IMPURITY-INDUCED SUPPRESSION OF TURBULENCE AND TRANSPORT IN DIII-D

George McKee

M. Murakami[2], J. Boedo[3], K. Burrell[4], N. Brooks[4], D. Ernst[5], R. Fonck, G. Jackson[4], M. Jakubowski, R. LaHaye[4], A. Messiaen[6], J. Ongena[6], C. Rettig[7], C. Rost[8], G. Staebler[4], R. Sydora[9], D. Thomas[4], M. Wade[2], P. West[4], B. Unterberg[6]

University of Wisconsin-Madison
[2] Oak Ridge National Laboratory
[3] University of California-San Diego
[4] General Atomics
[5] Princeton Plasma Physics Laboratory
[6] Forschungszentrum, Jülich
[7] University of California-Los Angeles
[8] Massachusetts Institute of Technology
[9] University of Alberta

American Physical Society-Division of Plasma Physics, Seattle, Washington, November 15, 1999

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

Abstract for an Invited Paper
for the DPP99 Meeting of
The American Physical Society

Impurity-Induced Core Turbulence Suppression and Reduced Transport in the DIII-D Tokamak[1]

G.R. MCKEE, University of Wisconsin-Madison[2]

Long wavelength turbulence and ion heat transport are significantly reduced on the DIII–D tokamak as a result of neon-seeding of an L–mode Negative Central Shear discharge. Correspondingly, particle and energy confinement are increased. Fully saturated turbulence measurements near $\rho = 0.7$ in the wavenumber range $0.1 \leq k_{\perp}\rho_{\rm s} \leq 0.6 (0.5 < k_{\perp} < 2.5\ \mathrm{cm}^{-1})$, obtained with Beam Emission Spectroscopy, exhibit nearly an order of magnitude suppression of total fluctuation power after neon injection. Fluctuation measurements obtained with Far Infrared scattering also show a reduction of turbulence in the core, while the Langmuir probe array measures reduced particle flux in the edge and scrape-off-layer. Gyrokinetic linear stability simulations of these plasmas are qualitatively consistent, showing a reduction in the growth rate of ion temperature gradient driven modes for $0 < k_{\perp} < 5\ \mathrm{cm}^{-1}$ as a result of impurity density gradient effects on the main fuel ion turbulence. The measured $\omega_{E\times B}$ shearing rate increased with neon at the BES observation radius, suggesting that impurity-induced reduction of growth rates is acting synergistically with $\omega_{E\times B}$ shear to decrease turbulence and reduce anomalous transport. Confinement time is nearly doubled in discharges with a neon puff, compared to similar reference discharges without any injected neon. Ion heat diffusivity is reduced to near neoclassical levels over much of the profile while the region of improved confinement expands radially well into a region of positive magnetic shear. Both ion and electron temperatures exhibit a broadened profile and higher peak temperatures. Effects of varying both the quantity and atomic number of the injected impurity on turbulence and resulting confinement are assessed. These results suggest an operational regime that achieves improved confinement while simultaneously maintaining a highly radiative L–mode edge.

[1]Work supported by U.S. DOE Grants DE-FG02-92ER54139, DE-FG03-95ER-54294, and DE-FG03-86ER54266, and Contracts DE-AC06-96OR22464 and DE-AC03-99ER54463.

[2]In collaboration with M. Murakami, J.A. Boedo, N.H. Brooks, K.H. Burrell, R. Fonck, G.L. Jackson, M. Jakubowski, C.L. Rettig, G.M. Staebler, R. Sydora, D.M. Thomas, M.R. Wade, and W.P. West.

