Highly Radiative Plasmas for Local Transport Studies and Power and Particle Handling in Reactor Regimes

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Motivation

- Study local thermal transport
  - Large increase in profile of electron power loss
  - Small change in neutral-beam power profile
  - Measure response of T_e, T_i, and χ's
- Reduce wall impurity influxes
  - Reduce power conducted and convected to edge
- Model highly radiative plasmas in ITER
  - "Calibrate" MIST from TFTR data

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Outline

- **Local transport studies**

  Measure effect on χ_e, χ_i, χ_φ
  Comparison of T_i with model with flow shear
  Change in v_θ and E_r near edge

- **Power and particle handling**

  Improvement in τ_E and S_n when blooms suppressed
  Record fusion energy (7.6 MJ)
  Reduction of wall influxes with high-Z gases and Li wall conditioning

- **Implications for reactors**

  Significantly reduced wall loading
  MIST P_{rad} "calibrated" by TFTR results
  MIST simulations for ITER

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Technique

- Puffing high-Z gases into steady-state supershot
- Feedback control of puff rate on radiated power fraction, γ = Prad / Pheat
- γ in range 40 - 90 %
- Density ~ 40 - 55% of Greenwald limit
- Enhanced confinement does not require gas puff.
- Different from RI Mode
  - Low-Z gases
  - High density
  - High Radiated Power Fraction

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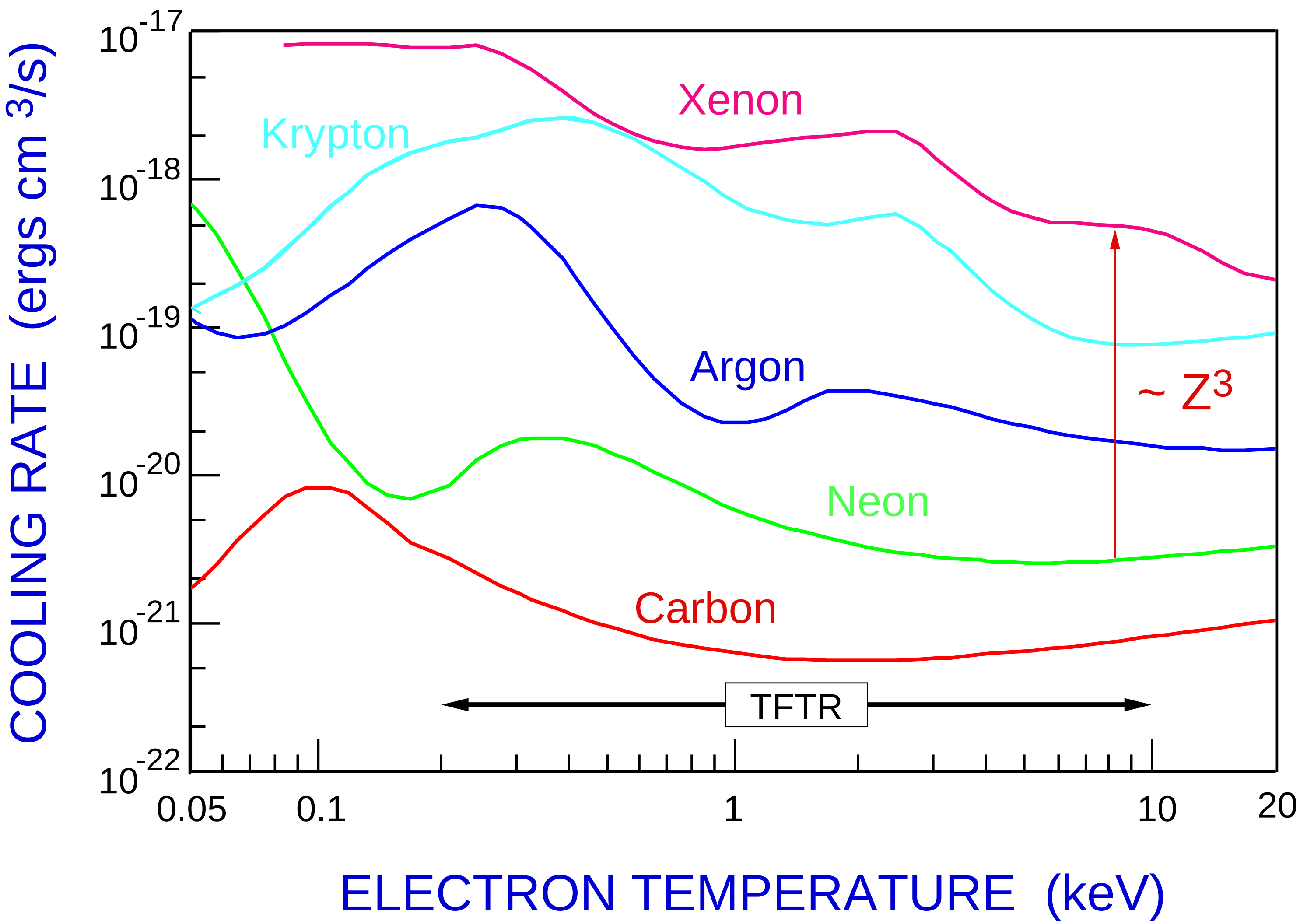
High-Z Ions Cool More Efficiently than Low-Z Ions.



- Fuel dilution ~ Z^{-2} at constant power.
- <Z> = 10, 32, 42 for Ne, Kr, Xe at T_e = 6 keV

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Local Transport Studies
(Modest Heating Power)

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Radiative Plasma Has High P_{rad} But T_e Drops Very Little

- Krypton or xenon puffing increases the radiated power.
- Core density rises, and
- Higher q_{ie} offsets increased P_{rad} in the electron channel.
- Lower net heating in ion channel, but T_i increases.
- Hydrogenic and carbon influxes significantly reduced.
    - Lower χ_i and χ_f; χ_e unchanged in core.

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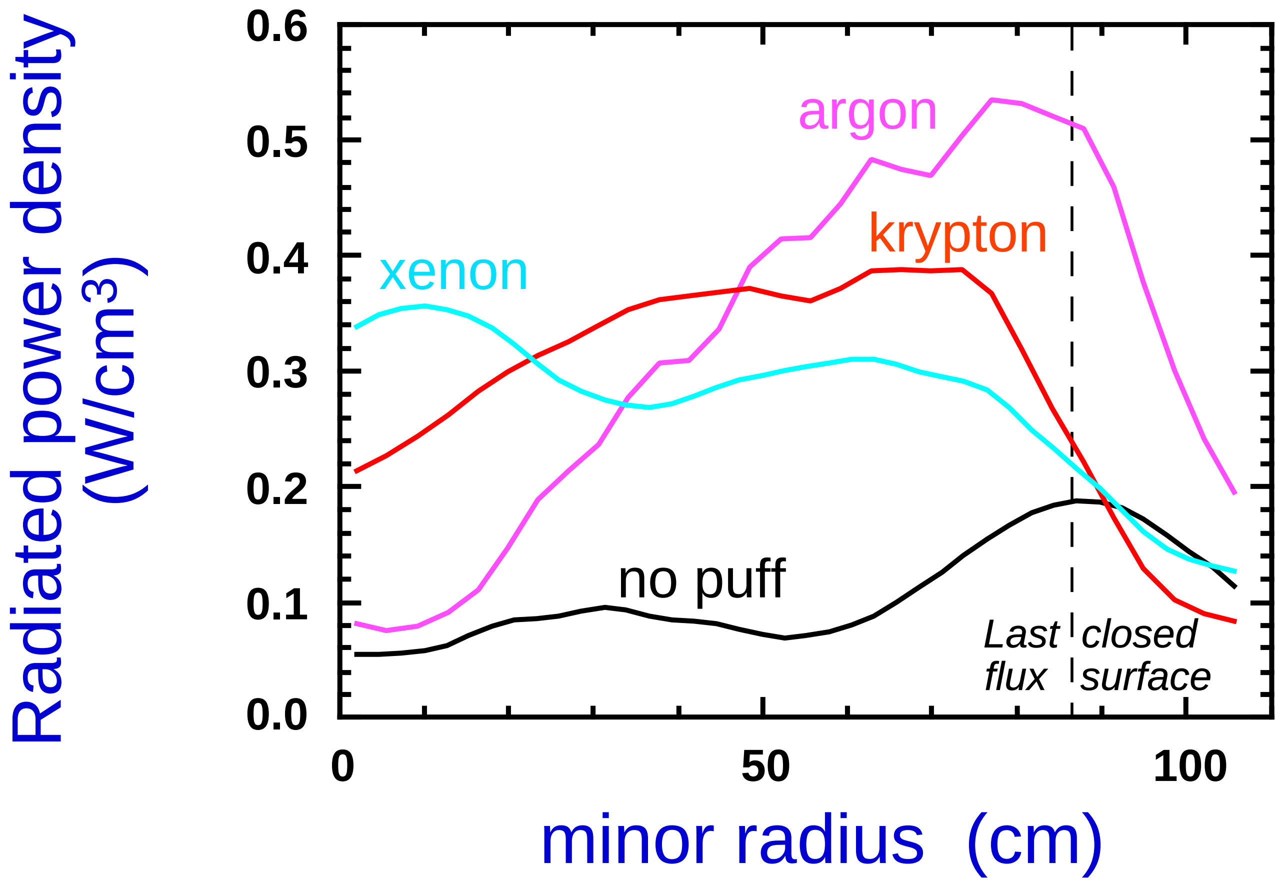
Measured Local Radiated Power Increased Up to Factor of 6



