Perspectives on Advanced Tokamak Issues from Considering TFTR and JET Operations

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with contributions from

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Abstract

The discovery of new modes of enhanced confinement in tokamaks when the q-profile is modified tantalized the tokamak community because it opened the possibility of achieving substantially higher Q in DT plasmas in JET and TFTR.

While research has confirmed that improvements in central confinement are a robust feature of plasmas with $q > 1$ and weak or negative magnetic shear in the central region, the nature of the improvements is variable and the promise of higher Q has not yet been realized in DT. In particular, whether the improvement is manifested in the density or temperature profiles, and the roles of ions and electrons depend on the details of the q-profile. Shear reversal seems to be needed for the density to show the strong response needed to improve DT fusion yields with NBI heating. Furthermore, in the large, high-field tokamaks, the internal transport barriers associated with the improvement are so narrow that MHD stability is compromised. Internal barriers also have a complex interaction with the H-mode edge.

Perspectives on the dilemmas of operating in these regimes and the possibilities for future experiments in JET will be discussed.

Topics

- Transport effects and operational limitations in TFTR reversed-shear plasmas
- Observations on recent JET experiments with Optimised Magnetic Shear (OMS) plasmas
- Stability issues
- Requirements and possibilities for future exploitation

Plasmas with Weak Positive or Negative Magnetic Shear and q(0) > 1 Exhibit Spontaneous Improvements in Confinement

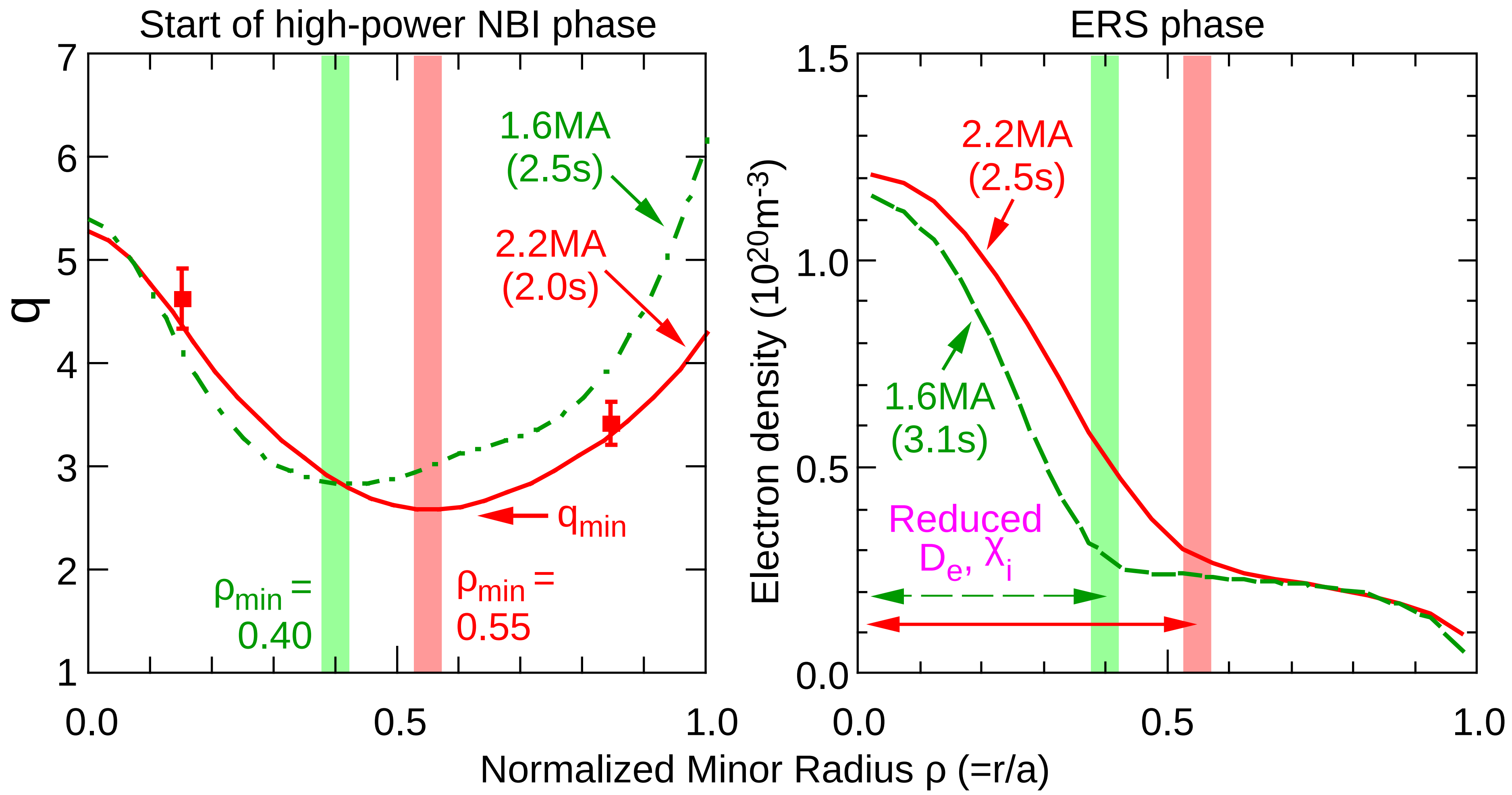
- Theory: *stability* (MHD and microstability) should improve in regions with reversed magnetic shear, $S = r/q \cdot \partial q/\partial r < 0$

- Experiments: improvements in *energy confinement*
  - ERS, NCS, Reversed-shear, Optimised-shear modes
  - factors 2 – 4 relative to L-mode scaling

- Formation of prominent internal transport barriers (ITB)
  - obvious in temperature and density profiles for NBI heating
  - sometimes exhibit structure in electron temperature profile

- Associated with transition phenomena in some tokamaks
  - power threshold - reminiscent of H-mode transition

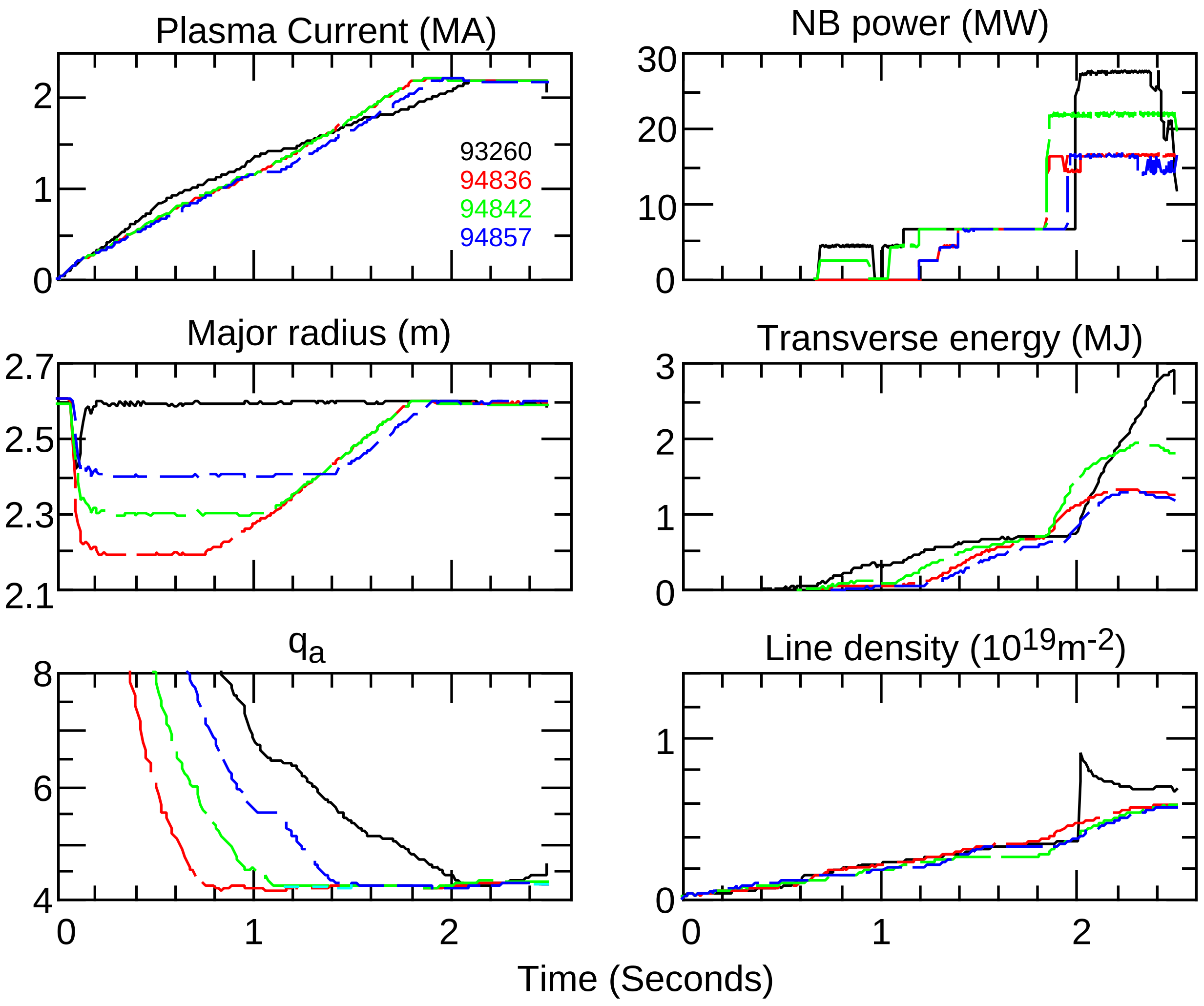
In TFTR, Improvements in Confinement Are Tied to Region of Shear Reversal



