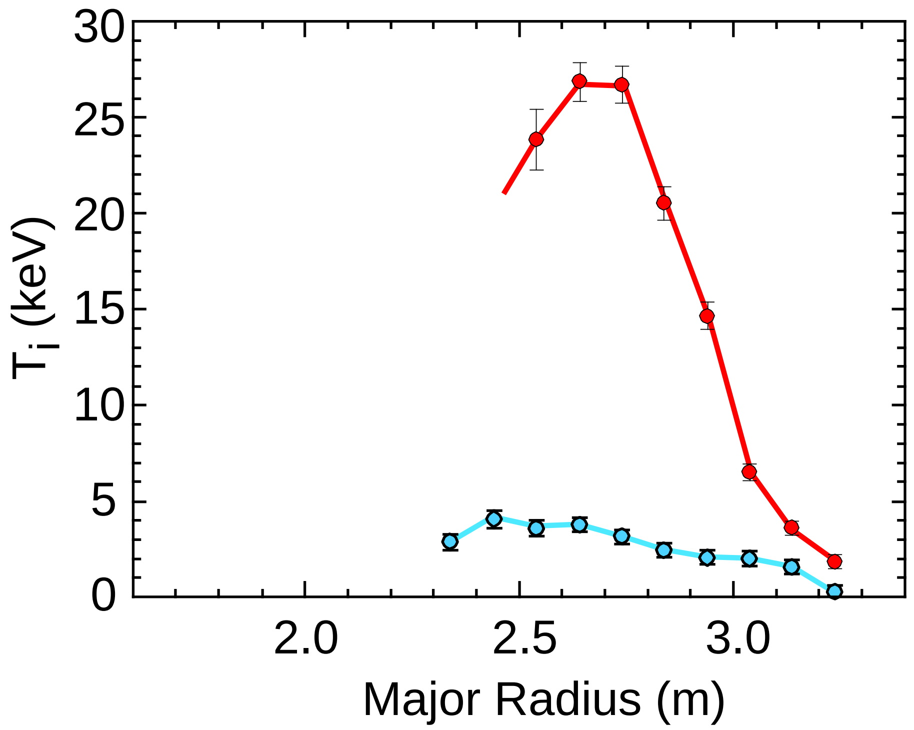
- Plasma TV
- IR Camera
- Filtered Diodes (C-II)
- Filtered Diodes (H-alpha)
- Sample Exposure Probe
- Disruption Monitor (IR Detector)
- Fabry-Perot (H/D/T ratios)

Supershots Had Dramatically Different Confinement

TFTR

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





L-mode:

$\tau_E = 0.060$ s

$n_e(0)T_i(0)\tau_E = 0.15 \times 10^{20}$ m^{-3} keV s

Supershot:

$\tau_E = 0.18$ s

$n_e(0)T_i(0)\tau_E = 4.3 \times 10^{20}$ m^{-3} keV s

Studies of Neoclassical Transport Phenomena in TFTR

- B 1/R dependence of toroidal magnetic field creates magnetic mirror which can reflect particles with large perpendicular velocity component

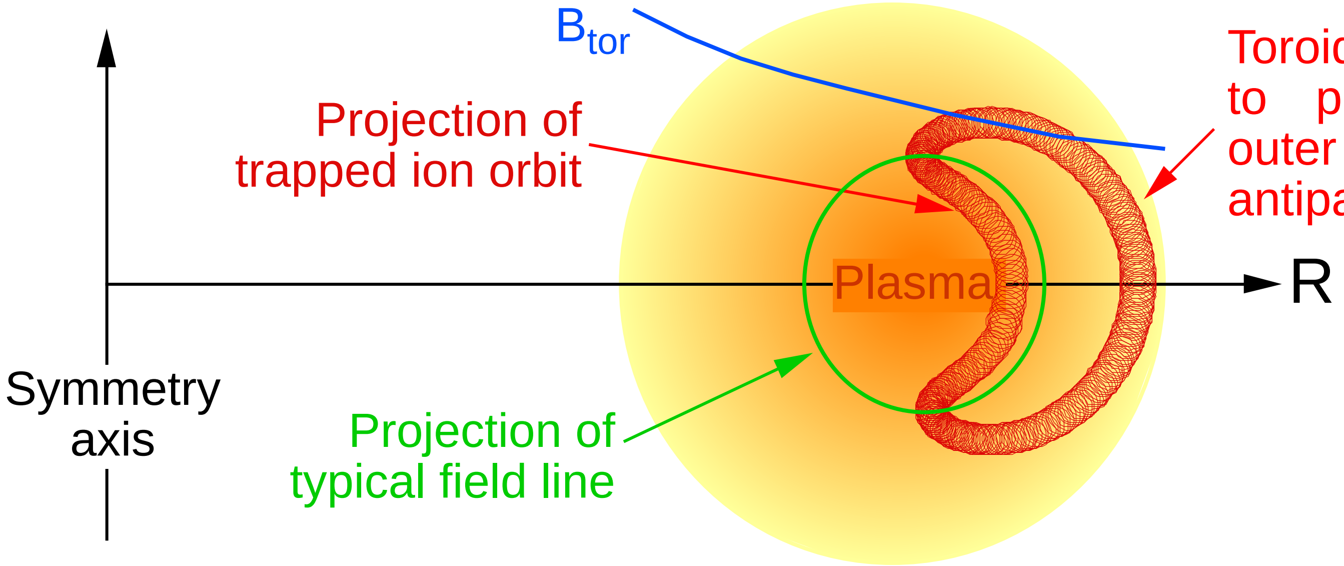
  "trapped" particles on "banana" orbits with large radial excursions

- Trapped particles dominate transport when collision frequency < bounce frequency

  effects are important in high-temperature, collisionless plasmas

- Collisions between trapped and "passing" particles in presence of a pressure gradient drives net current - *"bootstrap" current predicted in 1960s*

  bootstrap current became significant in supershot conditions



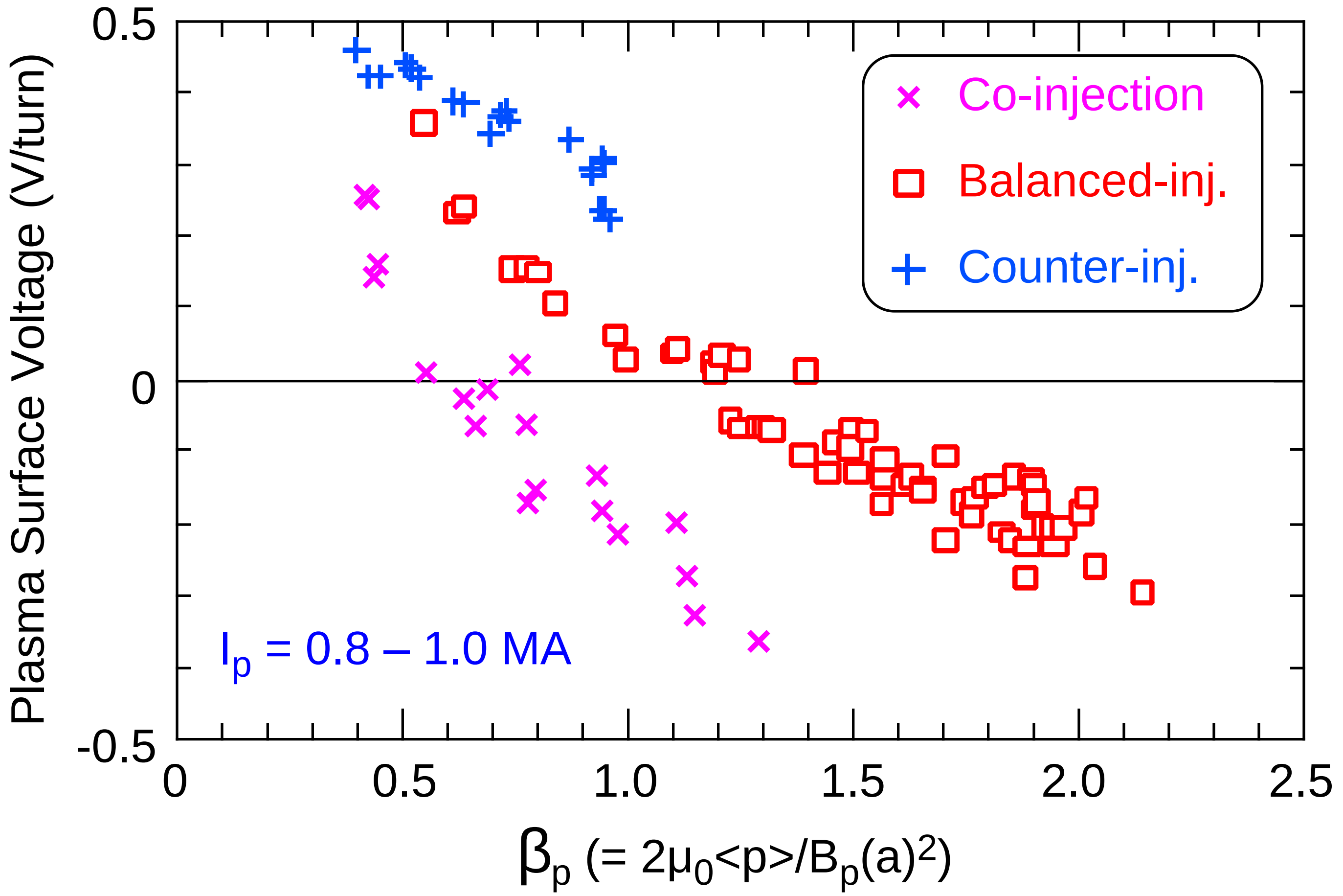
Projection of trapped ion orbit

Projection of typical field line

Toroidal motion parallel to plasma current on outer leg of banana orbit, antiparallel on inner

