Experiments to Maximize the Fusion Reactivity in TFTR*

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Abstract

During the DT phase in TFTR, a series of experiments was conducted aimed at increasing the fusion rate and the effects of the resultant alpha-particle population on the plasma. The reactivity of plasmas heated and fueled with the optimal DT mixture by neutral beams was found to be a strong function of the total plasma energy. Thus, producing high fusion reactivity required achieving good energy confinement at high heating power, and adequate plasma stability.

The first experiments concentrated on the supershot regime which reliably achieved the desired confinement. However, plasmas in this regime showed an inverse correlation of confinement and stability.

Alternative operational techniques and regimes were then investigated for their potential to extend the fusion performance of TFTR. These included new methods of reducing the plasma interaction with the limiter to improve confinement, and altering the plasma current profile to improve the MHD stability. The operational limitations, the results of these experiments and their implications for future DT experiments are discussed.

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Topics

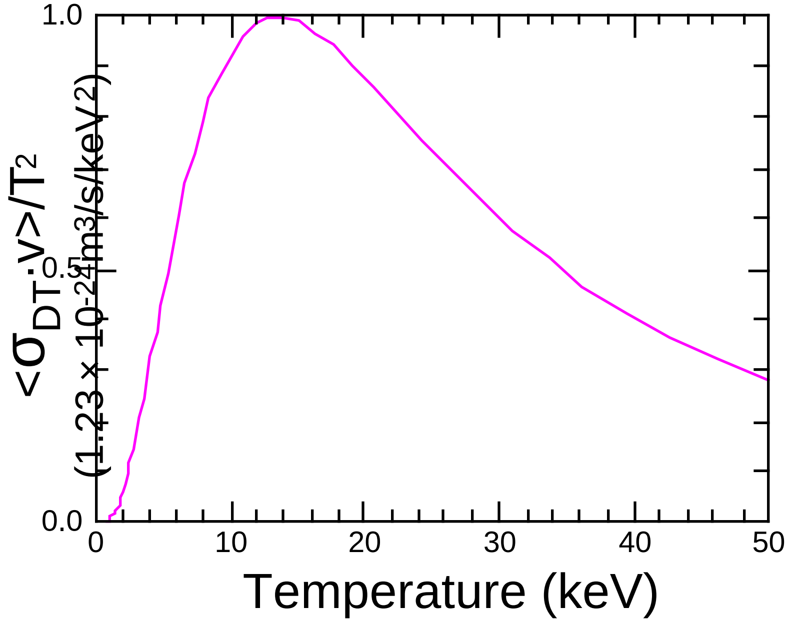
1. DT fusion basics
2. The DT reactivity of TFTR plasmas
3. Stability and confinement in TFTR supershots
4. Alternative operational regimes
5. Reversed-shear plasmas
6. High-l_i plasmas
7. New techniques for improving confinement
8. Power handling limits
9. Putting it all together

DT Fusion

- Fusion power from a DT plasma is given by

$$P_{fusion} = E_{DT} \int n_D \, n_T \, \langle \sigma_{DT} v \rangle dV \quad (E_{DT} = 17.6\text{MeV} = 2.82 \times 10^{-12}\text{J})$$

- For thermal ions in the range 10 – 20 keV, $\langle\sigma_{DT}v\rangle$ T_i^2 approximately



Dependence of the rate coefficient for DT fusion reactions on temperature for thermalized ions in conditions typical of TFTR supershots.

For $n_D = n_T = 5 \times 10^{19}\text{m}^{-3}$, $T_i = 14\text{keV}$:
$P_{DT} = 1.7\text{MW/m}^3$

- At optimum temperature, $T_i \approx 12\text{keV}$, a 50:50 D:T thermal plasma will produce ~230 times the fusion power of an identical D plasma

  - Actual ratio depends on T_i and presence of non-thermal ions from NBI

- Consider the ratio of the fusion power density to the energy density:

$$\frac{P_{DT}/V}{(W_{tot}/V)^2} \quad \frac{[\int n_D n_T \quad \sigma_{DT} v \ dV/V]}{[\int (n_i T_i + n_e T_e) dV/V]^2}$$

$$\frac{4\int n_i^2 T_i^2 \left(\frac{n_D n_T}{n_i^2}\right)\left(\frac{\sigma_{DT} v}{c_{DT} T_i^2}\right) dV}{\int n_i^2 T_i^2 dV} \times \frac{\int n_i^2 T_i^2 dV/V}{[\int n_i T_i dV/V]^2} \times \left[\frac{2\int n_i T_i dV}{\int (n_i T_i + n_e T_e) dV}\right]^2$$

$$F_{DT} \times F_p \times F_e$$

- We have separated the factors inside the integrals:
  F_{DT} depends on DT mixture, dilution, T_i, non-thermal enhancement;
  F_p increases with peaking of the ion pressure profile;
  F_e depends on the ratio of ion to electron energy.

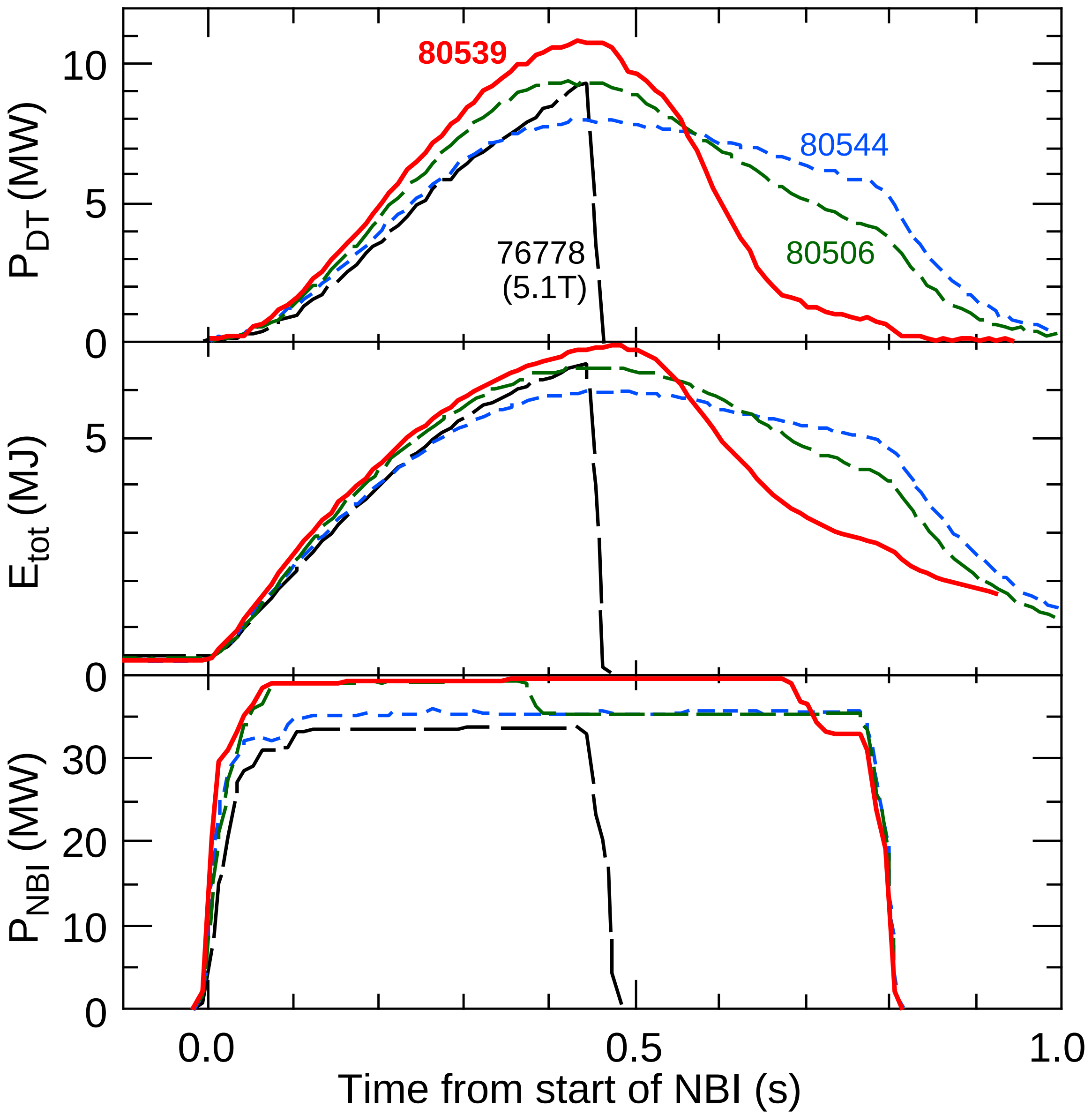
- In highest performance supershot (P_{DT} = 10.7MW), $\mathbf{F_{DT} \times F_p \times F_e \approx 2.2}$

  $F_p \approx 2.4$ (peaked); $F_e \approx 2.2$ ($T_i >> T_e$); $F_{DT} \approx 0.42$ (high T_i, small non-thermal enhancement);

- $T_e/T_i \sim 0.5$ at center improves β_α ($T_i^2 T_e^{3/2}$) at constant total β for alpha particle studies.

