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UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P,P.O. BOX 586,34100 TRIESTE,ITALY,CABLE:CENTRATOM TRIESTE

H4-SMR 1012 - 38

AUTUMN COLLEGE ON PLASMA PHYSICS

13 October - 7 November 1997

LECTURE NOTES

M.G. BELL

Princeton Plasma Physics Laboratory, Princeton, U.S.A.

These are lecture notes, intended for distribution to participants.

Tokamak Physics: 15 Years of Progress

M.G. Bell

Princeton Plasma Physics Laboratory[1]

Presented at the

Autumn College on Plasma Physics
International Centre for Theoretical Physics
Trieste, Italy

November 5, 1997

[1] *Supported by U.S. Department of Energy Contract No. DE-AC02-76-CH03073*

Contributors to TFTR D-T Experiments

Laboratories

Association Euratom-CEA, Cadarache, France
Ecole Royal Militaire, Brussels, Belgium
Environmental Measurement Laboratory, New York, NY
Idaho National Engineering Laboratory, Idaho Falls, ID
Institute of Plasma Physics, Academia Sinica, Heifei, China
Institüt für Plasmaphysik, Jülich, Germany
I.V. Kurchatov Institute of Atomic Energy, Russia
Ioffe Physical-Technical Institute, Russia
Japan Atomic Energy Research Institute, Japan
JET Joint Undertaking, United Kingdom
Lawrence Berkeley Laboratory, Berkeley, CA
Lawrence Livermore National Laboratory, Livermore, CA
Los Alamos National Laboratory, Los Alamos, NM
National Institute of Fusion Science, Toki, Japan
Oak Ridge National Laboratory, Oak Ridge, TN
Sandia National Laboratory, Albuquerque, NM
Sandia National Laboratory, Livermore, CA
Savannah River Plant, Aiken, SC
Southwestern Institute of Physics, Chengku, China
Troitsk Institute of Innovative and Thermonuclear Research, Russia
UKAEA Government Div., Fusion, Culham, UK

Industries

Burns and Roe Company, Oradell, NJ
Canadian Fusion Fuels Technology Project, Canada
Fusion Physics and Technology, Inc., Torrance, CA
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Raytheon Engineers and Constructors Inc., Ebasco Division, New York, NY

Universities

Colorado School of Mines, Golden, CO
Columbia University, New York, NY
Courant Institute, NYU, New York, NY
Institute for Fusion Science, Austin, TX
Lehigh University, Bethlehem, PA
Massachusetts Institute of Technology, Cambridge, MA
University of California, Davis, CA
University of California, Irvine, CA
University of California, Los Angeles, CA
University of California, San Diego, CA
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University of Tokyo, Tokyo, Japan
University of Toronto, Toronto, Canada
University of Wisconsin, Madison, WI

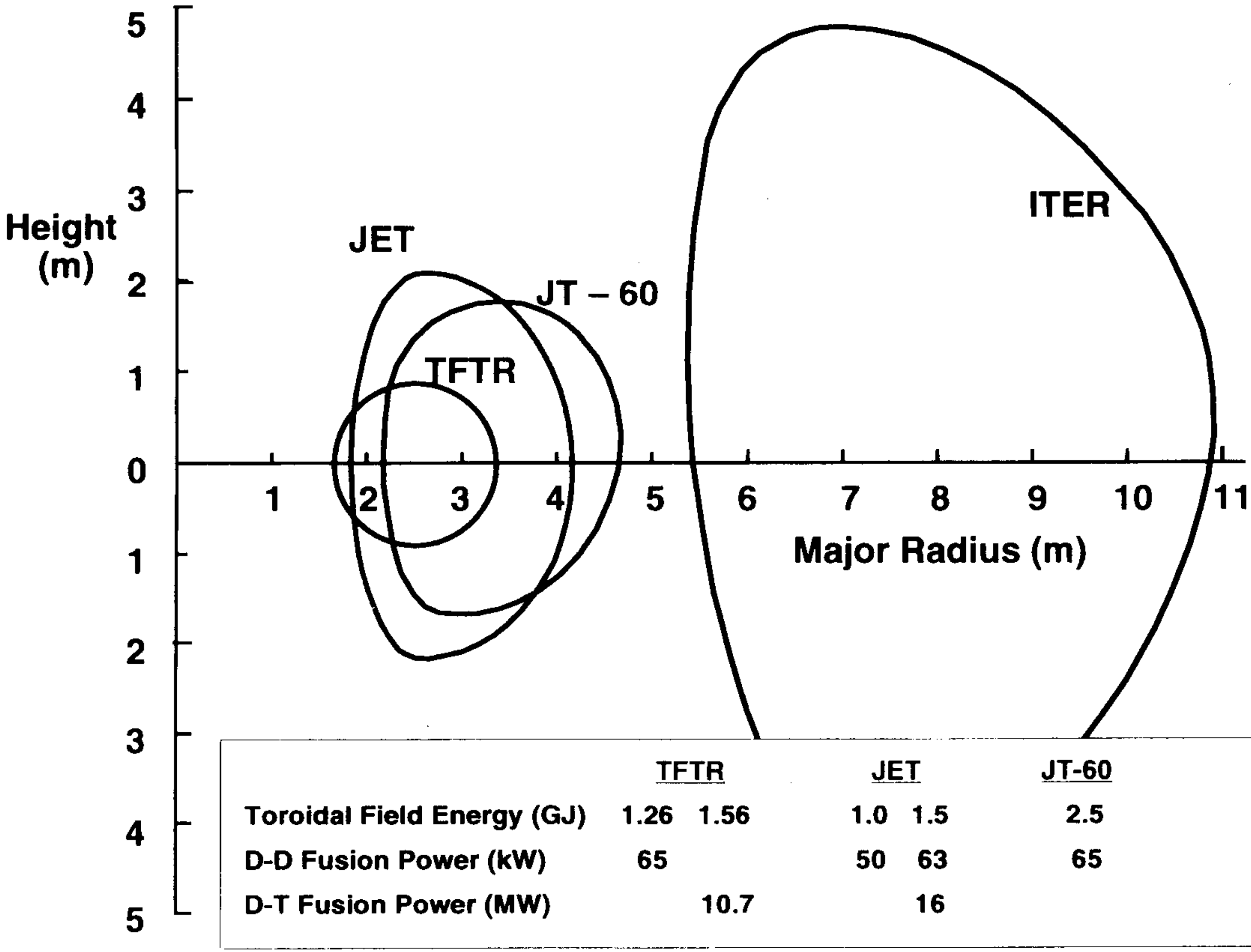
Topics

- The state of tokamak physics at the start of TFTR operation in 1983
- Developments in plasma diagnostics
- The discovery of regimes of improved plasma confinement
- Confirmation of the neoclassical bootstrap current
- Progress in our understanding of anomalous transport
- Improvements in understanding MHD stability
- Exciting developments in controlling anomalous transport

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.

Comparison of Plasma Size, Magnetic Energy and Fusion Power



	TFTR		JET		JT-60	ITER
Toroidal Field Energy (GJ)	1.26	1.56	1.0	1.5	2.5	100
D-D Fusion Power (kW)	65		50	63	65	7500
D-T Fusion Power (MW)		10.7		16		1500

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 (~2 $\times$ L-mode)

Developments 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

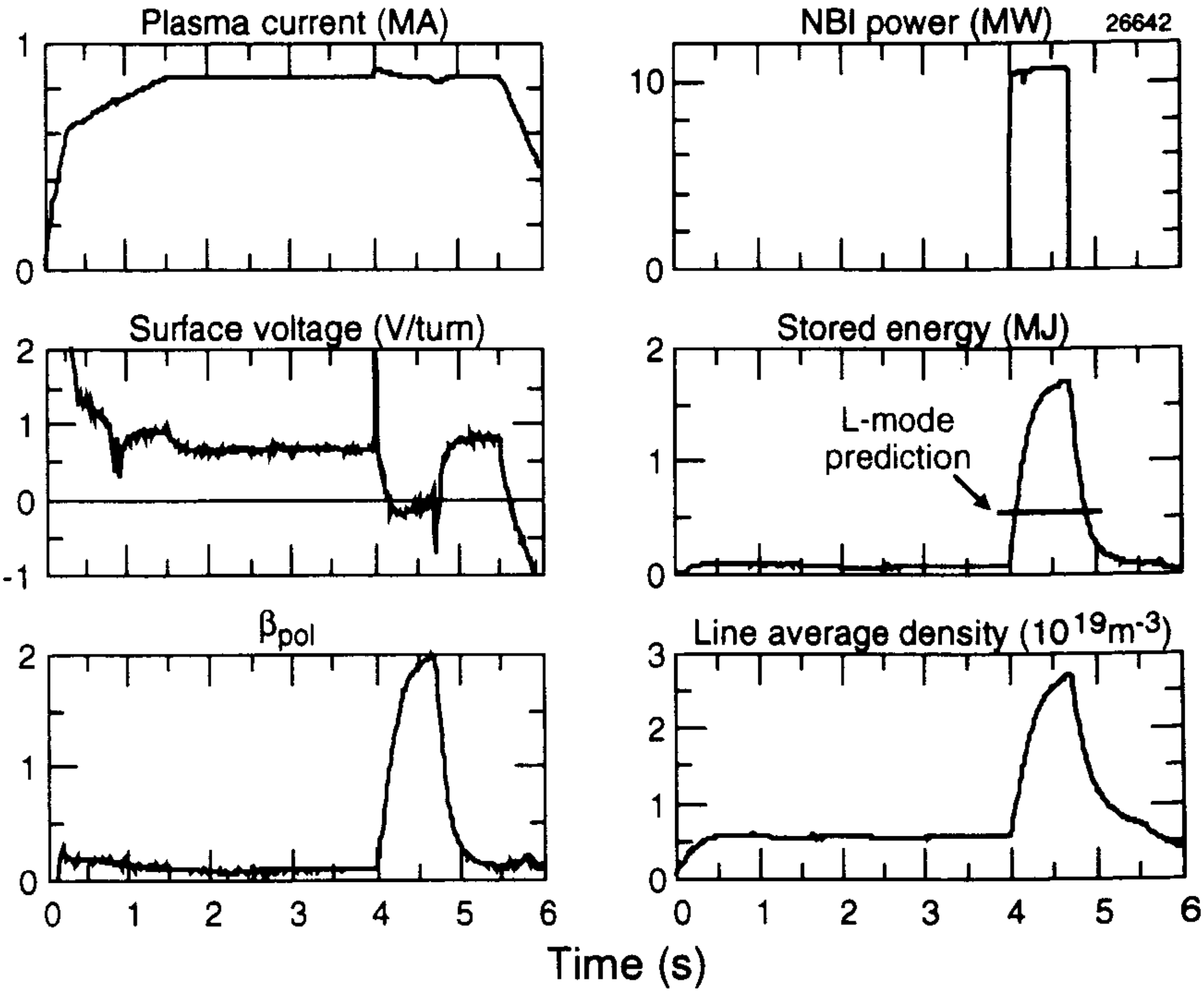
- Microwave Scattering
- X-mode Microwave Reflectometer
- Beam Emission Spectroscopy
- X-ray Imaging System
- ECE Grating Polychromator
- Neutron Fluctuation Detector
- Mirnov Coils
- ICE/RF Probes

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)

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



- Originally used sequences of low-density, ohmically heated helium plasmas for conditioning

  ⇒ reduced edge density during subsequent shots with NBI

- Subsequently developed additional techniques, including wall coating, to reduce influx from limiter

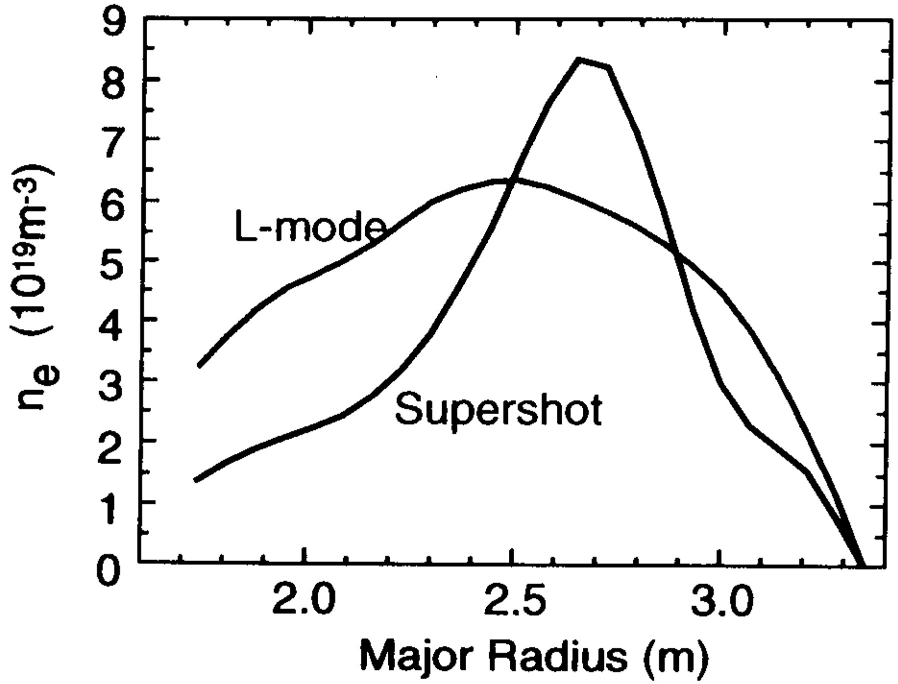
  ⇒ extended supershot confinement to 2.7MA, 40MW

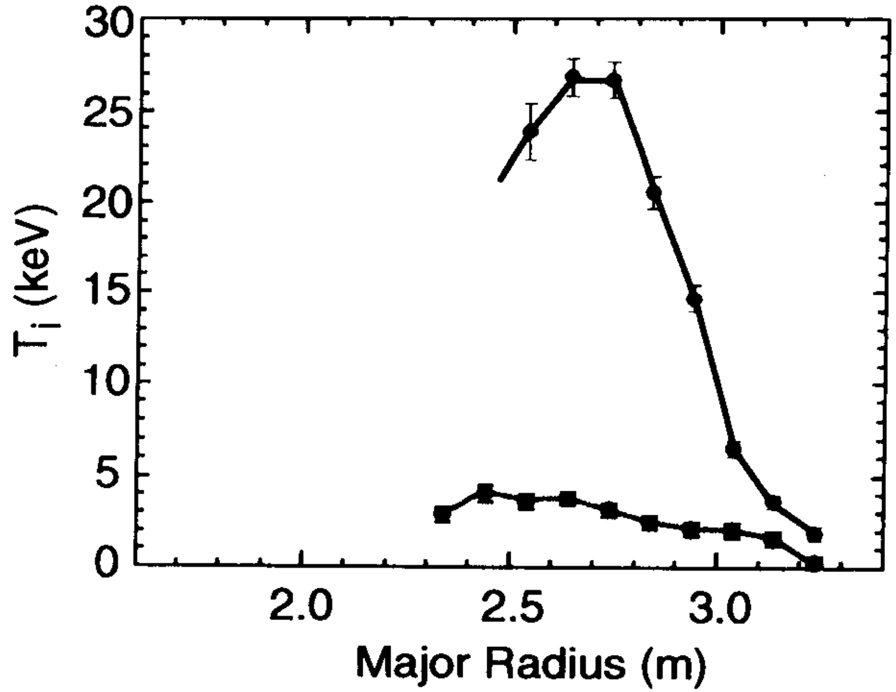
Supershots Had Dramatically Different Confinement

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:

τ_E = 0.060 s

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

Supershot:

τ_E = 0.18 s

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

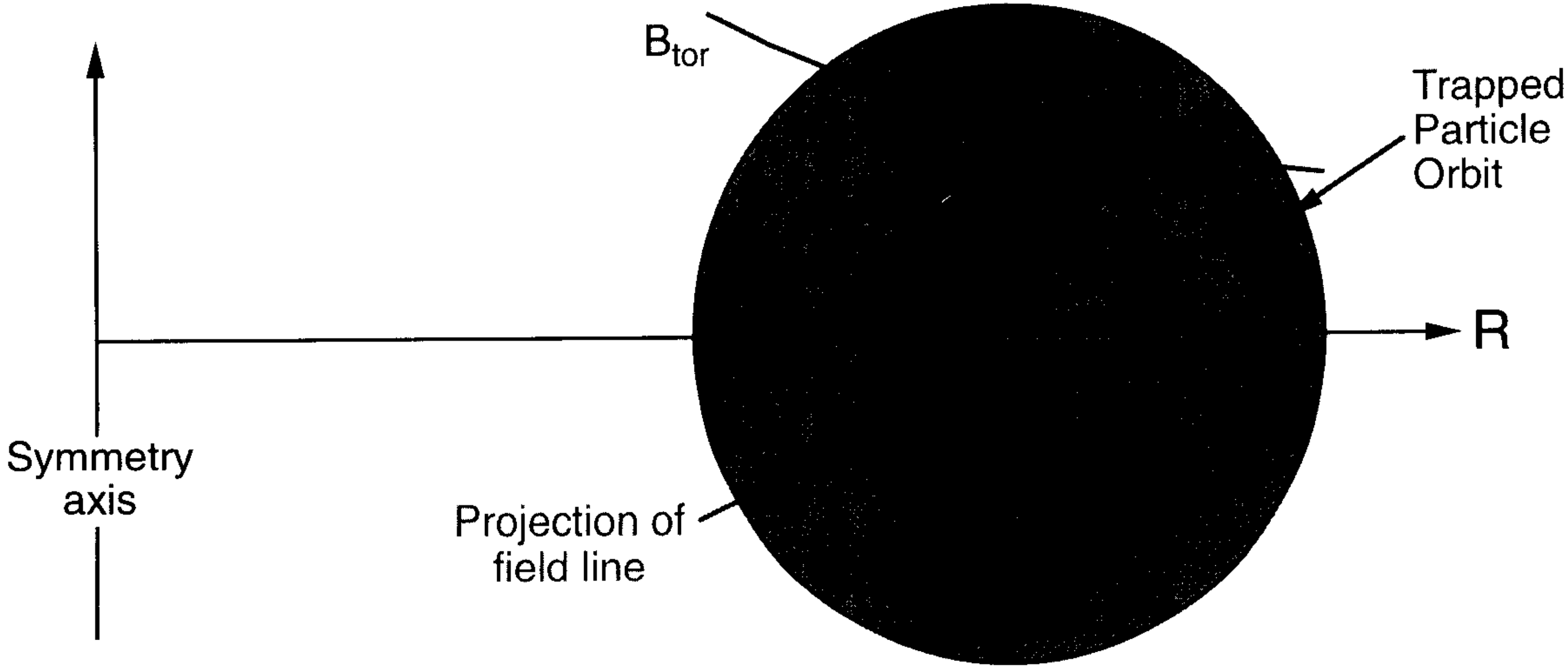
Origin of the Bootstrap Current in a Tokamak

- $B \propto 1/R$ 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

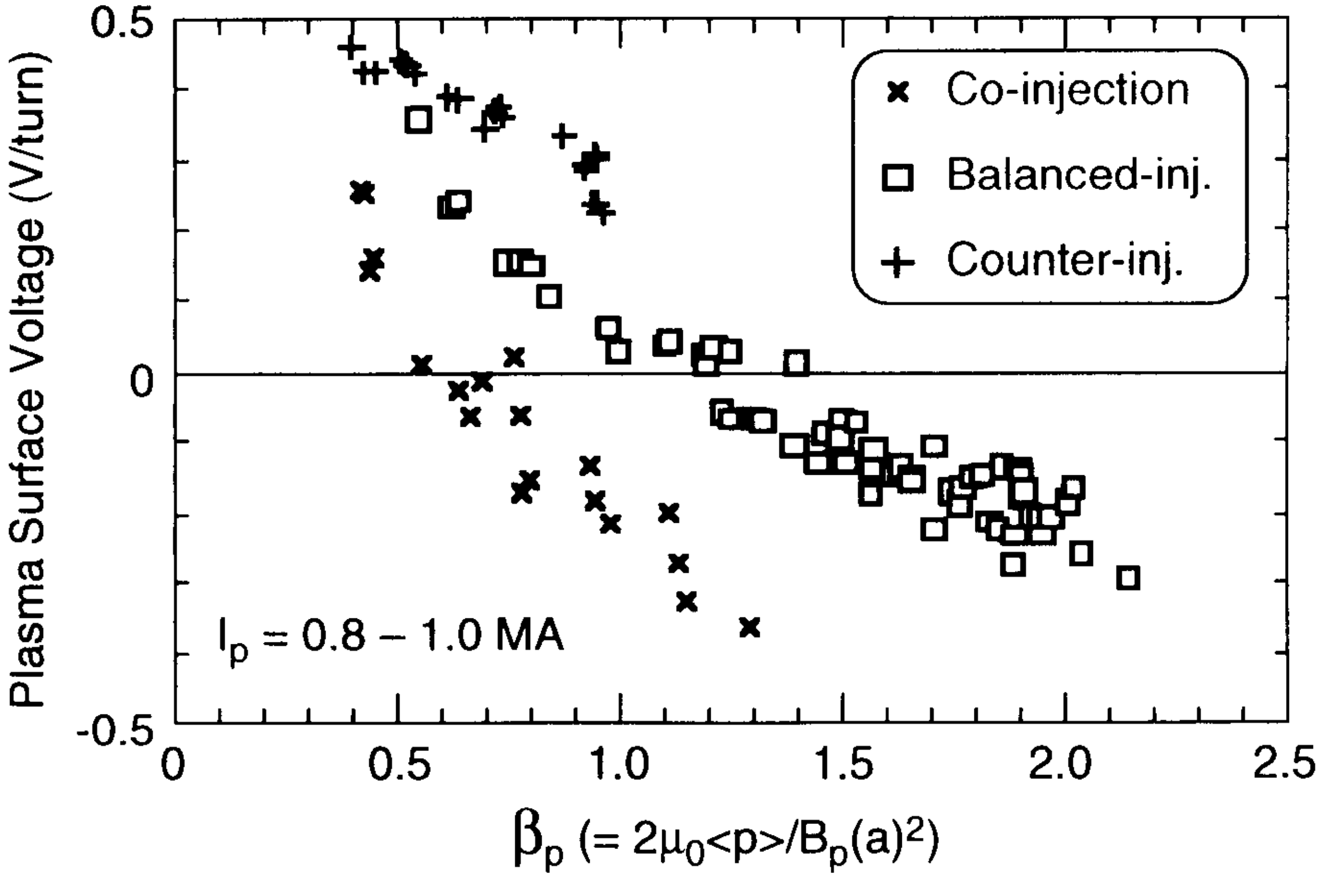
  ⇒ bootstrap current is zero on axis and becomes small in the cool, collisional edge



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

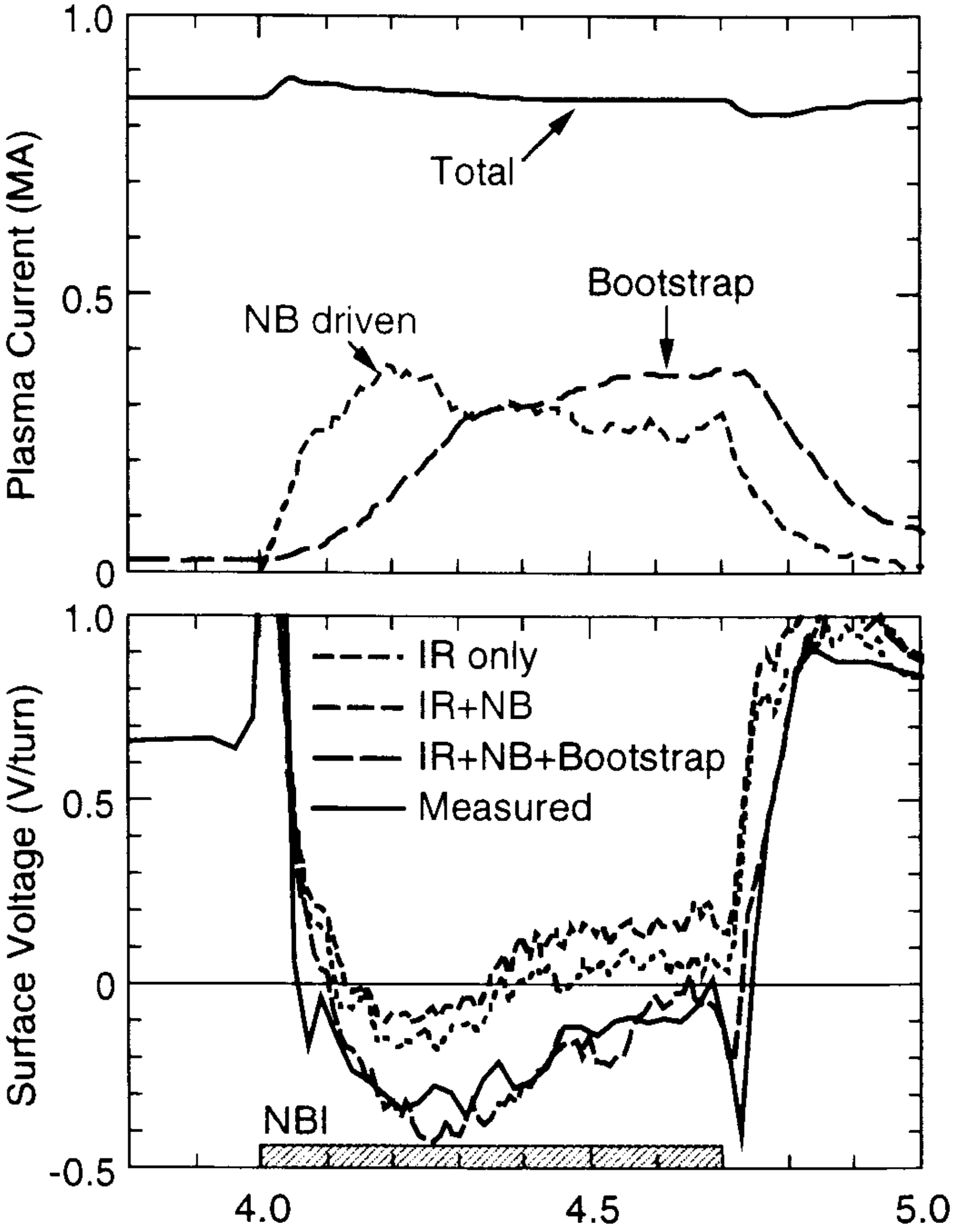
TFTR

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



Plasma Surface Voltage is Well Modeled by Including Beam-Driven and Bootstrap Currents