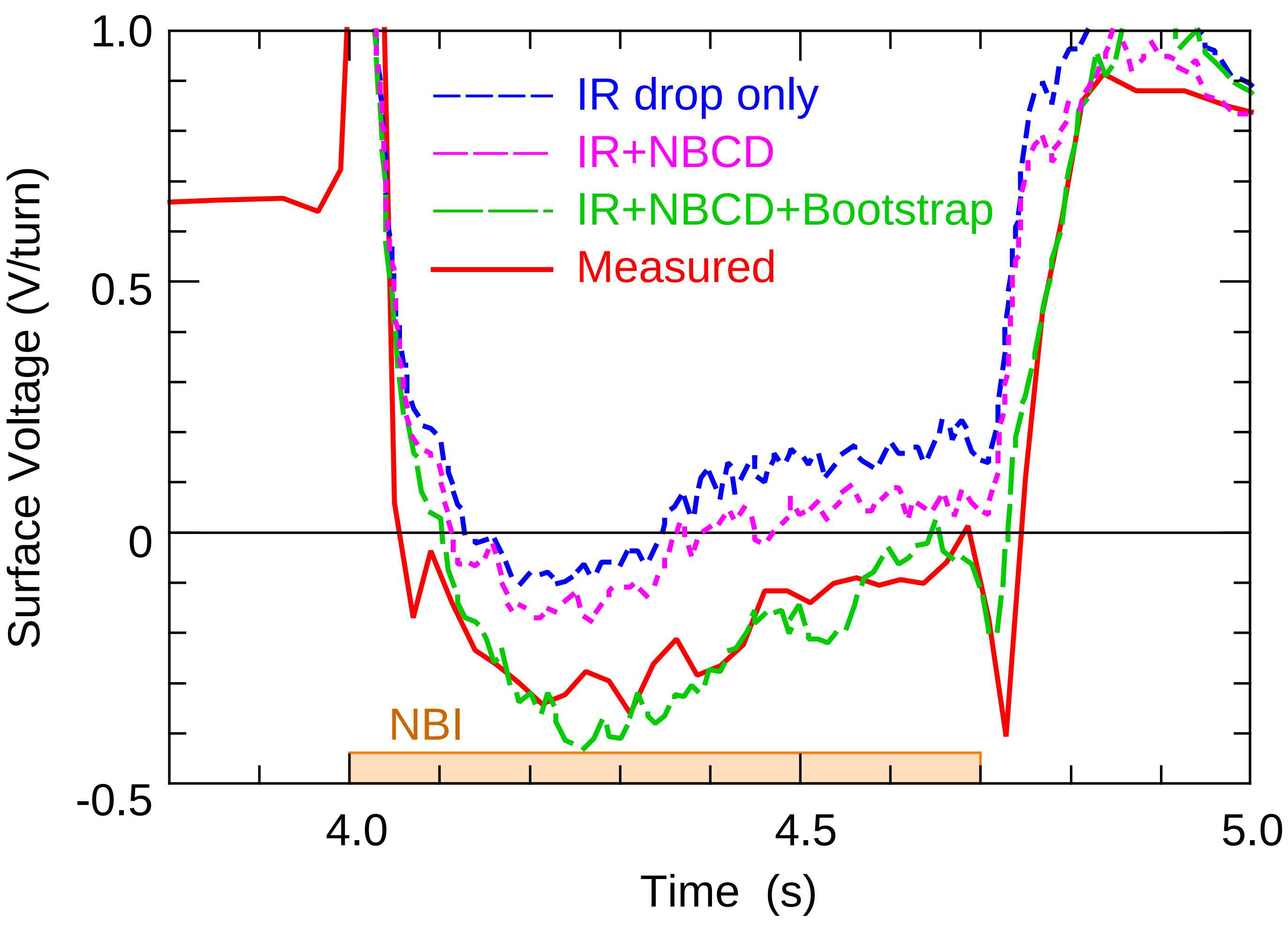
Supershots Provided Ideal Vehicle to Investigate the Bootstrap Current in a Tokamak

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



Plasma Surface Voltage in Supershots is Well Modeled *Only* by Including Beam-Driven and Bootstrap Currents

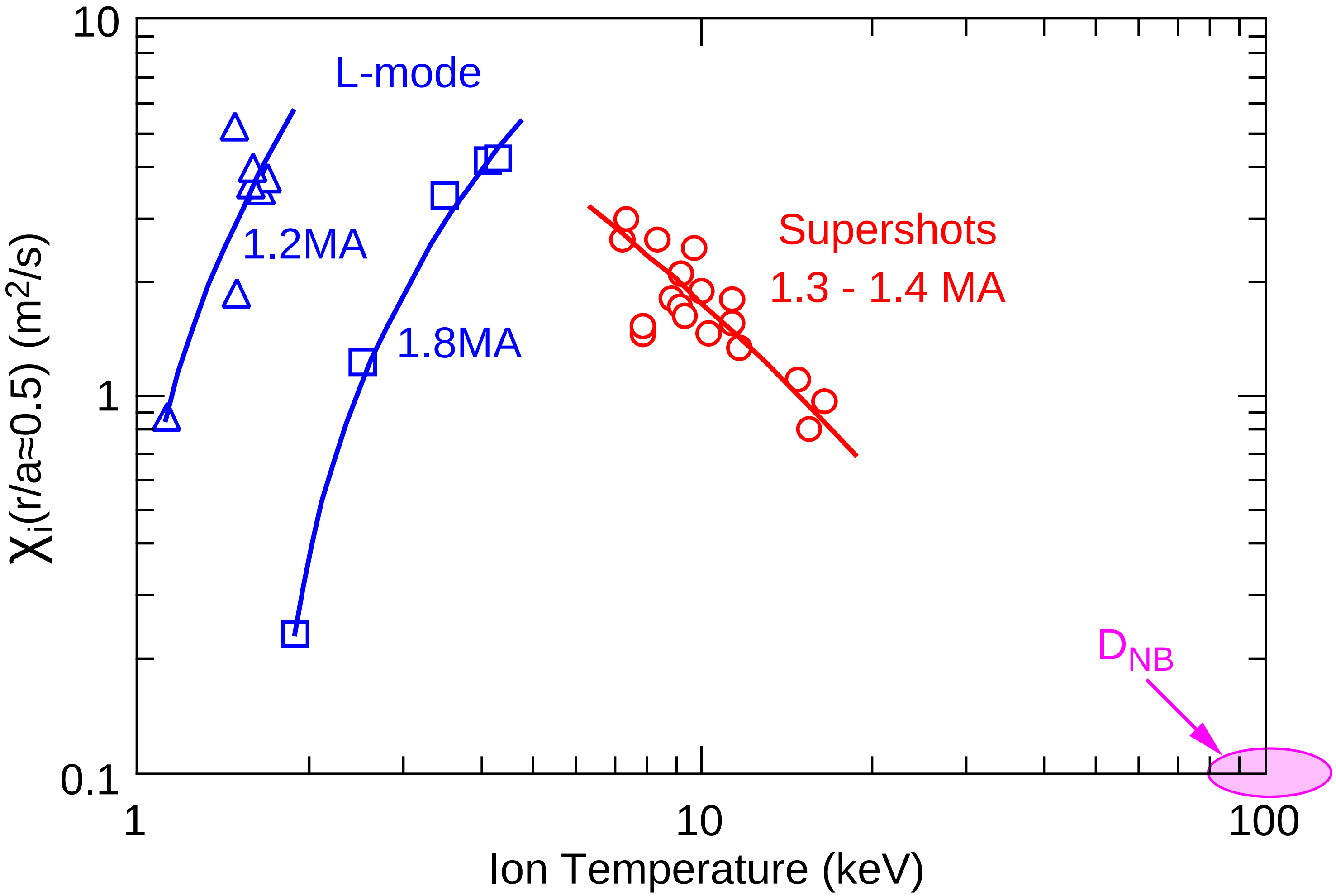
TFTR



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

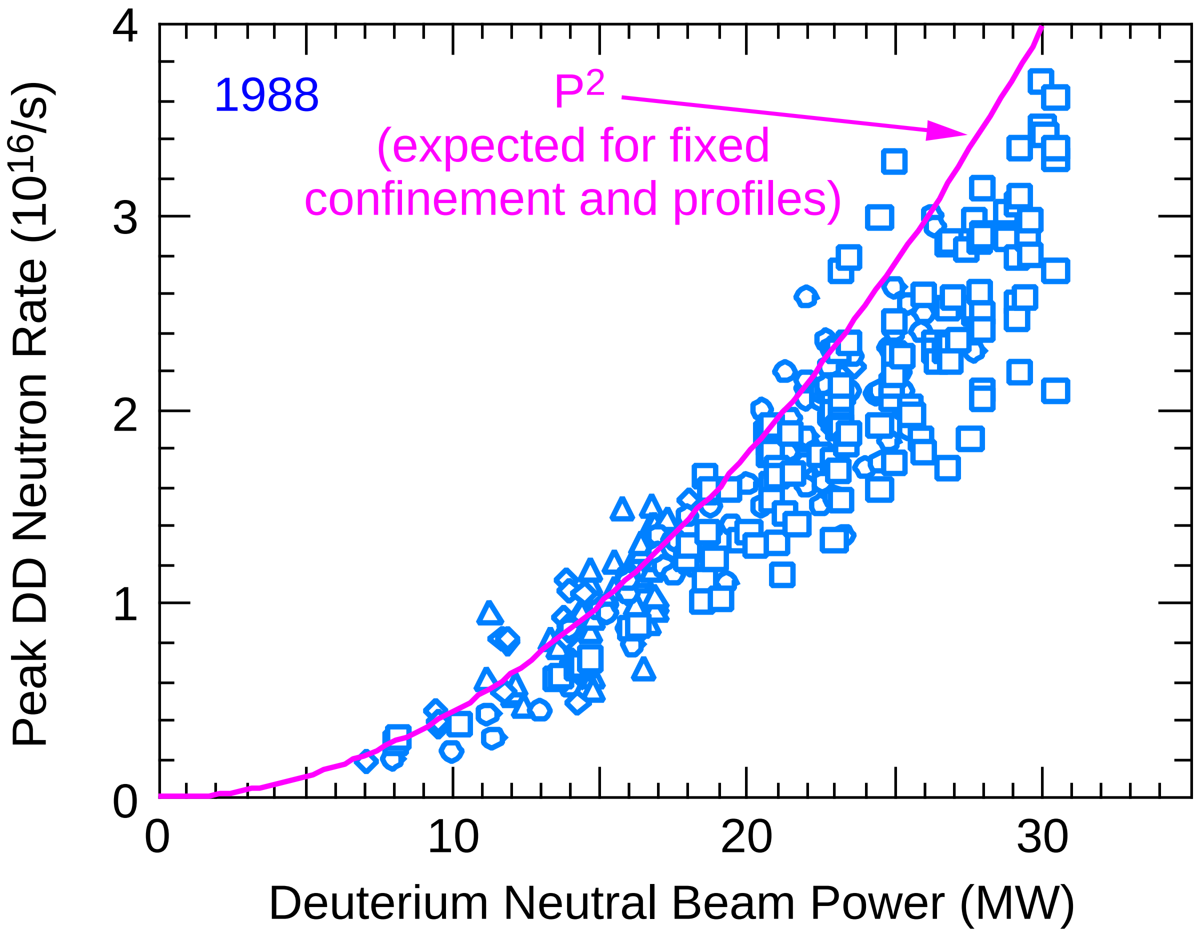
M. Zarnstorff et al., *PRL*, ***60***, *1306 (1988)*

