TFTR: What We Learned and Yet May Learn

M.G. Bell

Princeton Plasma Physics Laboratory[1]

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Astrophysical Sciences 558

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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

TFTR

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_φ, v_θ

- 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. (α-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)

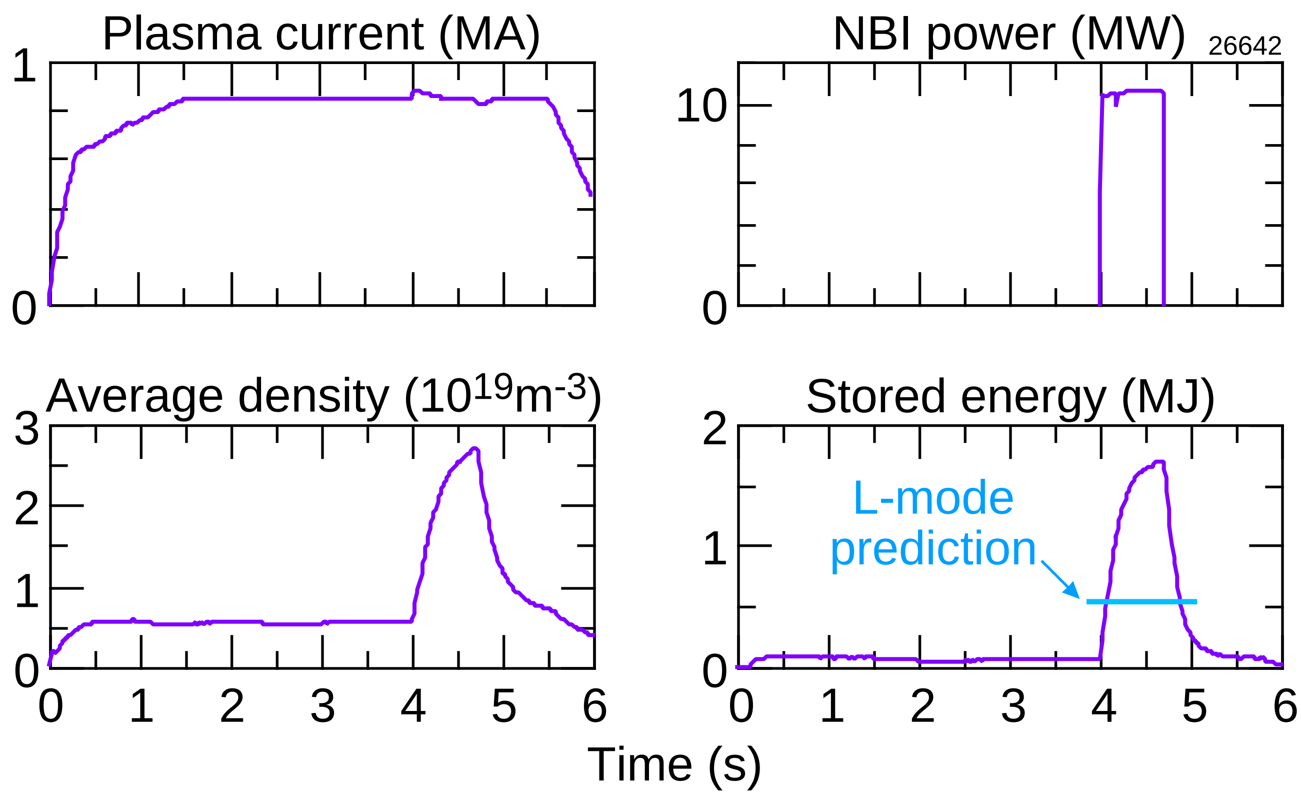
Tokamak Physics in 1983

- 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 β-limits
- Compressional heating (transient)
- Global confinement scalings:
  - "Alcator" scaling for ohmic heating (density)
  - L-mode scaling for NB heating (τ_E $I_p P_h^{-1/2}$): 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

TFTR

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

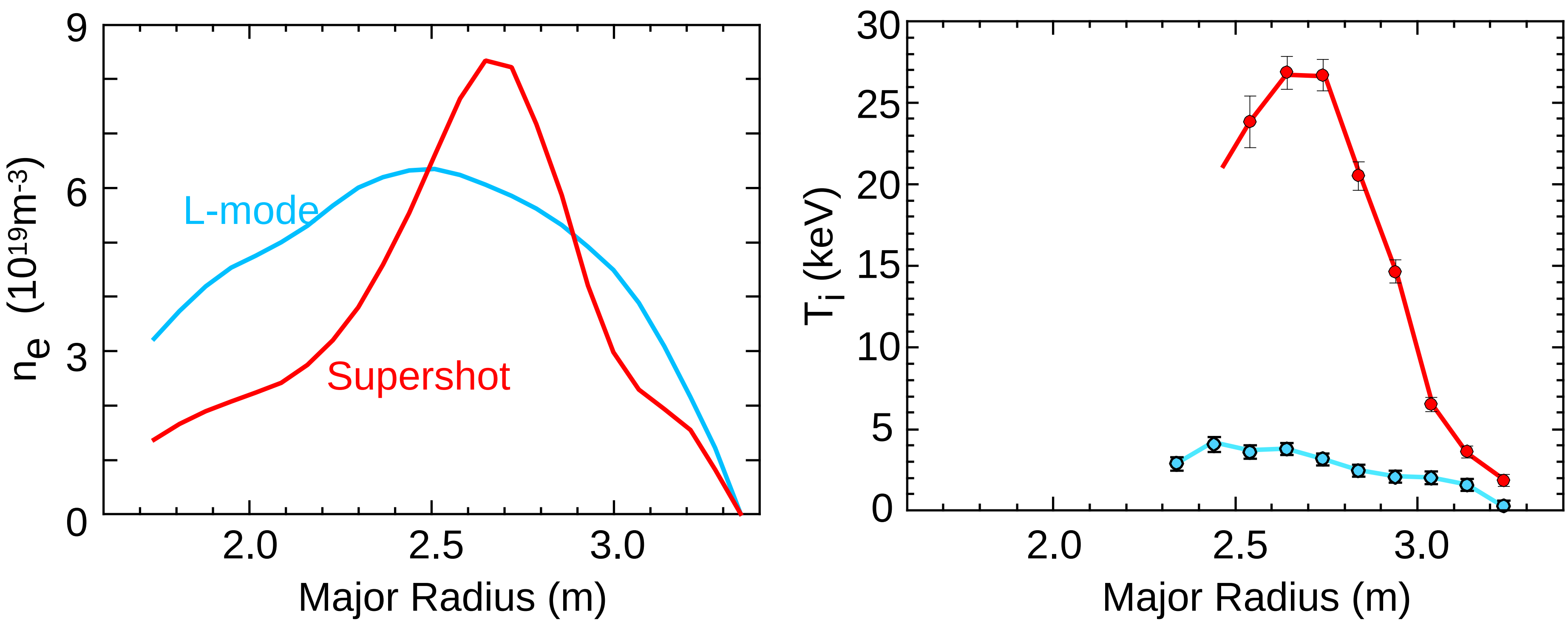


- Subsequently developed additional techniques, including wall coating, to reduce influx from limiter extended supershots to 2.7MA, 40MW
- Supershots are reliable, reproducible vehicles for studying high-temperature plasma phenomena and fusion physics

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

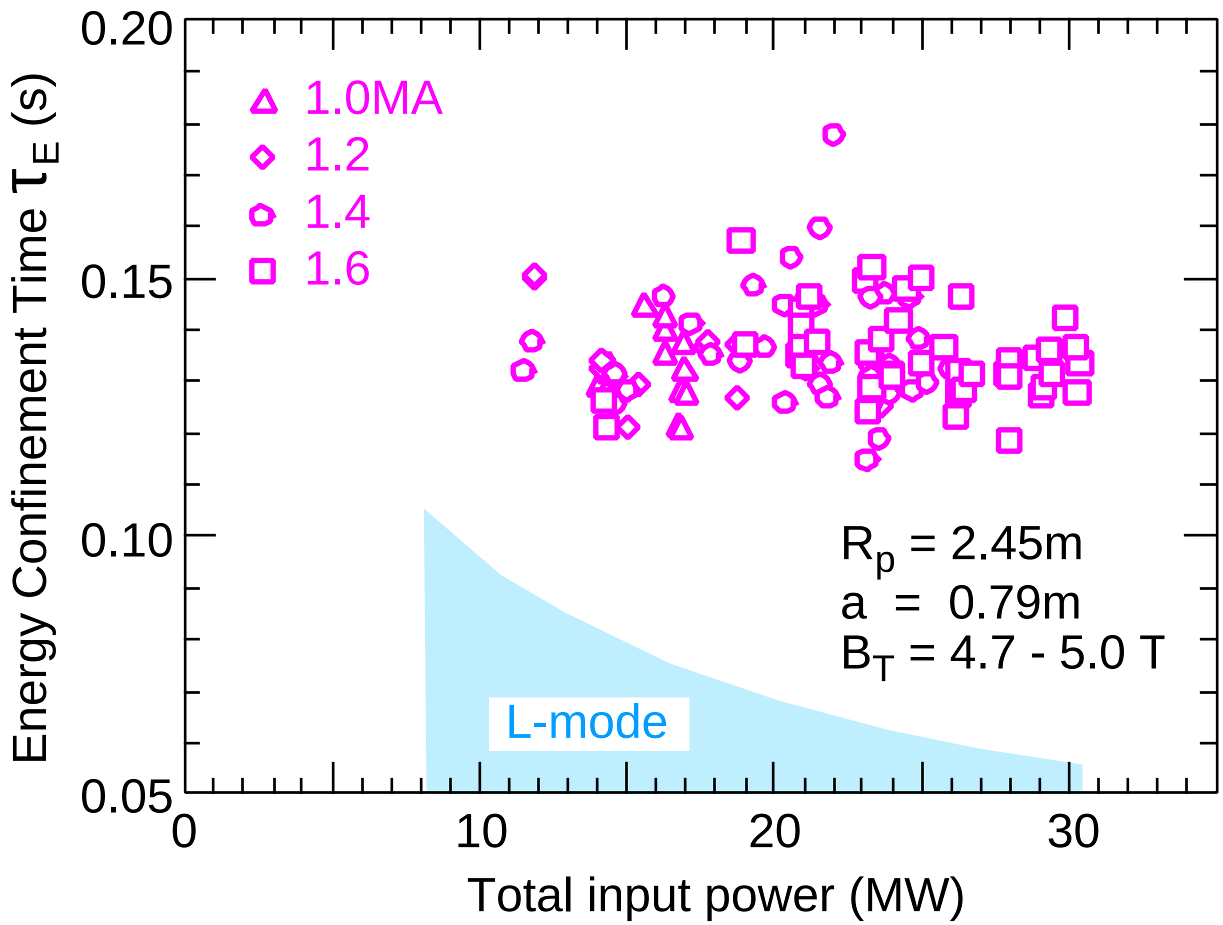
$n_e(0)T_i(0)\tau_E = 0.15 \times 10^{20}$ m^{-3} keV s

Supershot:

τ_E = 0.18 s

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

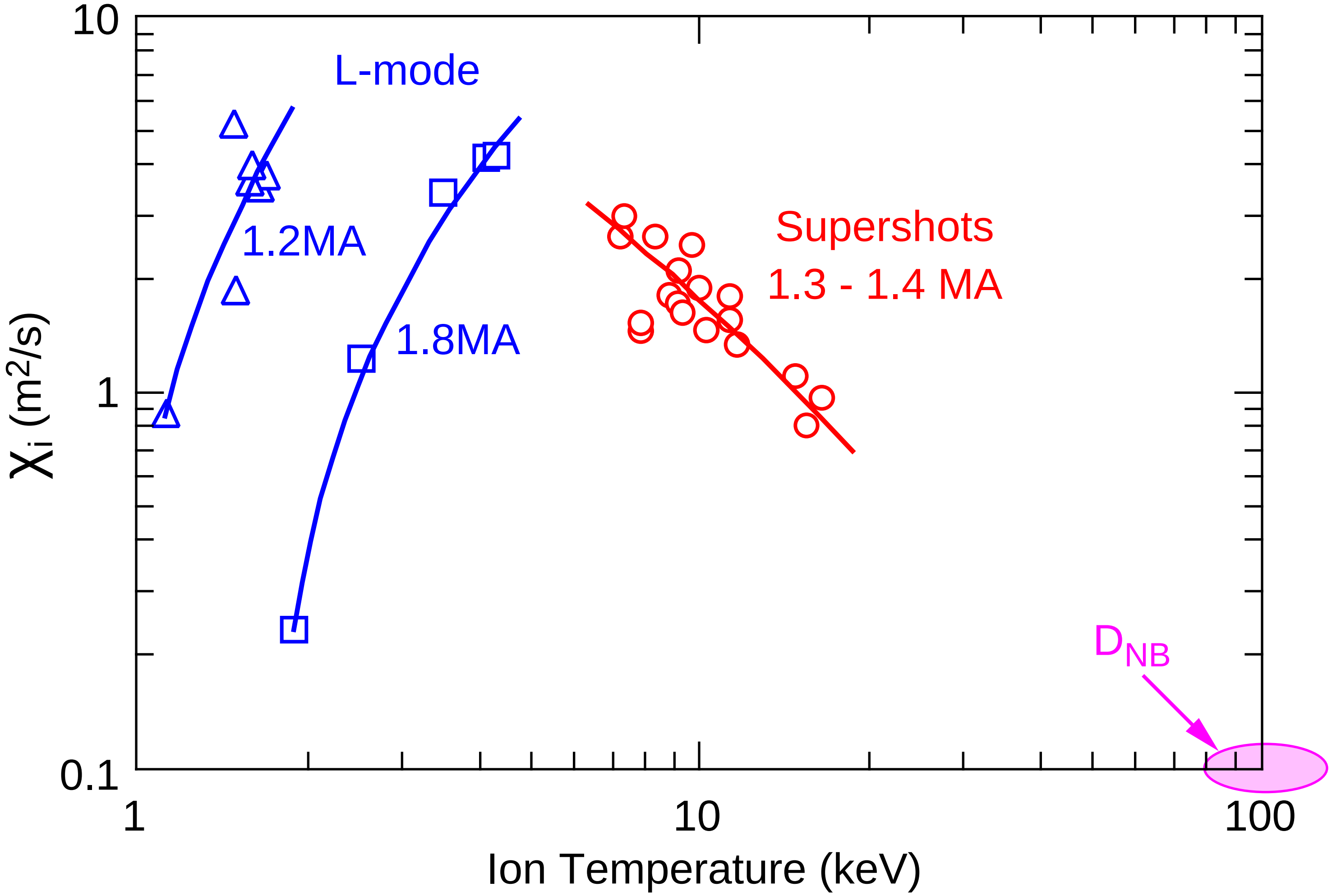
Supershots Did Not Follow L-mode Empirical Scaling



