FUSION PLASMA EXPERIMENTS ON TFTR
A TWENTY YEAR RETROSPECTIVE

Presented to:

American Physical Society
39th Annual Meeting of the
Division of Plasma Physics

by

R.J. Hawryluk

November 17, 1997

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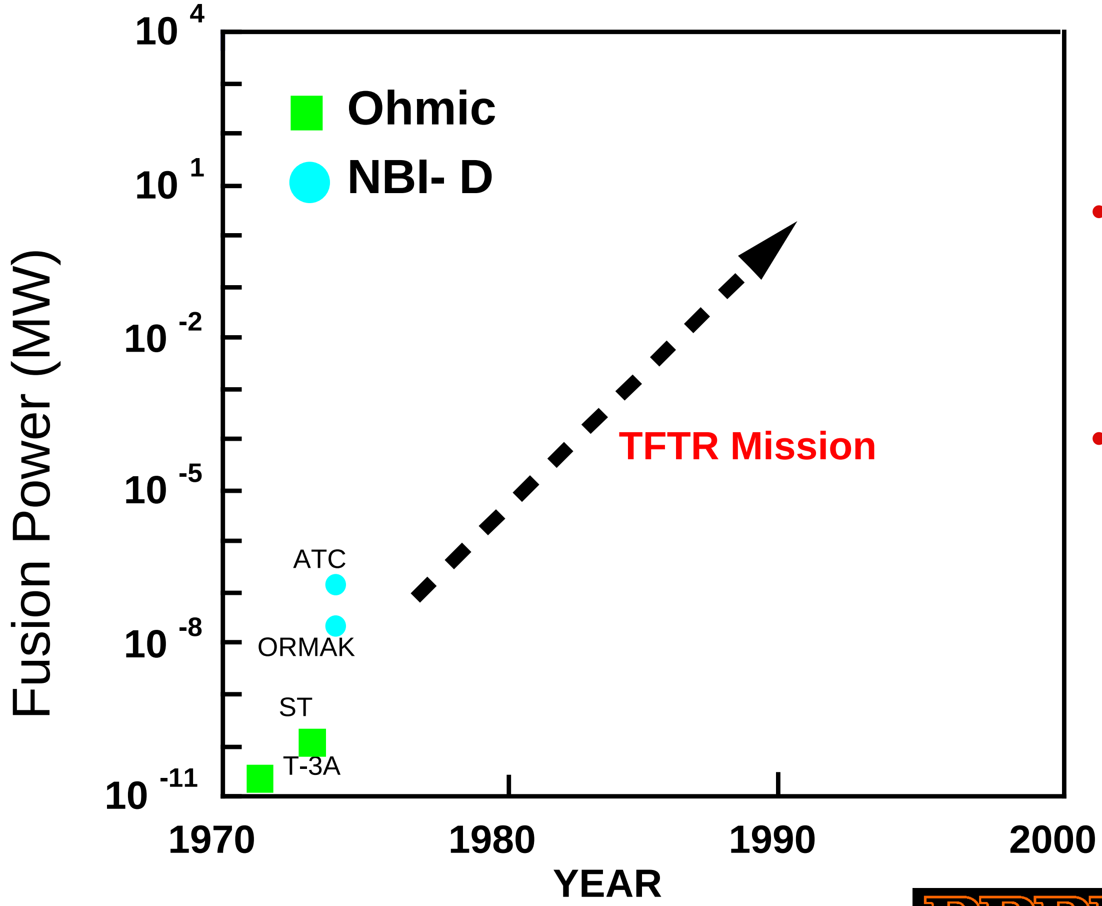
Opportunity to Demonstrate Fusion Energy Production

TFTR Mission (1976)

- Demonstrate D-T fusion energy production
- Study plasma physics of large tokamaks at *reactor parameters*
- Gain experience with reactor scale engineering



- **Need high ion pressure and good confinement.**
- **Enhanced reactivity due to beam-target reactions.**

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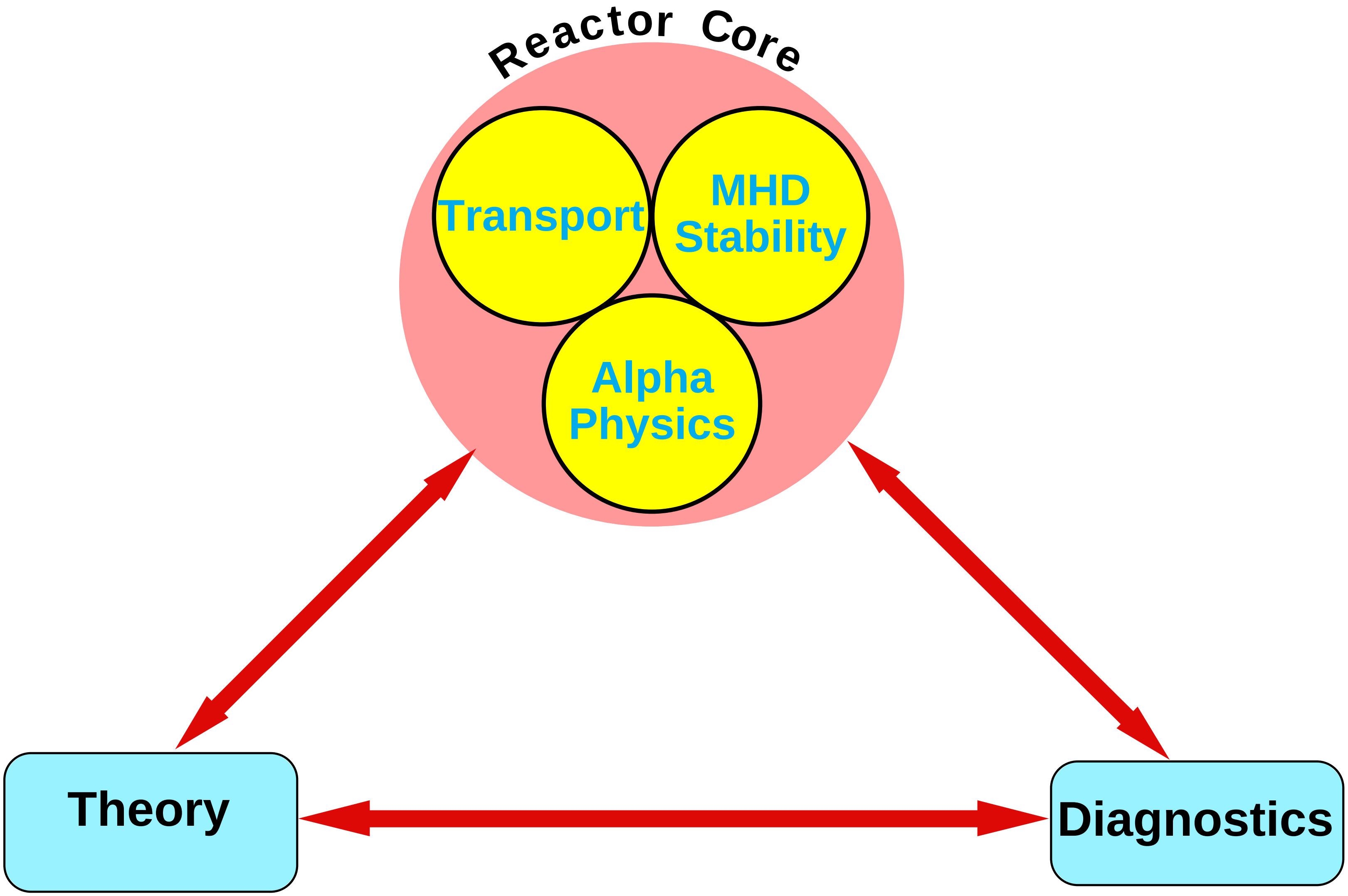
TFTR Explored the Science of a Reactor Core



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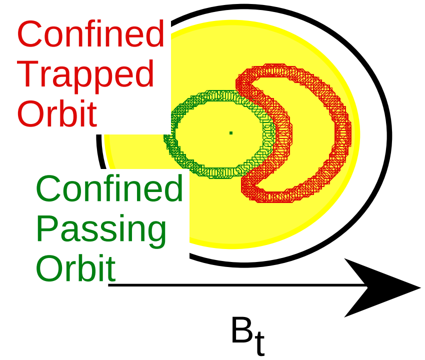
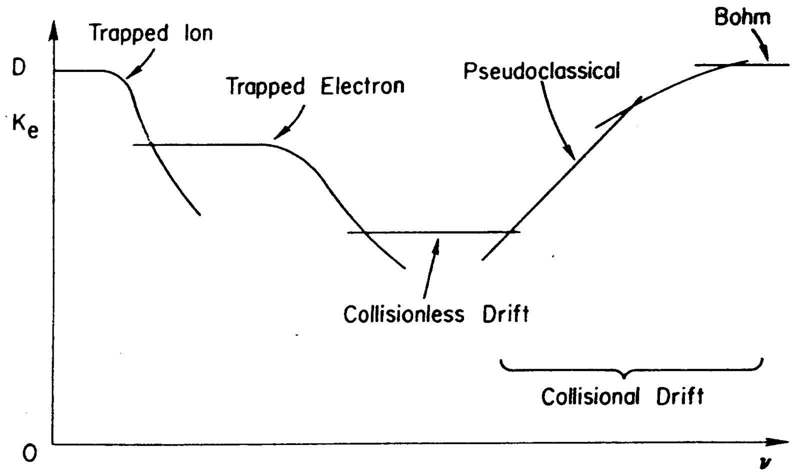
TRANSPORT STUDIES: STATUS 1976

- Neoclassical Transport
  Variation of ½B½causes some particles to mirror
  $\Delta r \quad \rho B_T/B_p$

  $$D^{neo} \sim (a/R)^{0.5} (B_T/B_p)^2 D^{cl}$$



- **Experimental**: Transport rates much larger than classical or neoclassical predictions.
- **Theory:** Turbulent Processes Due to Electrostatic Instabilities.



Predicted dependence of the diffusion coefficient D and electron thermal conductivity K_e on the collision frequency υ.

- **Empirical Scaling:** Widely used to estimate energy confinement
  - Bohm, psuedoclassical, Alcator ....

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TRANSPORT STUDIES ON TFTR

L-Mode Supershots ERS

Ohmic NBI DT Operation

1983 1988 1993 1998

Bootstrap and beam-driven current

Characterization of transport and turbulence and predictive modelling

ERS: Internal transport barrier formation

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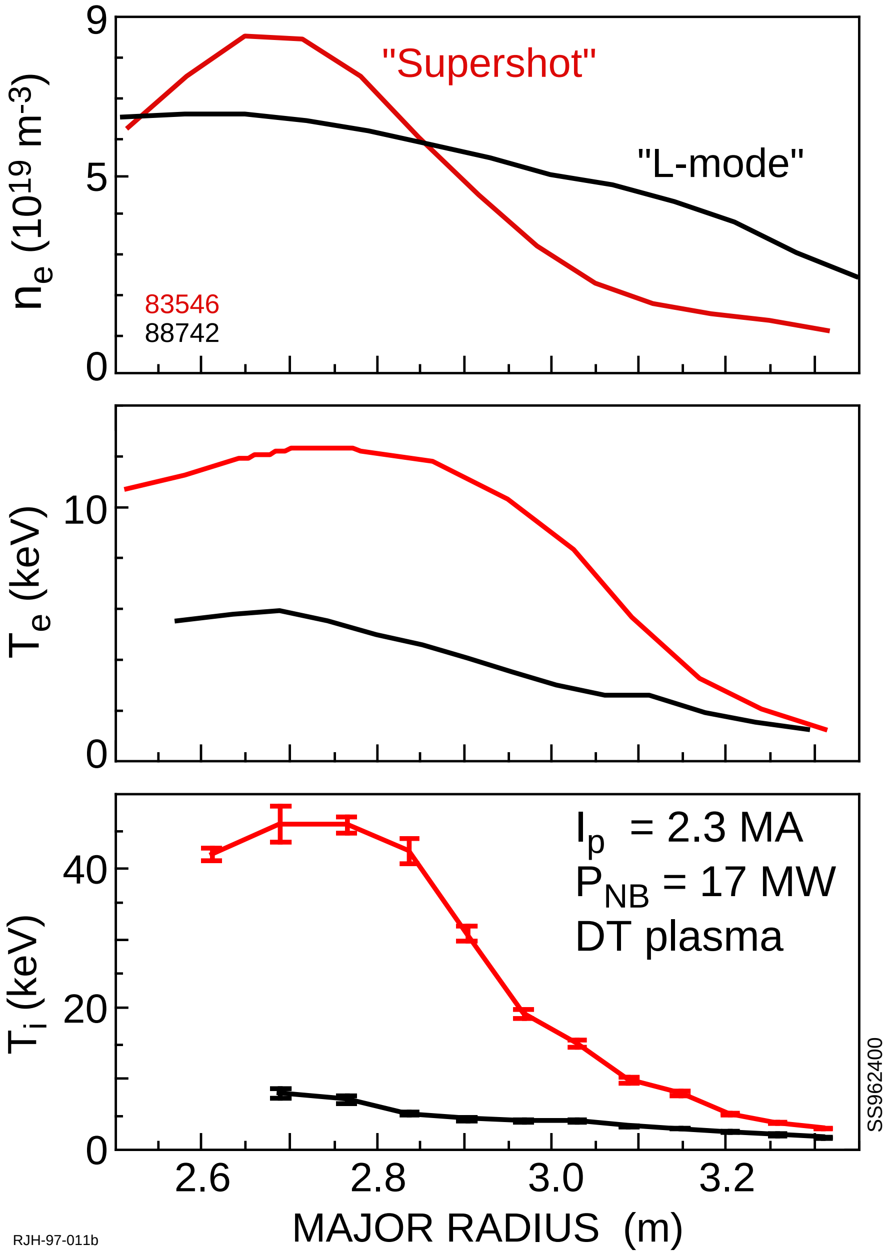
Reactor-like Plasmas Achieved by Reducing Wall Recycling



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- $n_i(0) \cdot T_i(0) \cdot \tau_E$ increased by a factor of 20:

L-mode: 0.48 ×10^{20} m^{-3}·keV·sec

Supershot: 9.9 ×10^{20} m^{-3}·keV·sec

- Empirical scaling fails to predict dependence on wall recycling and edge conditions.

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THE CORE PLASMA PARAMETERS ACHIEVED IN TFTR D-T PLASMAS ARE ITER-LIKE.

	TFTR(#80539)	ITER
$\beta(0)$, %	6.0	9
Collision frequency - ν_e^* (10^{-2})	1	.8
ρ_i/a (10^{-3})	6.5	2
Electron density (10^{20} m^{-3})	1	1.3
T_i (keV)/T_e (keV)	36/13	35/35
D/T	1	1
B_t (T)	5.6	5.7
Fusion Power Density (MWm^{-3})	2.8	2.5

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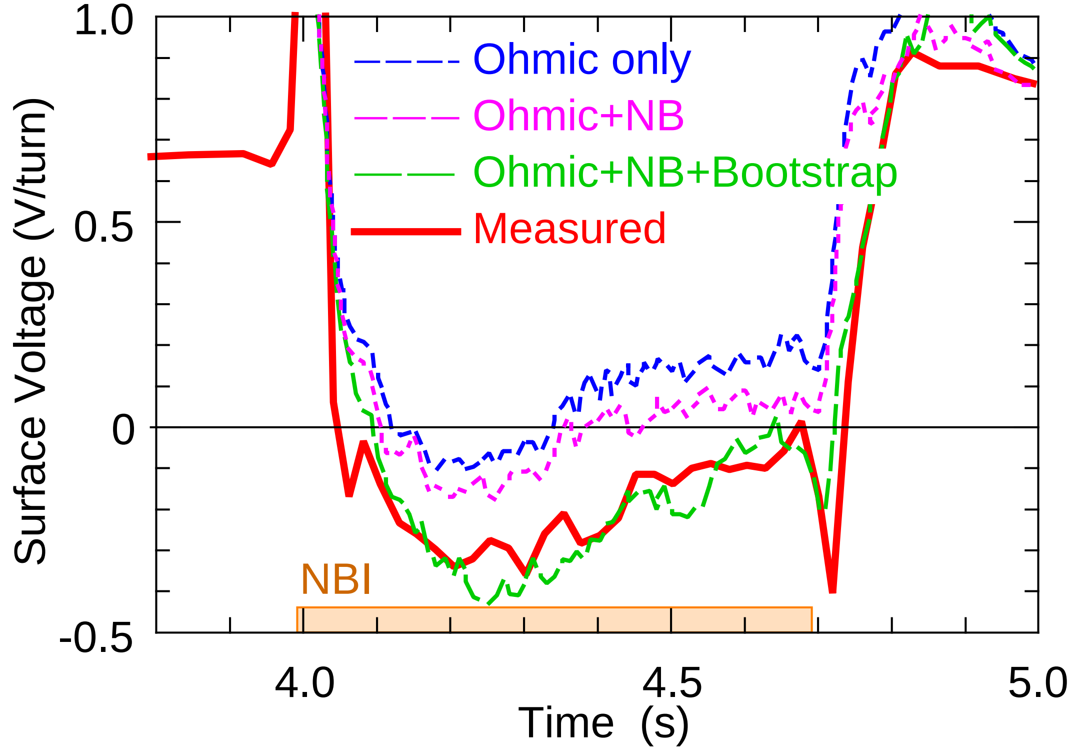
NEOCLASSICAL THEORY PREDICTIONS OF BOOTSTRAP CURRENT CONFIRMED



- Plasma Surface Voltage is Well Modeled by Including Beam-Driven and Bootstrap Currents
- In Ohmic discharges, good agreement with neoclassical resistivity.
- Impacted design of Advanced Tokamaks, Spherical Torus, and Stellarators.