Summary of Principal Results

- A substantial improvement in confinement is observed in discharges as a result of an impurity gas puff (neon, argon, krypton)

  - *near doubling of ion and increased electron temperatures*
  - *80% increase in energy confinement time*
  - *peaked density profile*
  - *doubling of neutron rate*

- Turbulence dramatically reduced: one cause of reduction in transport & confinement improvement

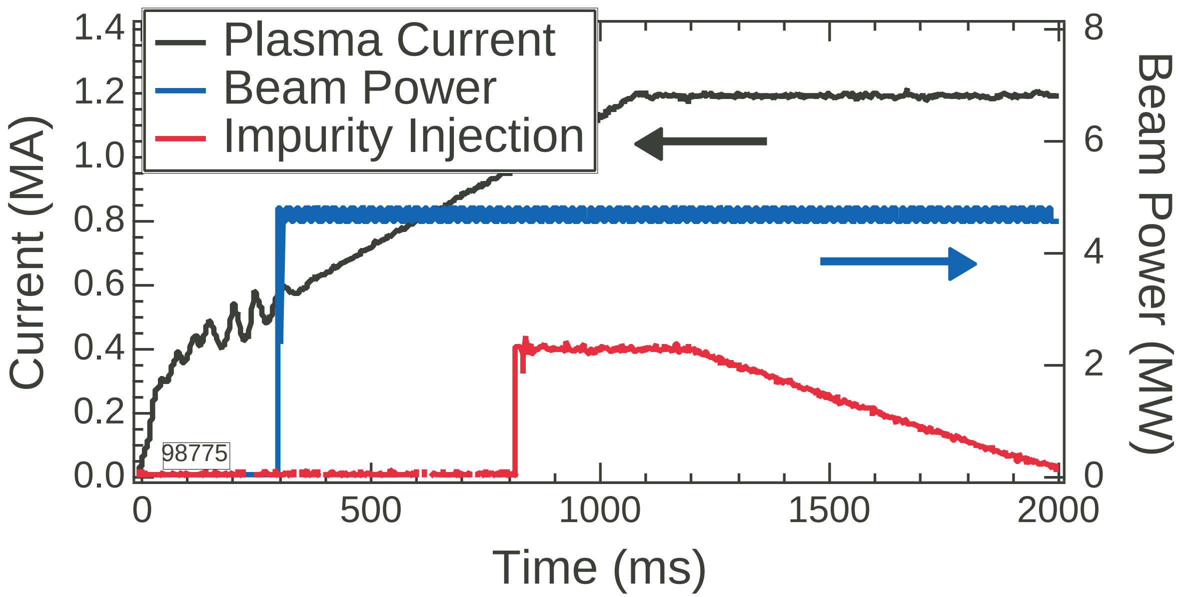
  - *Core and edge fluctuation measurements obtained:*
    (Beam Emission Spectroscopy, Far Infrared Scattering, Langmuir Probes)

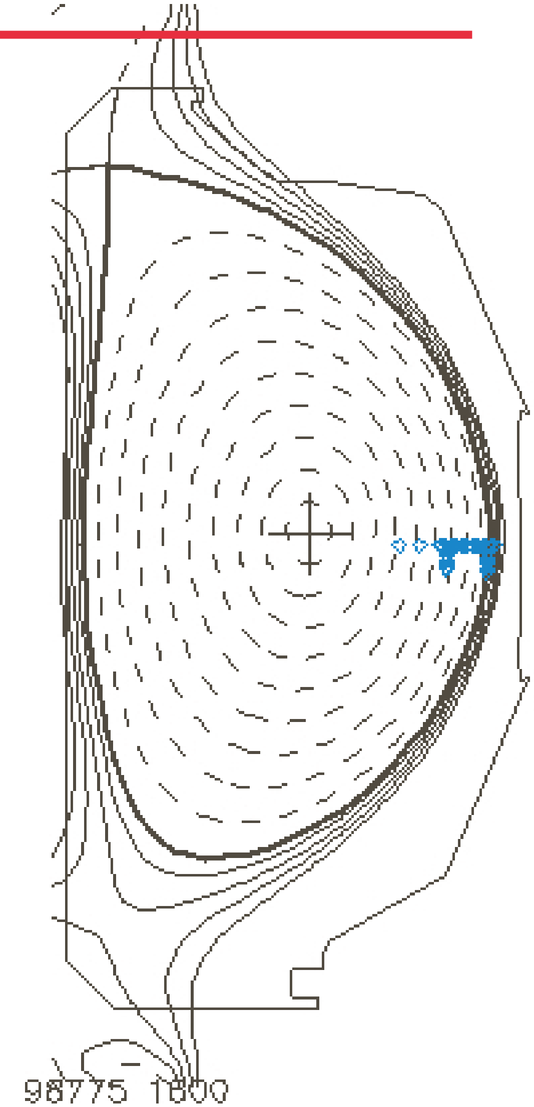
- Gyrokinetic simulations (linear and nonlinear) show impurities affect stability of microturbulent modes $\rightarrow$ suppression of turbulent transport