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

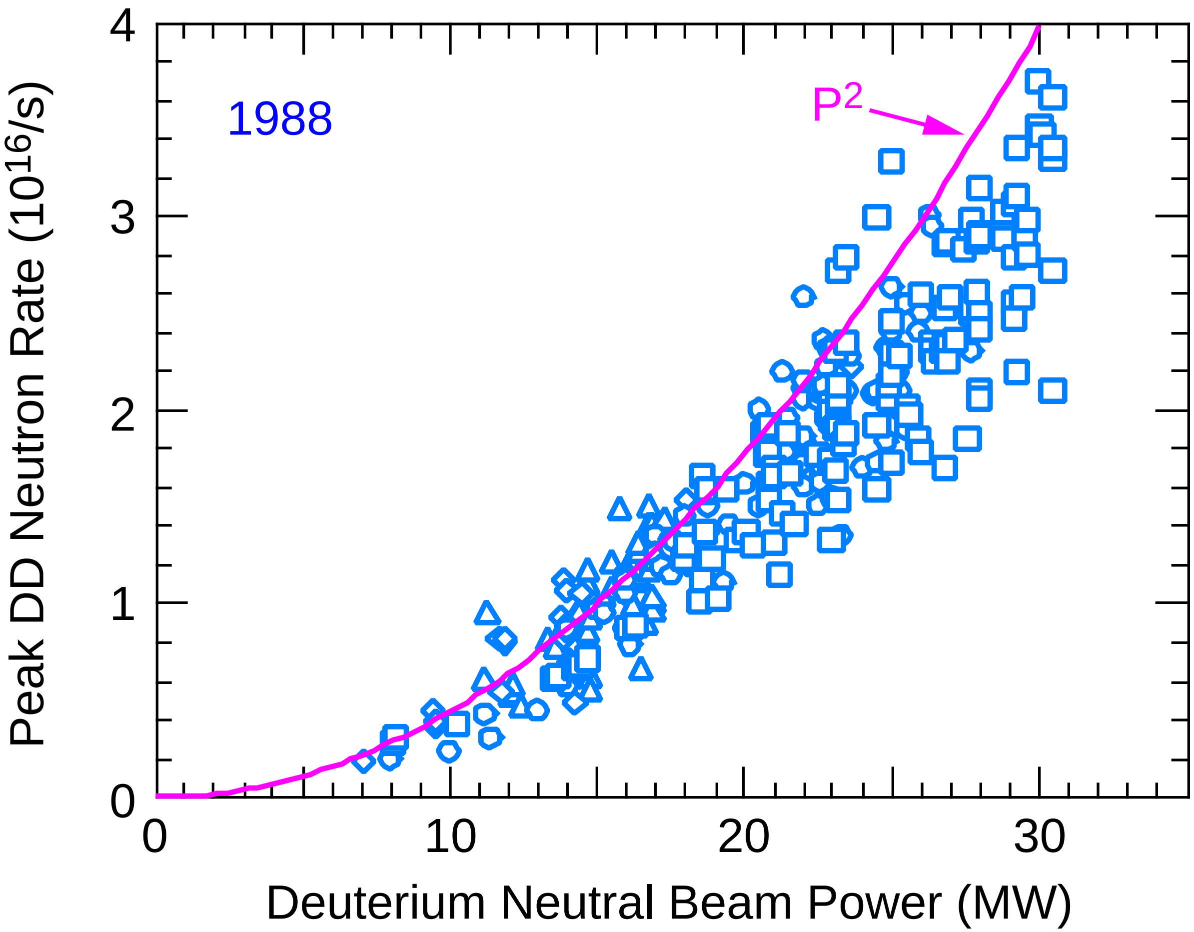
Supershots Exhibited Decreasing Ion Thermal Diffusivity with Temperature



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

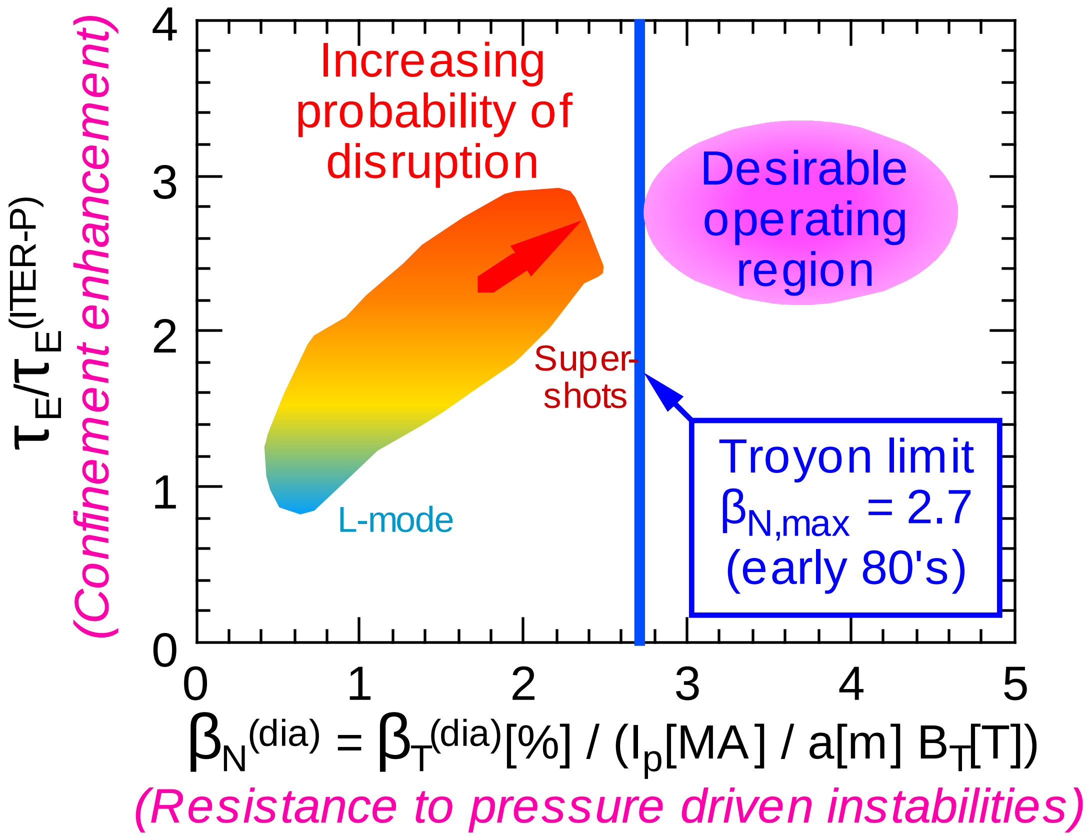
DD Fusion Reactivity Also Scaled Favorably in Supershots

TFTR



- 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



- Improving confinement by peaking pressure profile reduced plasma stability

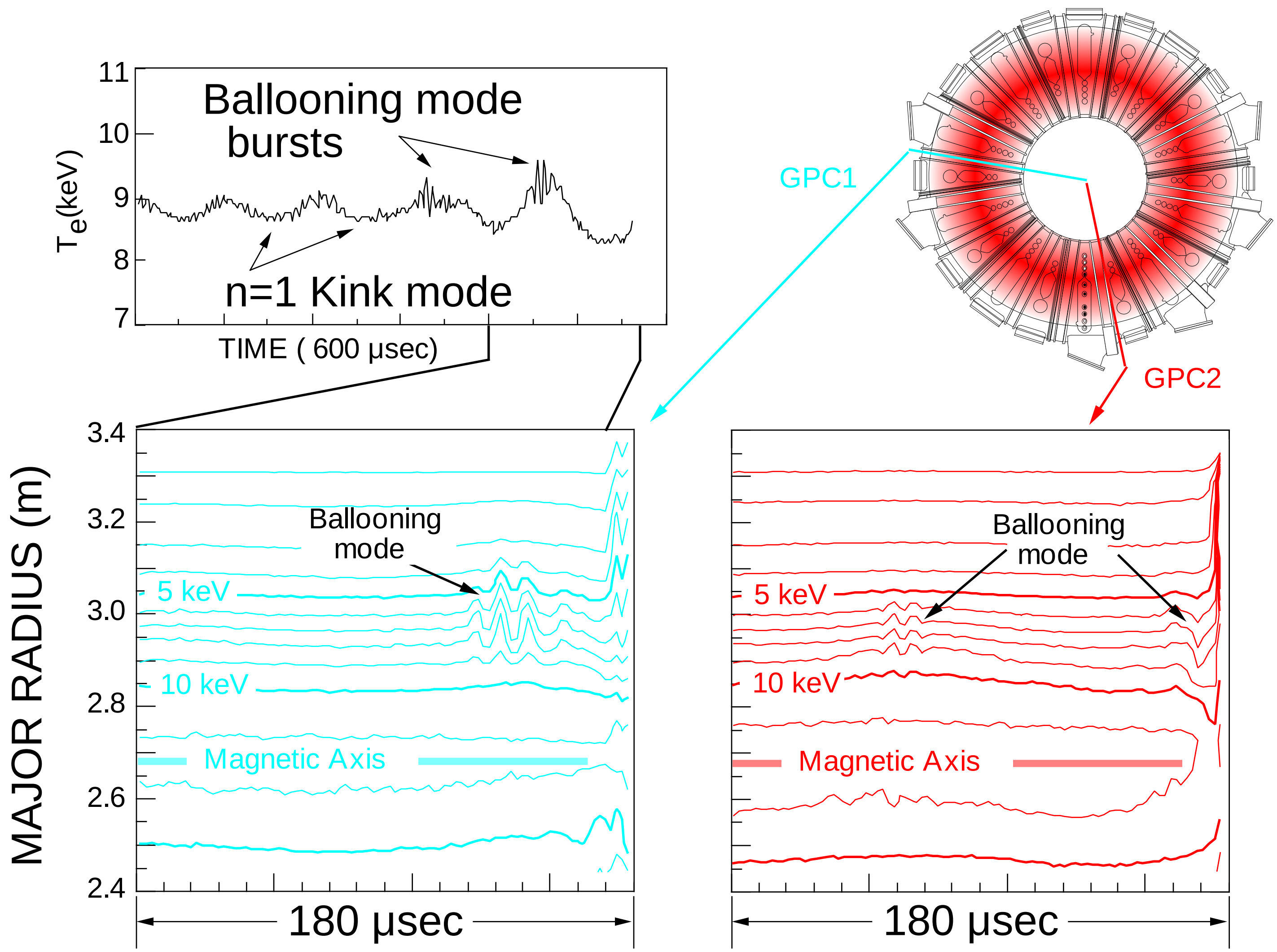
  fast β-limit disruptions at high field (ideal MHD modes)