- Radiated power 75 - 90% of heating power

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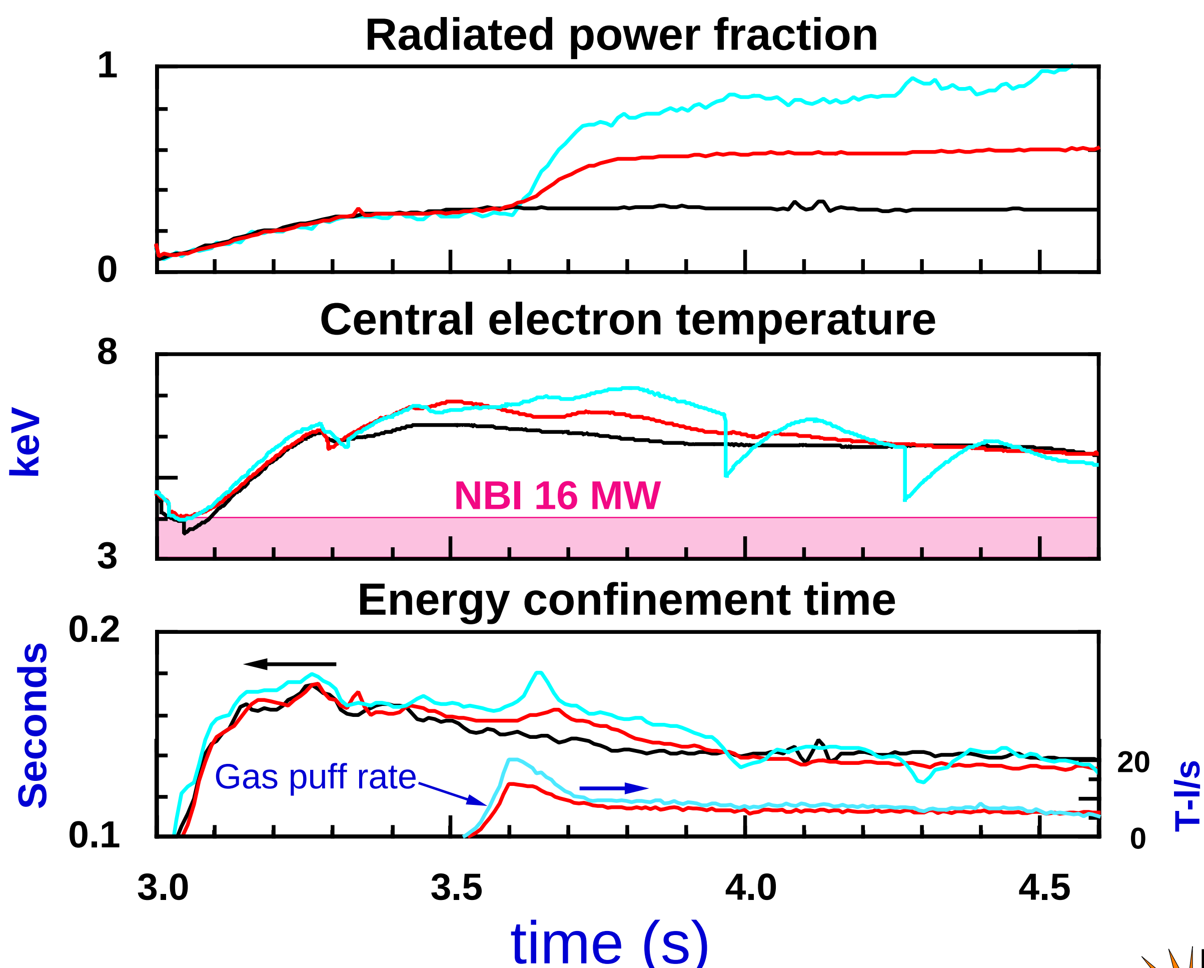
Central T_e and τ_E Little Changed at High Radiated Power Fractions, Modest Heating Power

Krypton puffing



• Dα brightness significantly reduced

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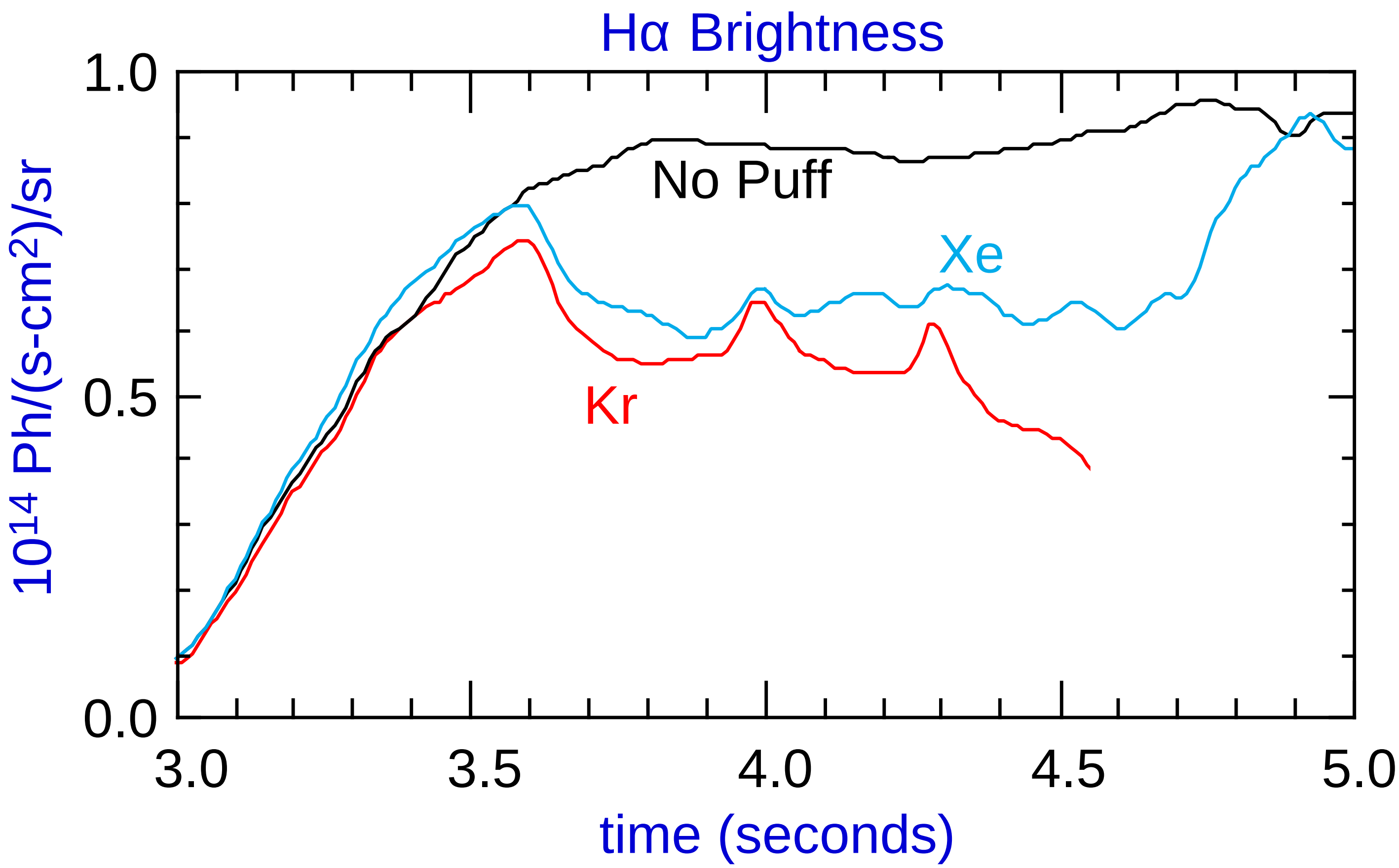
Deuterium Influx Lower with Krypton and Xenon Puffing



