Progress in Tokamak Physics during the TFTR Project

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Research School of Physical Sciences & Engineering

Australian National University

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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.

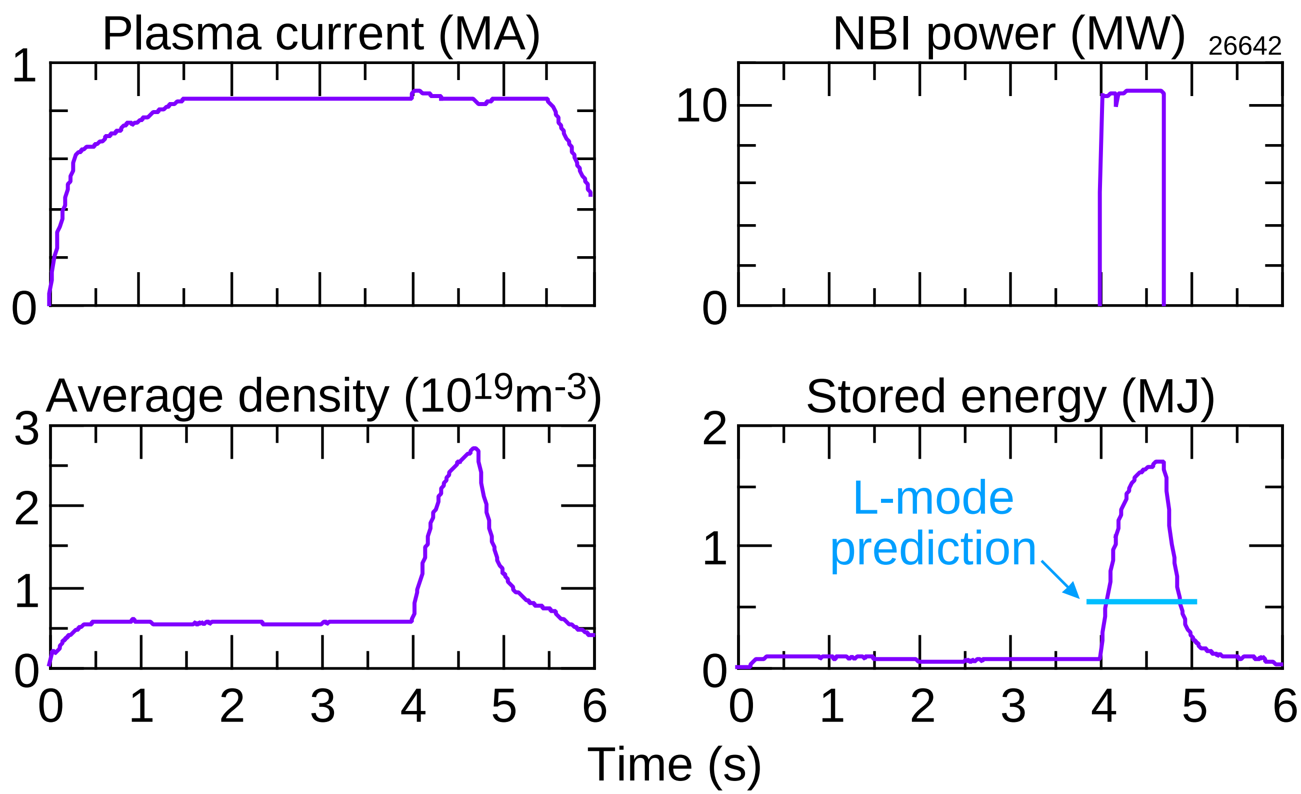
It is intended to show you that high temperature plasma physics has progressed, and can continue to do so, in the tokamak.

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 (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

- 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

$T_e(r)$

- 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

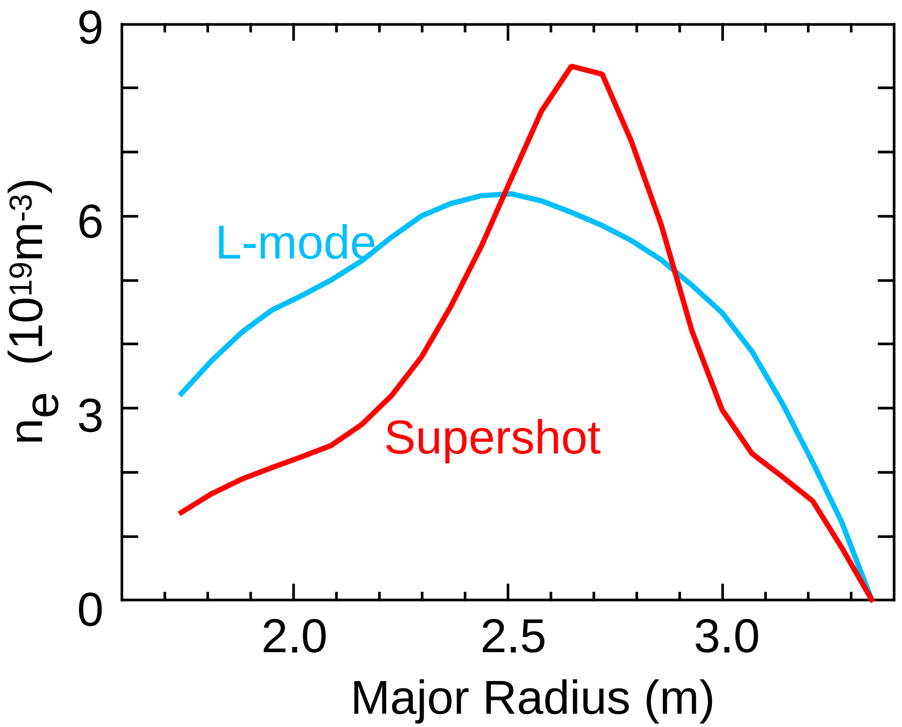
Plasma Edge/Wall

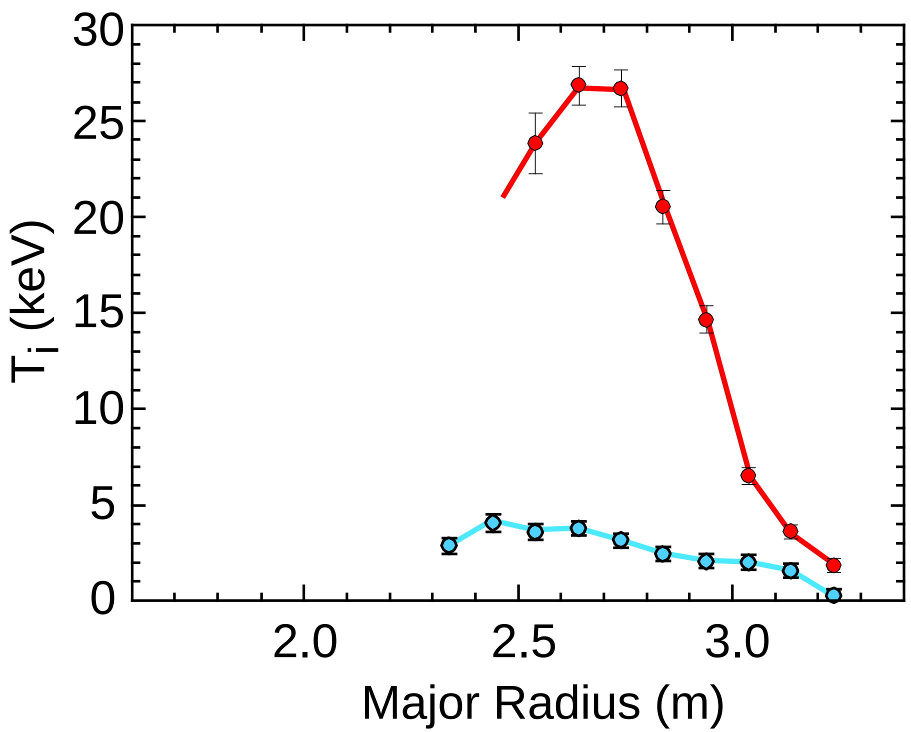
- Plasma TV
- IR Camera
- Filtered Diodes (C-II)
- Filtered Diodes (H-alpha)
- Sample Exposure Probe
- Disruption Monitor (IR Detector)
- Fabry-Perot (H/D/T ratios)

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:

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

TFTR

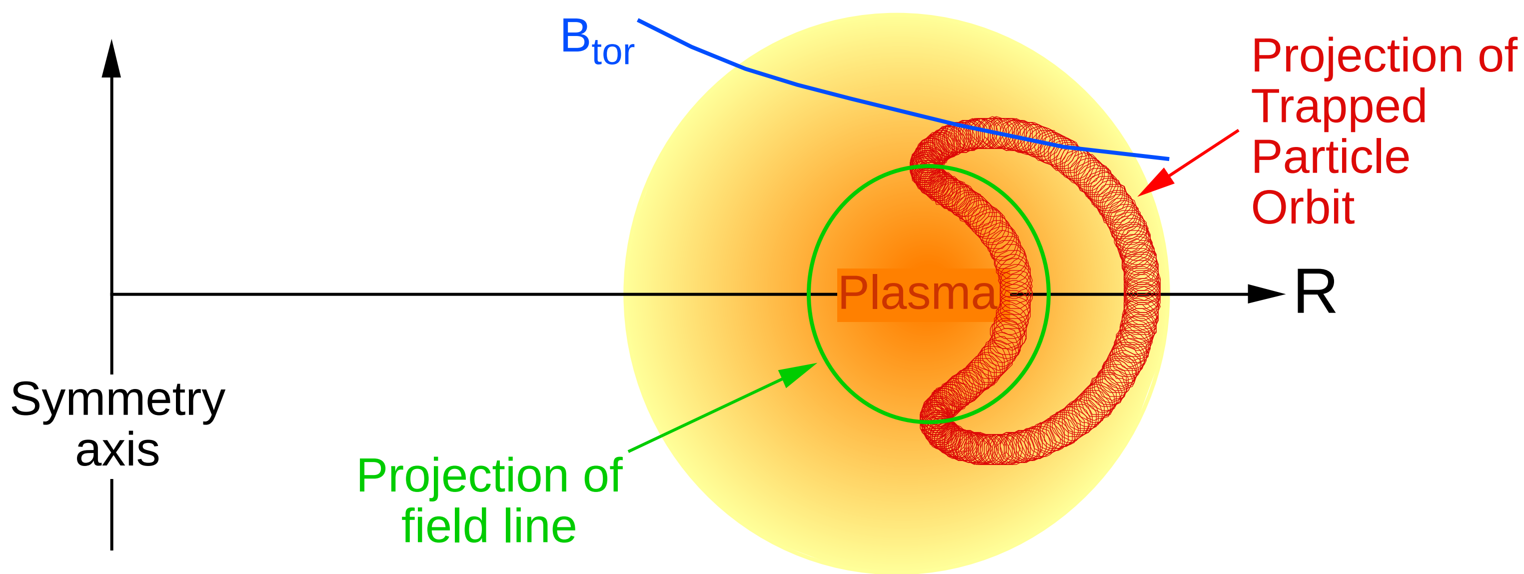
- B 1/R dependence of toroidal magnetic field creates magnetic mirror which can reflect particles with large perpendicular velocity component

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

- Trapped particles dominate transport when collision frequency < bounce frequency