  - *interaction of mode growth rates and ExB shearing rates consistent with improvements*

PLASMA CONTROL PARAMETERS FOR THESE IMPURITY INJECTION EXPERIMENTS

- L-Mode, upper-biased Double Null discharge
- Weak negative central magnetic shear (NCS) profile
- I_p=1.2 MA, B_t = 1.6 Tesla, P_{BEAM}=4.5 MW

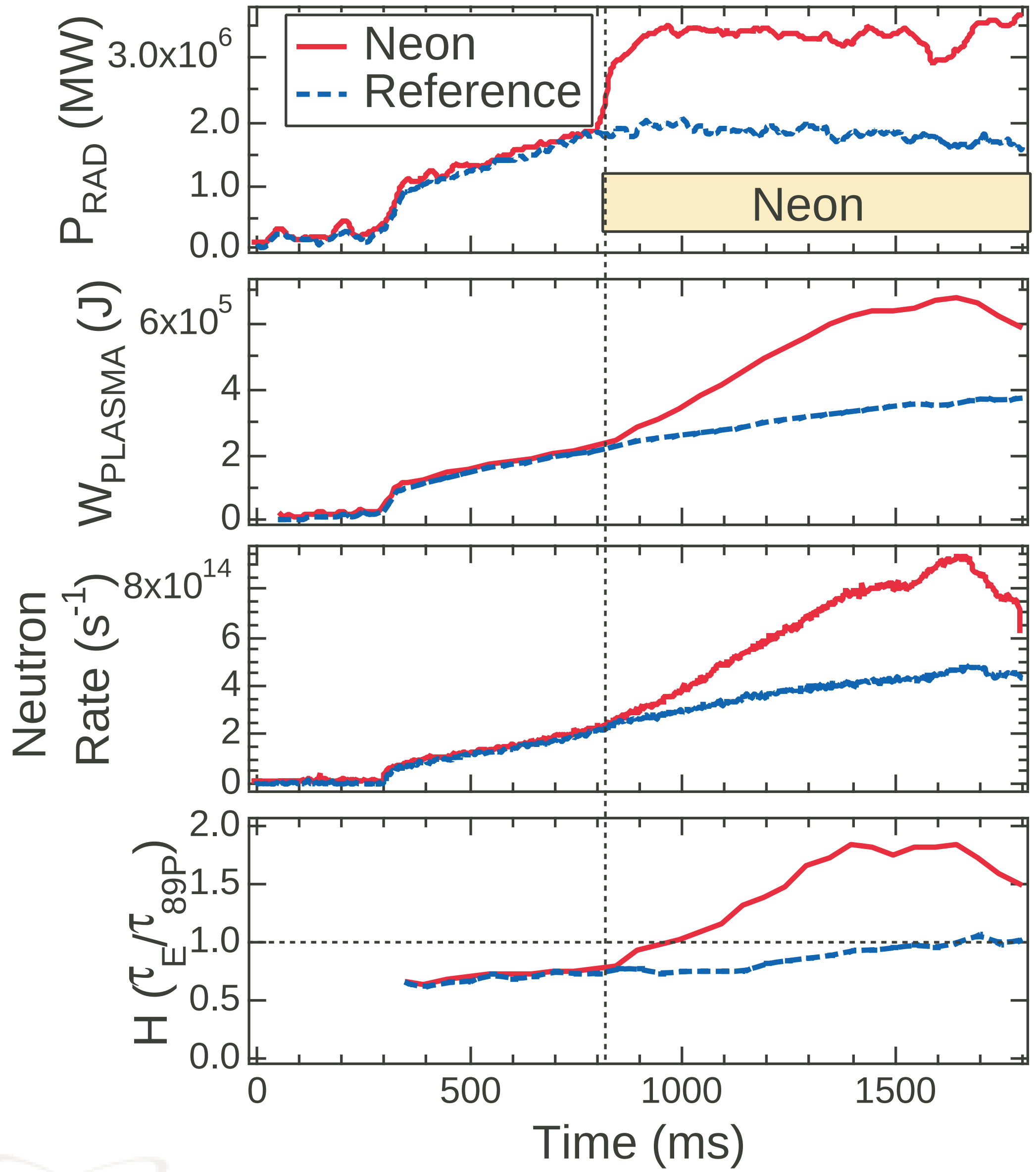




- Ne, Ar, Kr injected at 0.8 and 1.2 sec (≤ 2% of n_e)

George McKee, APS 1999