- Location of transport barrier in ERS phase moves with ρ_{min}

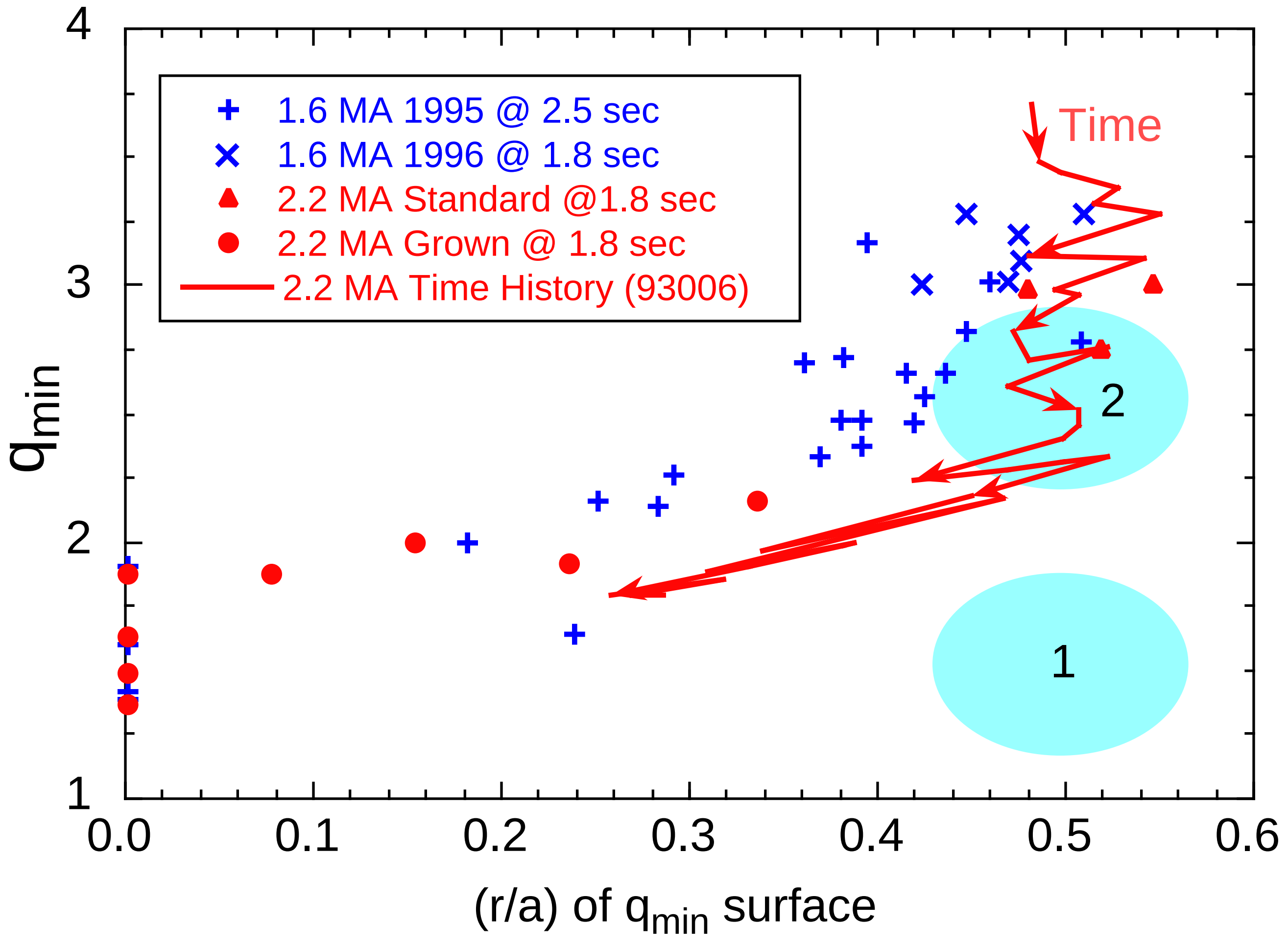
Current Ramp and Size Growth Used to Control q Profile

TFTR



- "Pauses" in I_p ramp suppress MHD activity at rational q_a for ungrown plasmas
- "Growing" plasma results in lower q_{min} but also smaller r_{min}
  - q profile eventually becomes monotonic

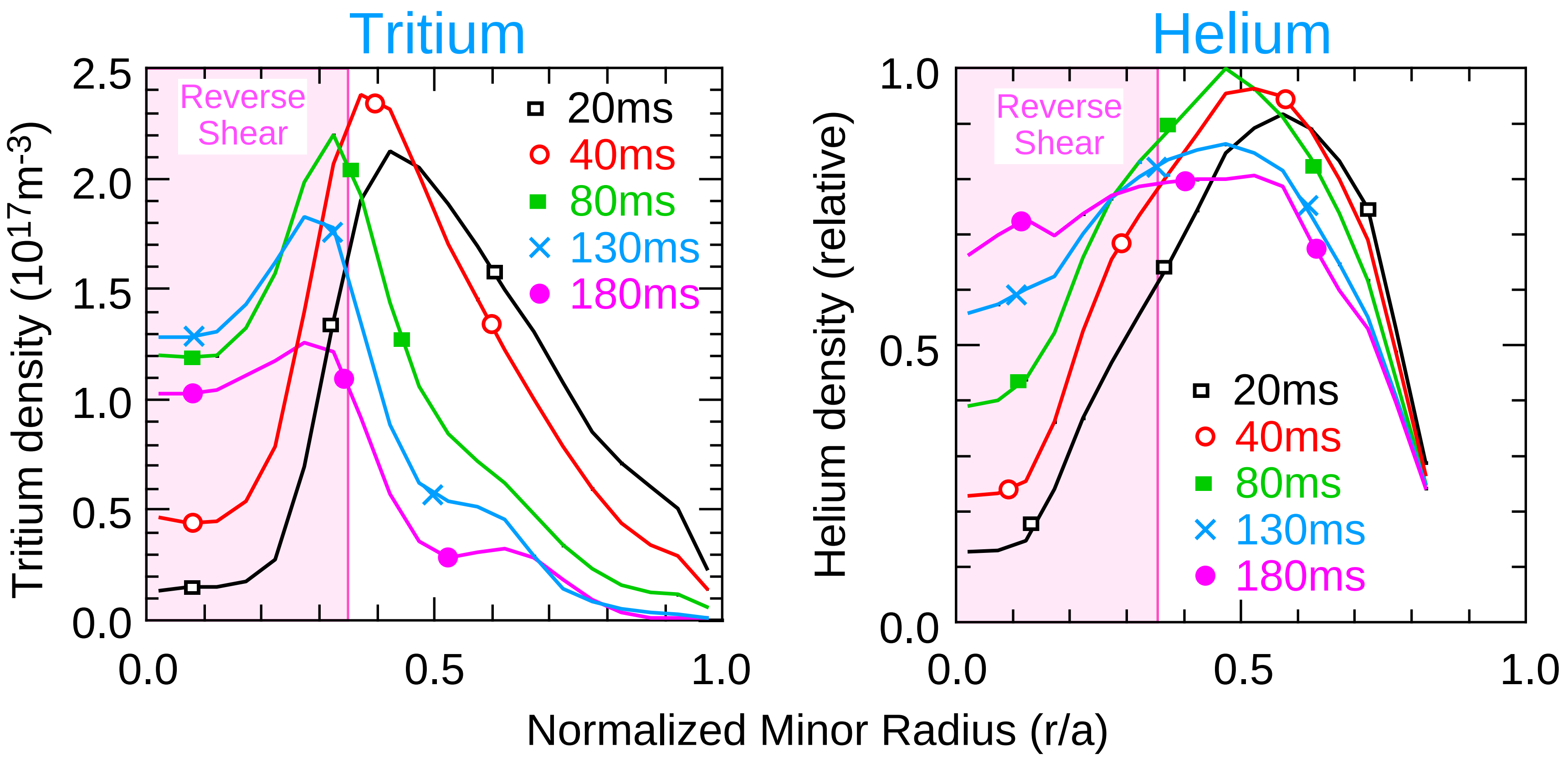
Achieving Optimum q Profiles Frequently Difficult Within Constraints on Stability and Reliability of Startup



- Shaded areas indicate predicted regions of improved stability
- Increasing current ramp rate to broaden r_{min} resulted in deleterious MHD activity

Density Profile Evolution Following Puffs of T and He Show Presence of Particle Transport Barrier in ERS

TFTR



- Times of profiles are from start of 16ms puffs during steady-state ERS phase
- T density inferred from chordal profile of 14MeV DT neutron emission
- He density measured by charge-exchange recombination spectrometry

P. Efthimion ,S. von Goeler, E. Synakowski

PPPL
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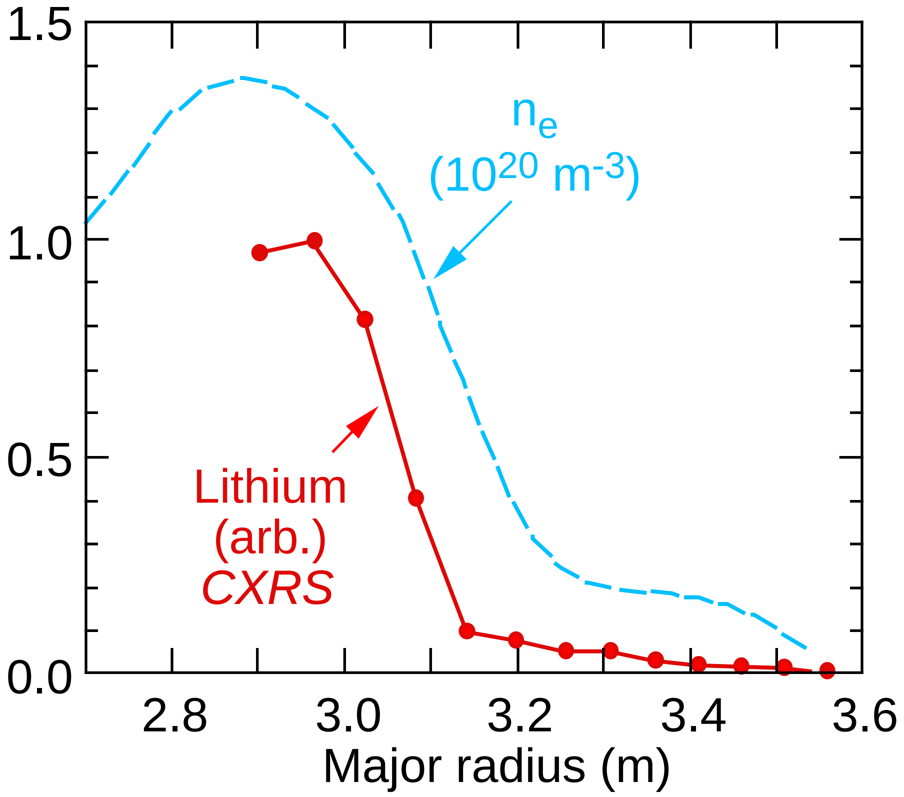
Injected Lithium Trapped Within Transport Barrier after ERS Transition