- 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

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

TFTR

Reversed-shear

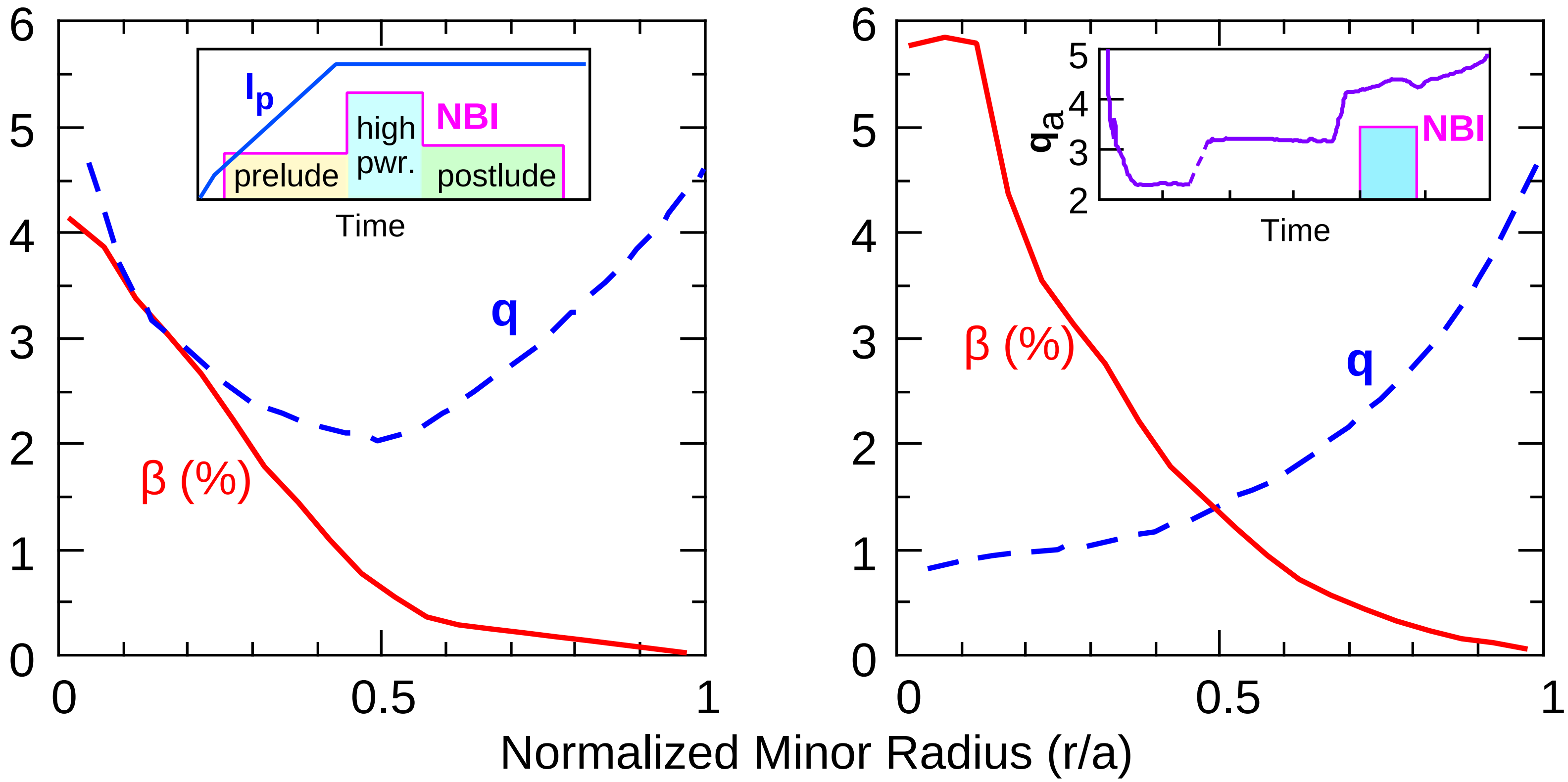
$\tau_E = 0.23s$

NBI heating during current ramp in large plasma

High-l_i

$\tau_E = 0.23s$

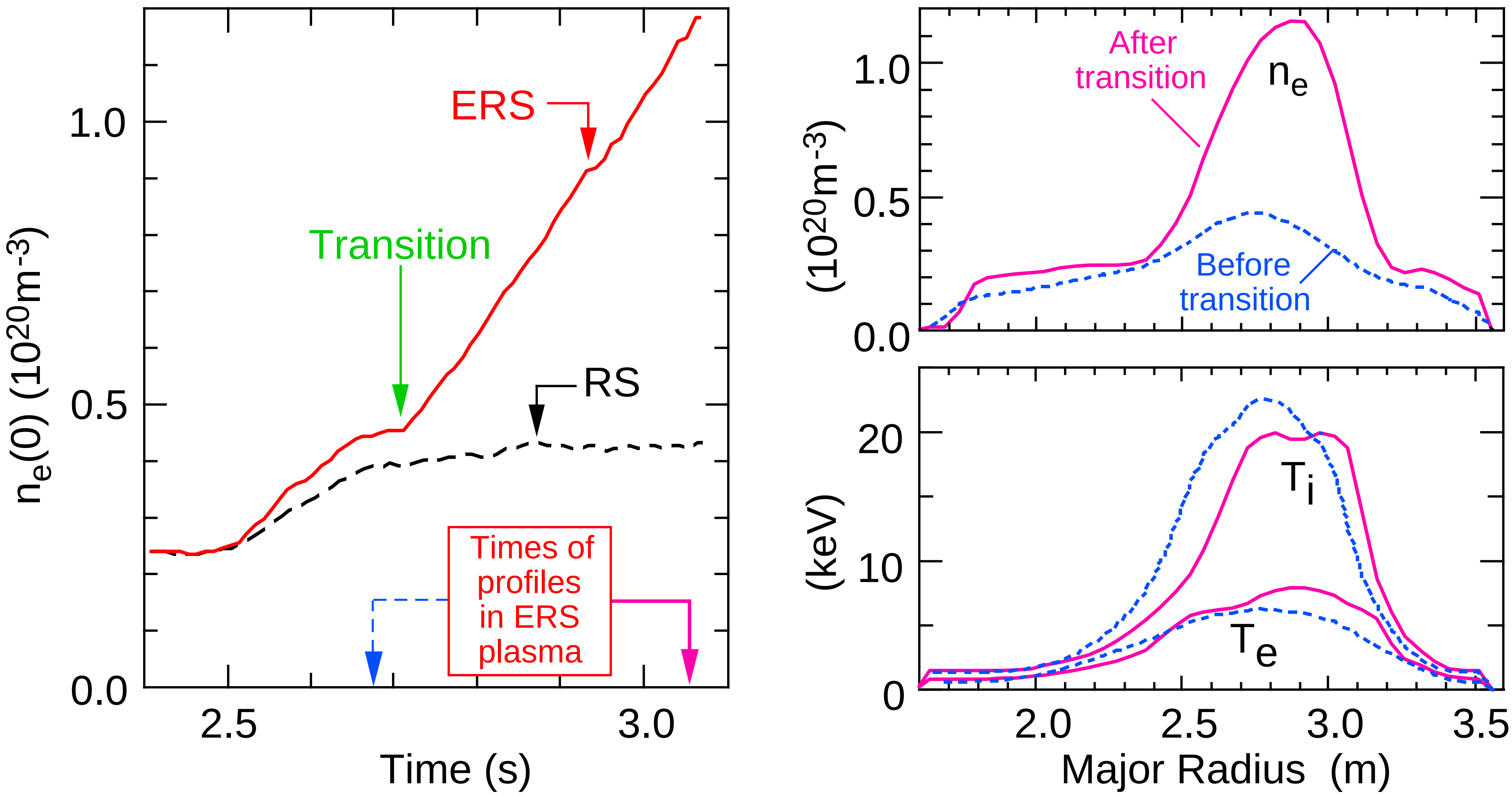
Low-q startup in small plasma followed by expansion



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

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

TFTR

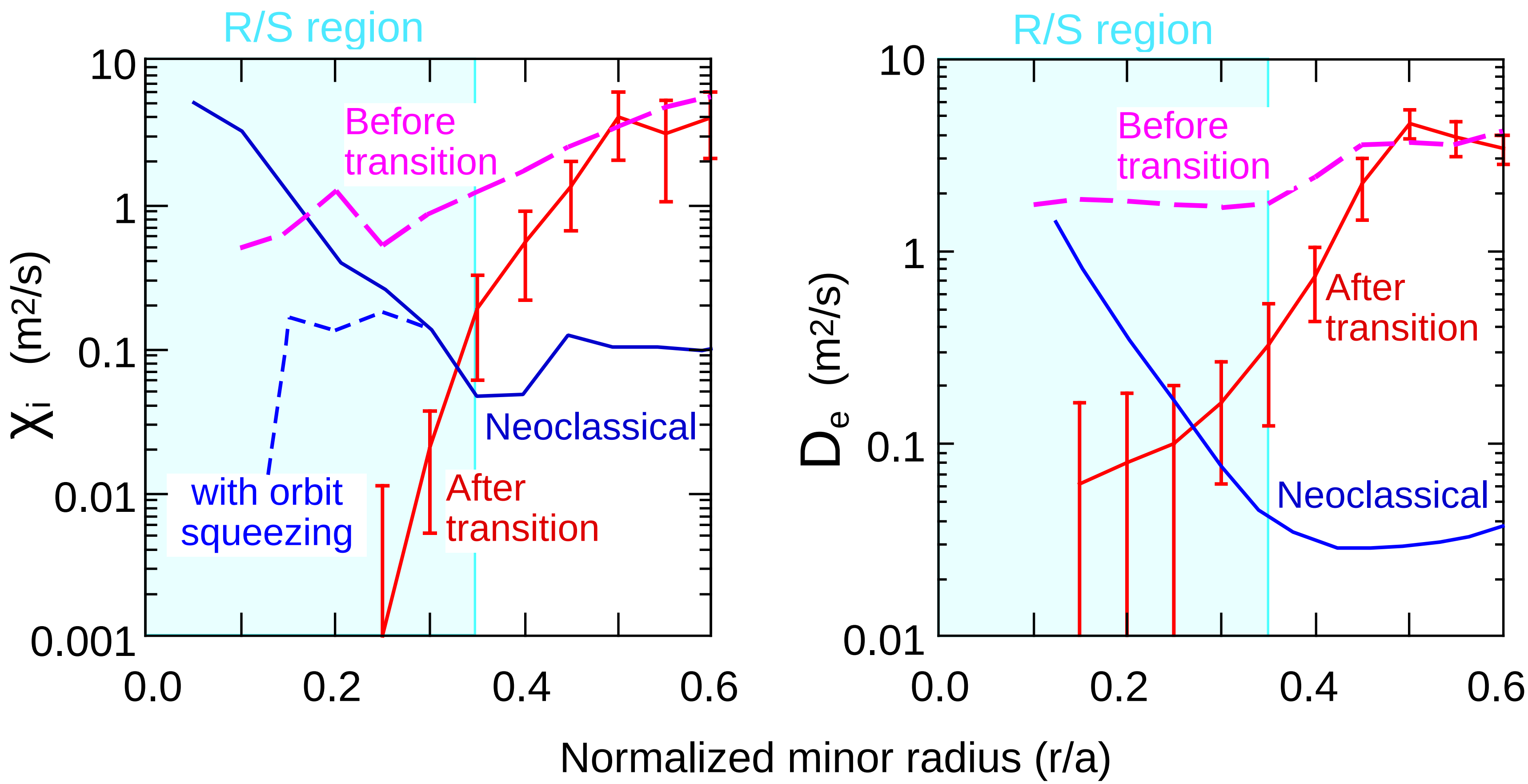


- **RS** - Similar to supershots: low χ_e, χ_i
- **ERS** - Reduced D_e, D_i, χ_i
  - turbulent fluctuations suppressed within "transport barrier"

T97096

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

TFTR



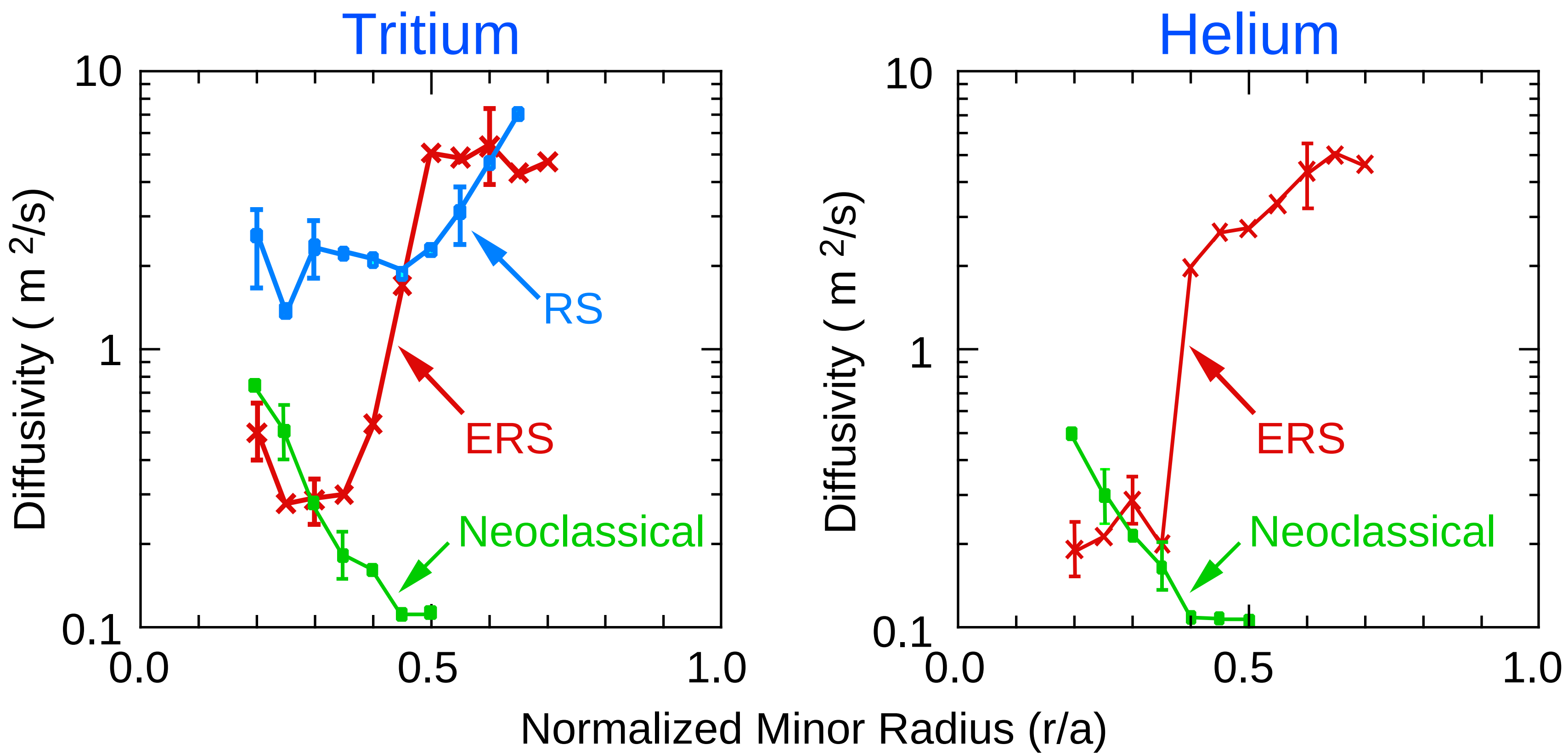
- Flux balance effective χ, D: $q \equiv -n\chi \quad T$ and $\Gamma \equiv -D \quad n$
- Neoclassical calculation includes off-diagonal contributions
- Orbit squeezing effects from Shaing *et al.* [Phys. Plasmas **1**, 3365 (1994)]