- τ_E Hα$^{-0.24}$ in supershots

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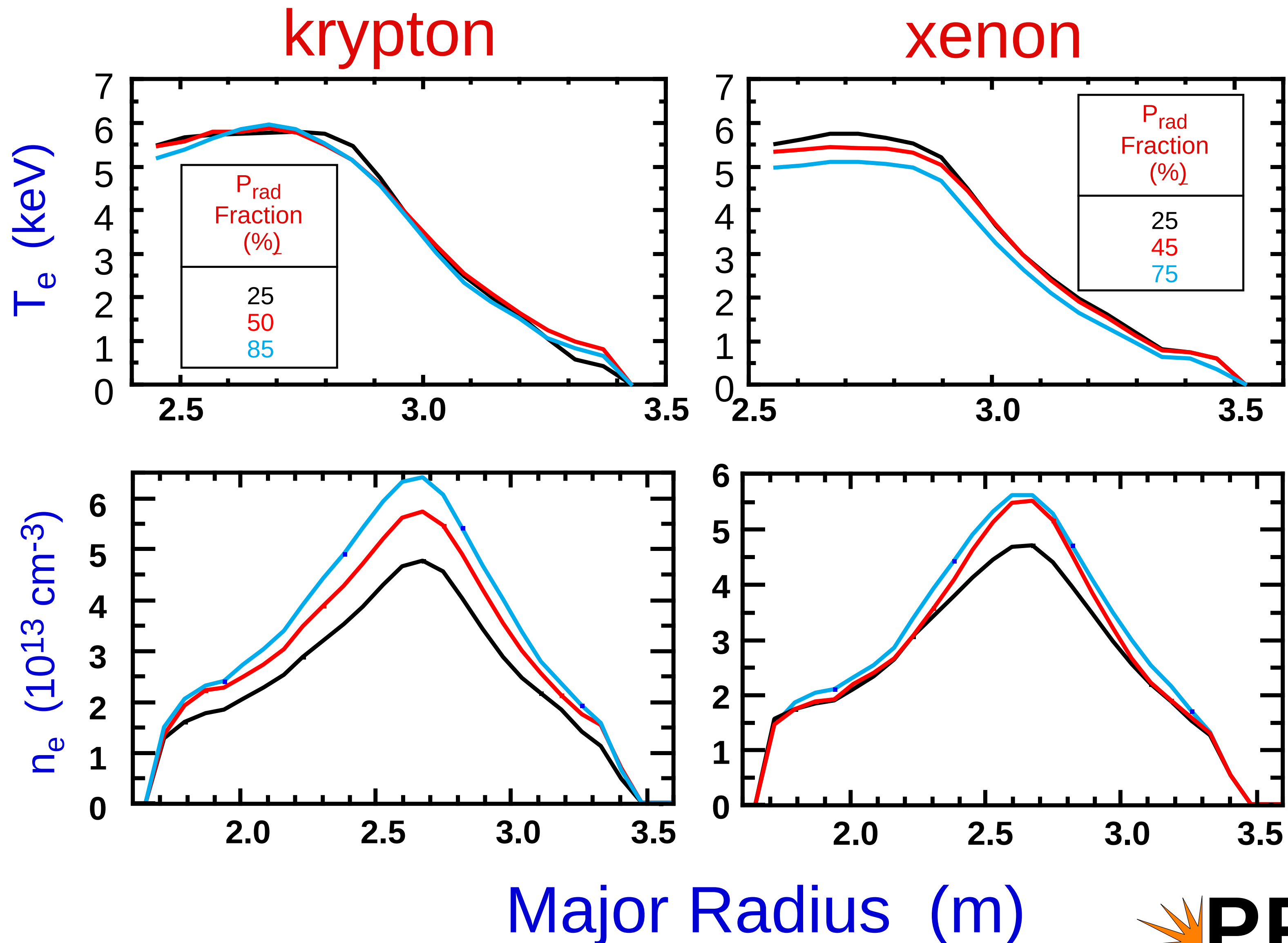
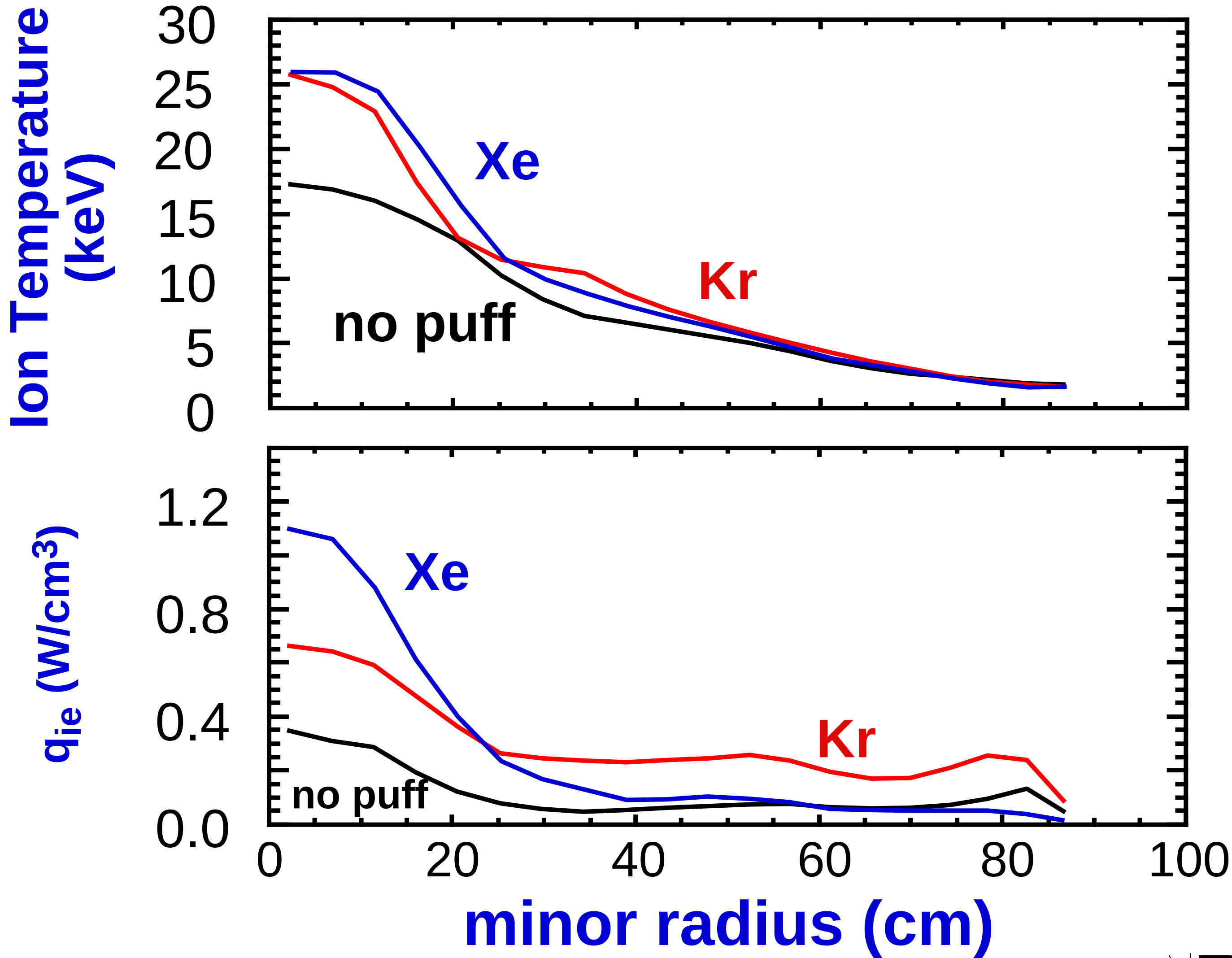
T_e Profile Unchanged, Particle Confinement Higher with Krypton or Xenon Puffing