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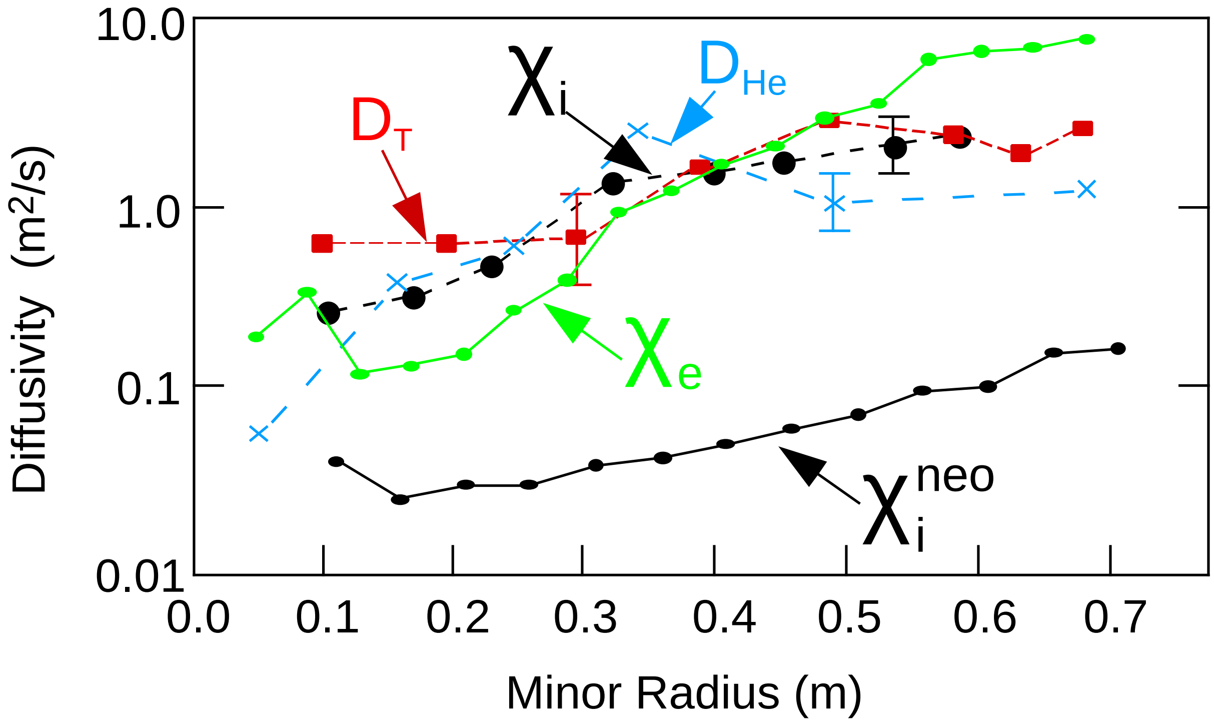
Radial Transport Measurements Indicate ElectrostaticTurbulence is Important



- **Experimental transport coefficients: $D_T \approx D_{He} \approx \chi_e \approx \chi_i >> \chi_i^{neo}$**
  - excludes strong magnetic stochasticity
- **Turbulence spectrum characterized by long wavelength modes ($k\rho_i \approx 0.2$)**
  - anisotropic spectrum
- **Ion dynamics are important in turbulent spectrum**
  - $T_i/T_i > n_i/n_i$

Univ. of Wisconsin

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THEORETICAL PREDICTIONS FOR ELECTROSTATIC TURBULENCE SUPPRESSION

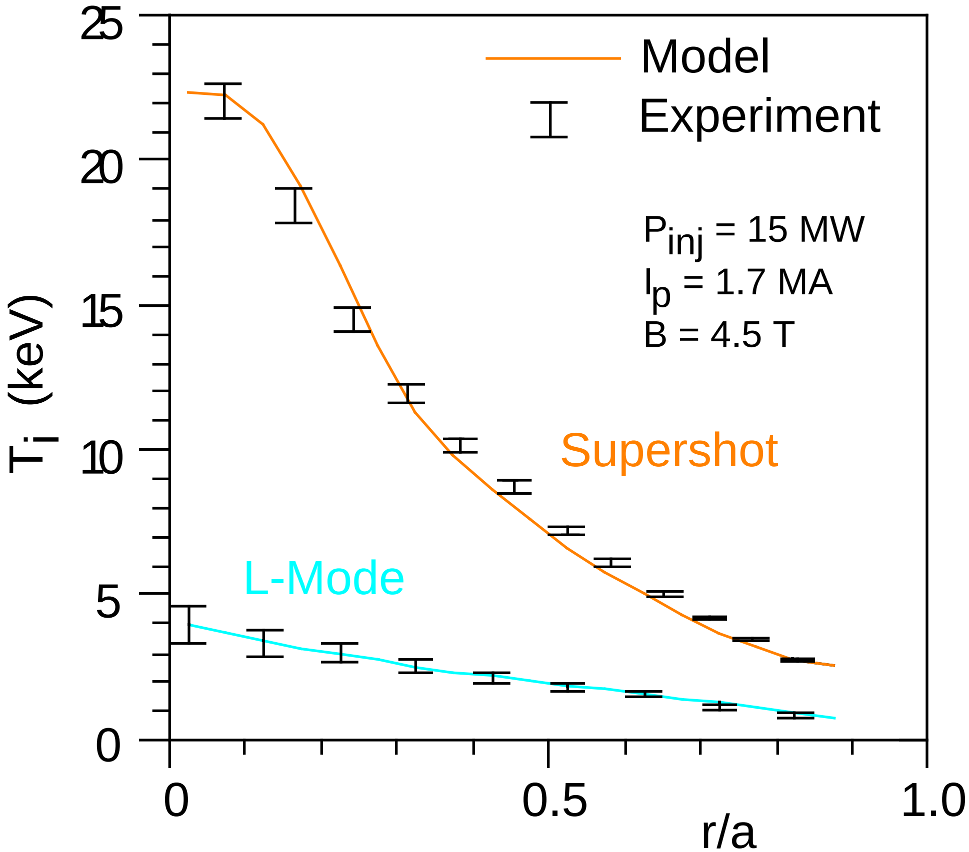
- **Suppression of Ion Temperature Gradient Modes by**
  - peaking of density profile
  - $T_i > T_e$

- **Flow shear stabilization due to gradients in E_r/B_p**

- **Current Profile Modification: Large shift of the Shafranov axis in the core region**

  $\alpha = -q^2R\,(d\beta/dr)$
  - increase fraction of trapped particles with favorable drifts

Model of ITG Modes with Radial Electric Field Shear Reproduces L-Mode to Supershot Trends



Reduced edge recycling produces Supershot:

- Core highly sensitive to edge
- χ_i reduced by factor of ~8
- Favorable power scaling

Toroidal Ion Temperature Gradient Mode with E_r shear:

- Instability threshold improves with T_i/T_e and $n_e(0)/n_e(\text{edge})$
- Central T_i dependent on edge T_i

D. R. Ernst
PhD Thesis
MIT (1997)

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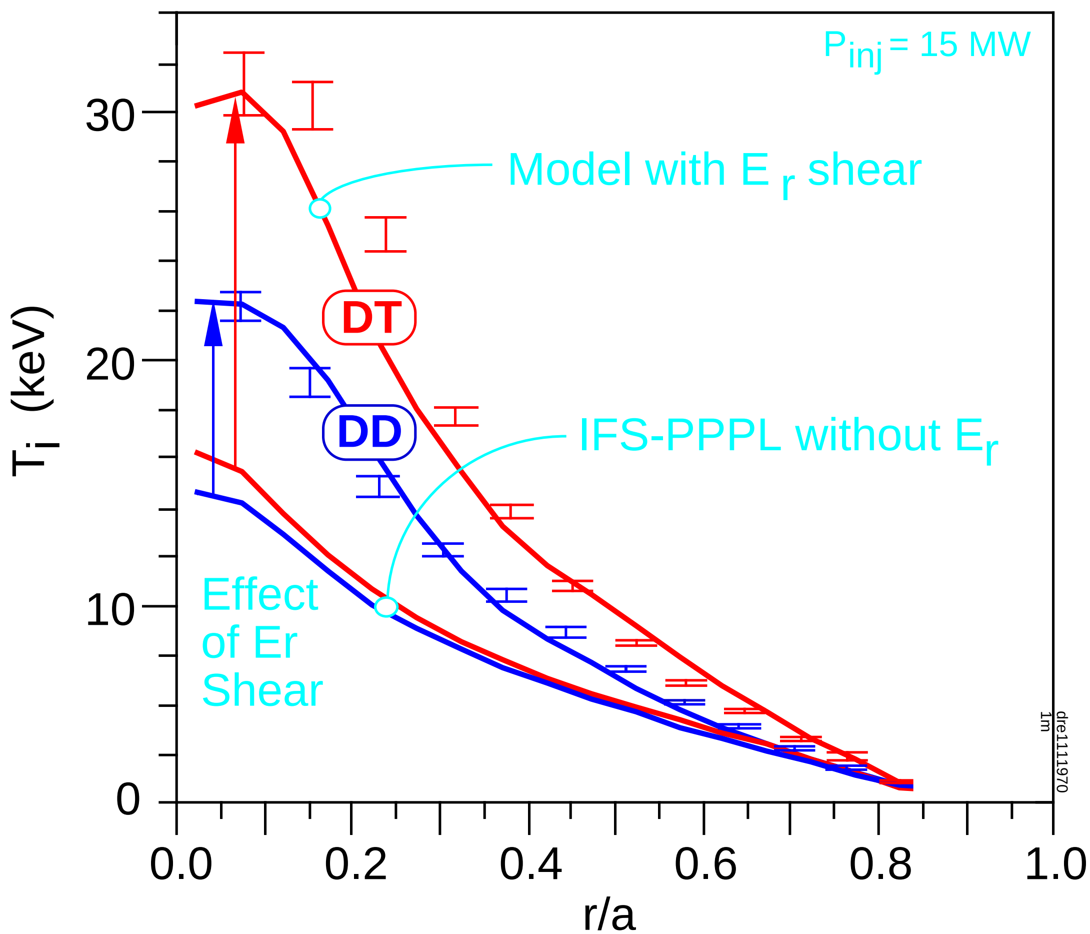
HIGHER ION TEMPERATURES ACHIEVED IN DT SUPERSHOTS



- χ_i is lower across the profile.
- Maximum linear growth rate decreases with ion mass.
- E_r shearing rate increases with T_i.
- **Radial Electric Field Shear Reproduces Strong Isotope Effect.**

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

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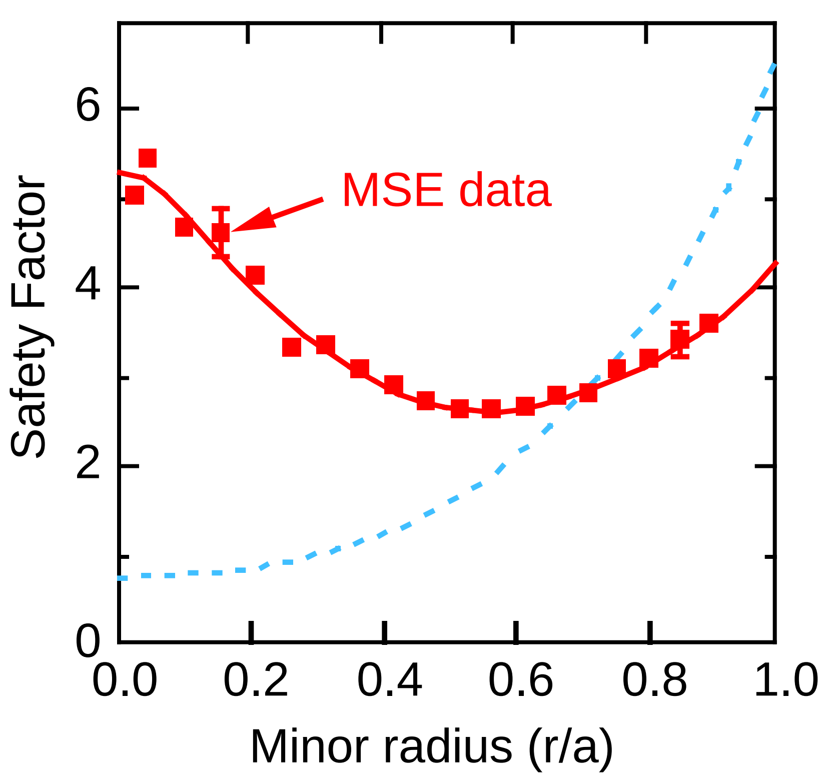
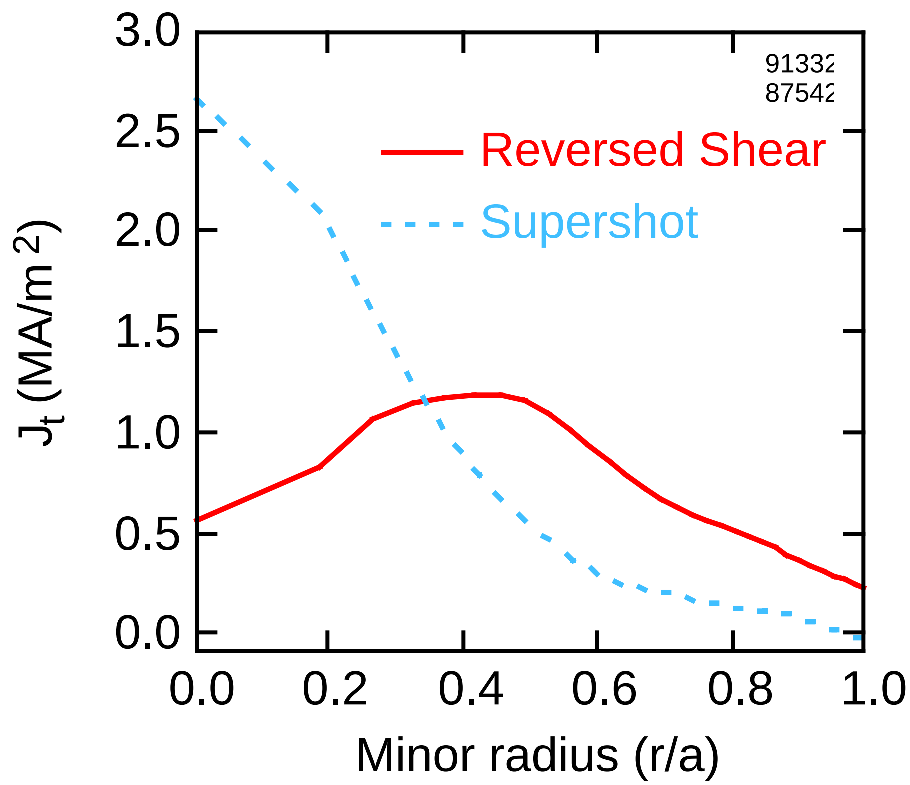
Current Profile Measurements Enabled Exploration of New Operating Regimes





F. Levinton

Fusion Physics and Technology

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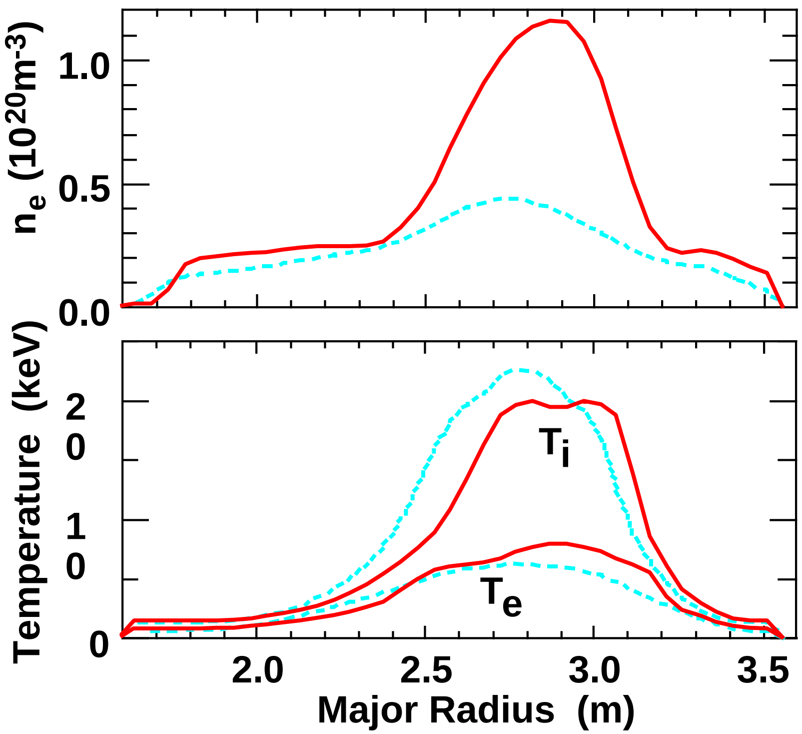
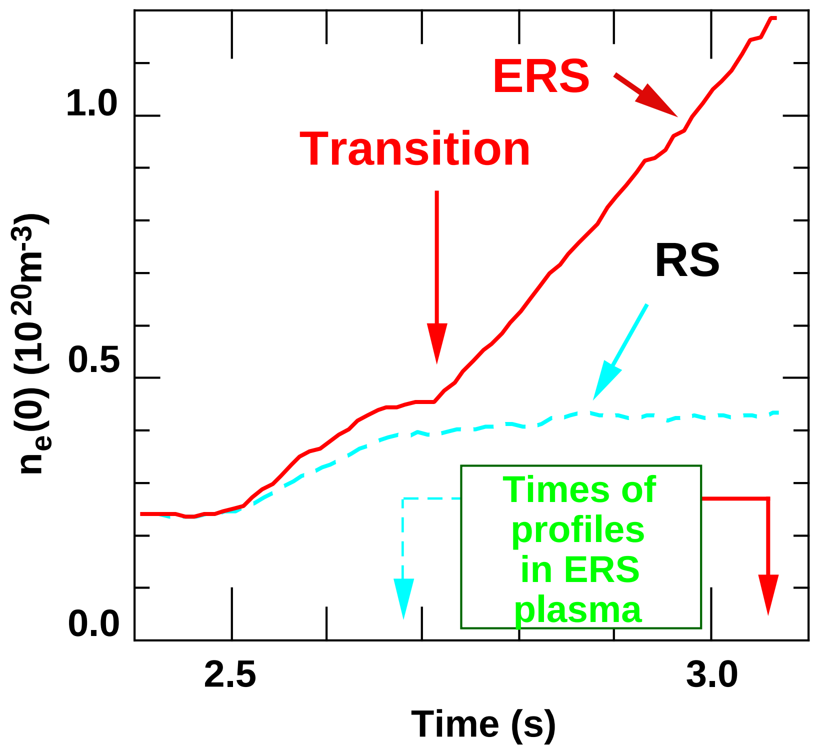
REVERSED-SHEAR PLASMAS CAN TRANSITION TO A REGIME OF ENHANCED CONFINEMENT: ERS