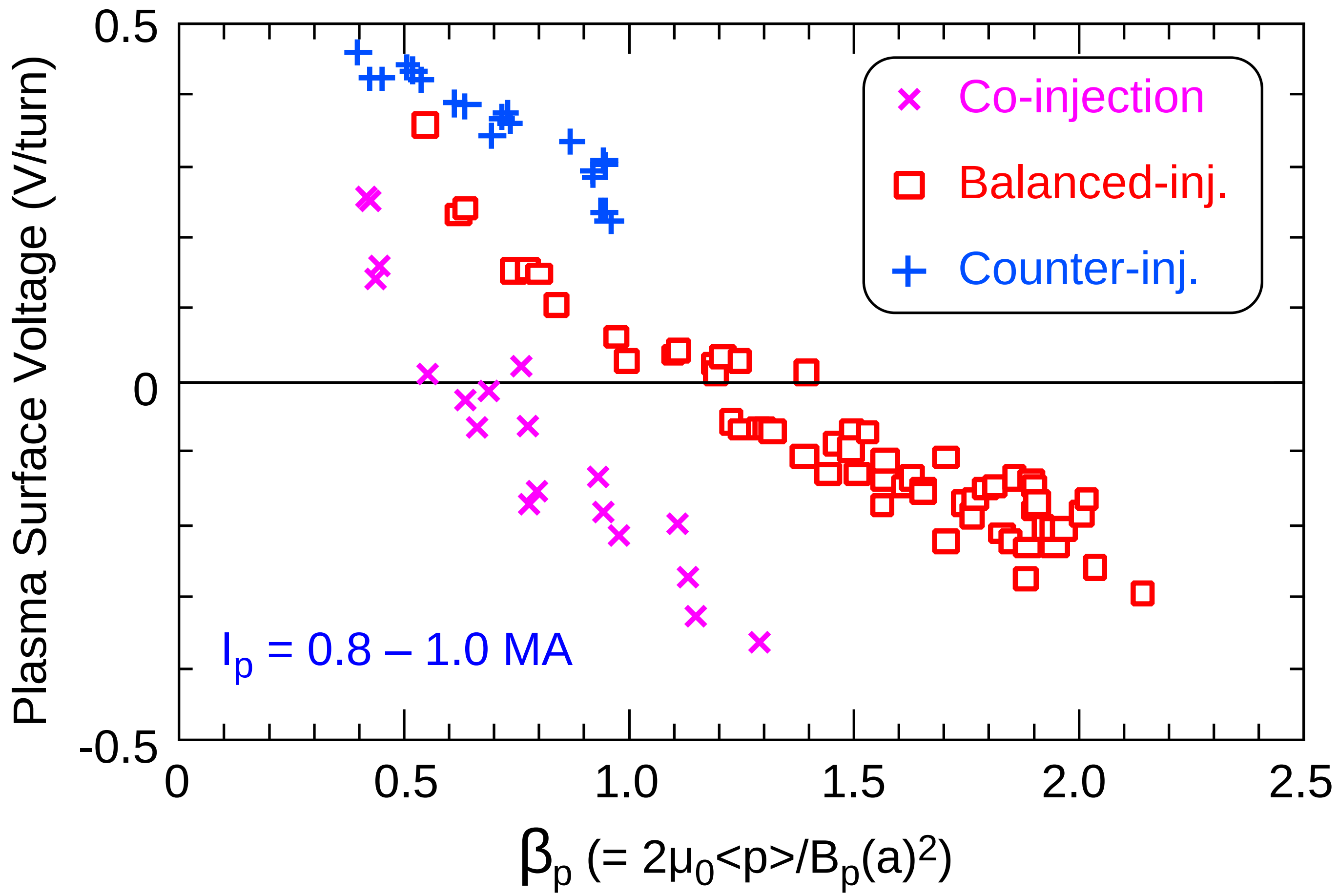
- Collisions between trapped and "passing" particles in presence of a pressure gradient drives net current

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



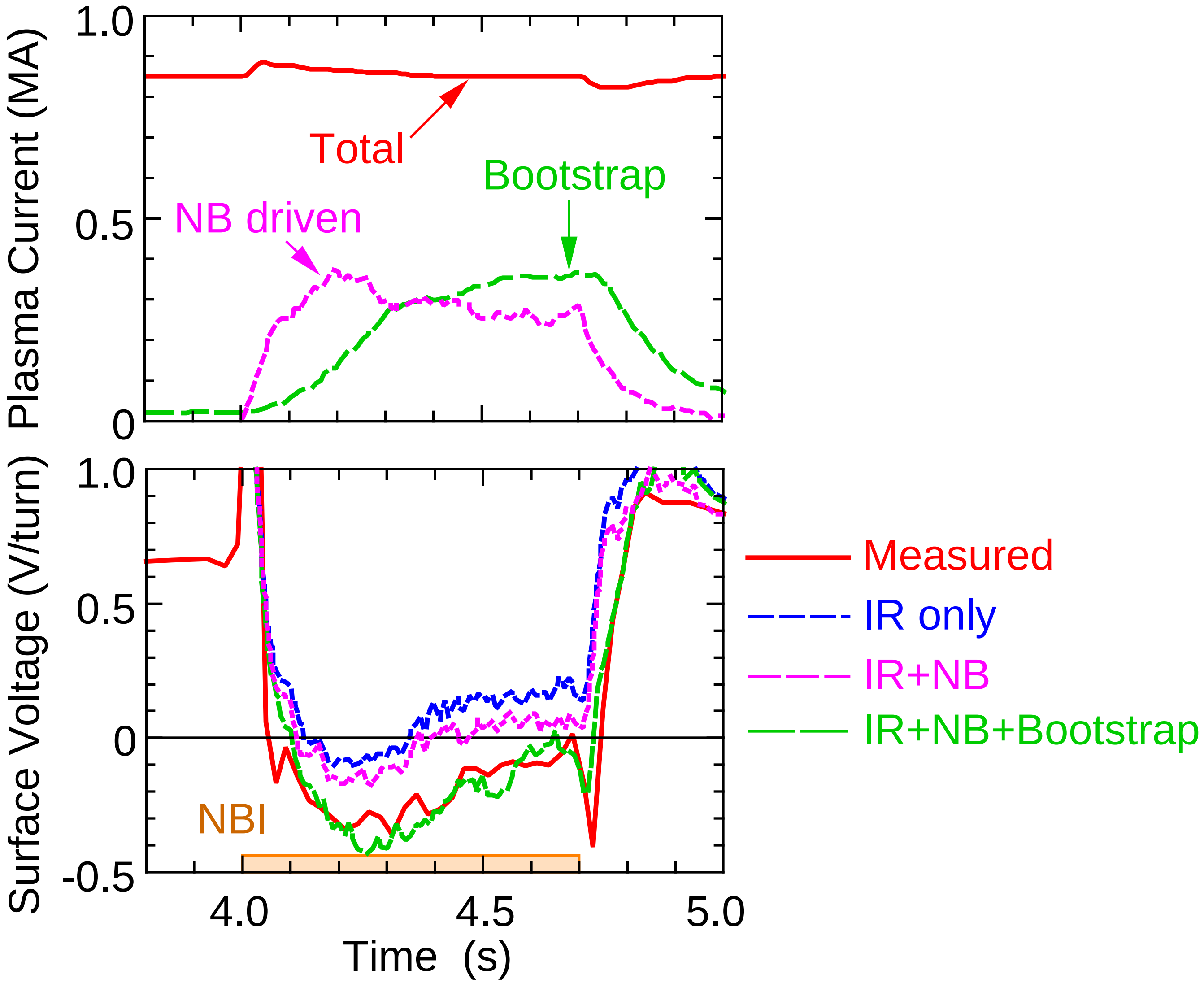
Supershots Provided Ideal Vehicle to Investigate the Bootstrap Current in a Tokamak

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



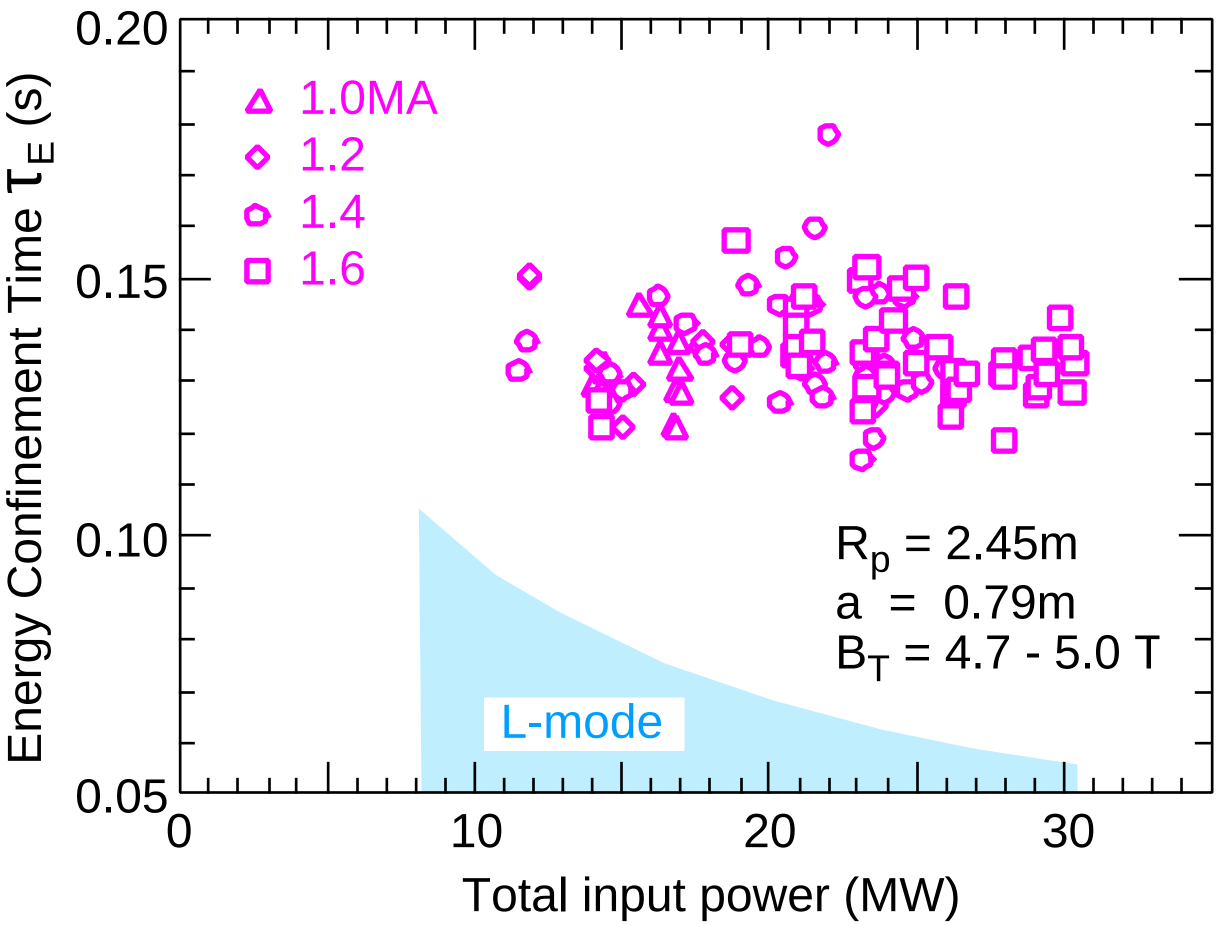
Plasma Surface Voltage is Well Modeled by Including Beam-Driven and Bootstrap Currents