Supershots Produced High DT Fusion Power, as Expected

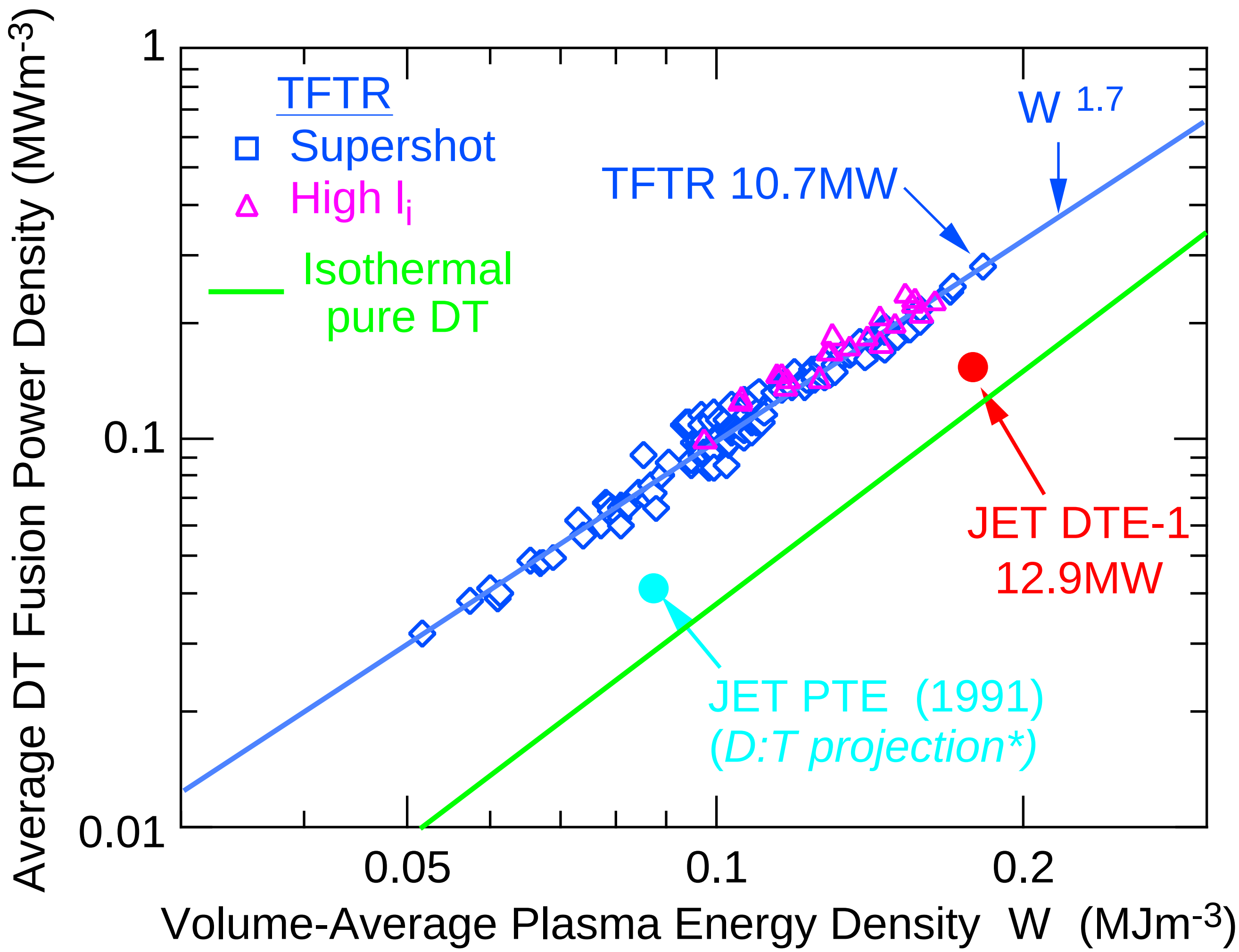
TFTR



- In shot producing 10.7MW of fusion power:

  $n_e(0) = 1.0 \times 10^{20} m^{-3}$, $T_e(0) = 13.5$keV, $T_i(0) = 40$keV

DT Fusion Power Density in TFTR



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

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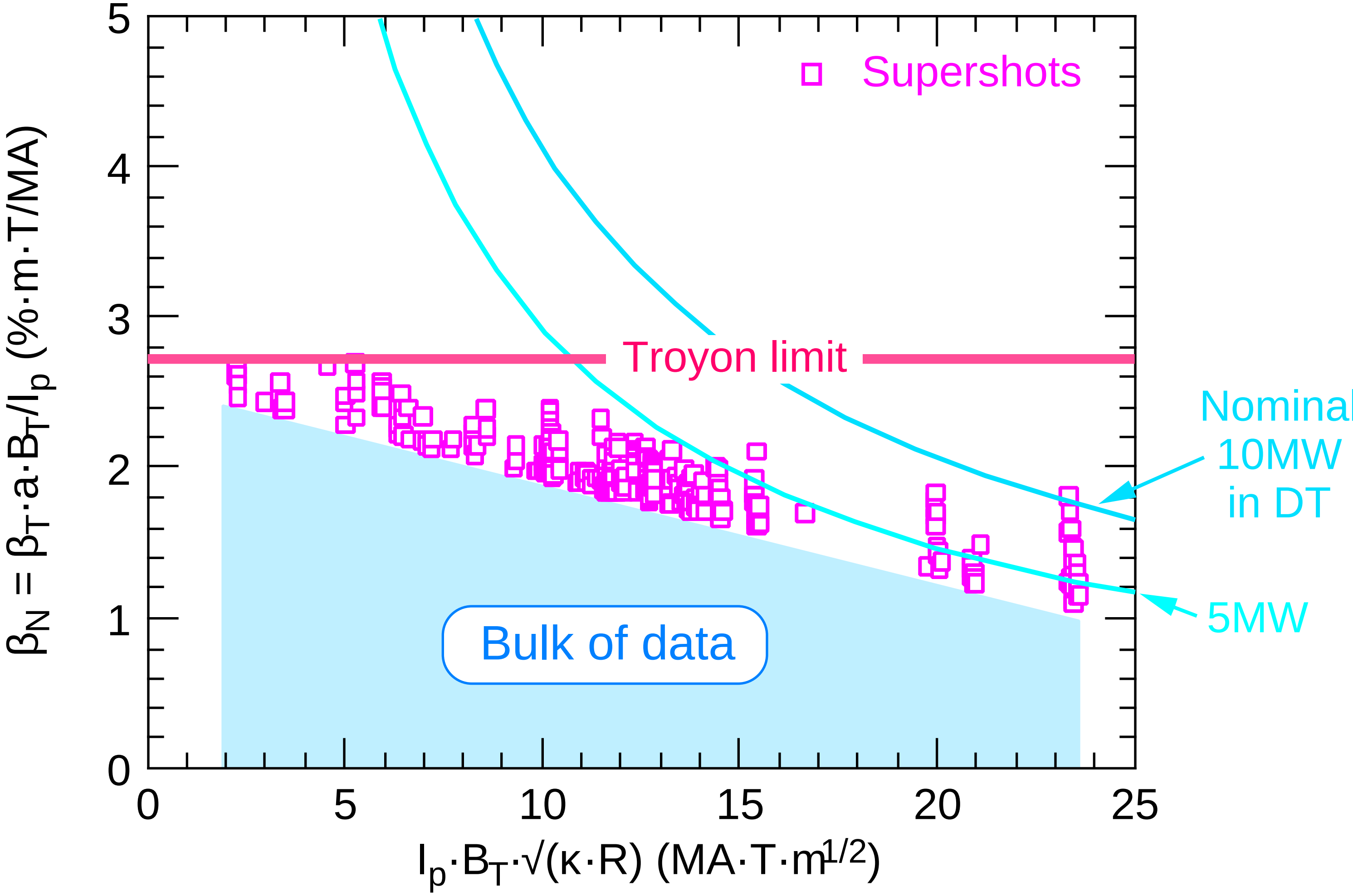
Supershot β-limit Decreased as Machine Parameters Were Increased to Raise Projected DT Power

TFTR



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

Hot ions, profiles	Non-Thermal	Stability	Machine parameters

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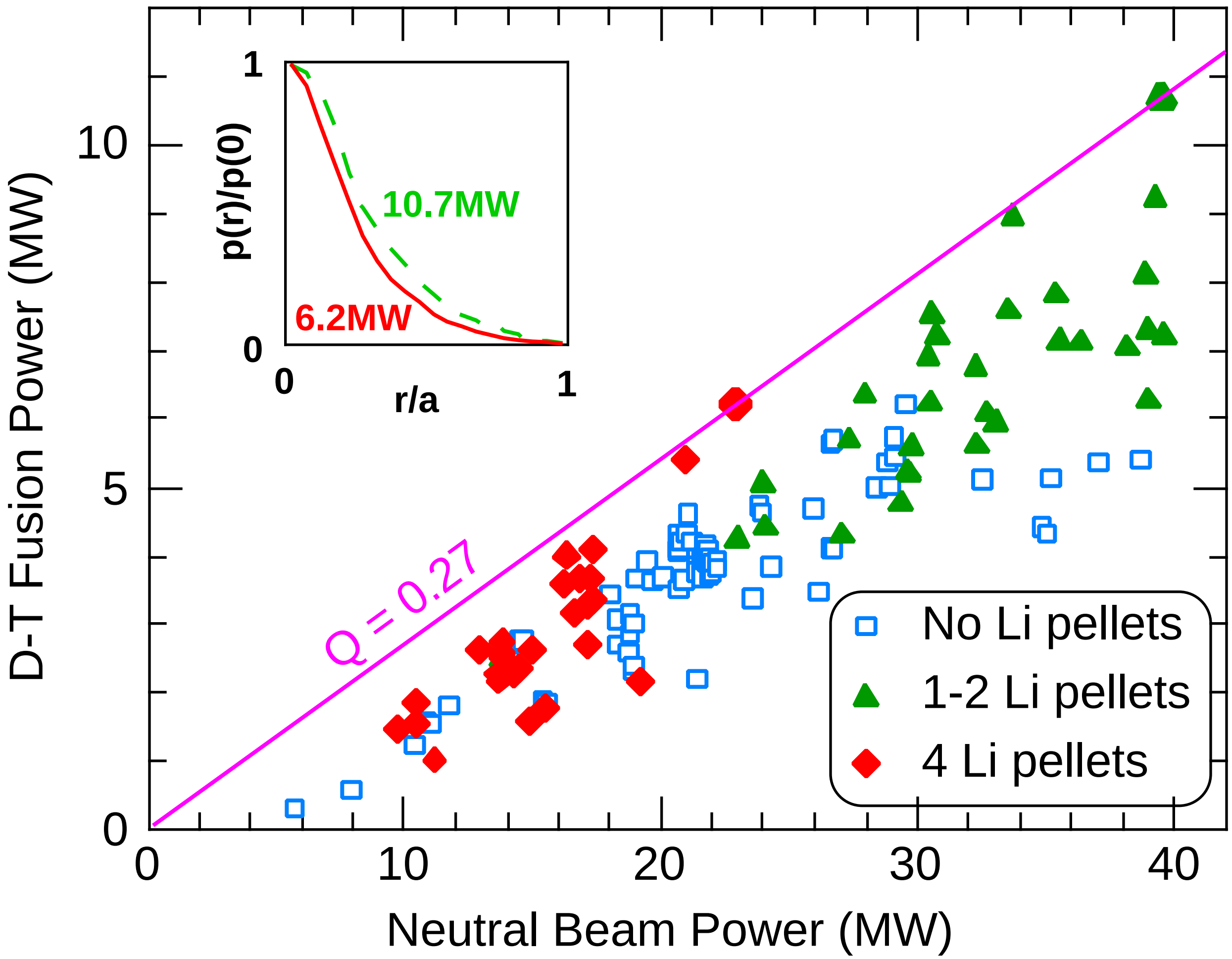
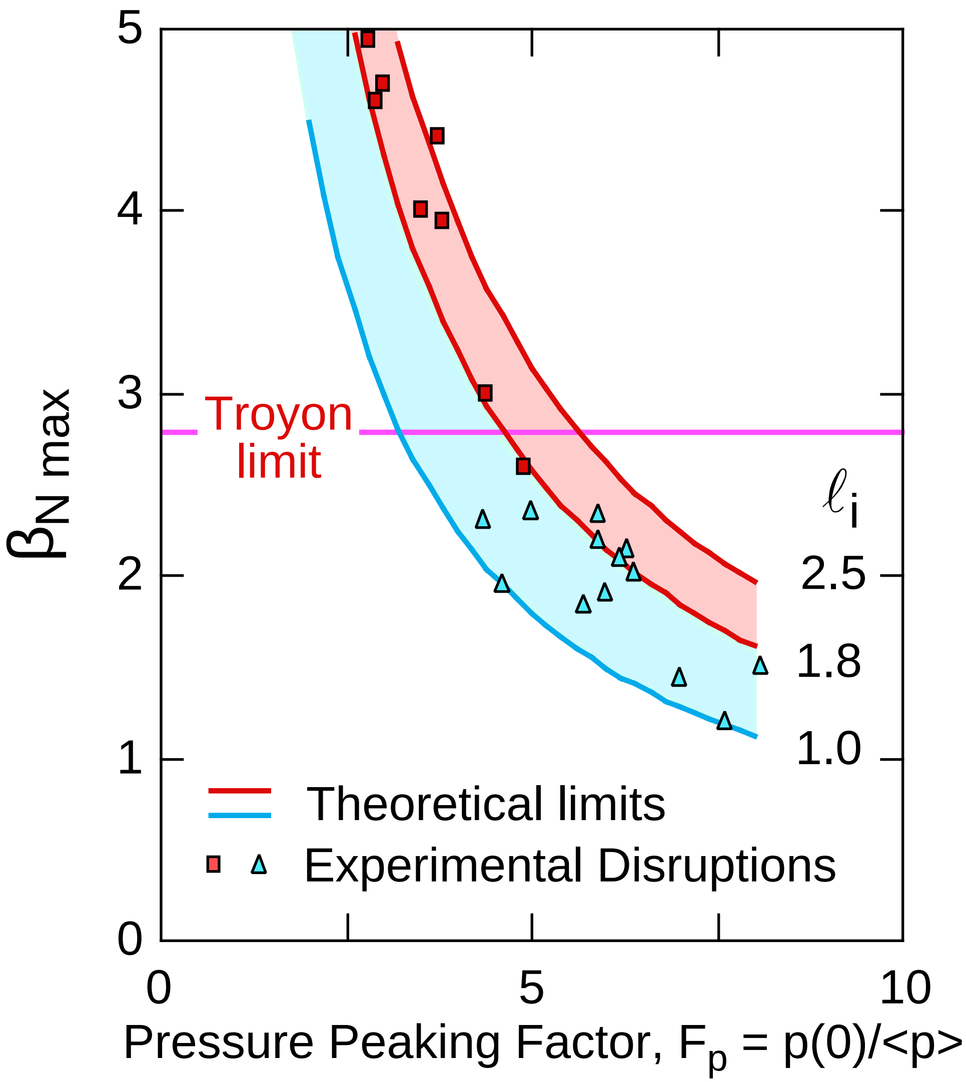
Lithium Pellet Conditioning Can Increase Supershot Confinement but Reduces Stability