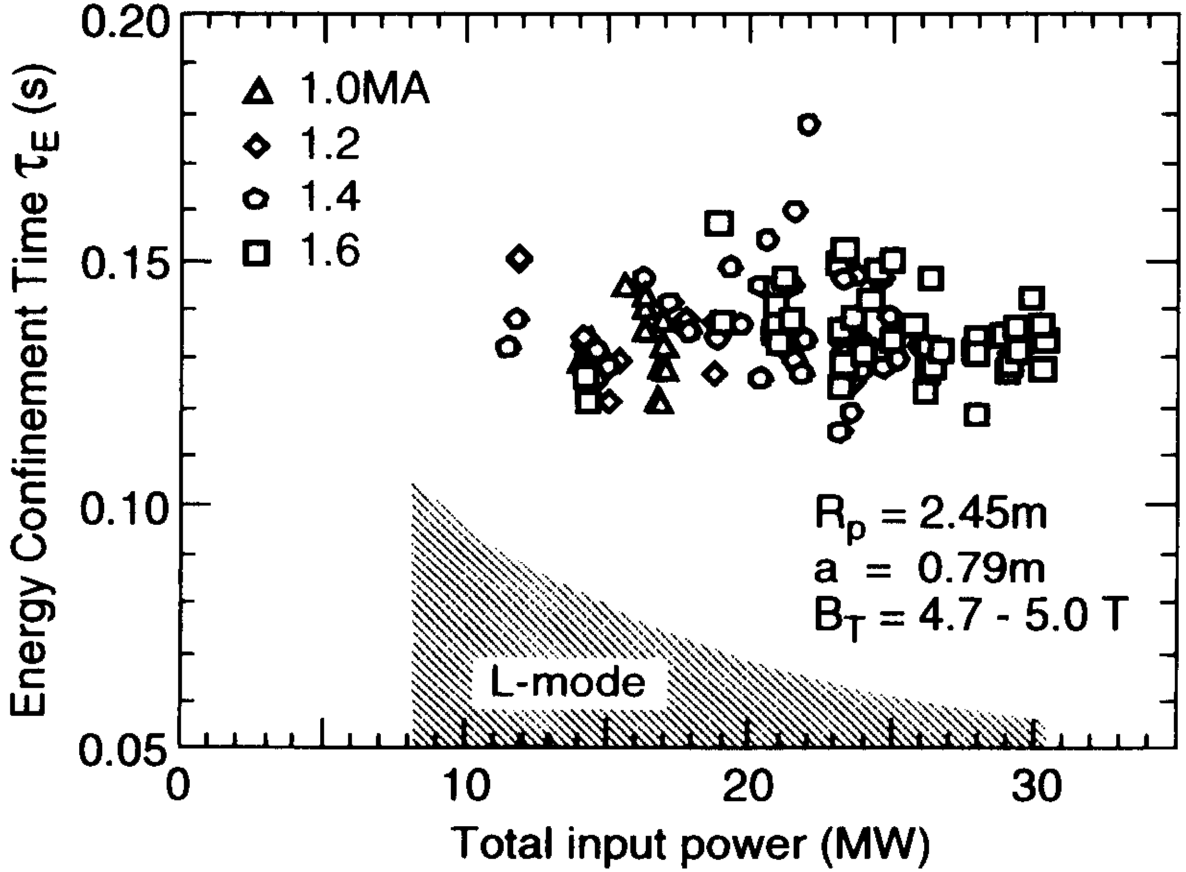
TFTR



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

Supershots Did Not Follow L-mode Empirical Scaling

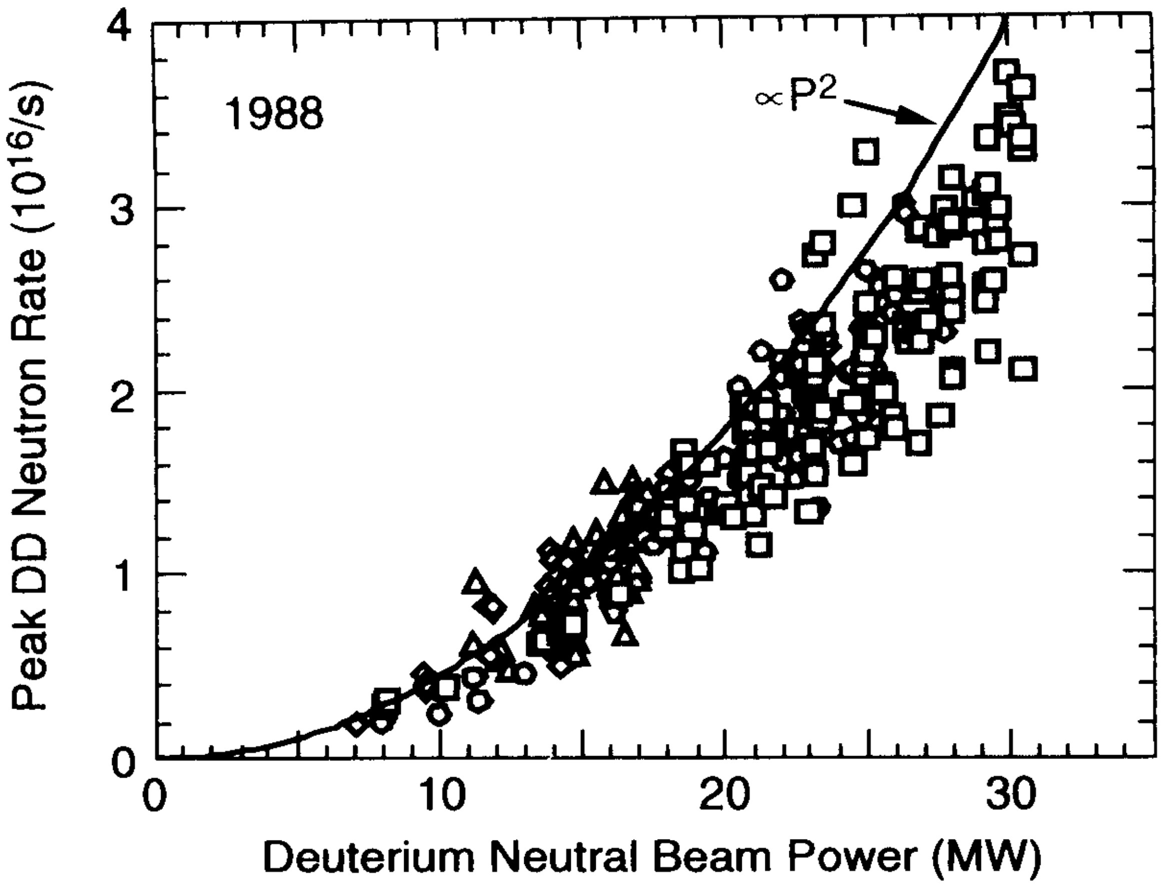
TFTR



1988 IAEA Conference

- 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

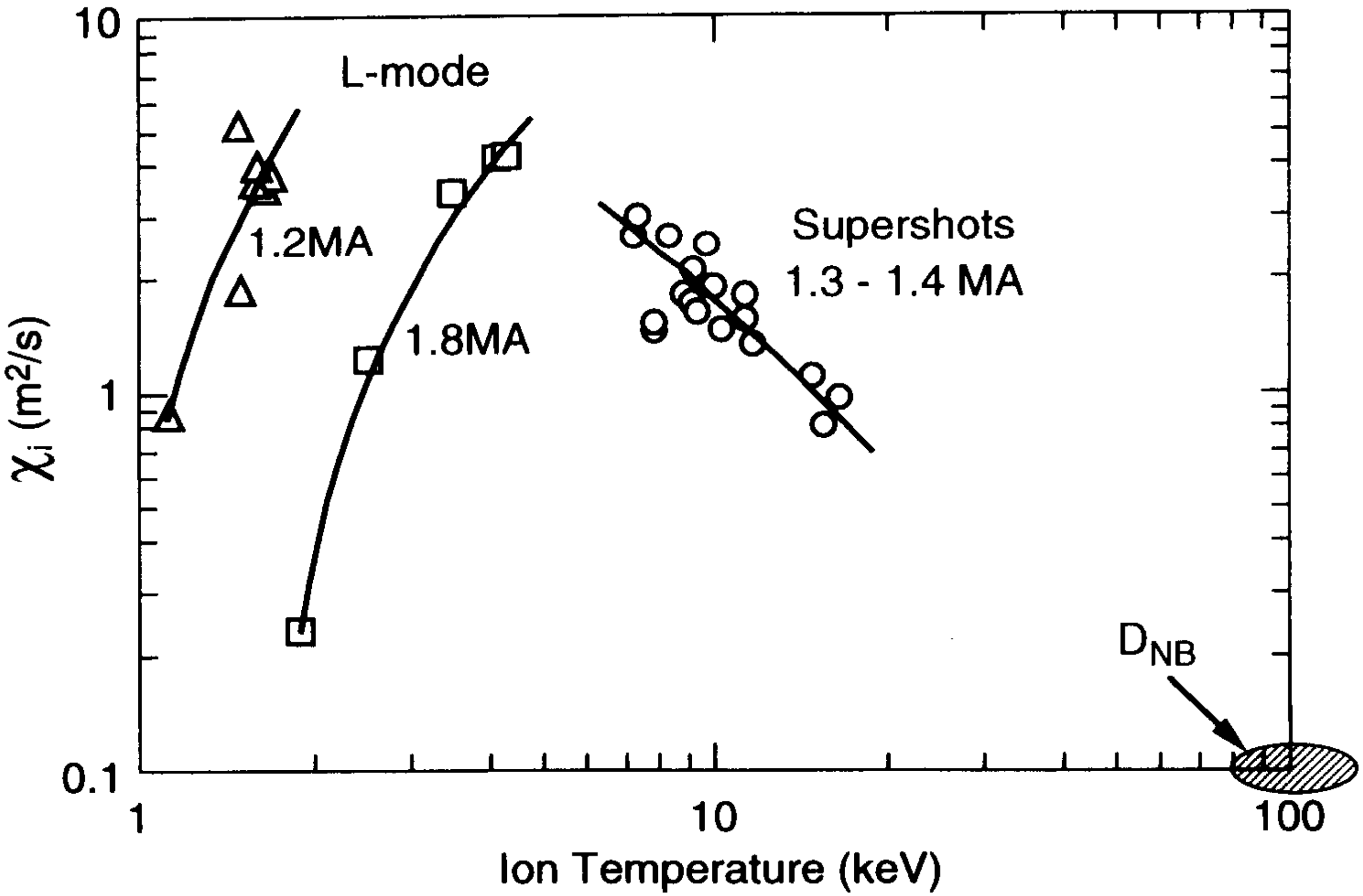
DD Fusion Reactivity Also Scaled Favorably in Supershots



- TRANSP code suggested DT fusion power of about 8MW might be possible
- Two related obstacles to higher performance:
  - Stability of plasmas $\Rightarrow$ increase plasma current
  - Difficulty of obtaining low edge influxes at higher current

Supershots Exhibited Decreasing Ion Thermal Diffusivity with Temperature

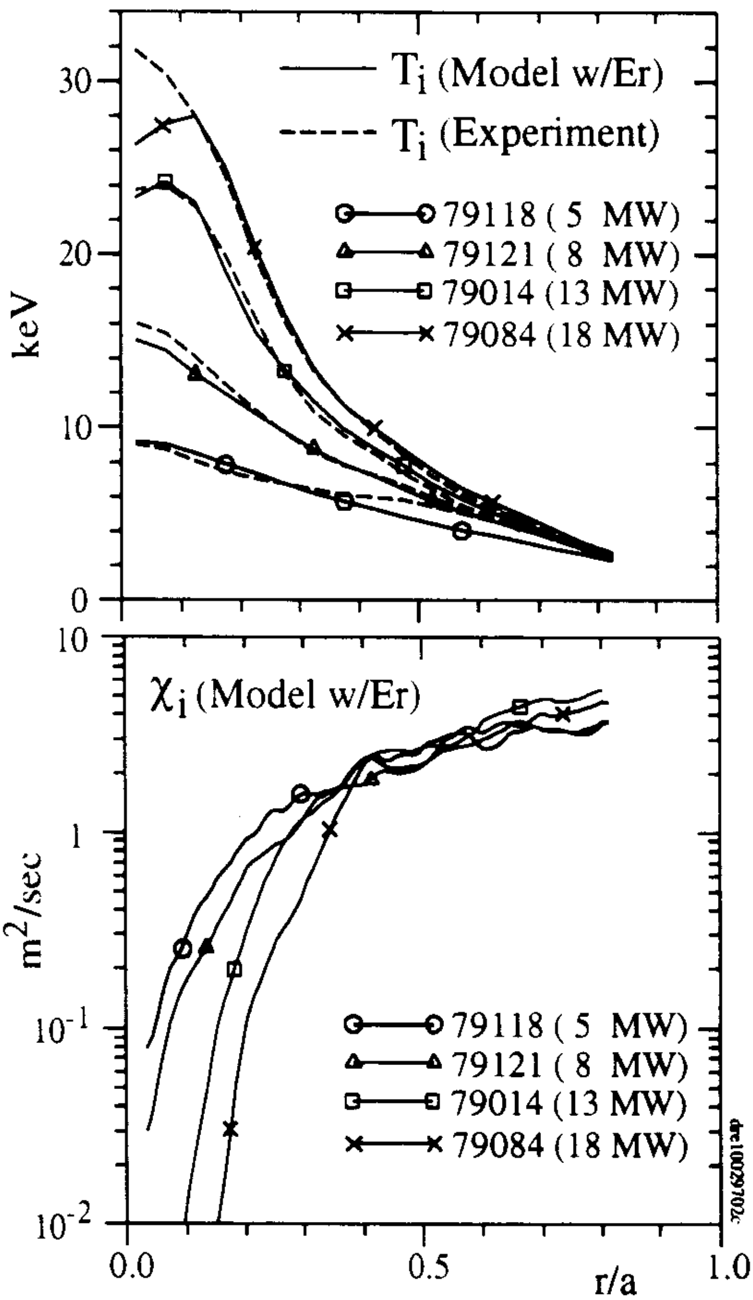
TFTR



- L-mode plasmas showed adverse dependence of χ_i with temperature
- Estimates of diffusivity of energetic beam ions continued supershot trend

T97092

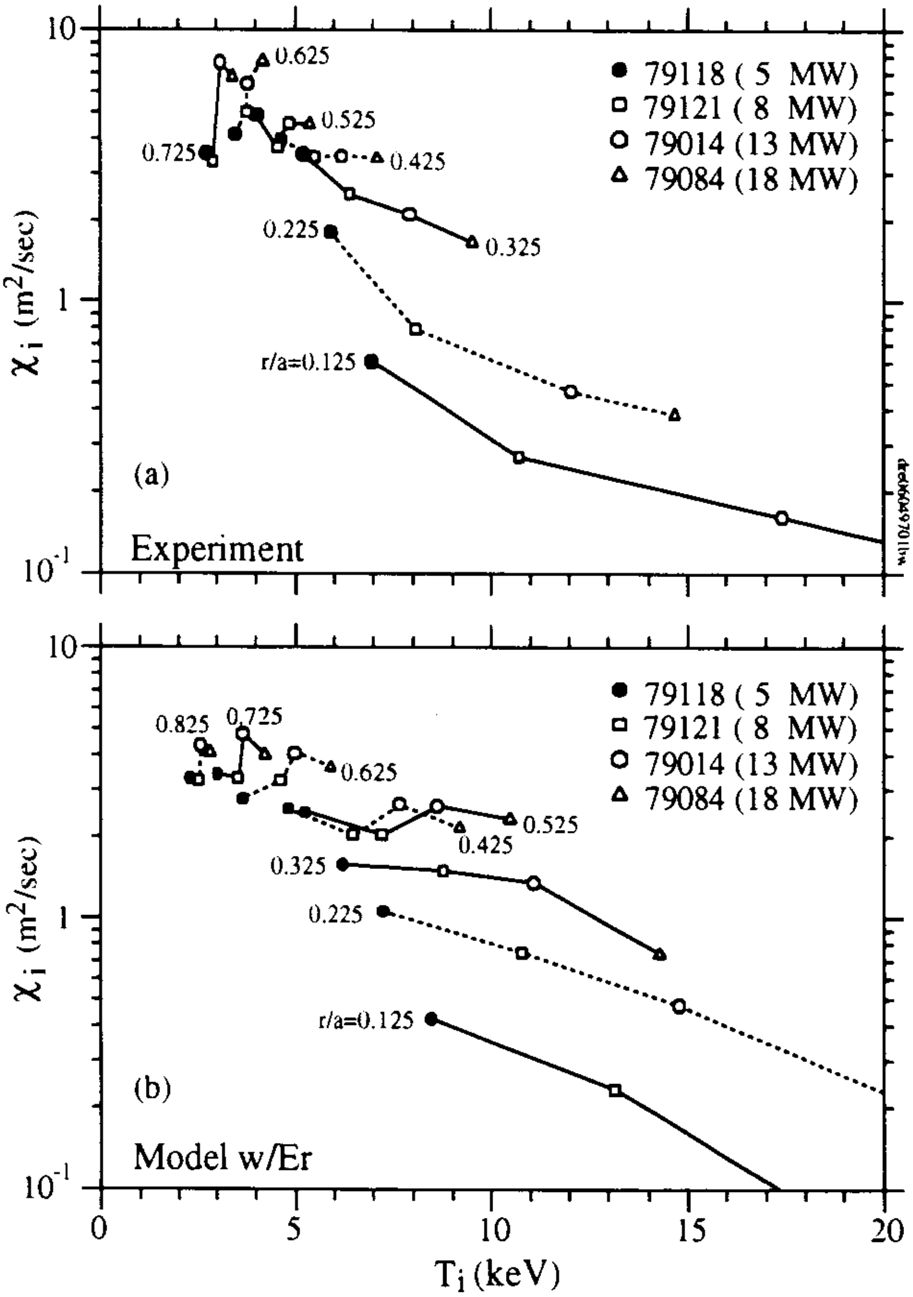
Tests of model describing toroidal Ion Temperature Gradient modes with self-consistent radial electric field



Expansion of enhanced confinement zone with heating power is well-reproduced.

D. R. Ernst, Ph.D. Thesis, MIT (1997).

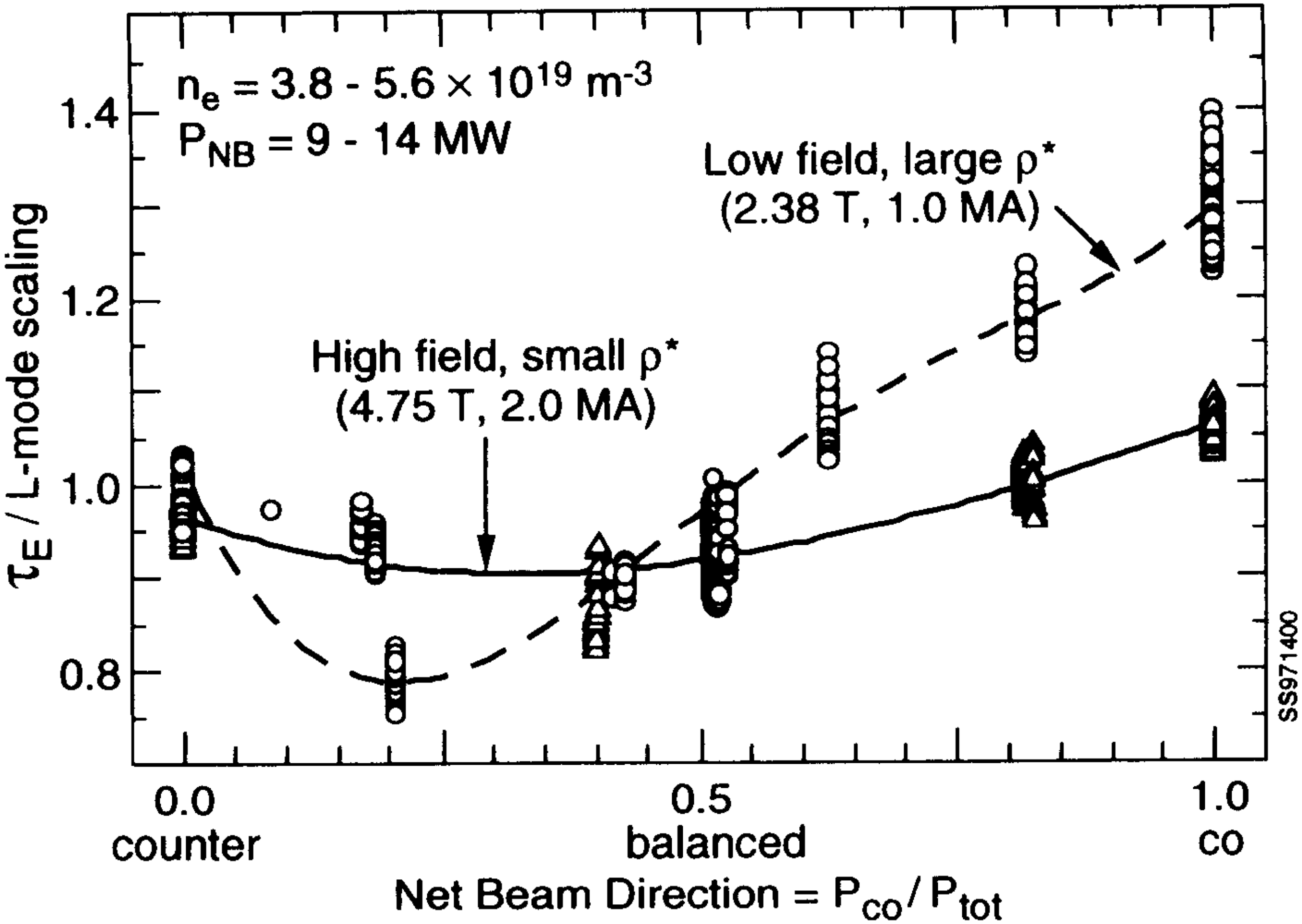
Simulation of favorable temperature scaling in inner half-radius



Apparent scaling $\chi_i \propto 1/T_i$ [D. M. Meade, IAEA (1990)] is reproduced (but is not a local scaling).

D. R. Ernst, Ph.D. Thesis, MIT (1997).

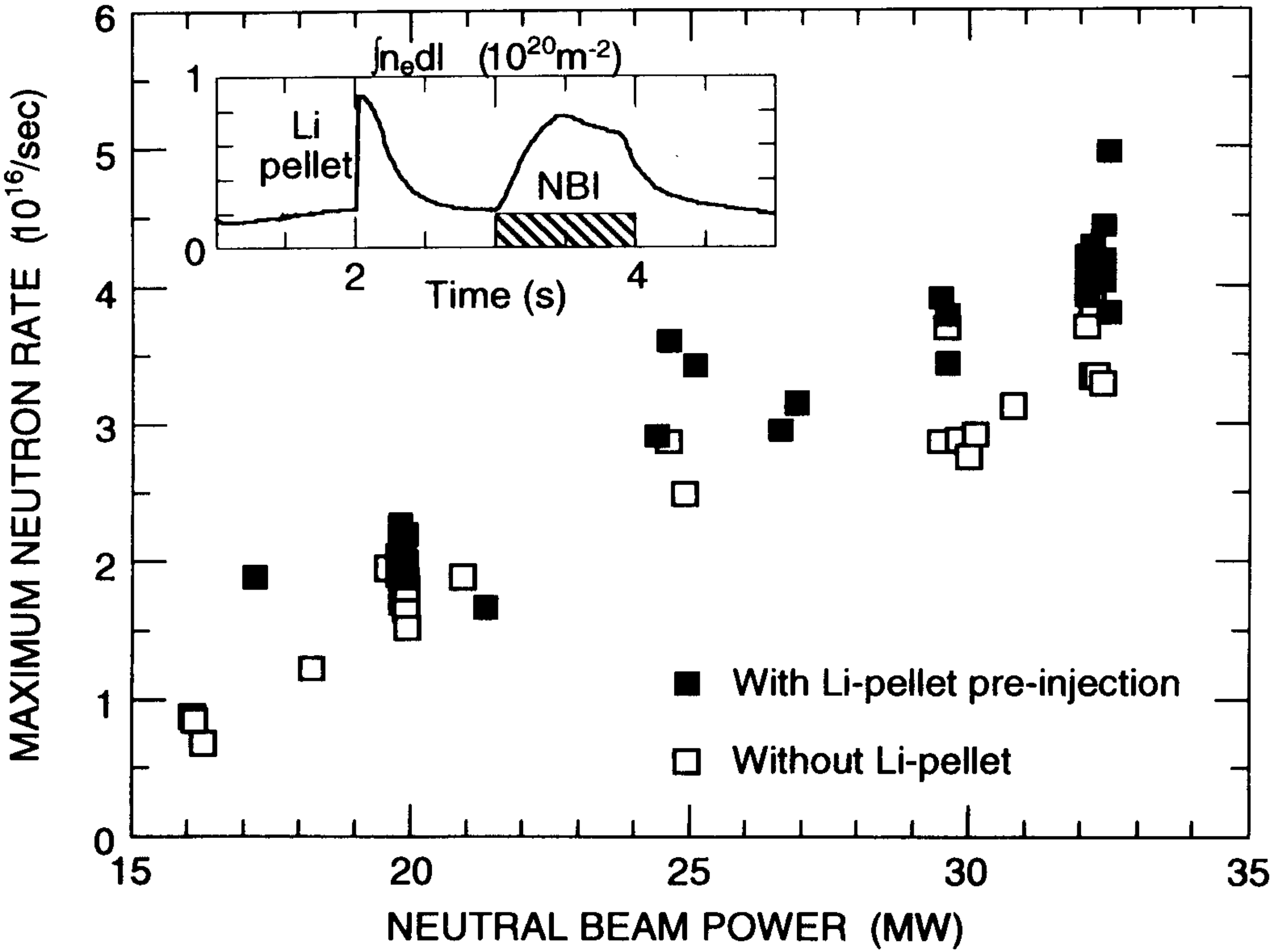
Global Confinement Is Also Affected by Flow Shear in L-mode Regime



- Effect is stronger at low magnetic field.
- Measurements of v_ϕ, v_θ, E_r (MSE), and density and T_i fluctuations are clarifying role of flow shear on turbulence and transport.

Injection of Lithium Pellets Before NBI Reduced Edge Influxes and Increased Fusion Performance at High Current

TFTR

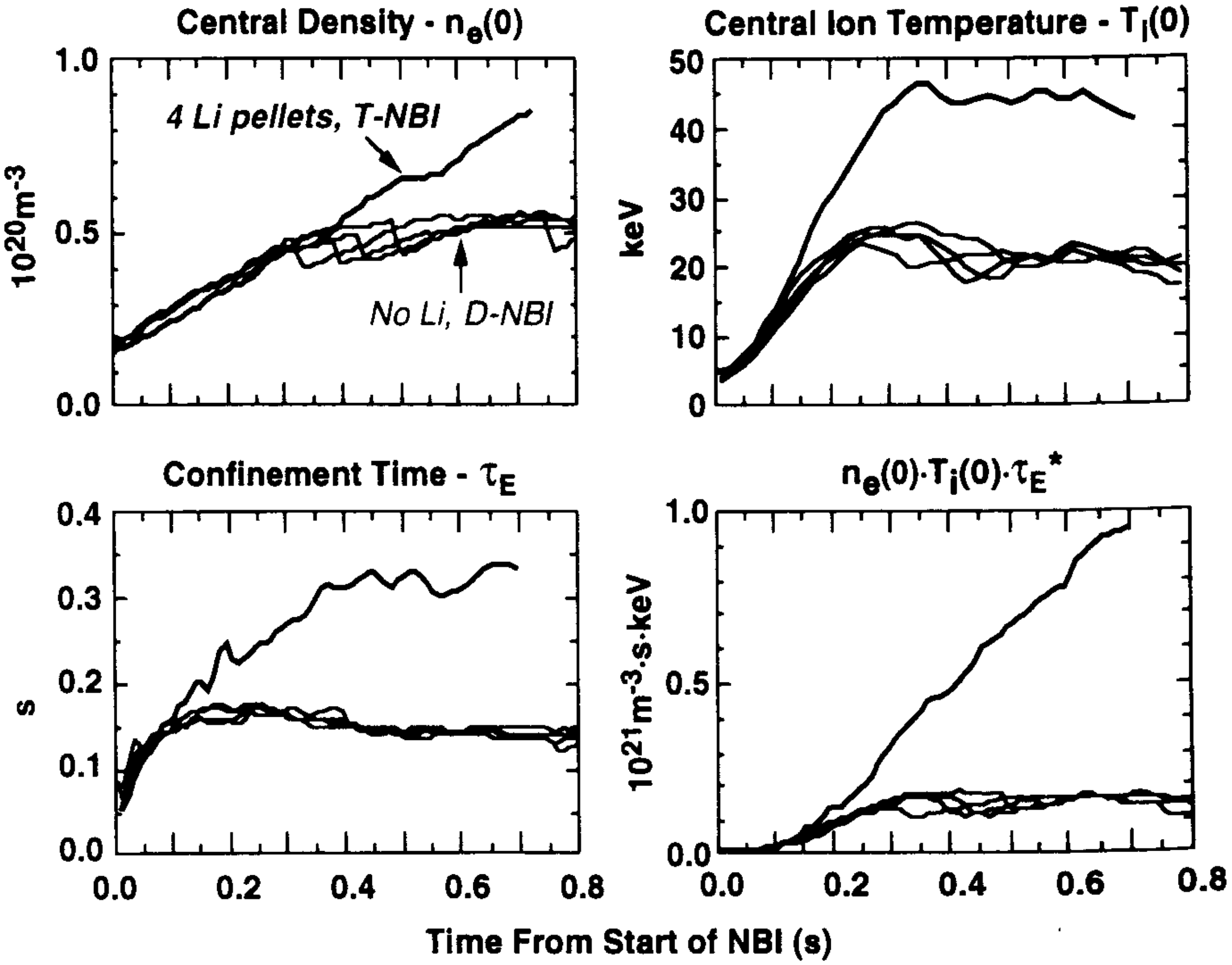


1990

• Injected lithium did not contaminate plasma. Effect was cumulative.