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

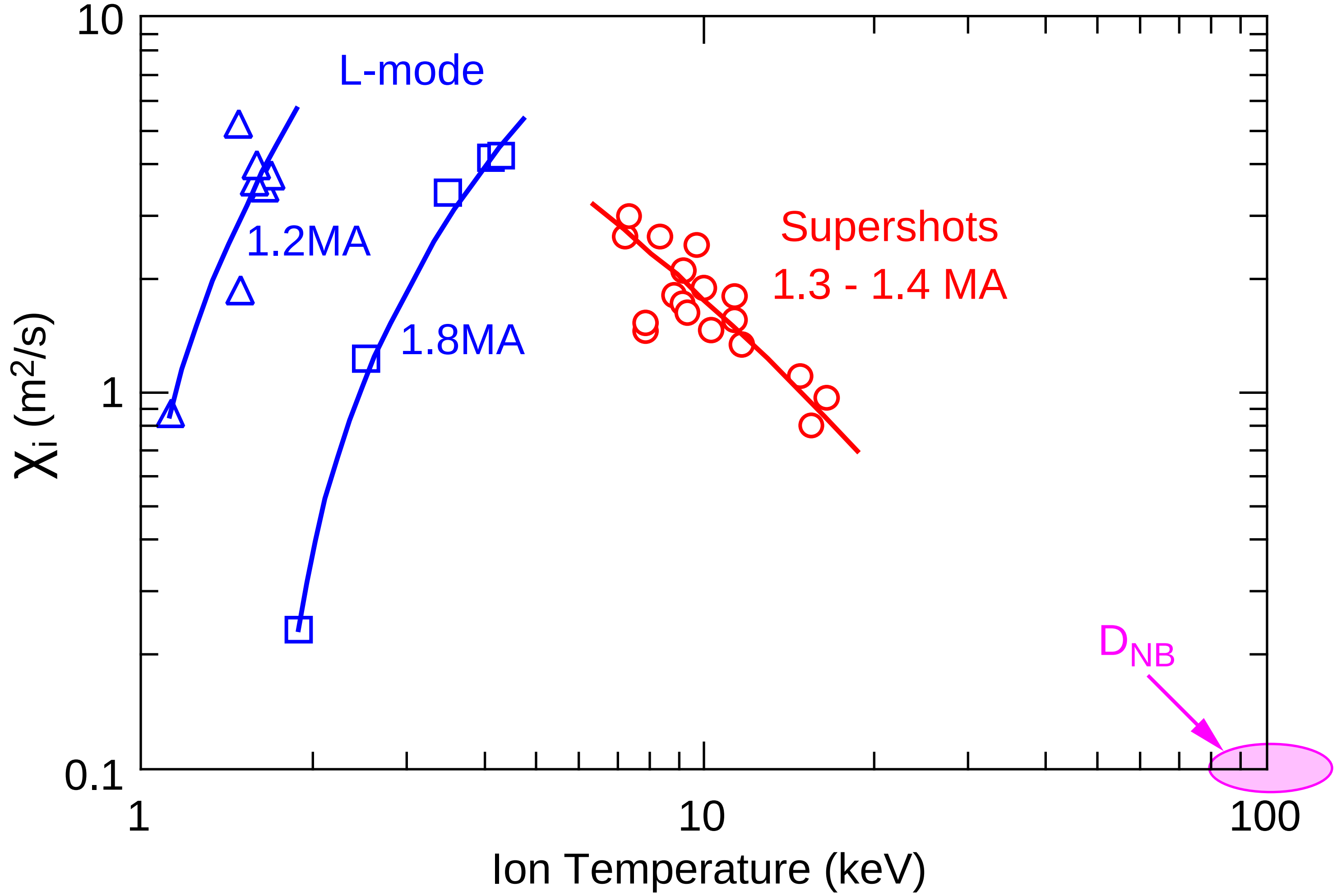


1988 IAEA Conference

- 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

TFTR



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

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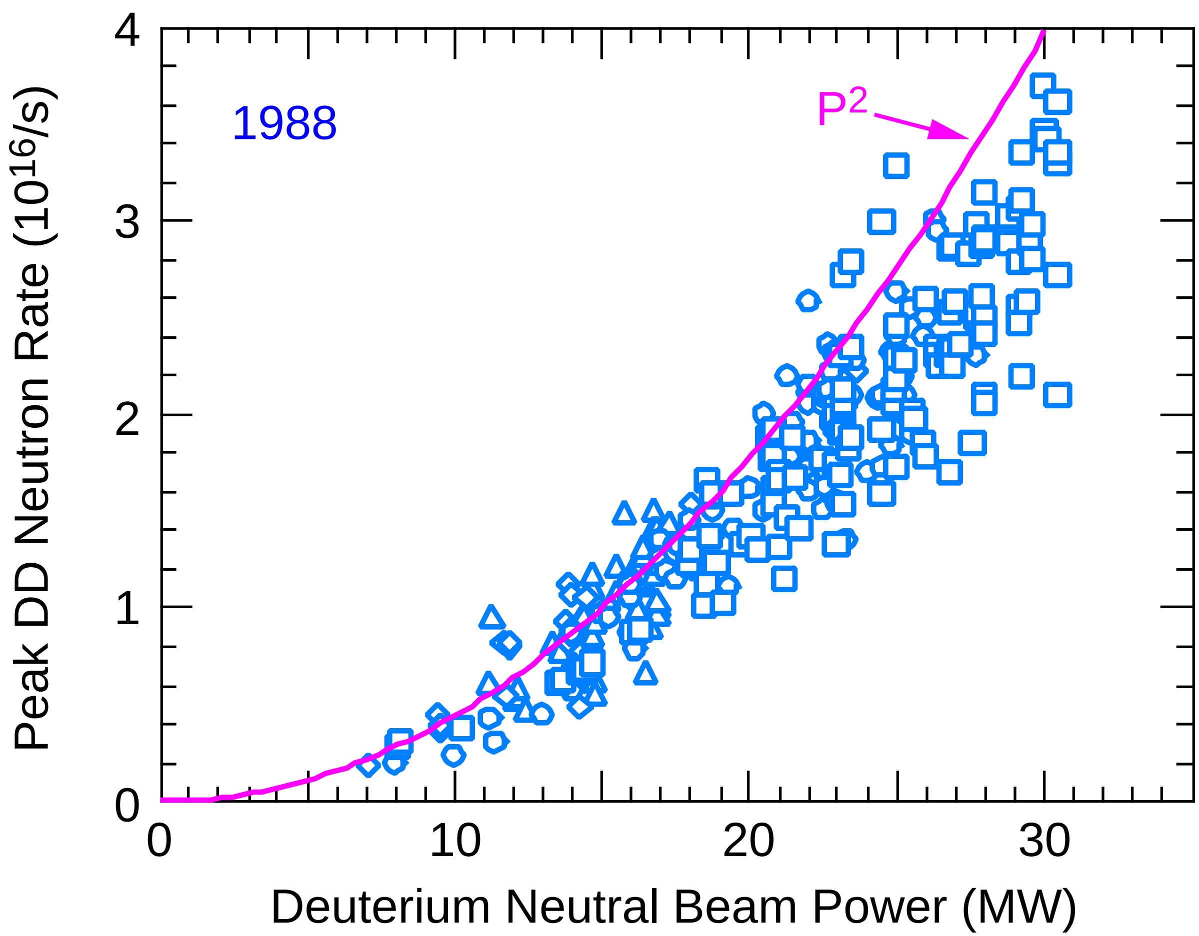
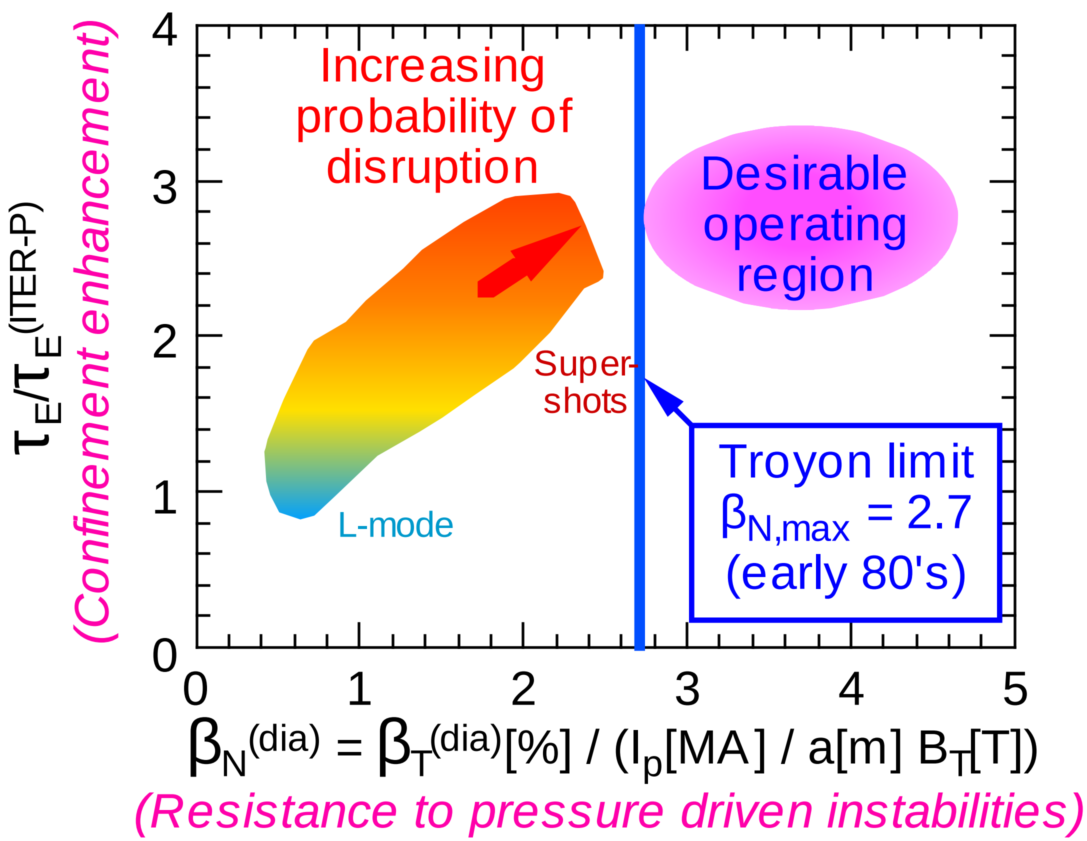
DD Fusion Reactivity Also Scaled Favorably in Supershots

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

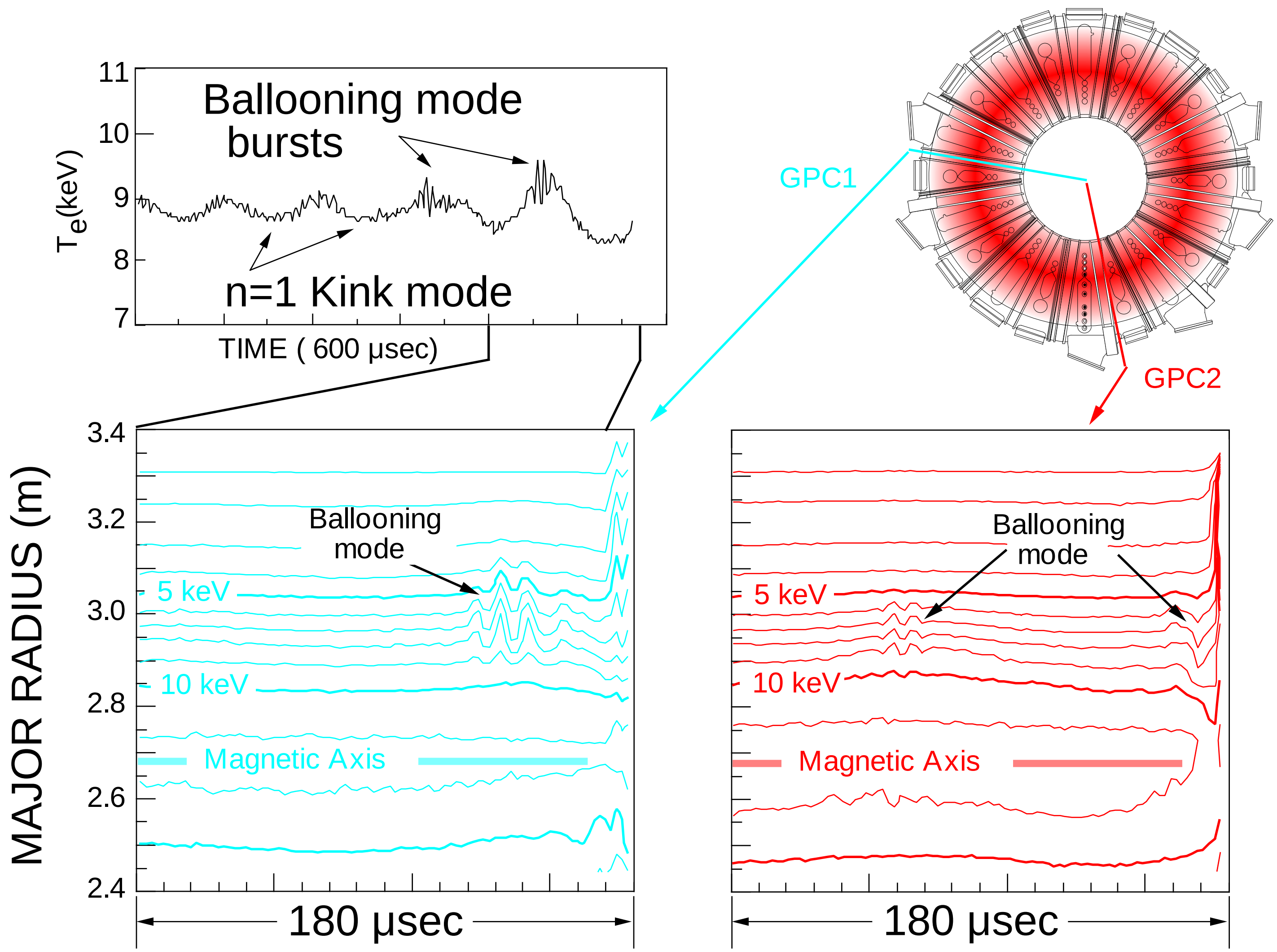
    fast β-limit disruptions at high field (ideal MHD modes)