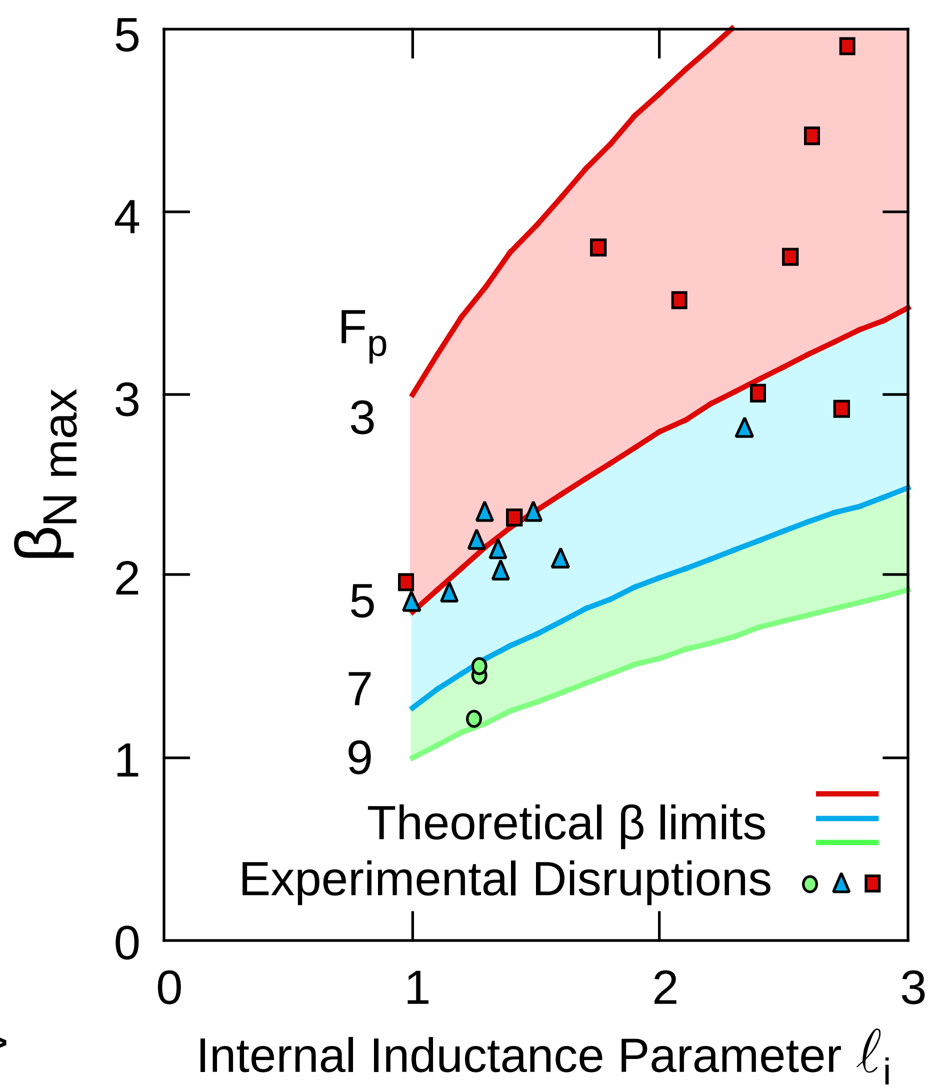
TFTR



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

Equilibrium Profile Shapes Modify β Limit





- Theoretical β limit computed with PEST code for families of equilibria
  - $q_0 = 1+\varepsilon$ to avoid n = 1 instability