Supershots Exhibited Decreasing Ion Thermal Diffusivity with Temperature



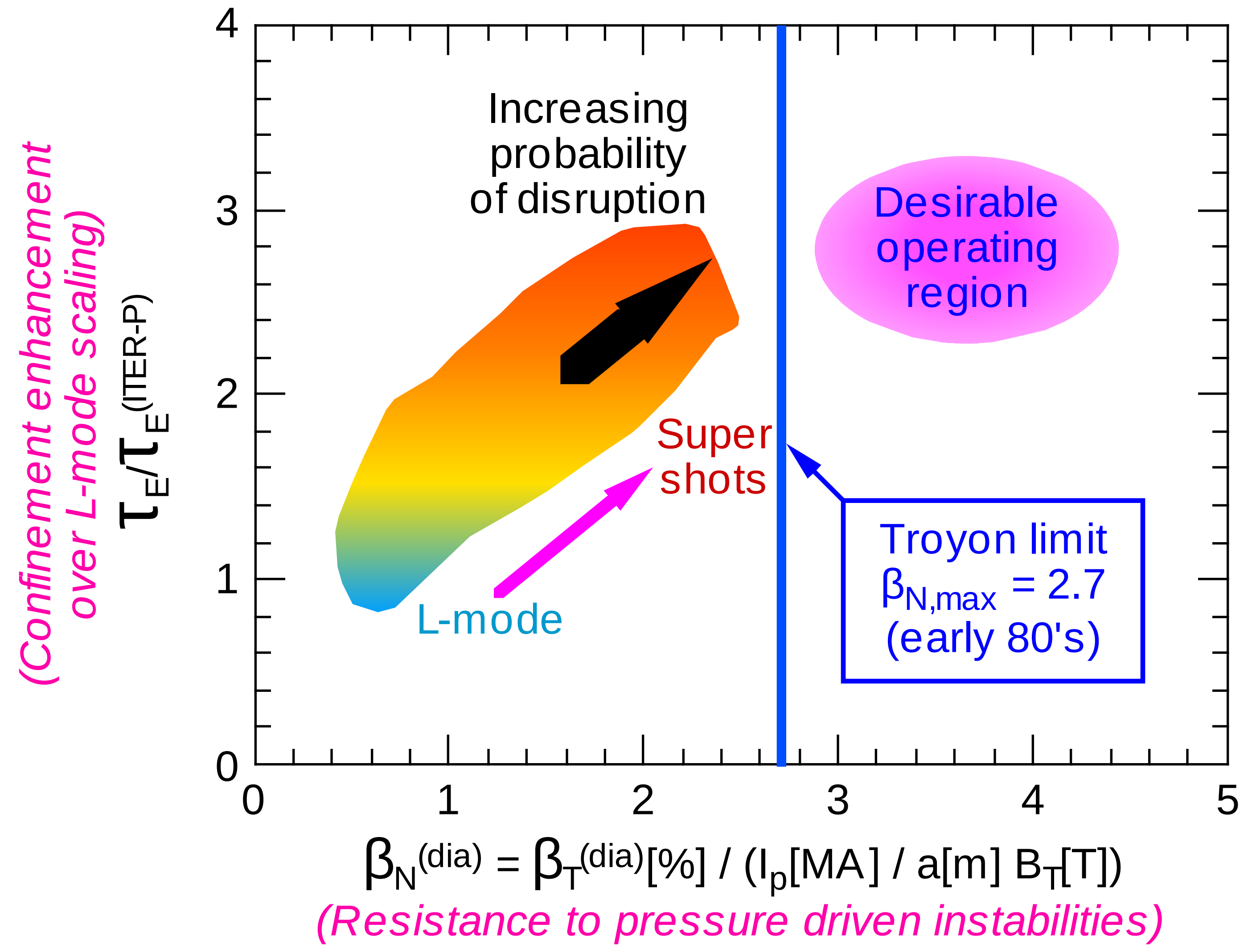
- L-mode plasmas showed adverse dependence of χ_i with temperature
- Estimates of diffusivity of energetic beam ions continued supershot trend, *but*
- Ion transport still above neoclassical levels

DD Fusion Reactivity Also Scaled Favorably in Supershots



- Code models 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

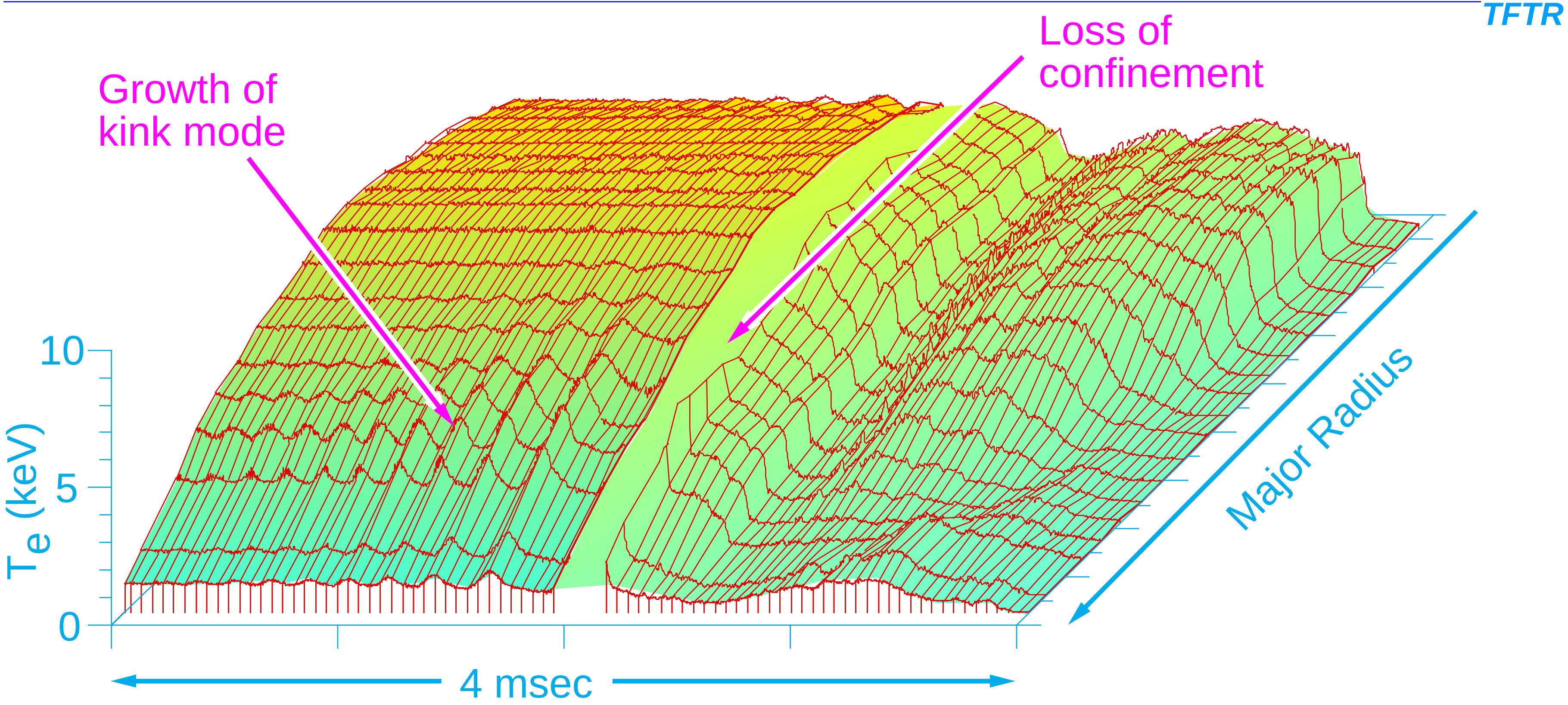
Supershots Were Limited by Pressure-Driven Instabilities Below the Predicted MHD Limit



- Improving confinement by peaking pressure profiles reduced global stability

  fast β-limit disruptions at high field (ideal MHD modes)

A Variety of MagnetoHydroDynamic Instabilities Driven by the Plasma Current and Pressure Occurs in Tokamaks



Growth of kink mode

Loss of confinement

- Fast "ideal" instabilities can occur in perfectly conducting fluids (Alfvén timescale)
- Others depend on plasma resistivity (resistive penetration timescale)
- Surfaces where the MHD safety factor q (=inverse rotational transform of field line) is rational are prone to resonant instabilities
- In extreme cases, instabilities can destroy the confinement

MHD Theory Suggested Ways to Improve Stability

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- Theory: *stability* to MHD ballooning and certain kinetic micro-instabilities should improve with reversed magnetic shear, $S = r/q \cdot \partial q/\partial r < 0$
- Experiments: diagnostics for q-profile permitted development of plasmas with reversed shear near plasma core
- Observed improvements in *energy confinement* in several tokamaks
  - formation of prominent internal transport barriers (ITBs)
  - factors 2 – 4 relative to L-mode confinement scaling, *but*
  - global stability limit not improved due to profile changes
- Global stability was improved by peaking the plasma current profile, as expected from theory
  - so-called “high-l_i” (l_i = internal inductance parameter) mode

Advances in Diagnostic Techniques Paved Way for Investigating New Regimes with Good Confinement