Extensive Lithium Conditioning can Produce Exceptional Performance in D-T Supershots

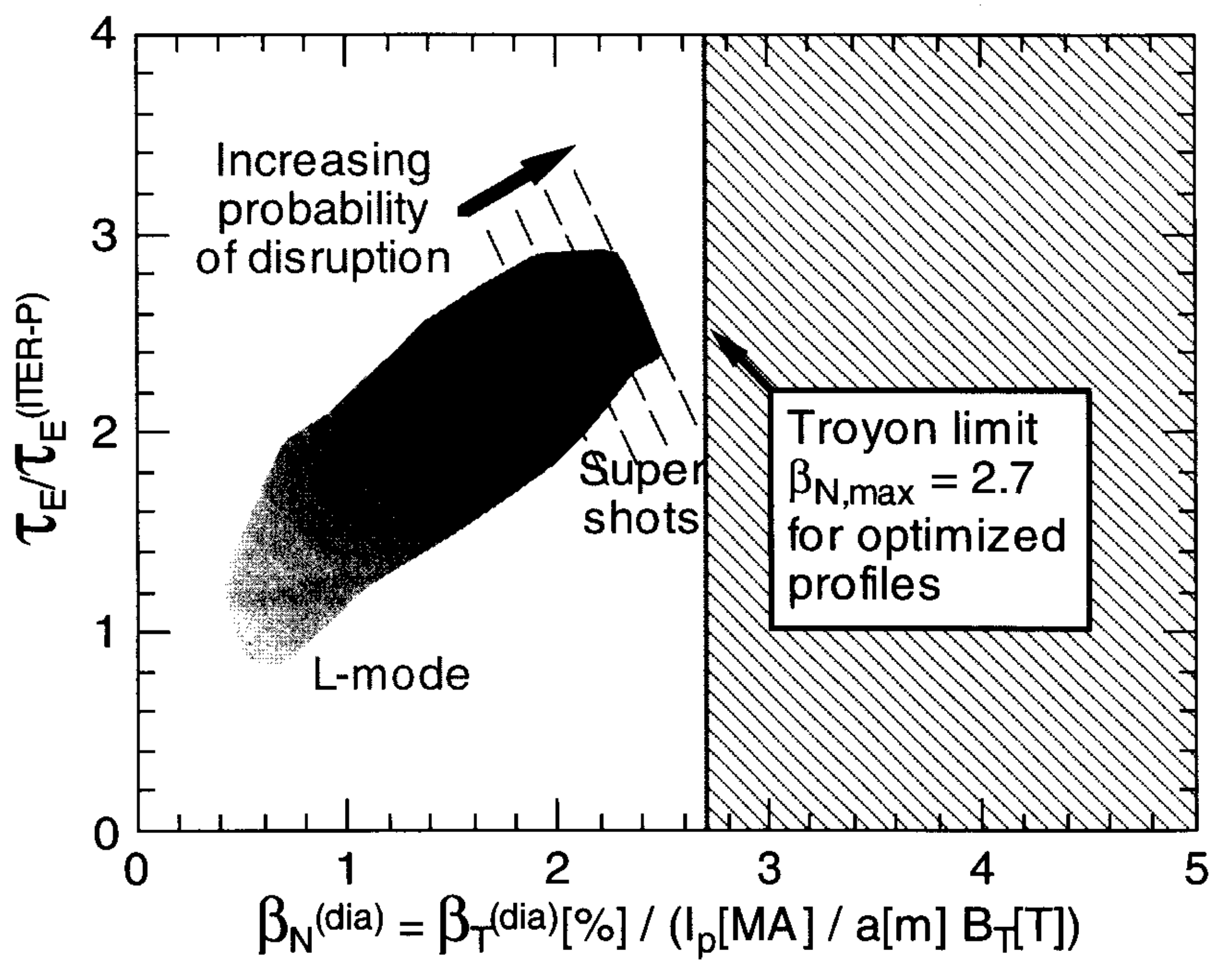
TFTR



- Neighboring shots at 2.1 – 2.3 MA with 17 – 18 MW NBI
- Confinement improved both by injection of 4 lithium pellets and by isotope effect with all-tritium NBI

Note: $\tau_E^* = W_{tot}/P_{tot}$ *in* $n_e(0)\cdot T_i(0)\cdot \tau_E^*$ *product*

Supershots Were Limited by Pressure-Driven Disruptions Below the Troyon-Scaling Limit



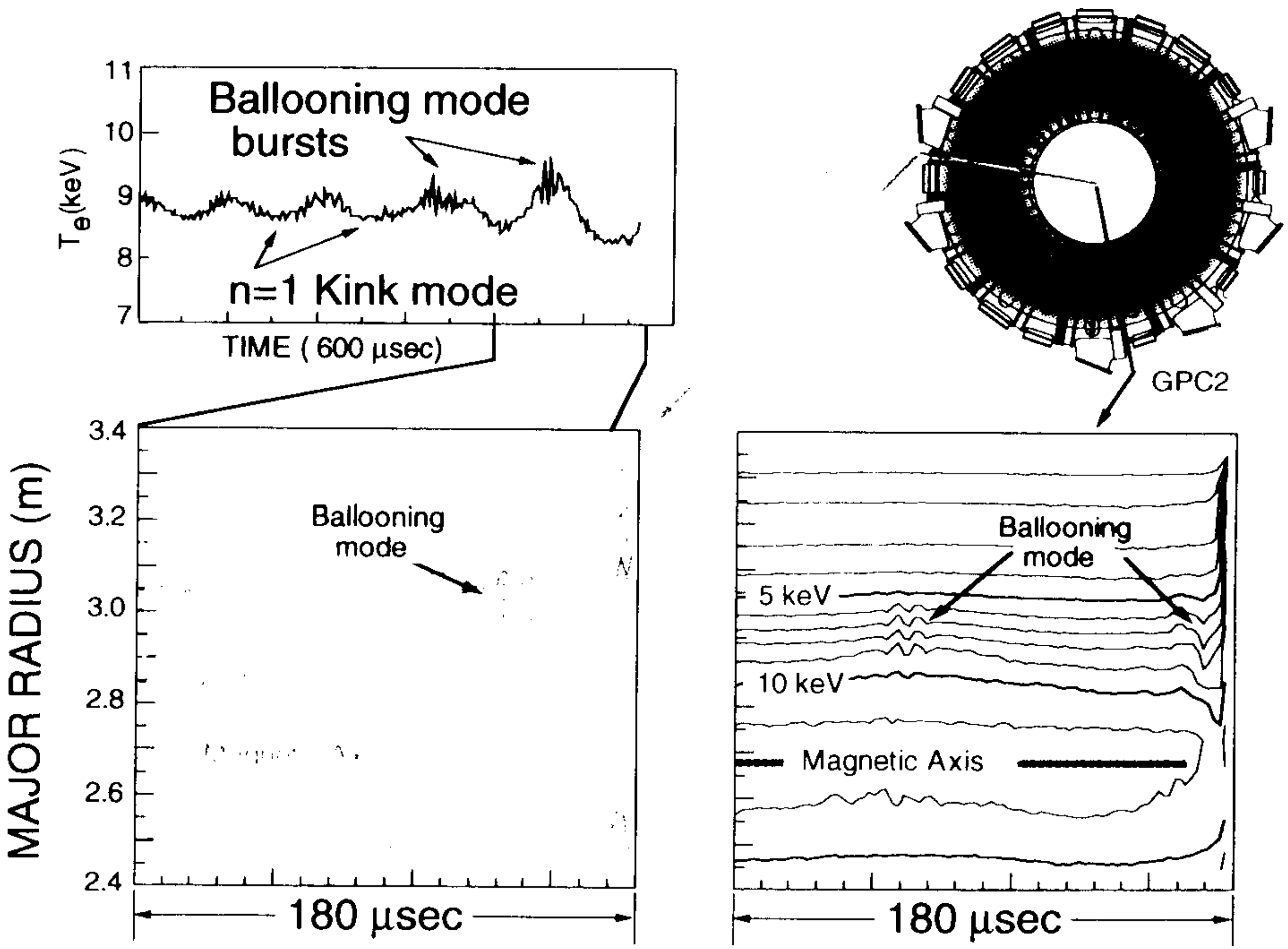
- Improving confinement by peaking density and pressure profiles reduced global plasma stability

  ⇒ fast β-limit disruptions at high field (ideal MHD modes)
- H-mode plasmas with broad pressure profiles exceeded Troyon limit, particularly in shaped plasmas at low field
- Since $P_{fus} \propto \langle p^2 \rangle$, peaked profiles can exceed fusion performance of broader profiles at higher β_N
- Stimulated search for methods to increase β-limit

Ballooning Mode Grows Rapidly Before High-β Disruption

TFTR

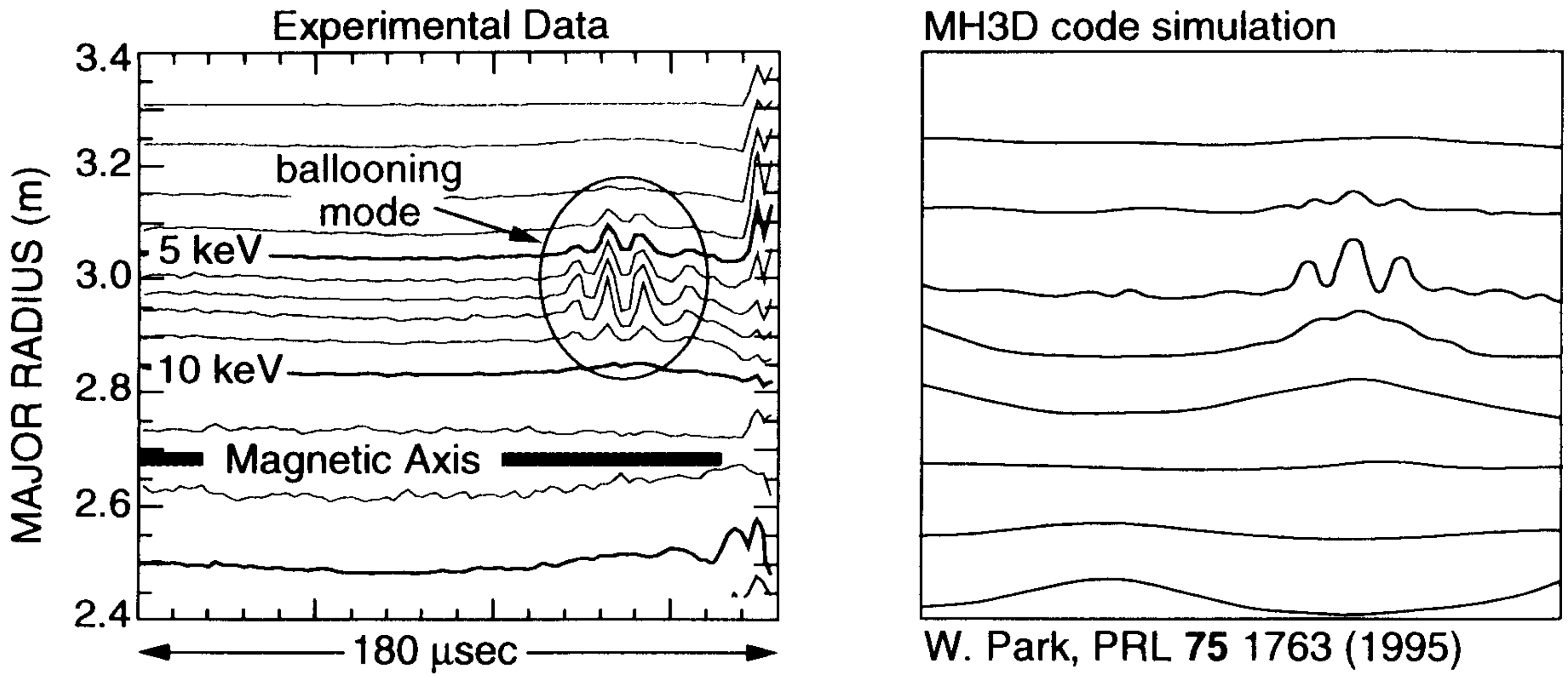
- Identification made possible by excellent spatial and time resolution of T_e diagnostics



Fredrickson,
Nagayama
Janos

Nonlinear numerical simulations find n=1 kink excites local ballooning modes

TFTR

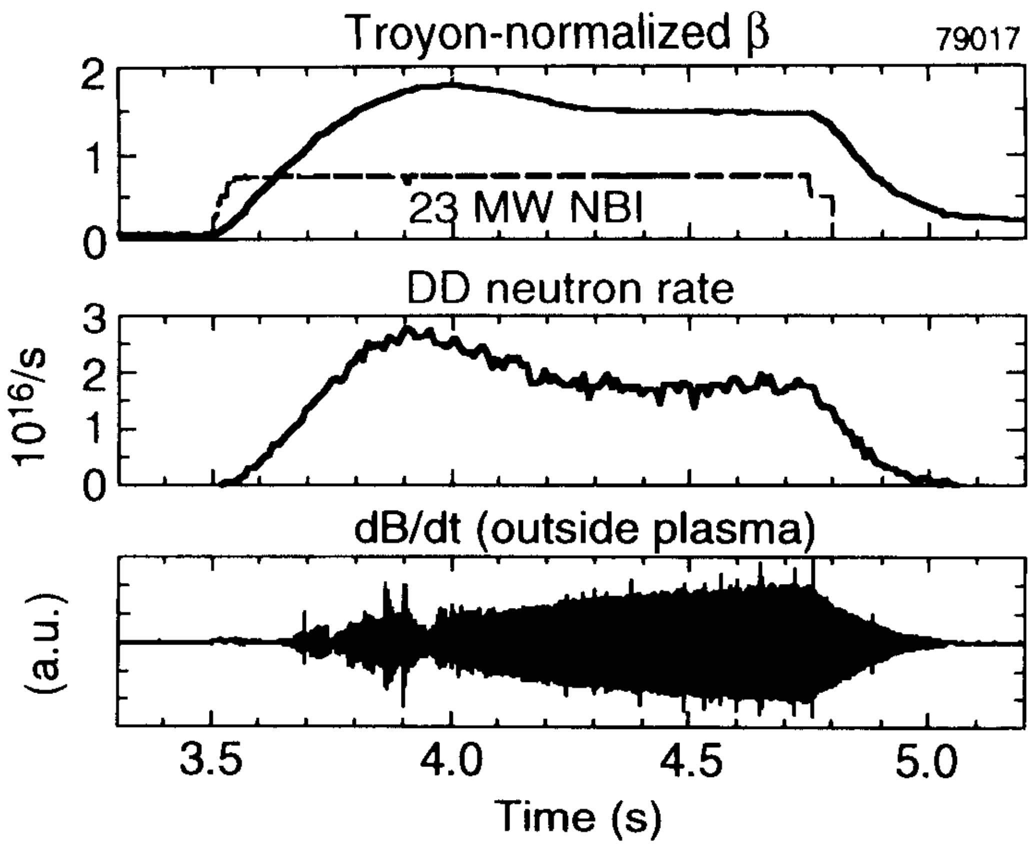


W. Park, PRL **75** 1763 (1995)

- Performance is limited by MHD stability
- TFTR diagnostics allow direct verification of theoretical modeling of MHD modes
- Validates MHD stability codes used to design experiments

Neoclassical MHD Instabilities Can Degrade Confinement Below Ideal β-Limit

TFTR



- Magnetic islands with low poloidal and toroidal mode numbers (m/n) can reduce the sustainable beta and fusion performance in steady-state

  ⇒ "Soft" β-limit

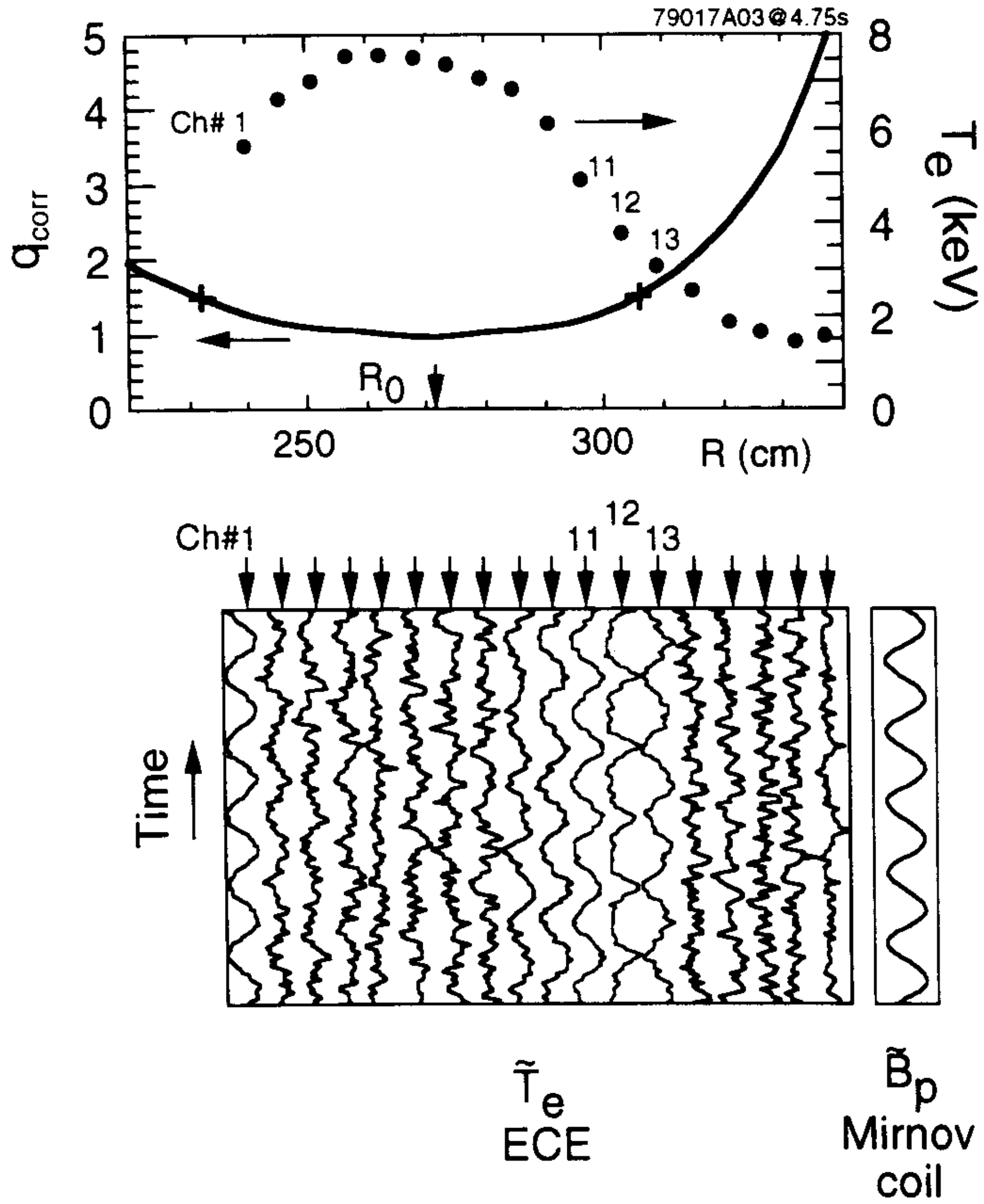
- These instabilities grow on resistive time scales (>> "ideal" timescale)

  ⇒ Growth determined by neoclassical effects

Z. Chang T97086

Rotating Internal MHD Modes Are Detected by ECE Diagnostics for Electron Temperature

TFTR



- The m/n=3/2 mode has tearing parity and island structure
- Location of MHD is used to correct q(R)

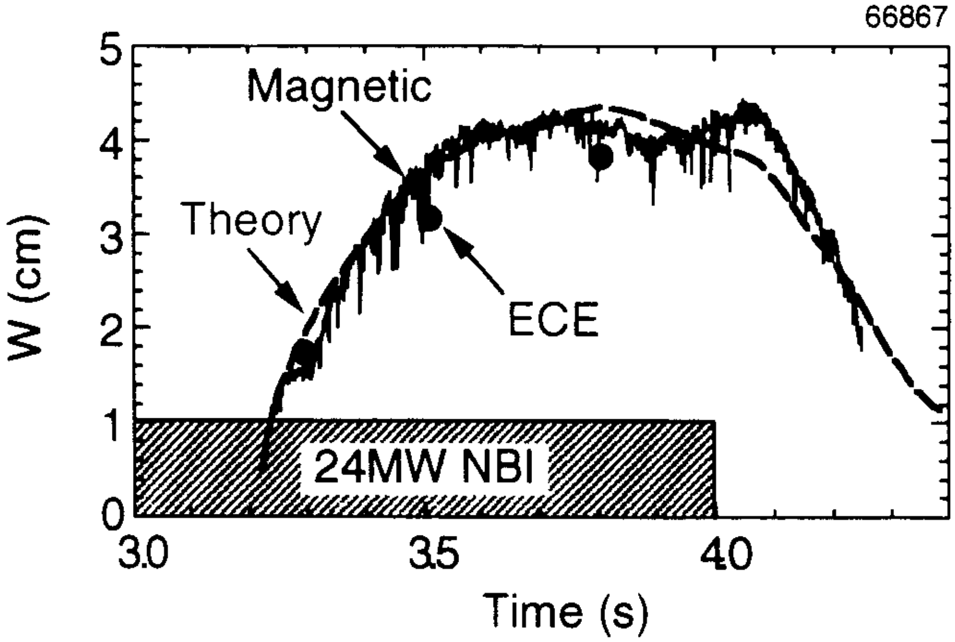
Z. Chang

T97089

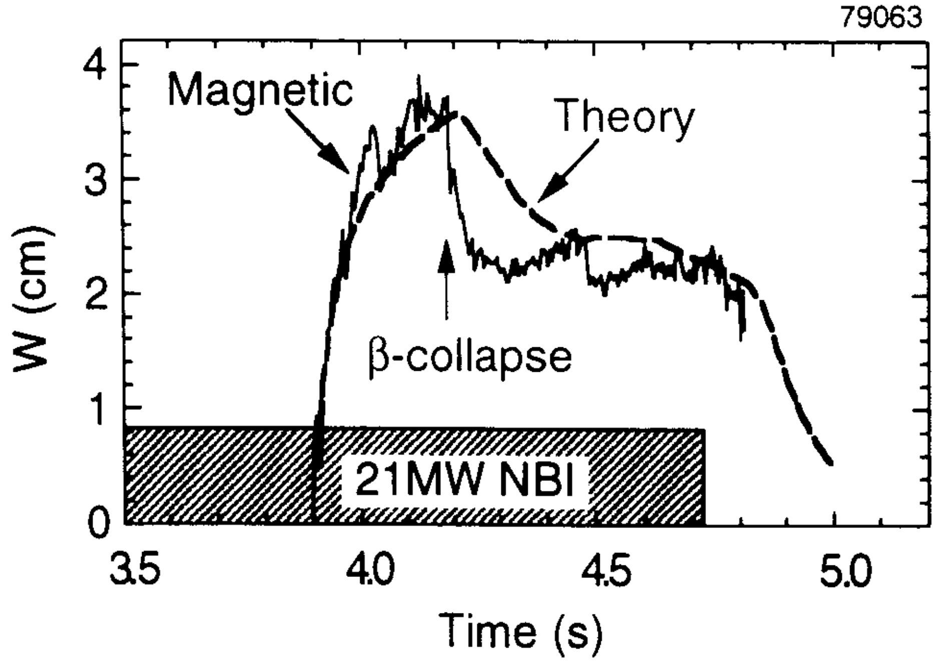
Theory Successfully Predicts Island Widths for Low m/n Neoclassical Modes

TFTR

- m/n=4/3 island



- m/n=3/2 island



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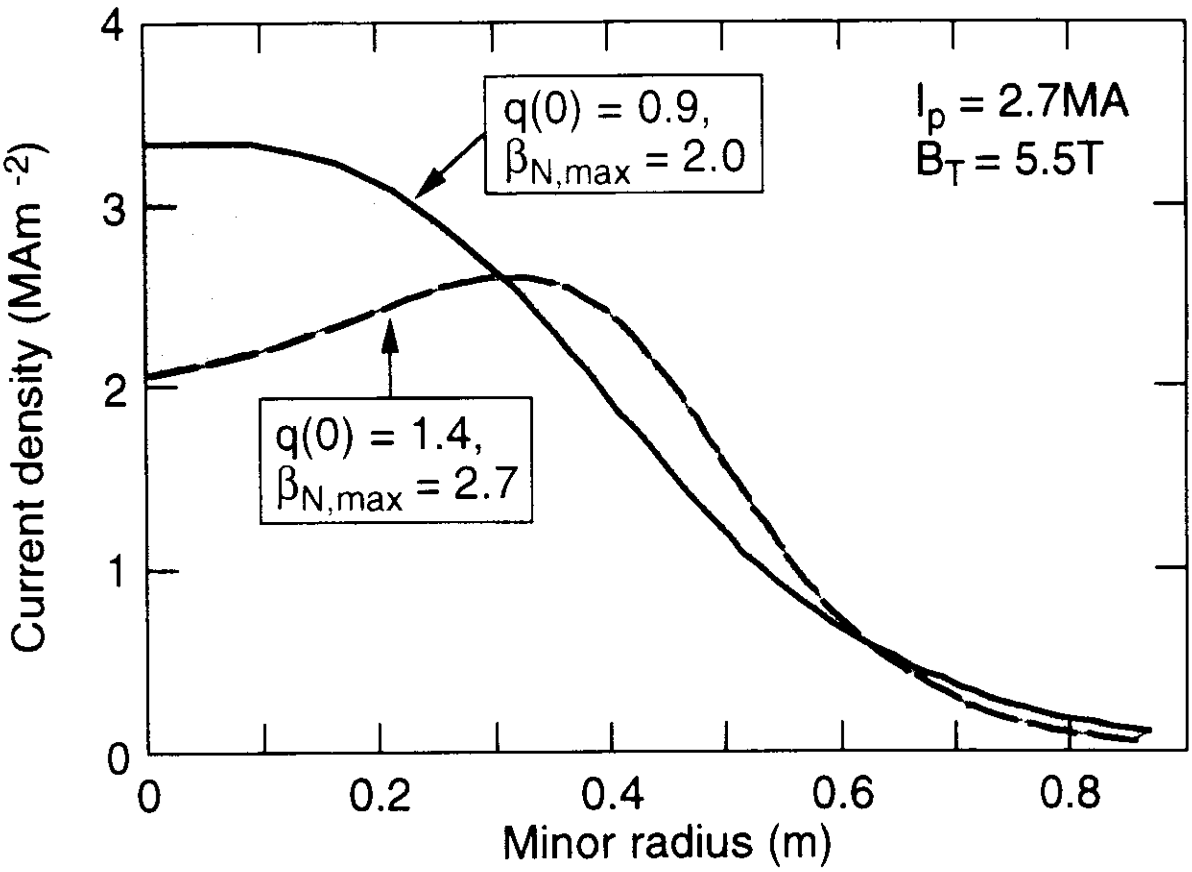
T97088

Theory Suggested Changes in Current Profile Could Improve Supershots

TFTR



- $q(0) = 0.9$ based on modelling for shot which achieved $P_{DT} = 10.7MW$
- $q(0) = 1.4$ case would require driven current of ~0.4MA

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

Reversed-shear

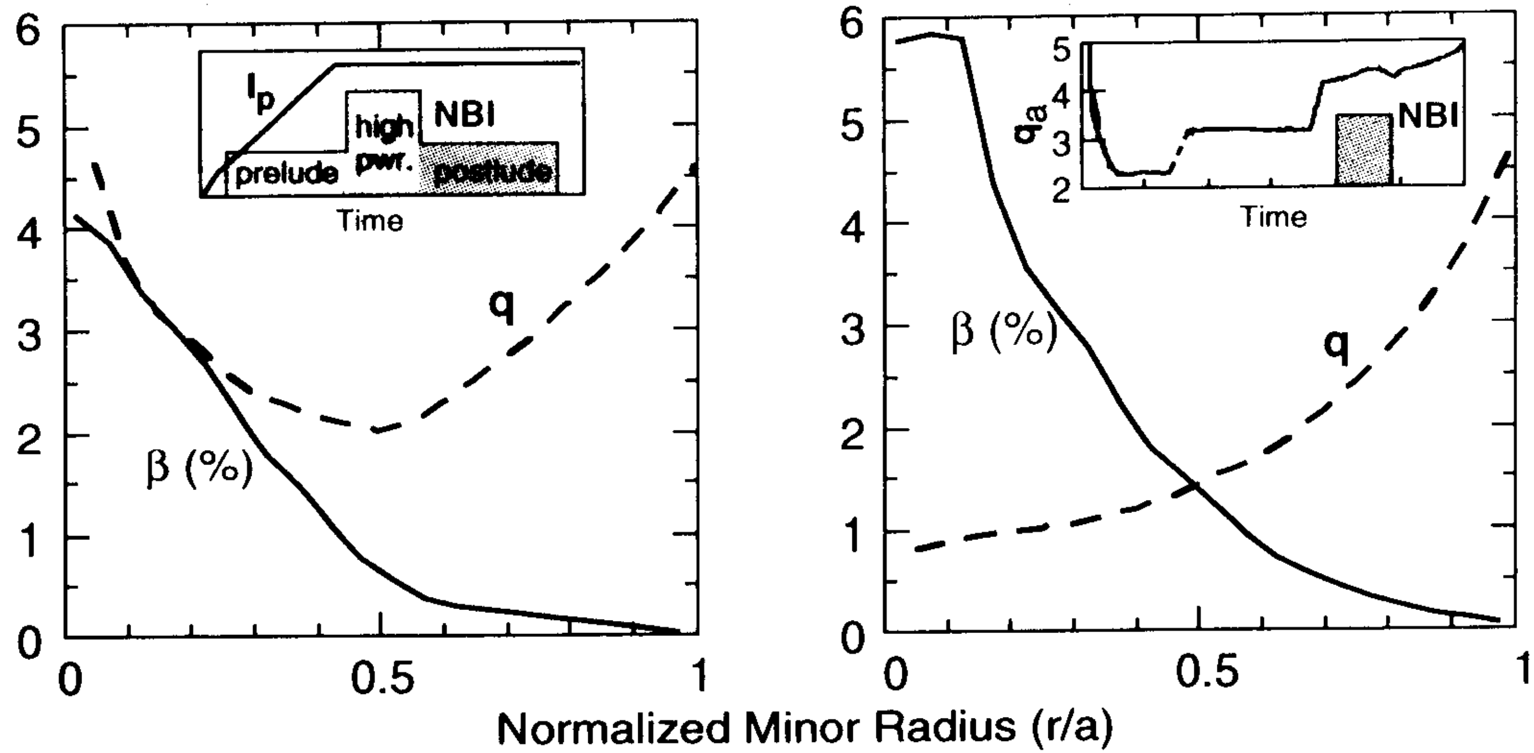
$\tau_E = 0.23s$

NBI heating during current ramp in large plasma

High-l_i

$\tau_E = 0.23s$

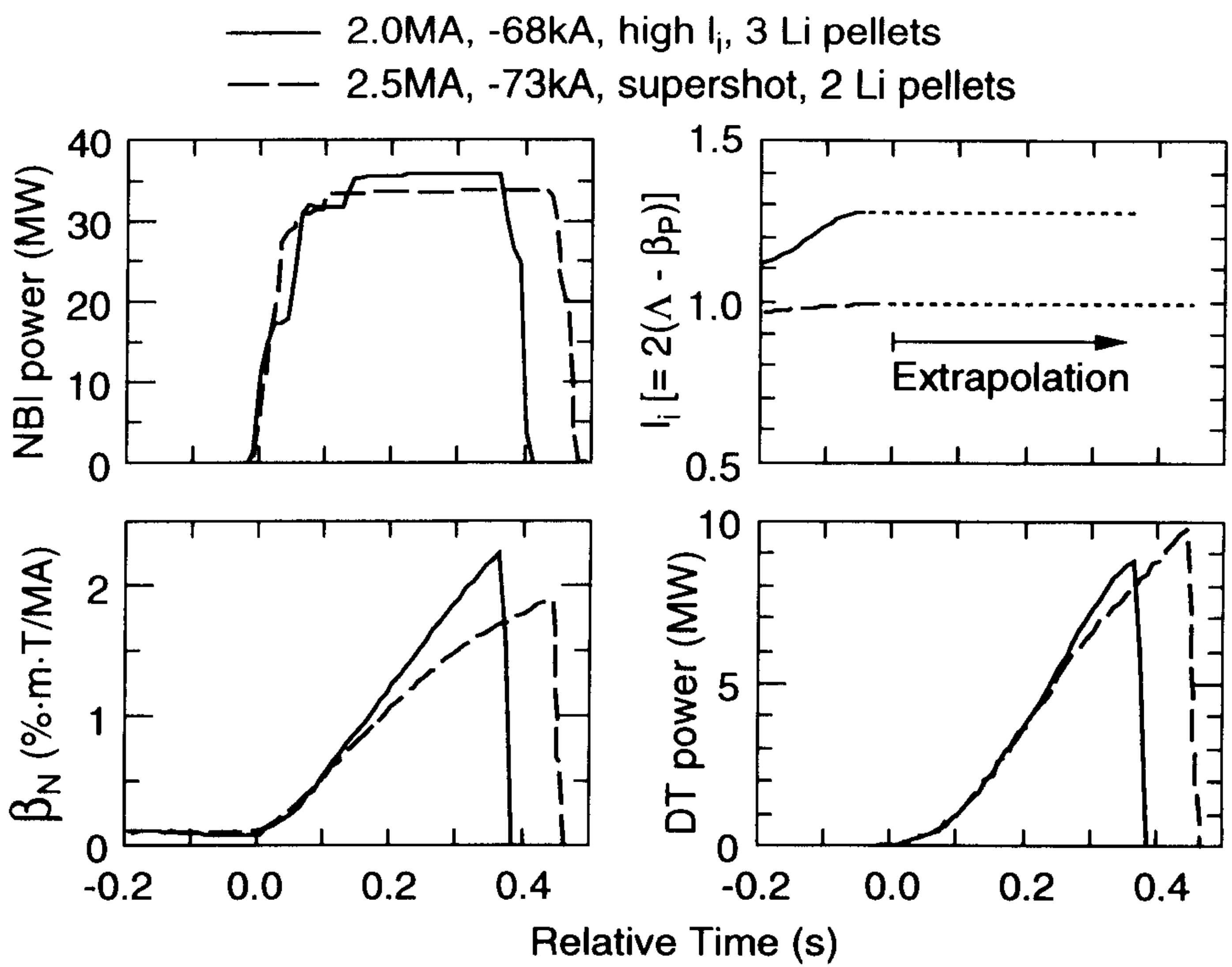
Low-q startup in small plasma followed by expansion