Columbia U. - PPPL Collaboration

S. Sabbagh

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

TFTR

Reversed-shear

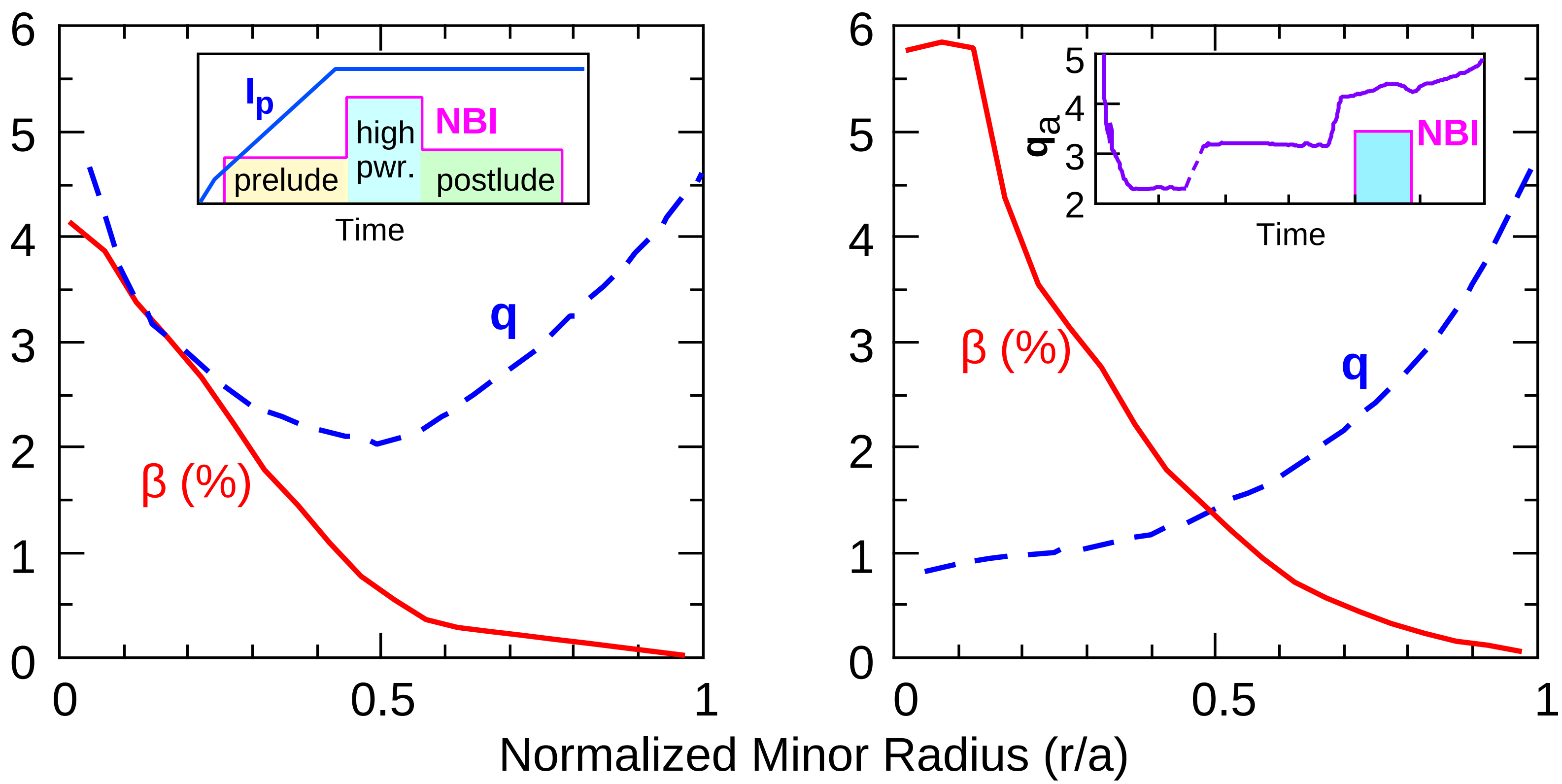
$\tau_E = 0.23$s

NBI heating during current ramp in large plasma

High-l_i

$\tau_E = 0.23$s

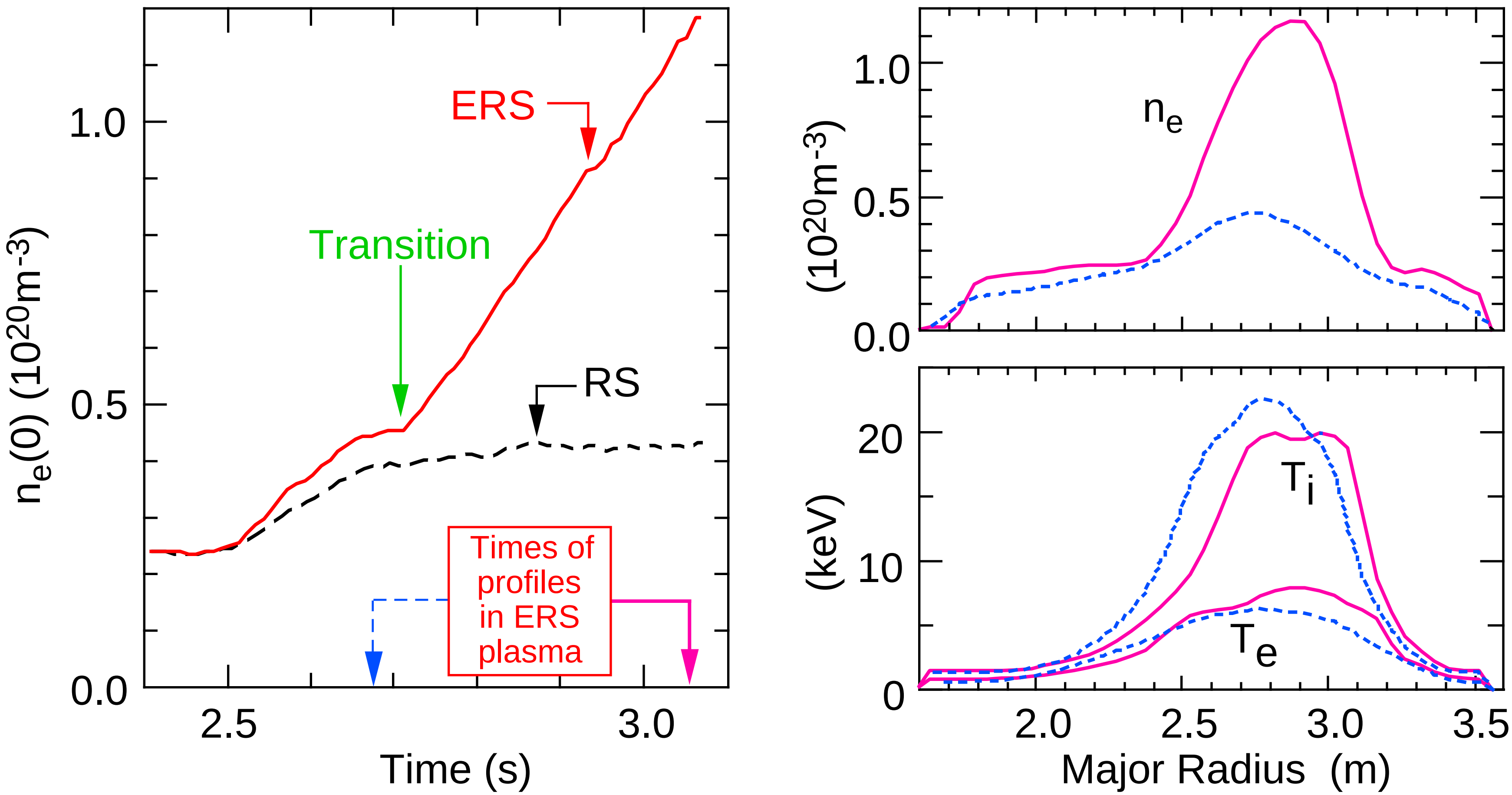
Low-q startup followed by expansion or current rampdown



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

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"

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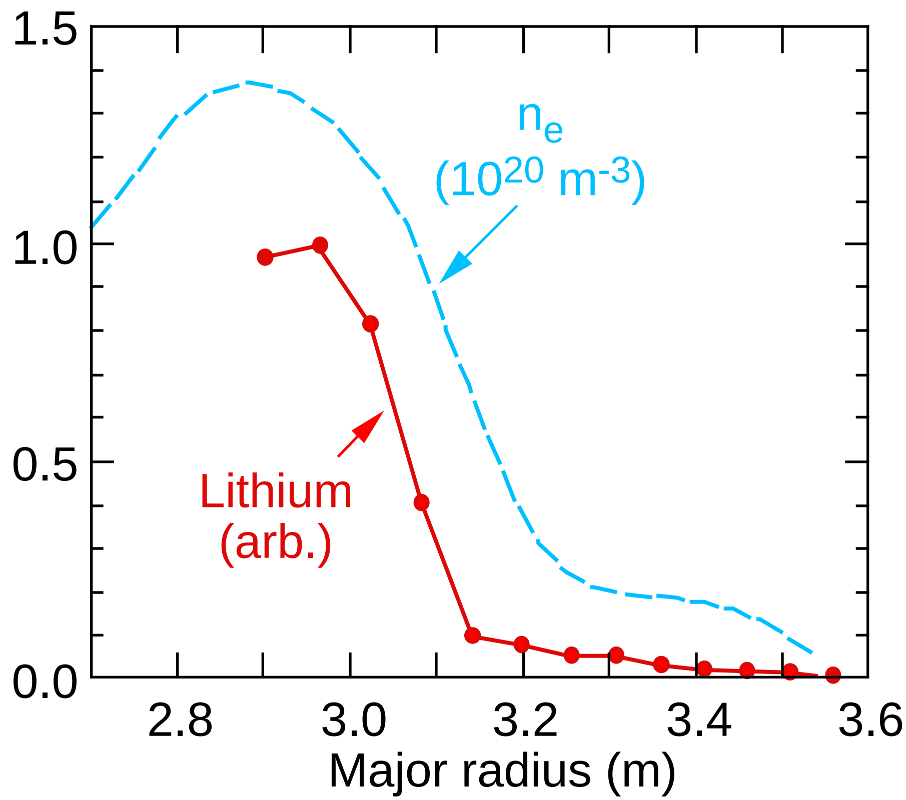
Injected Lithium Trapped Within Transport Barrier after ERS Transition

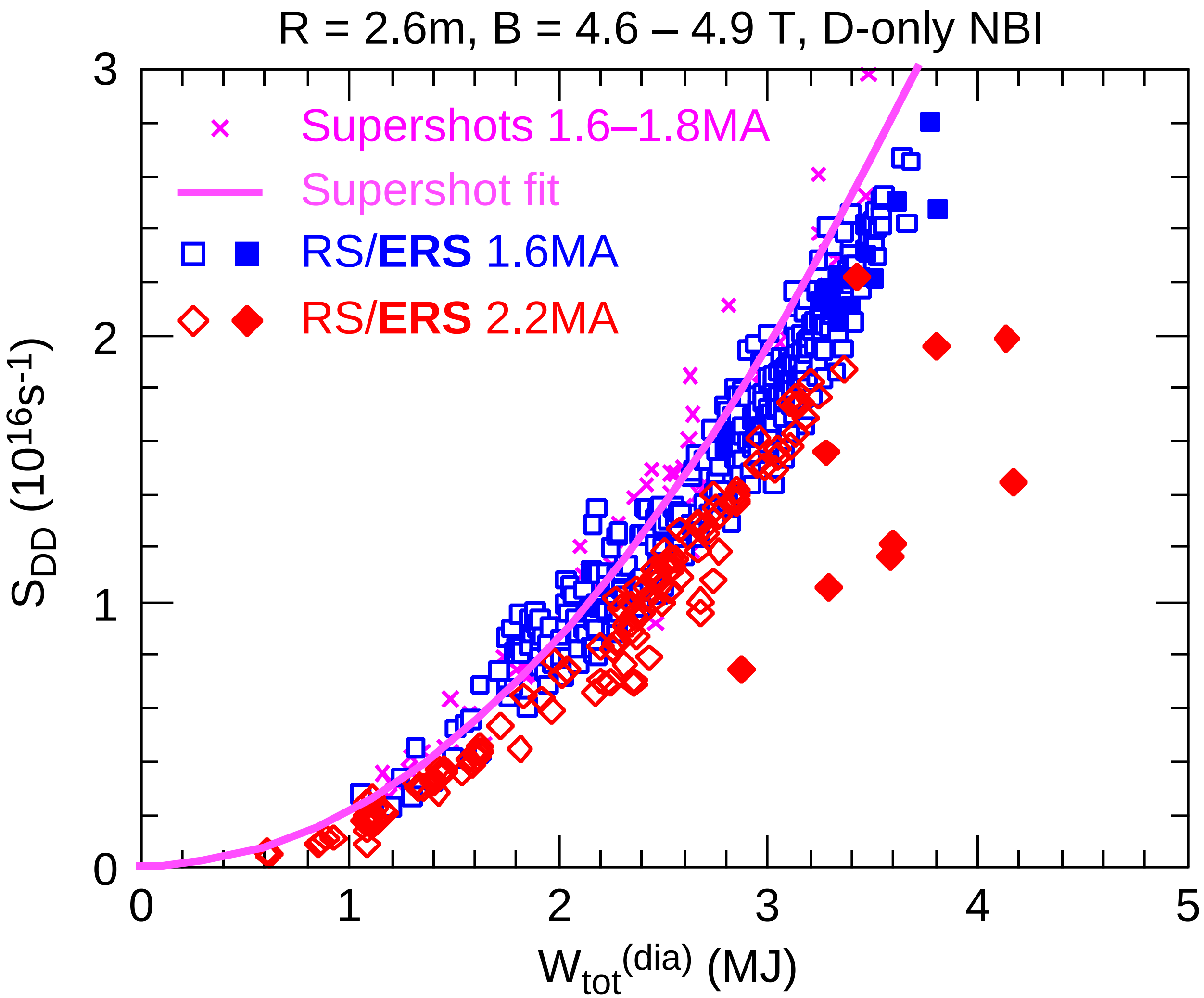
- Toachieve high fusion power in ERS plasmas it was necessary to operate at high plasma current (>2MA)
- Power threshold for ERS appears to increase with plasma current
- Lithium pellet at start of HP-NBI necessary to stimulate ERS at 2.2MA