TFTR

- Lithium pellet at start of HP-NBI necessary to provoke ERS at 2.2MA
  - mechanism of effect not understood

Densities 0.5s after pellet during ERS phase

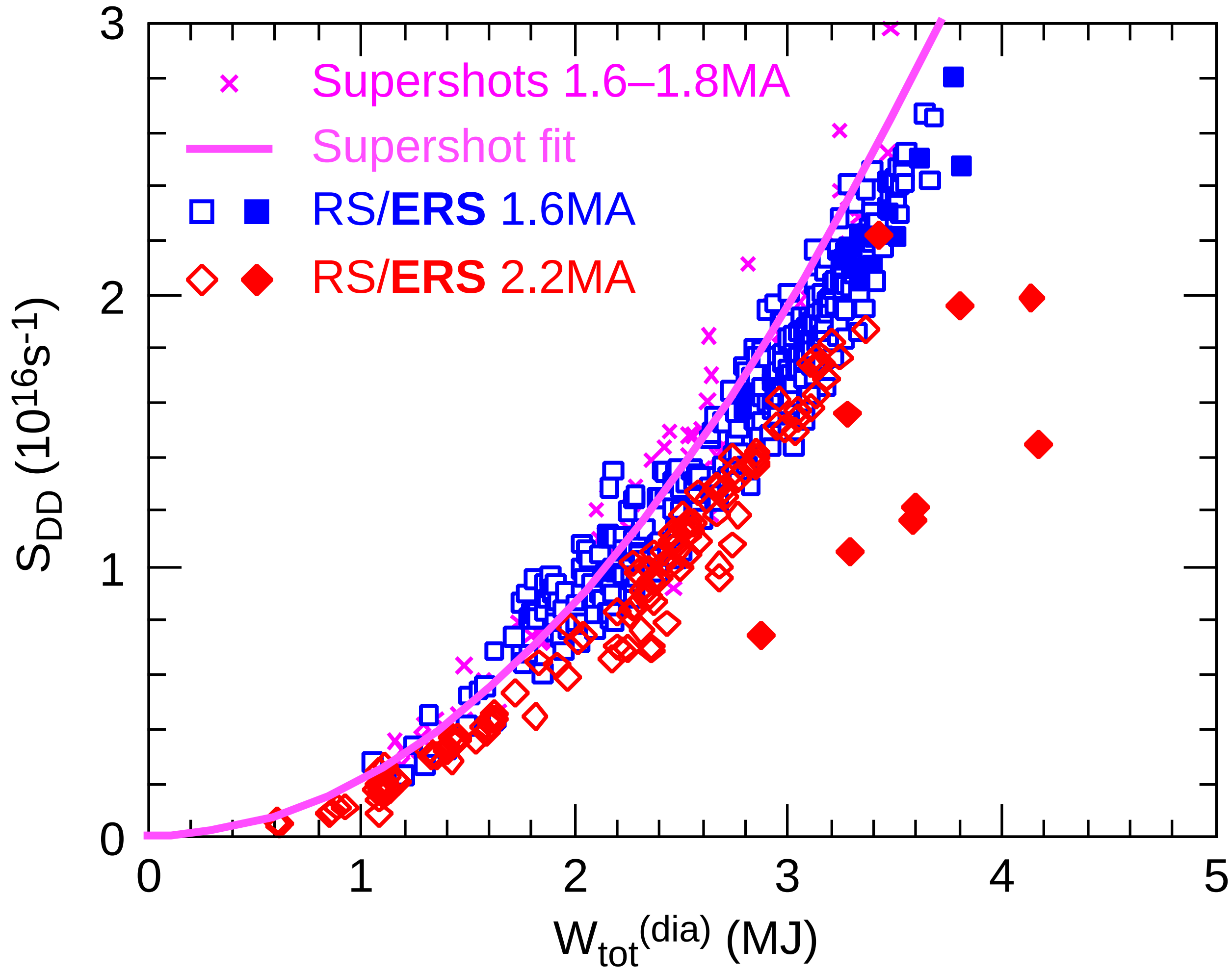


- Suggests an issue of helium ash accumulation in ignited ERS plasmas

E. Synakowski; A. Ramsey

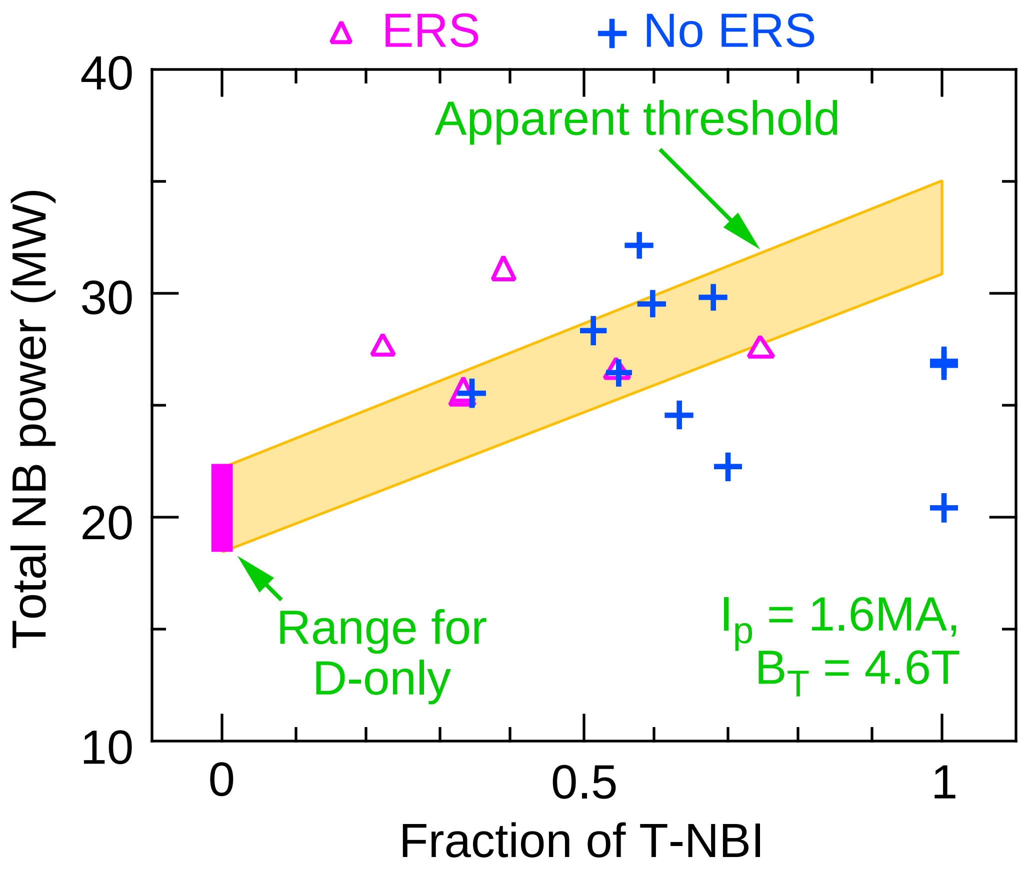
Retention of Lithium Affected High-Current ERS Reactivity

R = 2.6m, B = 4.6 – 4.9 T, D-only NBI



- Li pellet needed to stimulate transition at high current (2.2MA) - *threshold power?*
- Also suggestion from NBI-blip experiments that fast ions may not be as well confined in ERS plasmas - *ripple?*

Higher NB Power Required for ERS Transition in D-T



- In TFTR, threshold increased with plasma current and depended on wall conditions
- Contrary to 1997 experience in JET: *ITBs formed in D & D-T with similar power*
    - *but* H-mode threshold power *decreased* in D-T, limiting OMS performance

Plasma Turbulence Reduced or Suppressed in Vicinity of Internal Transport Barriers

- Clear association between changes in measured fluctuation levels and transport in the interior of tokamak plasmas
  - already established for reduction of edge turbulence in H-mode
  - observed in TFTR, DIII-D, JET, JT-60U
- In TFTR RS, fluctuations have repetitive bursting character
- Bursts disappear rapidly at transition into ERS and plasma becomes quiescent within shear-reversal surface
  - bursts reappear gradually at “back-transition” from ERS
- Behavior consistent with turbulence suppression by sheared plasma flow