- Both regimes have NBI fueling, low edge recycling, peaked profiles and $T_i > T_e$

Normalized β-Limit Increases with l_i in Expansion Plasmas

TFTR

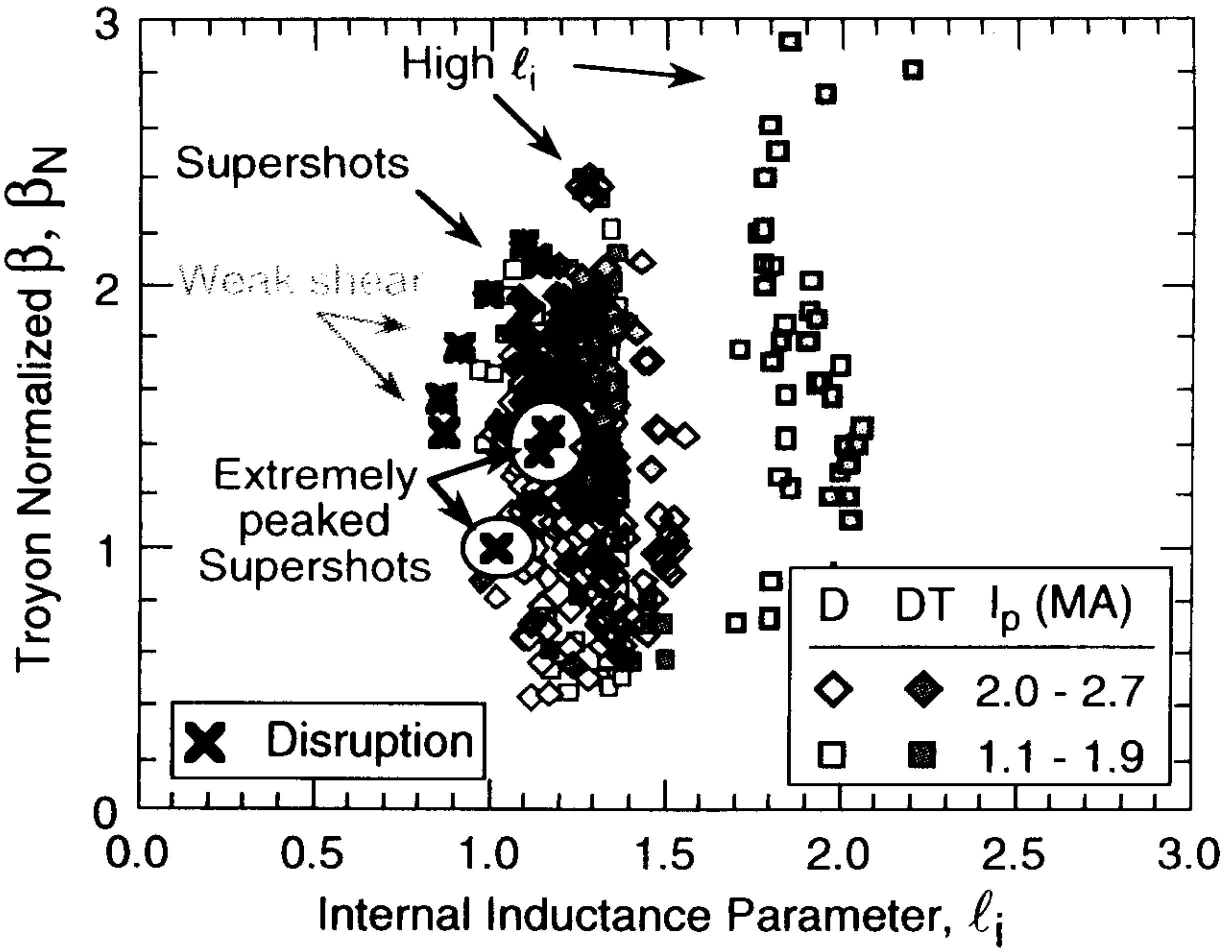


- β-limit was not reached with available NBI power and achievable confinement in 2.3MA high-l_i plasmas

T97077

Global Beta Limit Depends on Peaking of Current Profile for Similar Pressure Profiles

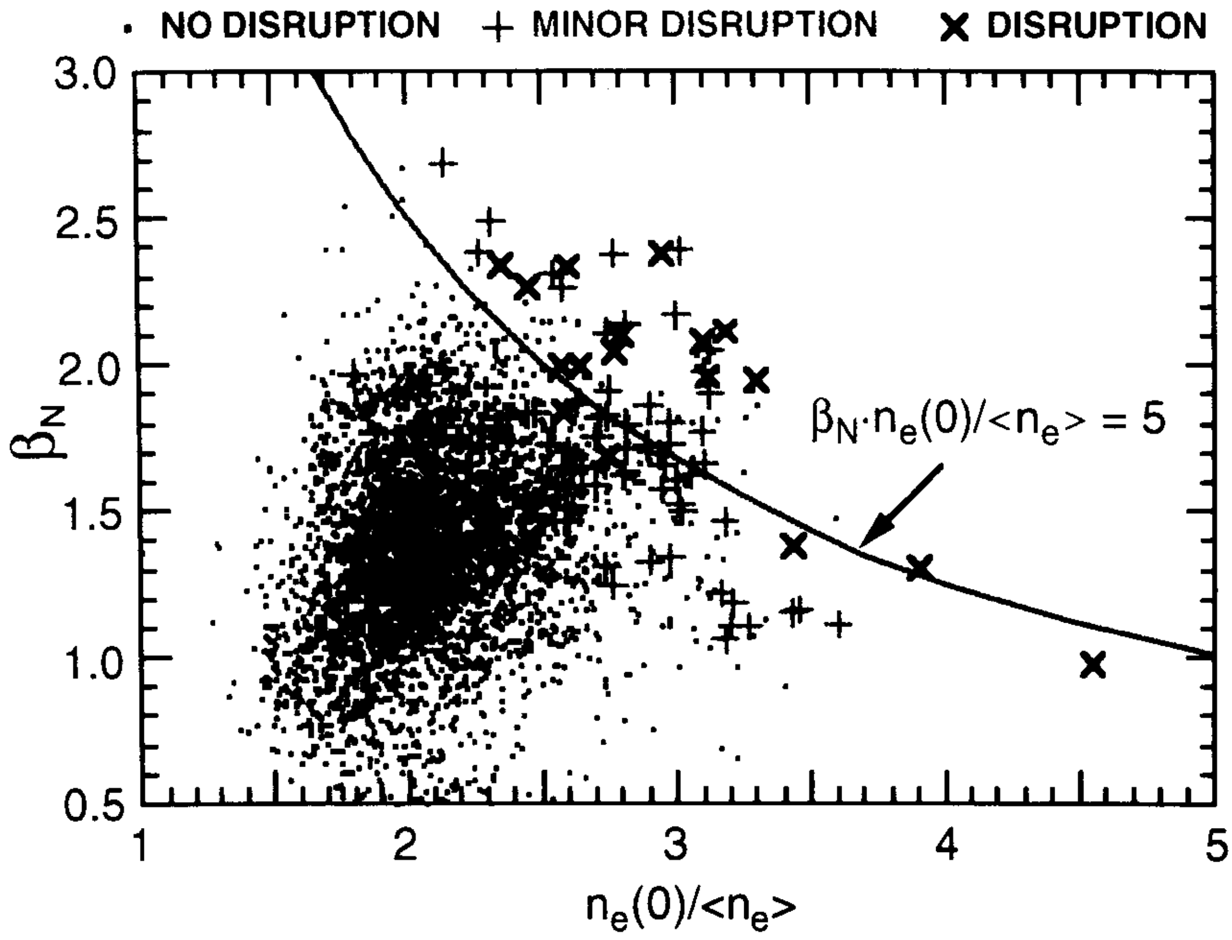
TFTR



- Internal inductance, ℓ_i, increases as plasma current profile becomes more peaked
- $\beta_{N,max} \propto \ell_i$ has been observed in DIII-D, and JT-60U also
- Extreme peaking of pressure profile produced by lithium conditioning or internal transport barriers reduces $\beta_{N,max}$

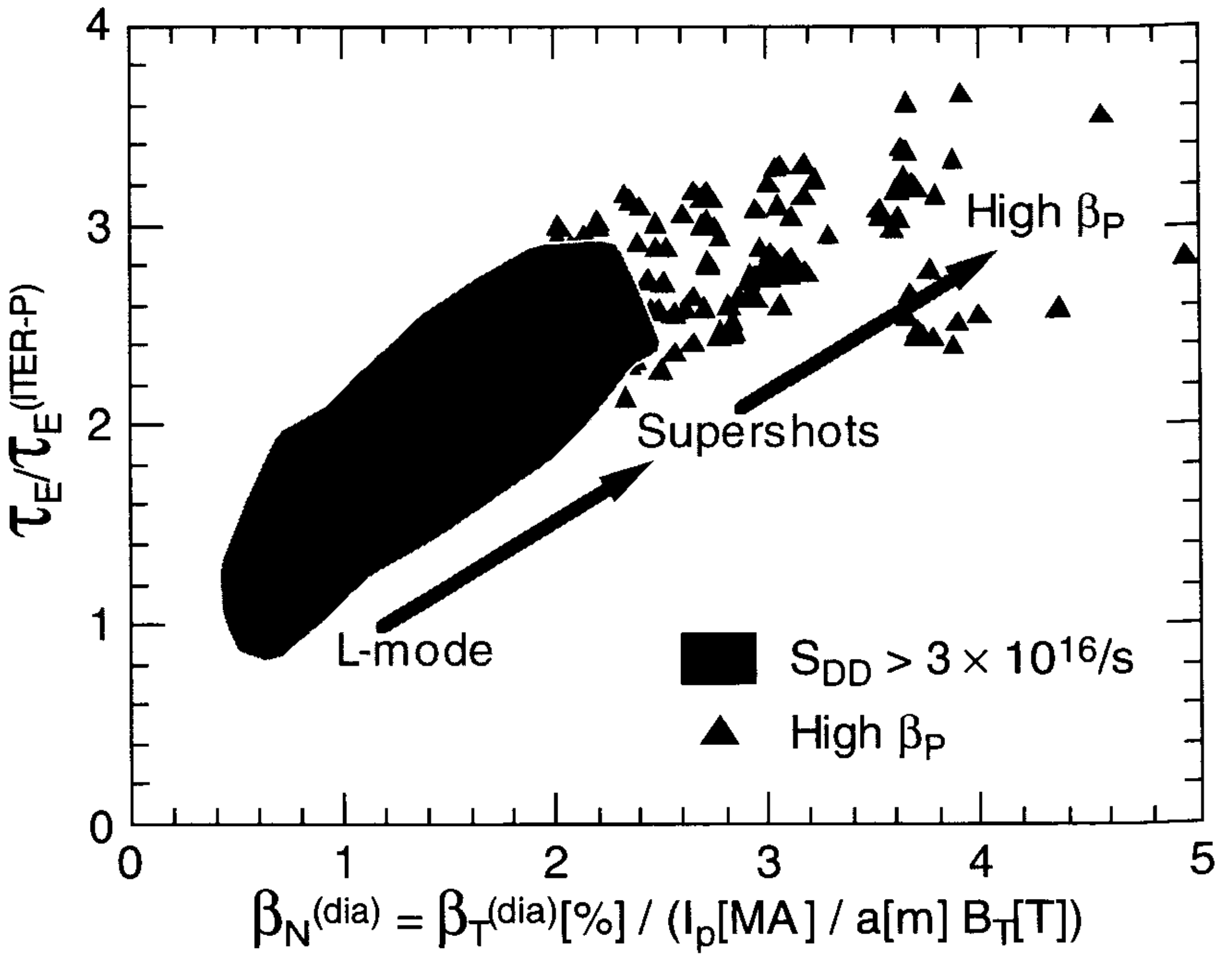
Global β_N Limit Decreases as Pressure Profile Becomes More Peaked in Supershots

TFTR



- Data for constant-current supershots (D and D-T)
- Local, not global, quantities are important

"Advanced Tokamak" Regimes Simultaneously Achieve Enhanced Confinement and β_N

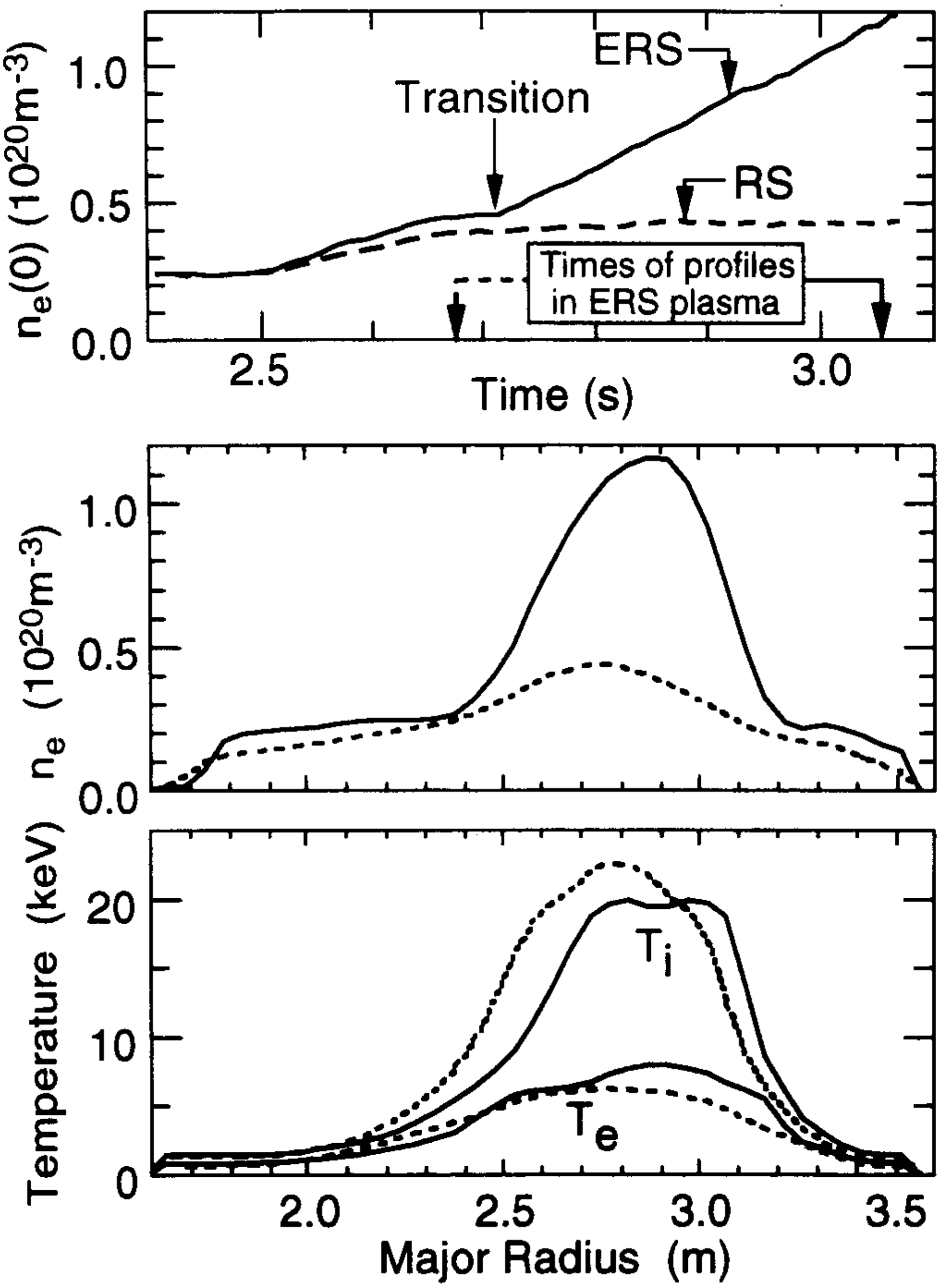


In TFTR, Supershots **at full machine capability** produced highest fusion performance:

Central density	$n_e(0) \leq 10^{20}$ m^{-3}
Central temperatures	$T_e(0) \leq 12$ keV
	$T_i(0) \leq 35$ keV
DD reactivity	★ $S_{DD} \leq 5.6 \times 10^{16}$/s
Enhanced confinement	$\tau_E \leq 3 \times \tau_{L\text{-mode}}$
	$\tau_E^{(th)} \leq 3 \times \tau_{L\text{-mode}}^{(th)}$

Reversed-Shear Plasmas can Transition to a Regime of Enhanced Confinement: ERS

TFTR

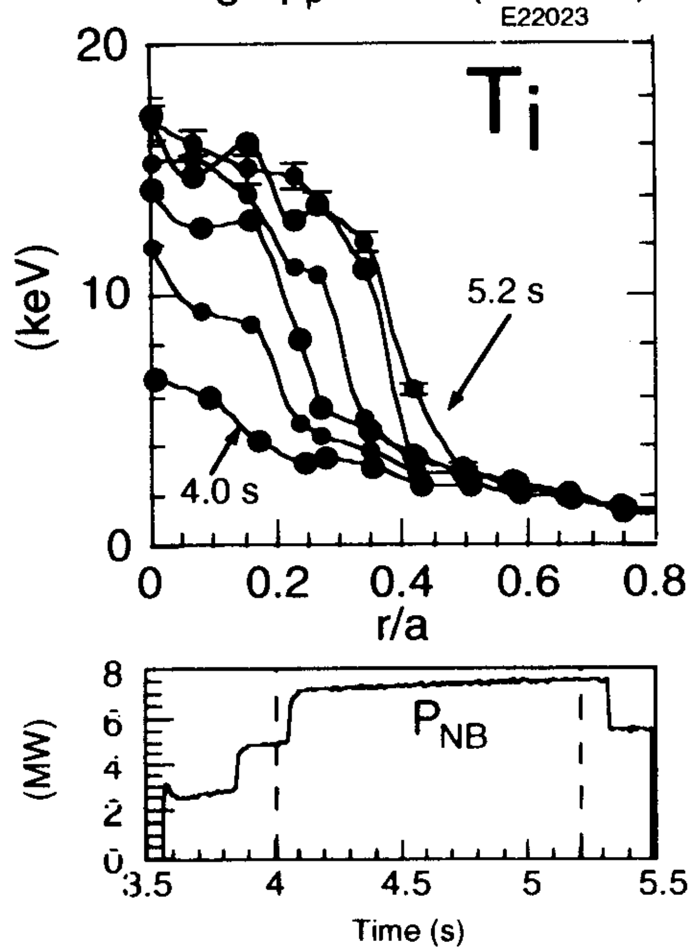


- **RS** - Similar to supershots: low χ_e, χ_i
- **ERS** - Reduced D_e, D_i, χ_i
  - turbulent fluctuations suppressed within "transport barrier"

T9706

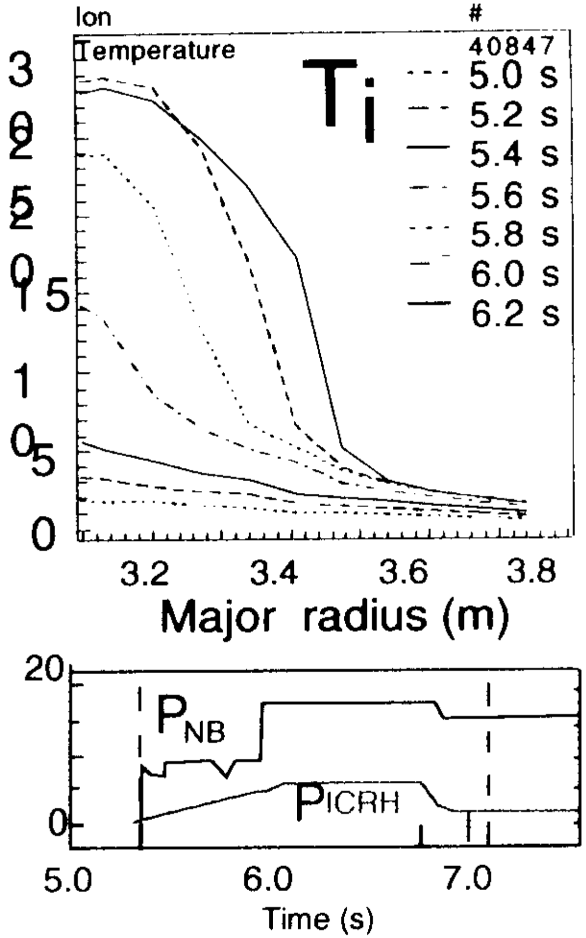
Barrier expansion is observed in a variety of enhanced confinement regimes

High β_p mode (JT-60U)



Koide et al., Pl. Phys. Cont. Fuson '96

Optimized shear (JET)

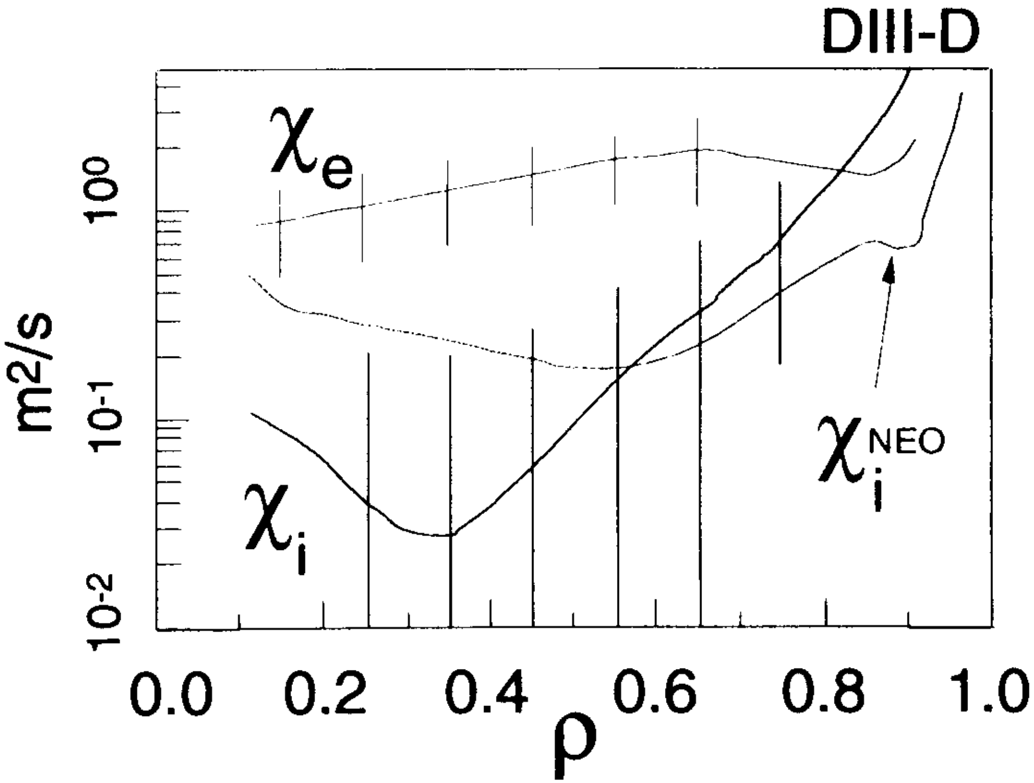


Sips et al., this workshop

- Monotonic q profile
- Stagnation point moves inward with higher edge q

- Weak shear
- gradients up to 70 kV/m

Barriers in edge and core can yield transport that is at neoclassical level or below across much of the plasma



Burrell, Phys. Plasmas 5, 1997

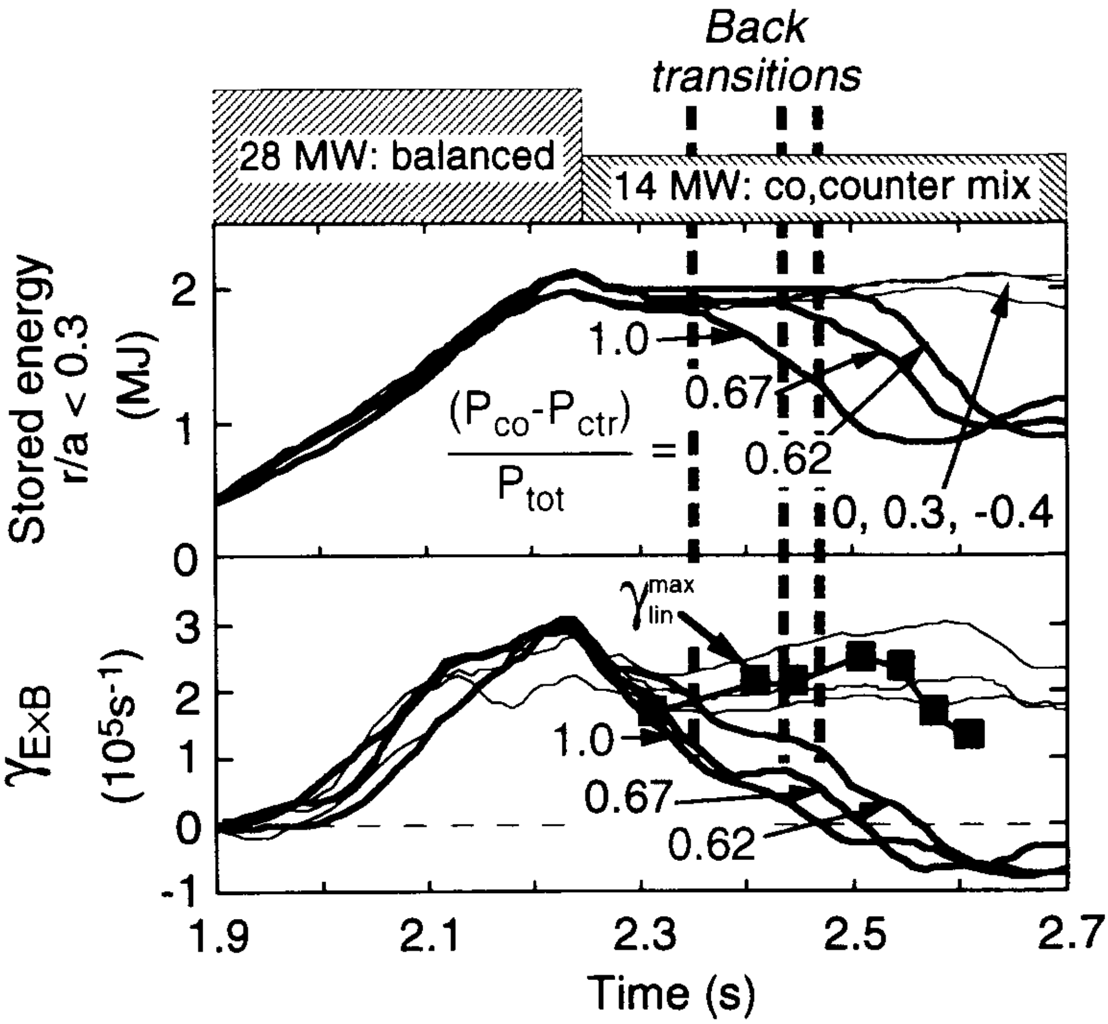
- H mode edge barrier combined with NCS core confinement
- Density fluctuations reduced across entire plasma

$E \times B$ Shear is Strong Candidate for Suppression of Turbulent Transport in ERS Plasmas

TFTR

Theory: Turbulence suppressed when $E \times B$ shearing rate ($\gamma_{E \times B}$) exceeds growth rate (γ_{lin}) of most unstable mode