T_i and Ion-Electron Equilibration Power Higher with Krypton or Xenon Puffing



- $q_{ie} \sim n_e^2 (T_i - T_e) / T_e^{3/2}$

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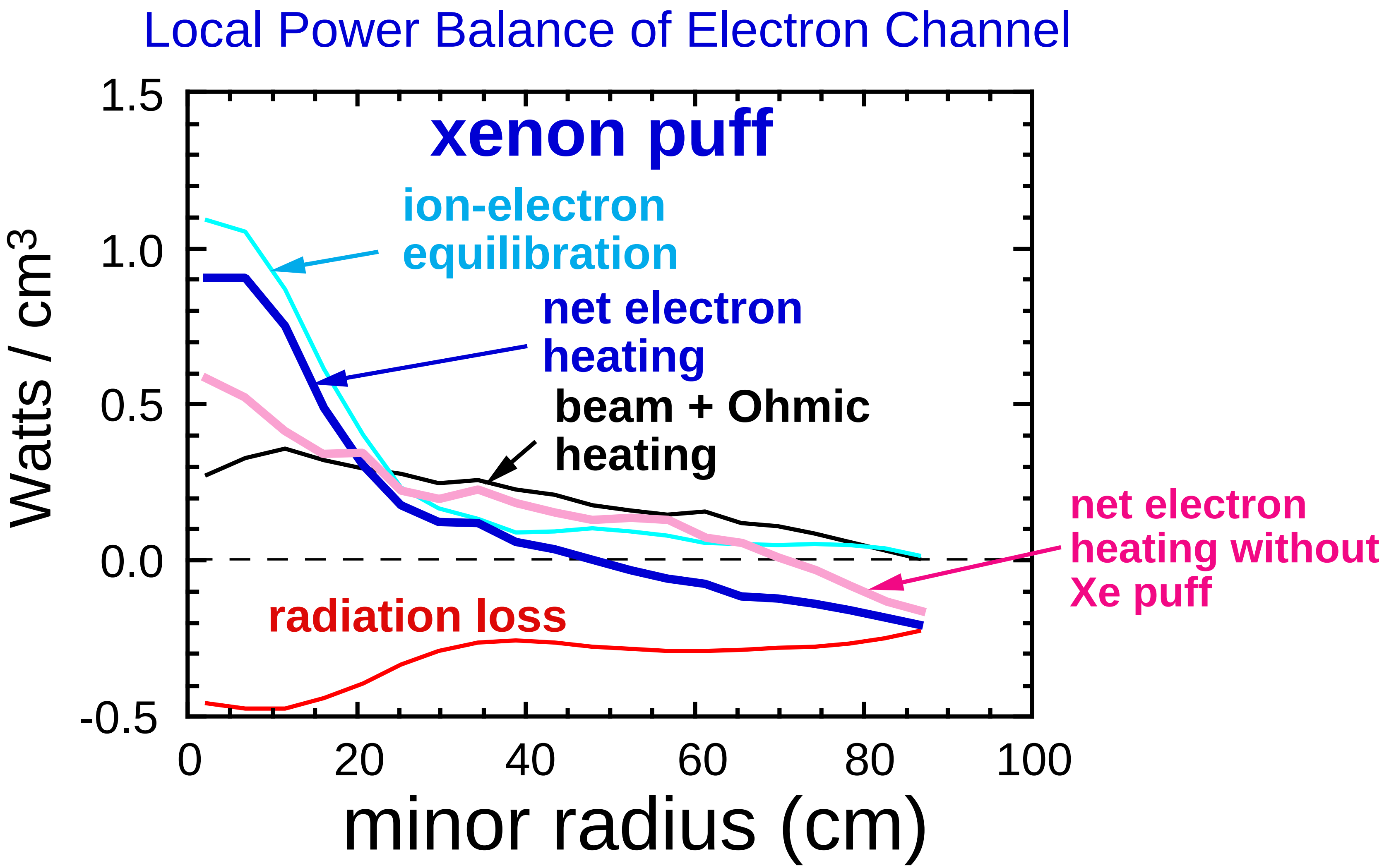
Ion-Electron Power Compensates for Increased Radiation Loss to Electrons



- $q_{ie} \sim n_e^2 (T_i - T_e) / T_e^{3/2}$

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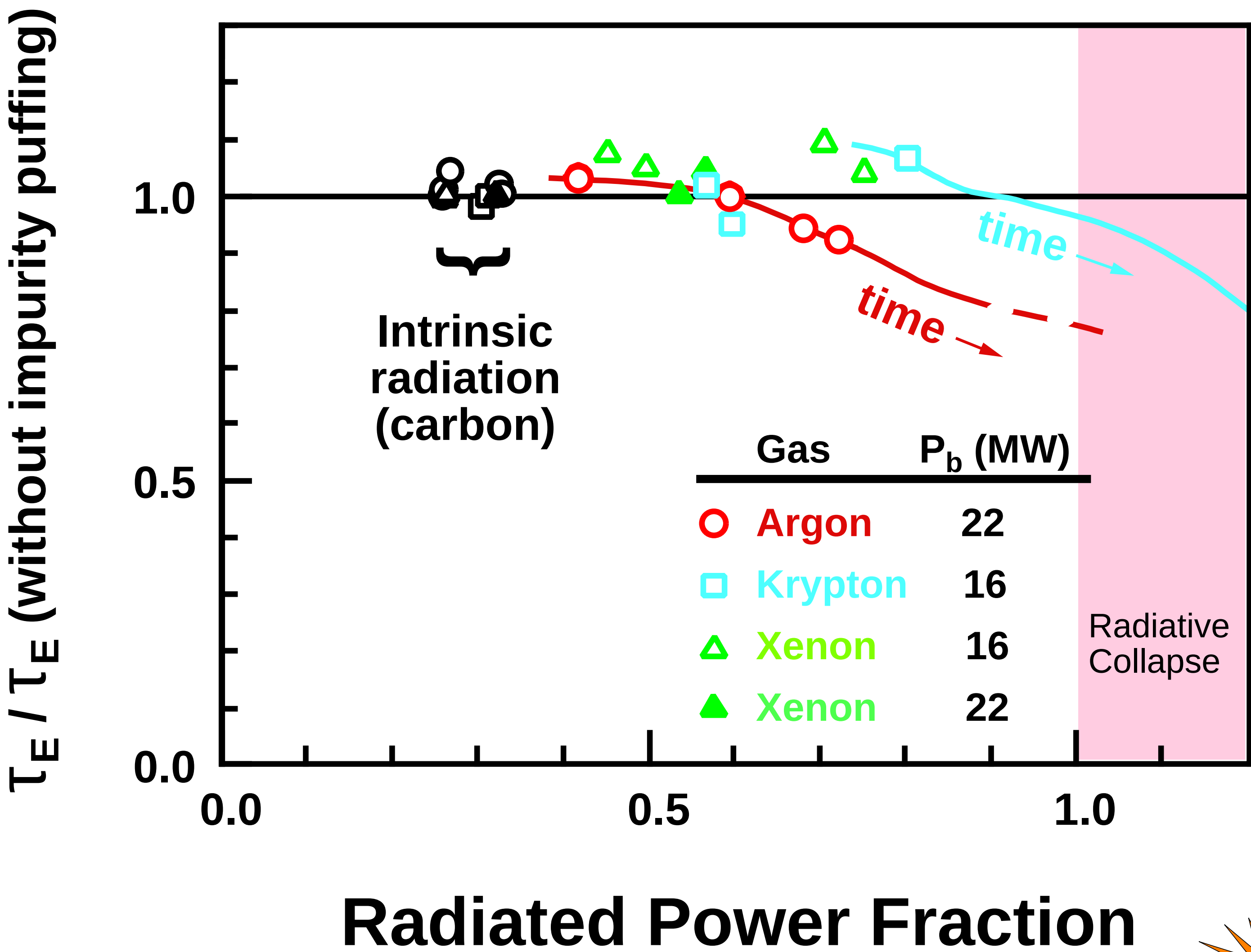
Kr and Xe Produce Less Confinement Degradation than Ar at High Radiated Power Fractions



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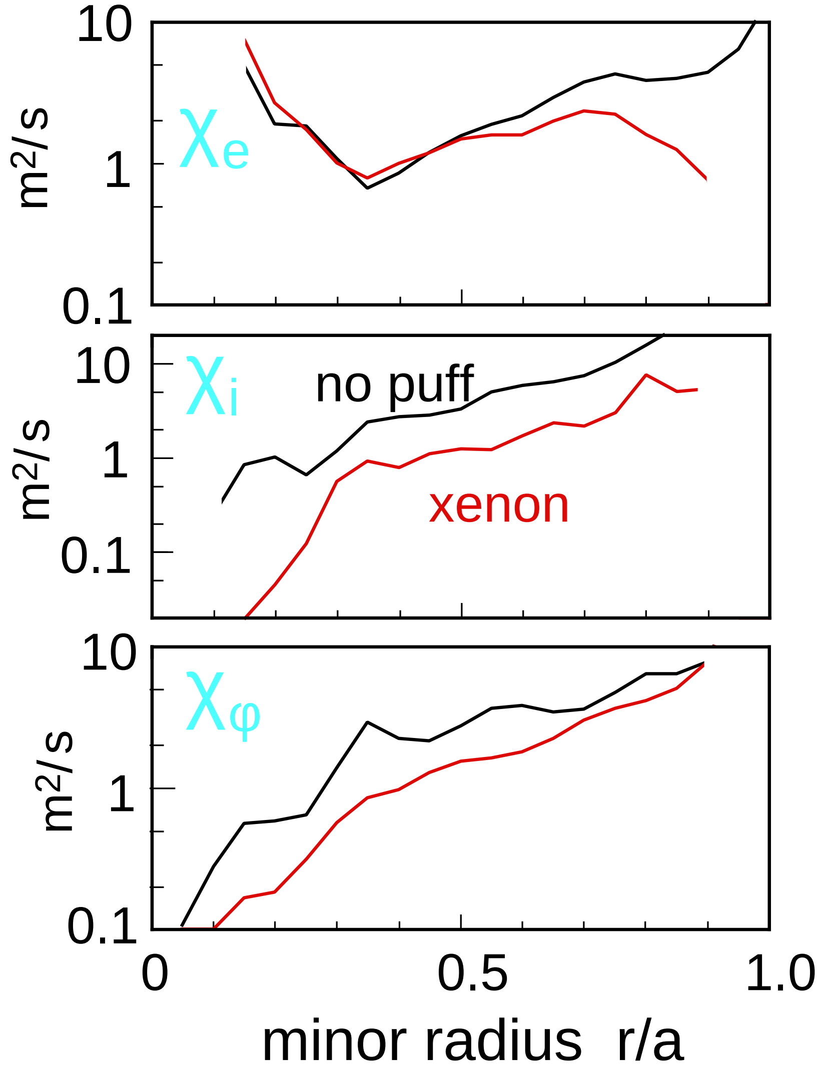
Xenon Puffing Reduces Ion Thermal and Momentum Diffusivities



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- Improvements in τ_E in tokamaks associated with formation of flow shear layers which suppress the turbulence responsible for anomalous transport.