- **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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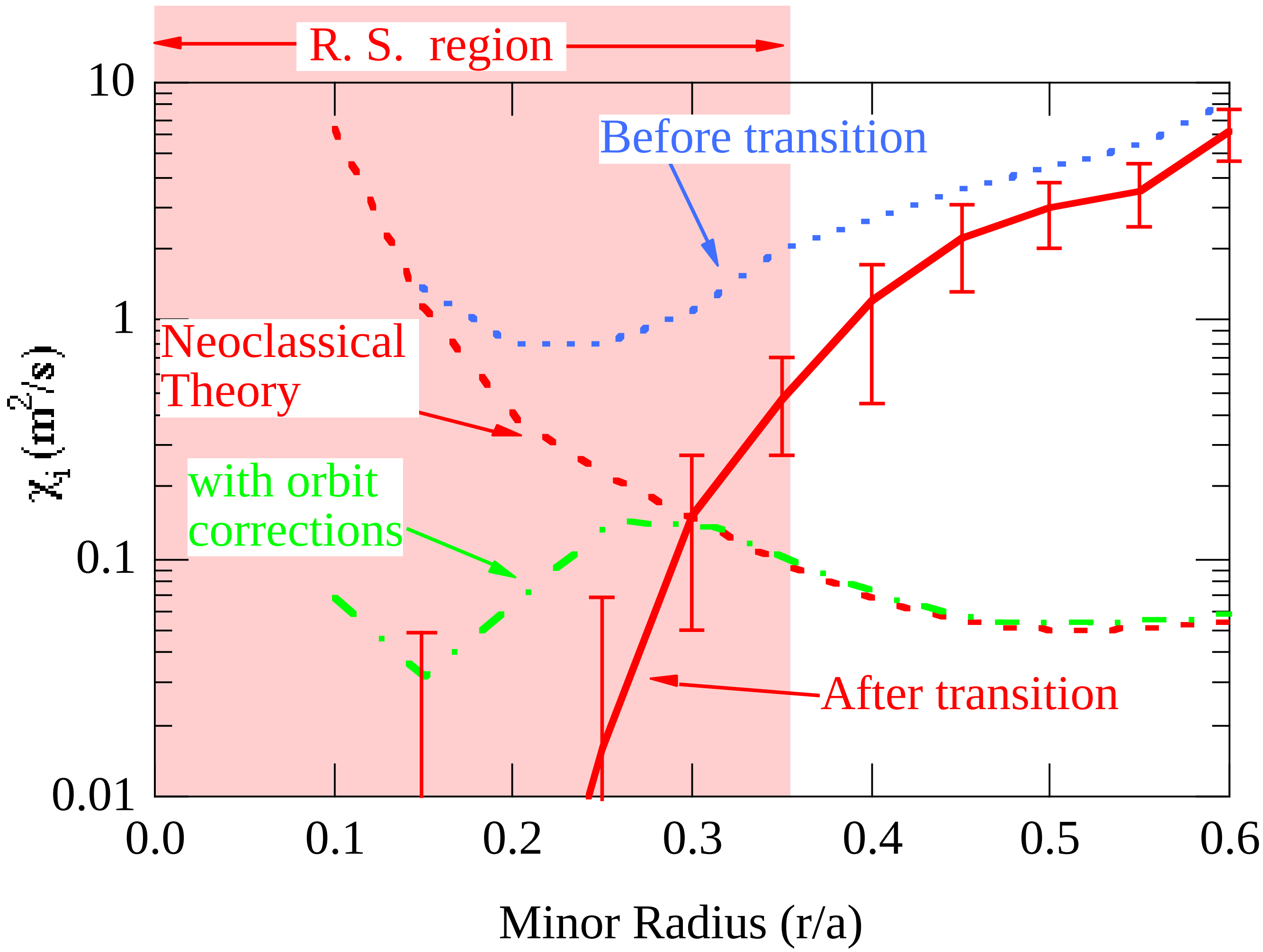
Ion Thermal Conductivity is Drastically Reduced in Core of Enhanced Reversed Shear Mode



- **D_e reduced by factor of 10-50 approaching D_e^{neo}**
- **χ_e relatively unaffected.**

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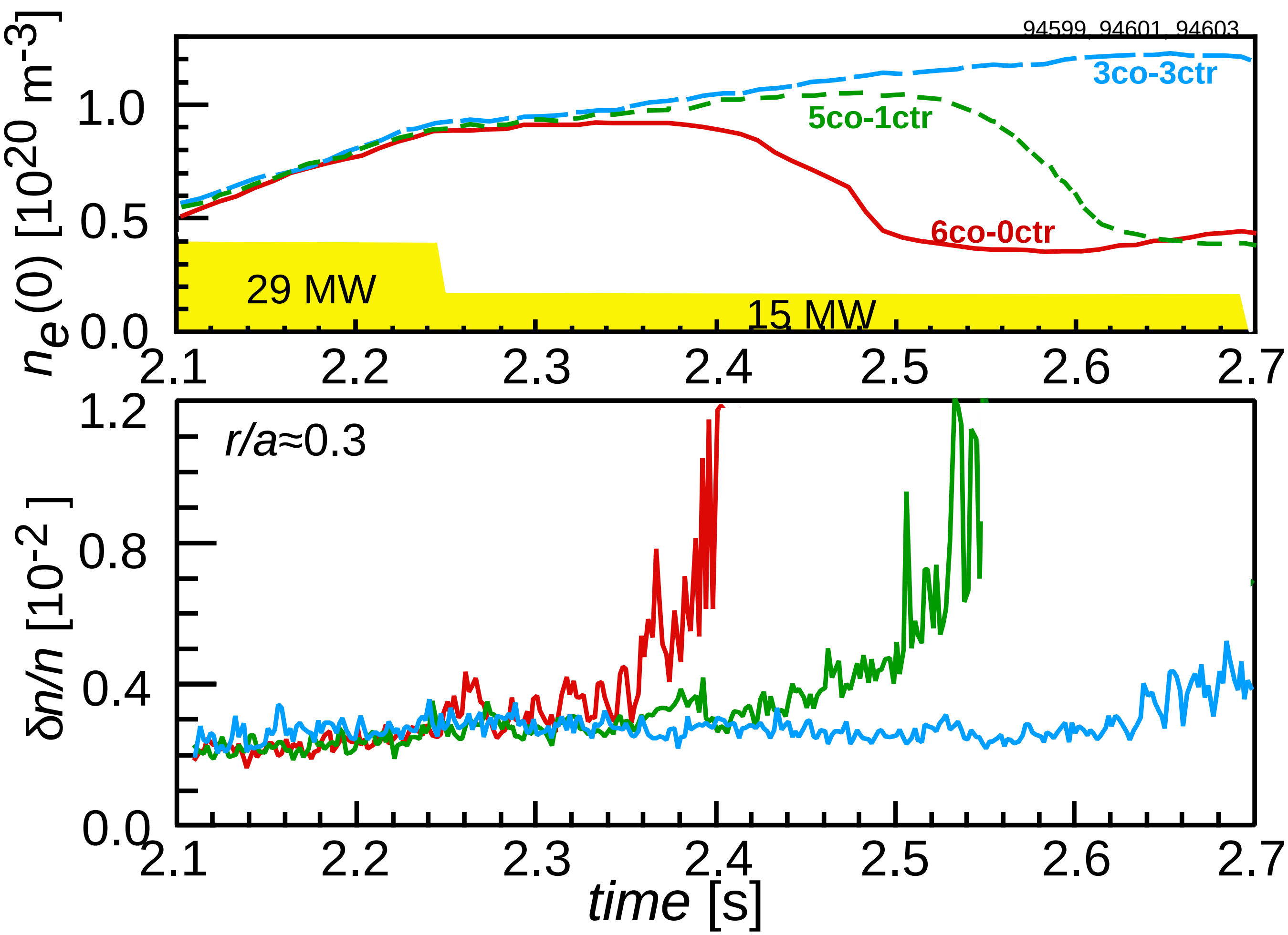
RJH-97-
013a

TRANSPORT BARRIER EVOLUTION CONTROLLED WITH NEUTRAL BEAM TORQUE



- ERS relaxation coincides with an increase in fluctuations
- Demonstrates the role of **E**x**B** velocity shear stabilization.

E. Synakowski; E. Mazzucato

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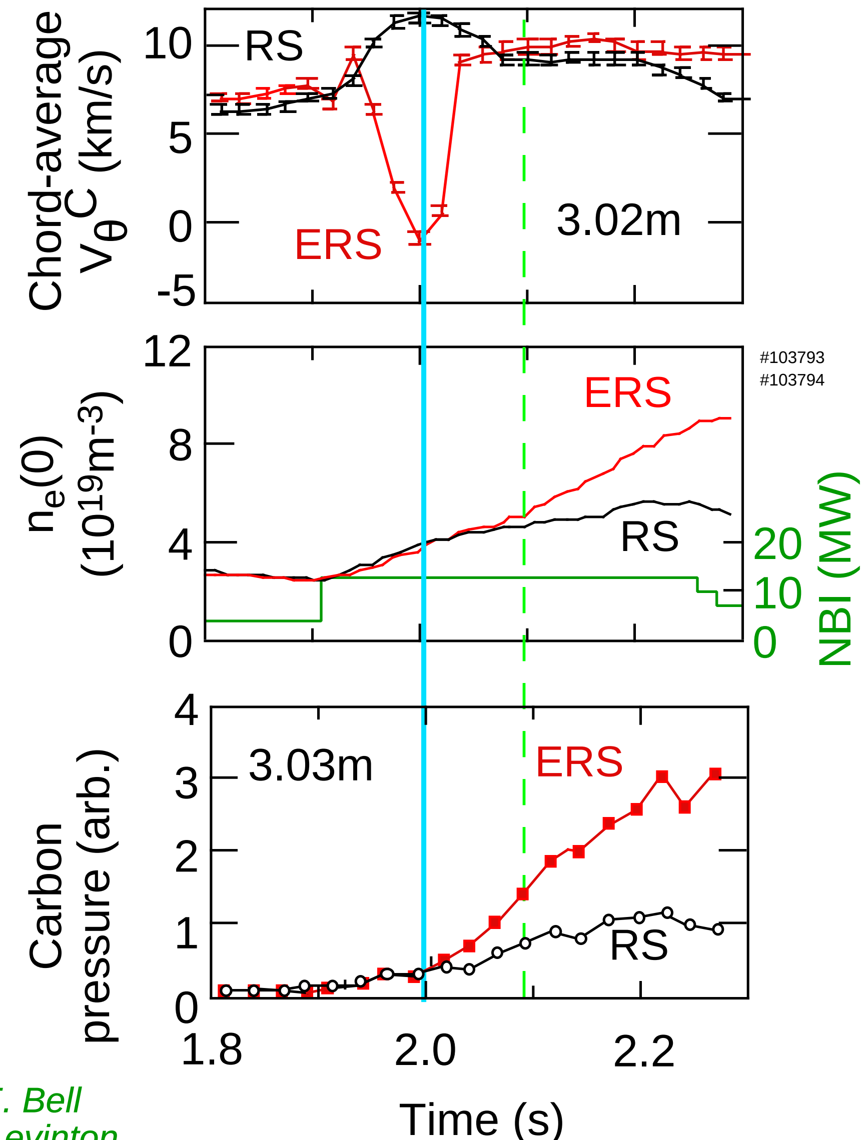
Large Excursion in V_θ^C Prior To Observed Confinement Change In ERS



- Excursion in V_θ^C implies a large radial electric field.
  - **Large electric field excursions observed on MSE measurements**
- Transition first evident as an increase in ion (carbon) pressure
- What is the cause for the excursion in $V_\theta^C >> V_\theta^{NC}$?

R.E. Bell
F. Levinton
E. Synakowski

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Fusion Physics and Technology

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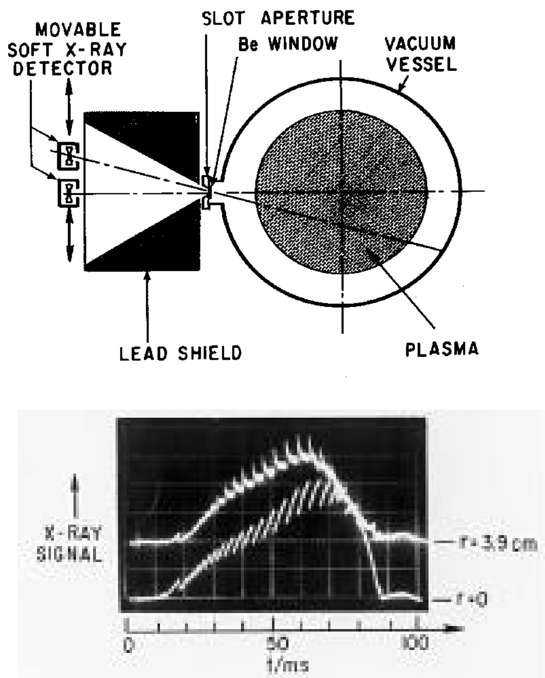
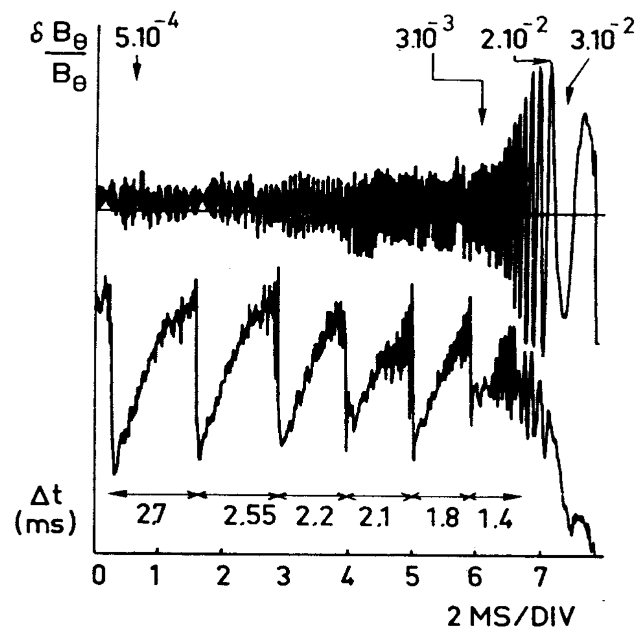
MHD STUDIES: STATUS 1976

- MHD equilibrium used to estimate the pressure limits
  - β_p ~ R/a

- Experimental and theoretical work identified
  - Resistive tearing modes
  - Sawteeth
  - Disruption mechanisms



Experimental arrangement of x-ray detectors and sawteeth on the ST tokamak



Development of sawteeth and an m= 2 mode before a disruption on TFR

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PROGRESS IN MHD STABILITY IS CRITICAL FOR FUSION

- **High power heating experiments revealed plasma pressure limits. (1980s)**

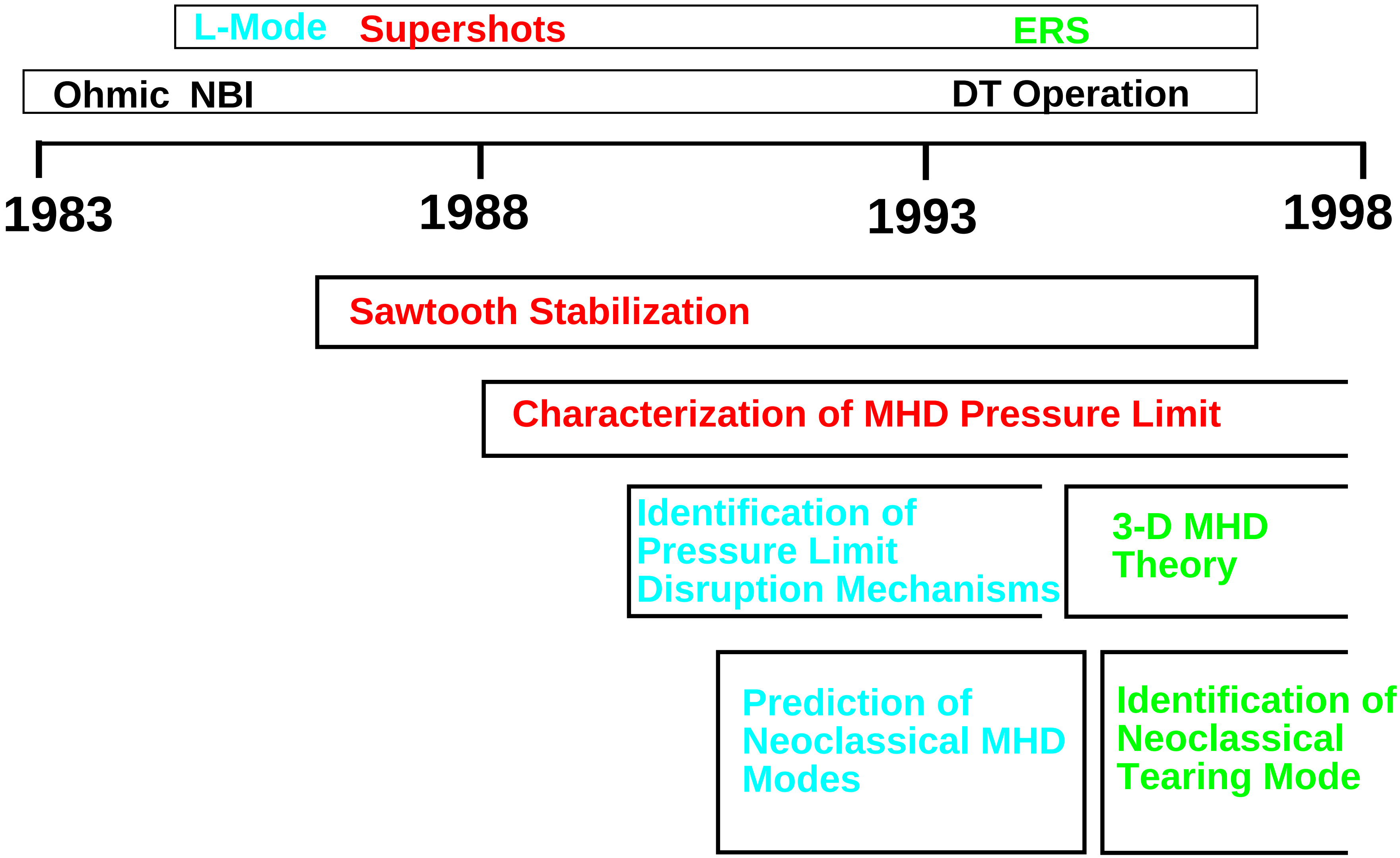
- **Two-dimensional ideal MHD stability limits evaluated** **for optimized profiles**:
  - Low n-modes: $\beta_N = \beta_T/(I_p/aB_T) < 2.8$ (Troyon scaling)
  - Ballooning modes: $\beta_N = \beta_T/(I_p/aB_T) < 4.4$ (Sykes scaling)

$$P_{fusion} = \int n_i^2 < \sigma\nu > (17.6\ \mathrm{MeV})dV \sim \int n_i^2\, T_i^2\, dV\, [< \sigma\nu >/T_i^2]$$

$$\beta_i^{*2} B^4 V \sim \quad (\beta_i^*/\beta_t)^2 \quad \bullet \quad (I_p B_T)^2\, \kappa R \quad \bullet \quad \beta_N^{\,2} \quad \bullet \quad [< \sigma\nu >/T^2]$$