M. Zarnstorff

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Particle Diffusivities for Trace T and He Approach Neoclassical Levels at ERS Transport Barrier

TFTR



- 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 $|v_r| < 3$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)

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

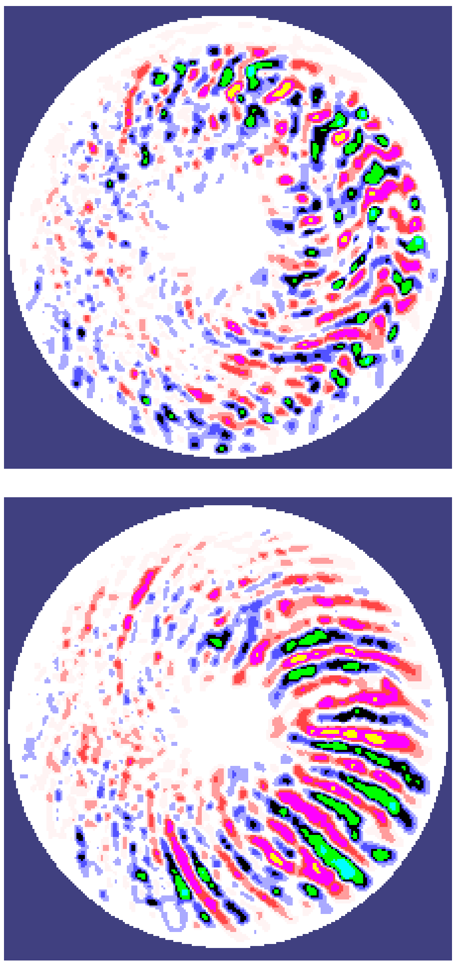
TFTR

Gyrokinetic Simulations

- Turbulent eddies disrupted by strongly sheared plasma flow

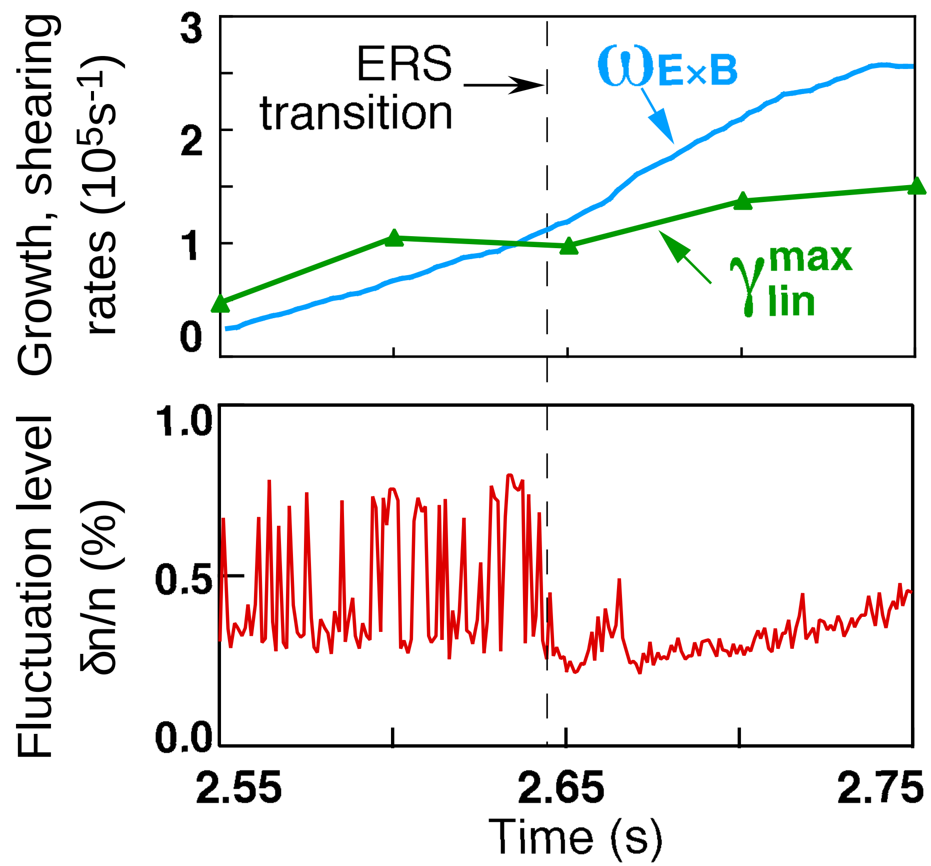
With Flow

Without Flow



Experiment

- Bursts of fluctuations are suppressed when **E×B** shearing rate exceeds growth rate of most unstable mode



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

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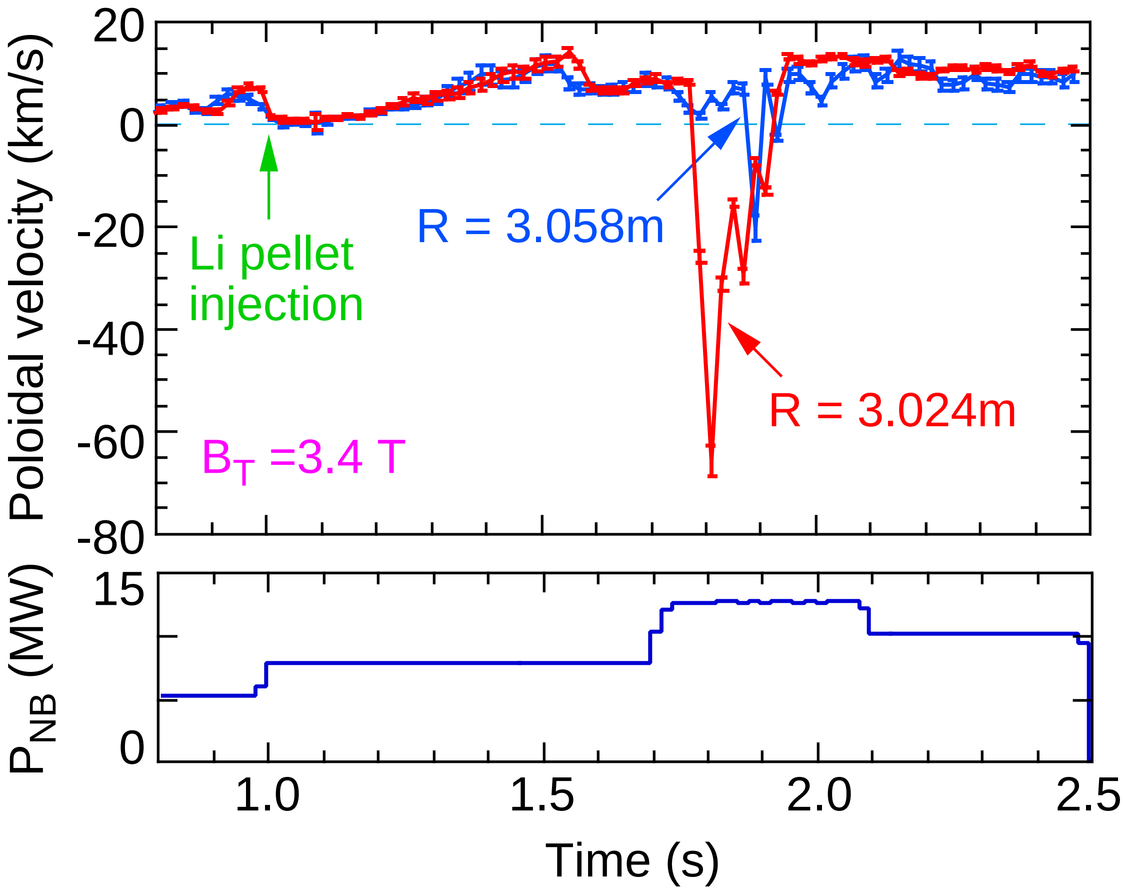
Large Transient Excursion in Poloidal Velocity Measured Prior to ERS Transition

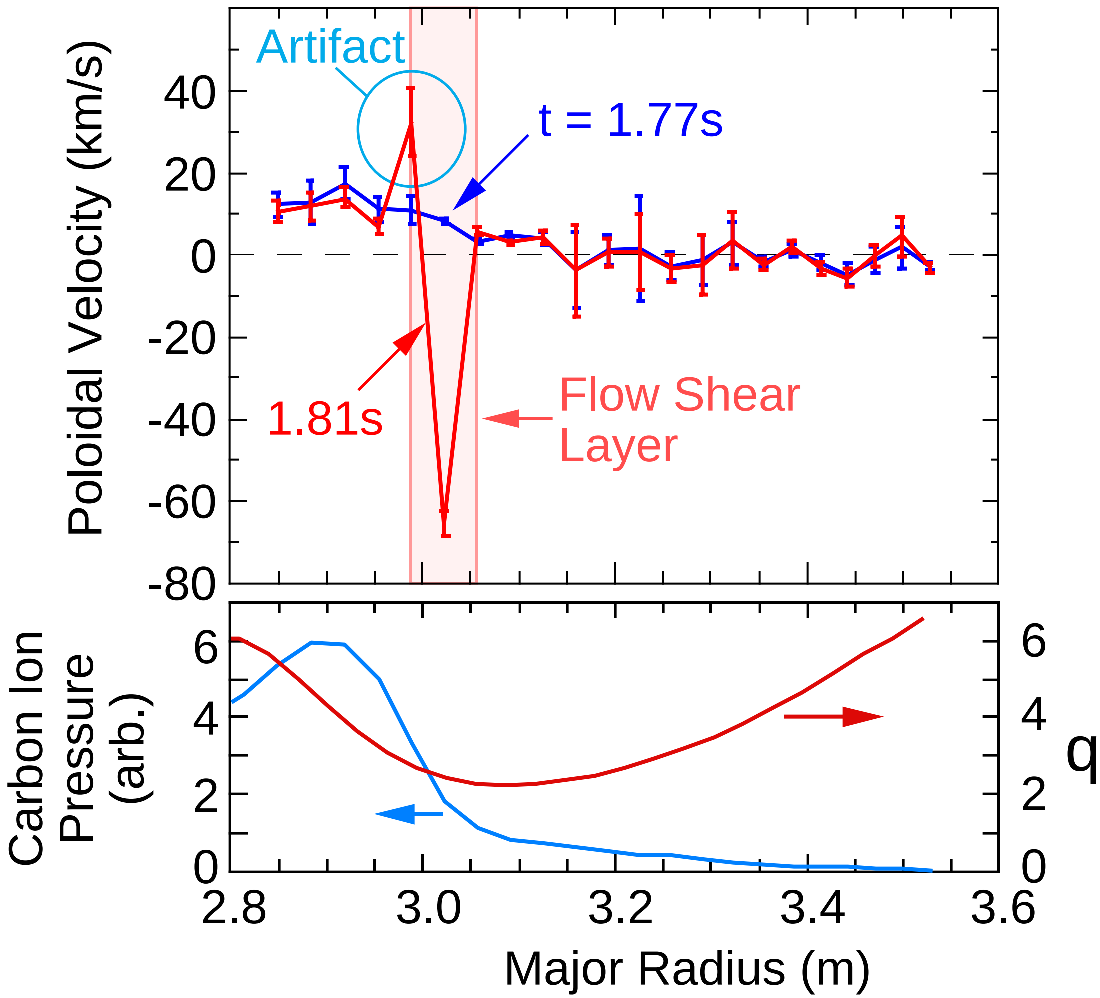


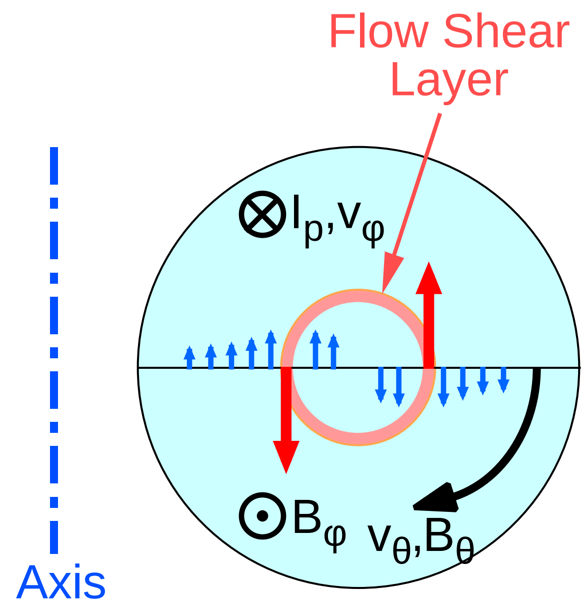
- Occurs in most *but not all* plasmas which make transition to ERS
- Excursion precedes signs of ERS in pressure profile by ~50ms