- Poloidal velocity of C impurities 13 cm inside LCFS increased from 1 km/s to 5 km/s just after Xe puff.

- Total radial electric field increased from 15 to 50 kV/m, mostly due to component from poloidal velocity.

- Changes in E_r of similar magnitude associated with formation of transport barriers in TFTR ERS plasmas [E.J.Synakowski].

- V_θ also proportional to T_i in supershots [R.E. Bell].

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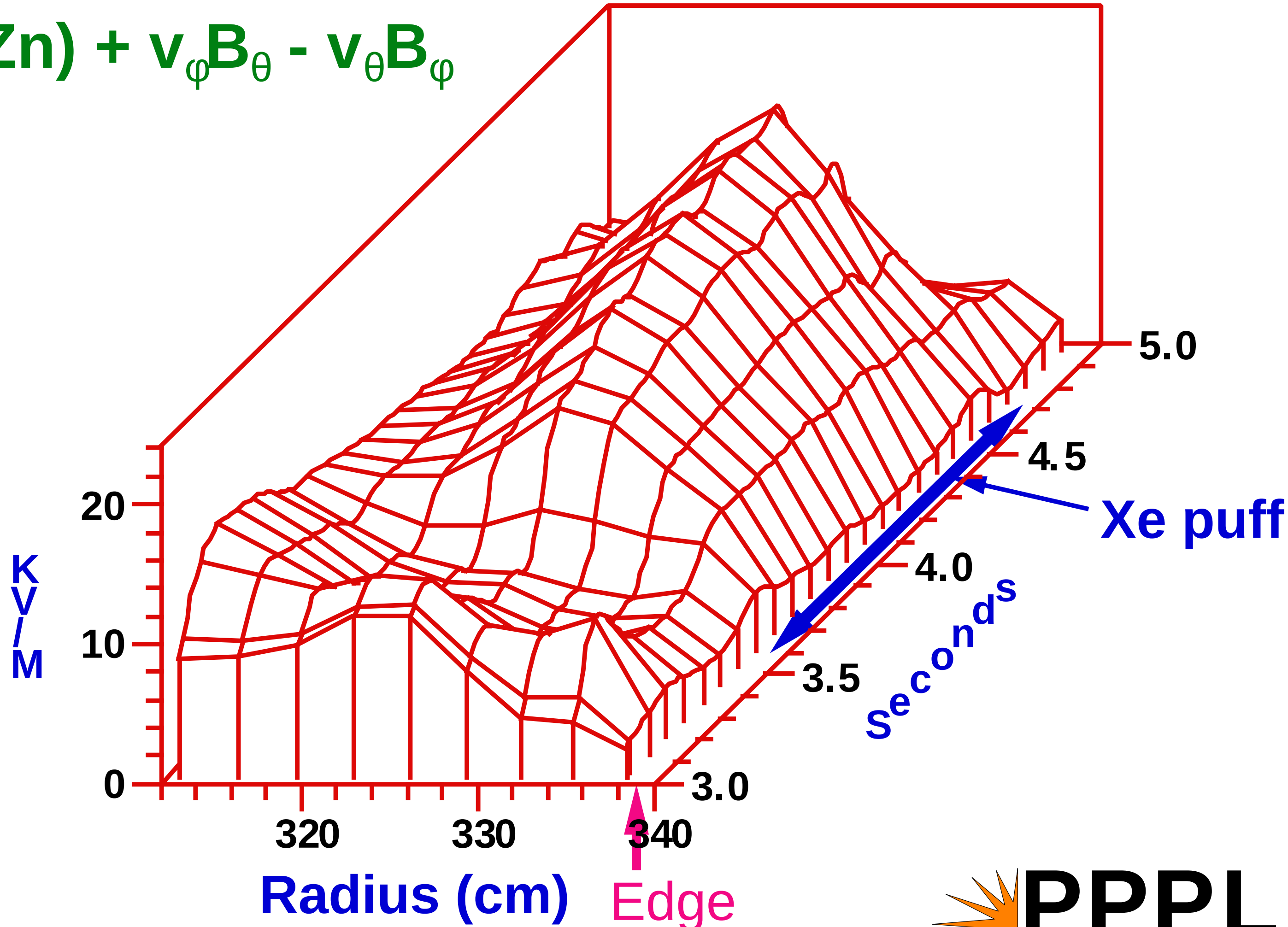
The Component of E_r From v_θ Increases Near Edge With Xenon Puff.

$$E_r = \quad p/(eZn) + v_\varphi B_\theta - v_\theta B_\varphi$$



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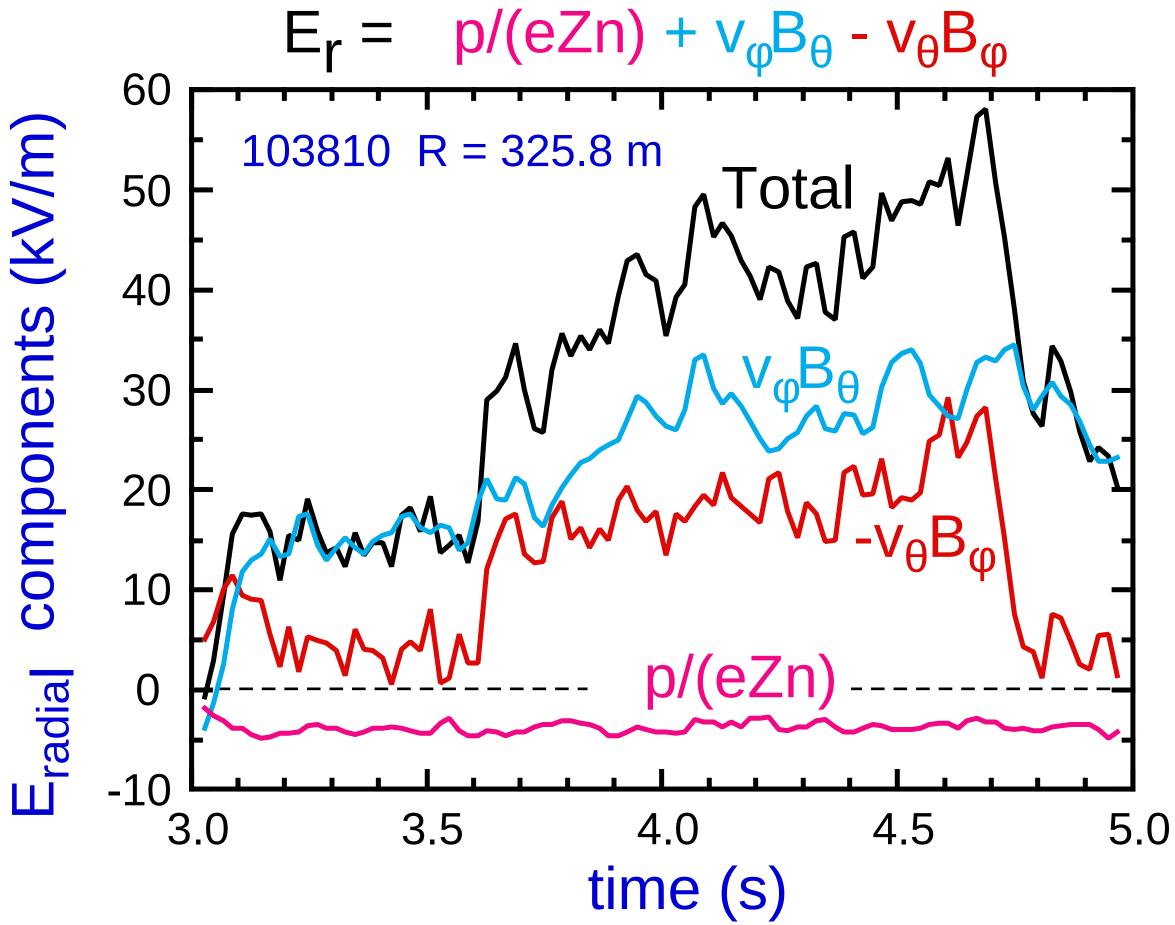
Increase in Radial Electric Field 13 cm from LCFS Dominated by Rapid Rise in Component from Poloidal Velocity



Comparison of T_i Response to Xe Puffing with Transport Model

- IFS-PPPL turbulent transport model without flow shear.
- Heuristic model for suppression of transport by flow shear.
- Self-consistent calculation of transport and v_θ.
- Using experimental v_θ T_i.