$(\beta_i^*/\beta_t)^2$	$(I_p B_T)^2\, \kappa R$	$\beta_N^{\,2}$	$[< \sigma\nu >/T^2]$
Hot Ion & Pressure Profile Peaking	Machine Parameters	MHD Stability	Non-Maxwellian

MHD STABILITY STUDIES ON TFTR



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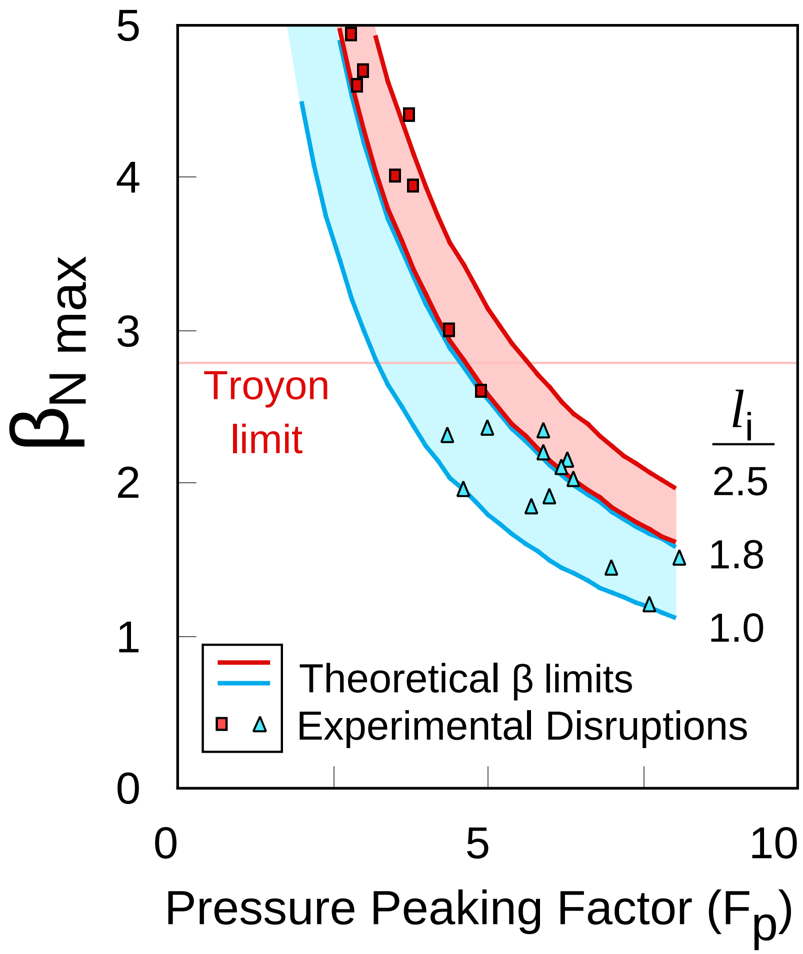
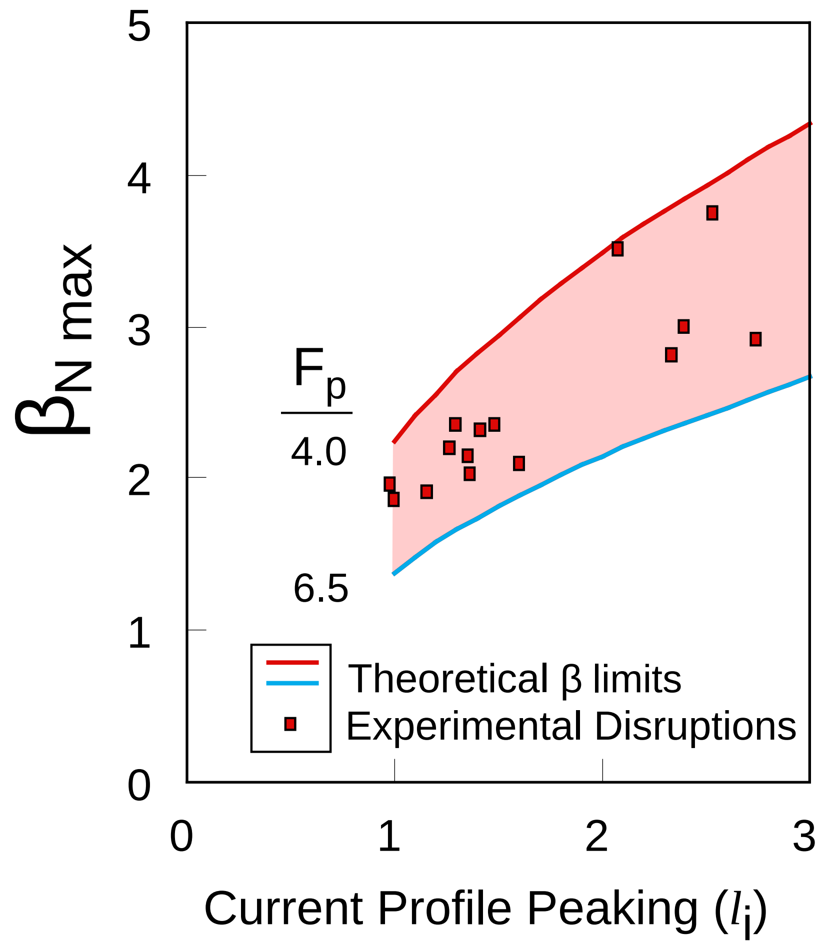
IDEAL MHD PROVIDES GUIDANCE OF β LIMIT DEPENDENCE ON PROFILE SHAPING





- Theoretical β limit computed from PEST with q(0) = 1
  - with q(0) < 1, experimental β_N exceeds ideal calculation

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S. Sabbagh

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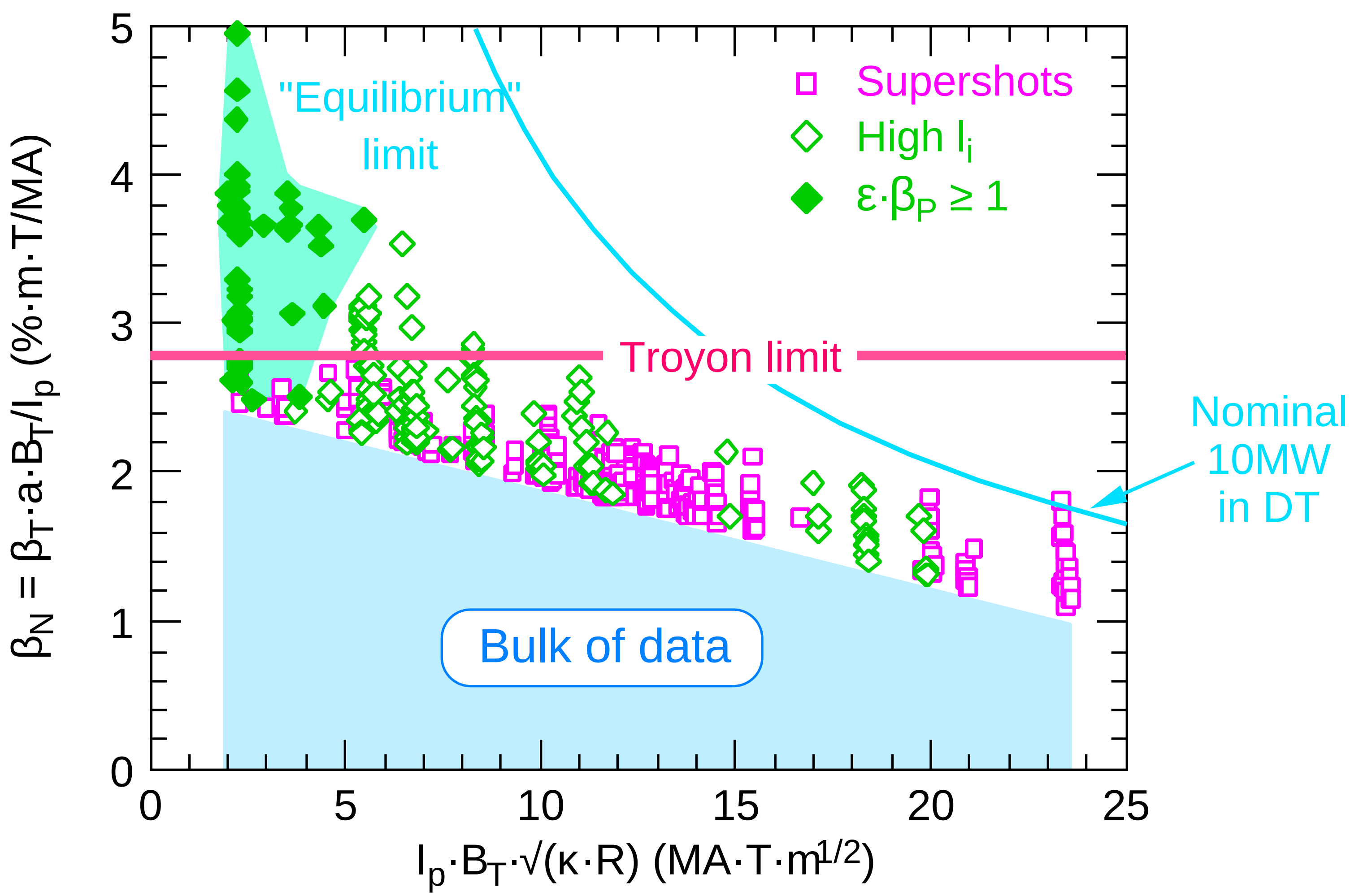
Advanced Regimes Achieved High Normalized Beta but at Reduced Machine Parameters



P_{DT} $(\langle p_i^2\rangle/\langle p\rangle^2)$ × β_N^2 × $I_p^2 \cdot B_T^2 \cdot \kappa \cdot R_p$ × $\langle\langle\sigma v\rangle/T^2\rangle$

Hot ions, profiles — Stability — Machine parameters — Non-Thermal

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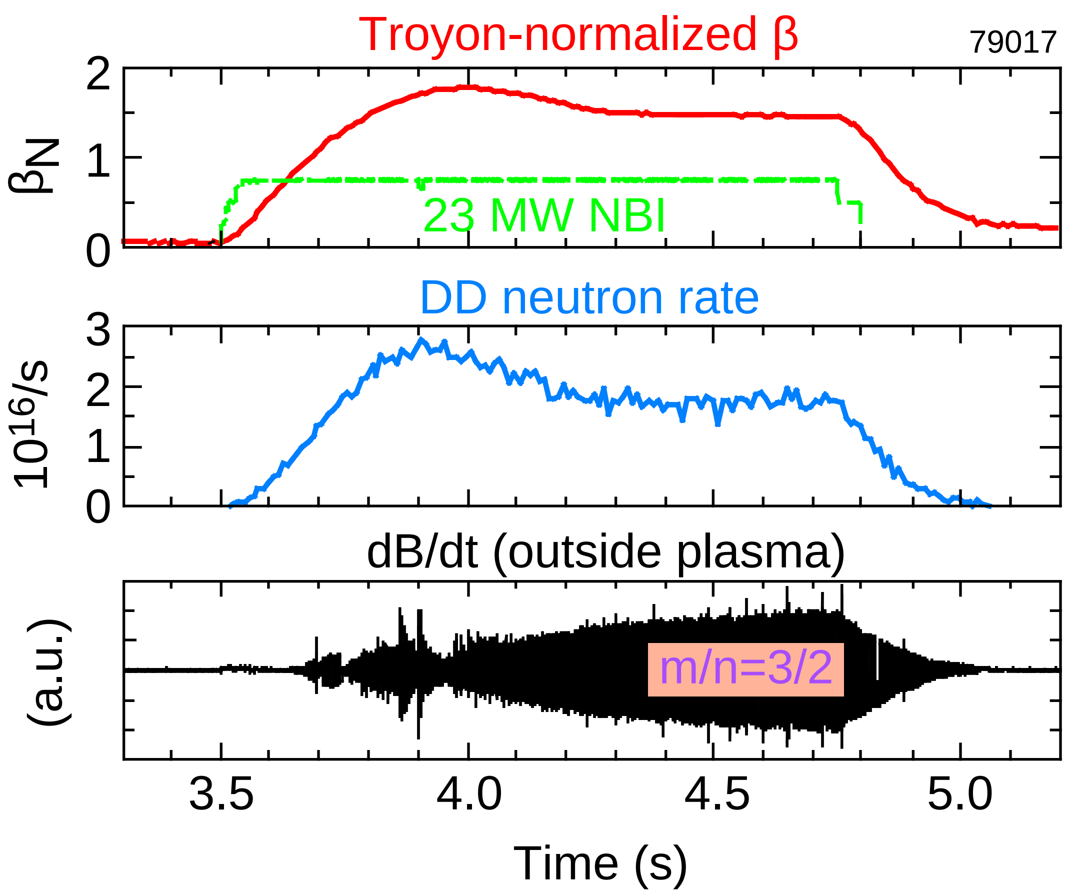
Neoclassical MHD Instabilities Can Degrade Confinement Below Ideal β-Limit



- 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

Z. Chang

University of Wisconsin

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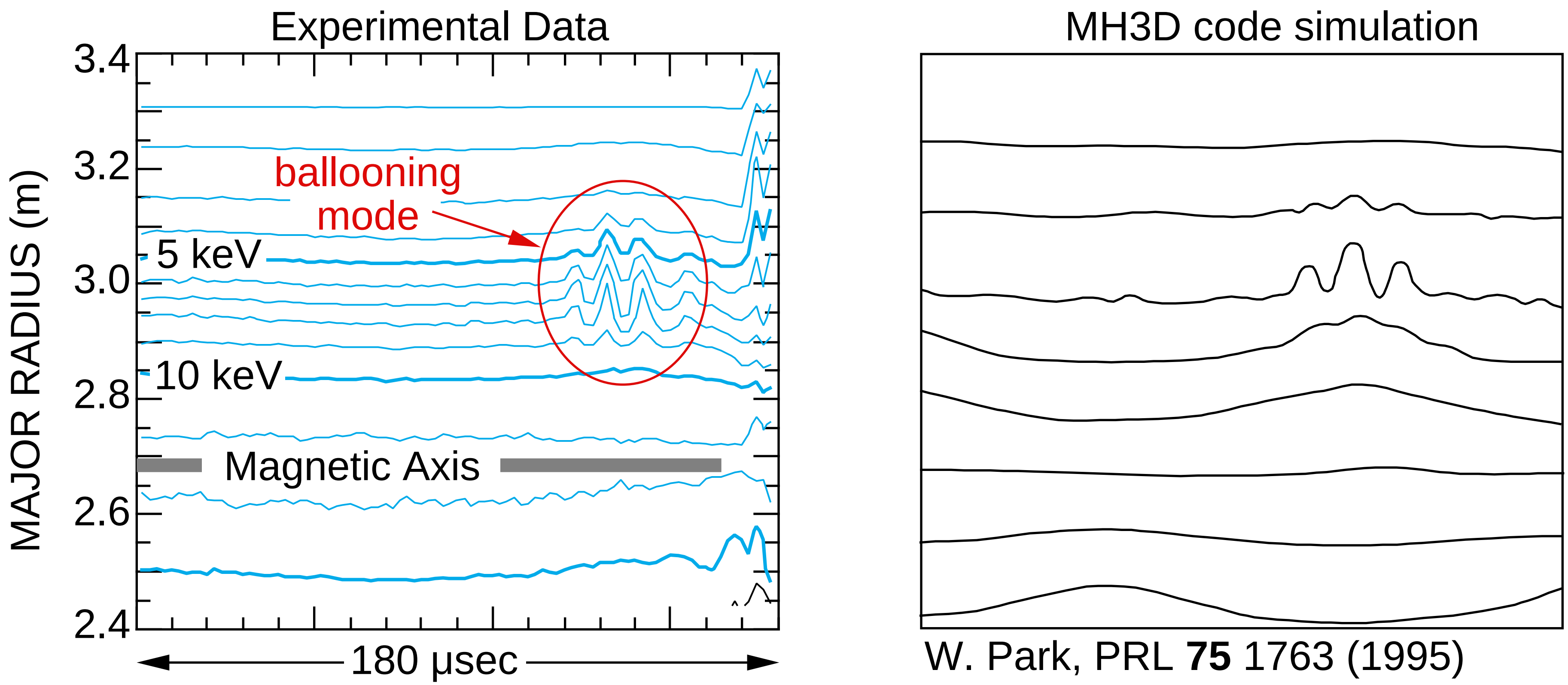
Successful Simulation of the Complex Interplay Between n=1 Kink and Ballooning Modes.