R. Bell

Narrow Poloidal Velocity Shear Layer Develops Inside q_{min} Surface Prior to ERS Transition

TFTR





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

R. Bell, E. Synakowski

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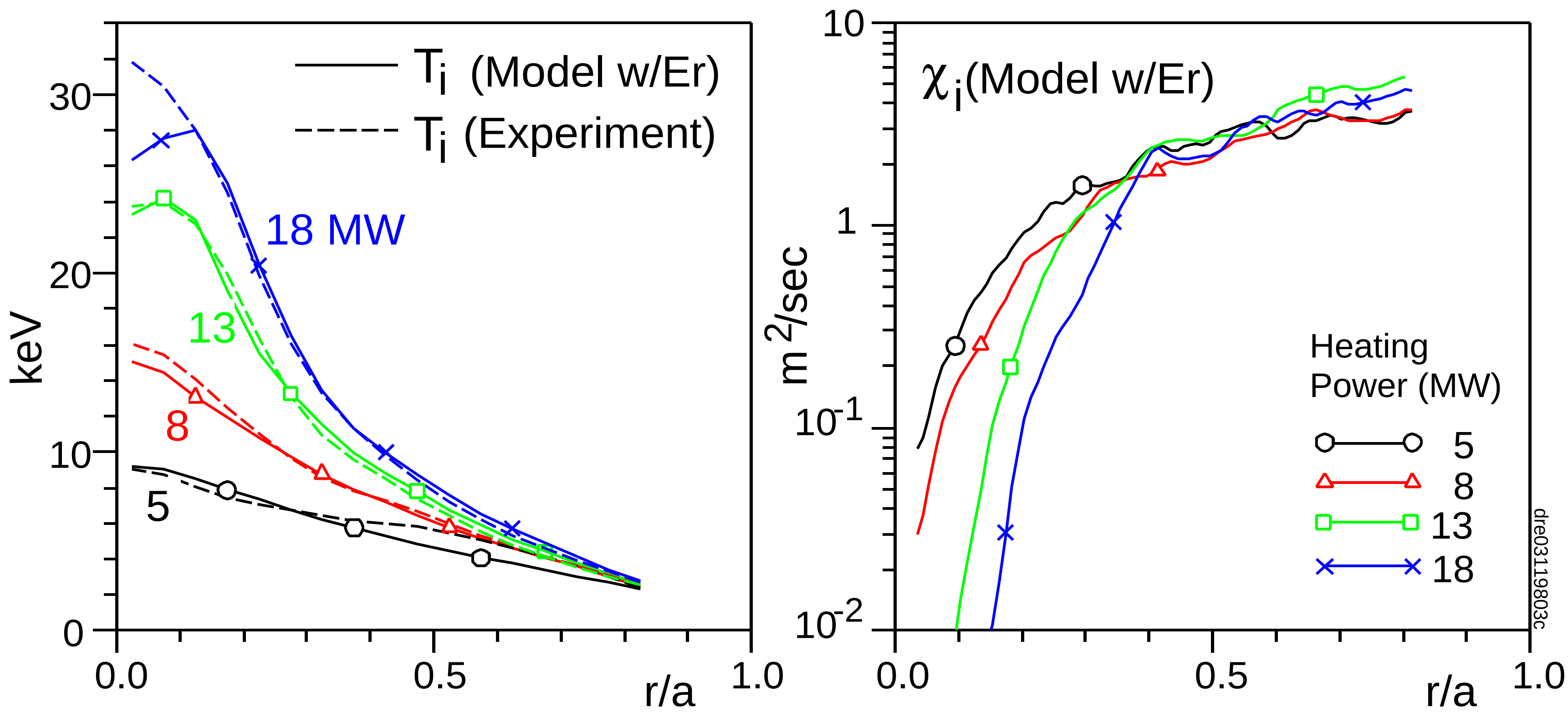
Suppression of Turbulence by Sheared Flow Important in Other Confinement Regimes

- 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 β-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 supppression of ITG turbulent ion thermal diffusivity when $\omega_{E\times B} \simeq \gamma_{lin}^{(IFS-PPL)}$ 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_{fus} = 1.7MW

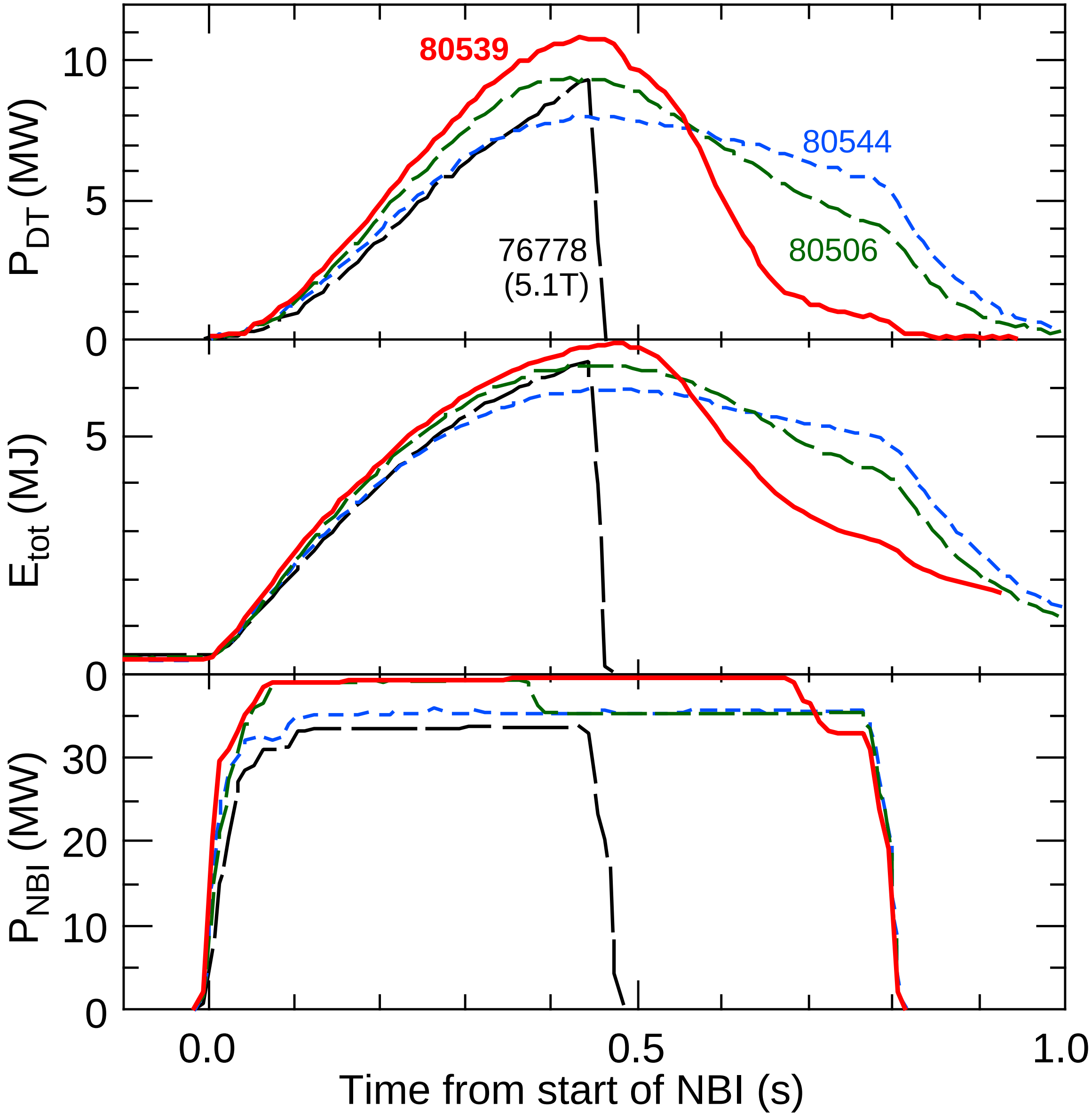
TFTR, December 1993 - April 1994

- 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")

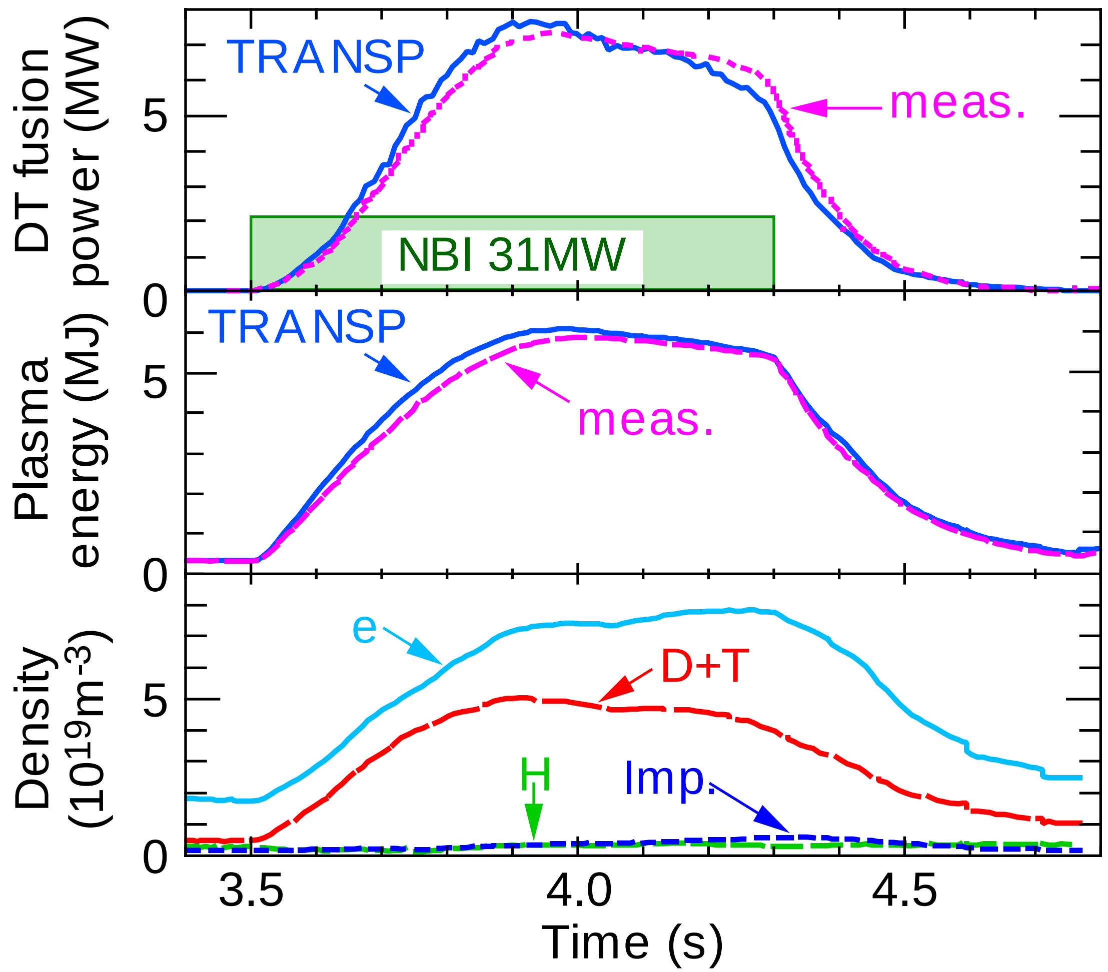
- High reactivity: P_{fus} = 16MW peak; $Q \approx 0.6$
- Prototype operating regimes for ITER
- ICRF physics in D-T plasmas