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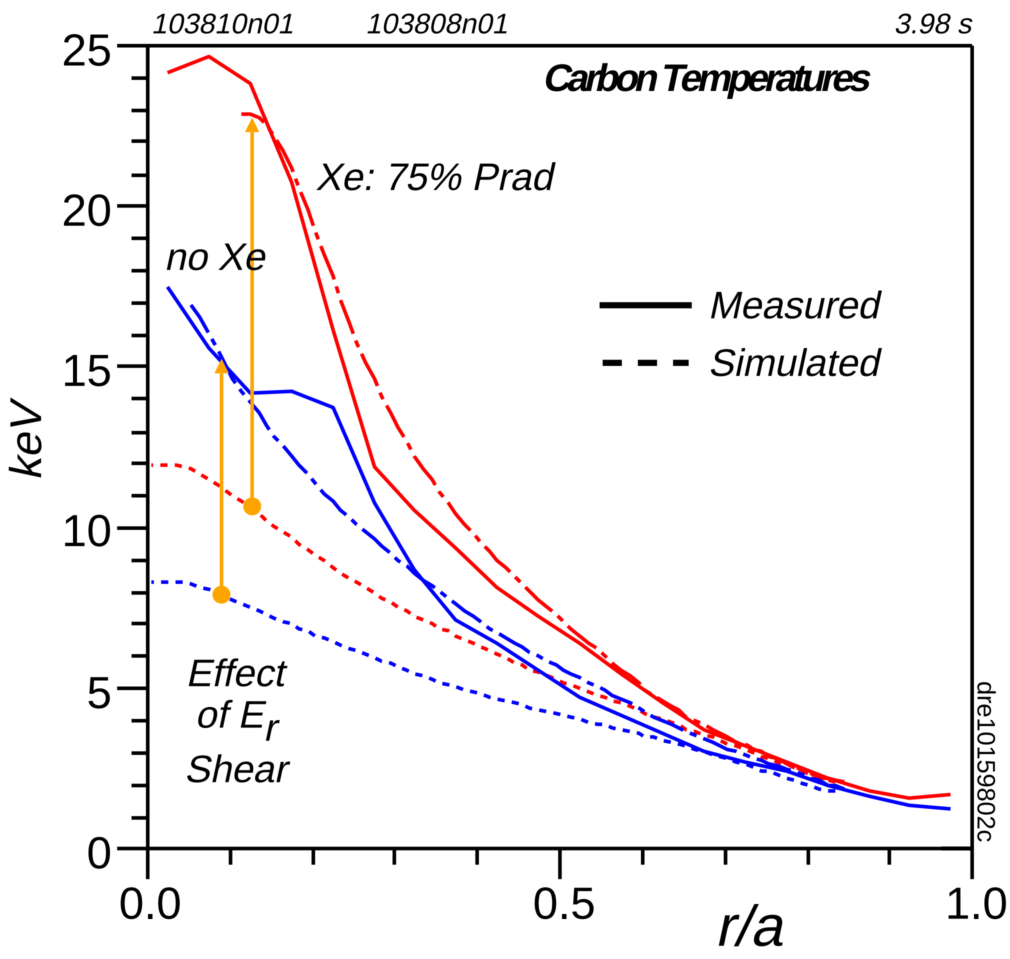
IFS-PPPL Model Augmented by Flow-Shear Effects Successfully Predicts T_i With and Without Xe Puffing.



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Power and Particle Handling
(High Heating Power)

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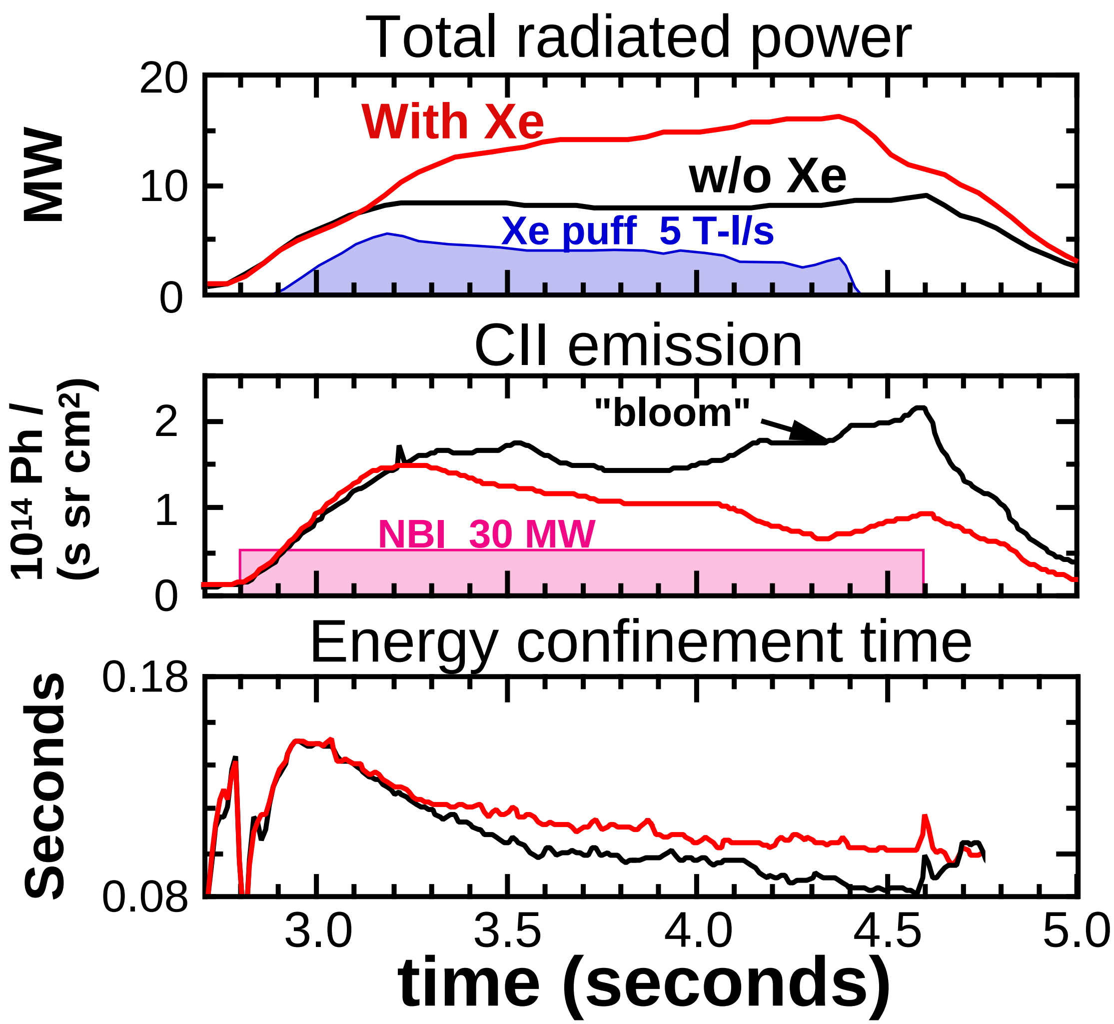
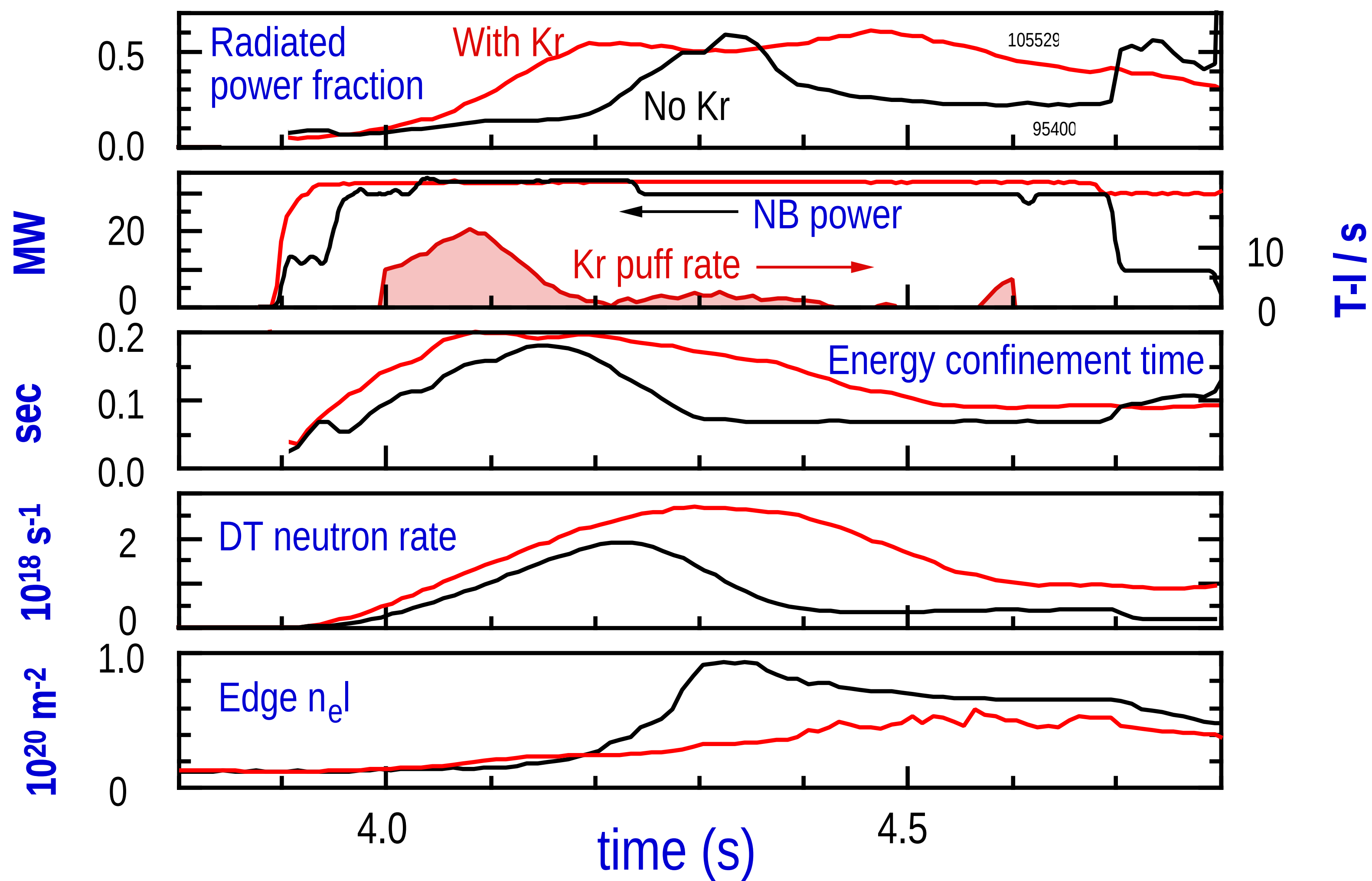
Xenon Puff Suppresses Carbon Influx ("Bloom")