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

- Nonlinear numerical simulations find n=1 kink drives local ballooning modes unstable leading to disruptive collapse

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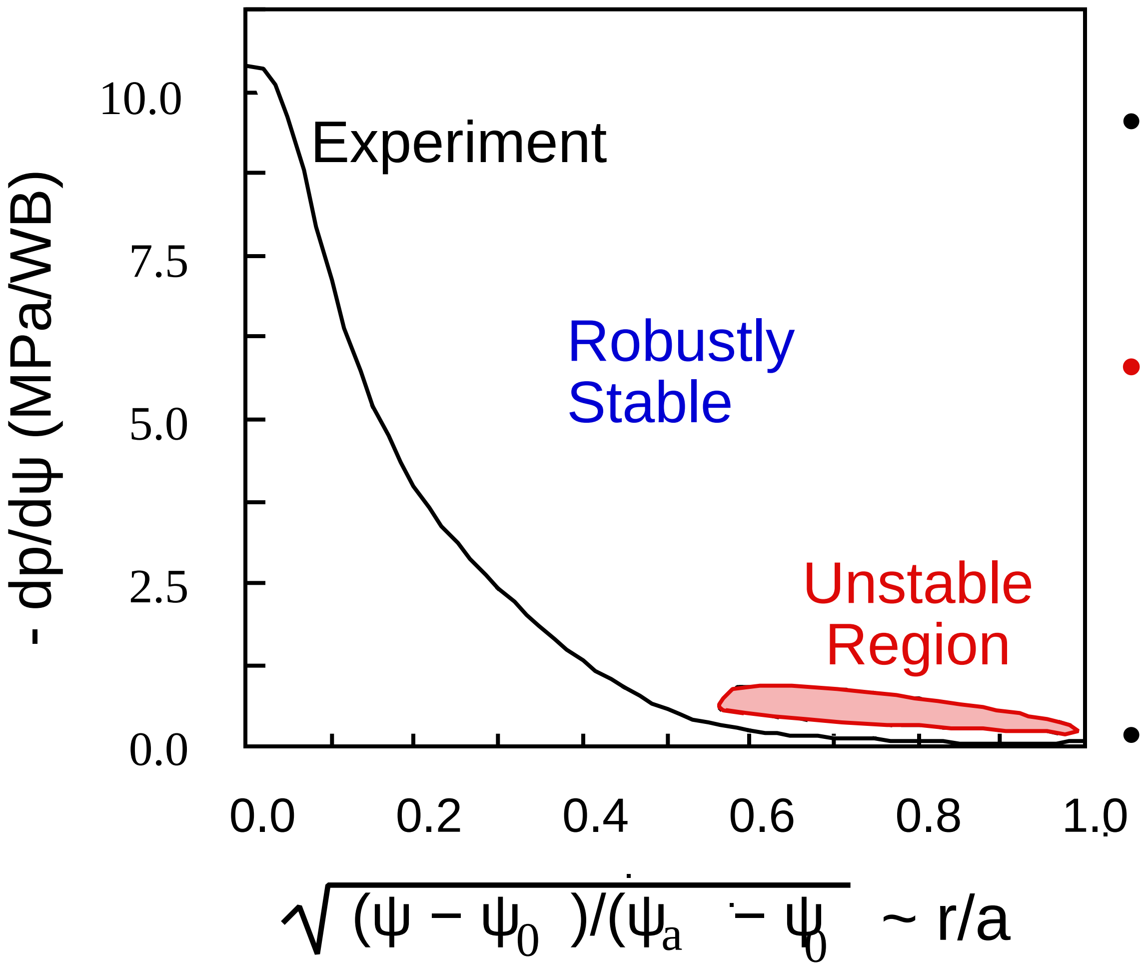
Reverse Shear Plasmas are Robustly Stable to High-n Modes in Plasma Core



- Robust stability region extends to 80% of minor radius in some plasmas.
- **Low n neoclassical tearing modes are observed to be stable in the reverse shear region.**
- Confirmation of theory

S. Sabbagh

RJH-97-028

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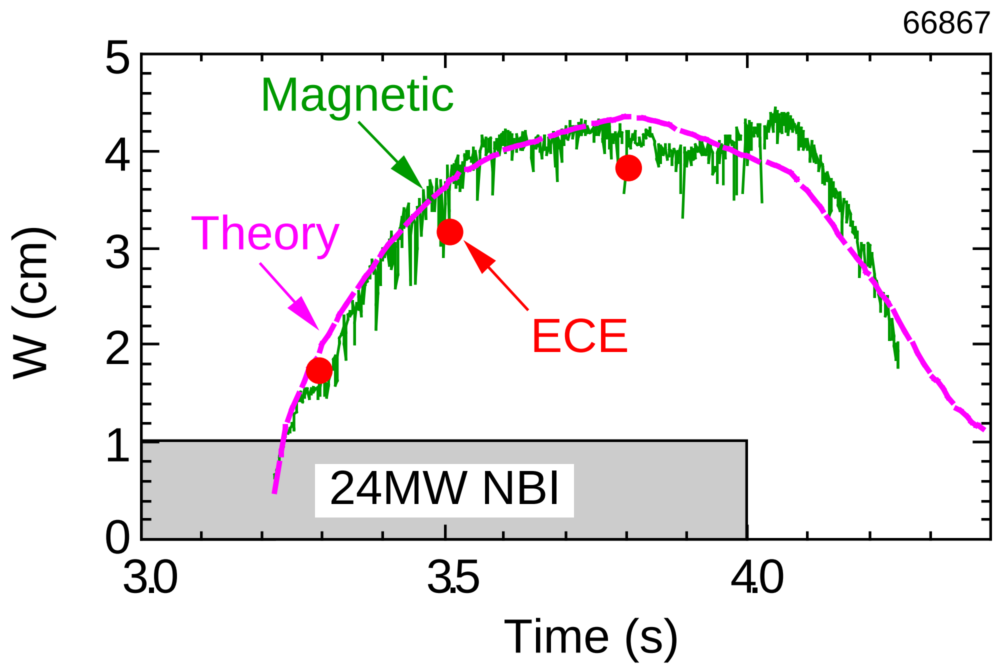
THEORY SUCCESSFULLY PREDICTS ISLAND WIDTHS FOR LOW m/n NEOCLASSICAL MODES

- m/n=4/3 island



- **Further work required on threshold criteria.**

Z. Chang

University of Wisconsin

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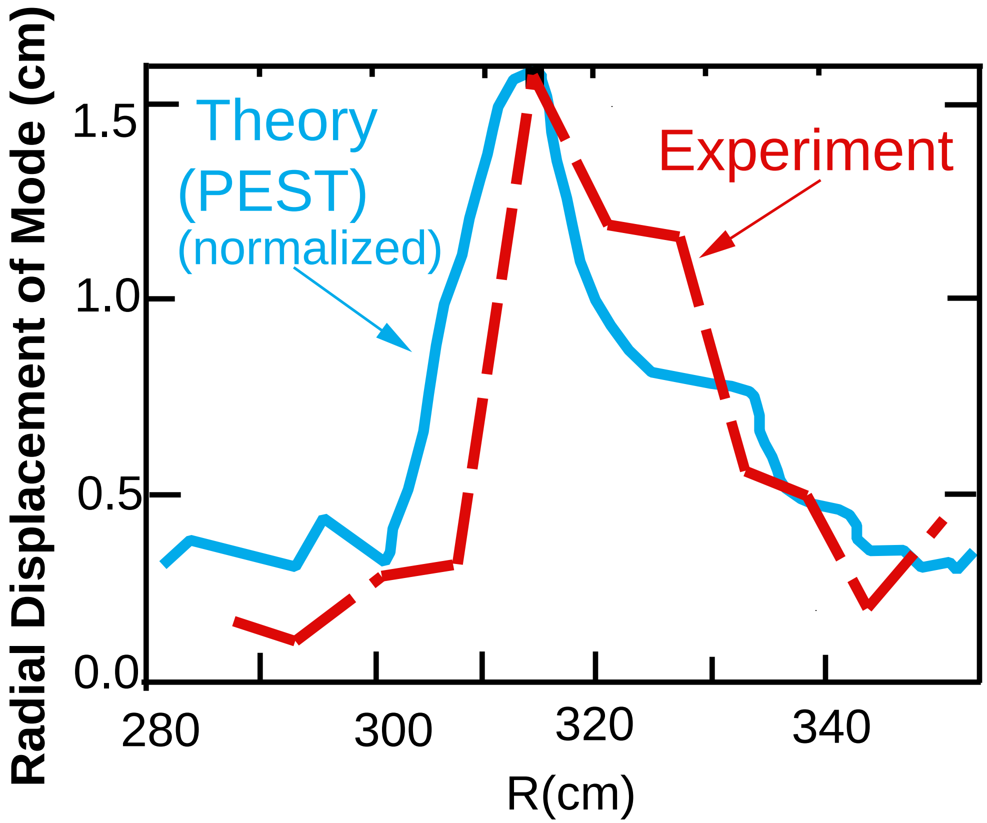
DISRUPTIONS IN ERS DISCHARGES ARE CONSISTENT WITH IDEAL MHD THEORY



- Pressure limit due to sharp pressure gradients and evolution of current profile.
- ERS beta limit consistent with low-n infernal mode destabilization.
  - $\beta_N < 2$.
- Mode localization and structure in good agreement.
- **Control of transport barrier and current profile evolution is essential.**

Northrop-Grumman Aerospace Corp.

Culham Laboratories

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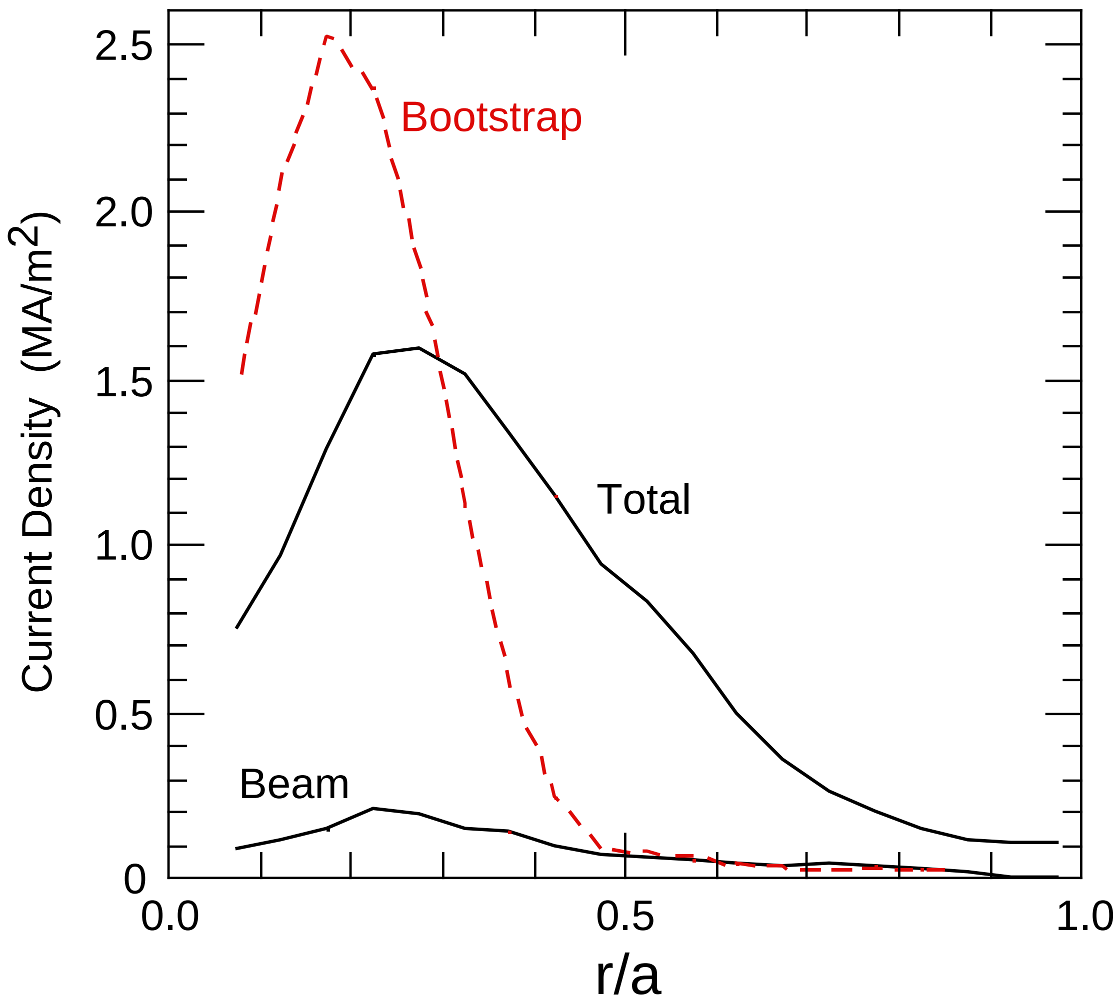
Highly Peaked Pressure Profiles in ERS Plasmas Create Too Much Bootstrap Current Inside q_{min}



- **Excess bootstrap current causes q-profile to evolve towards unstable configurations.**

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SAFE TRITIUM OPERATION DEMONSTRATED

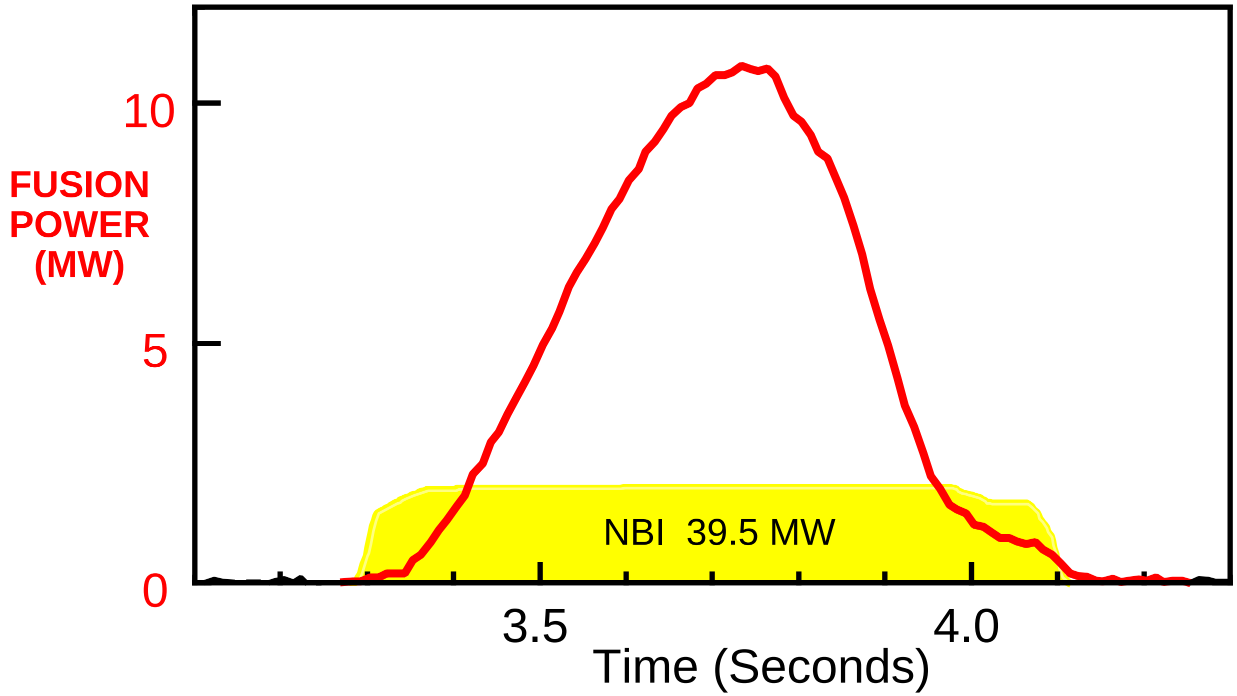
- **Tritium neutral beam and gas puffing used to fuel the plasma**

- **Tritium Purification System successfully processed tritium in a closed cycle.**
  - 99 grams of tritium processed

- **Dose at site boundary <0.4 mrem/year**
  - Design goal < 10 mrem/year.

Highest Fusion Performance in TFTR Achieved in Low Recycling Supershot Plasmas

P_{fus} = 10.7 MW, $P_{fus} / P_{heat} \approx 0.27$, $\beta_\alpha(0) \approx 0.3\%$



- **Increased fusion power by:**
  - Reducing recycling by Lithium conditioning
  - Increasing plasma current and toroidal field for stability (I_p=2.7MA, B_T=5.6T)
  - Operating at maximum neutral beam power

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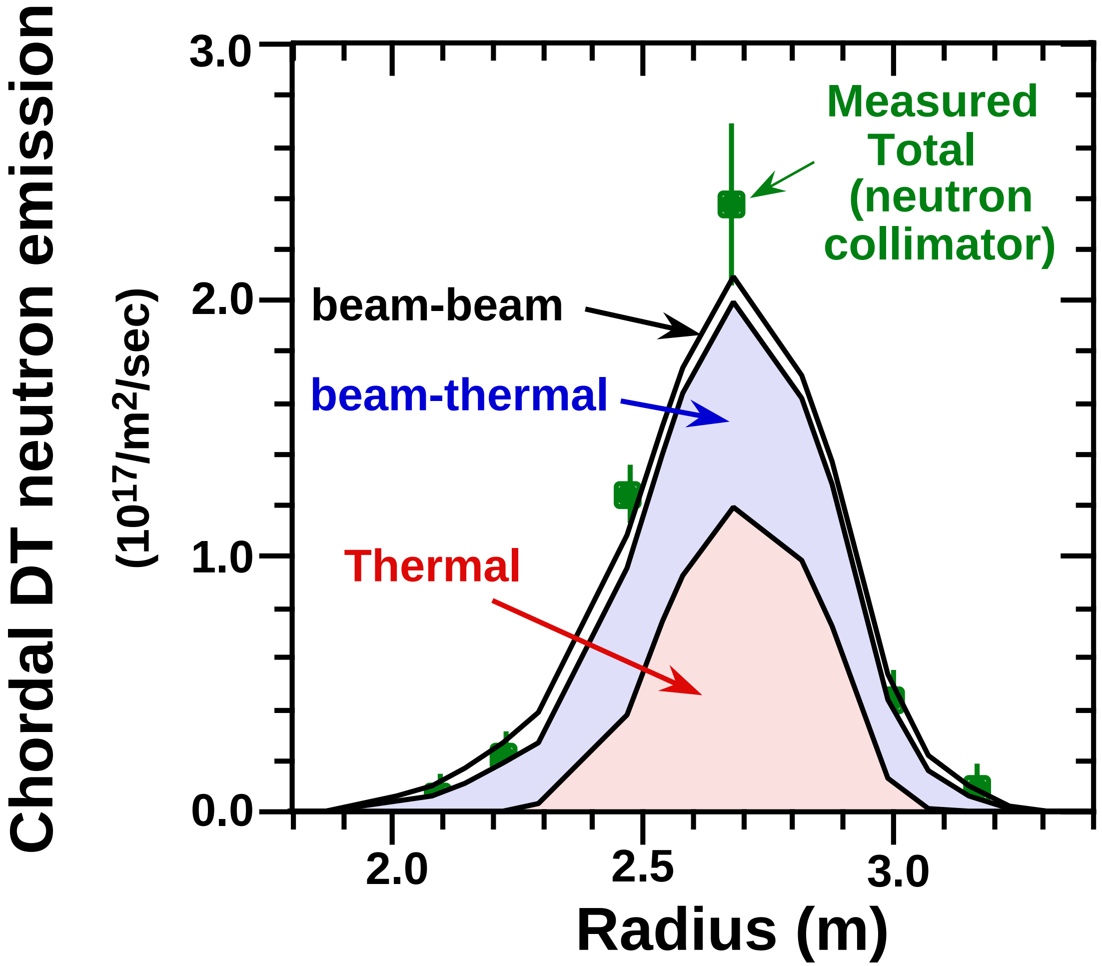
D-T Neutron Emission in Supershots is Consistent with Calculations Based on Plasma Parameters



- Validates classical beam thermalization
- Thermonuclear component of fusion power > 50% in core