Supershots Produced High DT Fusion Power, as Expected



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

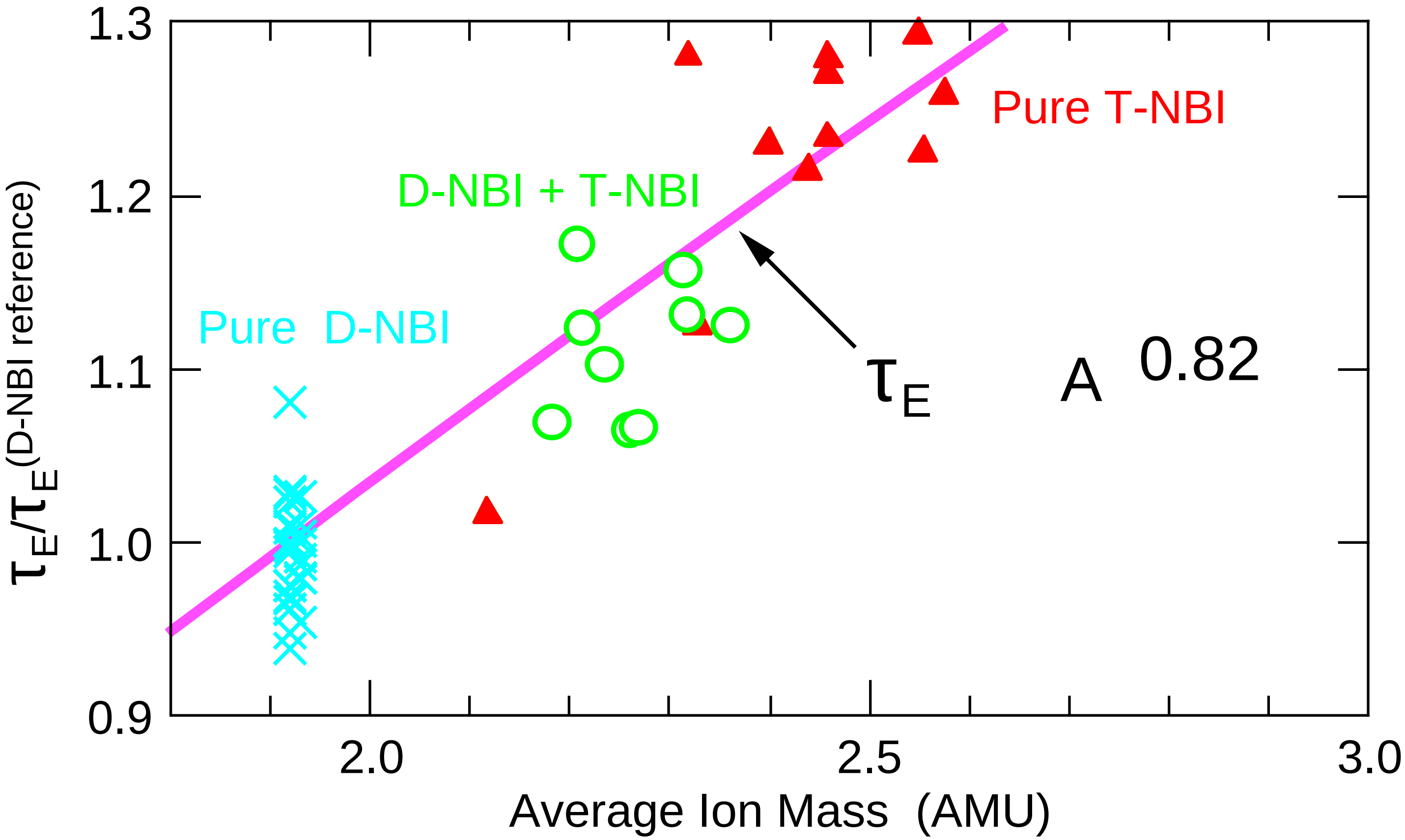
TRANSPORT Code Can Successfully Model DT Reactivity



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

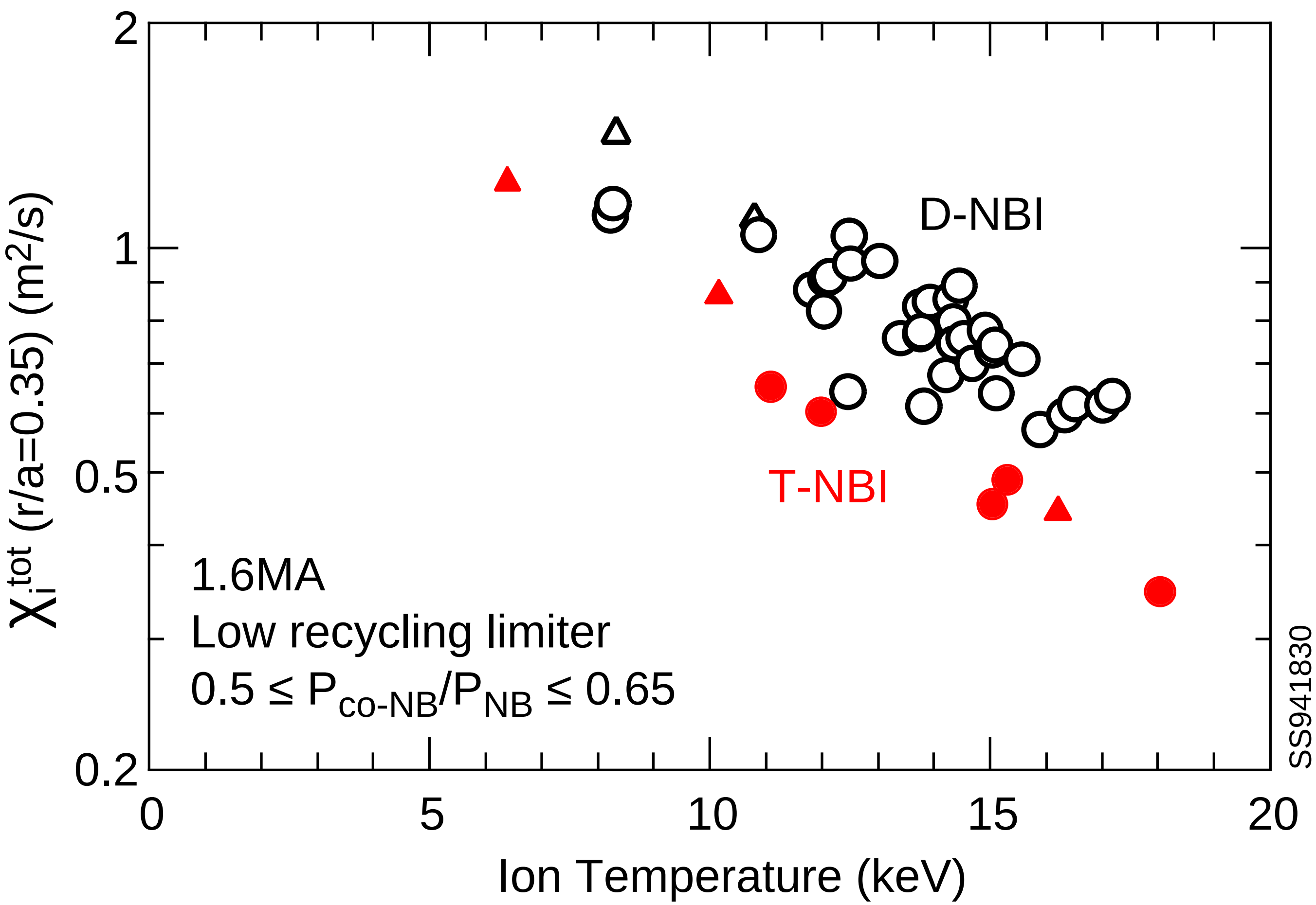
Global Confinement Increases With Tritium NBI

TFTR



- 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

Tritium NBI Extended Earlier Supershot Scaling Results



- 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

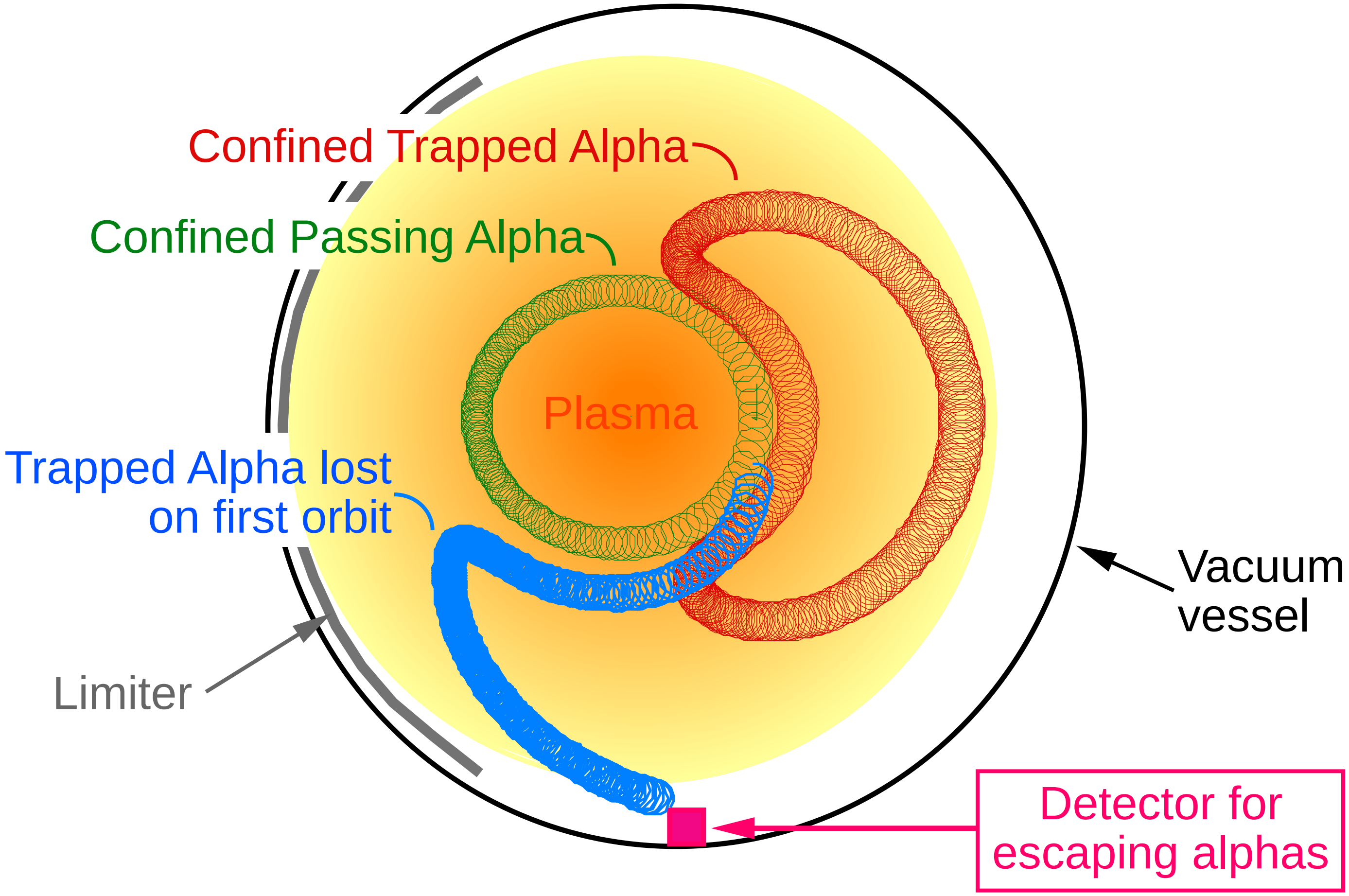
Alpha Particle Orbits in Tokamaks

TFTR

- Alpha particles from DT fusion reactions are born with energy of 3.5MeV

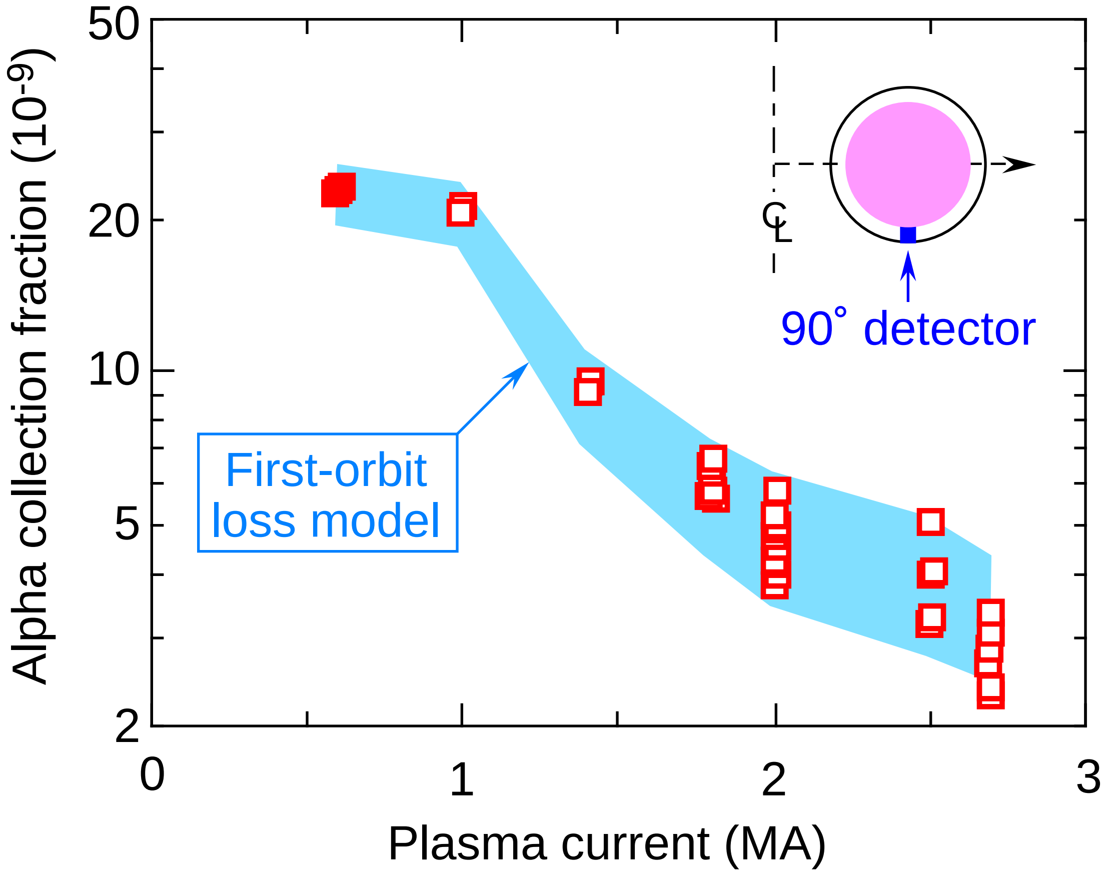
  Larmor radius up to 5cm in TFTR

  Radial excursions of trapped alphas are much larger
- Good confinement of alpha particles necessary for D-T ignition