University of Wisconsin Madison
Department of Engineering Physics
DIII-D National Fusion Facility San Diego

CONFINEMENT INCREASES DRAMATICALLY WITH NEON



- Radiated power: 3.5 MW, 75% of input power
- Stored energy increases by 80%
- Neutron rate doubles; confinement increase overwhelmns dilution
- τ_E increases to H_{89P}=1.8 despite radiation

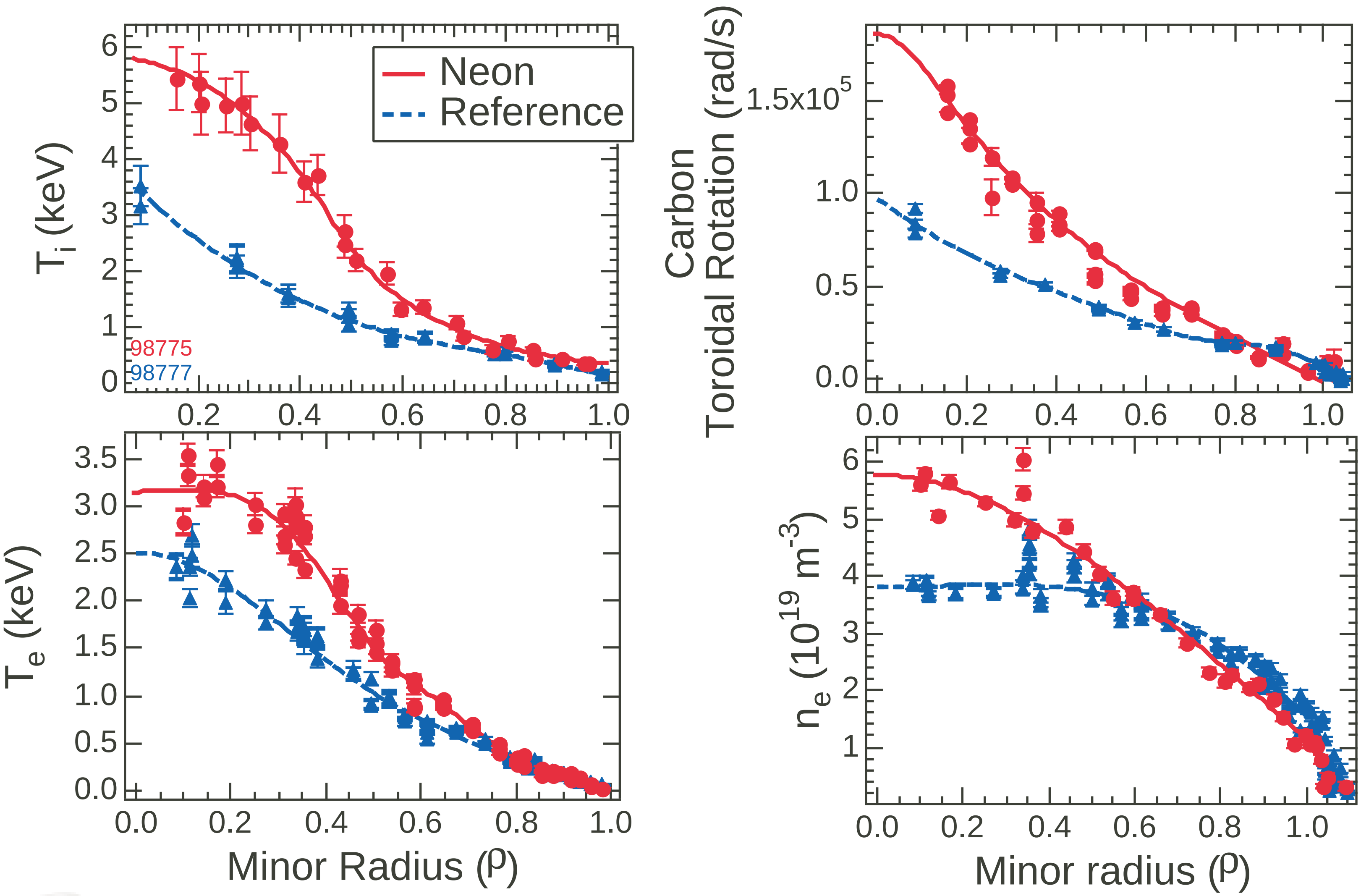
$\tau_E = W_{PLASMA} / (P_{INPUT} - dW/dt)$