RJH-97-033

R. Budny

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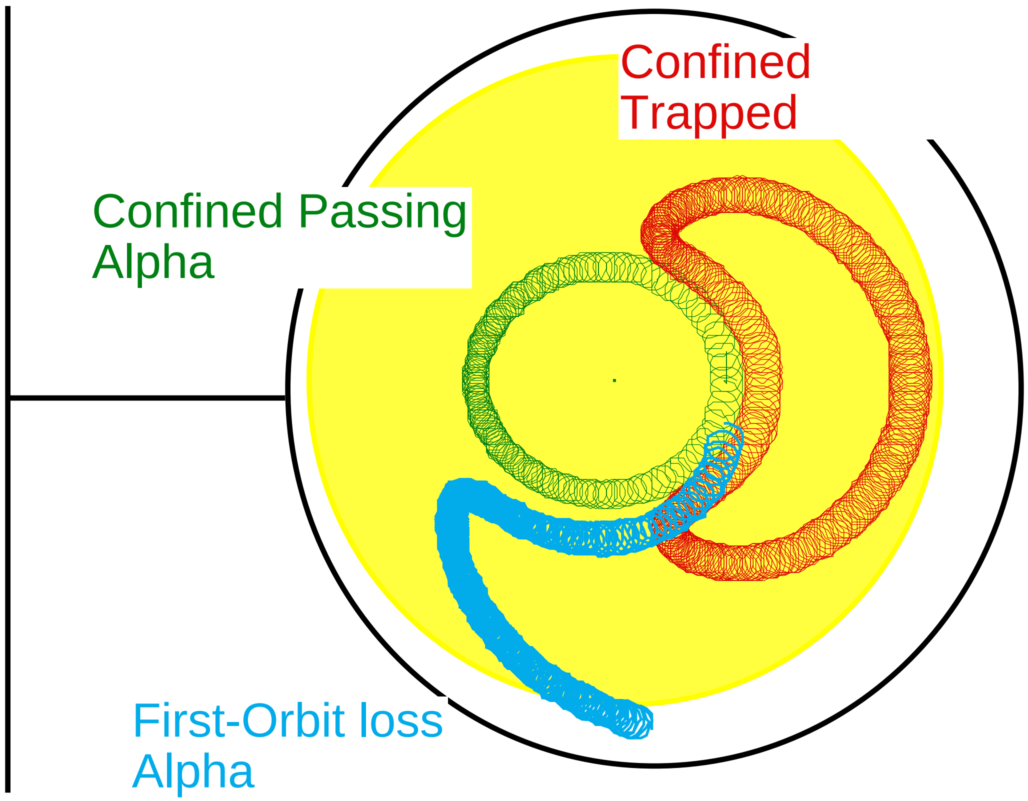
ALPHA-PARTICLE PHYSICS: STATUS 1976

- Transfer of energy to the background plasma by Coulomb collisions (1950's)
- Passing and Trapped particle orbit effects
- Slowing-down spectrum of beam ions in good agreement with theory



Alpha Particle Orbits

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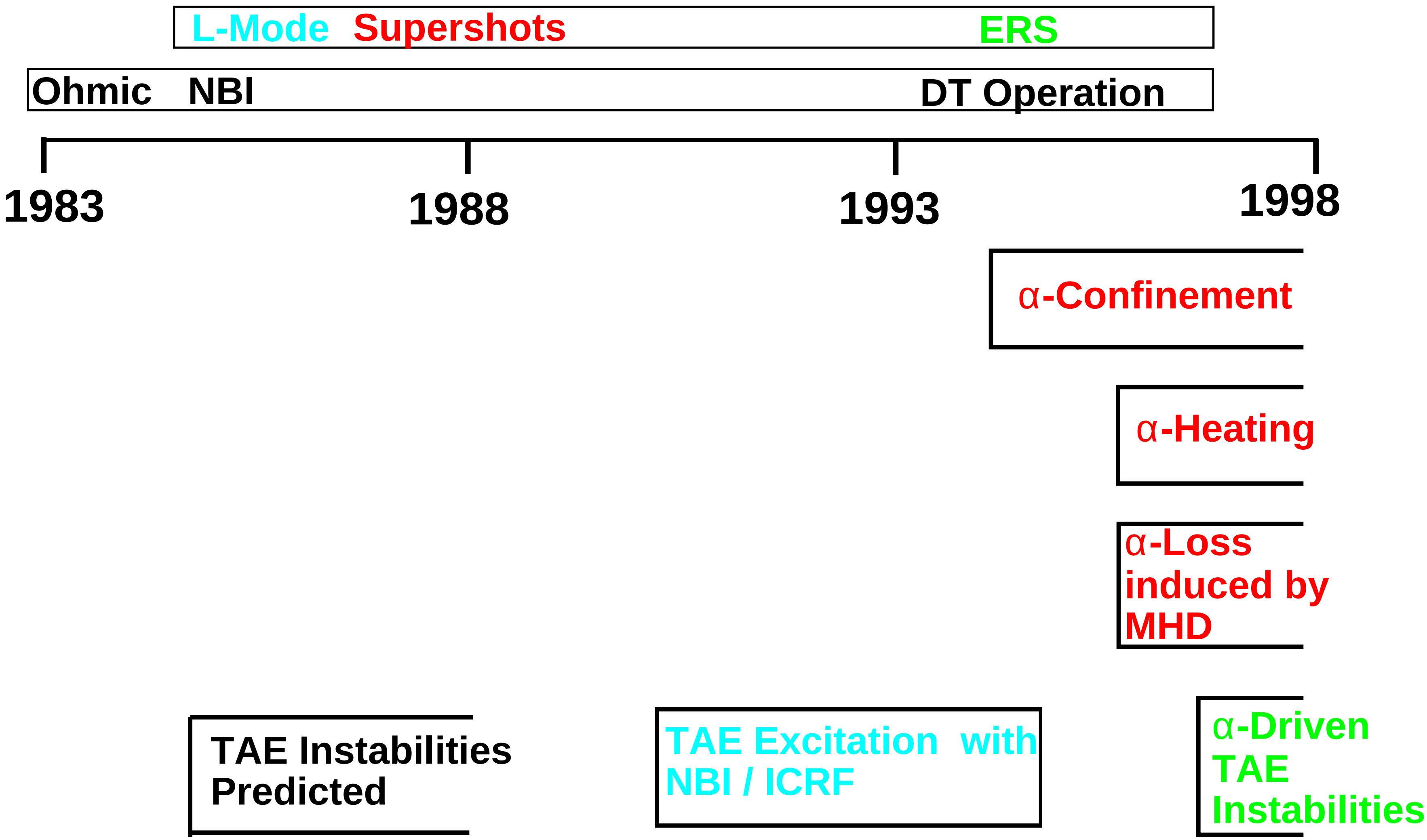
ALPHA-PARTICLE PHYSICS ON TFTR



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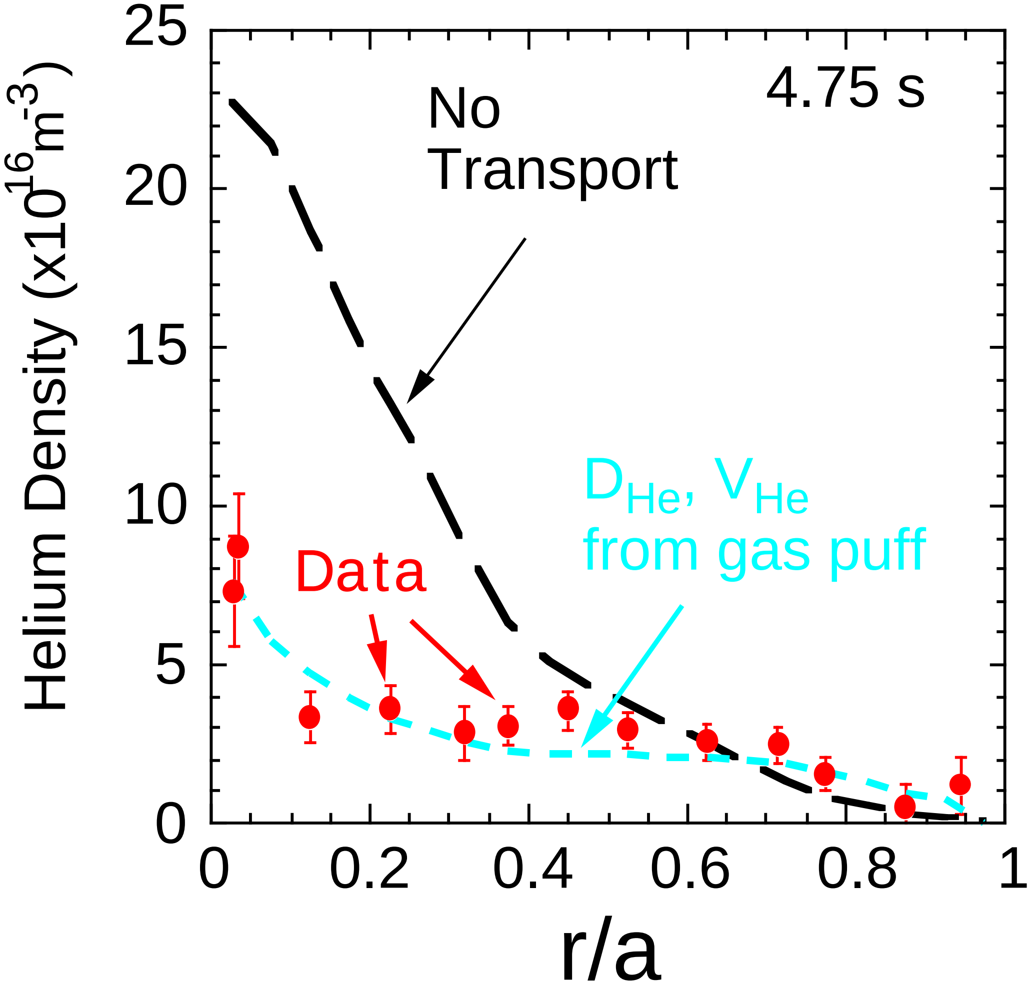
Rapid Ash Transport from the Core to the Edge in Supershots

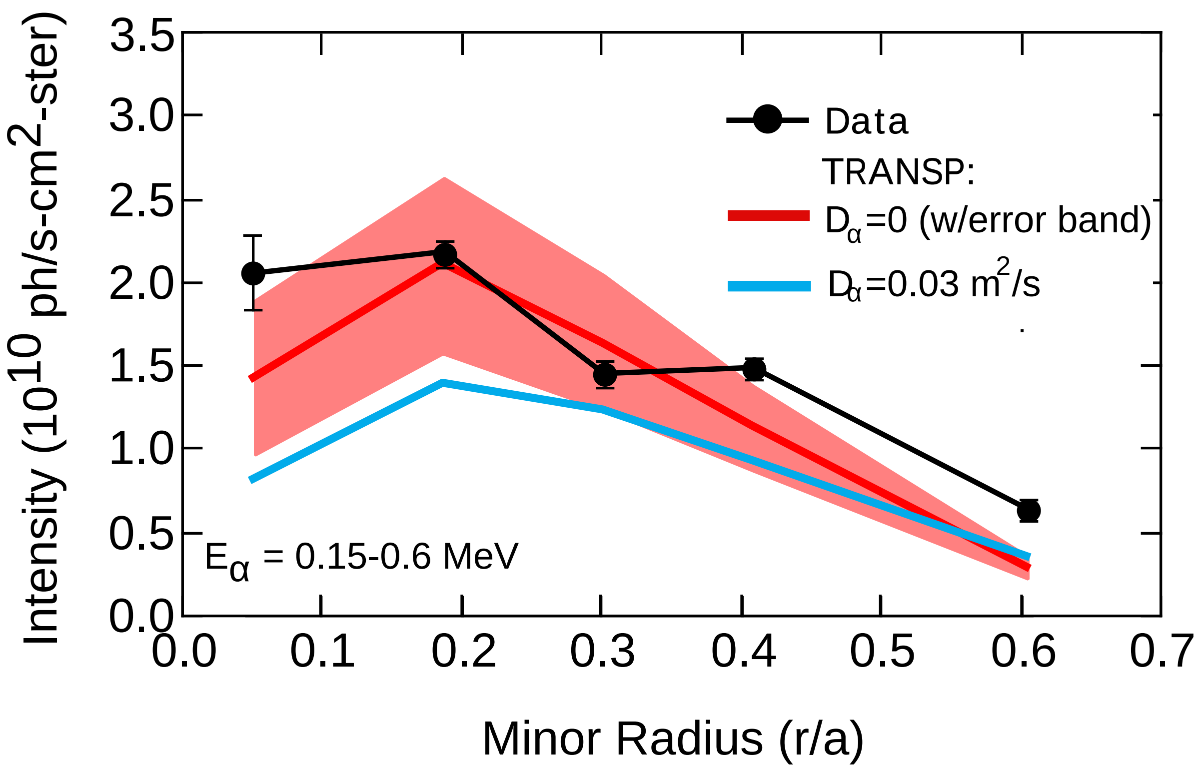


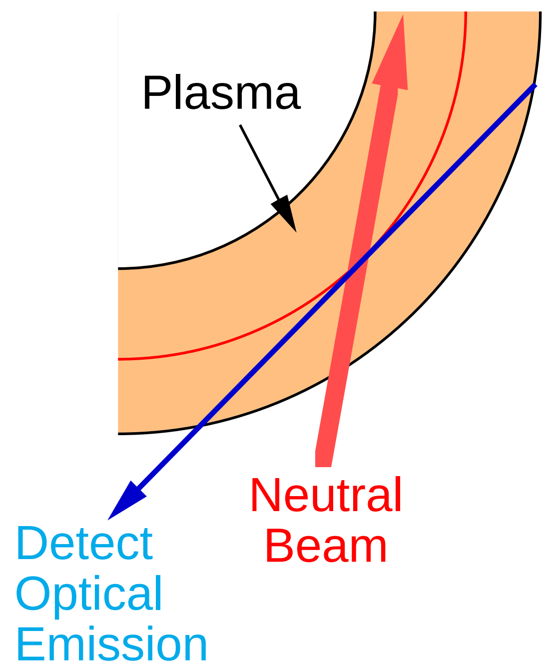
- Consistent with $\tau_p^{*He}/\tau_E = 8$, acceptable for a reactor

$D_{He} / \chi_D \sim 1$

E. Synakowski

ALPHA PARTICLES ARE WELL CONFINED

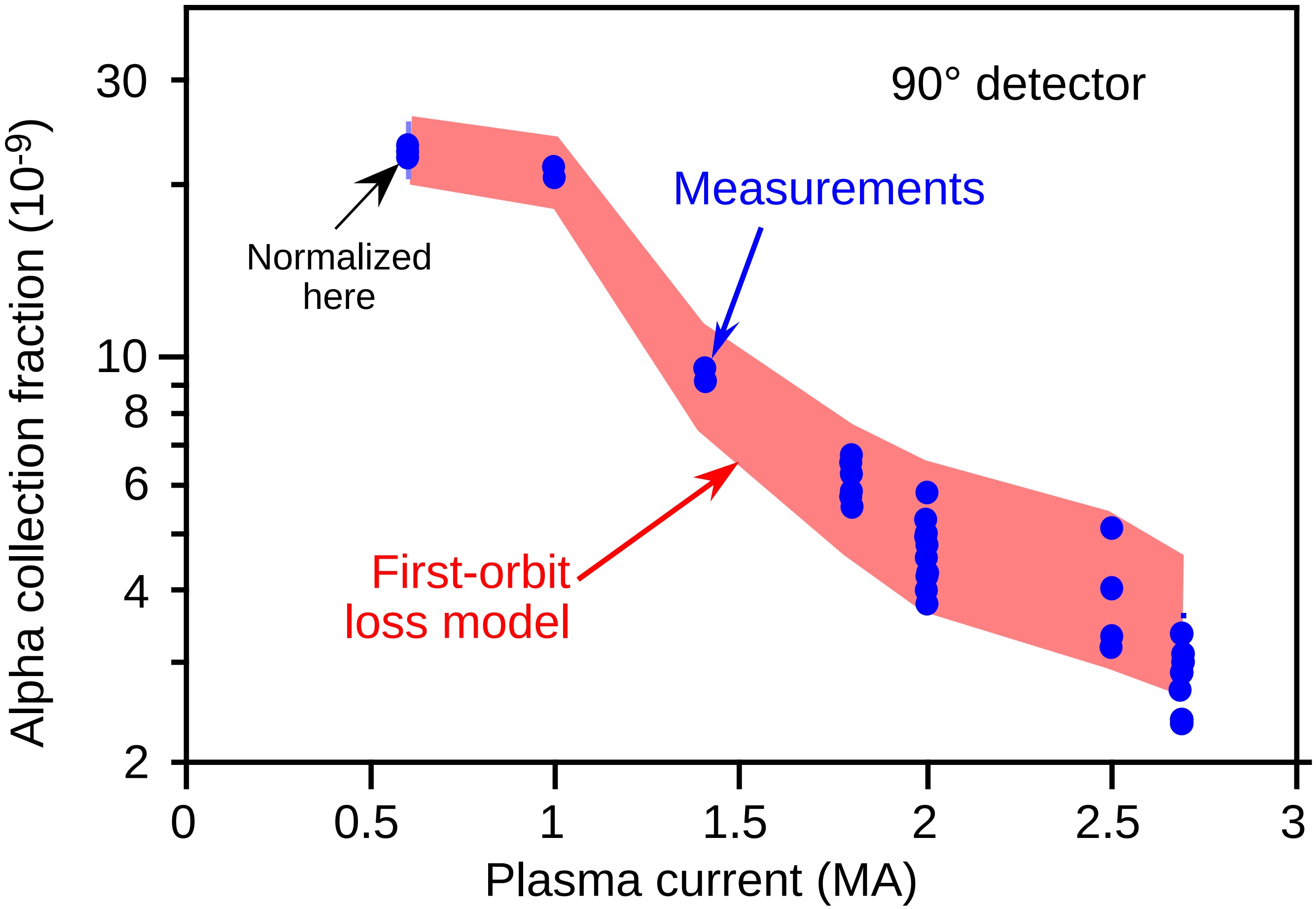


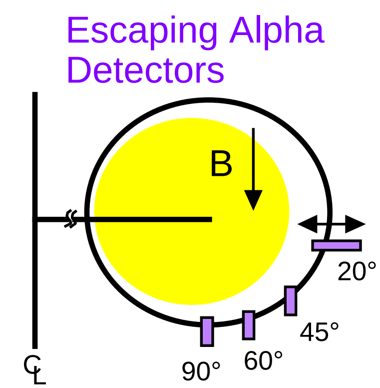


Charge exchange between fast beam neutrals and nonthermal alphas

· $0 \leq D_\alpha \leq 0.03$ m^2/s

Escaping Alpha Flux at 90° Detector is Consistent with Classical First Orbit Losses