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

General Characteristics of JET OMS Plasmas

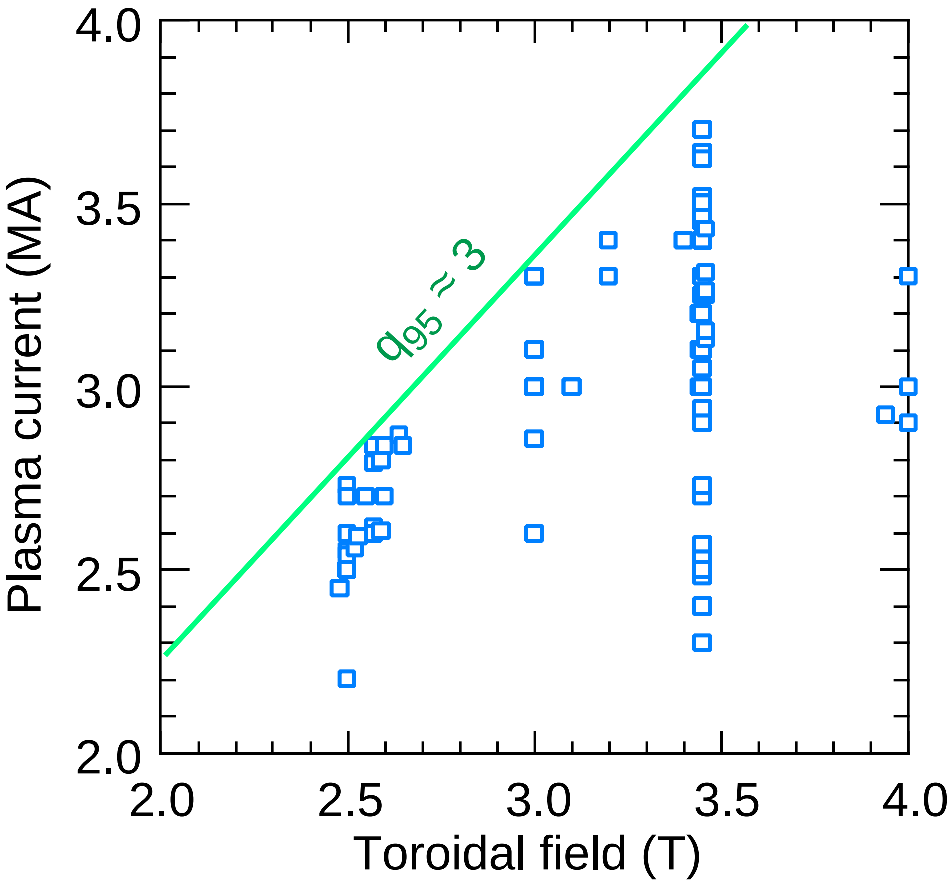
- Successor to Pellet Enhanced Performance (PEP) Mode
  - Persistent peaked density profile of PEP mode identified with $q(0) > 1$ and weak shear reversal in core
  - PEP recently obtained in OMS plasmas with low speed pellets

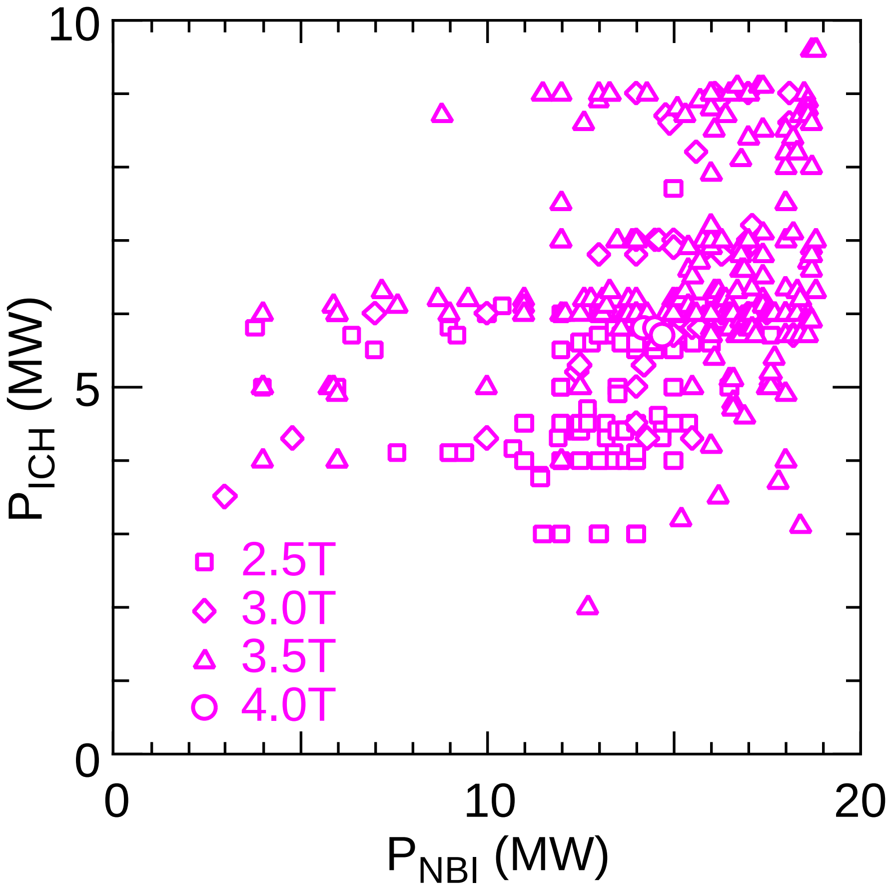
- OMS produced by ramping current during moderate early heating
  - $q(0) > 1$ everywhere but profile not yet well determined
  - rational q surfaces ($q = 3, 2, 3/2$) important in *triggering, evolving, destroying* barriers (MHD evidence)

- OMS barriers most evident on T_i, T_e profiles
  - $T_i(0) > 25$keV, $T_e(0) > 15$keV at high field (3.45T)

- OMS barriers less evident in density
  - $n_e(0)$ up to $6 \times 10^{19}m^{-3}$ in MkIIa, $4 \times 10^{19}m^{-3}$ in MkII Gas-Box

Task Force B Experiments, Nov 1997 - Feb 1998





- MkII-GB divertor configuration
- 470 "Optimised Magnetic Shear" OMS pulses
- ~ 200 recovery pulses in addition
- LH power, 1 - 2 MW, also applied early in many pulses

OMS Interaction with Edge Barriers (H-mode)

- "Double Barrier" mode (ITB + H-mode) produced sustained (>1s) good performance at lower field/current (2.5T/2.5MA), $\beta_N \approx 2.5$
  - Near threshold, edge density rises between infrequent ELMs
    reduced NBI penetration and erosion of barriers by large ELMs

- Highest peak performance in MkIIa divertor with L-mode edge
  - ramp current continuously to suppress H-mode
  - maintain low density to reduce NBI deposition near edge
  - optimize separatrix positioning

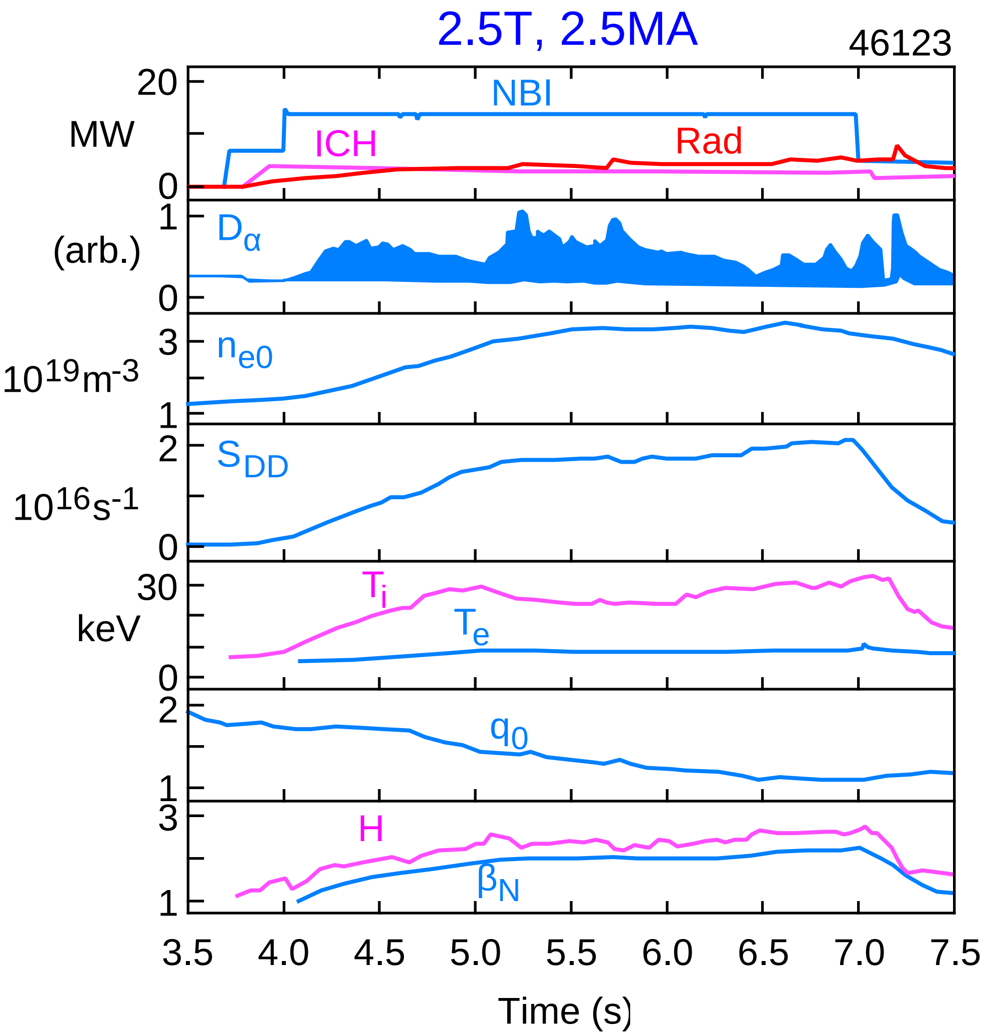
- With new MkII-GB divertor, have tried to control H-mode with
  - density control
  - configuration control: septum contact, Z-position
  - reduced power flow through separatrix: Ar, Kr radiation