Densities 0.5s after pellet during ERS phase



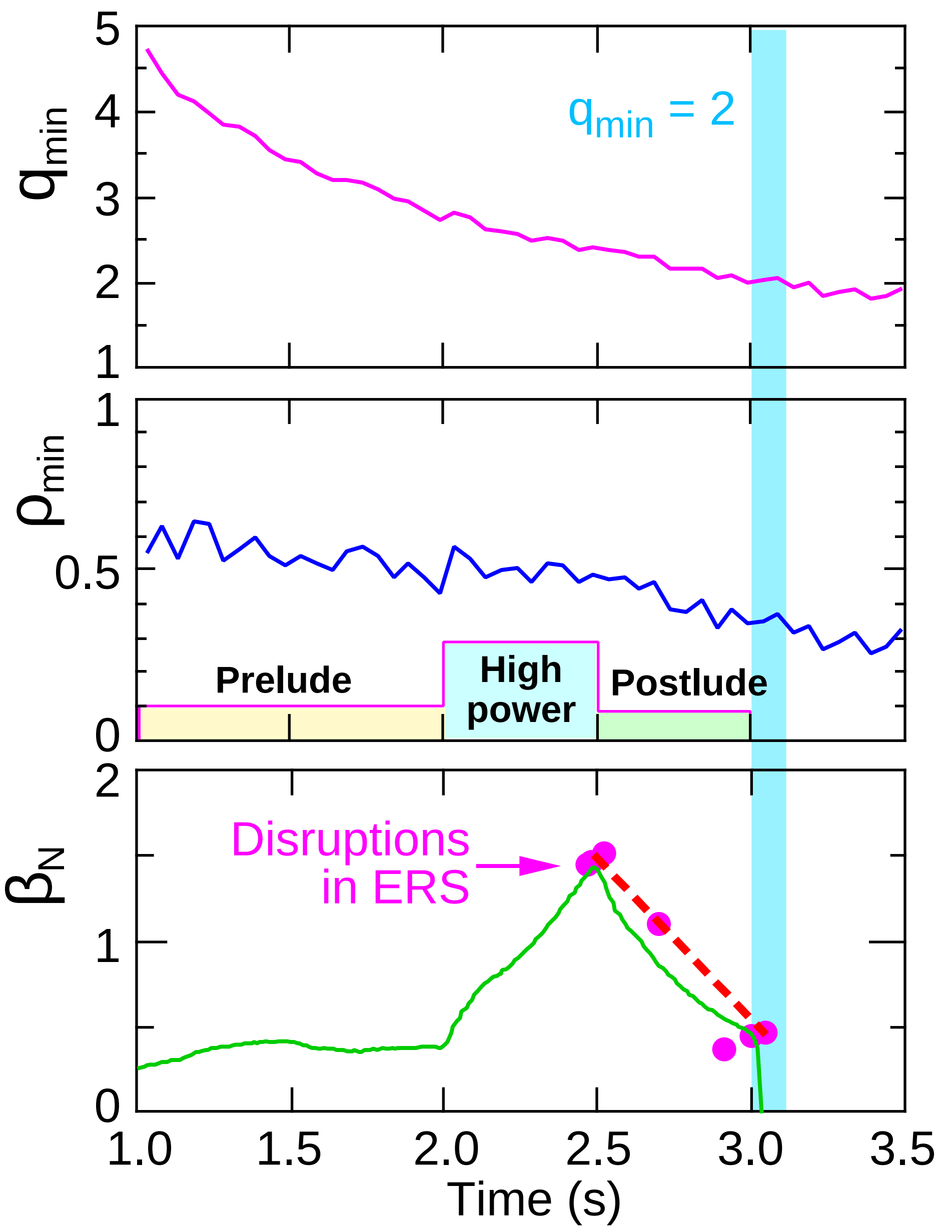
Dilution Reduced DD Reactivity of High-Current ERS Plasmas

TFTR



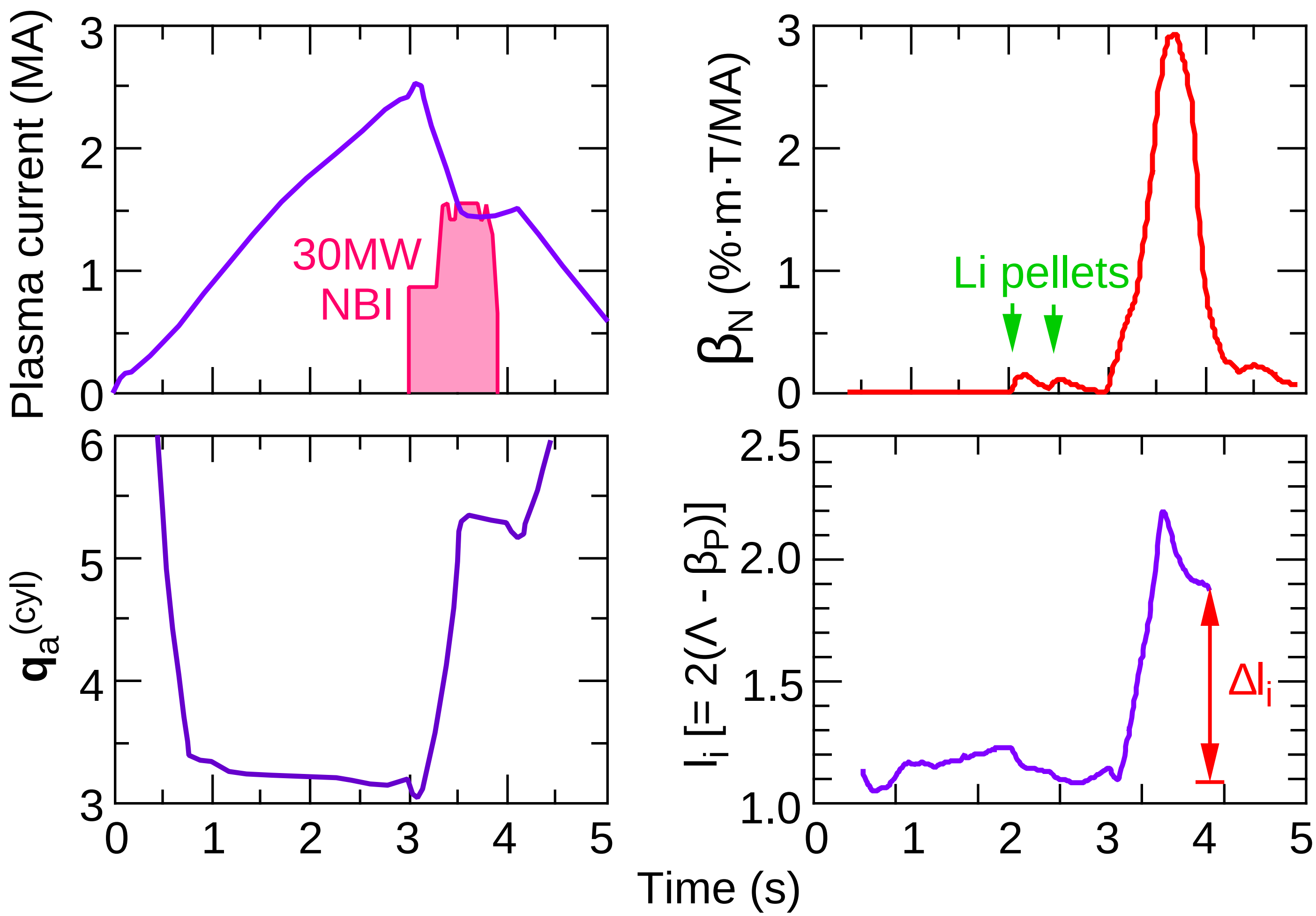
- 1.6MA RS/ERS plasmas have similar DD reactivity to comparable supershots
- 2.2MA RS plasmas also achieve good DD reactivity
- Li pellets used to provoke ERS at 2.2MA diluted deuterium in well-confined core

Natural Evolution of Pressure and q Profiles Reduces β-Limit During ERS Phase at High Current