- **At 2.5 MA, first orbit loss ≈ 3% globally**

S. Zweben
D. Darrow

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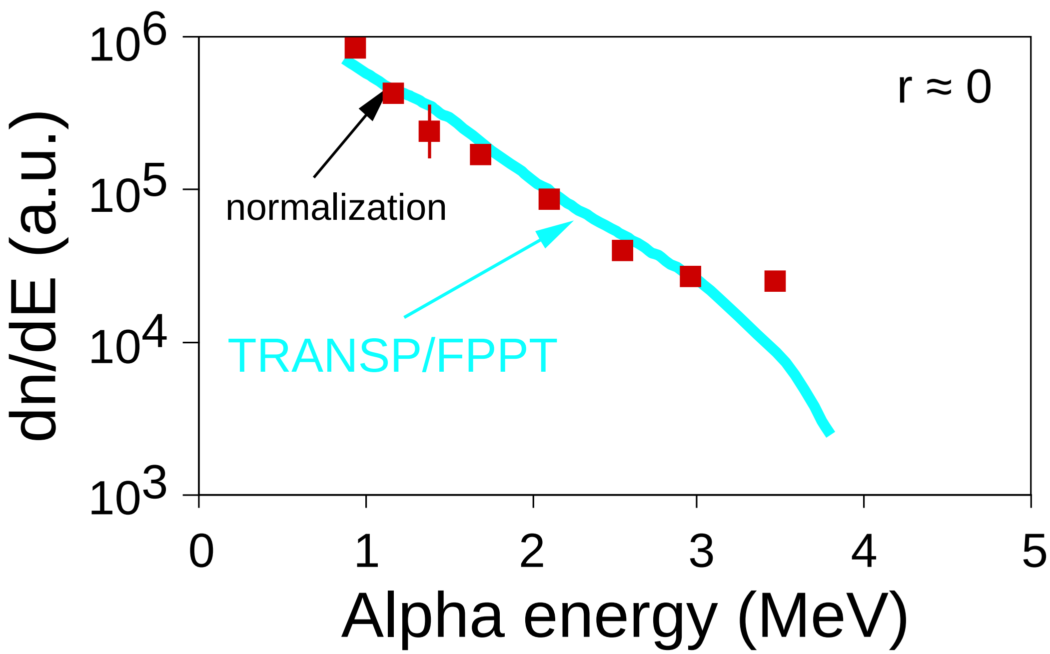
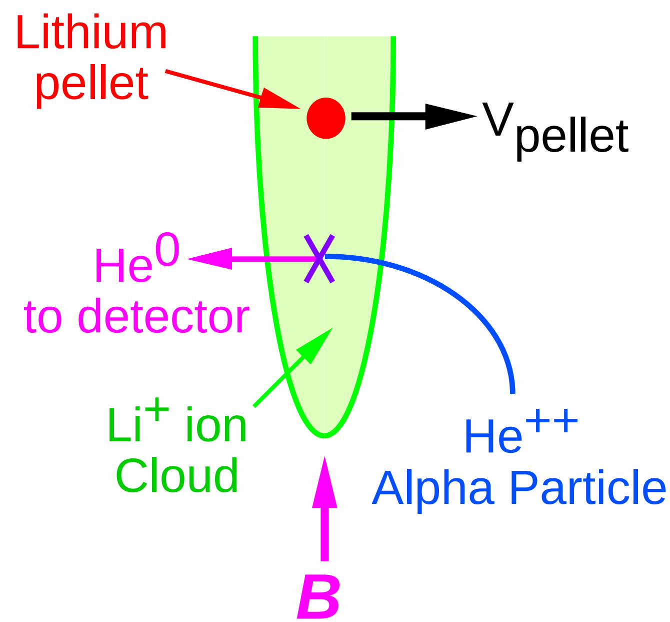
Confined Alphas in the Plasma Core show Classical Slowing Down Spectrum



Double Charge Exchange Technique

$He^{++} + Li^{+} \quad He^{0} + Li^{3+}$



- TRANSP calculation includes:
  - orbit trajectories
  - classical slowing down
  - time dependence of alpha production

RJH-97-041

GENERAL ATOMICS

Ioffe ФТИ

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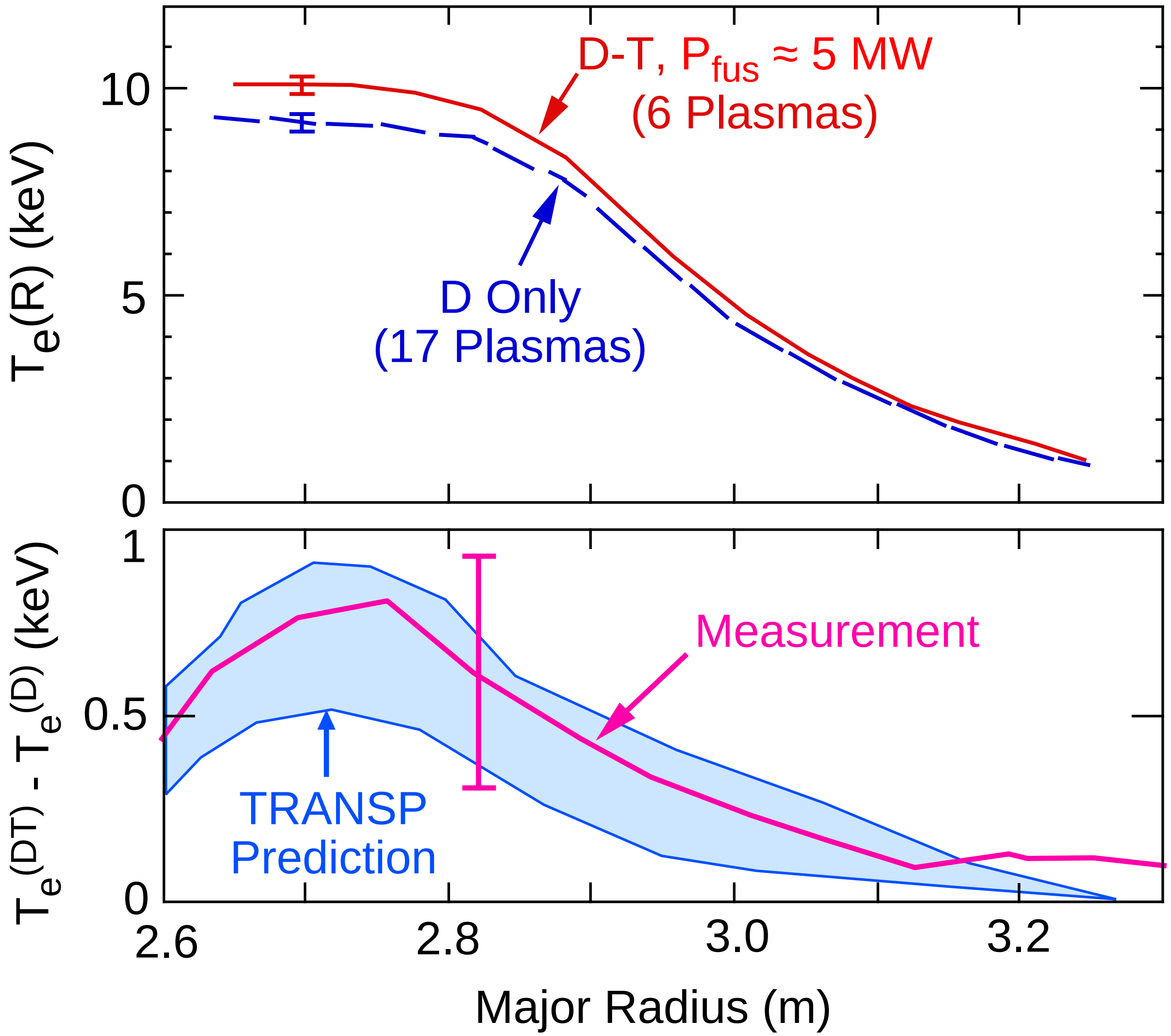
INITIAL EVIDENCE OF ALPHA-PARTICLE HEATING



- $p_\alpha(0)$ in TFTR comparable to that in ITER.
- Alpha heating ~10% of power through electron channel
- Plasmas matched for dominant T_e scaling in D only plasmas

- Comprehensive study of alpha heating requires $P_\alpha > P_{aux}$.

G. Taylor
J. Strachan

RJH-97-034

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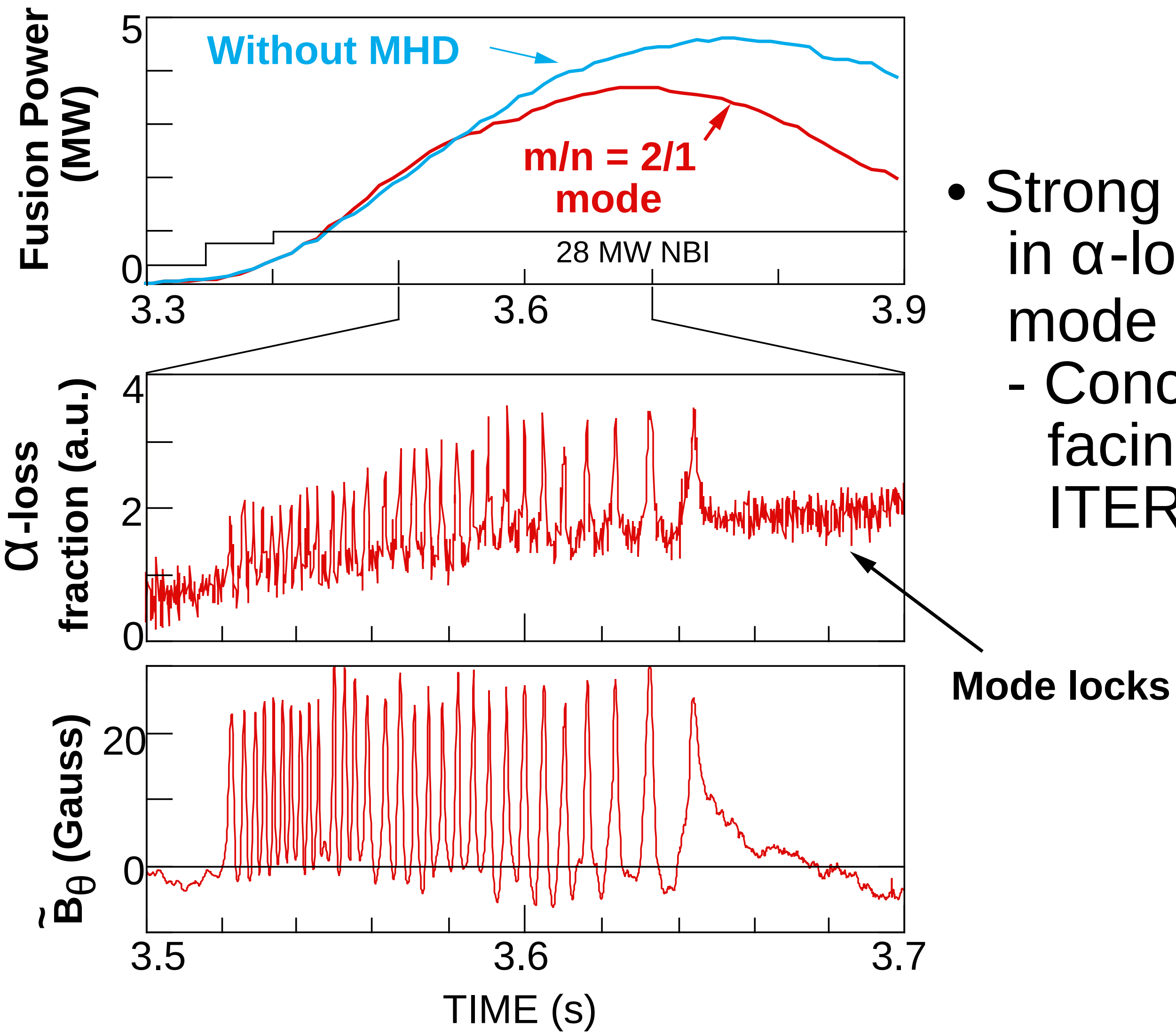
Enhanced Loss of Alpha-Particles Observed in Presence of MHD Activity



- Strong toroidal anisotropy in α-loss apparent when mode is rotating.
  - Concern for plasma facing components in ITER

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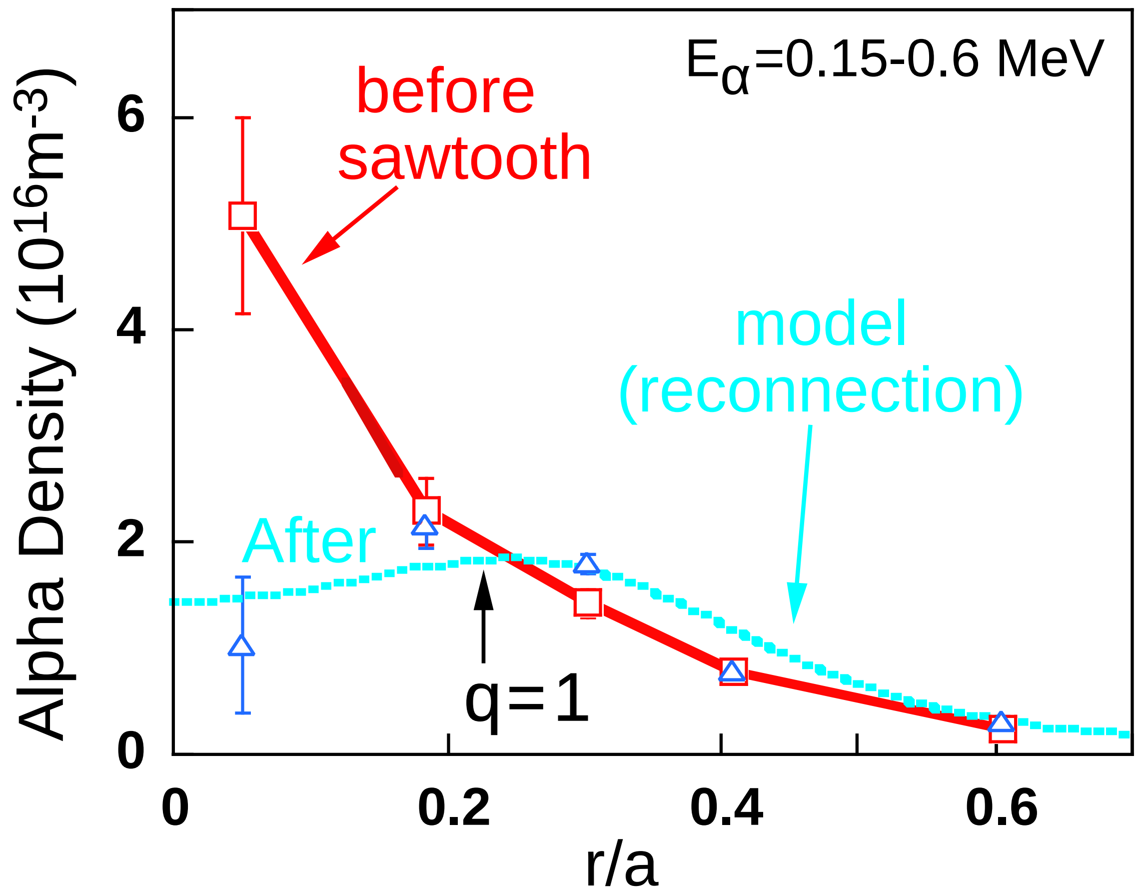
Sawteeth Cause a Large Radial Redistribution of Alpha Particles



Alpha heating profile in ITER will strongly depend upon the sawtooth activity, although only transiently

TOROIDAL ALFVÉN EIGENMODES CAN CAUSE SUBSTANTIAL FAST ION LOSS

- **TAE modes observed in D plasmas driven by:**
  - Beam ions
  - RF tail ions
  - 10-30% loss of fast ions was observed

- **Theoretically, energetic alpha particles can drive Alfvén waves unstable**.
  - $V_\alpha \sim V_{Alfvén}$
  - $R \quad \beta_\alpha > C$

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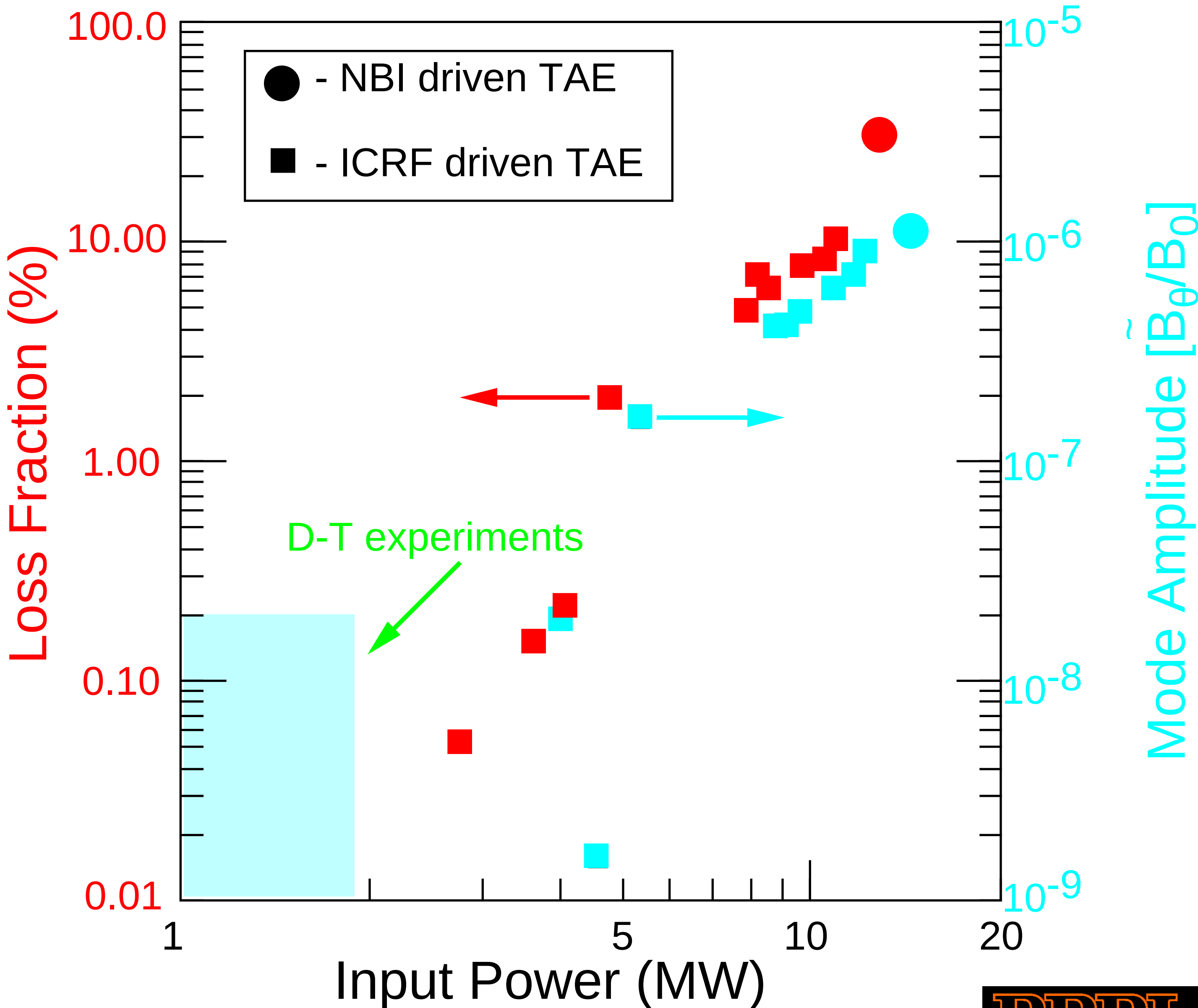
TAE MODES DRIVEN BY NEUTRAL BEAM OR ICRF
TAIL FAST IONS CAUSE SUBSTANTIAL FAST ION LOSSES