Impurity “Seeding” for Improving OMS Plasmas

- Ar, Kr added after ITB formation to help prevent retention in core
- Kr tried in 1998
  - both OMS and Hot-ion H-mode
  - success in suppressing H-mode transition in OMS
  - tendency to accumulate - increasing number of recovery pulses
  - not used in 1999
- Ar used routinely in 1999
  - success in suppressing/delaying H-mode
  - also controls ELM amplitude after transition
  - accumulates less *but* recovery pulses still needed
  - R_{nt}/W_{dia}^2 now lower: impurities or pressure peakedness?
  - best pulse in 1999 extrapolates to $Q_{DT} \approx 0.5$

Argon Puffing to Increase Radiation with "Double-Barrier"

OMS plasma with internal barrier plus H-mode edge

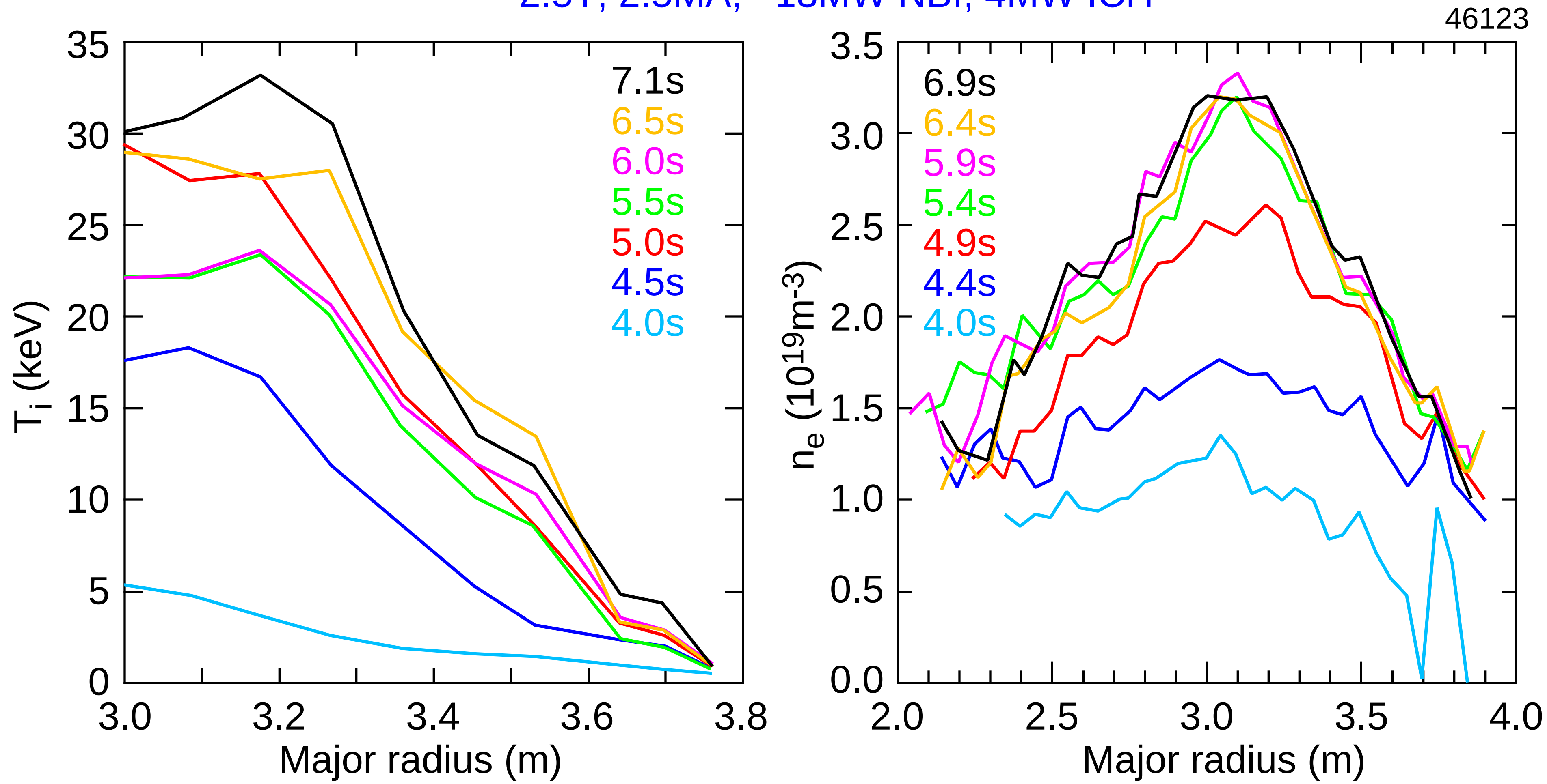


- Argon added at ~ 2 × 10^{21} elec./s
- P_{rad} / P_{tot} ~ 30%, mostly from edge
- Effective to prolong double barrier
  - prevents buildup of excessive pressure gradient at edge
- Argon more "user friendly" than krypton
  - Kr tended to accumulate; required frequent cleanup
  - Some cleanup shots also needed with Ar

C. Gormezano

Argon Prevents Buildup of Excessive Pressure Gradient at Edge

2.5T, 2.5MA; 13MW NBI, 4MW ICH



- Edge radiation prevents occurrence of large ELMs which can erode internal barrier

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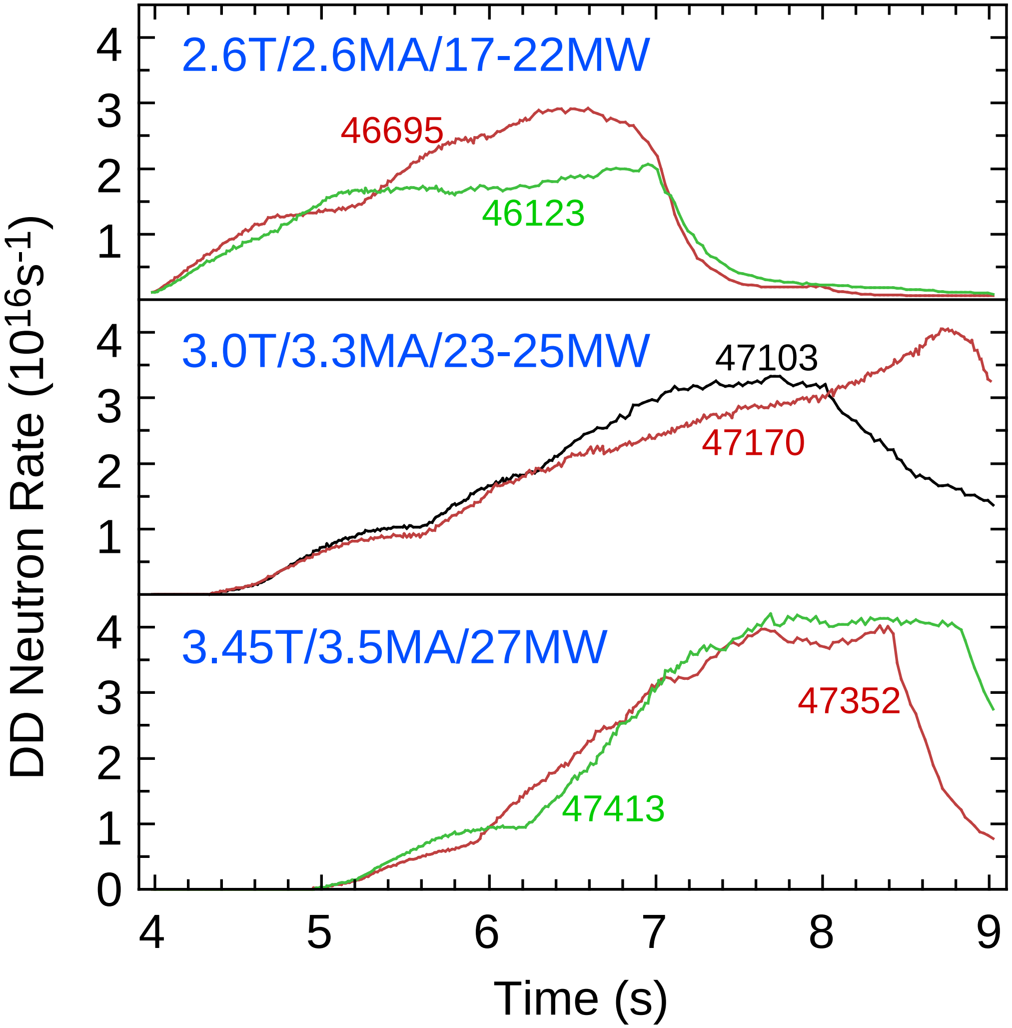
JET Has Made Progress in Sustaining Good ITB Performance Through High-Z Impurity Puffing



- Shots with Ar puffing during ITB phase to suppress H-mode and ELM impact
- Some shots suffered collapse of ITB before end of heating
  - increasing radius of barrier may reduce power flux below threshold