Experiment: Effect of co-/counter-NBI on "back-transition" from ERS

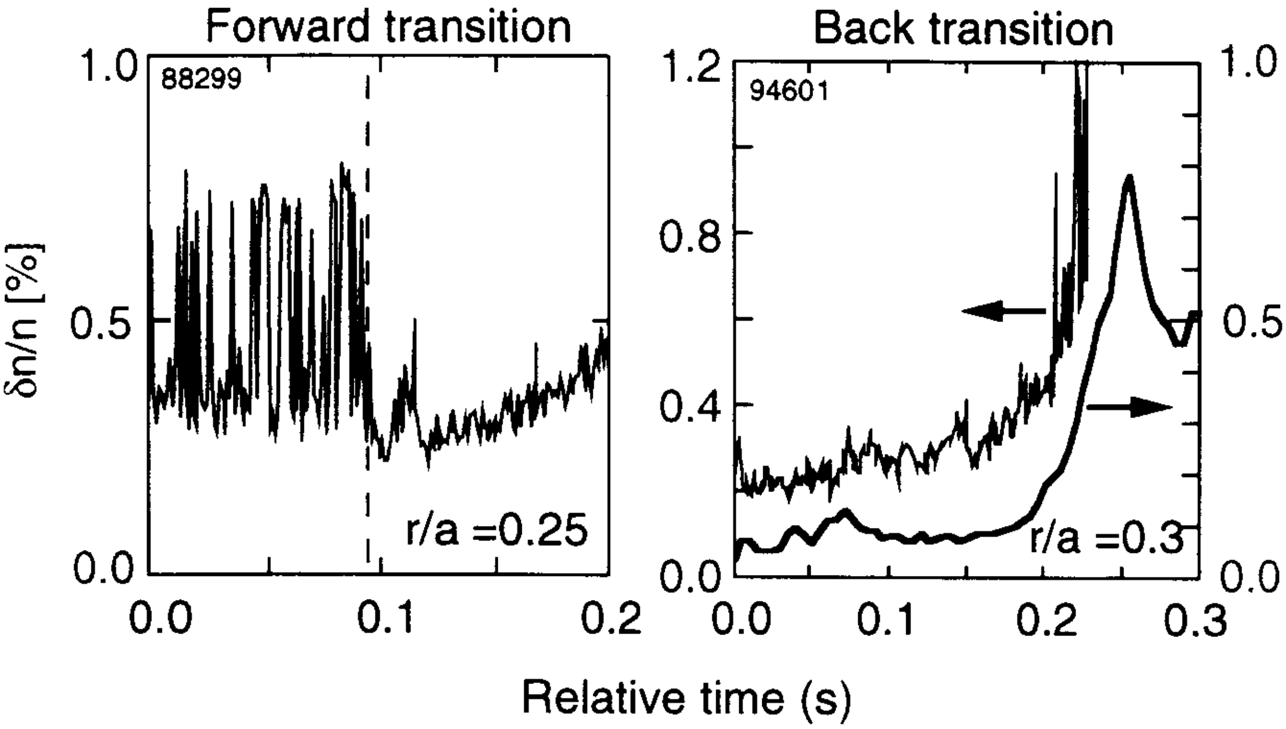


- Points show calculated growth rate of dominant ITG instability for profiles of case with beam balance of 0.62
- $\gamma_{E \times B}$ begins to decline before back transition

E. Synakowsl

Turbulent Fluctuations Are Suppressed During ERS Phase and Return After Back Transition

TFTR

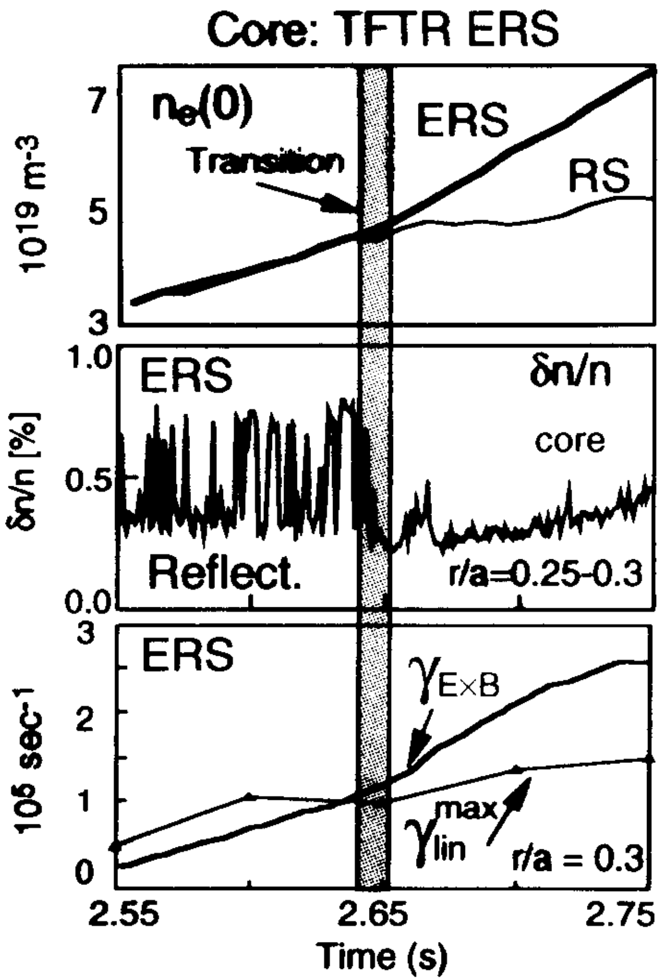


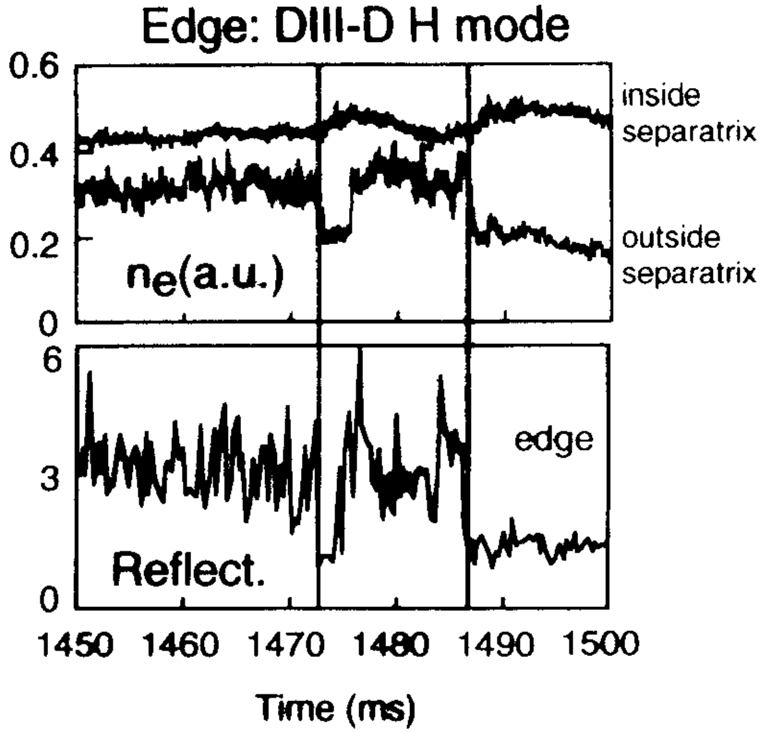
- Fluctuations measured by microwave reflectometer
- Change in fluctuation level is much more rapid for forward transition
  - Barrier formation: Increase in ∇p drives $\gamma_{E\times B}$
    $\Rightarrow$ *positive feedback*
  - Barrier collapse: As barrier peels away, high pressure core maintains ∇p and $\gamma_{E\times B}$
    $\Rightarrow$ *negative feedback*

E. Synakowski,
E. Mazzucato,
D. Newman (ORNL)

T97062

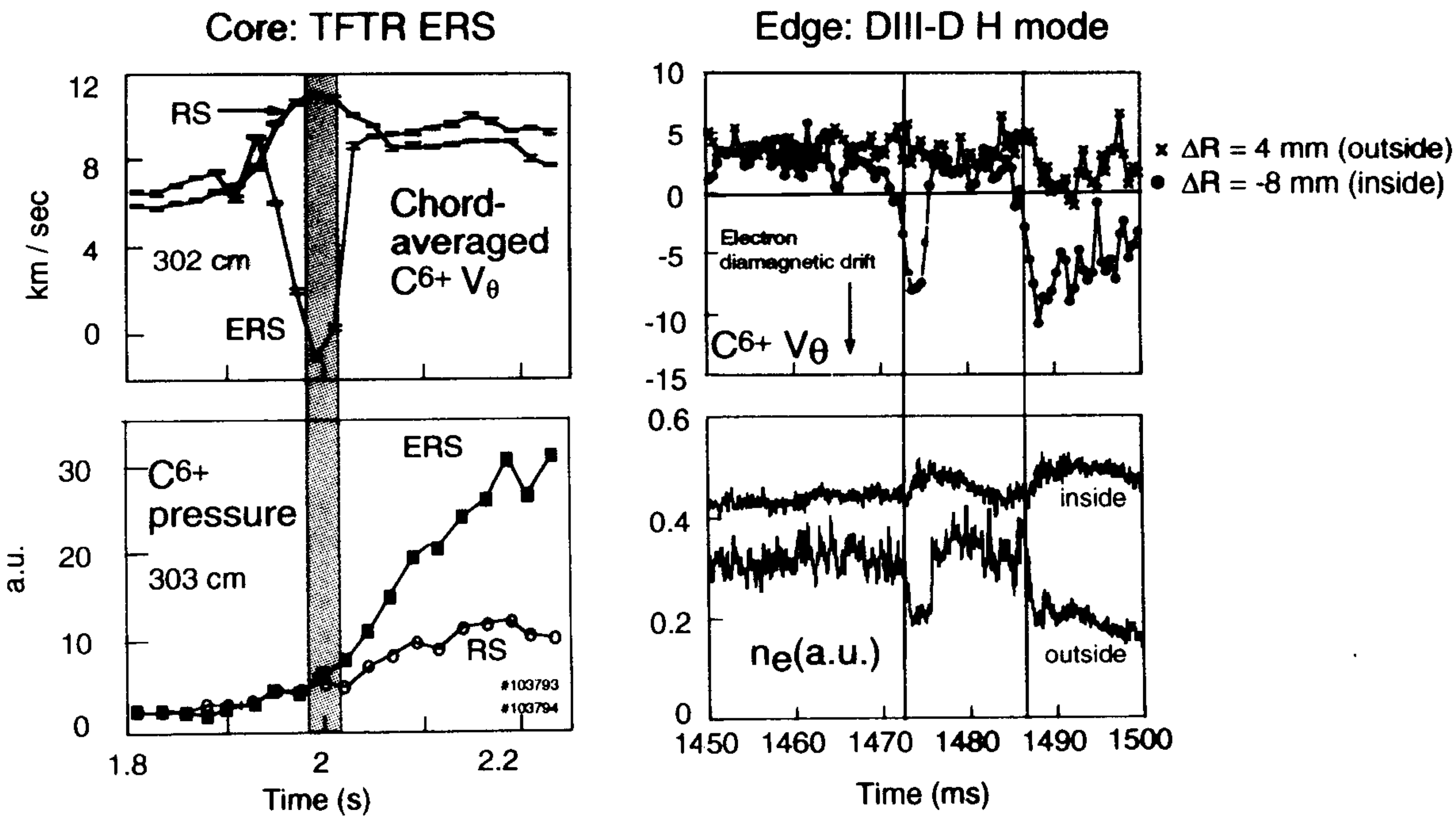
Density fluctuations are reduced across confinement bifurcations in both the core and the edge





- In core, $\gamma_{ExB}/\gamma_{lin}$ *increases* with rising ∇p
  $\Rightarrow$ positive feedback
- Closeness of shearing and growth rates at transition should be treated with caution

There is similar phenomenology between some core and edge barriers



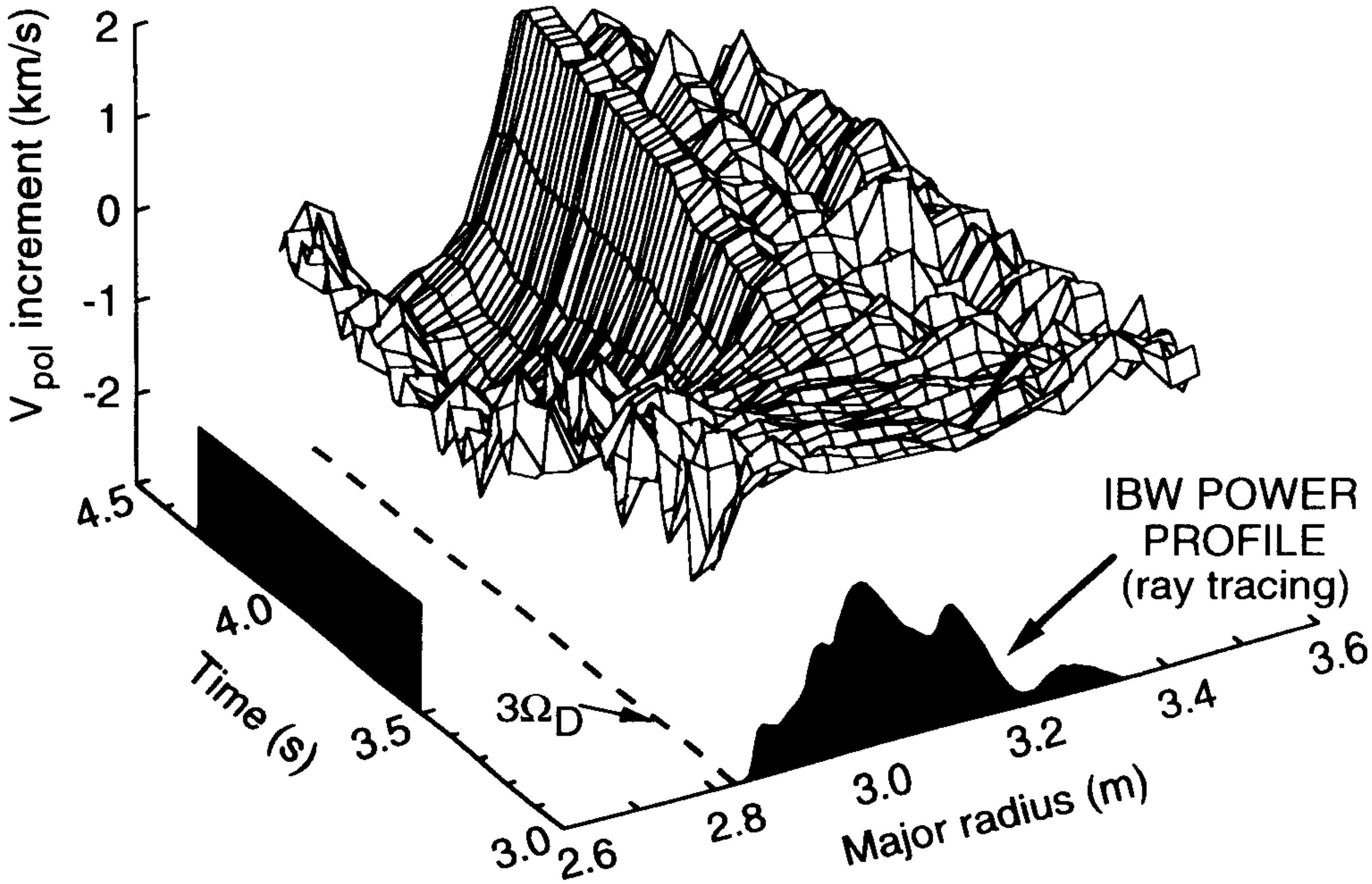
For both: impurity V_θ changes before confinement changes

$\Delta E_r'$ from V_θ change is negative and highly localized

Pressure gradient dominates E_r after transition

ejs090997

Direct-Launch IBW Produced Poloidal Velocity Shear in Absorption Region



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

R. Bell

T97069

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

The Physics of Deuterium-Tritium Plasmas in TFTR

M.G. Bell
Princeton Plasma Physics Laboratory[1]

Presented at the
Autumn College on Plasma Physics
International Centre for Theoretical Physics
Trieste, Italy

November 6, 1997

[1] *Supported by U.S. Department of Energy Contract No. DE-AC02-76-CH03073*

Topics

- Review of the basis of DT fusion
- The history of DT experiments in tokamaks
- Optimizing fusion reactivity in present scale experiments
- Study of the effect of isotopic mass on confinement in TFTR
- Alpha particle confinement, heating and loss in TFTR
- Toroidal Alfvén Eigenmodes excited by energetic alpha particles
- Summary

DT Fusion

- DT reaction has the highest cross-section:

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

- For Maxwellian ions near the optimum temperature (~13keV)

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

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

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

  $\Rightarrow Q = P_{fusion}/P_{aux} \propto [<n^2T^2>/<nT>]\, \tau_E$

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

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

  $<n^2T^2> \alpha \;<nT>/\tau_E$

  $\Rightarrow n_e(0)\cdot T_i(0)\cdot \tau_E = 6 \times 10^{20}\ m^{-3}\cdot keV\cdot s$ *(with same approximation)*

- Need high pressure and good confinement
- At the optimum temperature (~15keV), DT reactions produce about 200 times the fusion power of DD reactions in the same conditions

History of 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

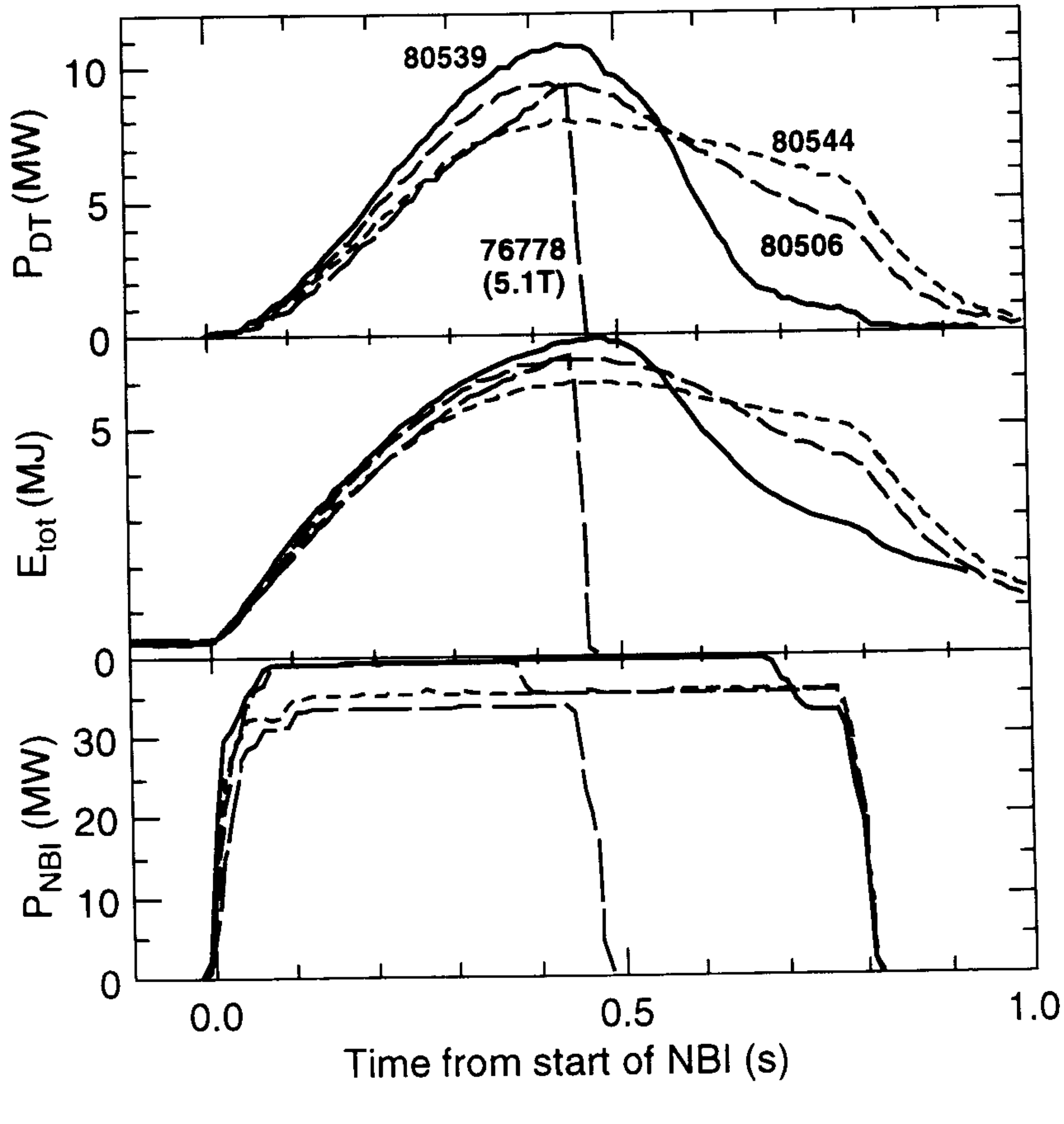
JET, May 1997 - November 1997 ("DTE1")

- 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 collaborators*

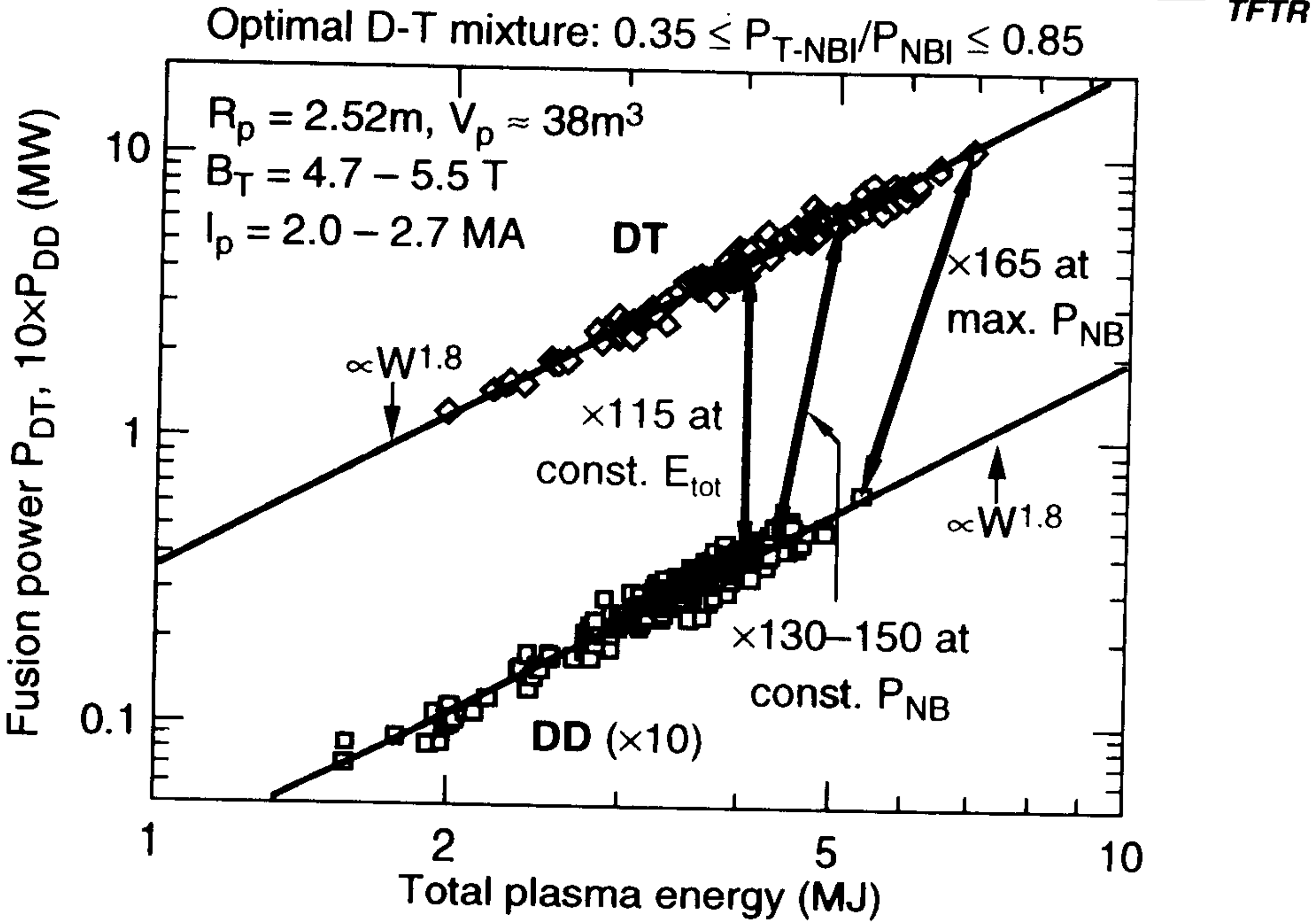
Predictions of Reactivity From Deuterium Plasmas were Largely Fulfilled in D-T



- For shot producing 10.7MW of fusion power:
  $P_{T\text{-}NBI}$ = 25MW, $P_{D\text{-}NBI}$ = 14.5MW
  $n_e(0) = 1.0 \times 10^{20} m^{-3}$, $T_e(0)$ = 13.5keV, $T_i(0)$ = 32keV
- *This met the TFTR goal established in 1975*

Fusion Power from D and D-T Supershots Depends Mainly on Plasma Energy for Fixed Plasma Size

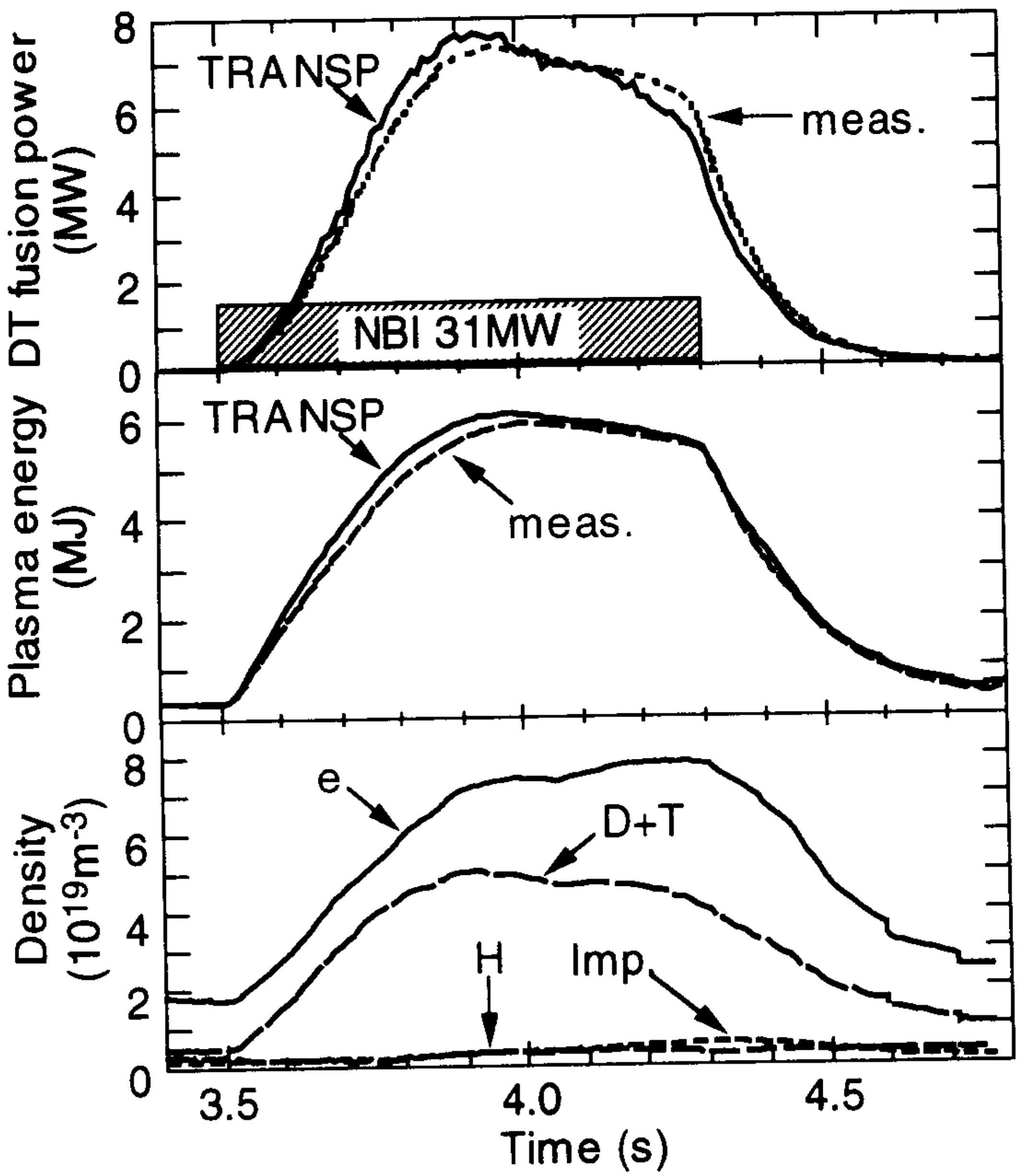
TFTR



- High ion temperatures in regimes of highest absolute reactivity reduce fusion power ratio below maximum achievable
- To utilize increased NBI power and confinement in D-T, necessary to increase toroidal field and current (5.6T, 2.7MA)