RJH-97-044

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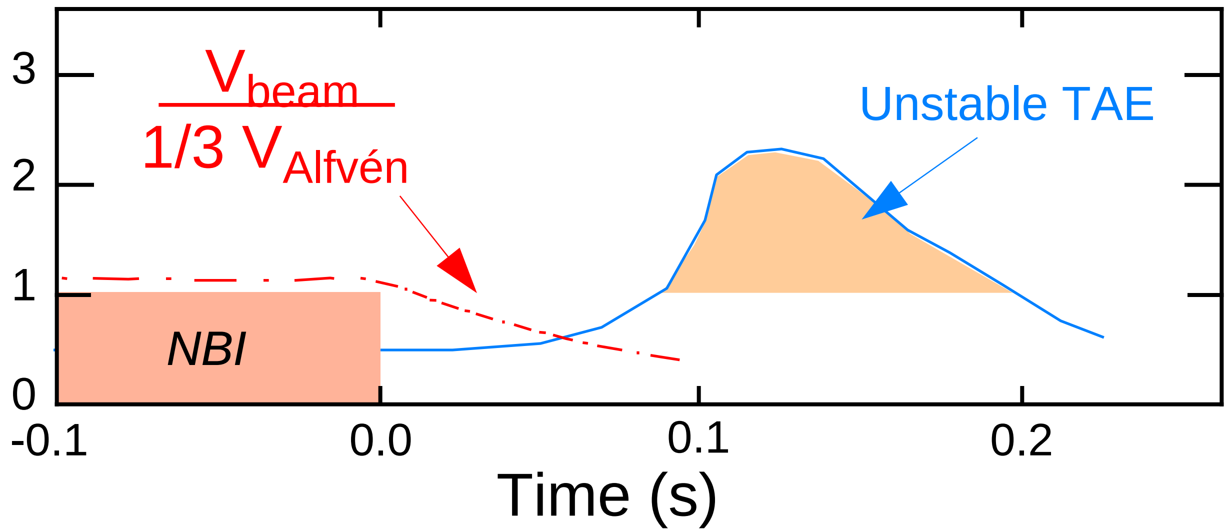
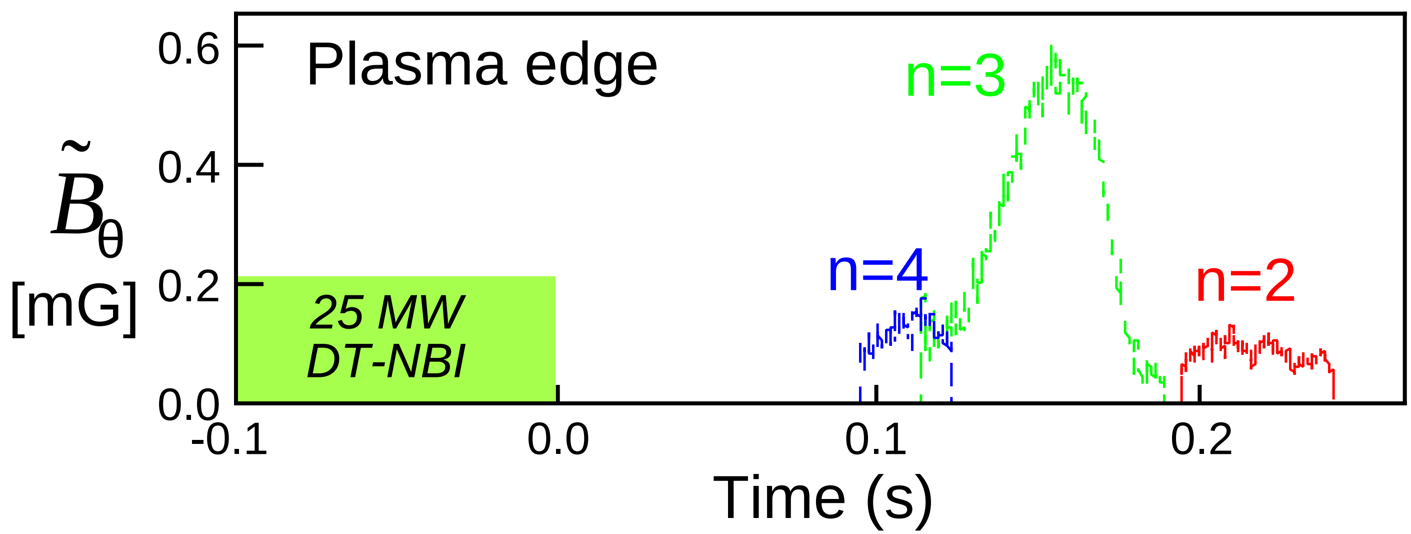
ALPHA DRIVEN TAEs IN WEAK SHEAR DISCHARGES

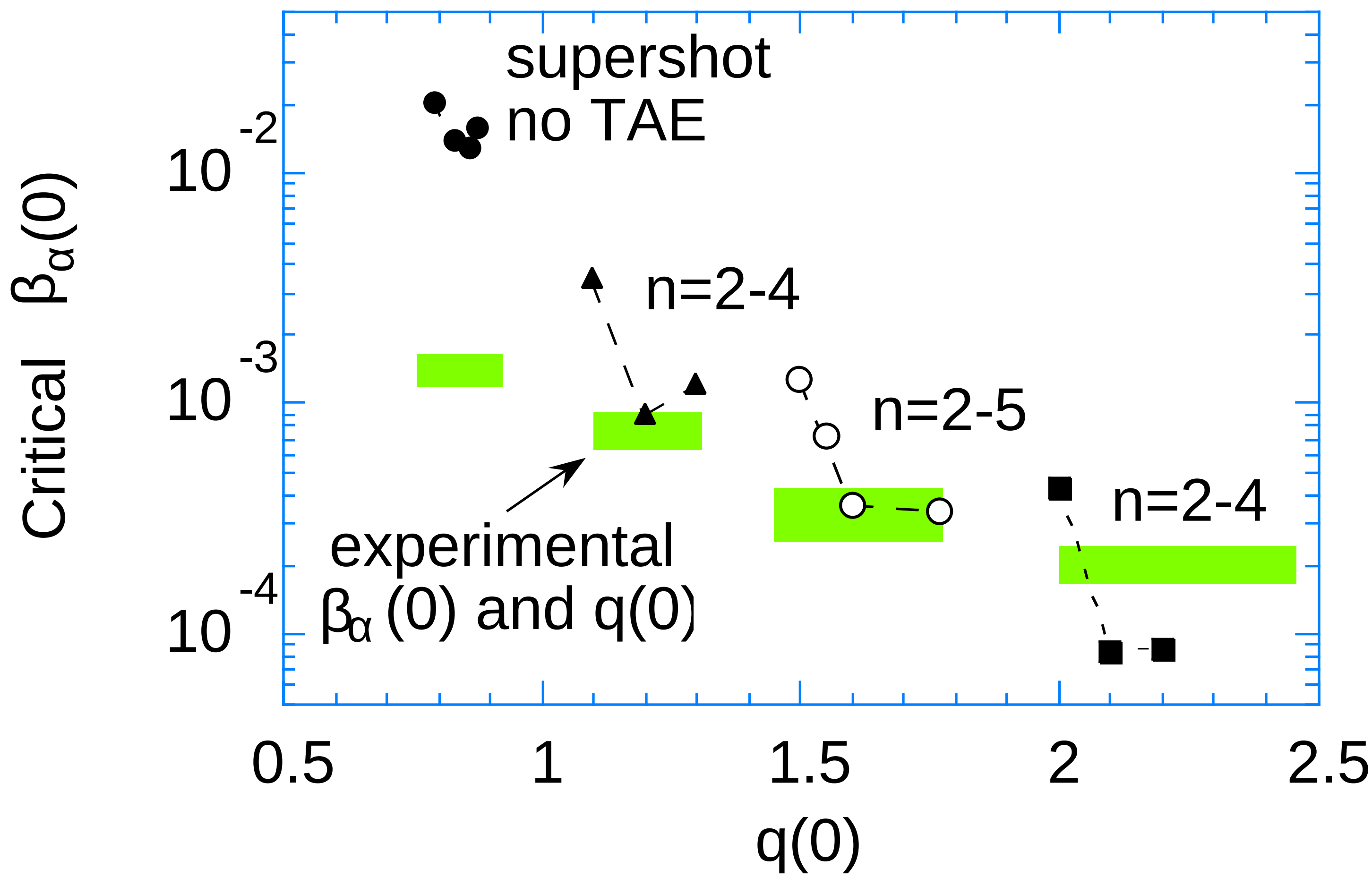
Theoretical Prediction: Fu, Spong

• Reduce magnetic shear, beam damping and raise q(0)





CALCULATED CRITICAL β_α DECREASES WITH INCREASING q(0)



- **Low shear and high q(0) are observed to be destabilizing.**
- **Implications for Advanced Tokamaks.**

R. Nazikian

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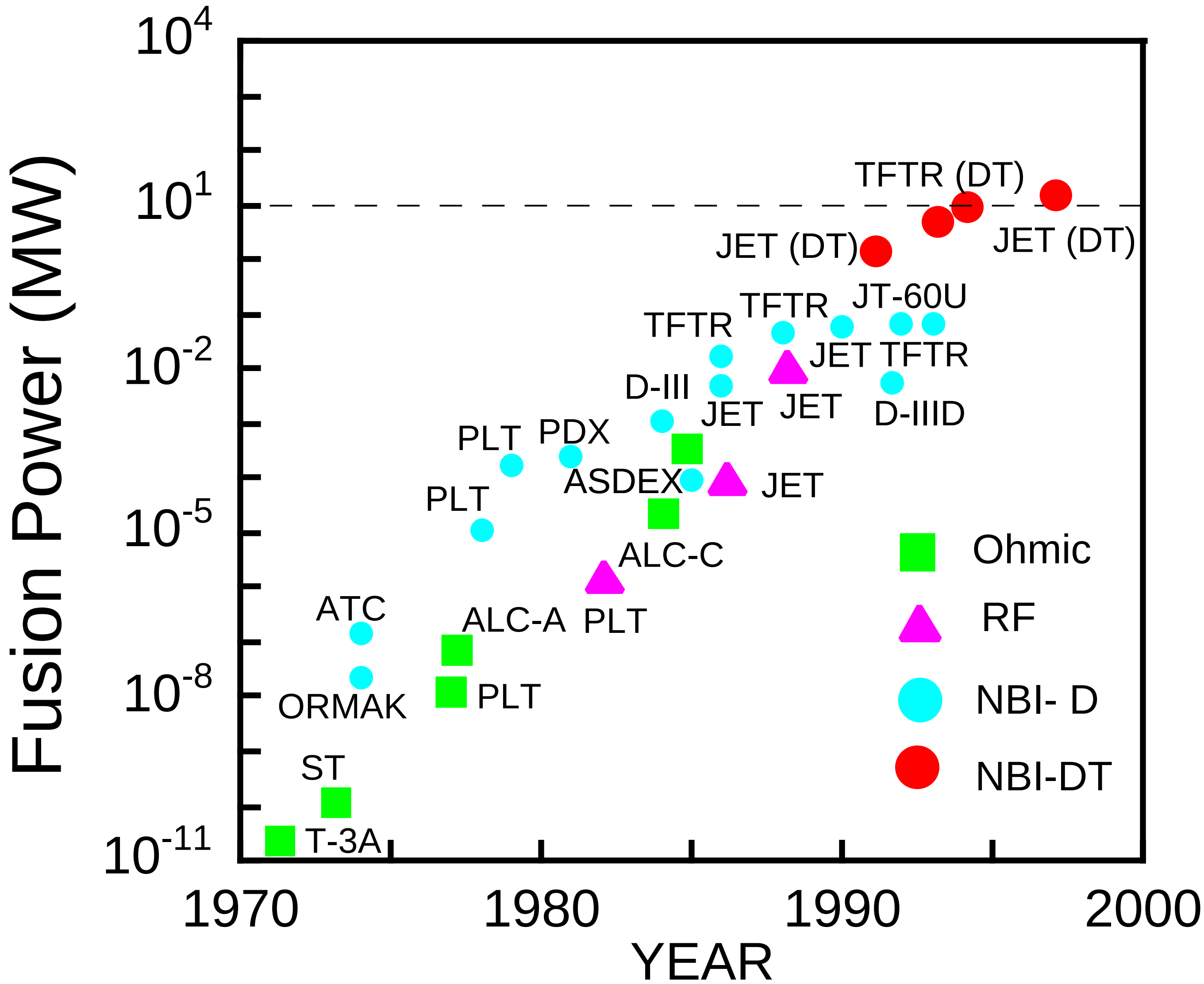
RJH-97-037

Tokamaks Have Made Excellent Progress in Fusion Power



RJH-97-031

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STUDY OF FUSION PLASMAS ON TFTR HAS INCREASED OUR UNDERSTANDING OF THE UNDERLYING PHYSICS

TRANSPORT

- Characterizing transport and developing a predictive understanding
- Experimental confirmation of the bootstrap current
- Reducing transport and demonstrating control of internal transport barrier

MHD STABILITY

- Better understanding of the role of current and pressure profile in MHD stability
- Identification of kink-ballooning mode as the disruption mechanism
- Identification of neoclassical tearing modes

ALPHA PHYSICS

- Confinement and loss of alpha particles in good agreement with theory in MHD quiescent discharges.
- Indications of alpha-particle heating
- Observed MHD effects on alpha distribution function and losses
- Observed Alpha-driven TAE modes in weak-shear discharges

TFTR HAS MADE MAJOR CONTRIBUTIONS TO ALL THREE ELEMENTS OF FUSION PROGRAM

- **Fusion Science**
  - Characterization and control of turbulence
  - Detailed comparison of experiment with MHD theory

- **Concept Innovation**
  - Advanced Tokamak
  - Alternates

- **Development of Fusion Energy and Technology**
  - Alpha Physics
  - Safe operation in D-T.

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Special Thanks to the Contributors to TFTR

Laboratories

Argonne National Laboratory, Argonne, IL
Chinese Academy of Science, Heifei, China
Environmental Measurement Laboratory, New York, NY
Ecole Royale Militaire, Brussels, Belgium
Idaho National Engineering Laboratory, Idaho Falls, ID
Institüt für Plasmaphysik, Jülich, Germany
I.V. Kurchatov Institute of Atomic Energy, Russia
Institute for Nuclear Research, Kiev, Ukraine
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
Max Planck Institut fur Plasmaphysik, Garching, Germany
National Institute of Fusion Science, Toki, Japan
Oak Ridge National Laboratory, Oak Ridge, TN
Sandia National Laboratories, Albuquerque, NM and Livermore, CA
Savannah River Plant, Aiken, SC
Troitsk Institute of Innovative and Thermonuclear Research, Russia
UKAEA Government Div., Fusion, Culham, UK

Industries

Asea Brown-Boveri Corp., Norwalk, CT
Aydin, Horsham, PA
Burns and Roe Company, Oradell, NJ
Canadian Fusion Fuels Technology Project, Missisauga, Canada
Chicago Bridge and Iron, Plainfield, IL
CVI, Columbus, OH
Digital Equipment Corporation, Maynard, MA
Encore, Fort Lauderdale, FL
Fusion Physics and Technology, Inc., Torrance, CA
General Atomics, San Diego, CA
General Electric Company, Fairfield, CT
General Physics Corporation, Columbia, MD
Lodestar Research Corporation, Boulder, CO
McDonnell Douglas Aerospace Corporation, St. Louis, MO
Millitech Corporation, South Deerfield, MA
Mission Research Corporation, Santa Barbara, CA
Rockwell International, Costa Mesa, CA
Northrop-Grumman Aerospace Corporation, Bethpage, NY
Phelps Dodge Copper Products, Phoenix, AZ
Raytheon Engineers and Constructors, Inc., New York, NY
Sarnoff Corporation, Princeton, NJ
Science Applications International Corp., San Diego CA.
Westinghouse Electric Corporation, Pittsburgh, PA

Universities

Auburn University, Auburn, AL
Colorado School of Mines, Golden, CO
Columbia University, New York, NY
Courant Institute, NYU, New York, NY
Georgia Institute of Technology, Atlanta, GA
Hebrew University of Jerusalem, Jerusalem, Israel
Institute for Fusion Science, Austin, TX
Lehigh University, Bethlehem, PA
Massachusetts Institute of Technology, Cambridge, MA
Royal Institute of Technology, Stockholm, Sweden
University of California, Davis, CA
University of California, Irvine, CA
University of California, Los Angeles, CA
University of California, San Diego, CA
University of Illinois, Urbana, IL
University of Maryland, College Park, MD
University of Missouri-Rolla, Rolla, MO
University of Nevada-Reno, Reno, NV
University of Oxford, Oxford, United Kingdom
University of Texas, Austin, TX
University of Toronto, Toronto, Canada
University of Tokyo, Tokyo, Japan
University of Wisconsin, Madison, WI