- Stimulated search for methods to increase β-limit

Ballooning Mode Grows Rapidly Before High-β Disruption

TFTR

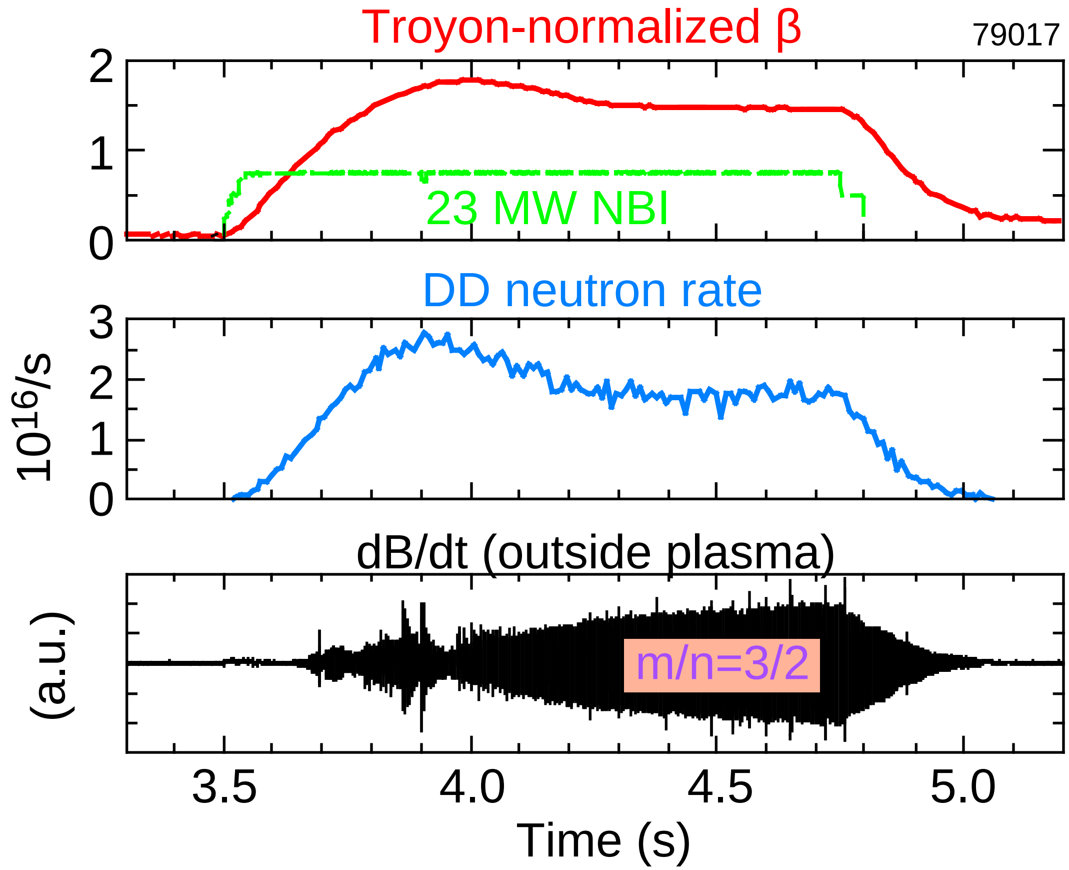
- Identification made possible by excellent spatial and time resolution of T_e diagnostics



Fredrickson,
Nagayama
Janos

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 "Soft" β-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

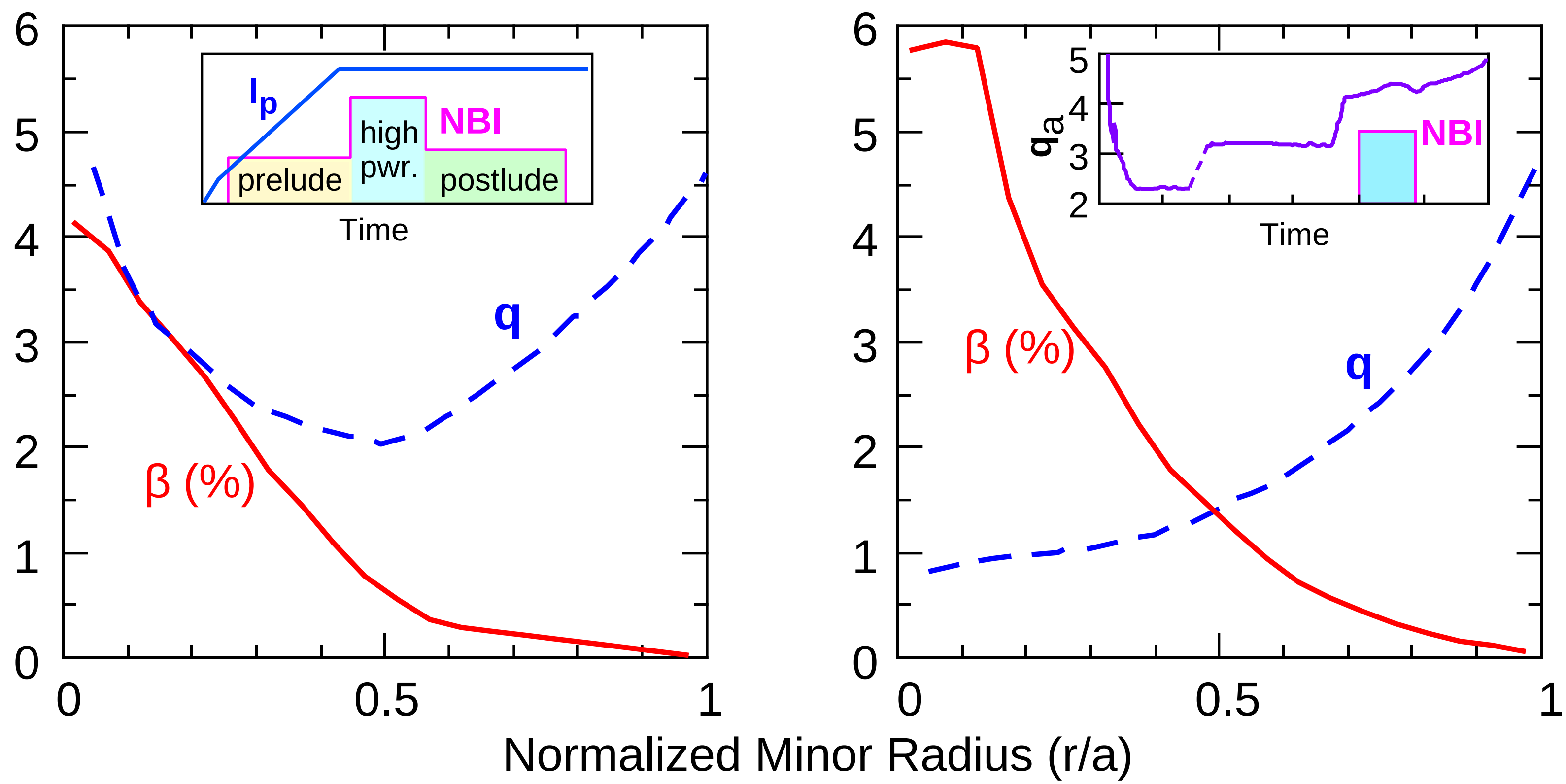
τ_E = 0.23s

NBI heating during current ramp in large plasma

High-l_i

τ_E = 0.23s

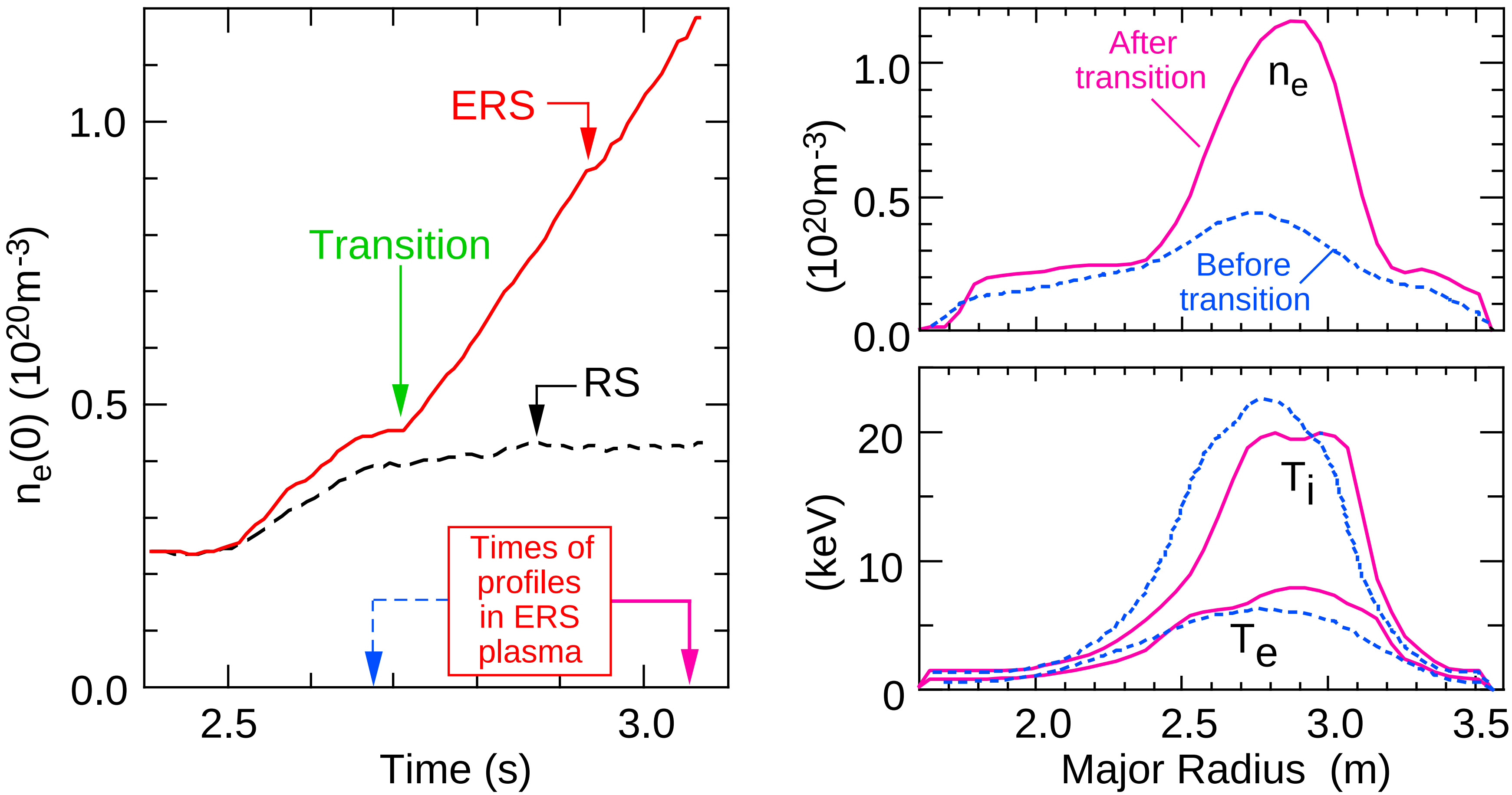
Low-q startup in small plasma followed by expansion



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

Reversed-Shear Plasmas can Transition to 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"