TRANSP Code Can Successfully Model DT Reactivity of Plasma

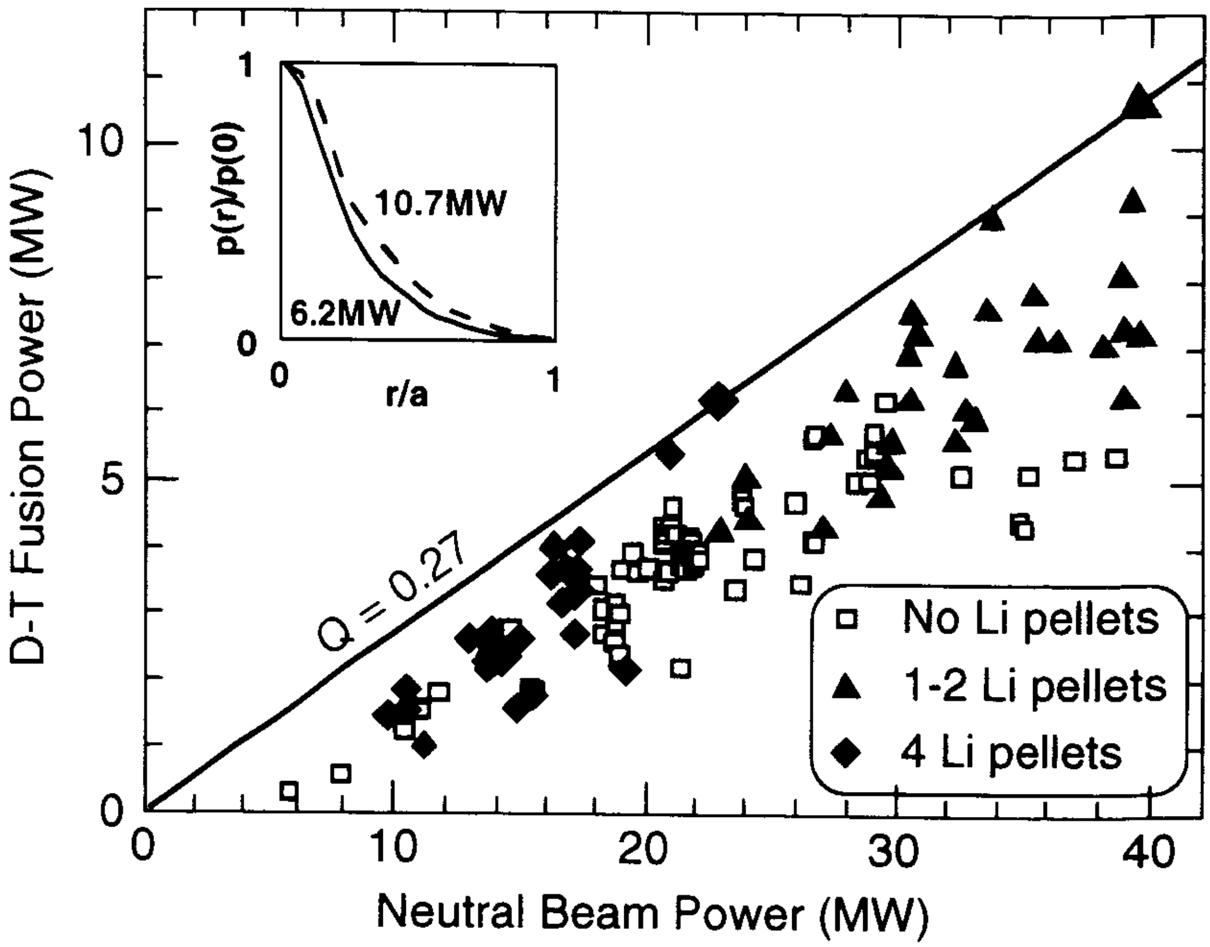
TFTR



- Code uses measurements of n_e, T_e, T_i profiles, Z_{eff} and NBI parameters
- Models atomic physics, classical orbits and thermalization of NB-injected particles on background plasma
- DT reactivity from nuclear cross-sections

Lithium Pellet Conditioning Can Increase Supershot Confinement but Reduces Stability

TFTR

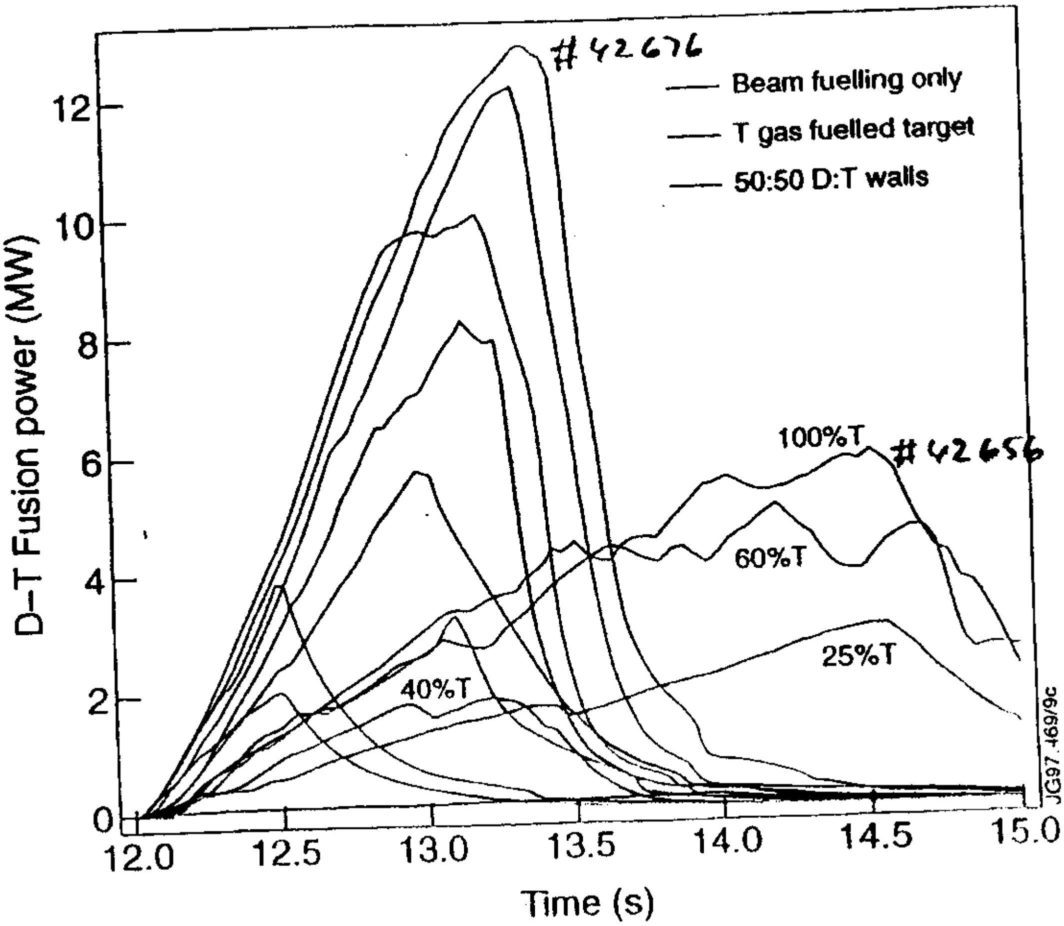


- Supershots at $R_p = 2.52$m, $I_p \geq 2$MA with $P_{T\text{-}NB}/P_{NB} \geq 0.3$
- Confinement improvement accompanied by increase in peaking of pressure profile

  $\Rightarrow$ ballooning instability growing on underlying n = 1 mode
- Lithium pellets also tend to broaden current profile in target plasma which adversely affects stability

T9705!

Development of Hot Ion H-mode in D-T

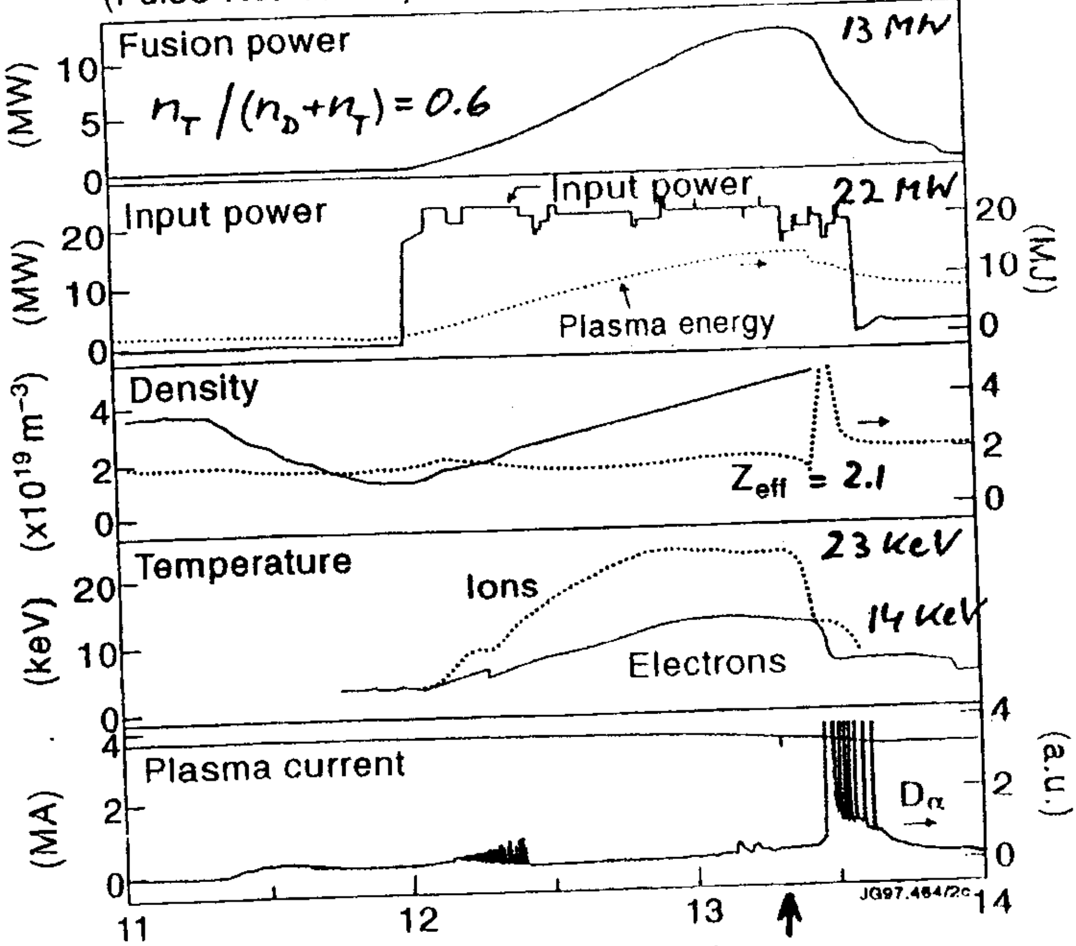


- 82 MJ of D-T fusion energy produced so far in hot ion H-mode discharges.

JET

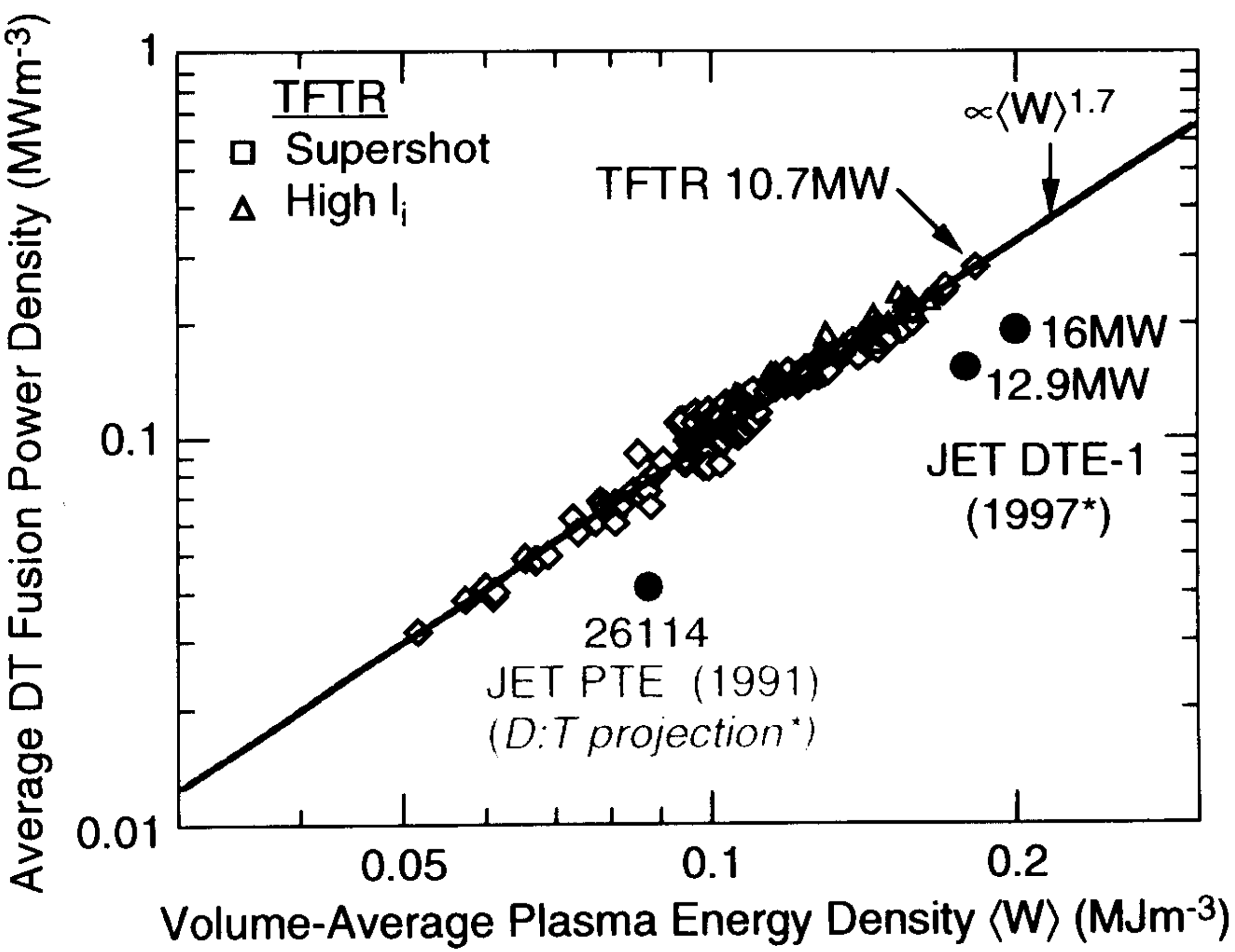
13MW of D-T Fusion Power

(Pulse No: 42676) 3.6MA, 3.4T



- Full NB heating power augmented by low levels of ICRH has allowed fusion power, energy and Q records in the hot ion ELM-free H-mode:
  - Fusion power of 12.9MW; > 10 MW for 0.5 s
  - Fusion energy of 12.5MJ; and
  - Q = 0.6. (0.8 with dW/dt)
- Similar results obtained with 21.5MW of NB alone.

DT Fusion Power Density in TFTR & JET

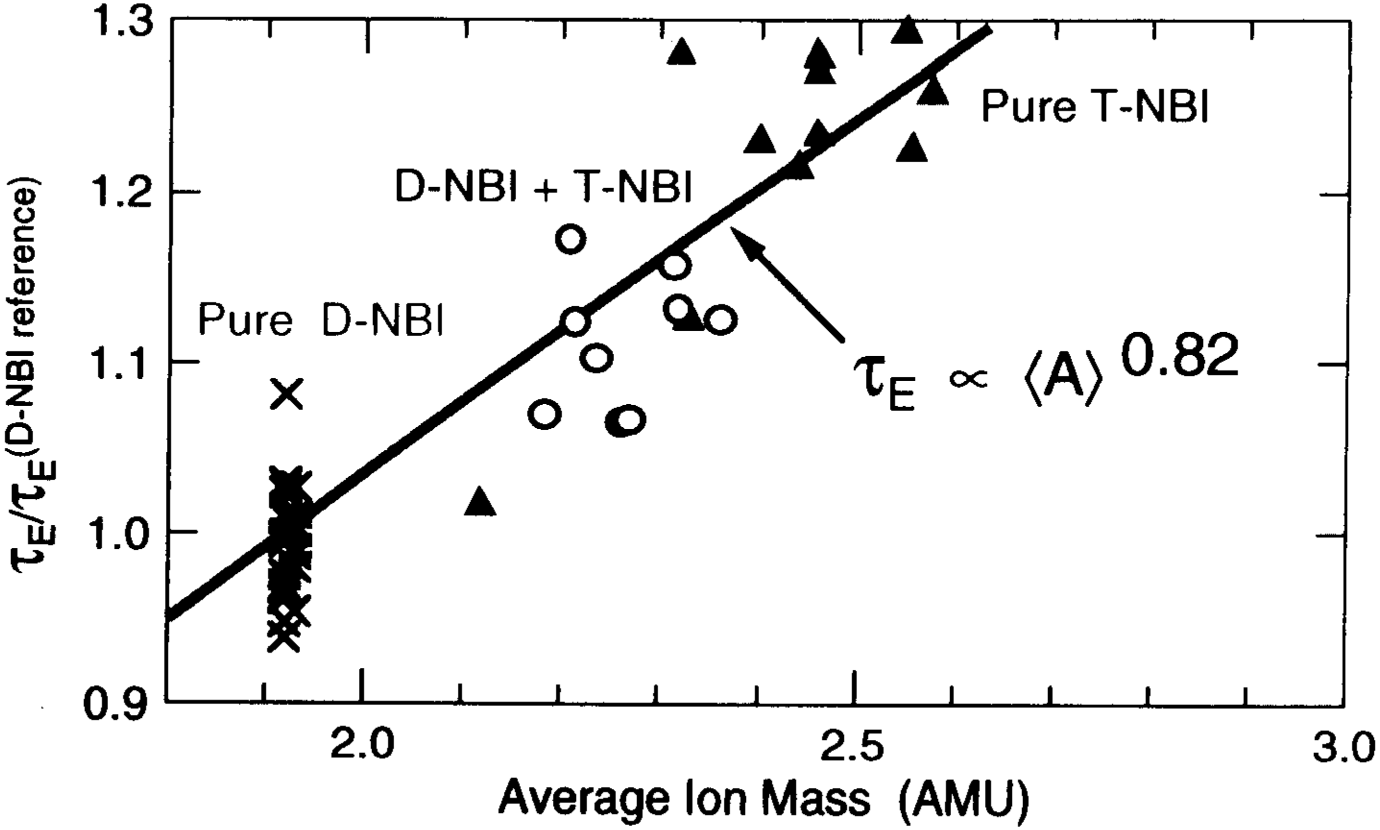


- For TFTR, restrict to optimal D-T mixture: $0.35 \leq P_{T\text{-}NBI}/P_{NBI} \leq 0.85$

*Nuclear Fusion **32** (1992) 187

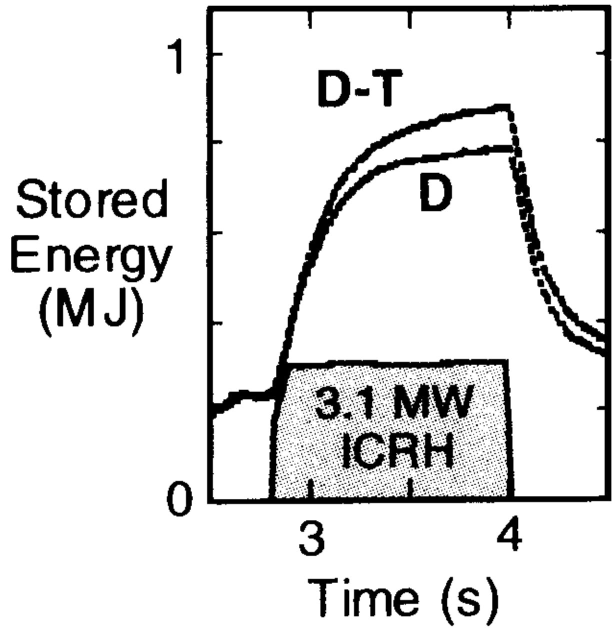
Unpublished JET data

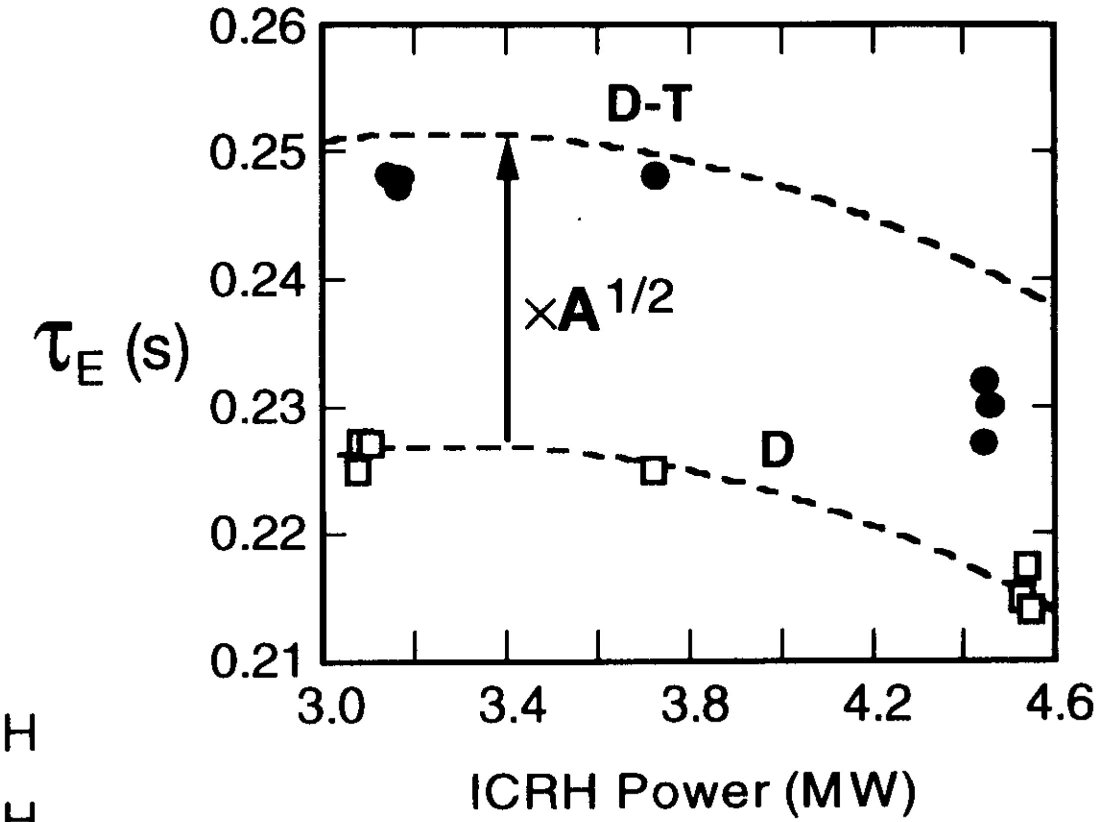
Global Confinement Increases With Tritium NBI



- Tritium concentration limited by D influx from limiter, even with pure T-NBI
- τ_E increase observed in supershot and H-mode regimes
  - slightly stronger than ITER global scaling: $\tau_E \propto \langle A \rangle^{0.5}$

Energy Confinement Scales $\propto A^{1/2}$ In D and D-T Plasmas With H-Minority ICRF Heating



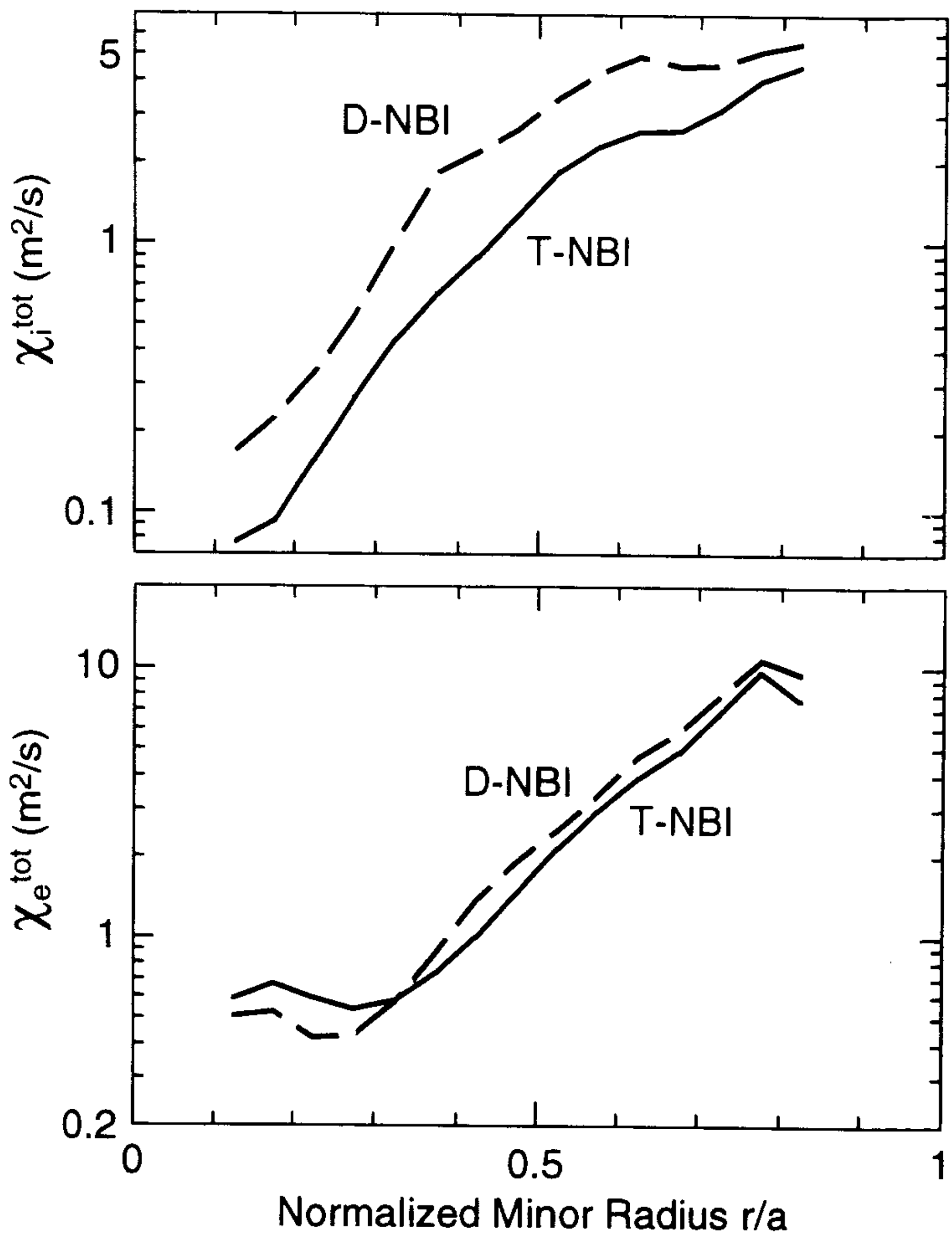


D-T: 40%T, 40%D, 5% H

D: 1%T, 78%D, 8% H

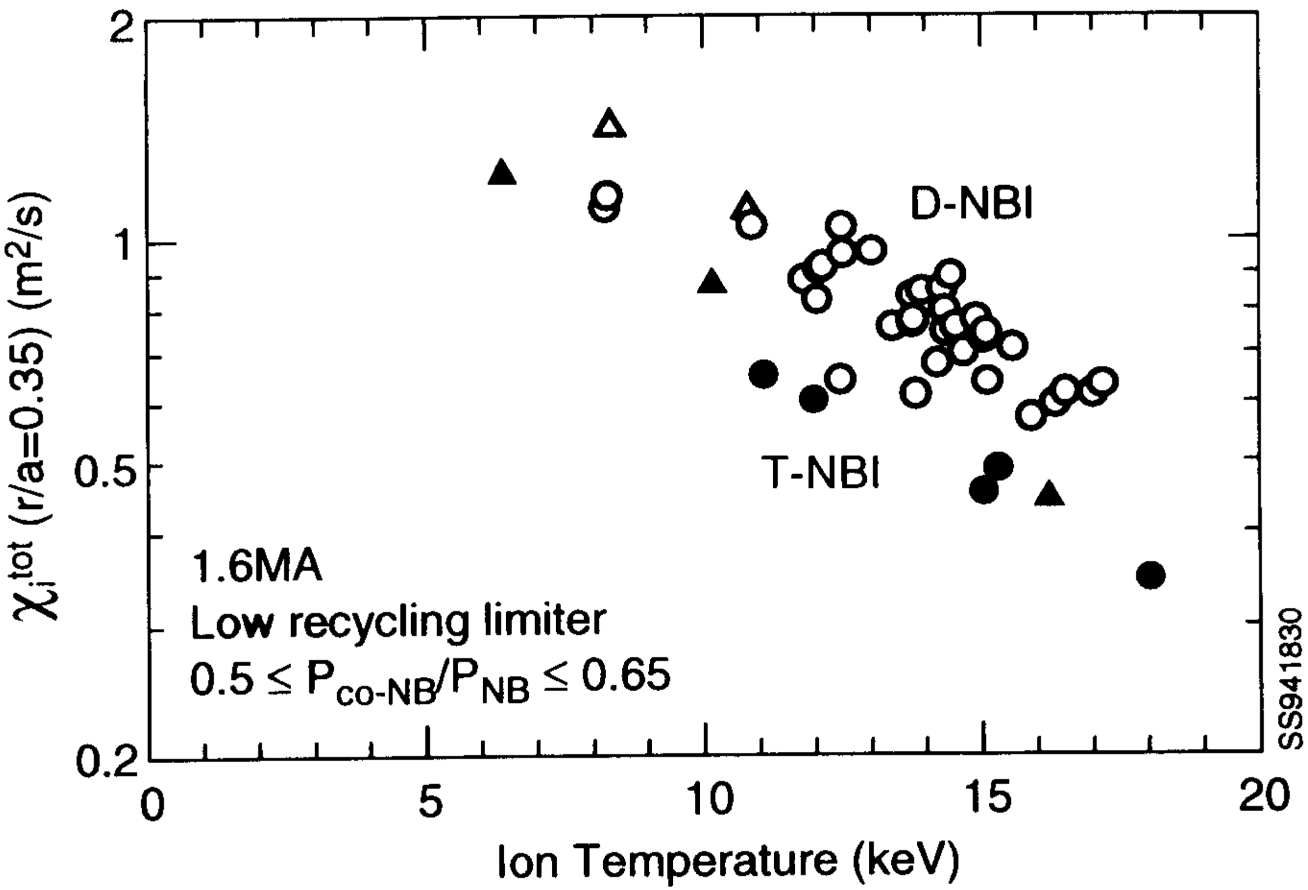
- H-minority ICRF heating only:
  - Heating and change in transport only through electrons.
  - No energetic D or T tails.