George McKee, APS 1999

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

NEON RESULTS IN HIGHER AND BROADER TEMPERATURE AND ROTATION PROFILES, PEAKED DENSITY NEAR HIGHEST PERFORMANCE (t=1.6 s)



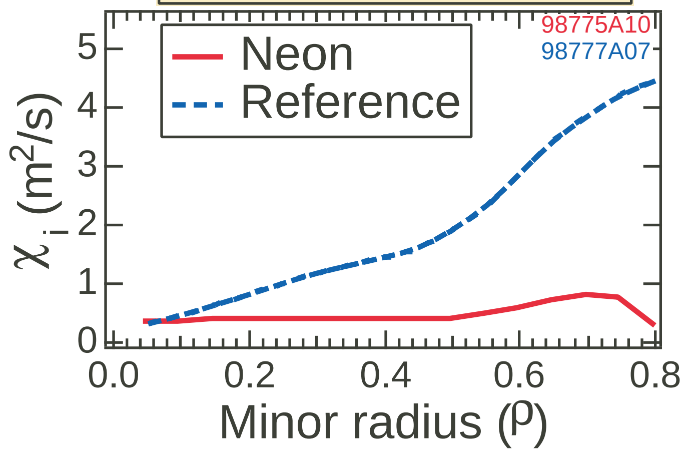
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

George McKee, APS 1999

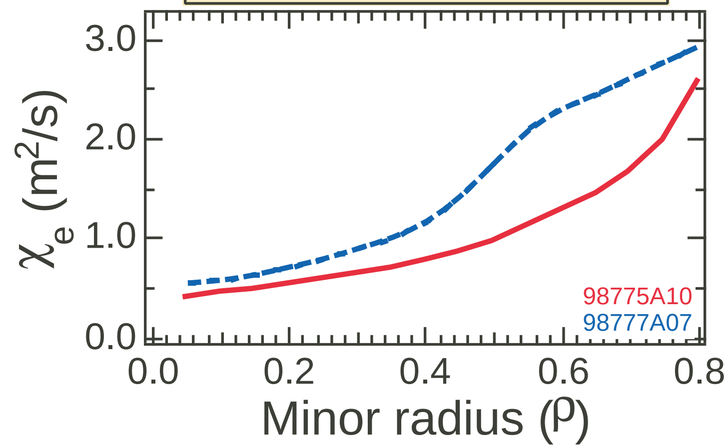
UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

TRANSPORT REDUCTION SEEN IN ION AND ELECTRON CHANNELS

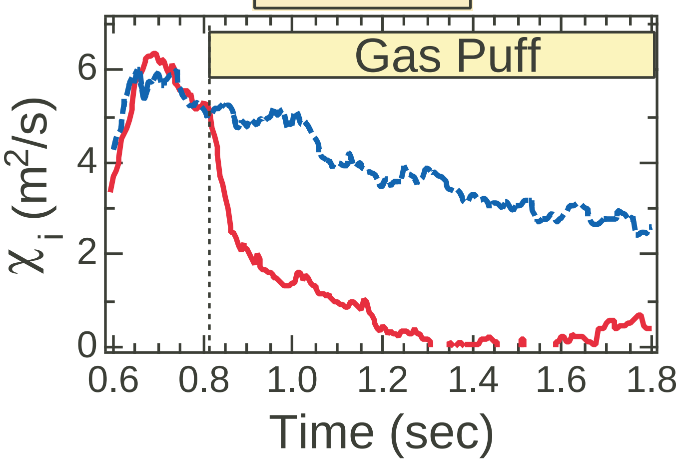
χ_i Profile (t=1.15 sec)