- **Fusion power 30% higher with Xe puff**

Higher τ_E and neutron rate maintained for longer time with krypton and DOLLOP.



- Large H, C influx without Kr

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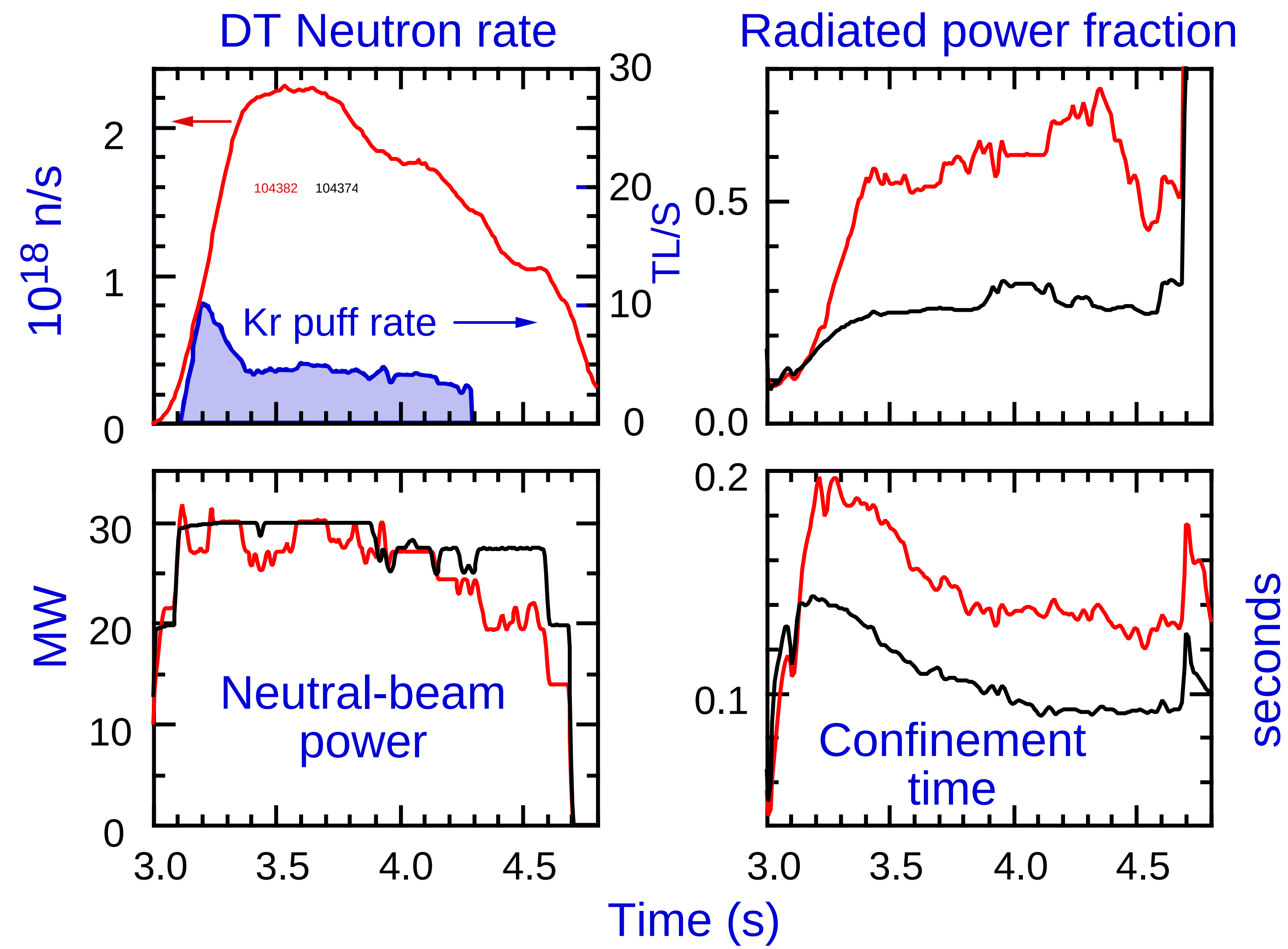
A TFTR Record 7.6 MJ of DT Fusion Energy Produced with Krypton Puffing



- CII emission greatly suppressed.

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Summary

- Significant improvement in performance at high power (Pb ≥ 30 MW) in DD and DT discharges
  - Suppression of carbon blooms
  - Higher energy confinement time
  - Higher fusion power

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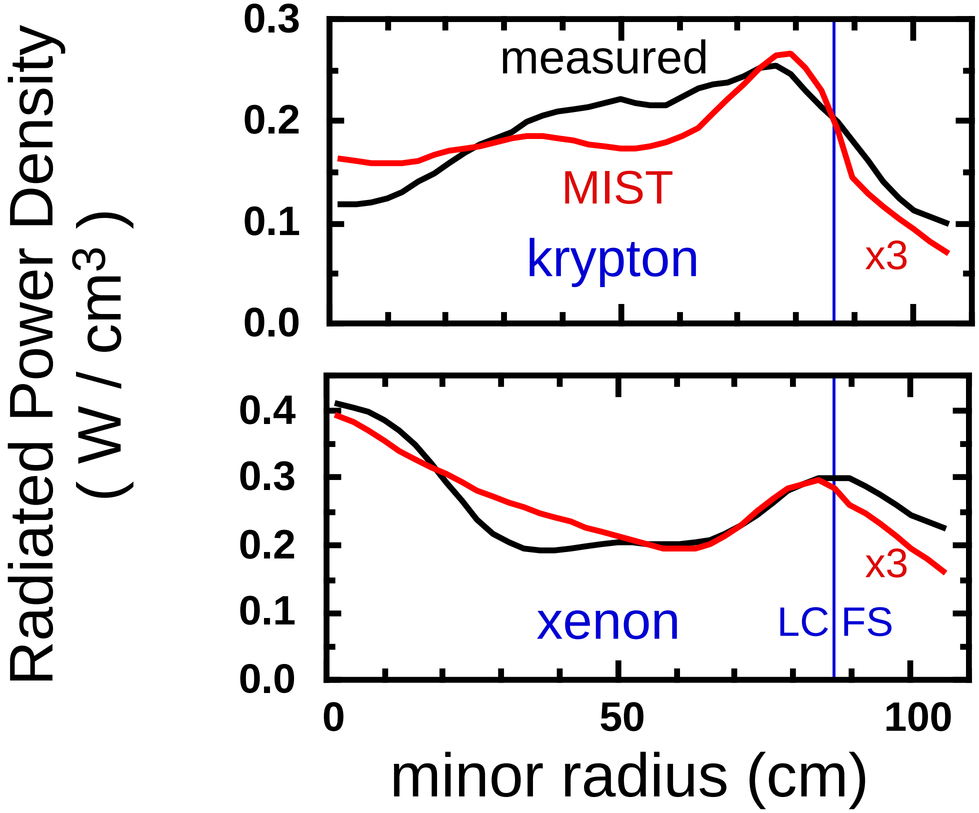
Implications for Reactors