Thermal Transport is Reduced in Plasmas with Tritium NBI



- Effect larger in ion channel
- Inconsistent with Bohm or gyro-Bohm scaling

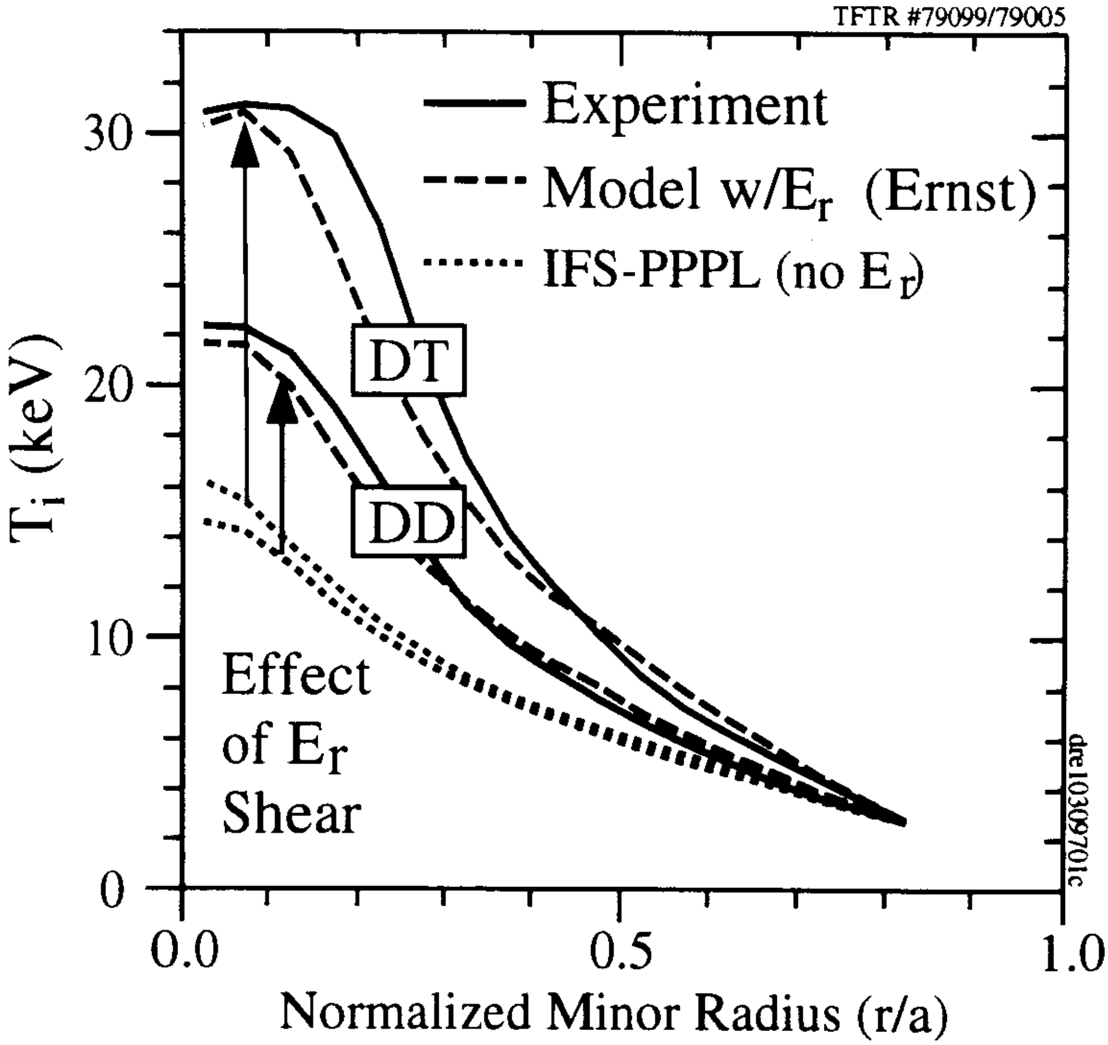
Tritium NBI Extended Earlier Supershot Scaling Results



- Favorable scaling of ion thermal transport with temperature and average ion mass appear to contradict Bohm and gyro-Bohm scalings of L-mode and H-mode plasmas
- $\chi_i^{tot} \propto \langle A \rangle^{-1.43}$

Radial Electric Field Shear Underlies the Strong Isotope Effect Observed in Deuterium-Tritium Supershot Plasmas

TFTR



- Max. Growth Rate $\gamma_{lin}^{max} \propto m_i^{-1/2}$ with $E \times B$ shearing rate

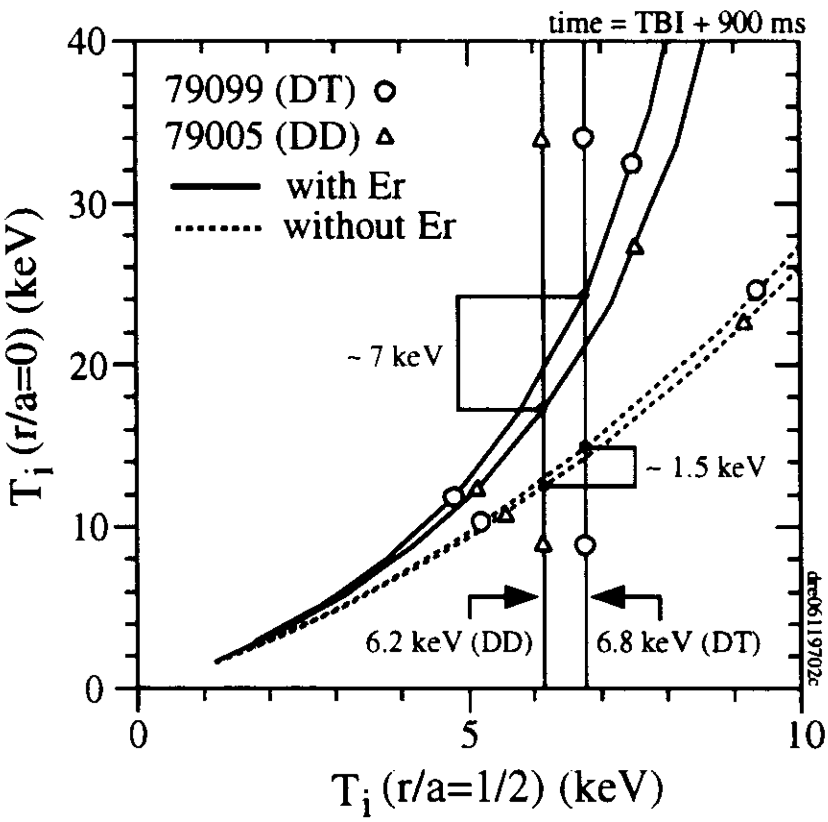
$$\omega_{E\times B} \simeq \frac{d}{dr}\left(-\frac{T_i}{n_i}\frac{dn_i}{dr}\right)$$

- Shear flow stabilization is nonlinearly stronger in heavier plasmas.

D. R. Ernst, Ph.D. Thesis, MIT (1997).

The Isotope Effect in supershots is strongly amplified by core $\mathrm{E_r}$ shear

TFTR

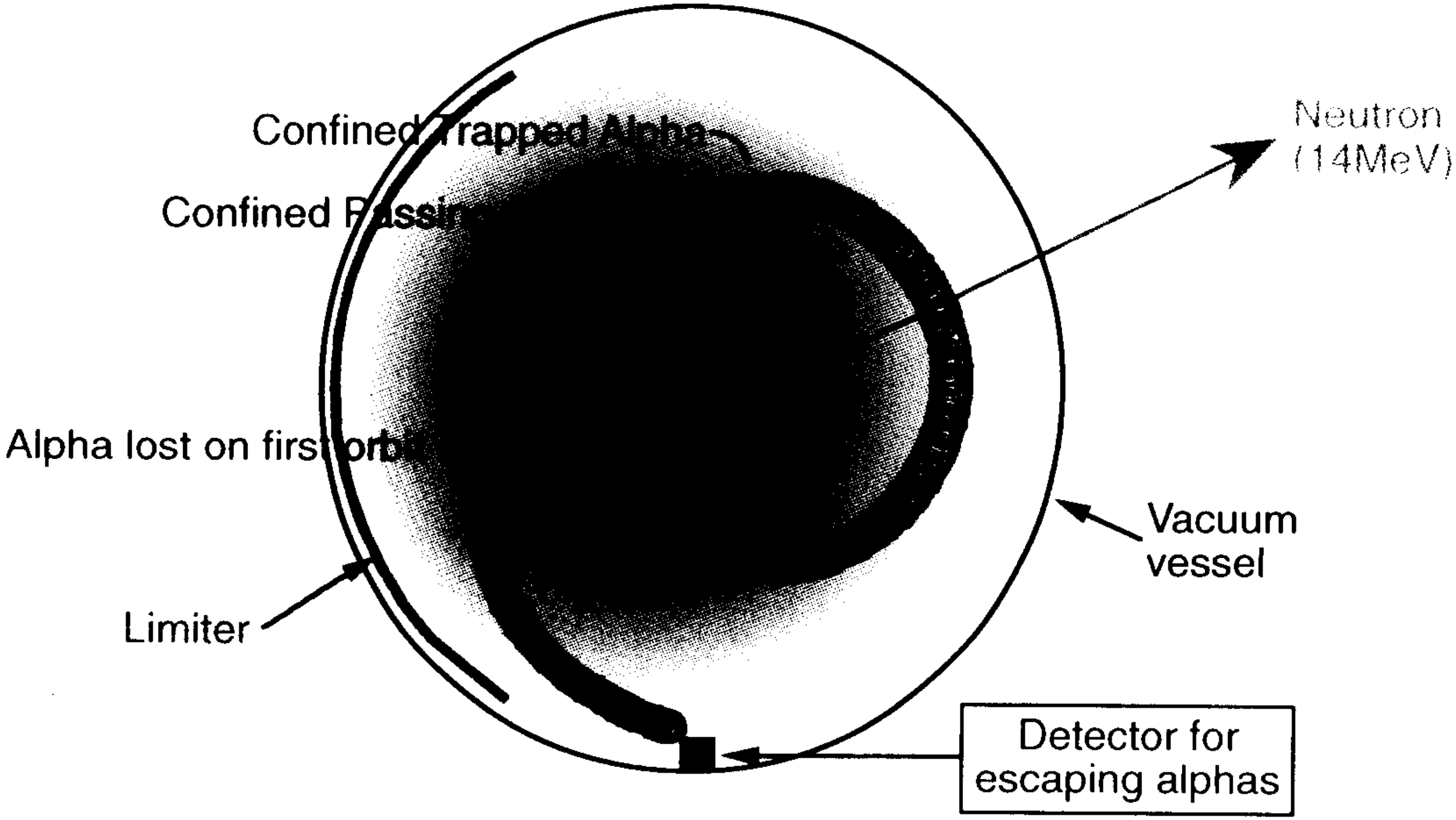


- $\boxed{\Delta T_i(1/2) = 0.6\ \text{keV}} \rightarrow \boxed{\Delta T_i(0) = 7\ \text{keV}}$
- The criterion $\omega_{E\times B} \sim \gamma_{\text{lin}}^{\text{max}}$ results in a strong nonlinear sensitivity of $T_i(0)$ to $T_i(r/a = 1/2)$.
- E_r shear amplifies the weaker $\tau_{\mathrm{E}} \propto \sqrt{\mathrm{A_i}}$ isotope effect observed in L-Mode plasmas to give strong Supershot scaling $\tau_{\mathrm{E}} \propto \mathrm{A_i^{0.89}}$.
- Without E_r shear, the calculated increase in $T_i(0)$ is only 1.5 keV.

D. R. Ernst, Ph.D. Thesis, MIT (1997).

Alpha Particle Orbits

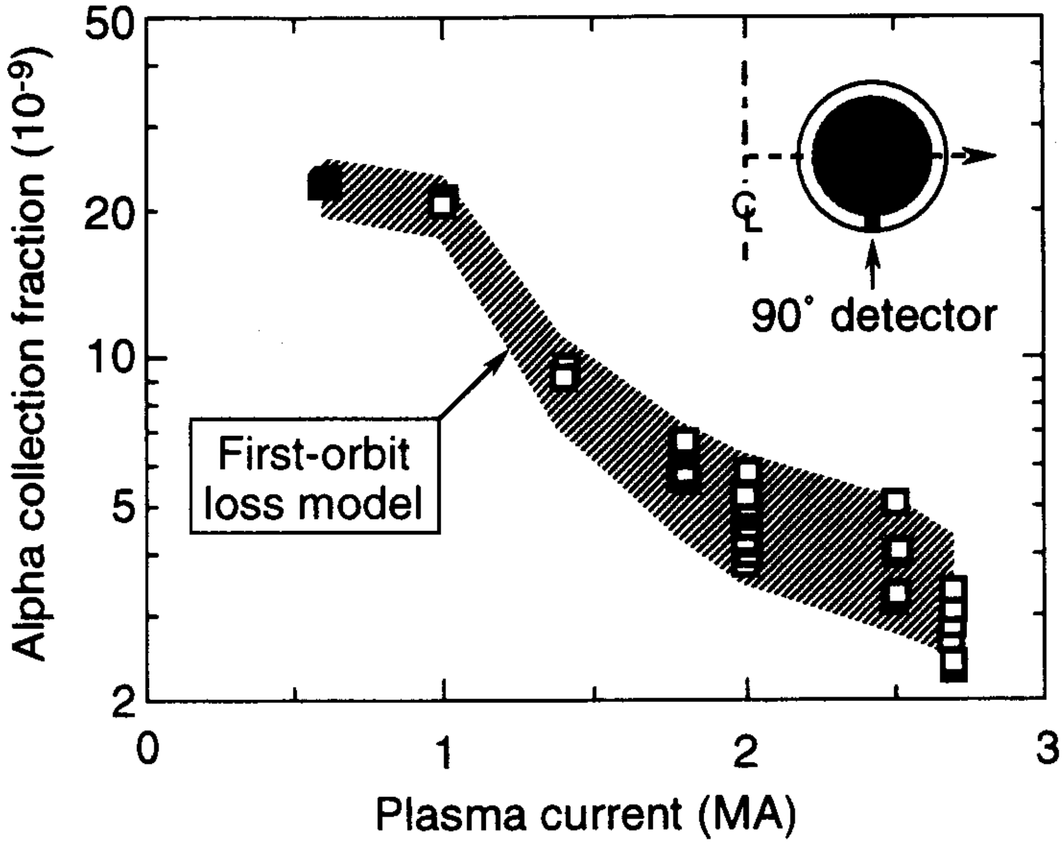
- Alpha particles from DT fusion reactions are born with energy of 3.5MeV
  - ⇒ Larmor radius up to 5cm in TFTR
  - ⇒ Radial excursions of trapped alphas are much larger



Alpha Orbits in TFTR at Various Pitch Angles (I_p = 2.5 MA)

Flux of α-Particles to 90° Detector Agrees with Calculated Loss for Unconfined Orbits

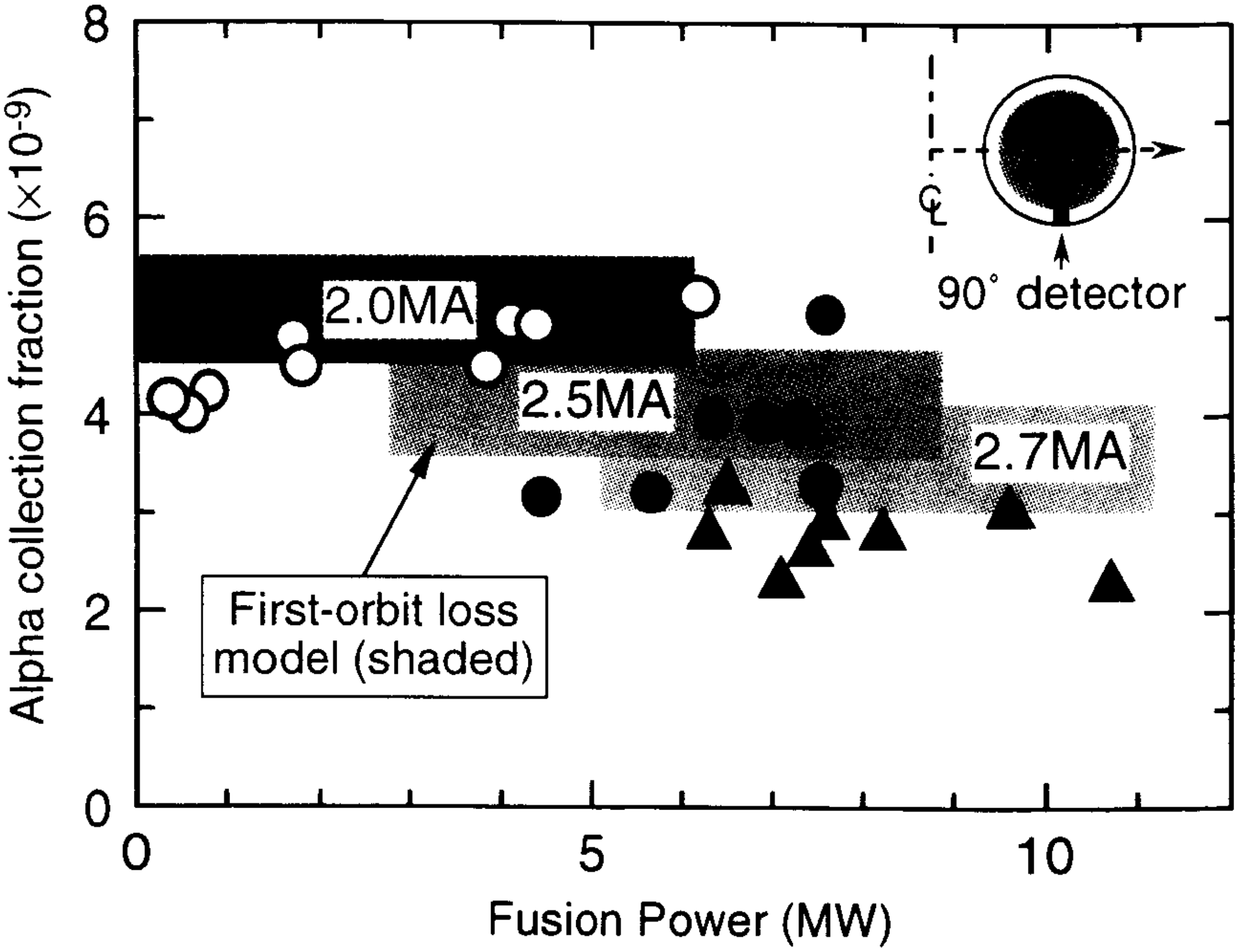
TFTR



- Shaded region shows result from an orbit-following code based on TRANSP calculations of alpha-particle birth and current profiles.
  - Probe data normalized to calculation at 0.6MA where all trapped alpha particles are expected to be lost
- At 2.5 MA, ~3% of alphas are lost on first orbit after birth

S. Zweben
D. Darrow

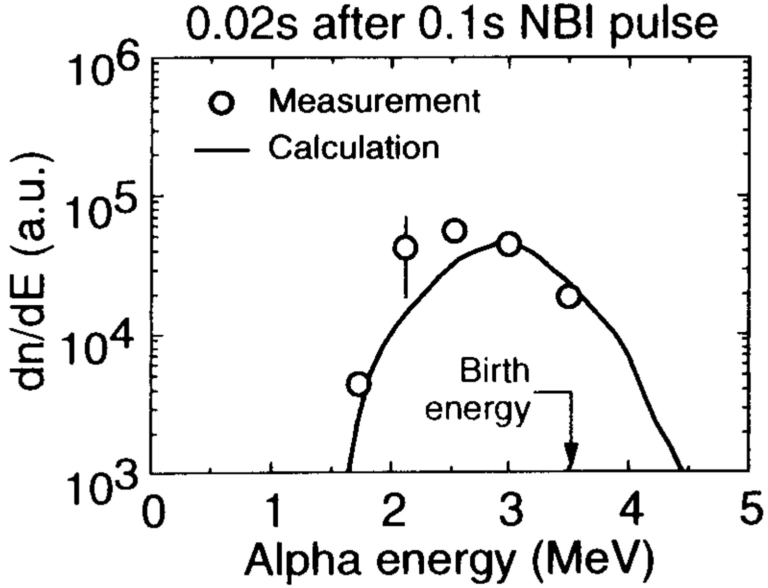
Alpha Loss Fraction does not Increase with Fusion Power

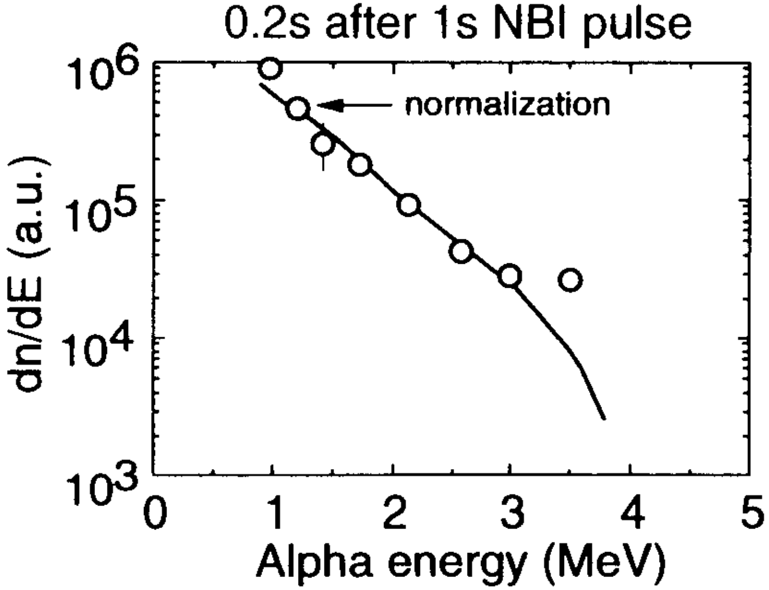


- Data for MHD-quiescent phases of D-T supershots
- No indication of loss processes driven by alpha-particles themselves

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

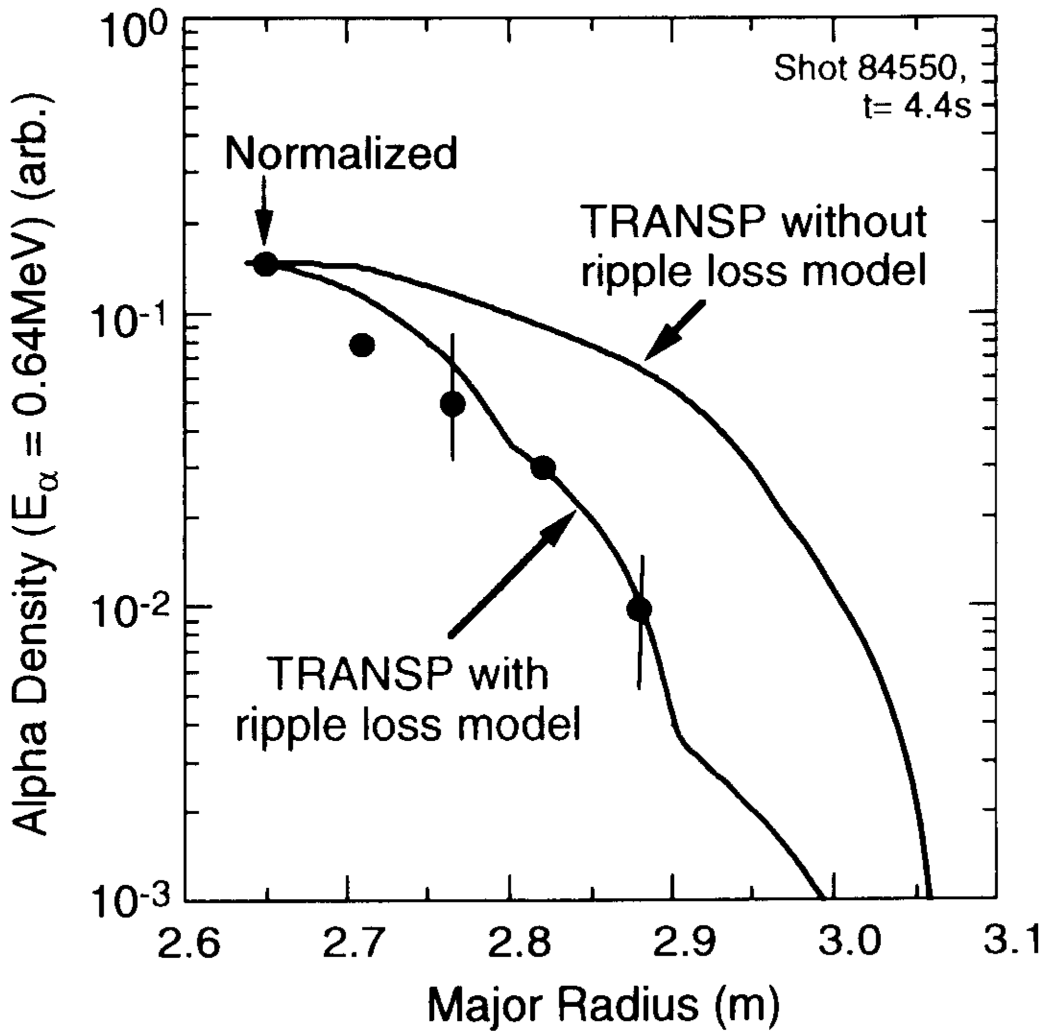




- Calculation with TRANSP/FPPT code based on classical Coulomb collisions using measured plasma parameters
  - alpha-particle velocity slowing time typically 0.5 - 1 s
- High ion temperature and presence of unthermalized NB injected ions results in broadening of alpha spectrum above birth energy

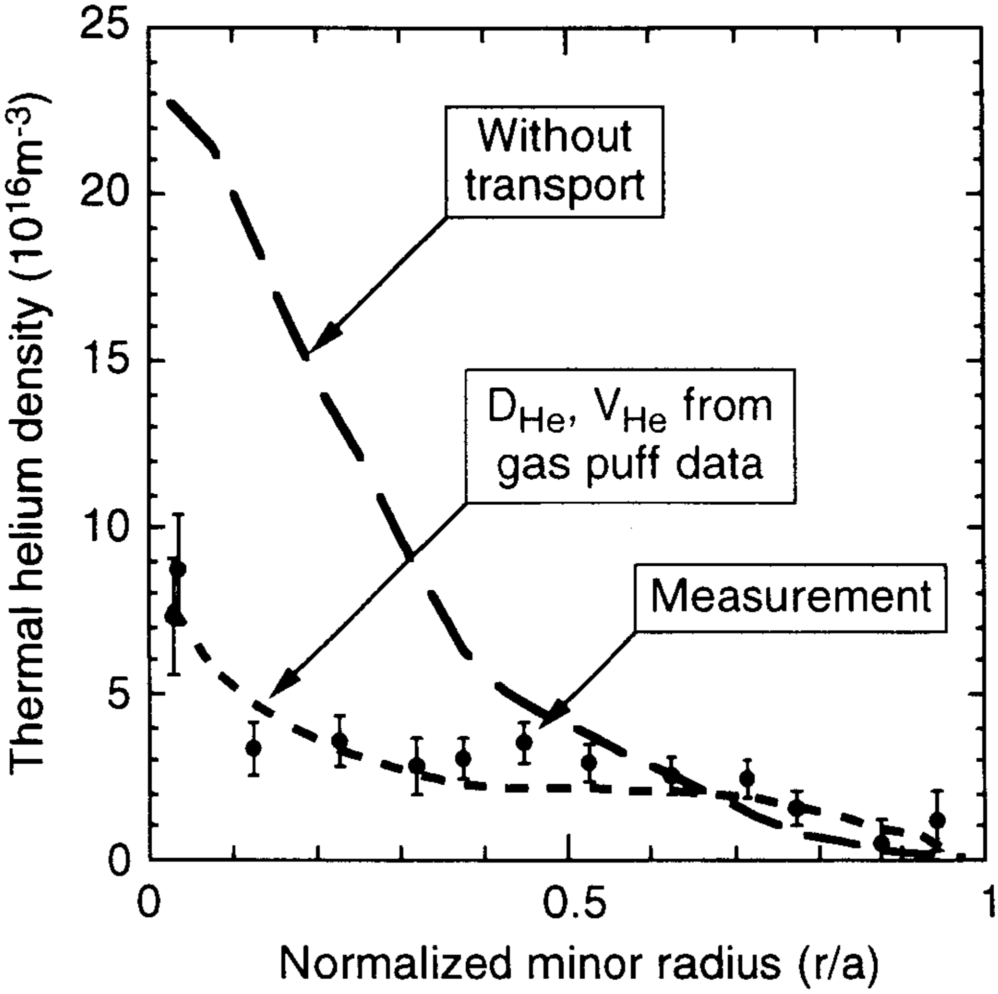
GAT, IOFFE, PPPL Collaboration

Inclusion of Ripple Diffusion Needed to Model Measured Radial Profile of Alphas



- Stochastic ripple diffusion produces significant losses of trapped alphas in reversed-shear plasmas because of high central q

Transport of Thermal Helium Ash from Center to Edge is Rapid

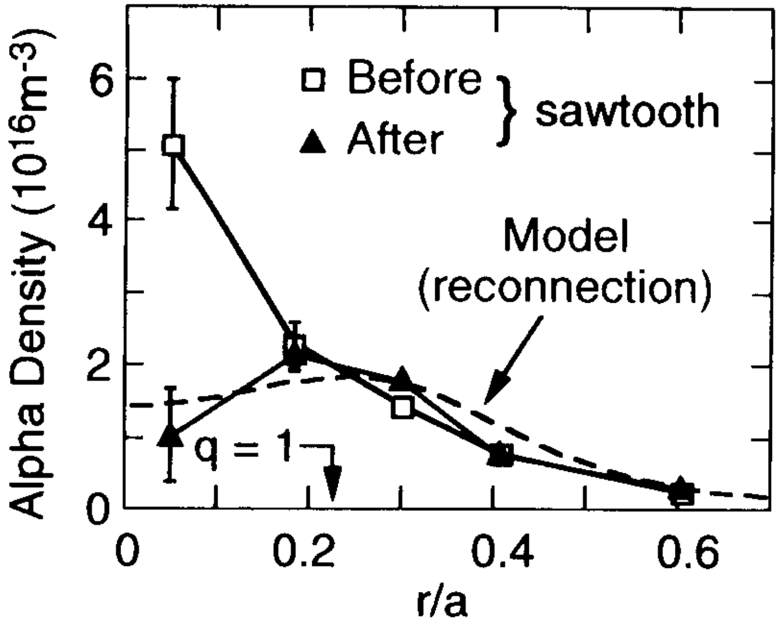


- Measured by charge-exchange recombination spectrometry calibrated against He gas puff
- Data consistent with modelling based on He transport deduced from gas puff experiments
- $D_{He} / \chi_D \sim 1$
- Consistent with $\tau_{p}^{*}{}_{(He)}/\tau_E \approx 8$: acceptable for reactors