Reversed-shear

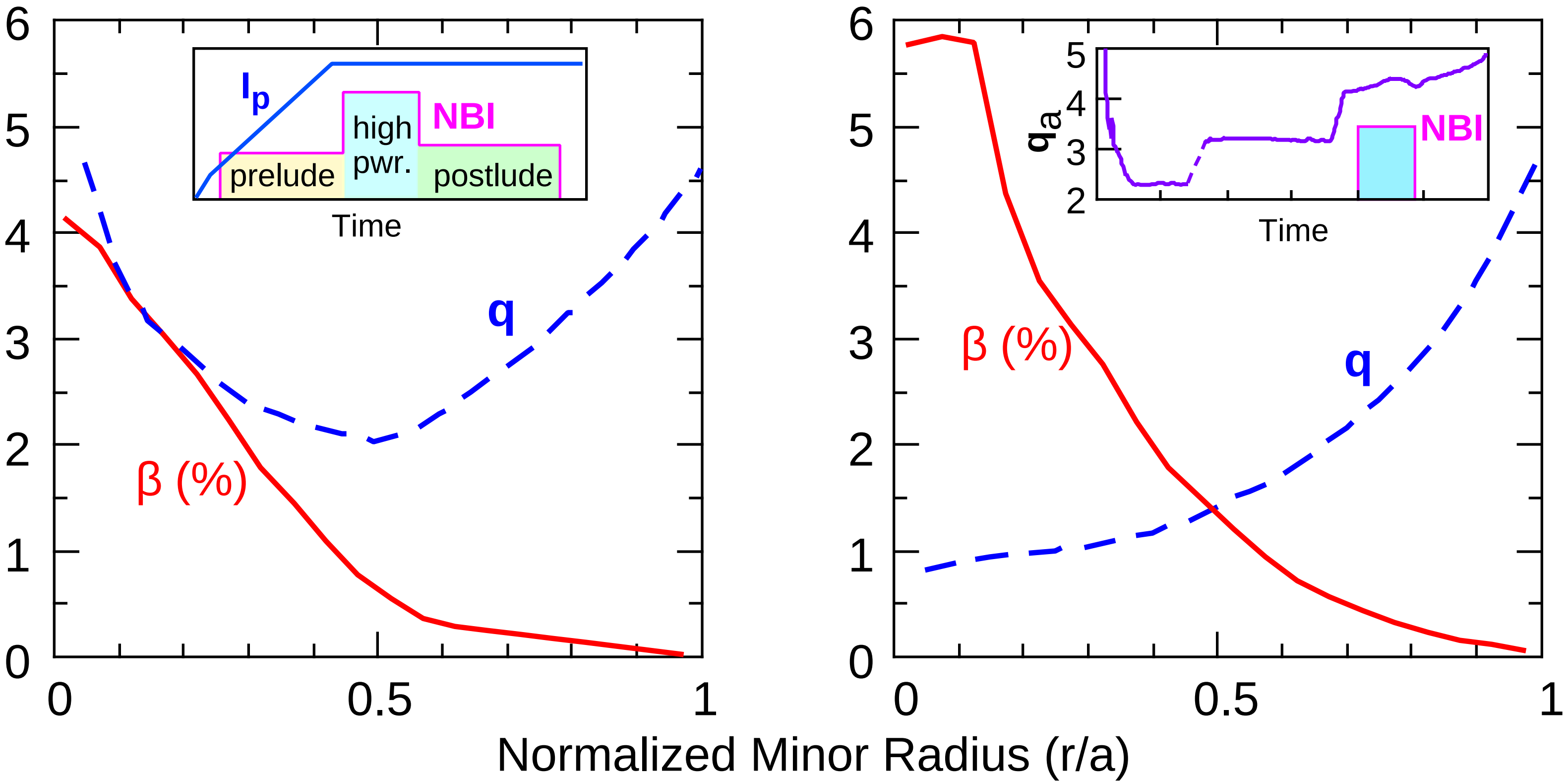
τ_E = 0.23s

NBI heating during current ramp in large plasma

High-l_i

τ_E = 0.23s

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 A Regime of Enhanced Confinement: ERS

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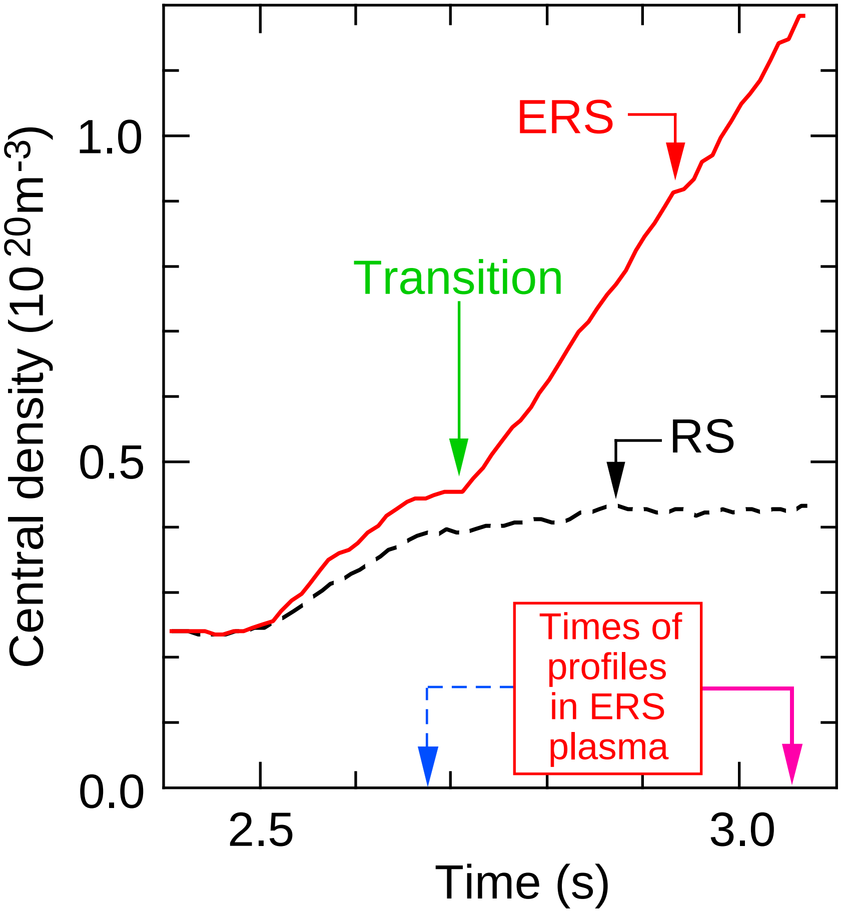

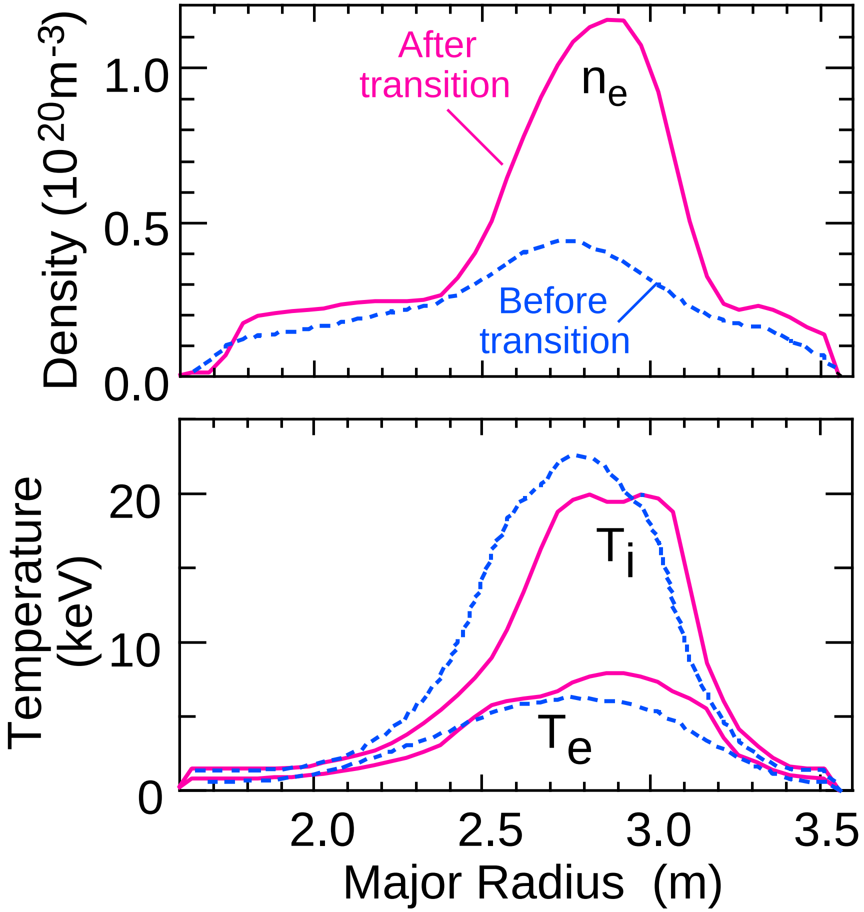

- **RS** - Similar to supershots: low χ_e, χ_i
- **ERS** - Reduced D_e, D_i, χ_i
  - turbulent fluctuations suppressed within "transport barrier"

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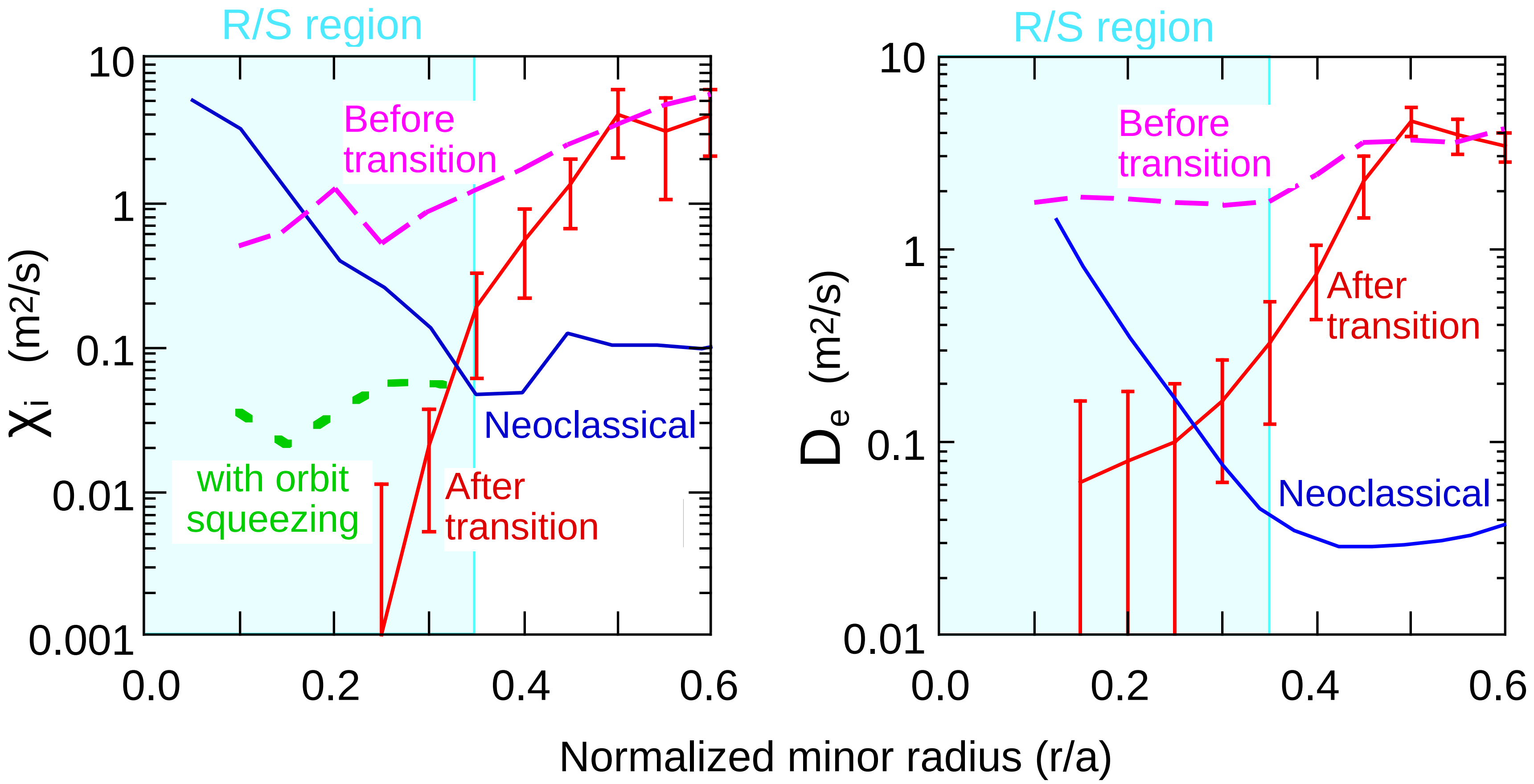
Ion Thermal and Electron Particle Transport Sharply Reduced in Plasma Interior after ERS Transition