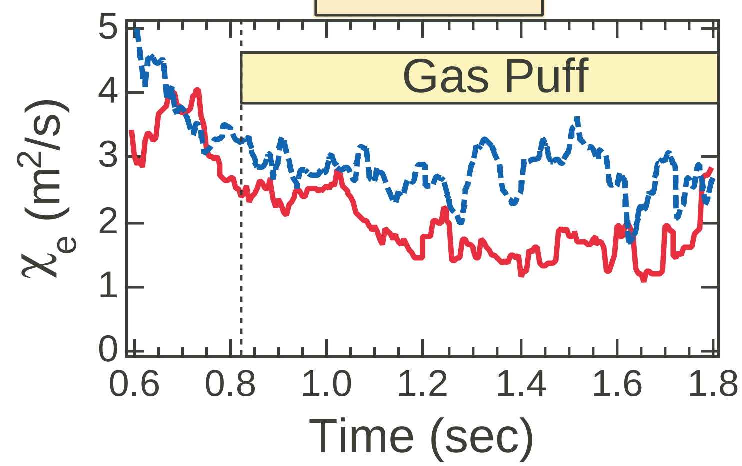
χ_e Profile (t=1.15 sec)



χ_i (ρ=0.7)



χ_e (ρ=0.7)

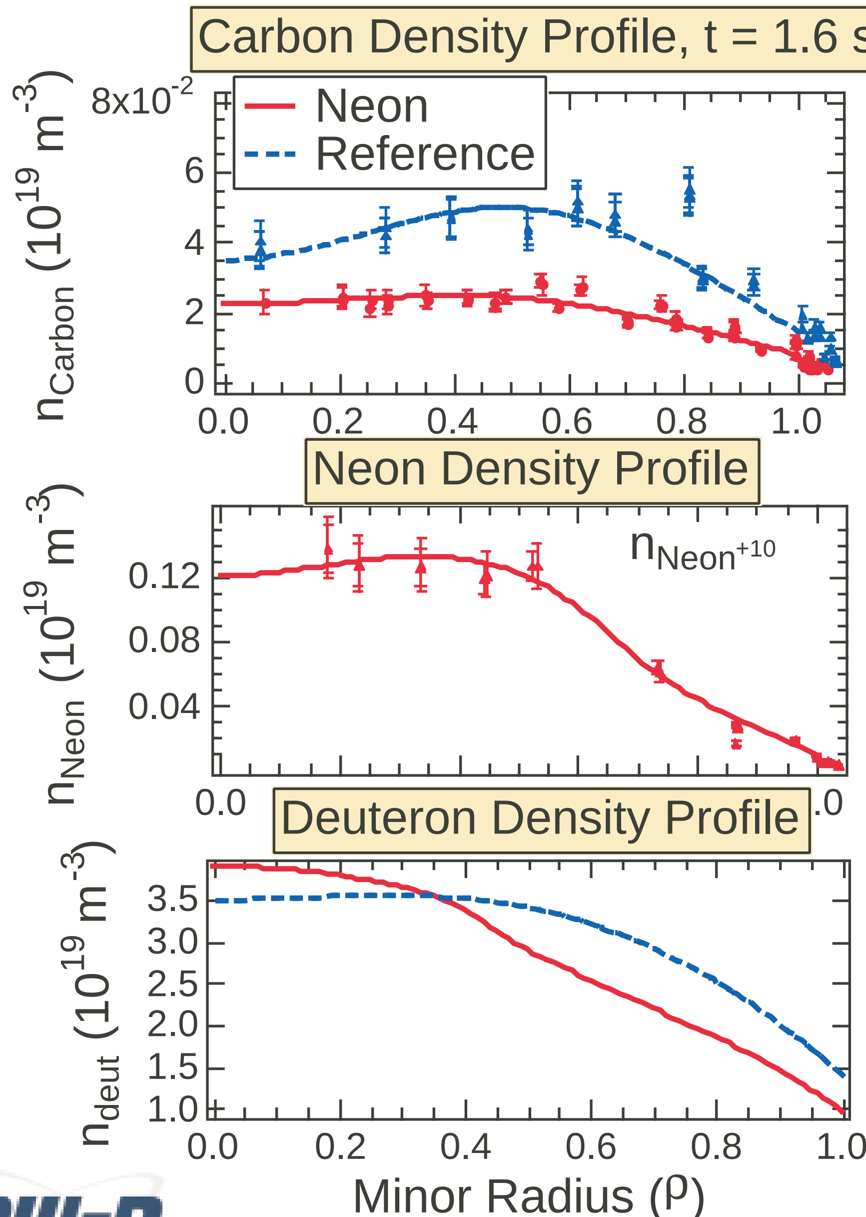


- See discussion by Murakami, *et al.*, G02.06, Tuesday afternoon

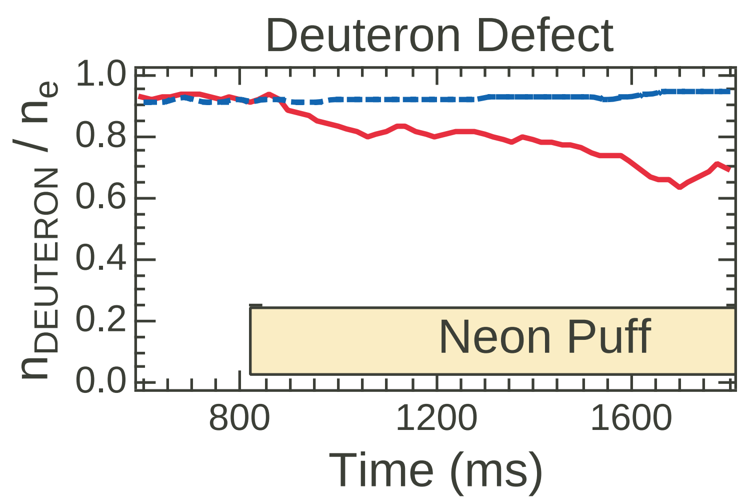
George McKee, APS 1999

Department of Engineering Physics

CENTRAL DEUTERON DENSITY APPROX. CONSTANT; CARBON DENSITY DECREASES



- Carbon density reduced by factor of two with neon: reduced physical sputtering?
- Z_{eff} increases from1.5 in reference discharge to 3.0 in neon discharge
- Particle profile changes result in little net change to deuteron profile



George McKee, APS 1999

WHY DO THESE CONFINEMENT IMPROVEMENTS OCCUR?

- Similar experimental results have been observed on other tokamaks:

  - *Z-mode on ISX-B (Neon), 1984*
  - *RI-mode on TEXTOR (Neon & Argon), 1992*
    - *Probe measurements of reduced edge particle flux*
  - *TFTR transport reduction with Krypton & Xenon-1997*

- DIII-D results:

  - *extended earlier experiments to divertor tokamak geometry* [G. Jackson, G02.05]
  - *experimental identification of underlying physical mechanism relating to confinement improvement*

- Transport reductions observed: *is anomalous transport being reduced*?