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

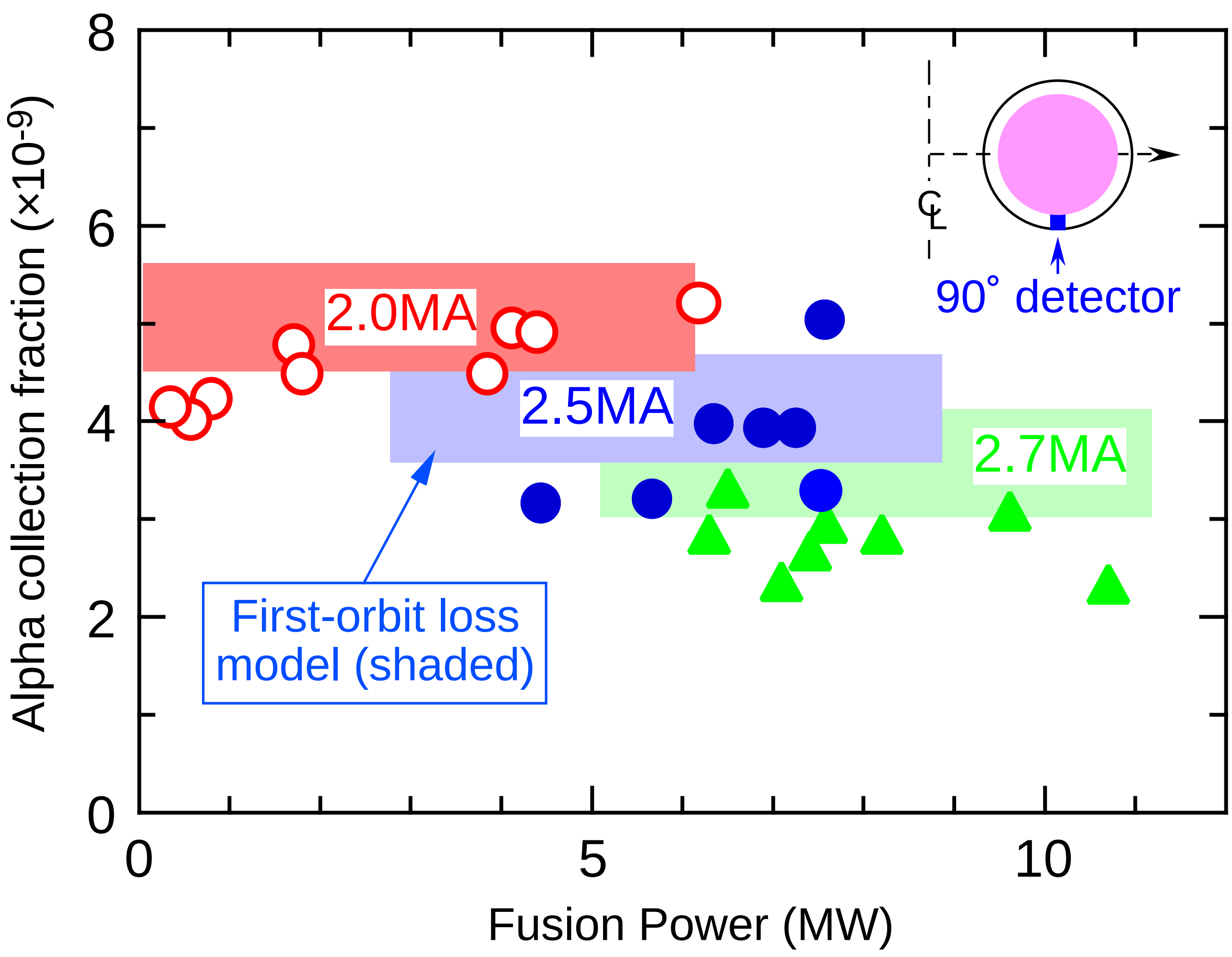


- Shaded region shows result from an orbit-following code based on TRANSP calculations of alpha-particle birth and current profiles.
- At 2.5 MA, ~3% of alphas are lost on first orbit after birth

S. Zweben
D. Darrow

Alpha Loss Fraction does not Increase with Fusion Power

TFTR

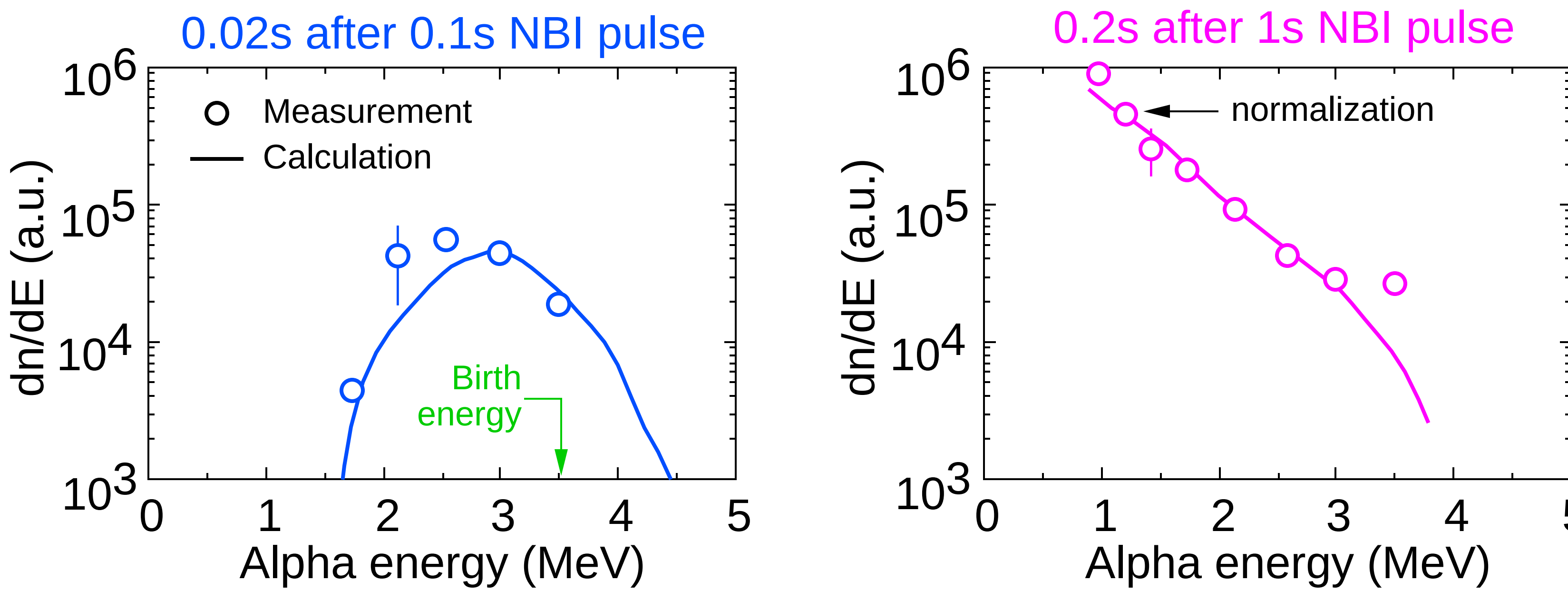


- Data for MHD-quiescent phases of D-T supershots
- No indication of loss processes driven by alpha-particles themselves

Measurements Confirm Classical Slowing Down of DT Fusion Alpha Particles

TFTR

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

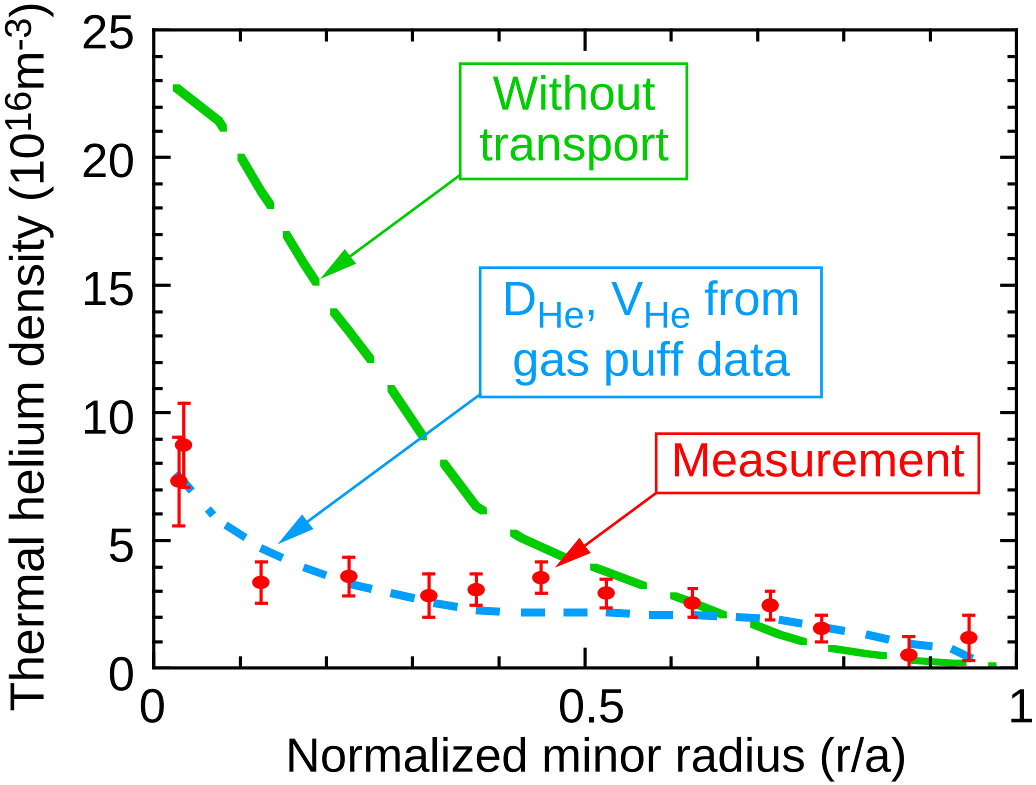


- Calculation with TRANSP/FPPT code based on classical Coulomb collisions using measured plasma parameters
  - alpha-particle velocity slowing time typically 0.5 - 1 s
- High ion temperature and presence of unthermalized NB injected ions results in broadening of alpha spectrum above birth energy

GAT, IOFFE, PPPL Collaboration

Rapid Transport of Thermal Helium Ash from Center to Edge

TFTR



- Charge-exchange spectrometry calibrated against He gas puff
- Data consistent with modelling based on He transport deduced from gas puff experiments
- D_{He} / χ_D ~ 1
- Consistent with $\tau_p^*{}_{(He)}/\tau_E \approx 8$: acceptable for reactors