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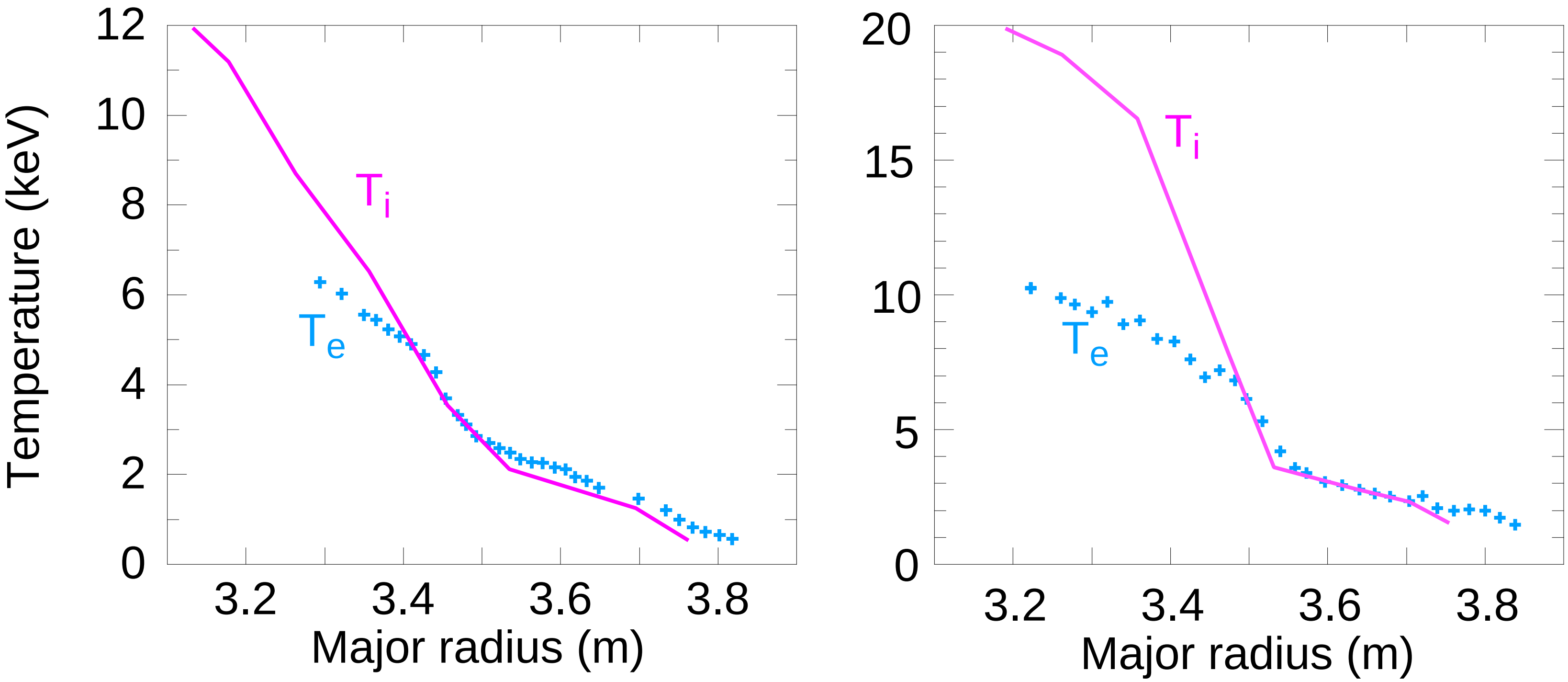
Barriers are Steeper at Higher Field in JET



2.5T, 2.5MA
12MW NBI, 6MW ICH

3.5T, 3.2MA
17MW NBI, 6MW ICH

- Both pulses in MkII-GB divertor with OMS startup
- Density rise with NBI fueling is not as large in MkII-GB pulses

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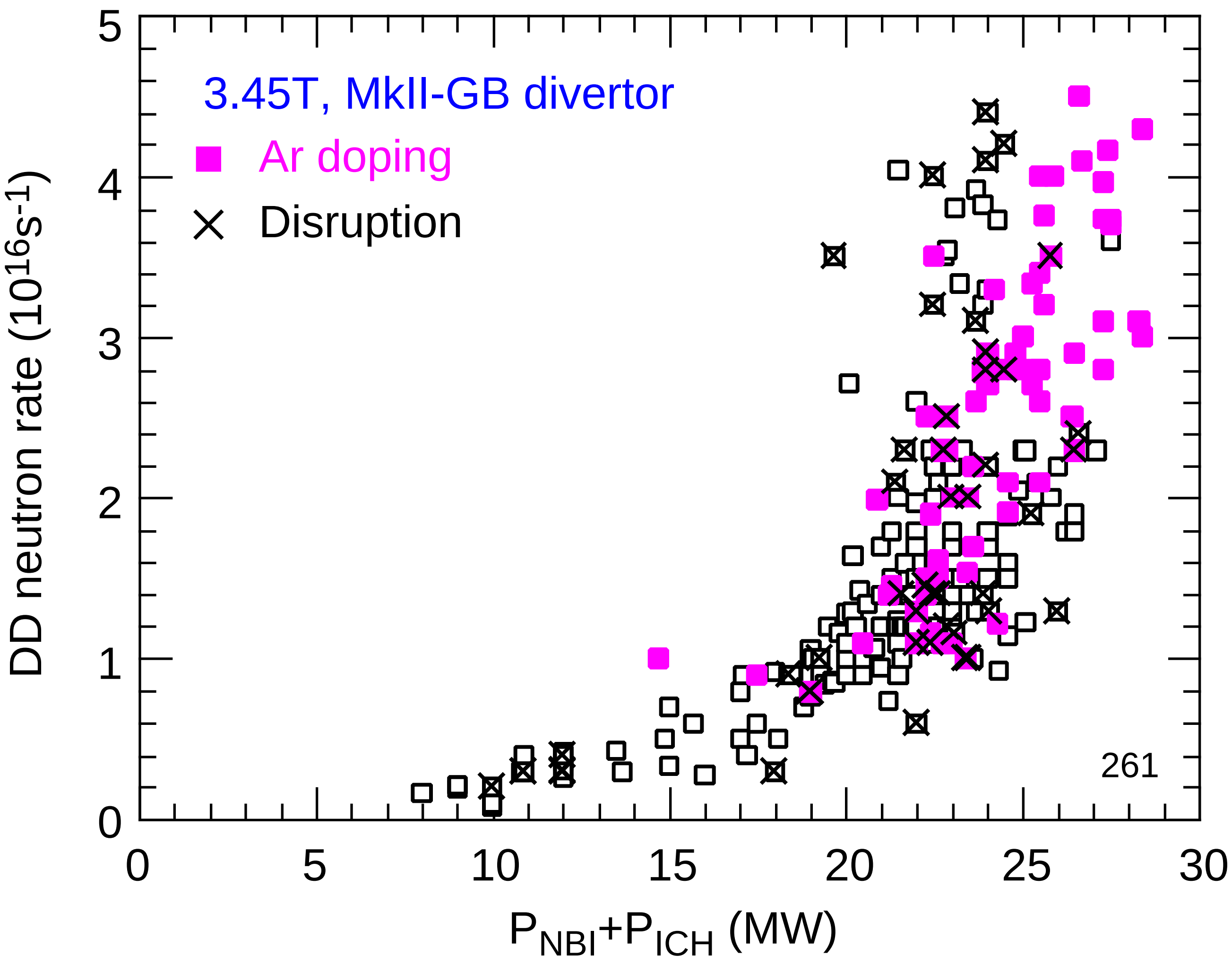
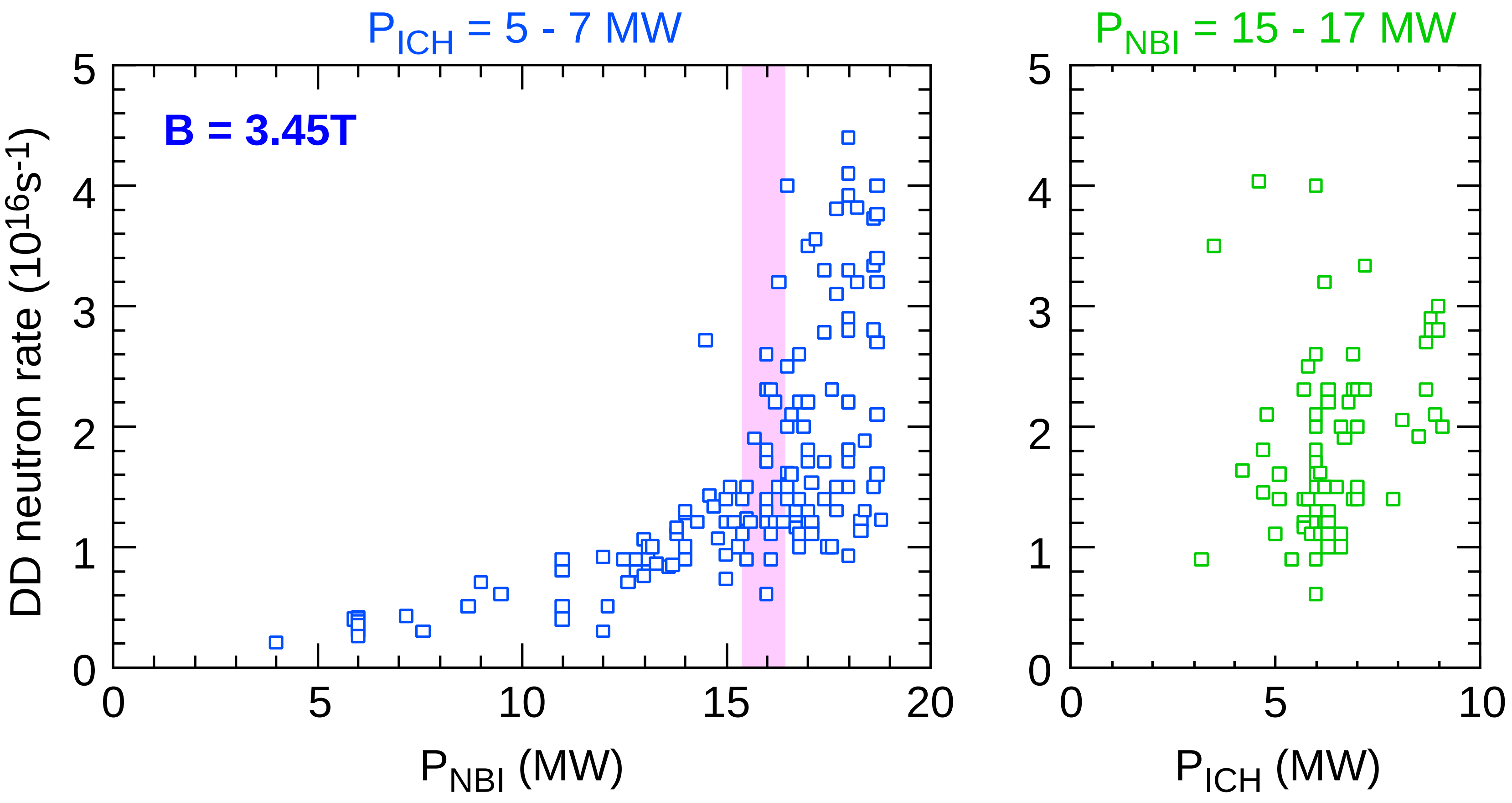
Formation of Internal Barriers Greatly Increases DD Reactivity