MIST Code Reproduces Radiated-Power Profile Shape but Not Magnitude



- P_{rad} / P_{heat} = 45 - 65 %. $T_e(0)$ = 6 keV
- MIST n_I/n_e multiplied by 3 to match total radiated power
- Uniform radial profile of concentration - ~ 10^{-3}
- D = 1 m^2/s; Lotz ionization rates

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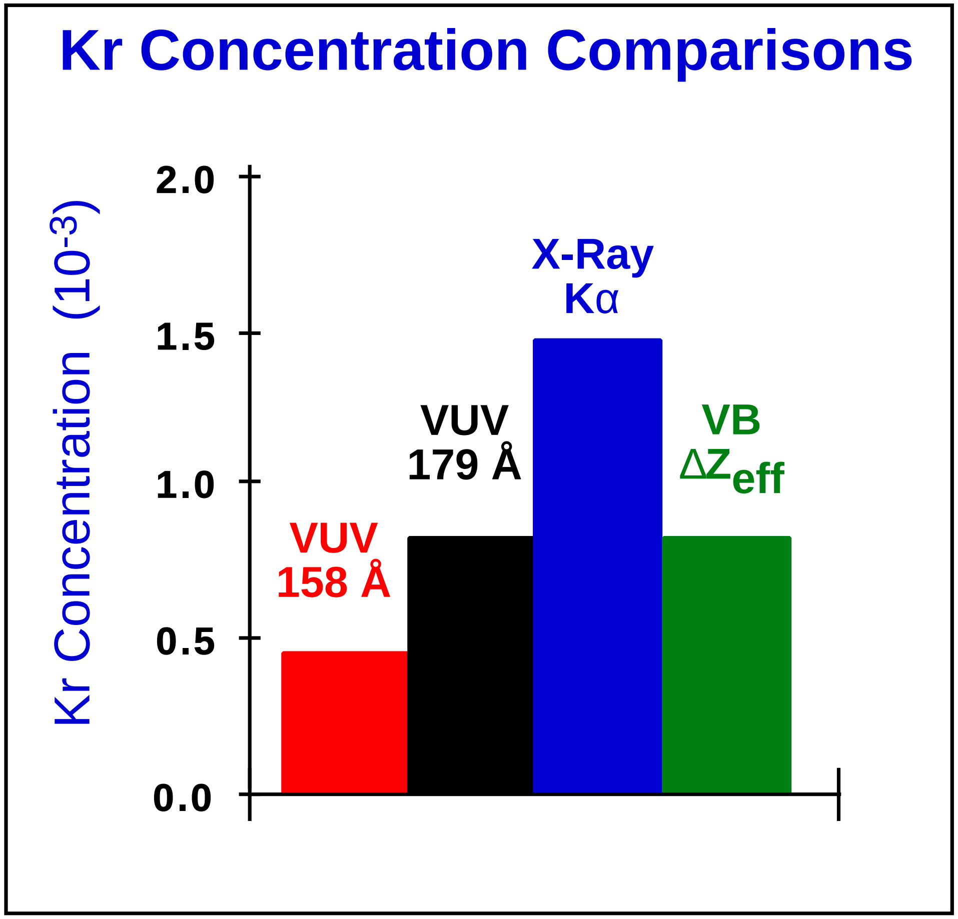
Concentration of Injected Impurity Estimated by Several Techniques



• **Negligible fuel dilution**

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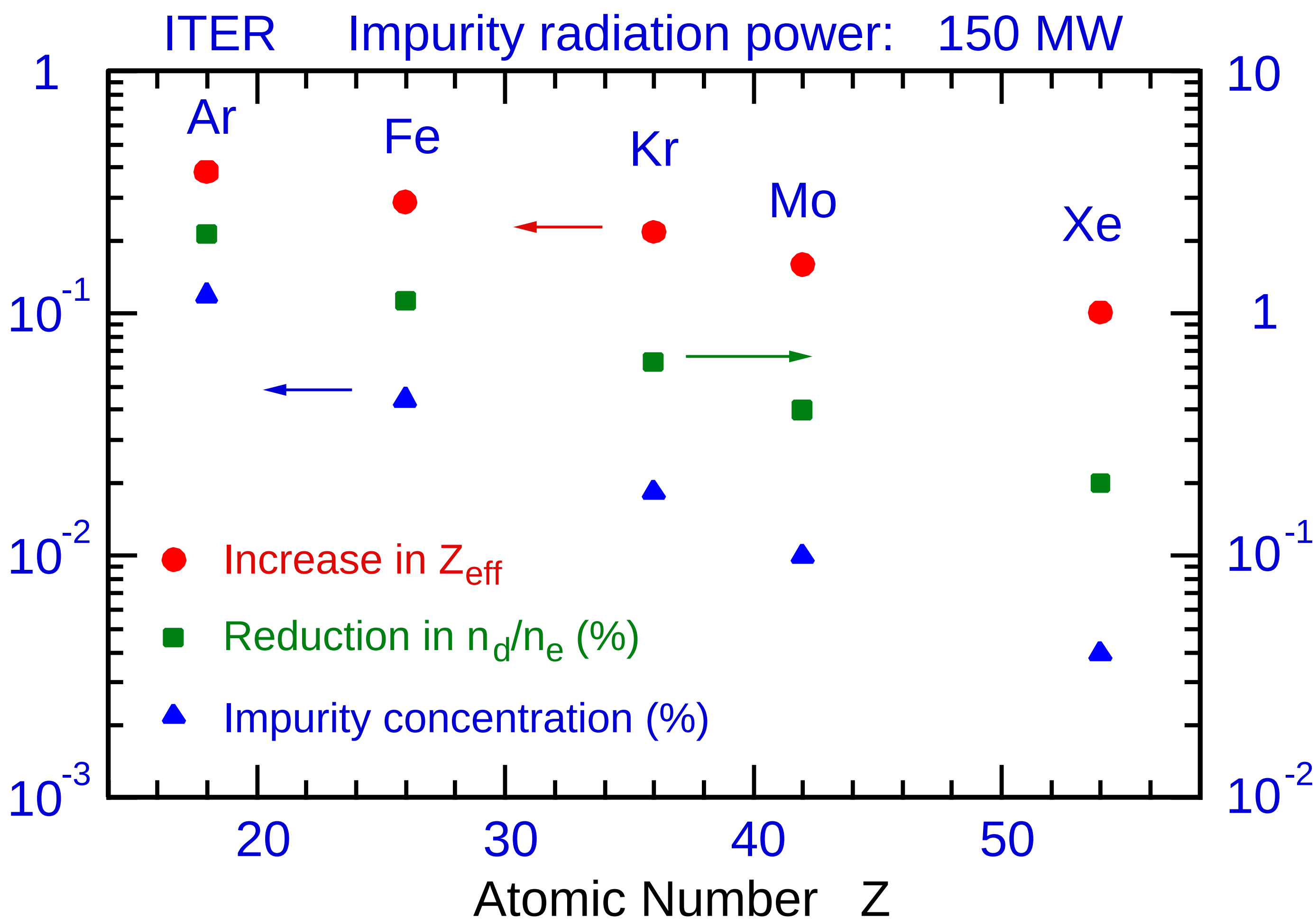
Small Concentrations of Kr or Xe Required for 150 MW of Radiation Power in ITER



- $T_e(0) = 21$ keV, $n_e(0) = 1.33 \times 10^{20}$ m^{-3}
- MIST "calibration" implied by TFTR data.

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Summary

- Z_{eff} and spectroscopy roughly agree on injected impurity concentrations for krypton.

- Measured total radiated power higher than MIST prediction by factor 3.0 ± 0.4 for measured concentration.

- Very low concentrations of Kr or Xe, dilution, and increase in Z_{eff} for additional 150 MW radiated power from ITER.

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Summary - Kr and Xe

- Confinement unchanged for γ up to 80% at moderate heating power (16 MW).
- Confinement and fusion power significantly improved at high power (30-32 MW).
  - C blooms suppressed.
- MIST underestimates P_{rad} by factor of ~3.
- Negligible fuel dilution and Z_{eff} increase for 150 MW radiated power in ITER.

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