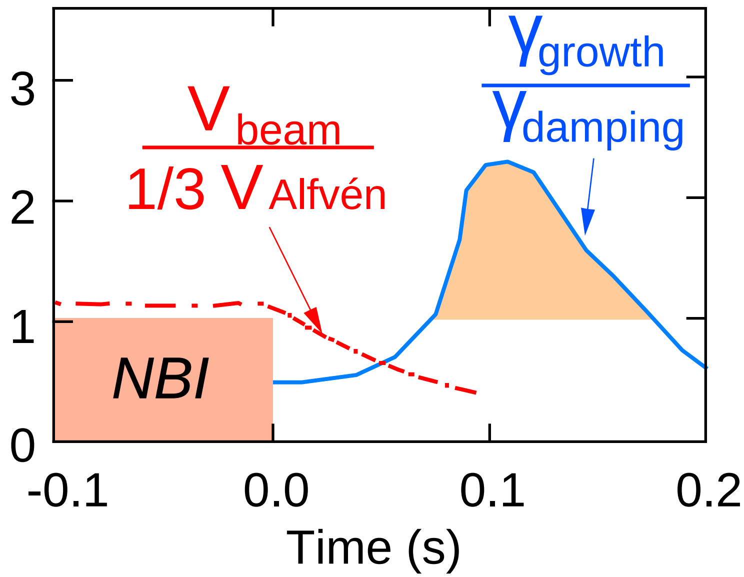
Alpha-Driven Toroidal Alfvén Eigenmodes

TFTR

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

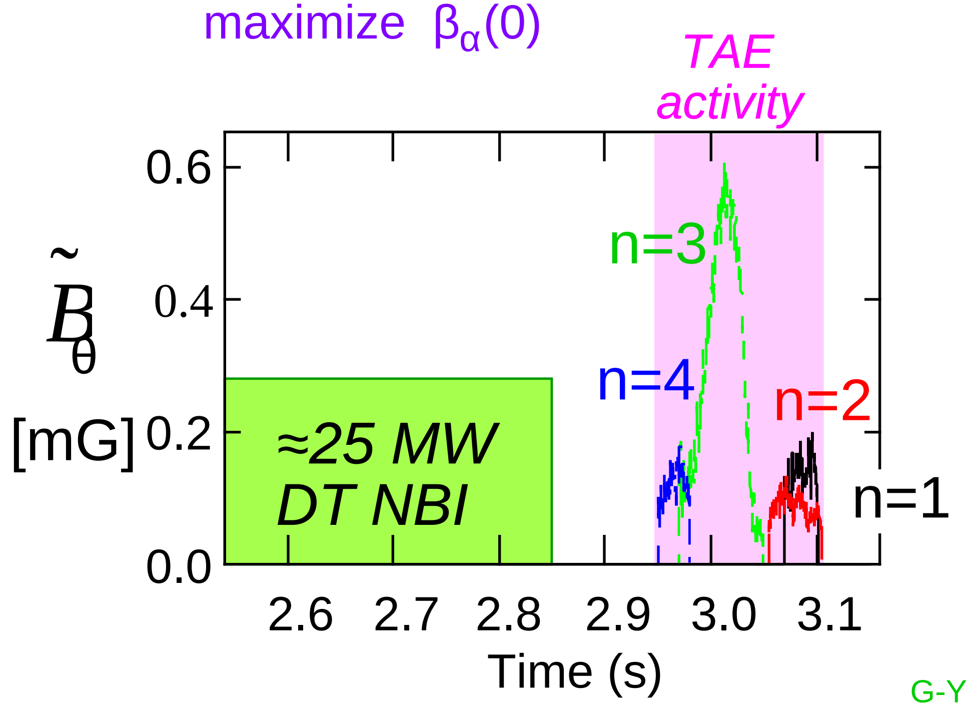
Theory

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



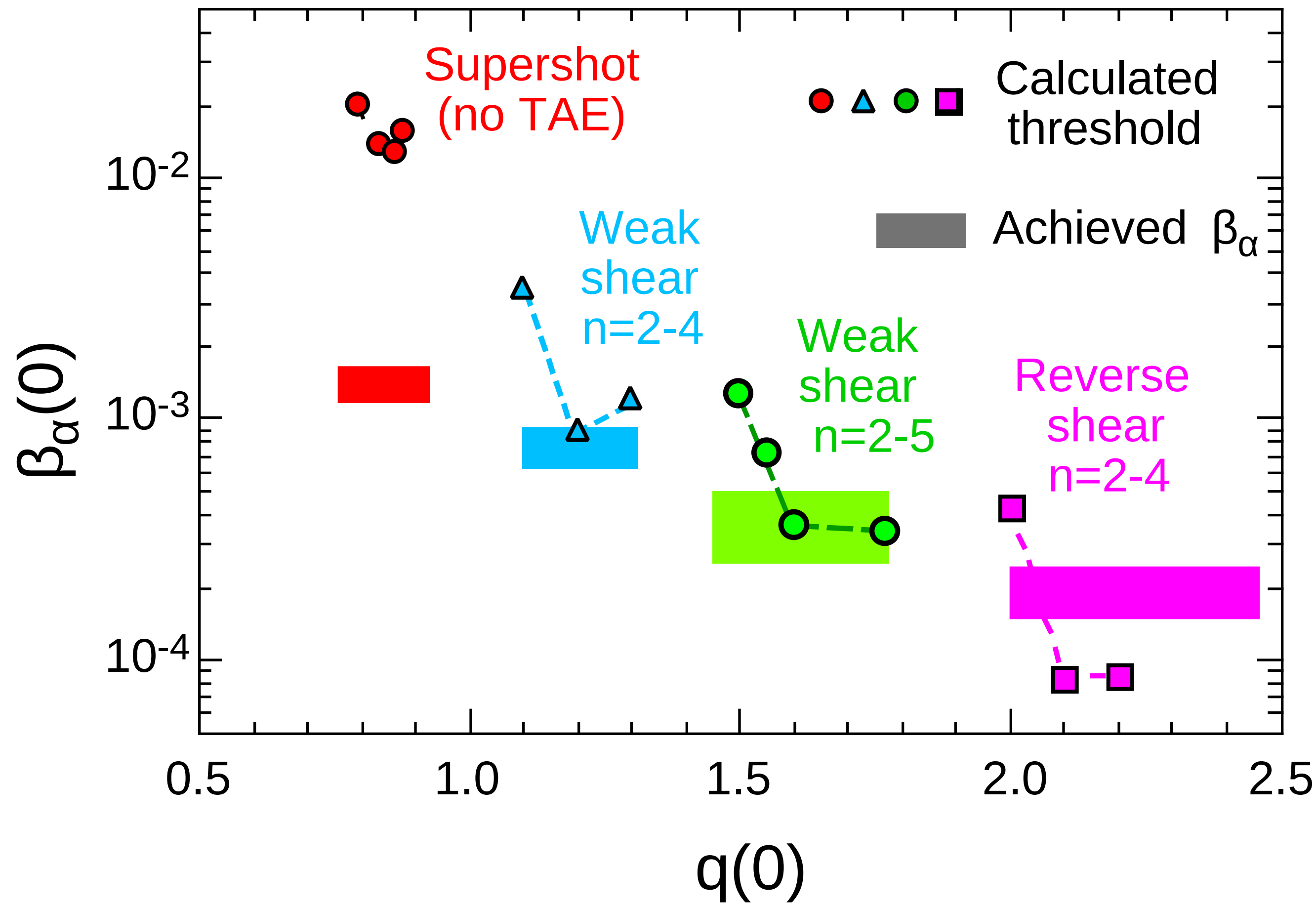
Experiment:

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



G-Y. Fu,
D. Spong,
R. Nazikiar

Observed α-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)
  - $^{1}/_{4}$ of alpha energy thermalizes to ions at $T_e \approx$ 20keV
  - reactivity at fixed β optimizes at higher T_i

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

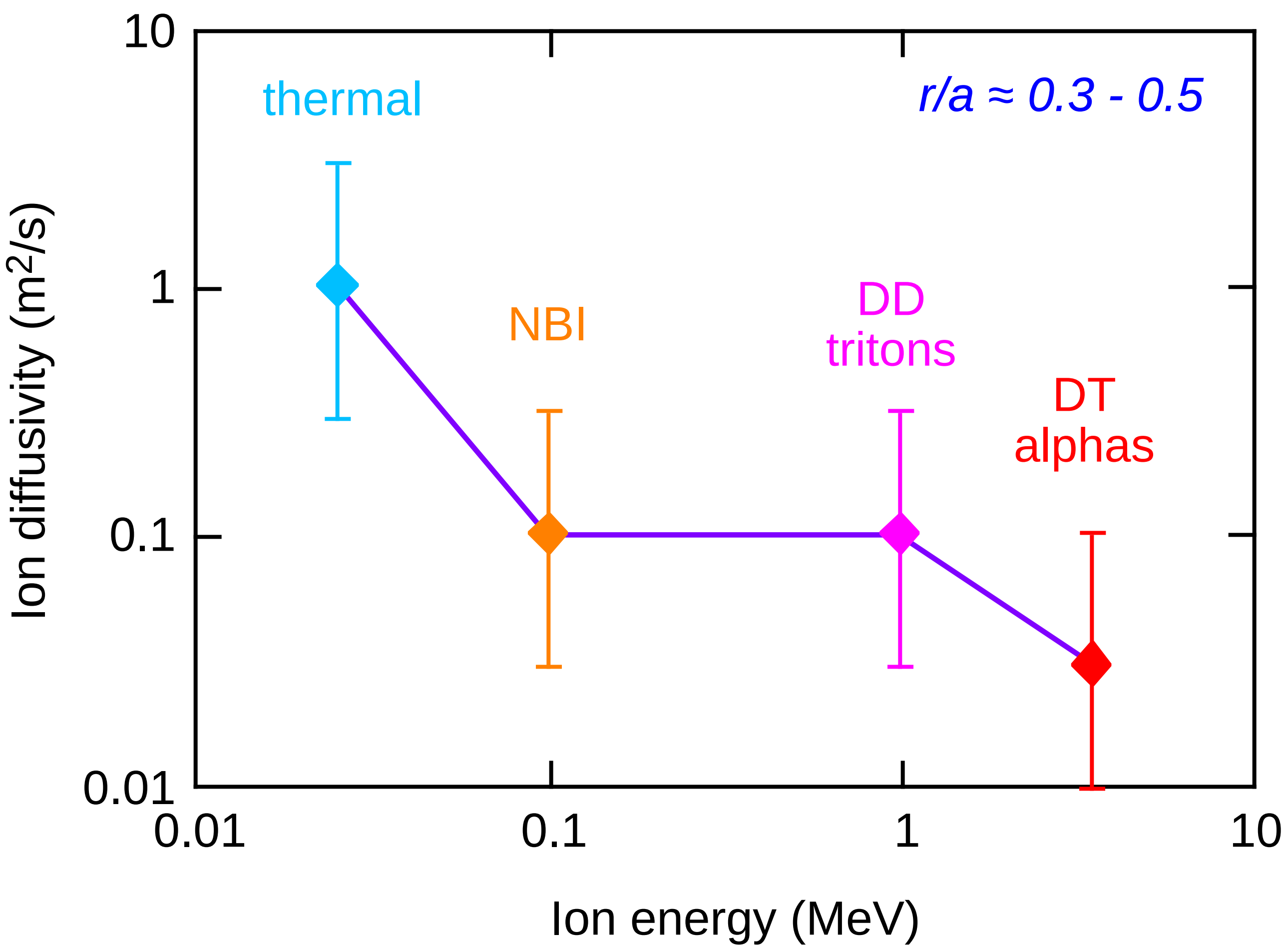
- Tokamaks confine energetic ions extremely well
  - *e.g.* Meade IAEA, IAEA, Washington (1990)
  - $q_{conv,i} < {}^{5}/_{2} \cdot \Gamma \cdot T_i$ implies transport is predominantly of lower energy ions
  - sawteeth stabilized: essential for peaked density
  - operation with q(0) > 1: χ_i reduced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

TFTR



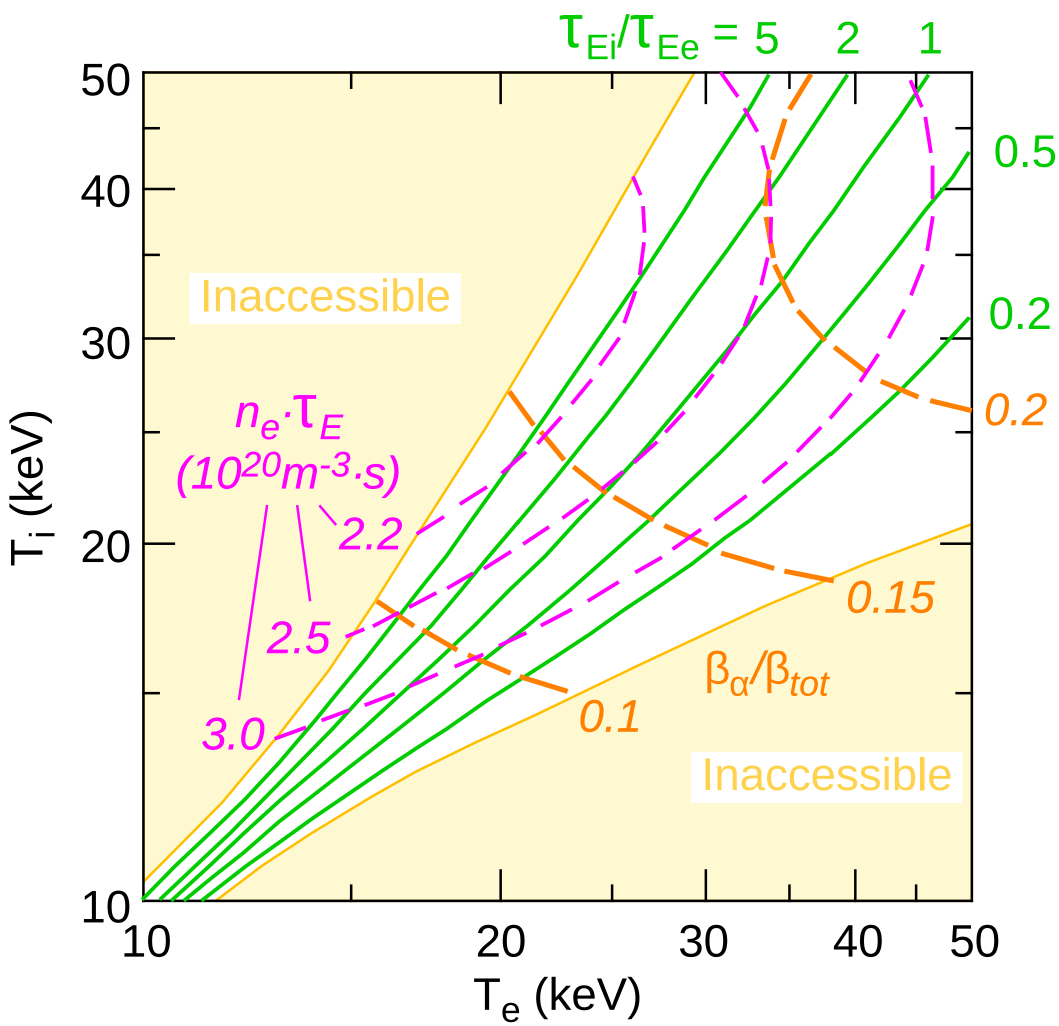
- Consistent with behavior of ion thermal diffusivity in various TFTR regimes
- Suggests that orbits of energetic ions can "average" over turbulence causing anomalous transport

S. Zweben

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Hot-Ion Ignited Plasmas Possible with Good Ion Confinement

TFTR



- 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
  - $n_{DT} : n_H : n_{He} : n_C = 0.80 : 0.05 : 0.05 : 0.01$

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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 β-limit
  - feature of *all* regimes with high fusion reactivity (TFTR, JET, JT-60U; supershots, HIHM, ERS, "optimized shear" *etc.*)
  - β-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