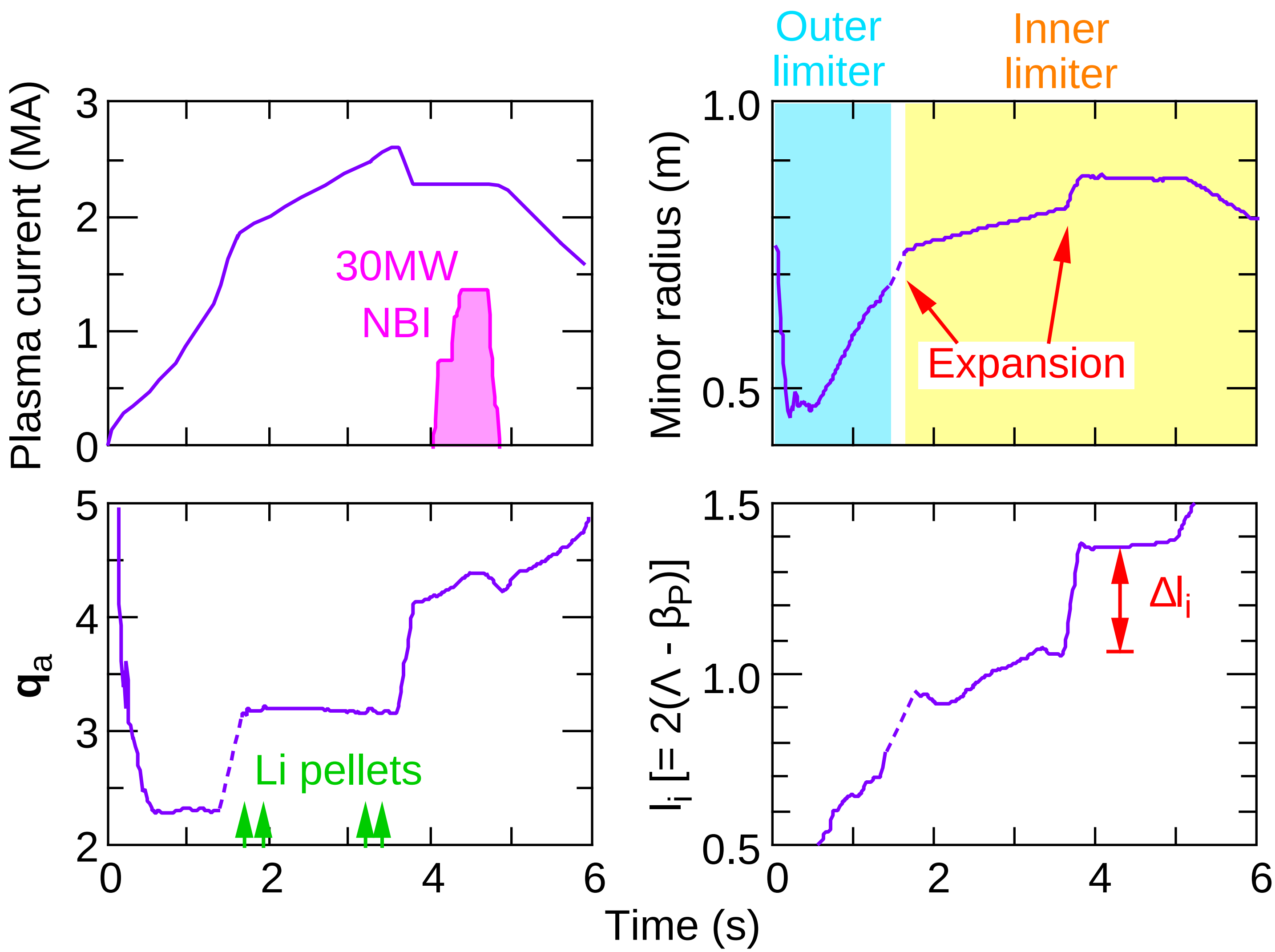
- Large pressure gradient inside ρ_{min} persists even in "postlude" phase
- q_{min}, ρ_{min} both decrease with time
- β-limit is reduced as $q_{min} \rightarrow 2$
- β_N = 2.0, β^*_N = 4.1 achieved at 1.6MA
- **Challenge**: control barrier location and shape of q-profile near ρ_{min}

Current Rampdown Increases l_i for Investigating Effect of Current Profile on Stability



- Confinement was similar to supershots during NB heating
- Demonstrated that β_N limit increases with l_i but improved stability only available at reduced plasma current with this technique
  - Achieved fusion power of 6.7MW at I_p = 1.5MA

Expansion of Ultra-Low-q Discharge Reliably Produces High-l_i Plasma During NBI Heating Phase



- Confinement during NBI also responds favorably to lithium coating
- High-l_i startup was combined with DOLLOP (Li "aerosol") coating and radiating mantle in final TFTR D-T experiments

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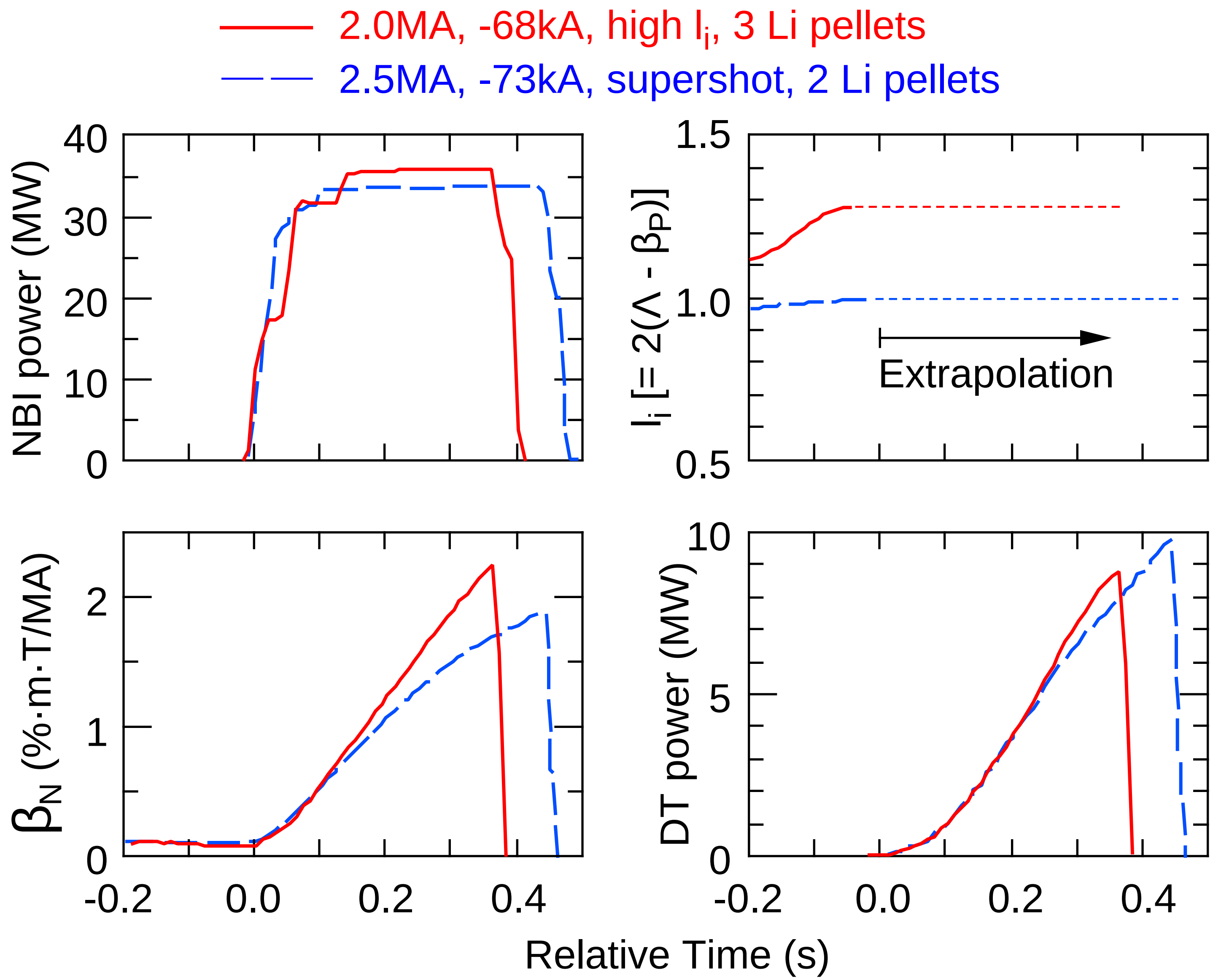
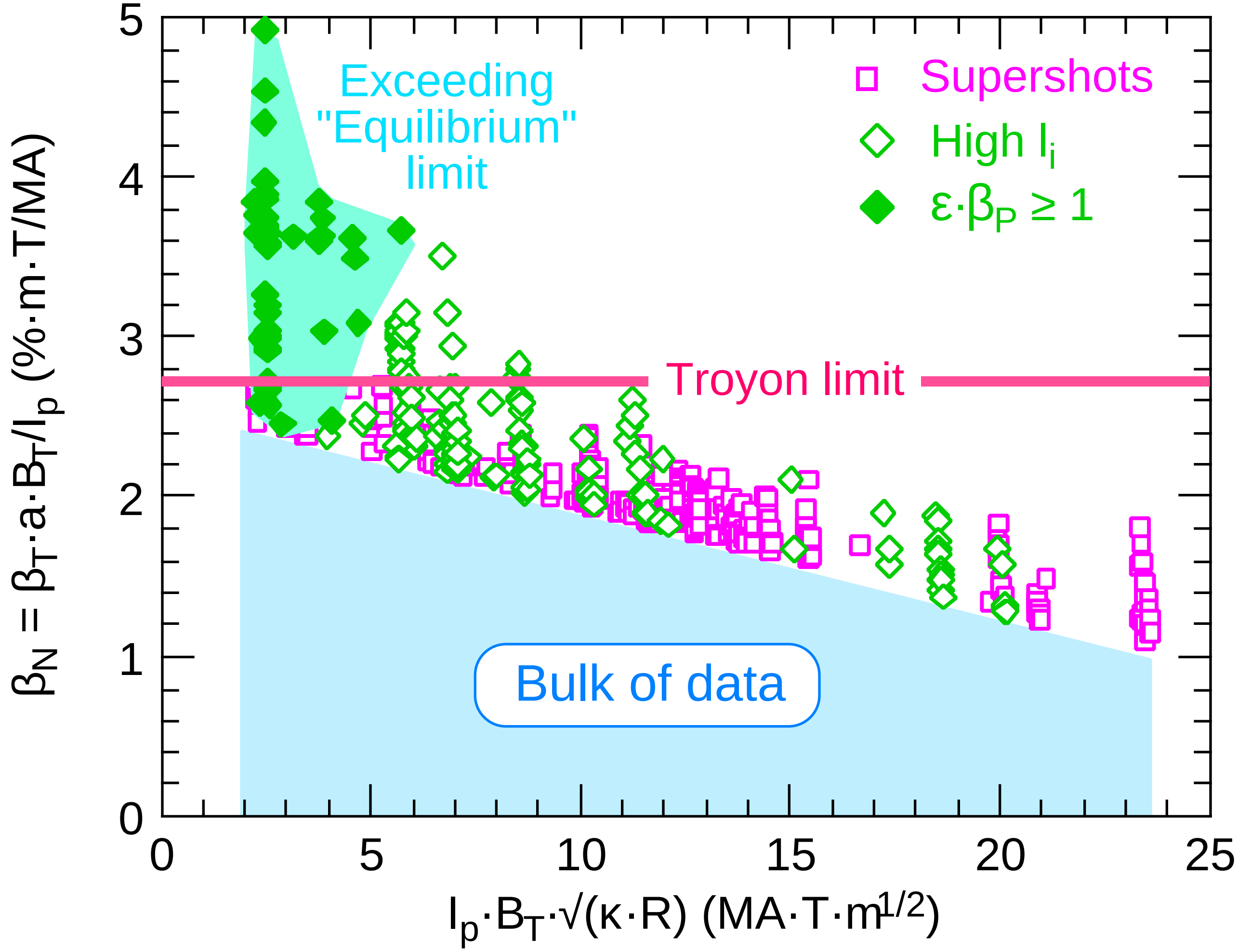
Normalized β-Limit Scales ∝ l_i in Expansion Plasmas