- Threshold for barrier formation is not well defined in total power
- Performance is very variable above the threshold

NBI Power More Critical than ICH Power for Barrier Formation at High Field



- Argon added to many pulses but mainly after time of barrier formation
- At 2.5T, NBI and ICH power shown to be equivalent in substitution experiment *(F.X. Söldner* et al., *13th Topical Conf. on RF Power, Annapolis, 1999)*

Limitations on OMS Performance

- Evolution of q profile
  - rational q surfaces, particularly q_{min} affect MHD stability
  - bootstrap current (~   p) not fully aligned with inductive J(r)

- Evolution of the pressure profile
  - development of extreme pressure gradients at barriers
  - power flow to *trigger* barrier higher than can be *sustained*
  - need for very smart feedback - *is this consistent with ignition?*

- Variety of MHD phenomena can affect performance
  - n = 1 kinks - fast disruptions
  - “Snakes” - localized helical perturbation at q = 2, $\Delta T_e = \pm 1$keV
  - Neoclassical tearing modes - develop in steady-state phases

Challenge to Achieve Good MHD Stability in Presence of Internal Transport Barriers

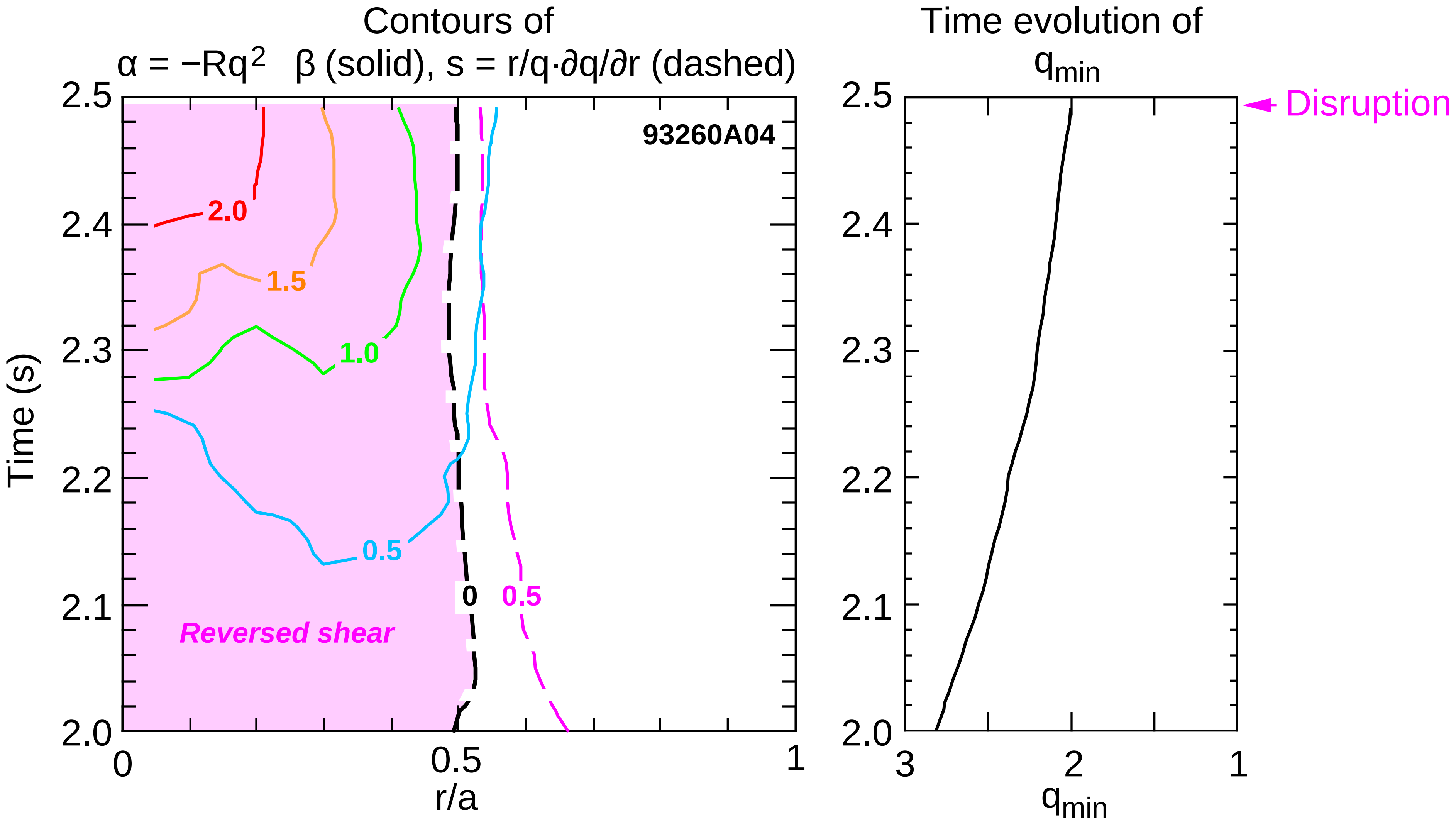
- Most regimes with strong internal transport barriers do *not* achieve high Troyon-normalized-β, $\beta_N = \beta_T \cdot a \cdot B_T / I_p$

- Maximum $\beta_N < 2$ in reversed (or weak) shear plasmas with strong *internal* transport barriers only (no H-mode barrier at edge)
  - TFTR, JT-60U, JET
  - barriers create extreme local pressure gradients
  - resulting bootstrap current causes q profile to evolve
  - in JET OMS and TFTR Supershots, β_N limit *decreases with* B_T

- $\beta_N \approx 4$ and good performance achieved transiently in DIII-D by combining ITB with H-mode edge barrier
  - transport barriers “in series” reduce local pressure gradient
  - not yet achieved *at high performance* in JET

Low β-limit in ERS Plasmas due to Expansion of Transport Barrier into Weak Positive Shear Region and $q_{min} \rightarrow 2$

TFTR

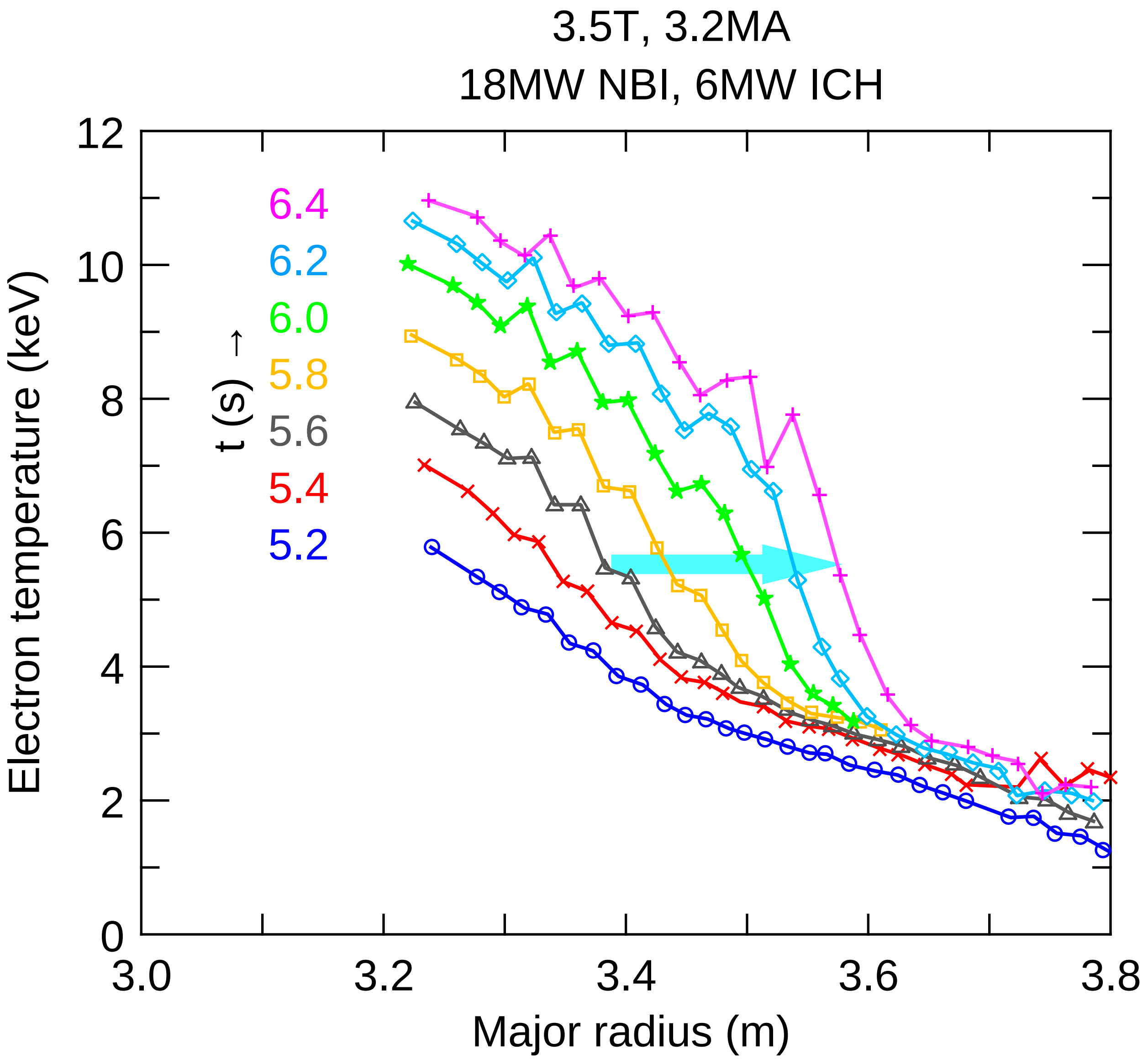


Contours of $\alpha = -Rq^2\beta$ (solid), $s = r/q \cdot \partial q/\partial r$ (dashed)