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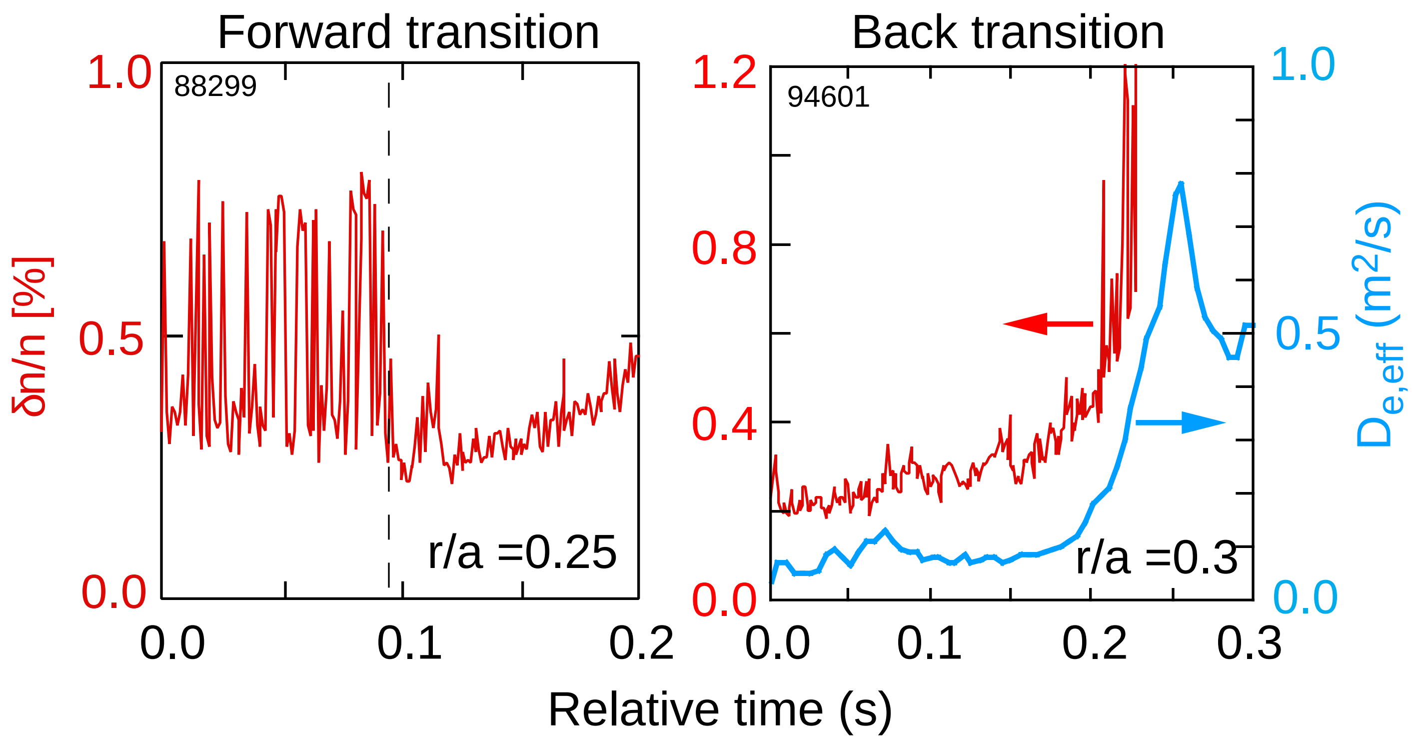
Turbulent Fluctuations Are Suppressed During ERS Phase and Return After Back Transition

TFTR

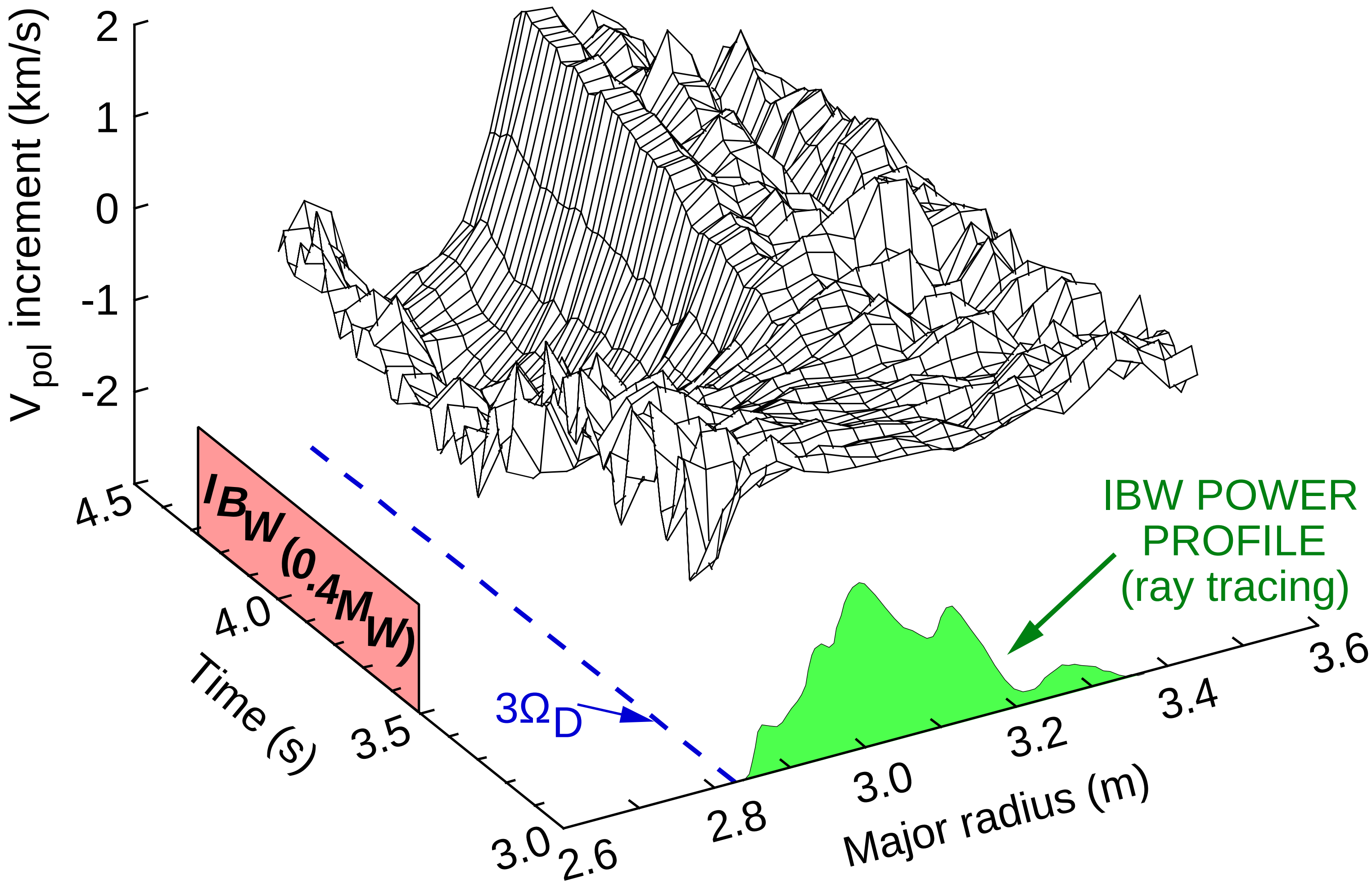


- Fluctuations measured by microwave reflectometer
- Turbulence suppressed by generation of flow shear between flux surfaces
  - flow driven by pressure gradient itself and external momentum sources (NBI, RF waves)
- Stimulating expansion of theory to cover other regimes of enhanced confinement: supershots, H-modes

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

Externally Driven Ion-Bernstein-Waves Produced Poloidal Velocity Shear in Absorption Region

TFTR



- 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:

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

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

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

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

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

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

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

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

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

  $n_e(0)\cdot T_i(0)\cdot\tau_E = 6 \times 10^{21}\ m^{-3}\cdot keV\cdot s$ *(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: $P_{fus} = 1.7MW$

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")

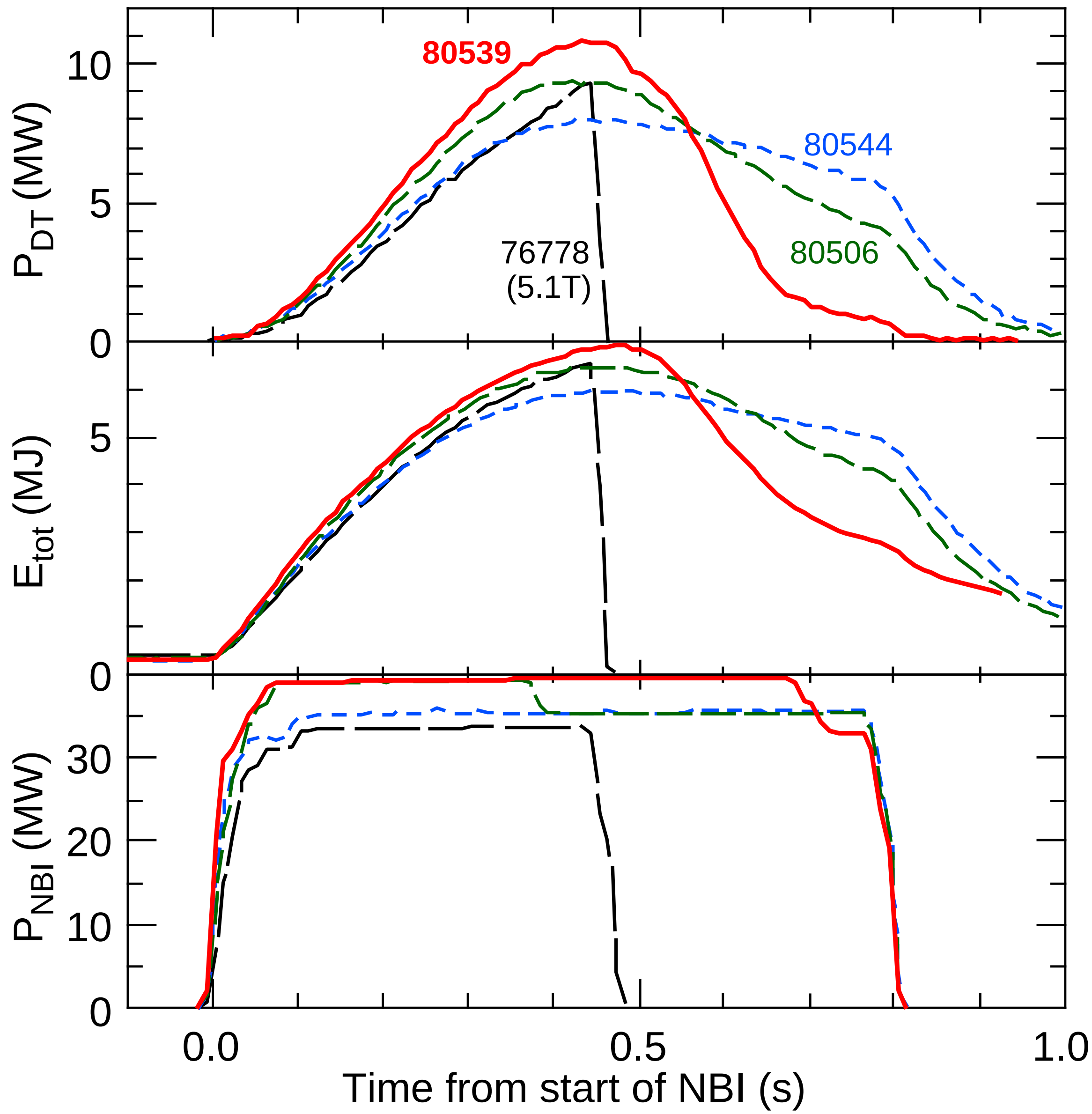
- High reactivity: $P_{fus} = 16MW$ peak; $Q \approx 0.6$
- Prototype operating regimes for ITER
- ICRF physics in D-T plasmas