Sawtooth Instabilities Redistribute Alphas

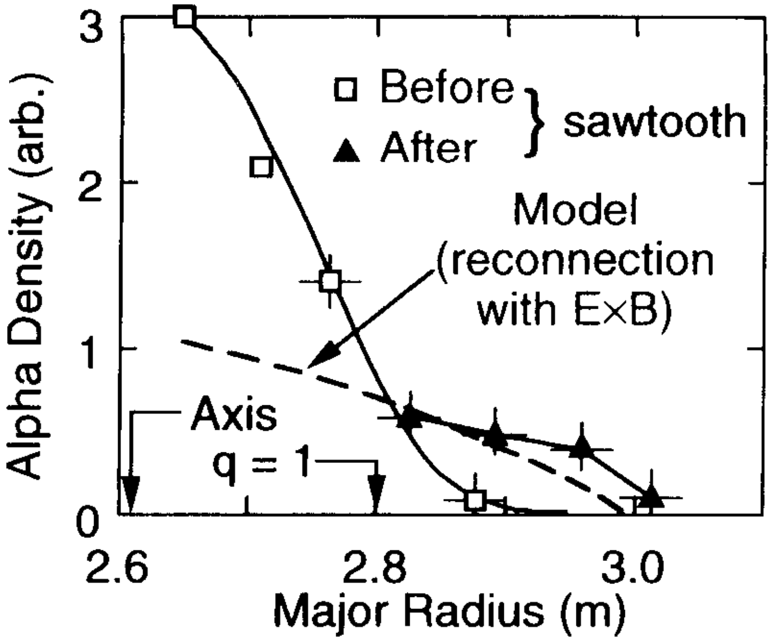
TFTR

Alpha Charge-Exchange Recombination Spectroscopy



- Measures passing alpha particles in energy range 0.15 – 0.6 MeV
- Absolutely calibrated

Alpha-Pellet Charge Exchange



- Measures deeply trapped alpha particles at energy 1.2 MeV
- Relative calibration

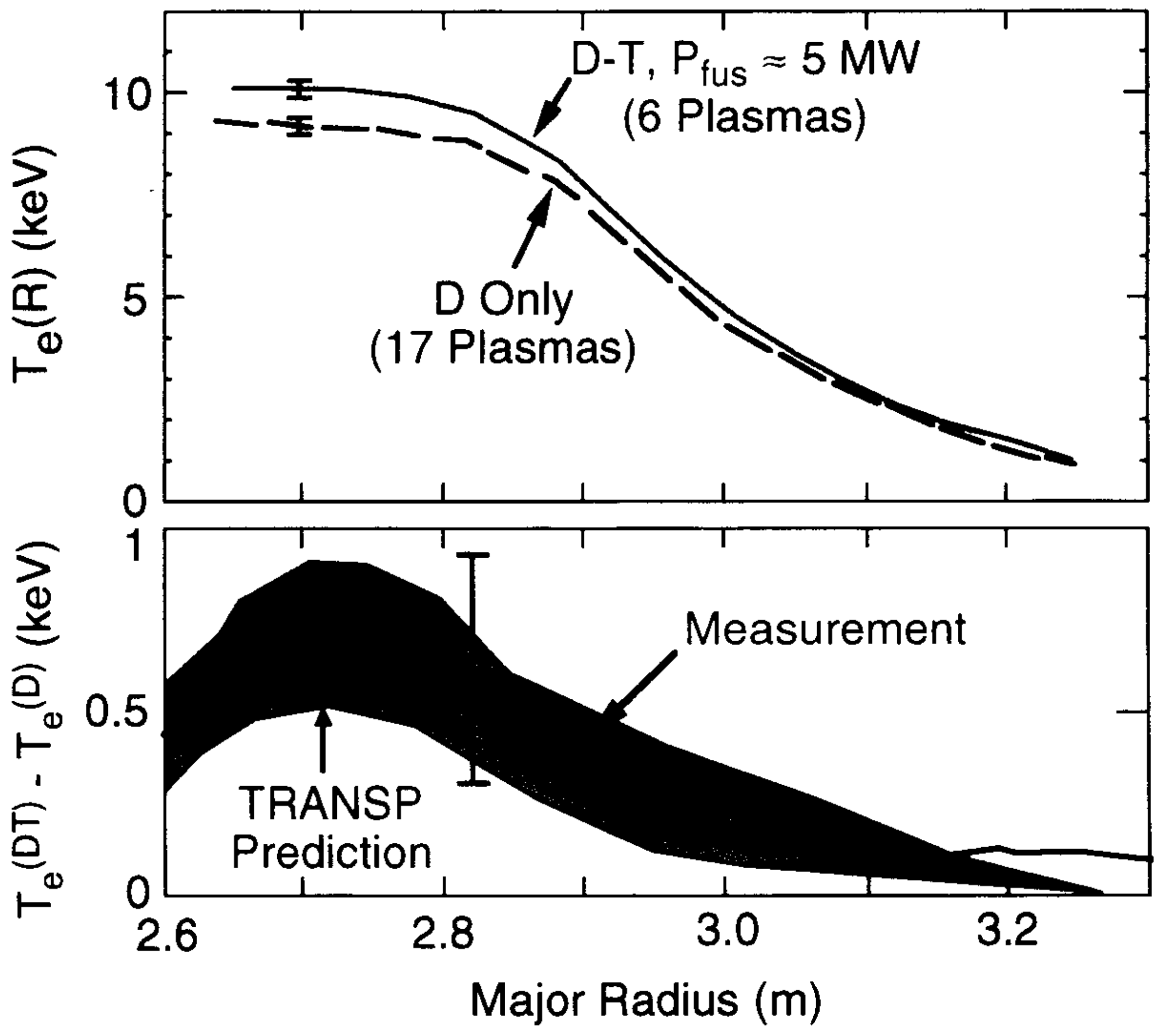
- Sawtooth reconnection causes significant redistribution of the alphas from inside to outside the q = 1 radius.
- Dashed lines are calculated profiles after the crash based on reconnection models

Plasma conditions: I_p = 2.0MA, B_T = 5.1T, R_p = 2.52m, a = 0.87m

In Matched D and D-T Plasmas, Change in T_e Consistent with Alpha Particle Heating

TFTR

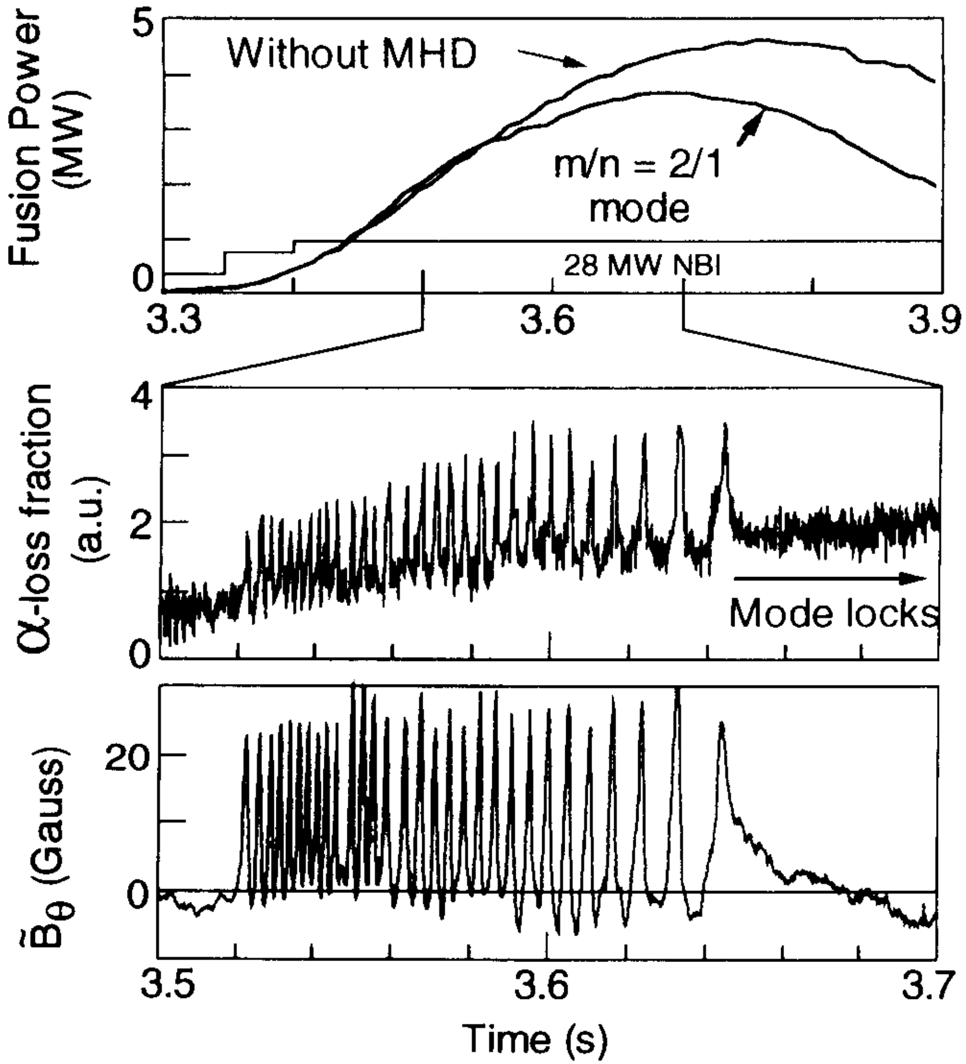
- Alpha heating ~10% of power through electron channel
- Must compensate for effect of isotope on confinement



- Plasmas matched for dominant T_e scaling in D only plasmas
- TRANSP prediction shown includes alpha particle heating
  - shaded region indicates uncertainty range of prediction
- Without alpha heating, measured difference is above uncertainty range of prediction

Increased Loss of α-Particles Occurs During Periods of MHD Instability

TFTR



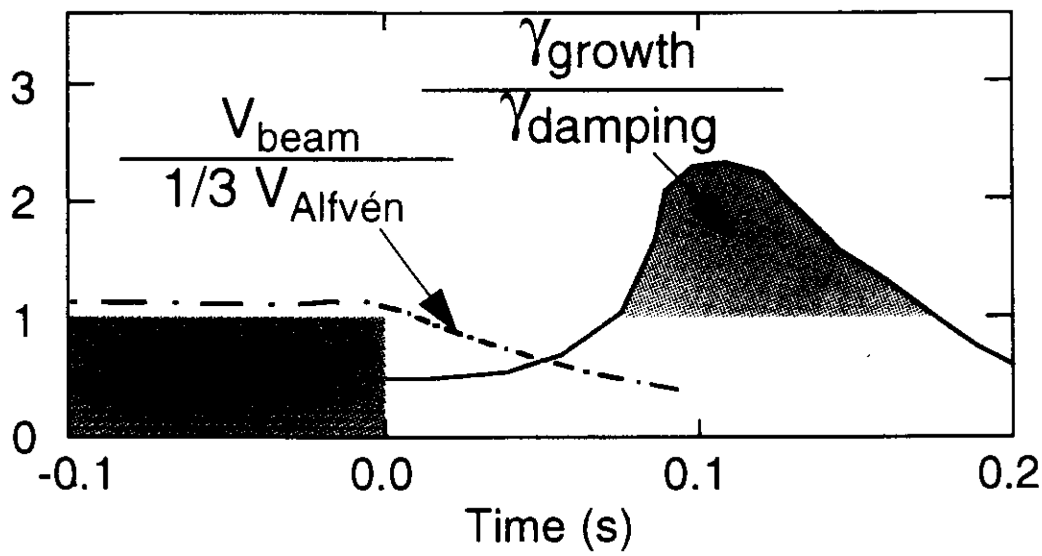
- Strong toroidal anisotropy in α-loss apparent when mode is rotating

Alpha Driven TAEs in TFTR

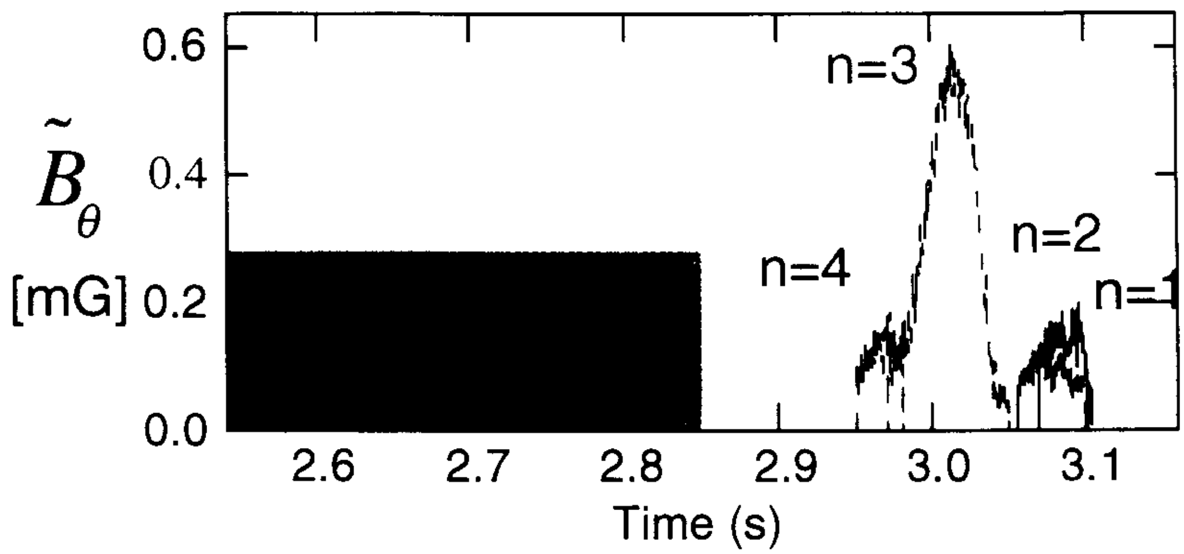
- Toroidal Alfvén Modes driven by alpha particles were not seen in D-T supershots for P_{DT} up to 10.7MW

Theory: Fu(PPPL), Spong (ORNL) suggested ways to observe alpha-driven TAEs:

- Increase alpha drive by reducing shear;
- Wait until beam damping is reduced after NBI



Experiment:



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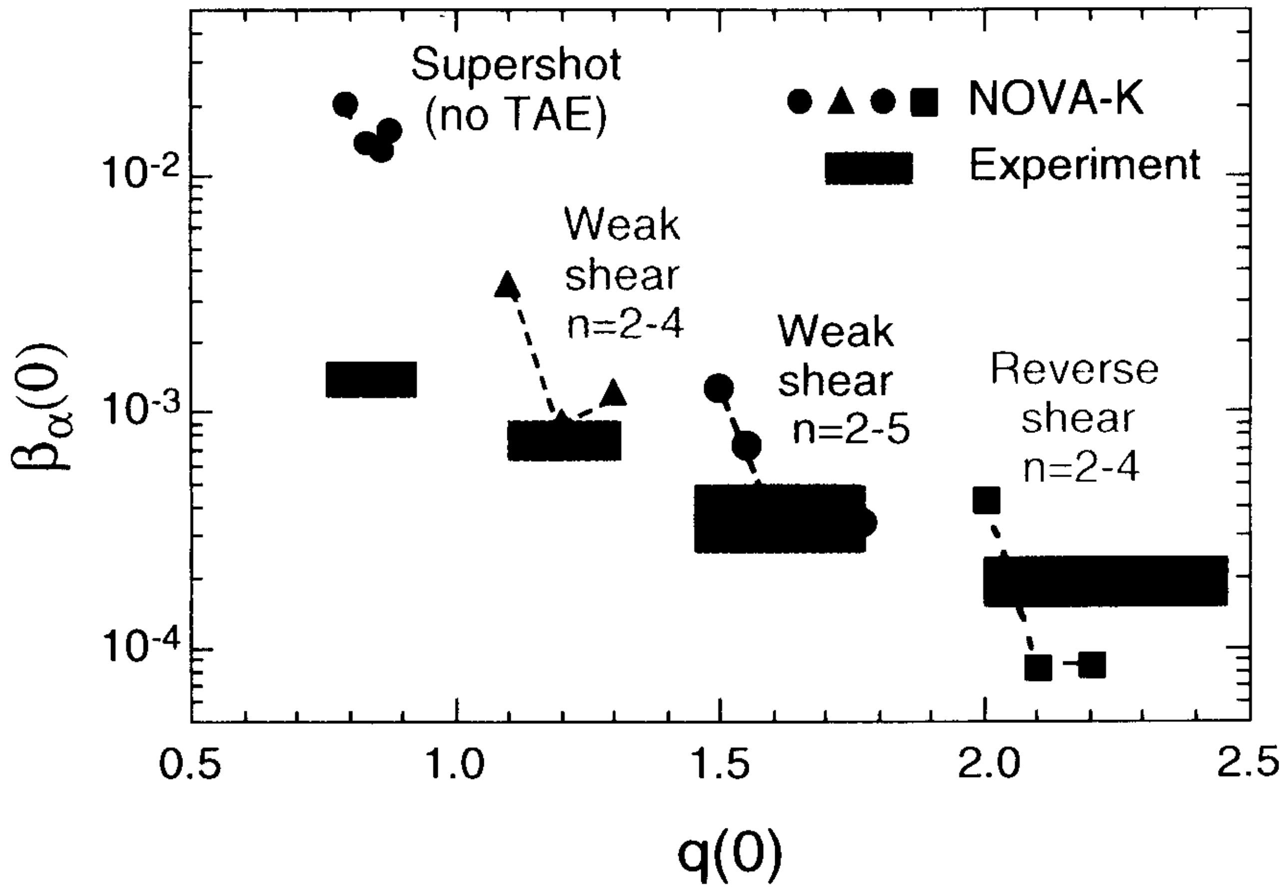
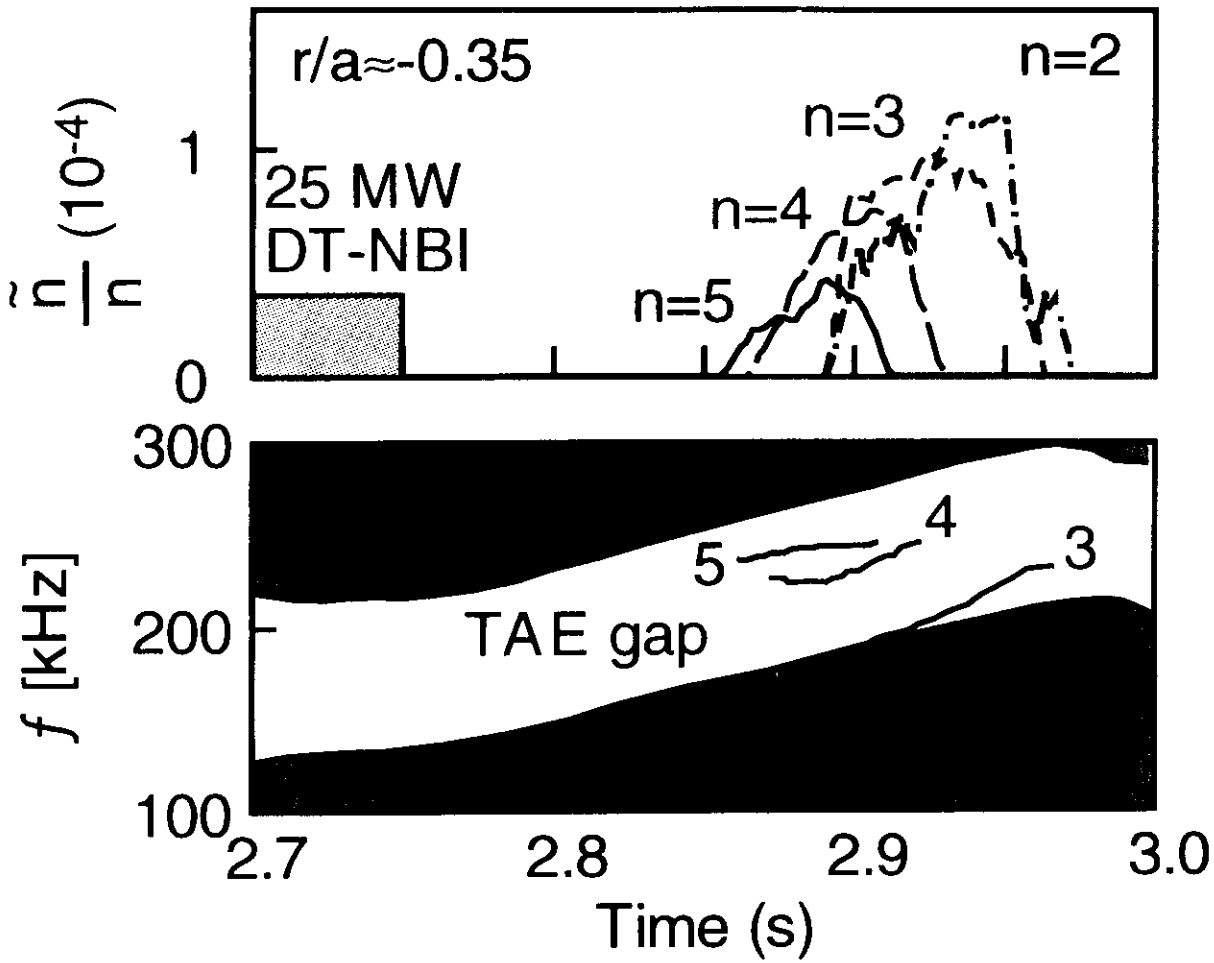
Observed α-Driven TAEs Consistent with Linear Theory



- Theory predicts low shear and high q(0) are destabilizing.
- Weak or reverse magnetic shear plasmas in a reactor may be unstable to high-n TAEs.

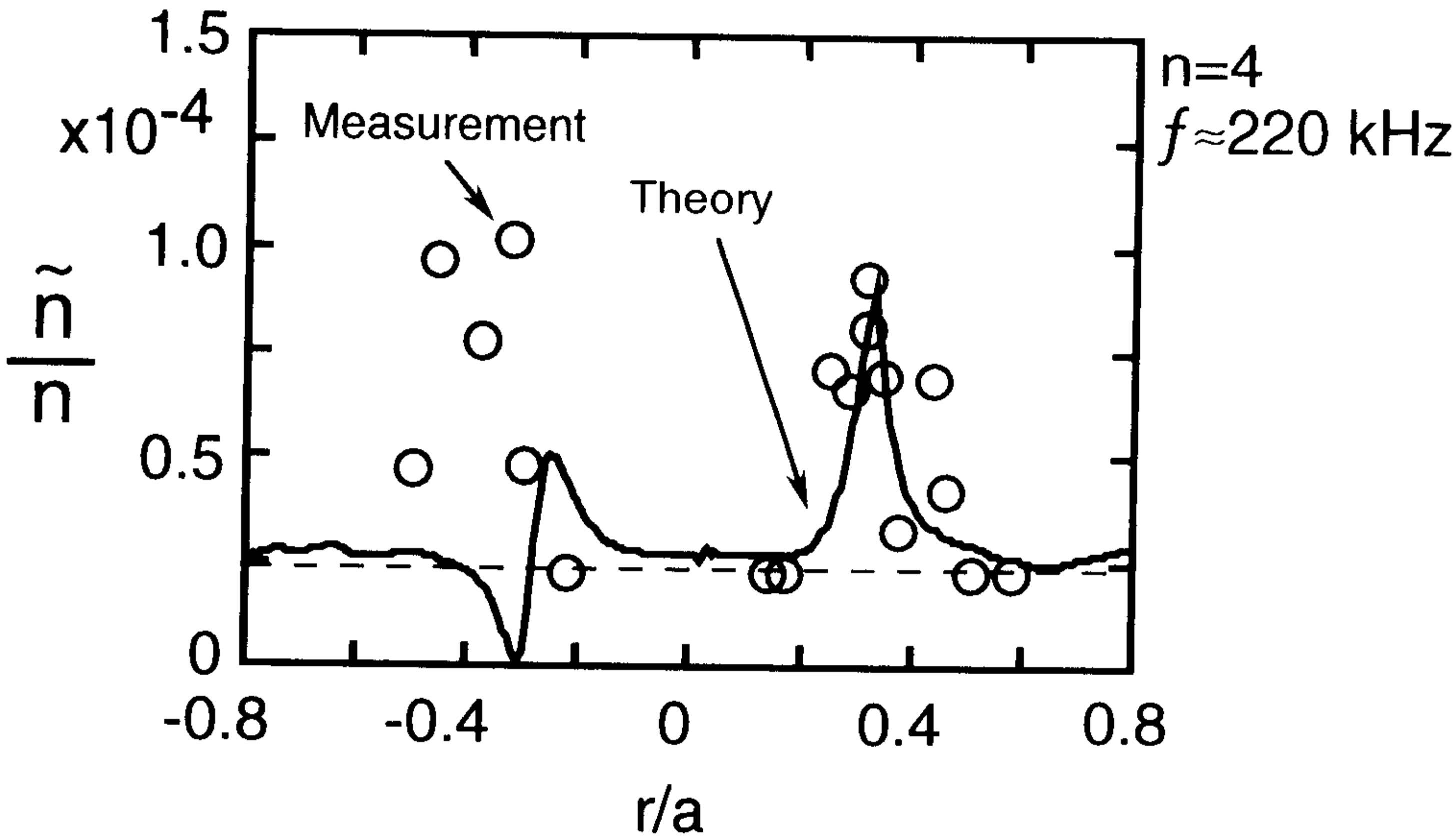
G. Fu, R. Nazikian

Sequence of Modes Detected as q and Drive Profiles Evolve



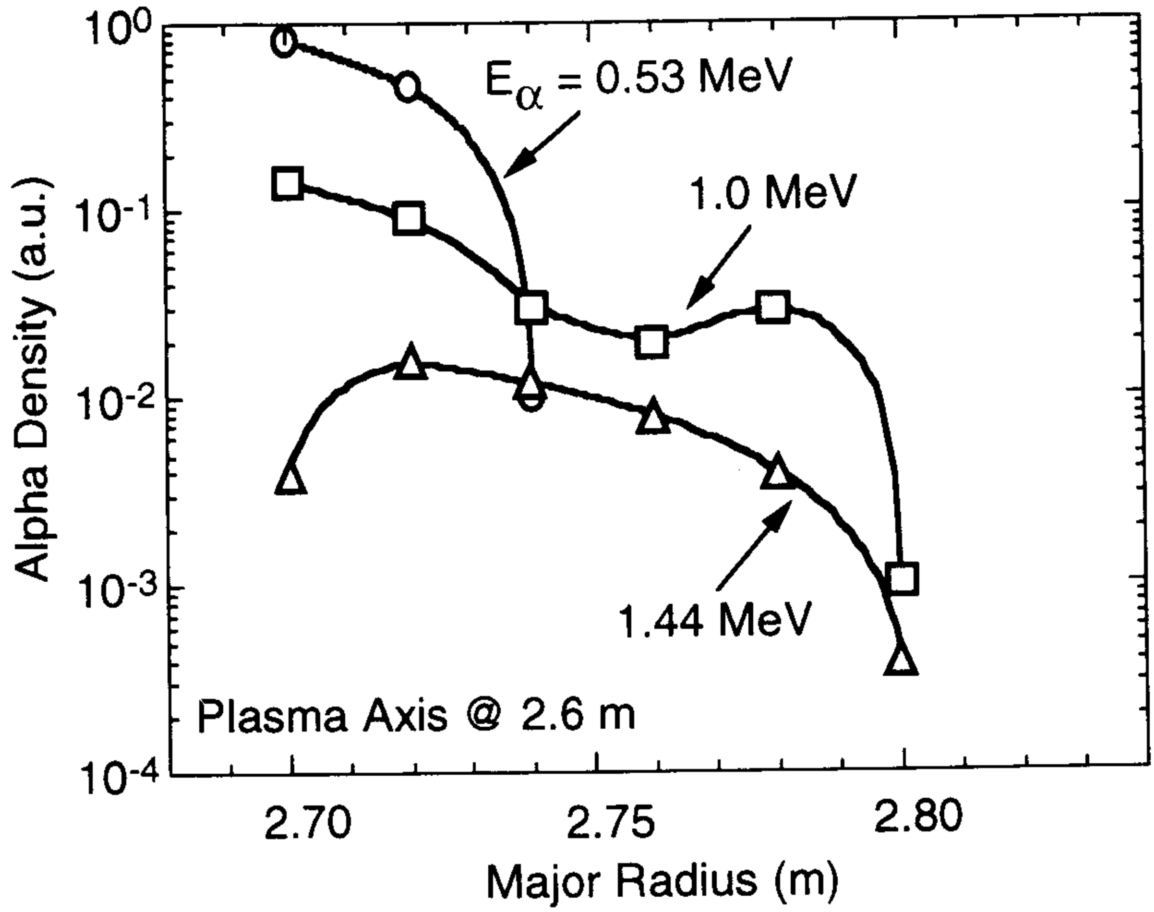
- Density fluctuation level measured by microwave reflectometer
- n=2 mode anomalous:
  - below calculated TAE gap at r/a=0.35
  - highly core localized: $\tilde{B}/B \approx 2 \times 10^{-9}$ outside plasma

Internal Measurements Confirm Core Localization of Alpha-TAEs



- Mode detected by microwave reflectometer
- Peak mode amplitude vs. cutoff layer position indicates core localization and narrow width of n=4 mode

PCX Indicates Redistribution of Trapped Alpha Particles in Presence of TAE Modes



- PCX diagnostic detects deeply trapped alphas on inner leg of their banana orbits
- Broadening is most evident in higher energy alphas
- Pitch-angle scattering "fills in" radial profile of alphas at lower energy

M. Petrov, S. Medley

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
  - $2\omega_T$ 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!