TFTR



- Flux balance effective χ, D: q ≡ – n χ T and Γ ≡ – D n
- Neoclassical calculation includes off-diagonal contributions
- Orbit squeezing effects from theory of Lin

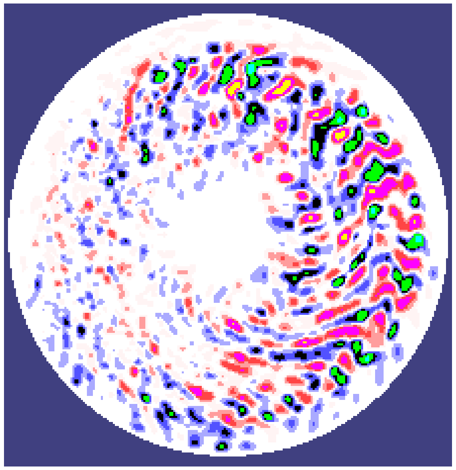
Turbulent Fluctuations Suppressed When E×B Shearing Rate Exceeds Maximum Linear Growth Rate of Instabilities

TFTR

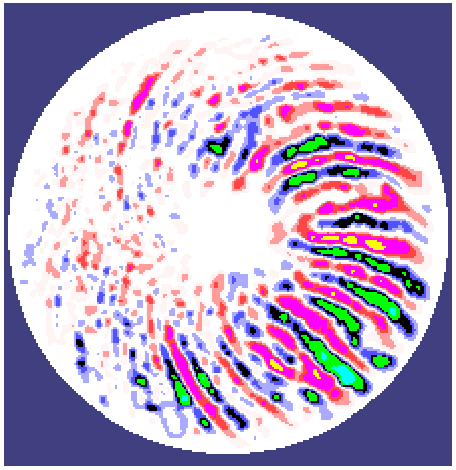
Gyrokinetic Simulations

- Turbulent eddies from Ion Temperature Gradient instability disrupted by strongly sheared **E×B** plasma flow

With Flow



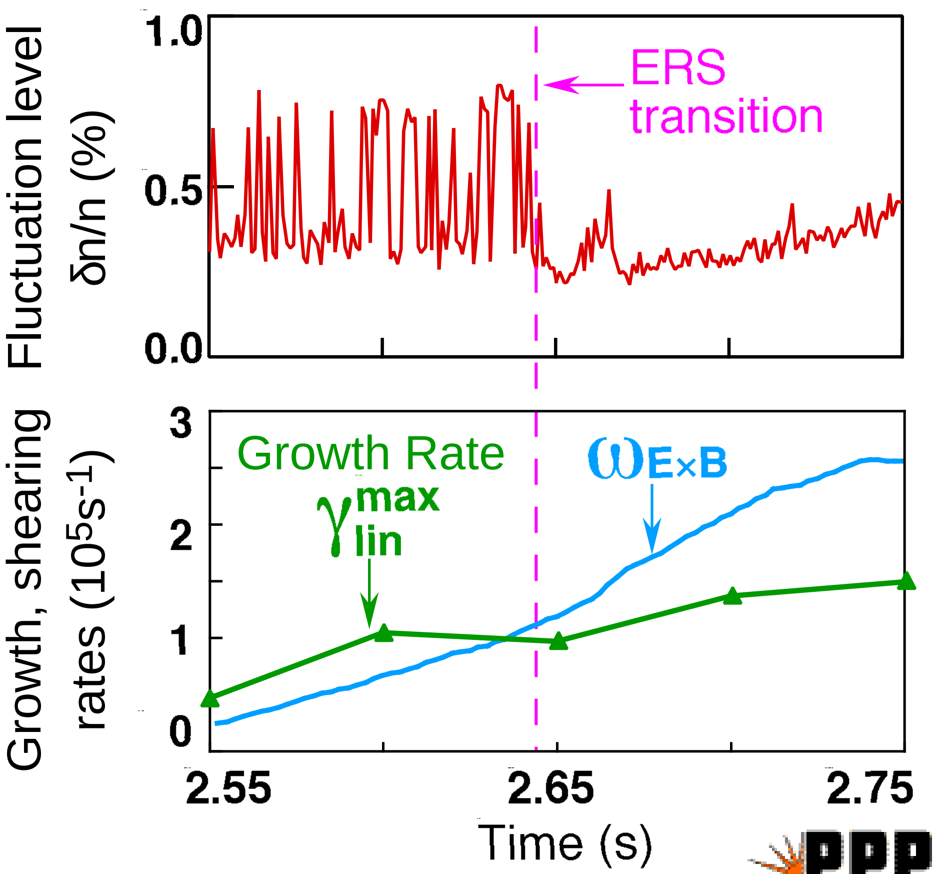
Without Flow



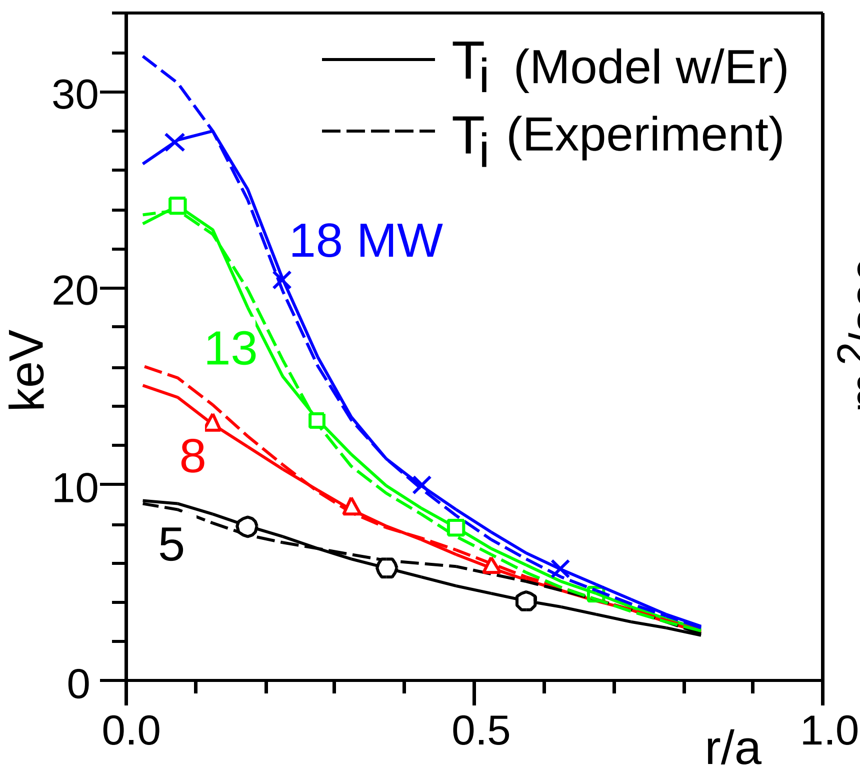
W. Lee, Z. Lin, E. Mazzucato, E. Synakowski, M. Beer

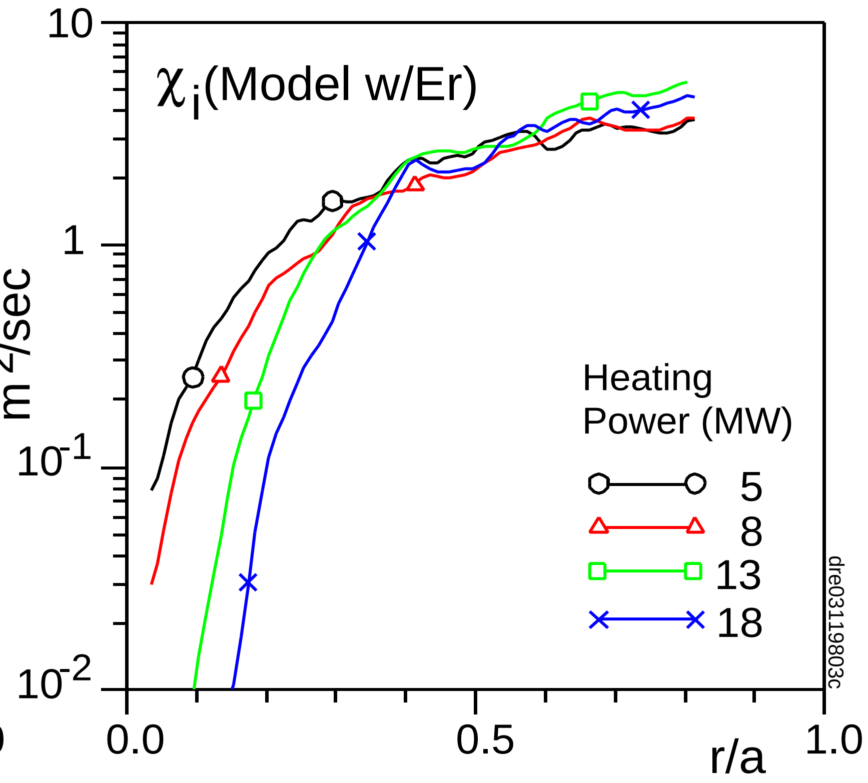
Experiment

- Bursting fluctuations are suppressed at transition to improved confinement
- Occurs when **E×B** shearing rate exceeds growth rate of most unstable mode



Model with Turbulence Suppressed by Velocity Shear Reproduces Ion Temperature Profiles in Supershots





- Based on supppression of ITG turbulent ion thermal diffusivity when $\omega_{\mathrm{E\times B}} \simeq \gamma_{\mathrm{lin}}^{\mathrm{(IFS-PPL)}}$ with self-consistent calculation of neoclassical plasma flow.
- Leads to apparent $\chi_{\mathrm{i}} \propto 1/\mathrm{T_i}$ scaling at fixed radius.
- Enhanced confinement zone expands with heating power.
- Supershot behavior resembles ERS, NCS, JT-60 ITB, etc.