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*

Supershots Produced High DT Fusion Power, as Expected

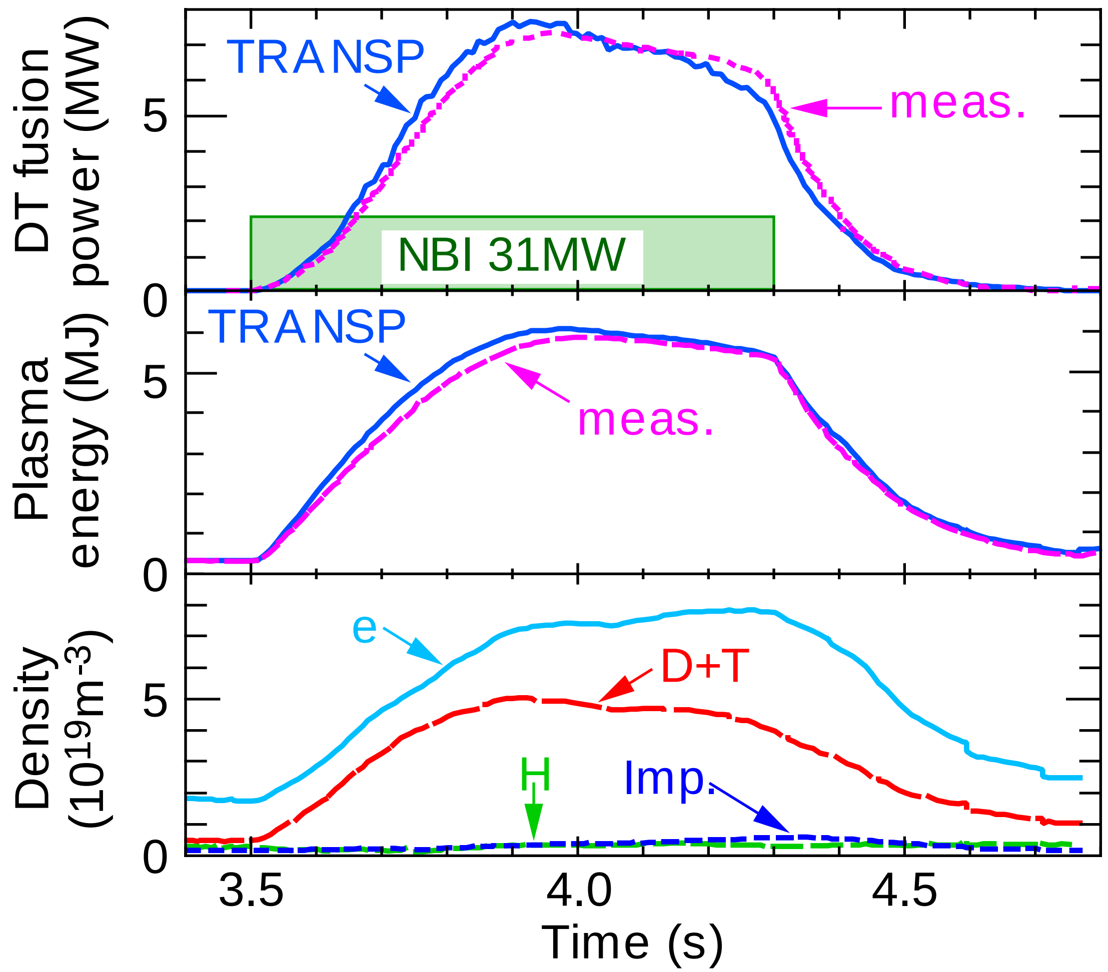
TFTR



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

TRANSCP Code Can Successfully Model DT Reactivity

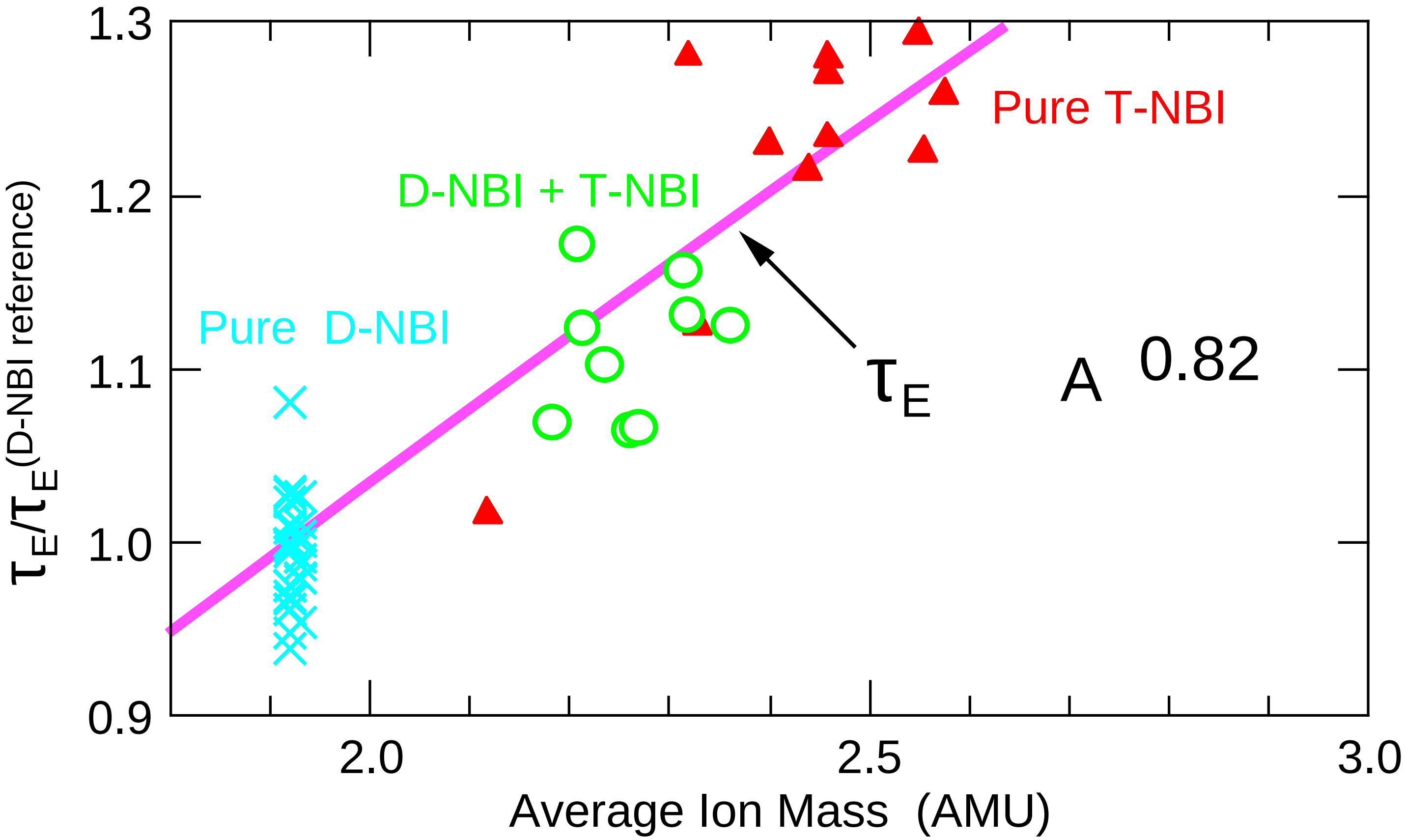
TFTR



- 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

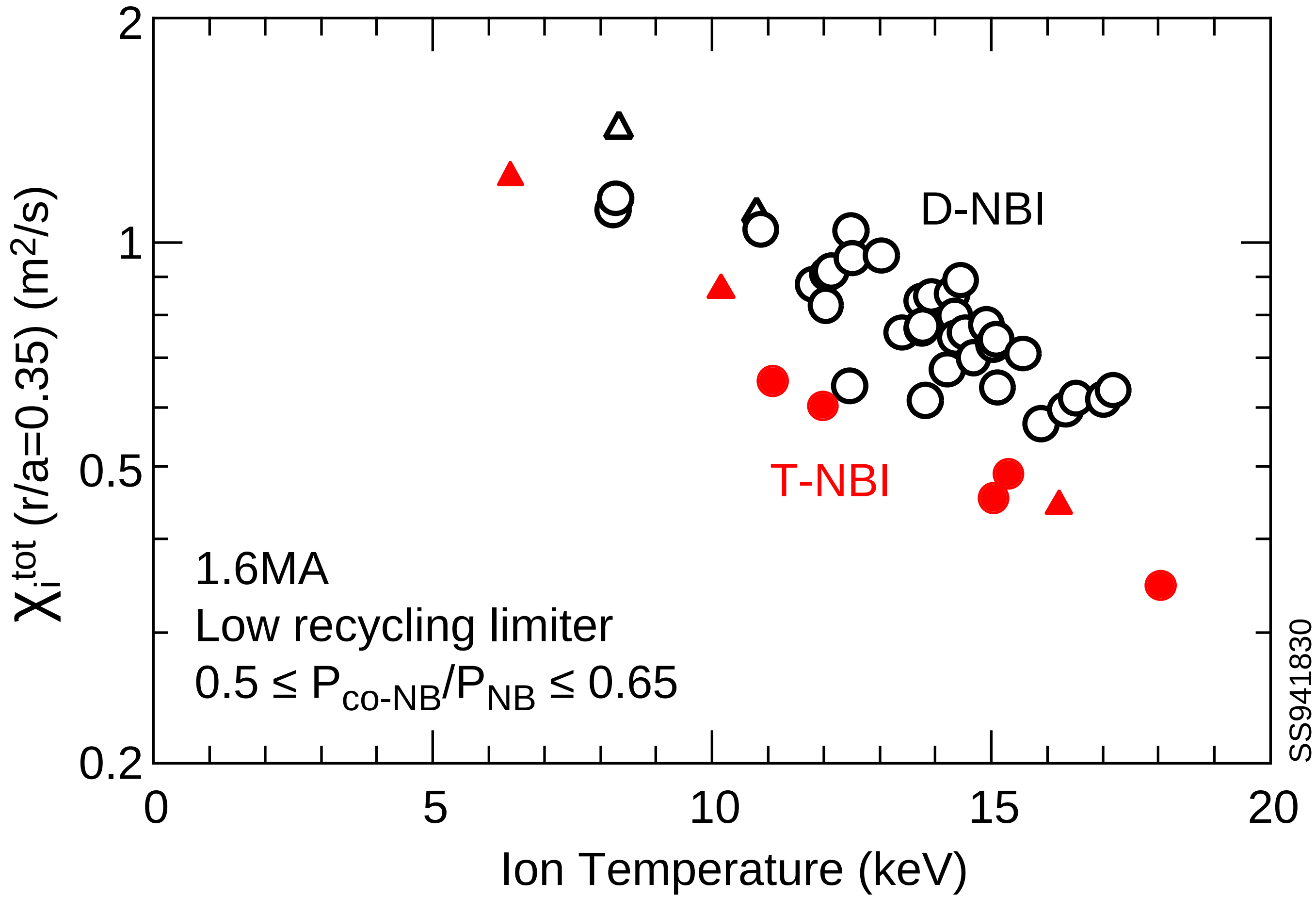
Global Confinement Increases With Tritium NBI

TFTR



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

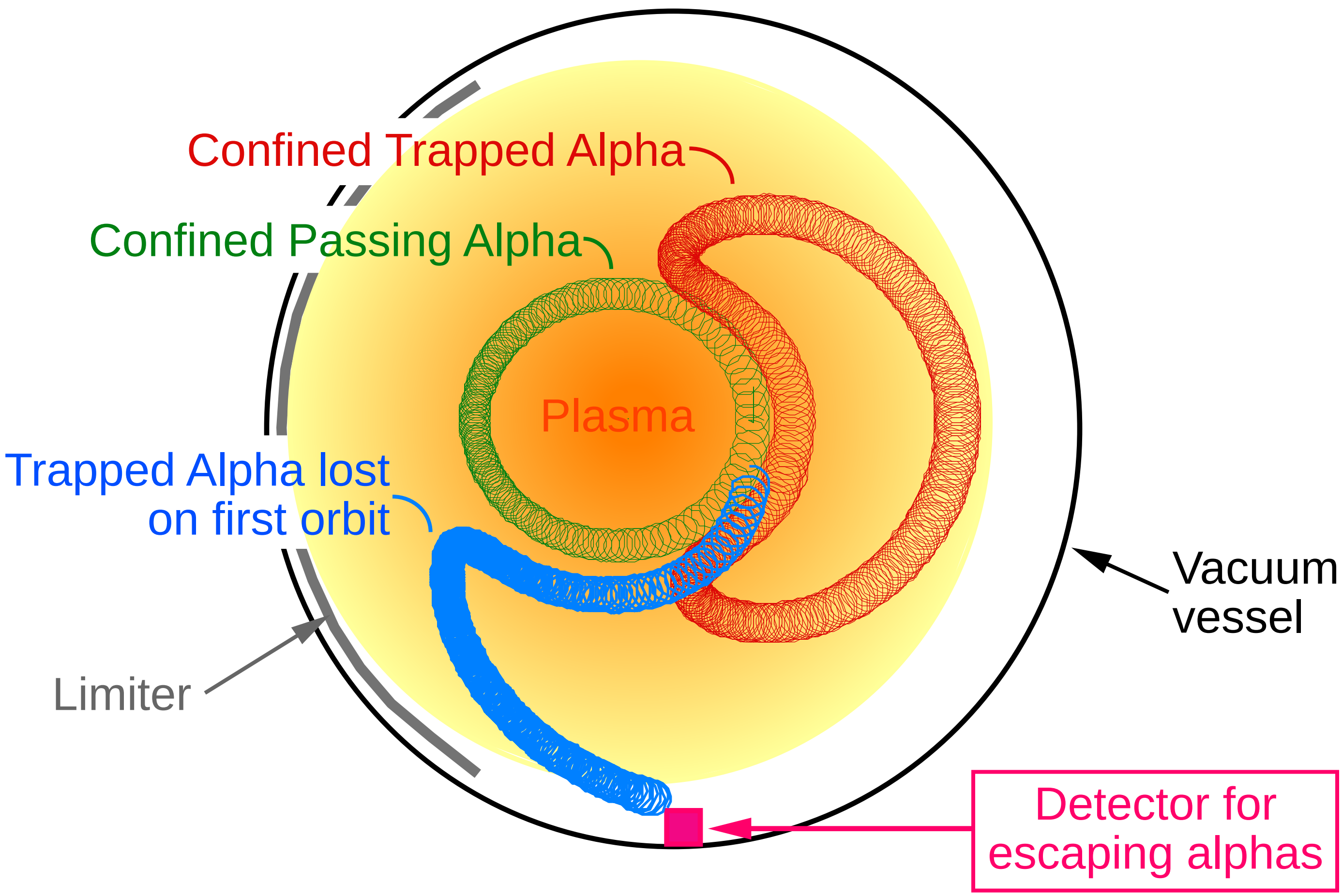
Tritium NBI Extended Earlier Supershot Scaling Results