TFTR



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

High-l_i Regime Achieved Very High Normalized Beta but at Reduced Machine Parameters



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

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

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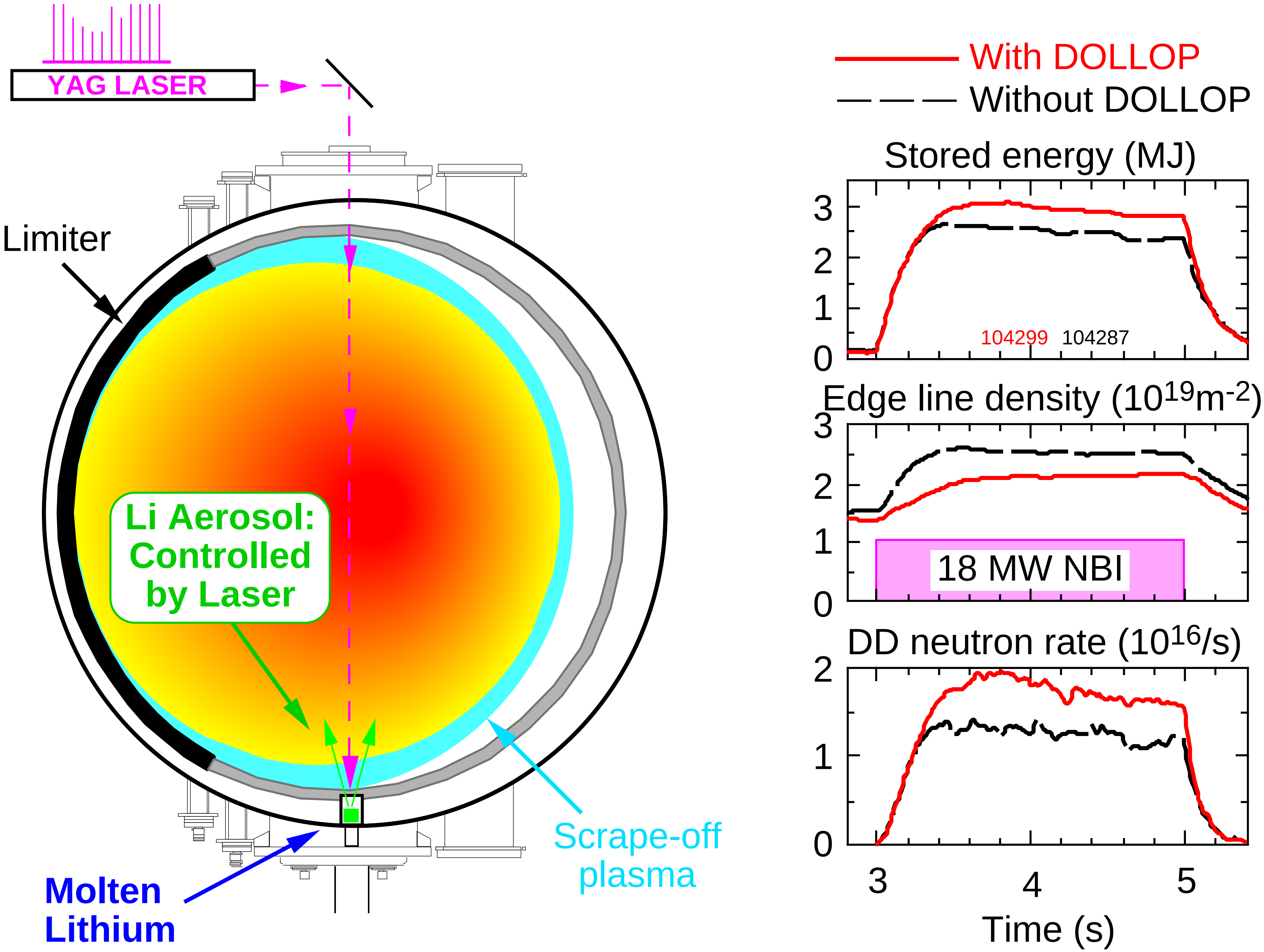
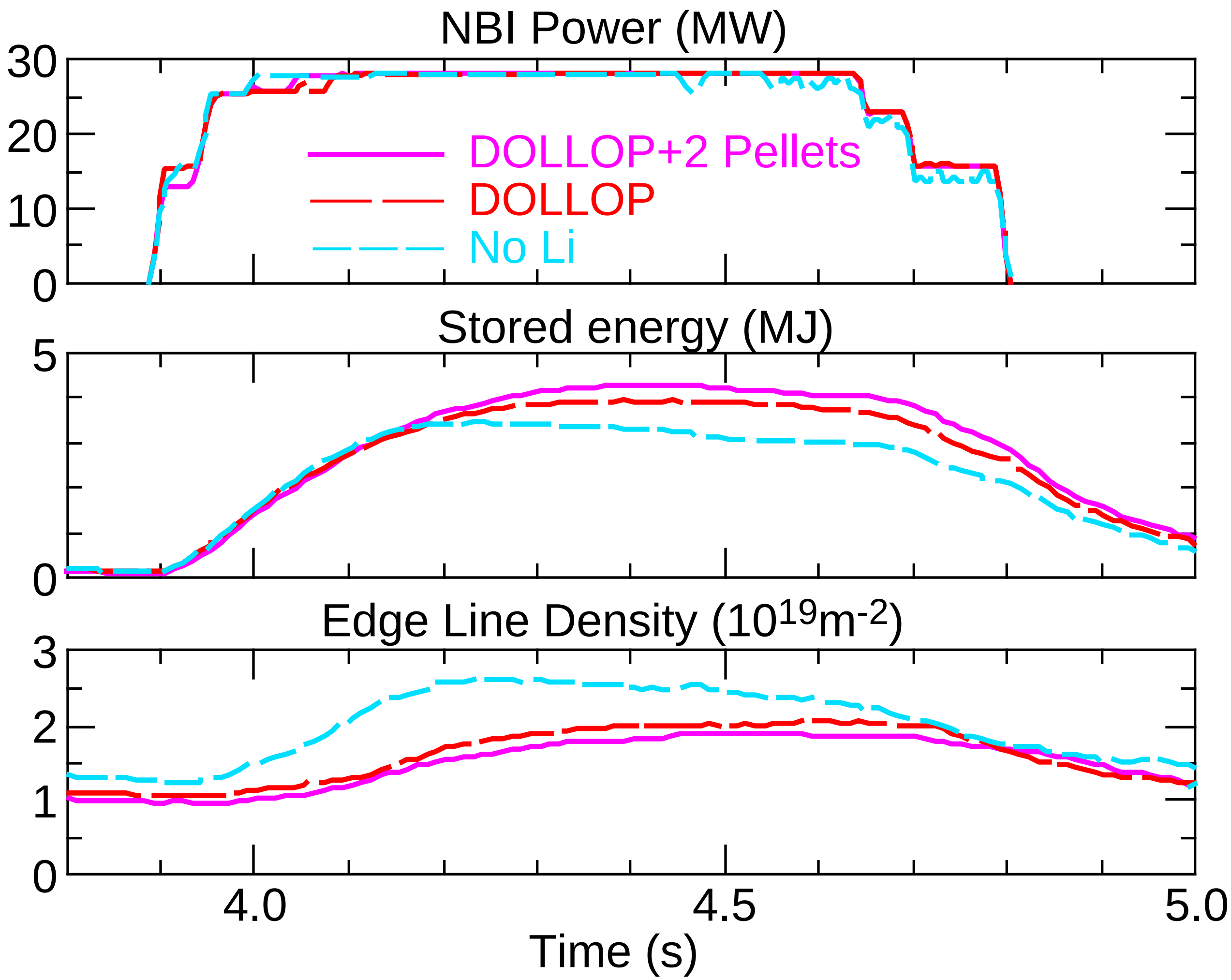
DOLLOP: Li Aerosol Controls Influxes and Increases Performance - Nonperturbing and Controllable

TFTR



DOLLOP and Li Pellets Combined To Improve Confinement in High-Current High-l_i Shots

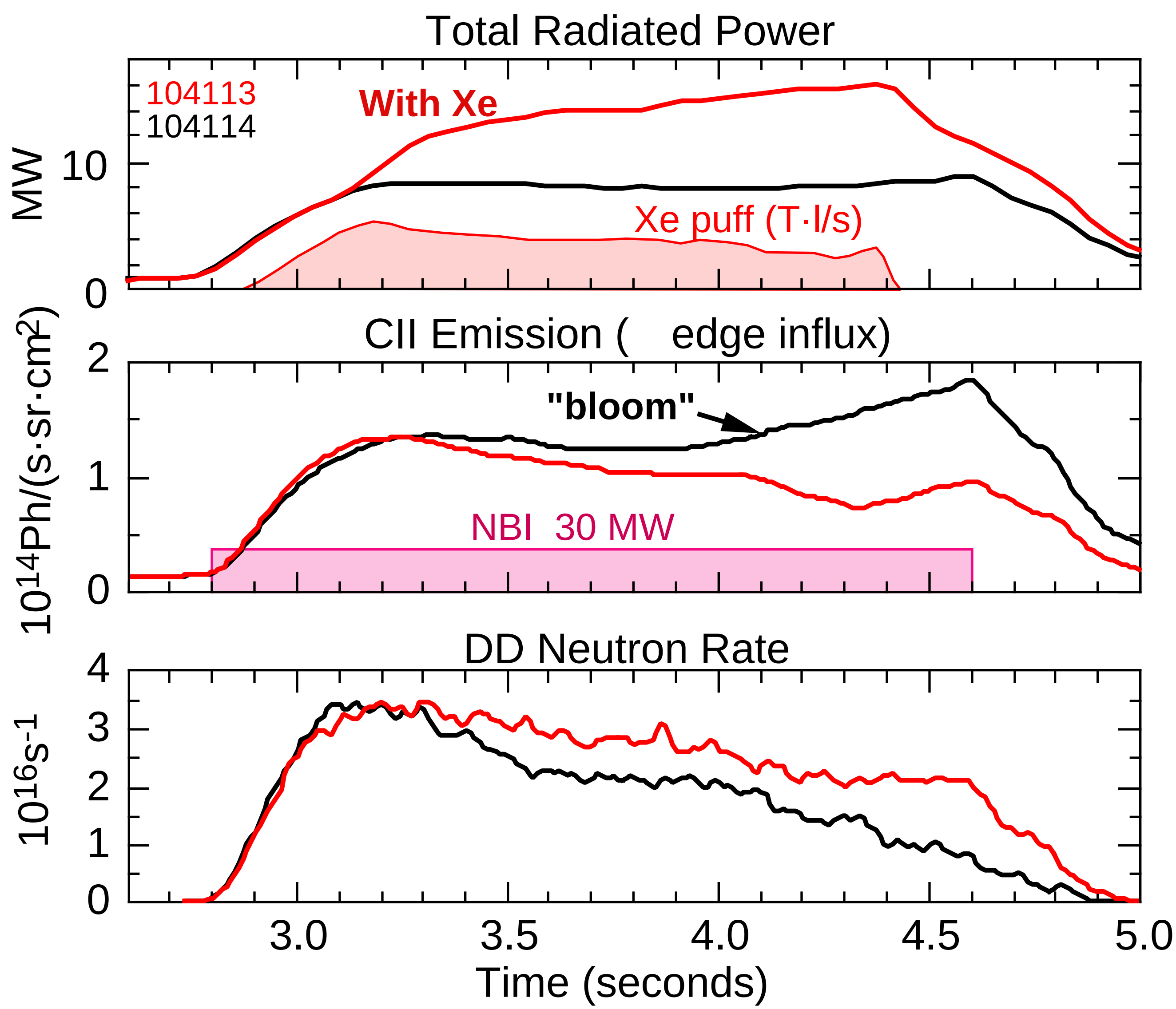
TFTR



- 2.3MA/5.5T High l_i plasmas predicted to be capable of producing >14MW DT fusion power on basis of β-limit at 2.0MA/4.7T case
- Needed to suppress blooms at full DT-NBI input power