History of Tokamak D-T Experiments 1991-7

JET, November 1991 (“PTE”)

- First DT experiments with low concentrations of tritium: $P_{fus} = 1.7MW$

TFTR, December 1993 - April 1994

- High fusion reactivity: $P_{fus} = 10.7MW$ 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”)

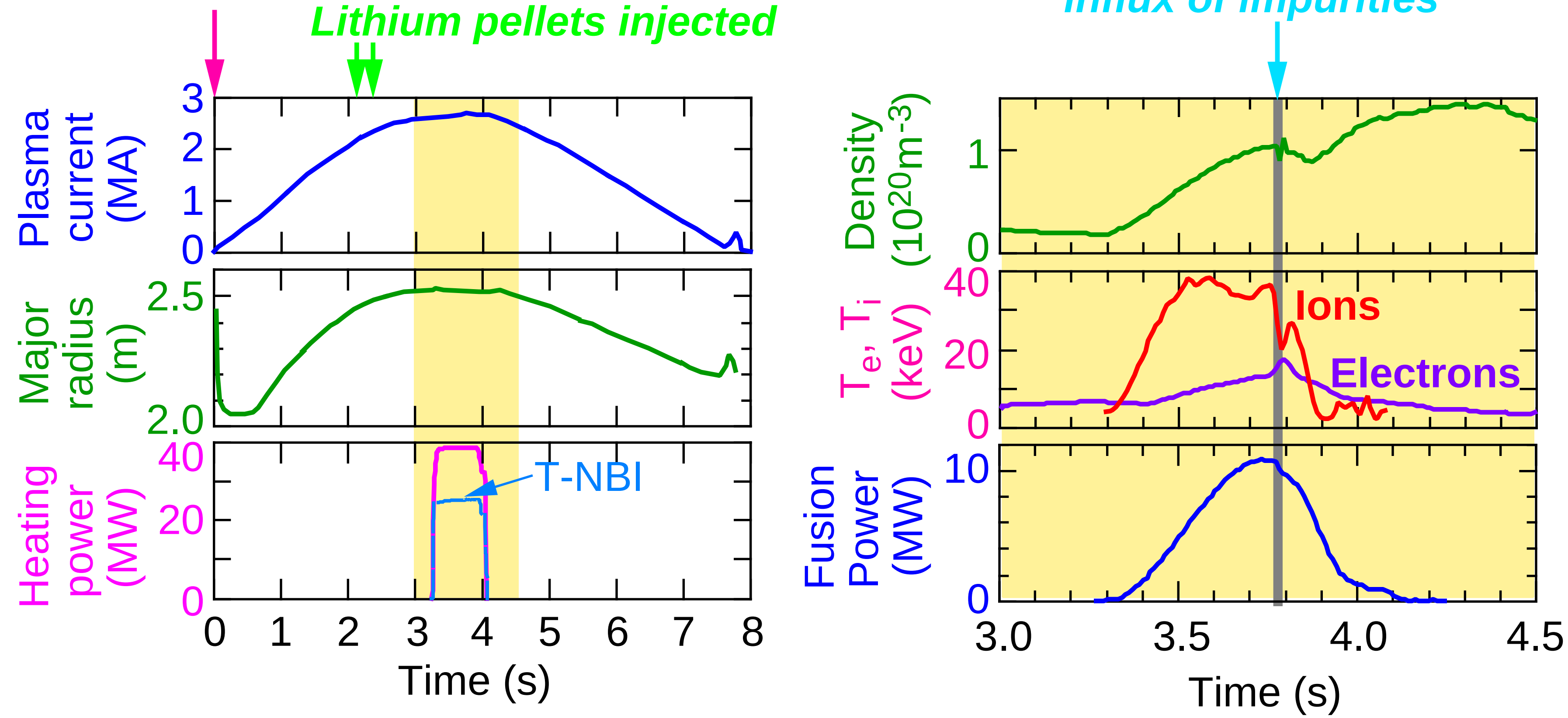
- High reactivity: $P_{fus} = 16MW$ peak; $Q \approx 0.6$
- Prototype operating regimes for ITER
- ICRF physics in D-T plasmas

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 many collaborators in the physics and engineering communities*

Time Evolution of the 10.7MW D-T Pulse

TFTR



Toroidal magnetic field established
Vacuum vessel prefilled with D_2

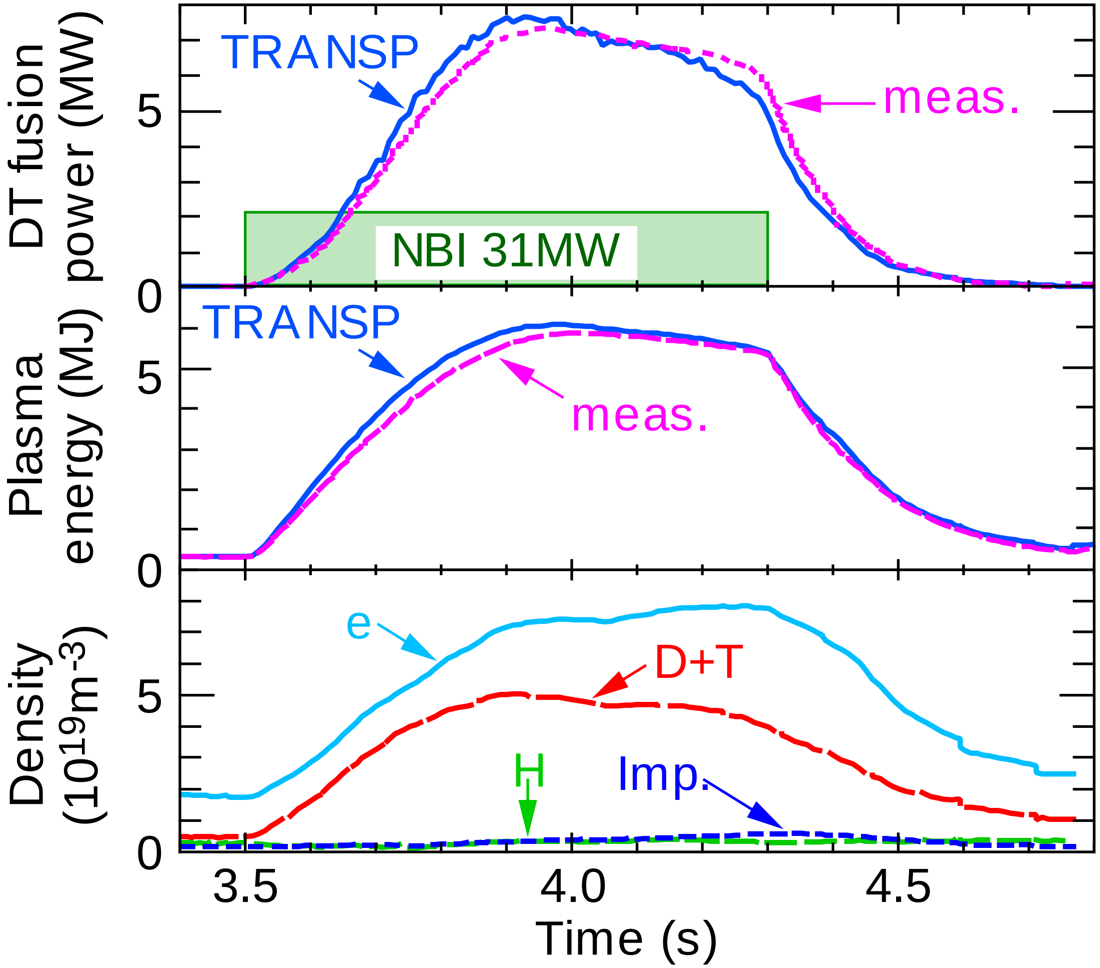
Lithium pellets injected

MHD instability degrades confinement, triggering influx of impurities

- TFTR operated at or beyond original specifications in field, current, pulse length
- Lithium injected as pellets during ohmic heating phase coat carbon limiter and reduce influxes of hydrogen isotopes and carbon during NBI heating
  - coating equivalent to a few monolayers over geometric area of limiter
  - negligible lithium content in plasma during NBI