- 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

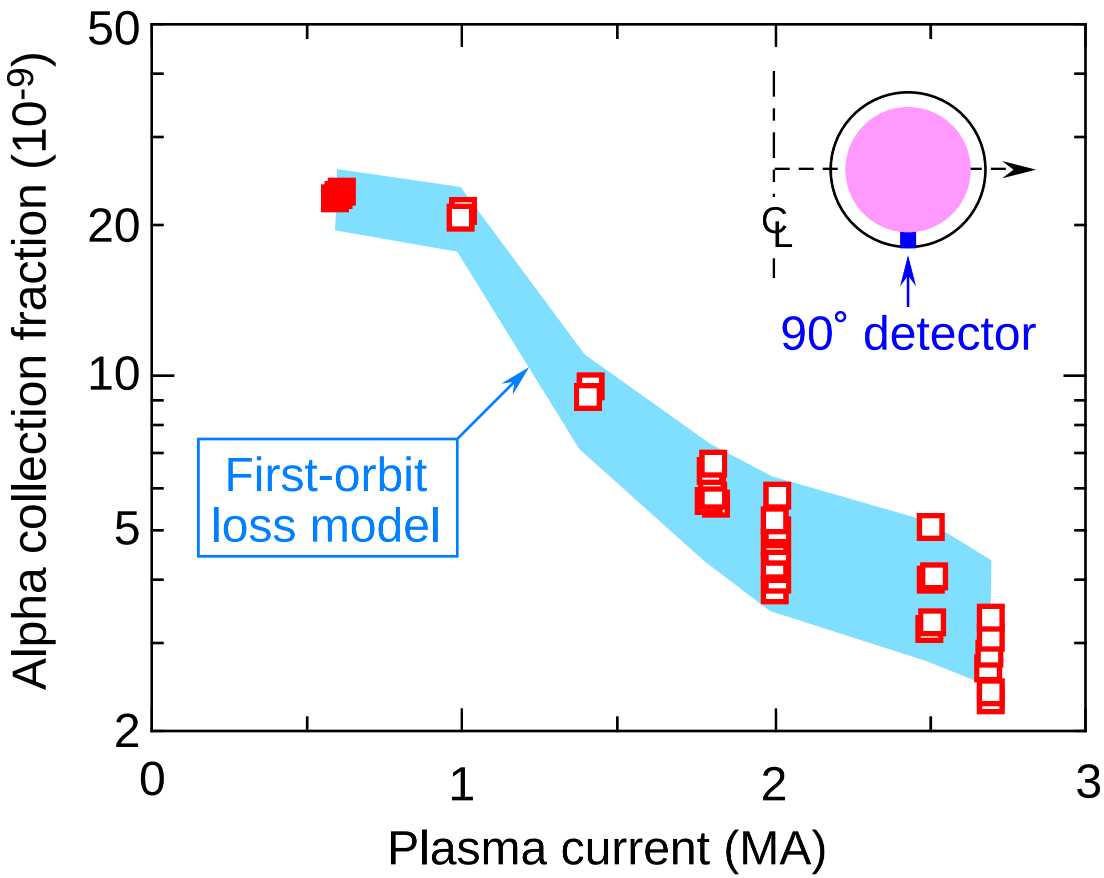
- Alpha particles from DT fusion reactions are born with energy of 3.5MeV
  - Larmor radius up to 5cm in TFTR
  - Radial excursions of trapped alphas are much larger
- Good confinement of alpha particles necessary for D-T ignition



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

TFTR

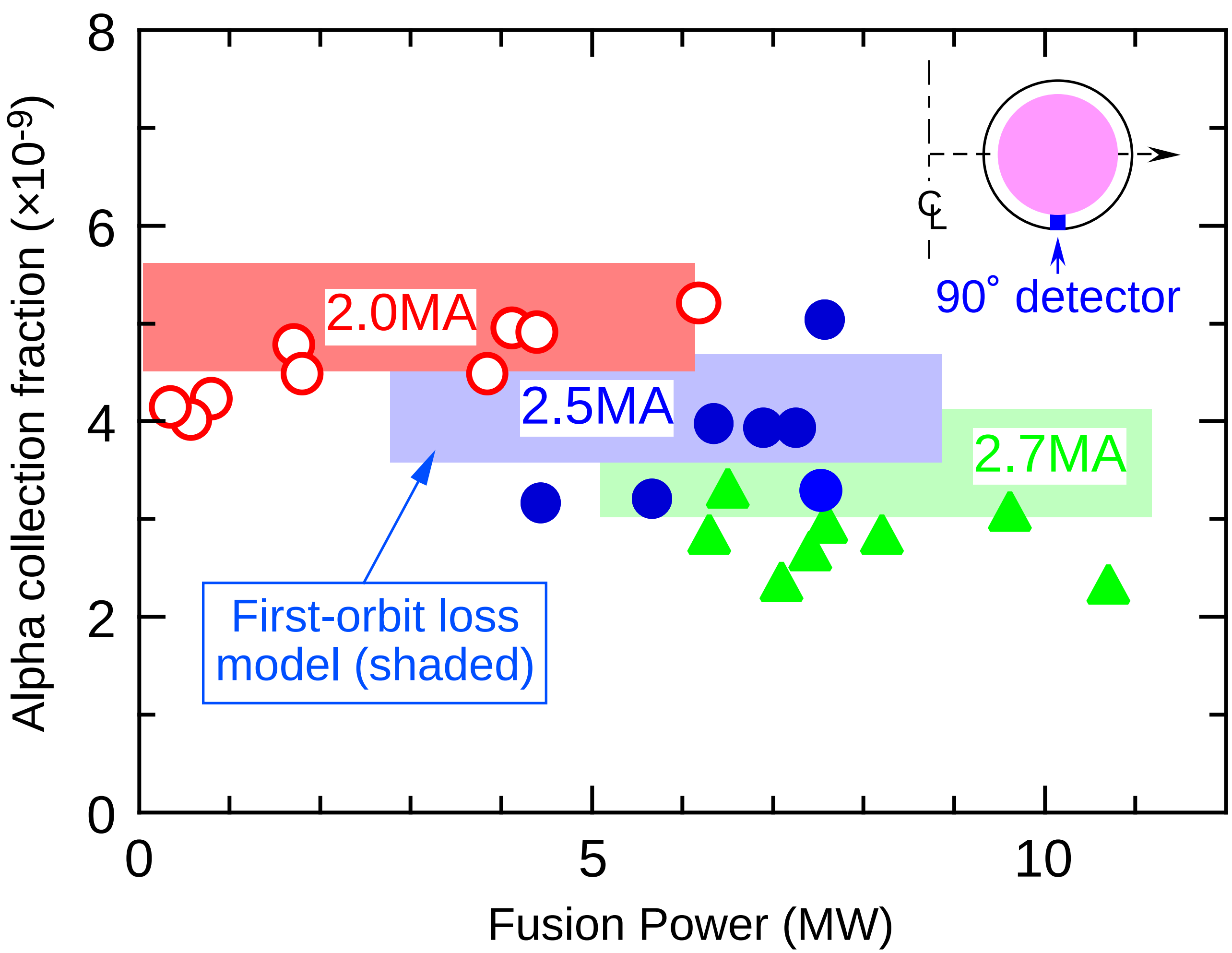


- Shaded region shows result from an orbit-following code based on TRANSP calculations of alpha-particle birth and current profiles.
- At 2.5 MA, ~3% of alphas are lost on first orbit after birth

S. Zweben
D. Darrow

Alpha Loss Fraction does not Increase with Fusion Power

TFTR

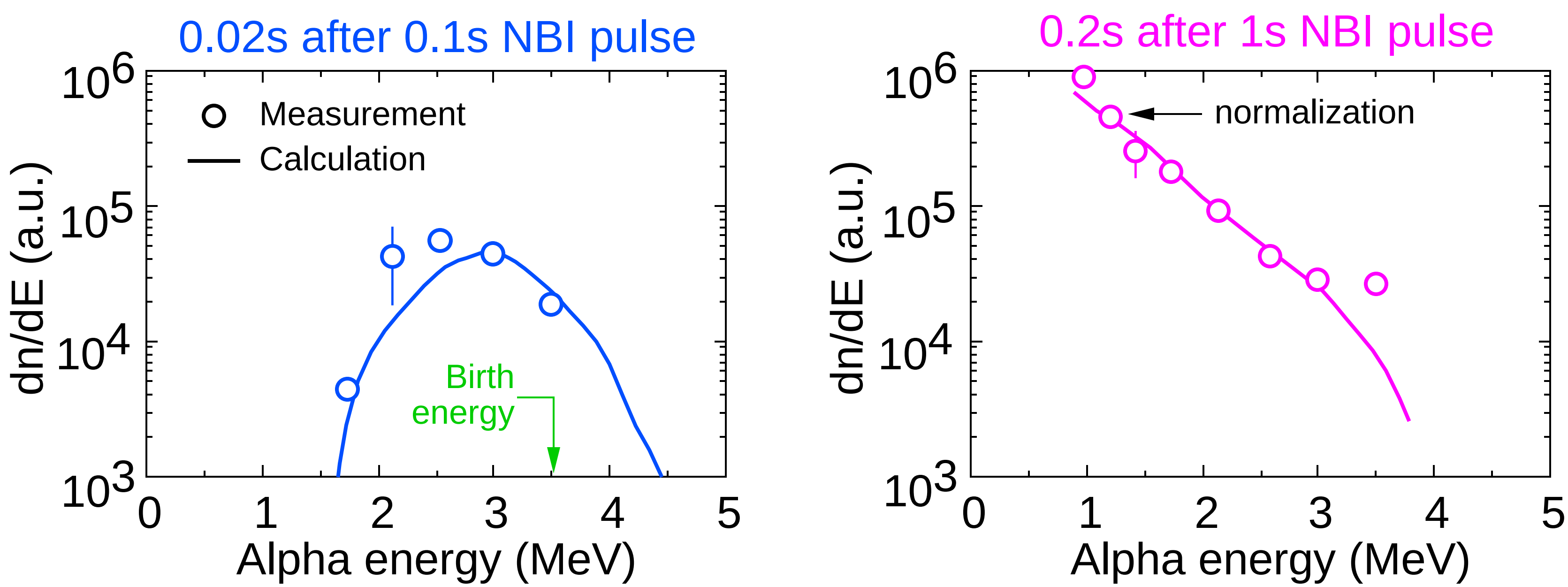


- Data for MHD-quiescent phases of D-T supershots
- No indication of loss processes driven by alpha-particles themselves

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

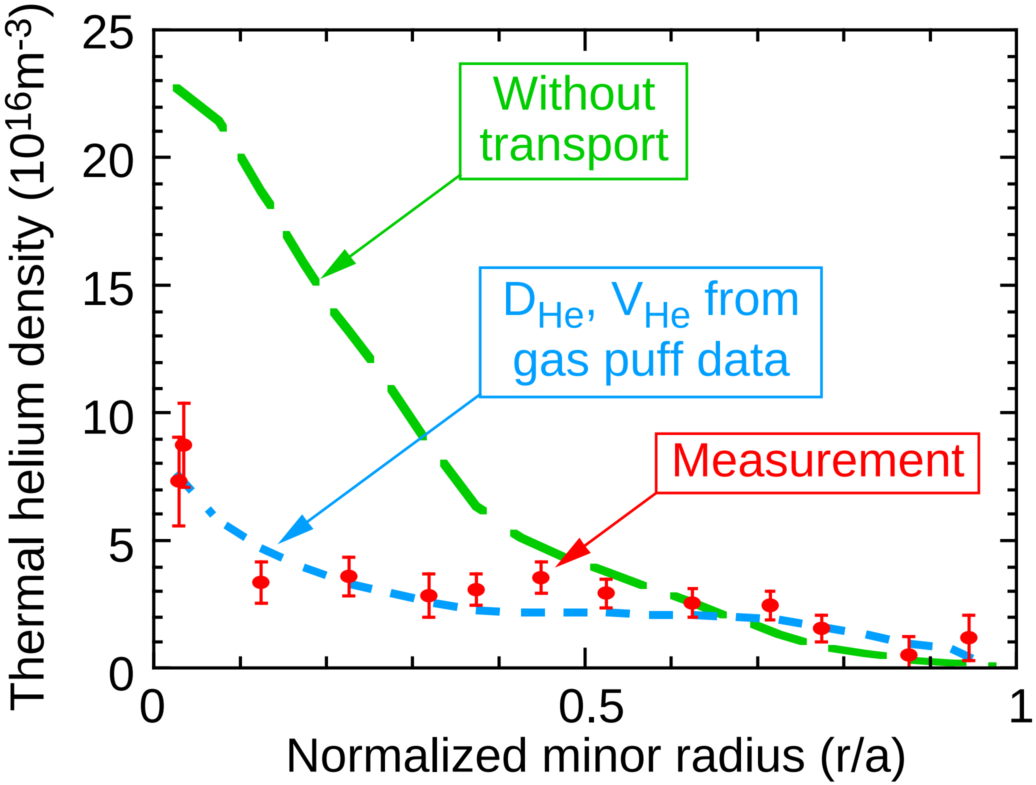


- Calculation with TRANSP/FPPT code based on classical Coulomb collisions using measured plasma parameters
  - alpha-particle velocity slowing time typically 0.5 - 1 s
- High ion temperature and presence of unthermalized NB injected ions results in broadening of alpha spectrum above birth energy