Xe Radiation Can Suppress Carbon "Bloom" in Supershots

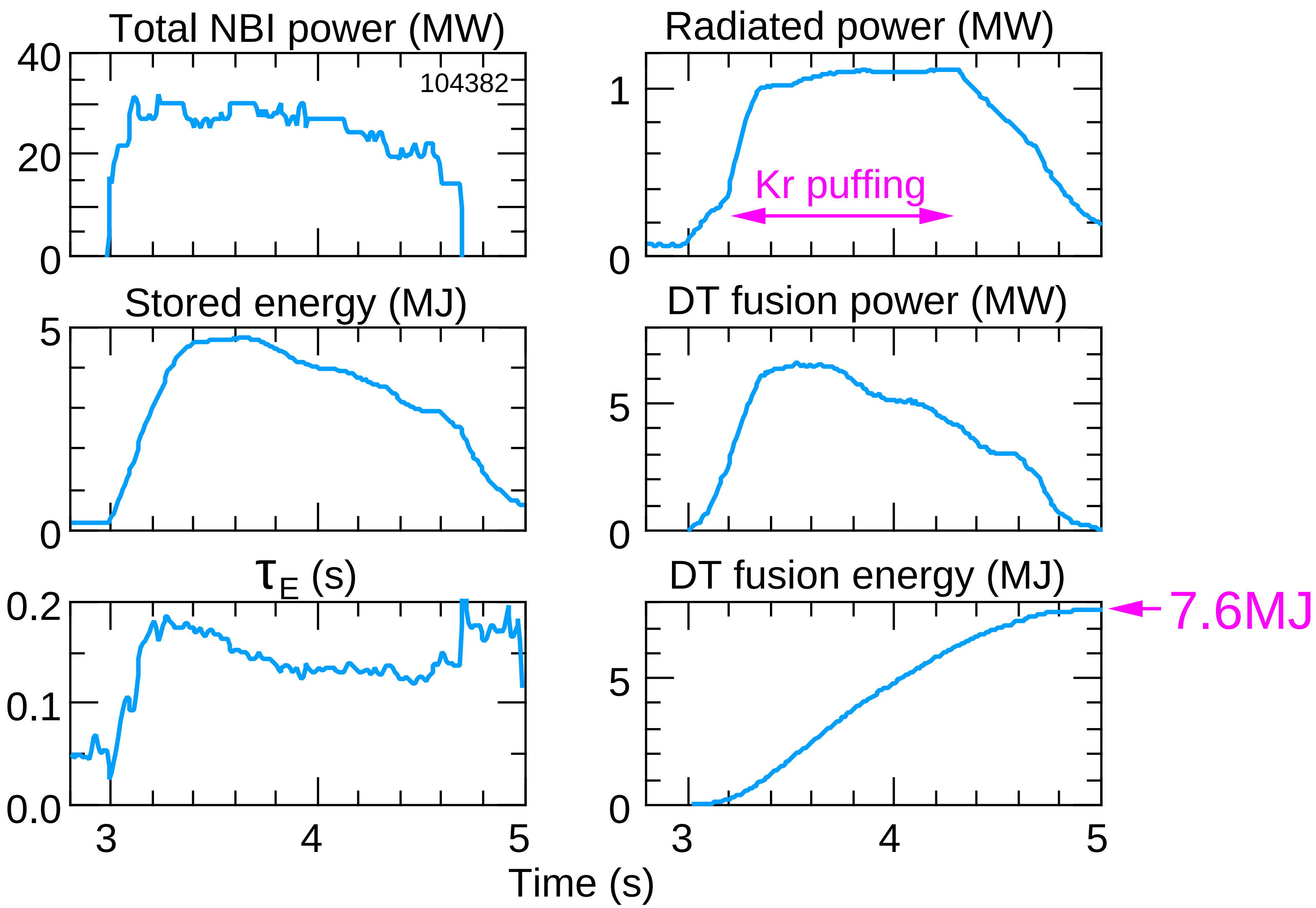
TFTR



- Minimal effect on confinement
- DD neutron rate remains high - no significant dilution

DOLLOP, Pellets and Krypton Were Combined to Produce the Highest Fusion Yield from TFTR

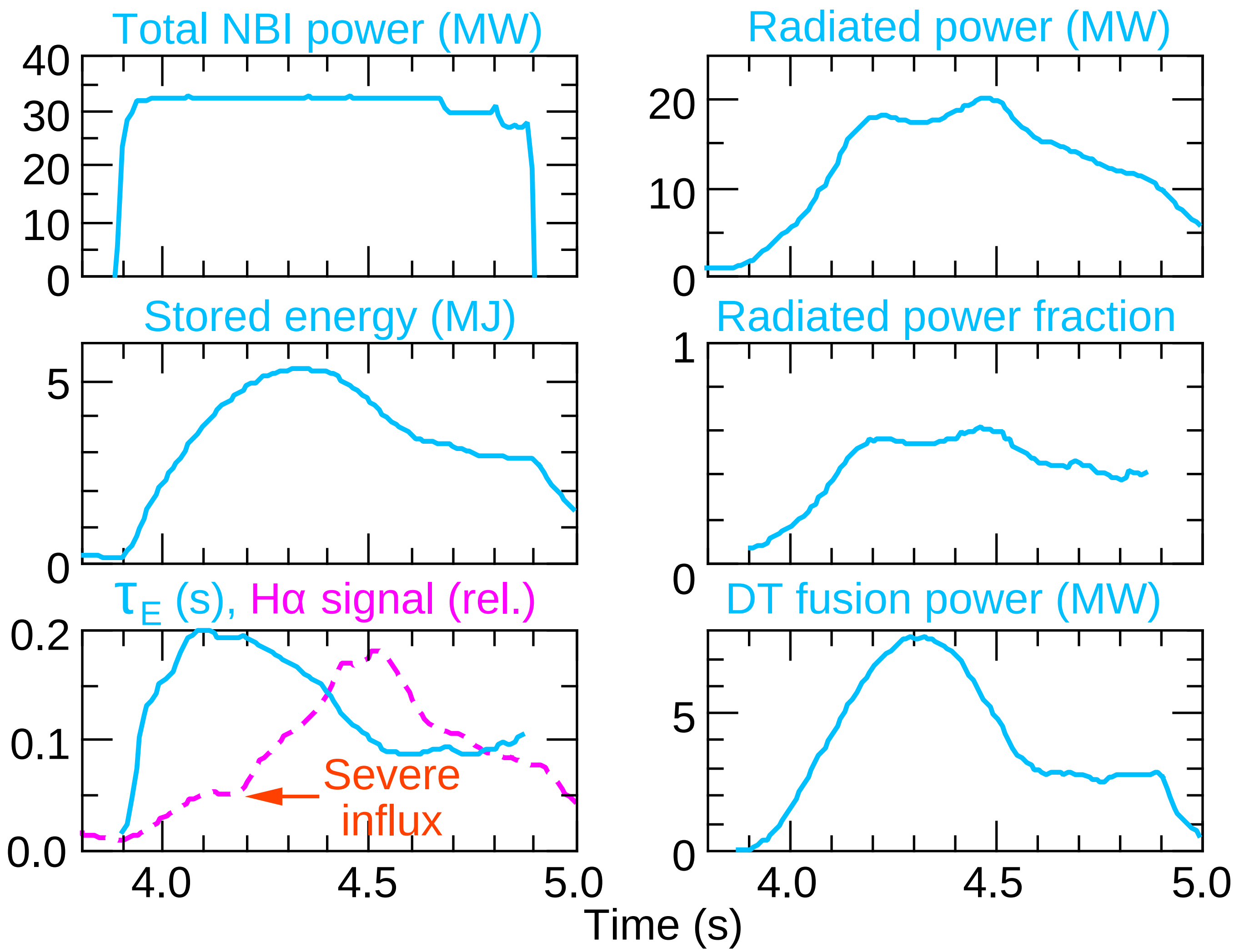
TFTR



- Insufficient Kr radiation and NBI power reduction contributed to significant rollover of fusion power

Combined DT-NBI, High-l_i, DOLLOP, Pellets and Krypton Radiating Mantle for the Last TFTR Shot

TFTR



- Shot 105529 taken at 1:30am on April 4, 1997.
- Kr was insufficient to suppress the limiter influx at 32MW input power
  - real-time bolometer signal became non-linear, reduced Kr flow prematurely

Conclusions

- DT supershots largely fulfilled predictions from deuterium prototypes
  - 10.7MW peak D-T power; Q = 0.27
  - Higher ion temperature in DT reduced gain over DD by 10 - 20%
- Trade-offs between idealized physics parameters and real machine operation must be made for each operational regime
- ERS regime is an excellent testbed for physics development but has practical problems for high performance DT operation
  - low practical β-limit, uncontrolled evolution
- The high-l_i regime yielded good fusion performance
  - its good stability despite $q_0 < 1$ remains a challenge for theory
- New techniques being developed up to the last TFTR shot showed promise for obtaining better fusion performance from today's tokamaks