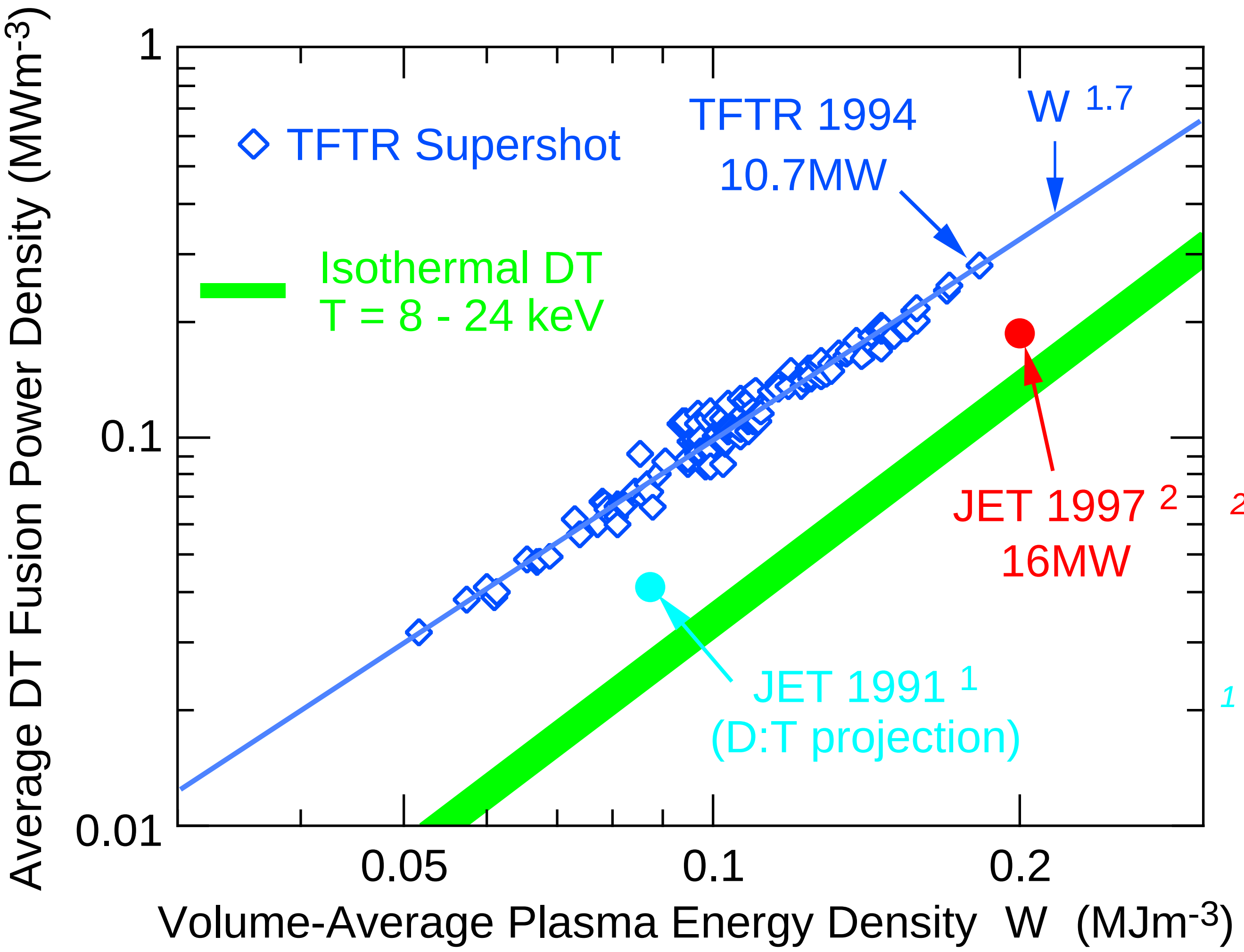
Codes Can Successfully Model DT Reactivity

TFTR



- TRANSP code uses measurements of n_e, T_e, T_i profiles, impurity content and NBI parameters
- Models atomic physics, classical orbits and thermalization of injected particles, DT reactivity from nuclear cross-sections

High Ion Temperature and Peaked Pressure Profiles Increased Reactivity of Supershots over Alternative Regimes

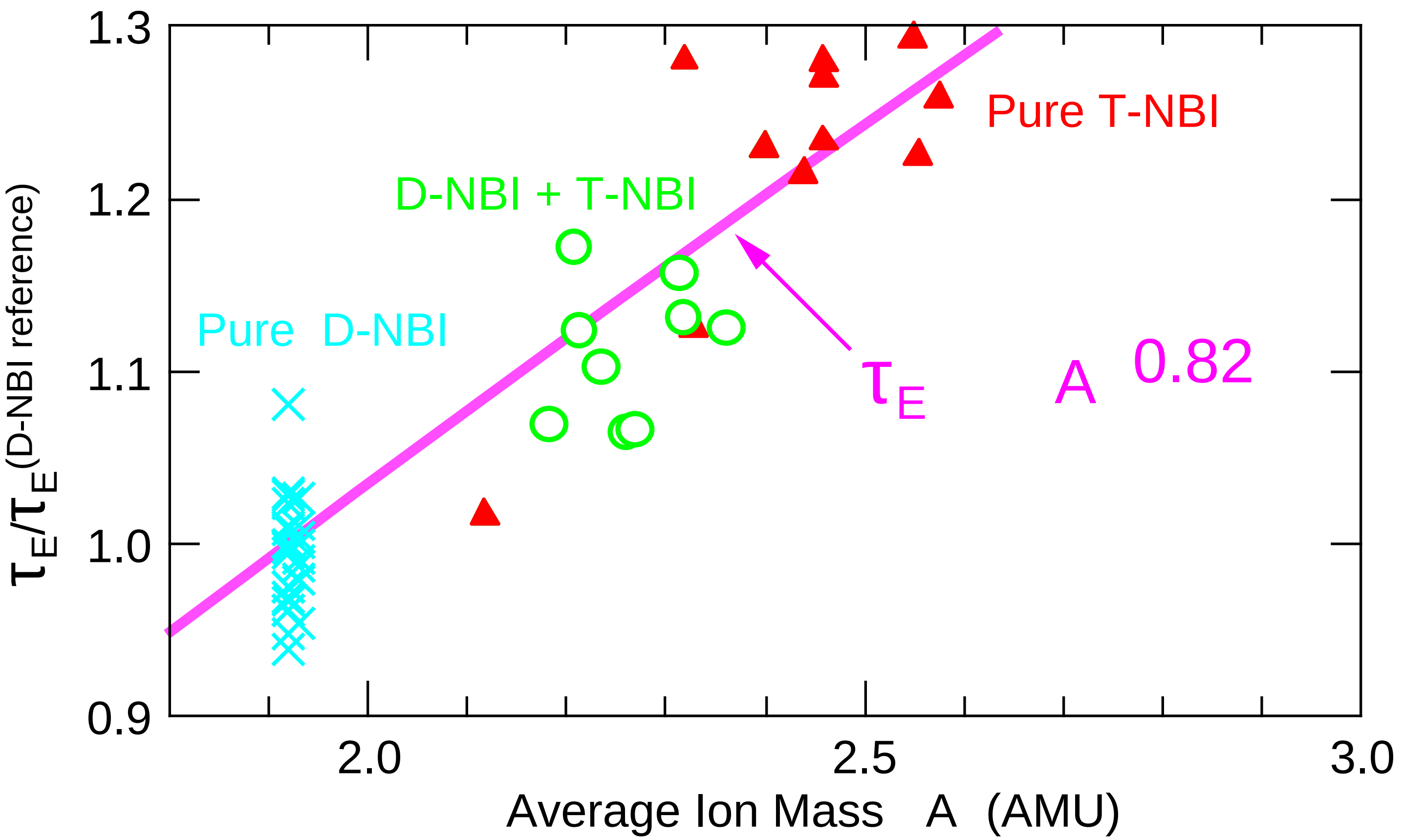


[2] *Phys. Plasmas* ***5*** *(1998) 1839*

[1] *Nuclear Fusion* ***32*** *(1992) 187*

- High reactivity allowed investigation of fusion alpha-particle physics in tokamak with moderate size and, therefore, confinement

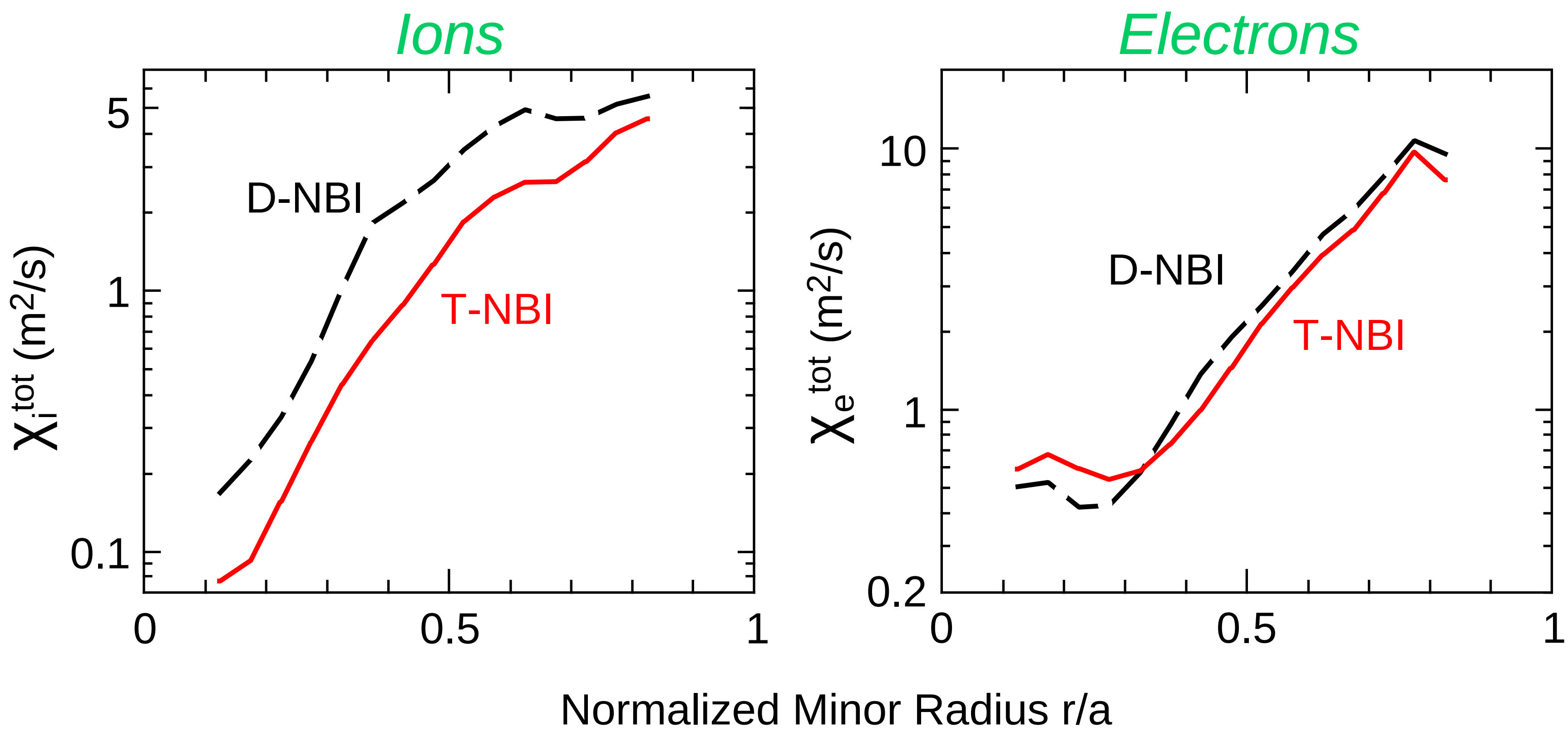
Global Confinement Increased With Tritium NBI