GAT, IOFFE, PPPL Collaboration

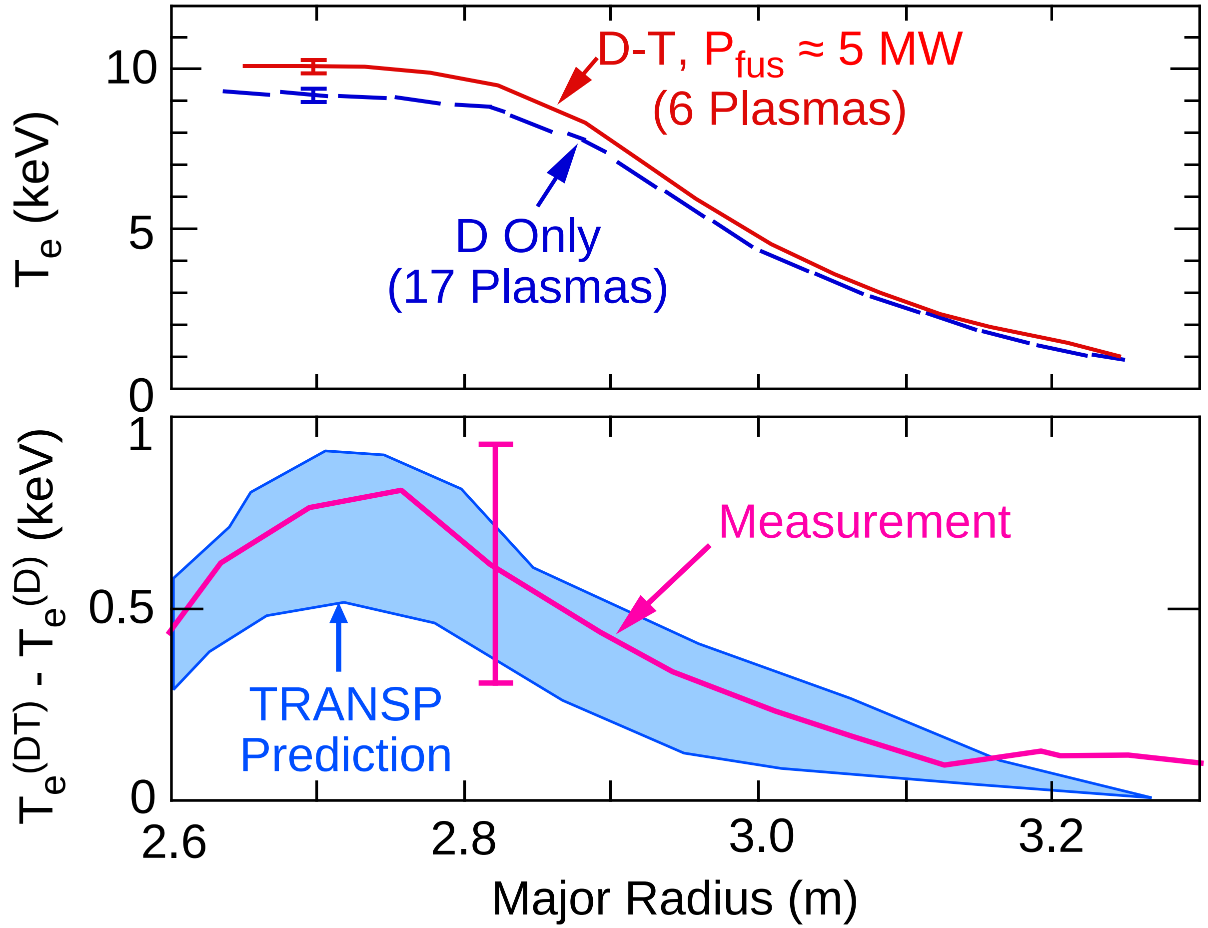
Rapid Transport of Thermal Helium Ash from Center to Edge

TFTR



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

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



- Alpha heating ~10% of power through electron channel
- TRANSP prediction shown includes alpha particle heating
  - shaded region indicates uncertainty range of prediction

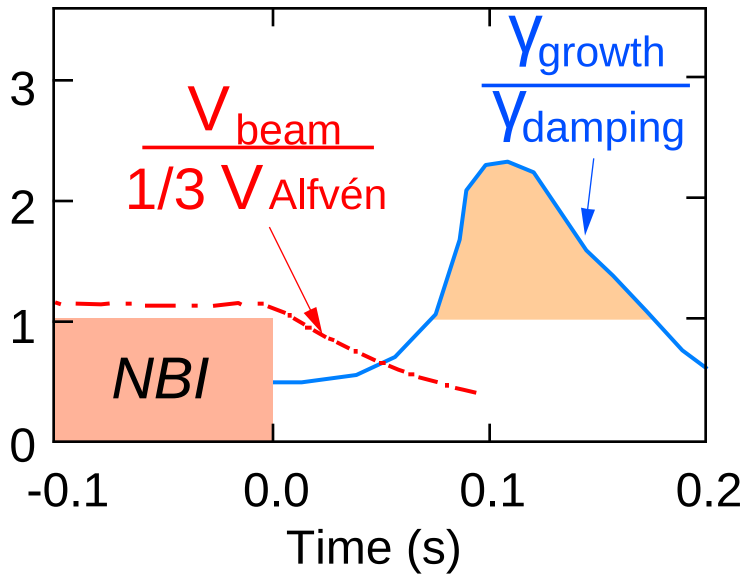
Alpha-Driven Toroidal Alfvén Eigenmodes

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

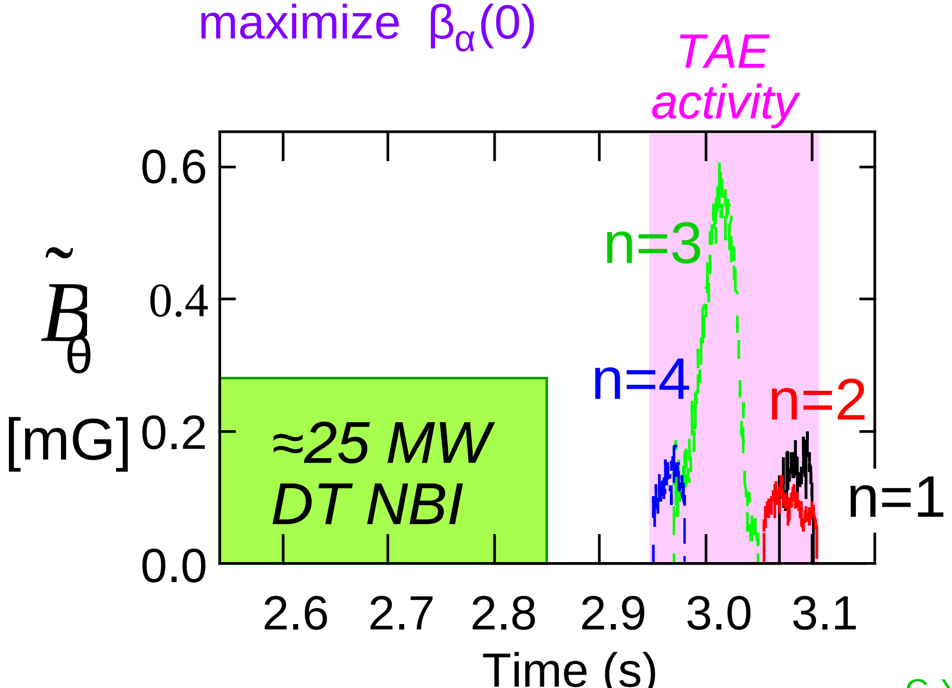
Theory

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



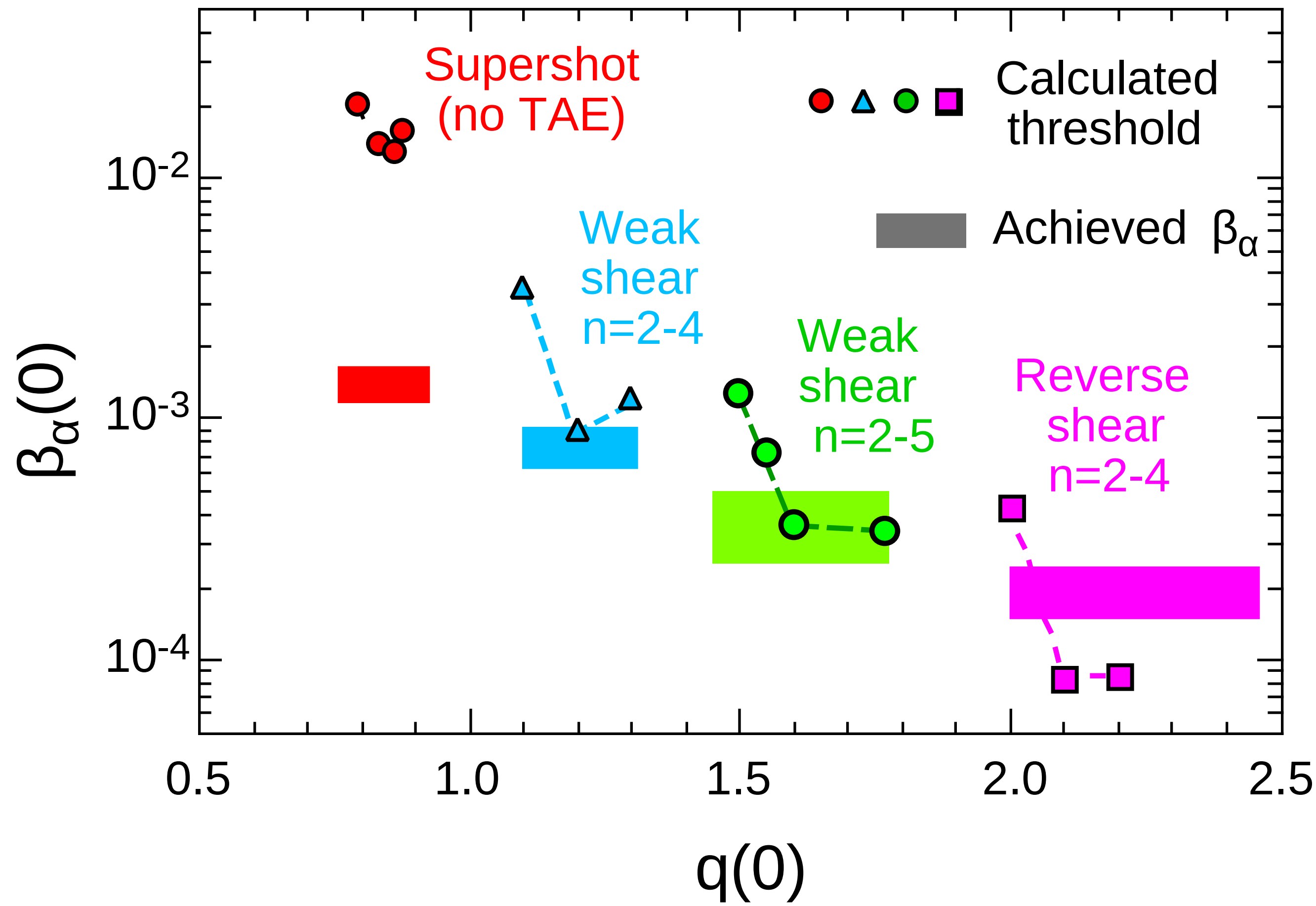
Experiment:

- 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. Nazikiar

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!