Time evolution of q_{min}

- TRANSP calculation of p and q profiles through high-power phase (27MW)
  - Initialized with MSE data at 2.0s (start of high-power phase)

Barrier Expansion is Pronounced in Longer JET Pulses



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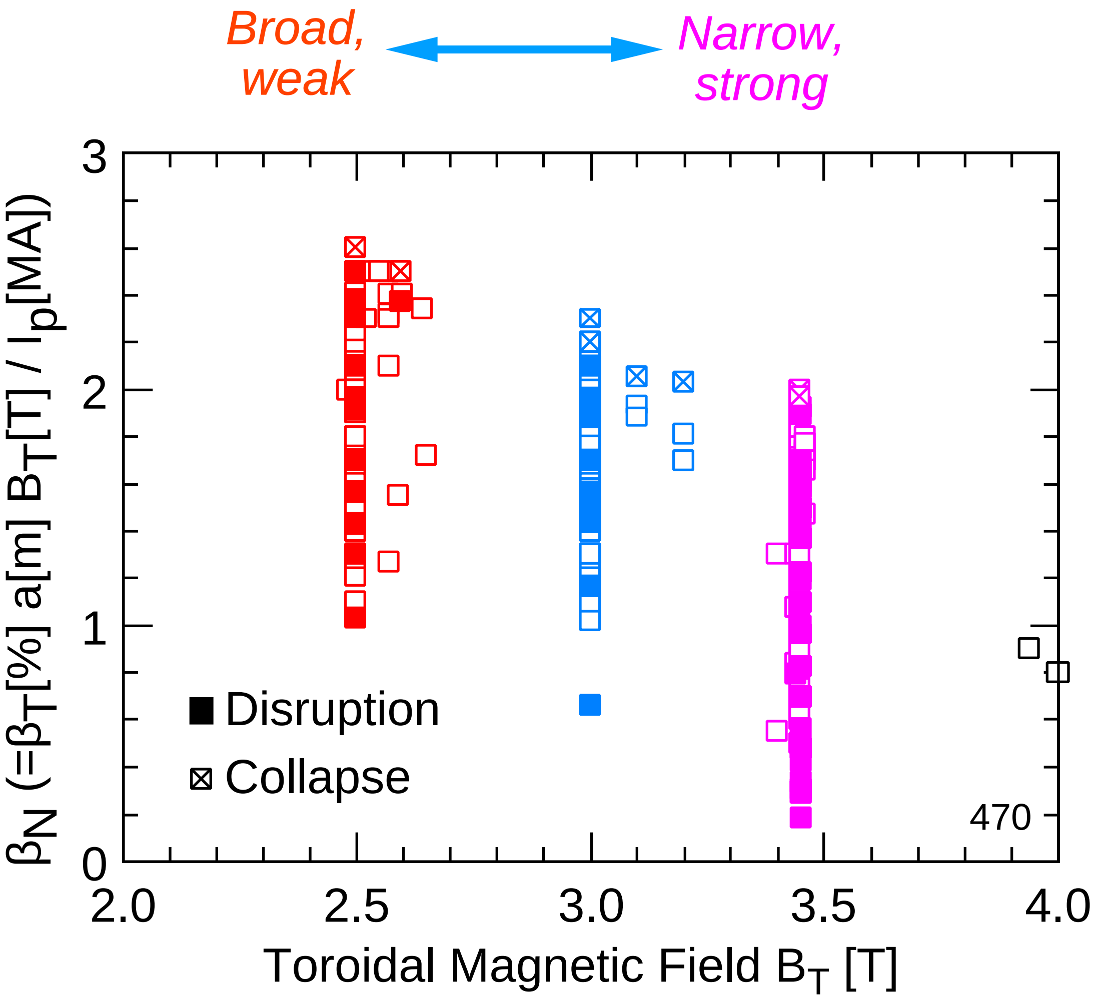
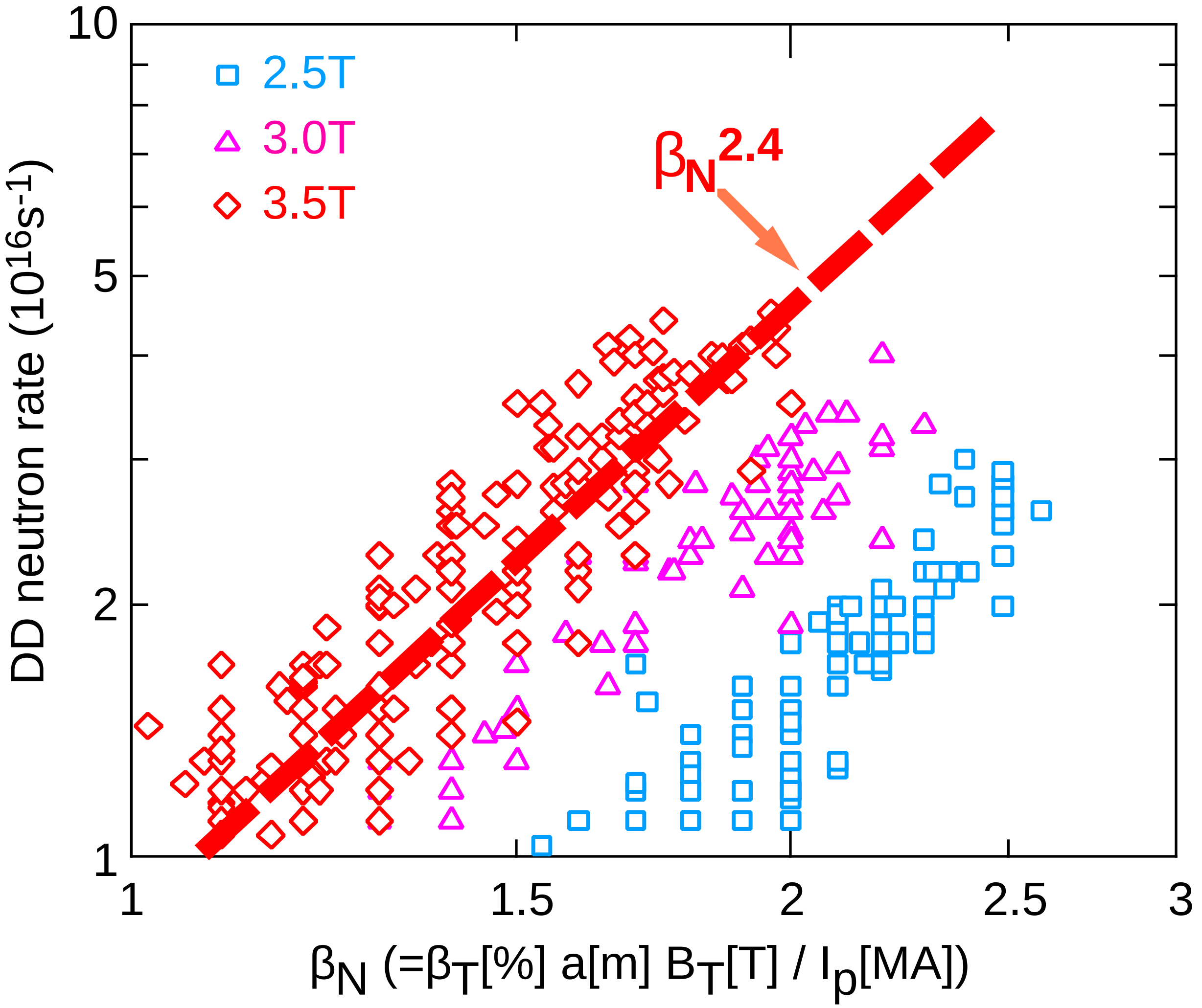
β_N Limit Decreases with Increasing Field in OMS Plasmas



- This is *not* a power limitation at high field (up to 3.5T)
  - plasmas with strong barriers have adequate confinement to reach limit
- Plasmas with good confinement disrupt or collapse below the maximum
- Similar to trend observed for supershots in TFTR *(E. Fredrickson)*

Reduction in β-Limit With Strong Barriers at High Field is Limiting Achievable Fusion Performance



- OMS plasmas in Mark II-GB divertor configuration (plasma volume ~80m^{-3})
- At 3.5T, rapid increase in DD rate caused by formation of strong barriers increase in central pressure and pressure peaking ($<p^2>/<p>^2$)

Requirements and Issues for Higher DT Performance in Future JET Experiments

- Higher central fuel density (~1 × $10^{20}m^{-3}$)
  - higher temperature (>25keV) of marginal benefit to DT reactivity
  - need to induce *particle transport barriers* - *c.f.* PEP or ERS
  - *does this depend on strong shear-reversal in the center?*
  - central fueling: can inside-launch pellets penetrate ITB?

- Higher stability at high field and current
  - for P_{DT} = 25MW (Q ≈ 1): $\beta_N \approx 2.8$ in standard OMS at 3.45T *but*
    $\beta_N \approx 2.1$ at 4T and same q
  - challenge to develop scenario with very limited shots

- Control of H-mode onset and density pedestal
  - higher β-limit in “double-barrier” mode at low field *but*
  - H-mode edge has lower reactivity (higher β for given P_{DT})

Summary and Issues

- Modifying the magnetic shear has revealed a wealth of transport phenomena in tokamaks
  - improved confinement and normalized performance
  - suppression of fluctuations and anomalous transport
  - *but*, necessary and sufficient conditions still not established
- Maintaining stability in presence of transport barriers and resulting bootstrap current is a real challenge
  - MHD stability benefits of reversed shear have not been realized at reactor relevant fields
  - will be particularly difficult in self-heated (ignited) plasmas
- Development of tools to control location and “impedance” of transport barriers will be vital
  - flow control by RF a possibility