- Tritium concentration limited by D influx from limiter, even with pure T-NBI
- Strong τ_E increase in supershot and H-mode regimes <A>$^{0.8}$, weaker in ICRF heated D-T plasmas <A>$^{0.5}$ (no supra-thermal tritons present)
  - ITER global scaling: τ_E <A>$^{0.5}$
- Contrast with JET where no isotope scaling observed in D-T plasmas

Ion Thermal Transport is Reduced in TFTR Supershot Plasmas with Tritium NBI

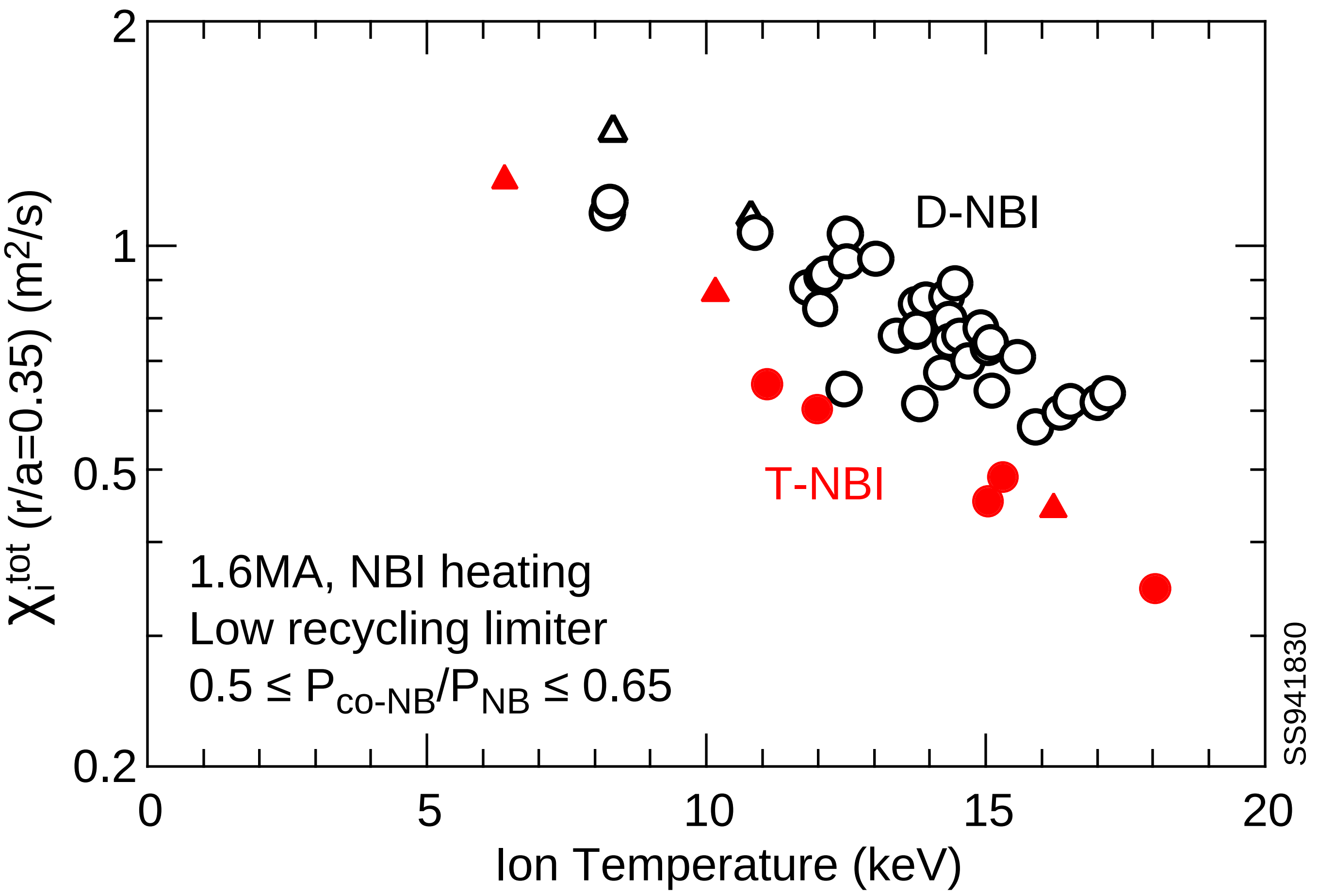
TFTR



- Effect is much more pronounced in ion channel
- Inconsistent with naive Bohm or gyro-Bohm scaling

Tritium NBI Extended Earlier Supershot Scaling Results

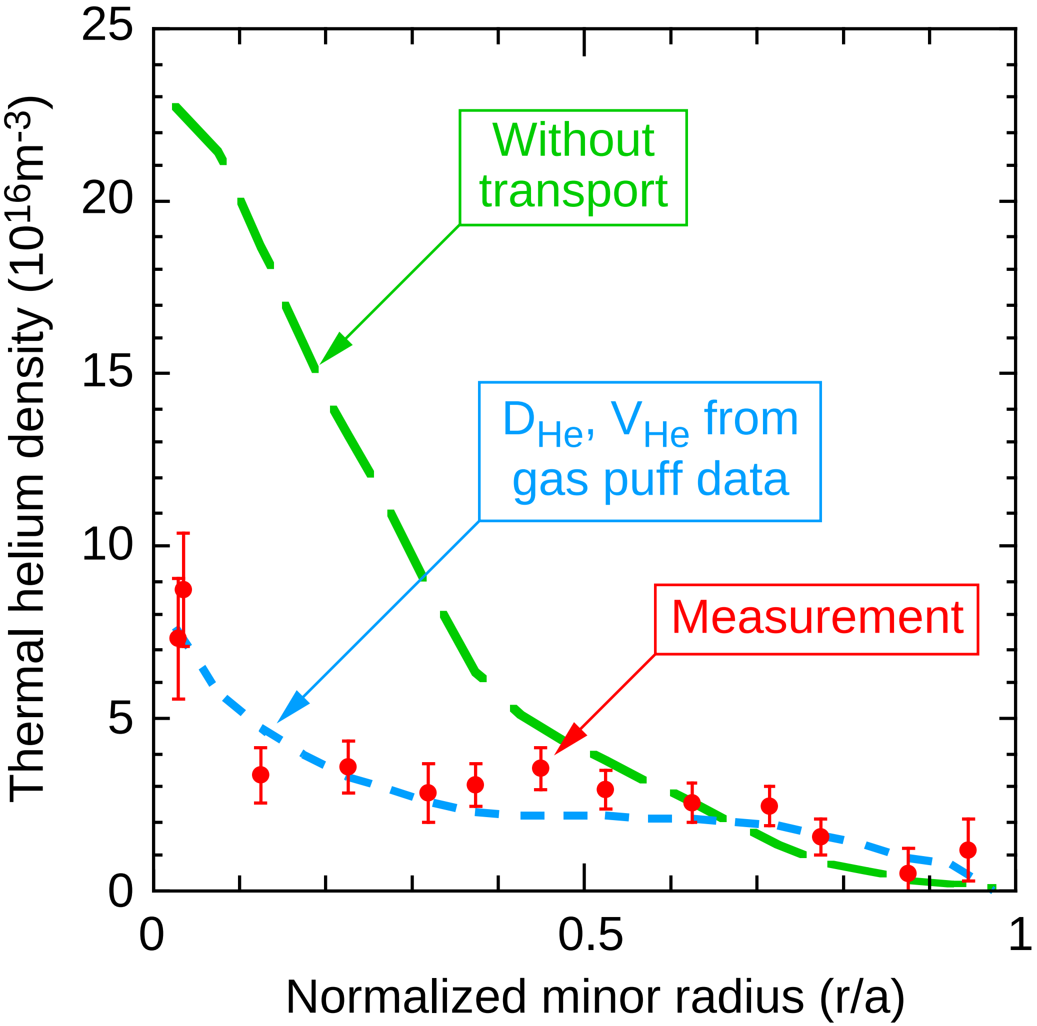
TFTR



- Favorable scaling of ion thermal transport with temperature and isotopic mass at variance with Bohm and gyro-Bohm scalings of L-mode (and H-mode) plasmas
- Isotope scaling also occurred in TFTR with minority ion-cyclotron heating which heats electrons rather than ions

Transport of Thermal Helium Ash from Center to Edge is Rapid

TFTR



- Measured by charge-exchange recombination spectrometry
- Consistent with modelling based on transport deduced from He gas puff
- D_{He} / χ_D ~ 1: consistent with $\tau_p{}^*{}_{(He)}/\tau_E$ ≈ 8 needed for reactors

E.J. Synakowski

Comparison of Achieved Plasma Conditions with ITER Design

Central values	**ITER[1]**	**TFTR**	**JET[2]**	**JT-60U[3]**
Plasma composition	DT	DT	DT	D
Mode	ELMy H-mode	Supershot	Hot-ion ELM-free H-mode	Reversed-shear High-β_P
n_e [$10^{20}\mathrm{m}^{-3}$]	1.3	1.02	0.42	0.85
n_{DT} [$10^{20}\mathrm{m}^{-3}$]	0.8	0.60	0.35	0.48 (n_i)
n_{He} [$10^{20}\mathrm{m}^{-3}$]	0.2	0.002		
T_I [keV]	19	40	28	16
T_e [keV]	21	13	14	7
Z_{eff}	1.8	1.8	2.1	3.2
p_{tot} [MPa]	0.8	0.75	0.37	0.22
P_α [MWm^{-3}] (source)	0.5	0.45	0.14	
P_{aux} [MWm^{-3}]	0	3.4	0.8	0.3

[1] ITER Final Design Review Document

[2] A. Gibson *et al.* Phys. Plasmas **5** (1998) 1839

[3] S. Ishida *et al.*, paper IAEA-CN-69/OV1/1, IAEA Fusion Energy Conference, Yokohama, Oct. 1998

- *Confinement and pulse length are the remaining issues!*

Progress in Tokamak Physics in TFTR

- *Tokamaks have continued to provide the most simple, reliable and cost-effective vehicle for studying the physics of high-temperature, high-pressure plasmas prototypical of a magnetic confinement reactor*

- We have made major strides in understanding plasmas in tokamaks:
  - Neoclassical transport phenomena
  - Anomalous transport, including link to plasma fluctuations and turbulence
  - MHD stability

- New regimes of improved performance were developed and exploited

- Precise control of the plasma in a tokamak will be required to take advantage of these improved confinement regimes

- A sustained campaign of D-T operation was completed in TFTR confirming fusion's promise and revealing a wealth of new physics