  - *fluctuation diagnostics utilized to characterize turbulence behavior:*

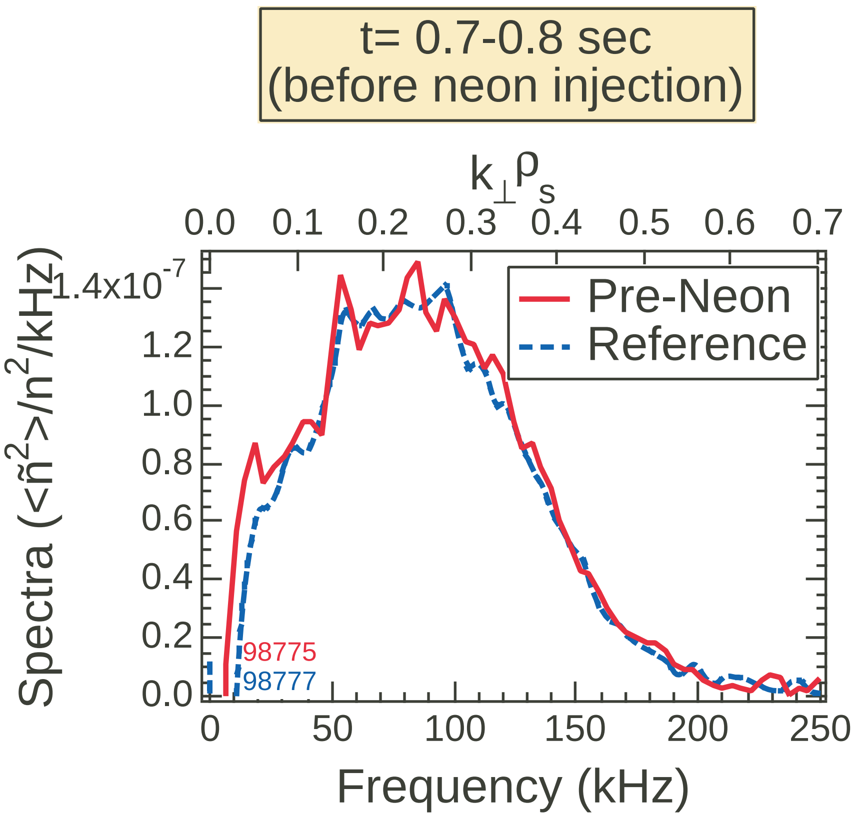
    - Beam Emission Spectroscopy
    - Far Infrared Scattering
    - Edge Langmuir Probe Array

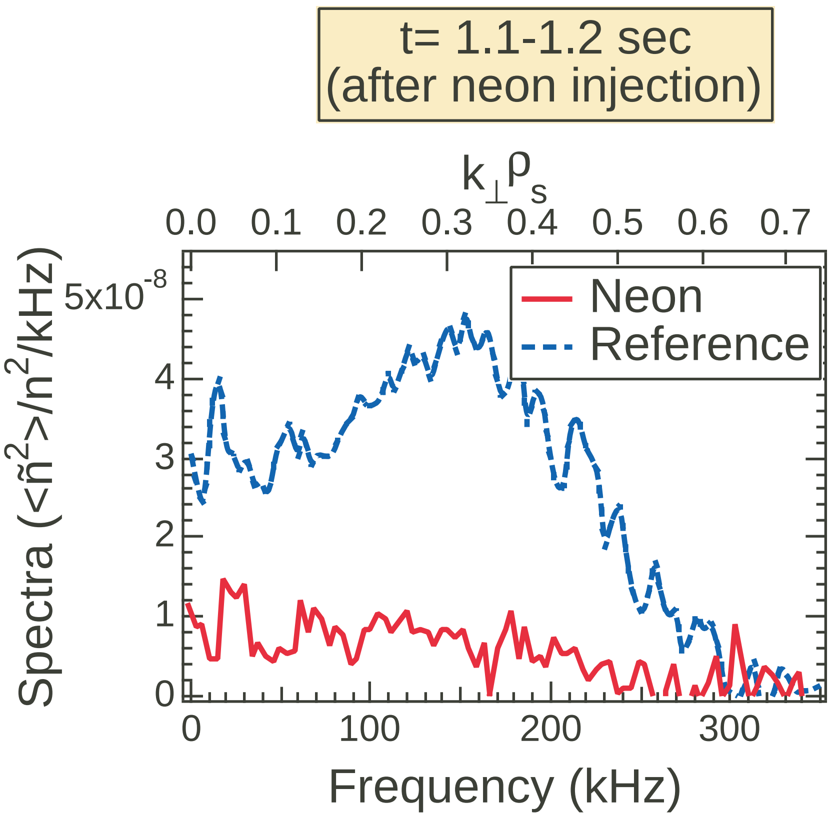
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

MEASURED DENSITY FLUCTUATIONS DRAMATICALLY SUPPRESSED AFTER NEON INJECTION

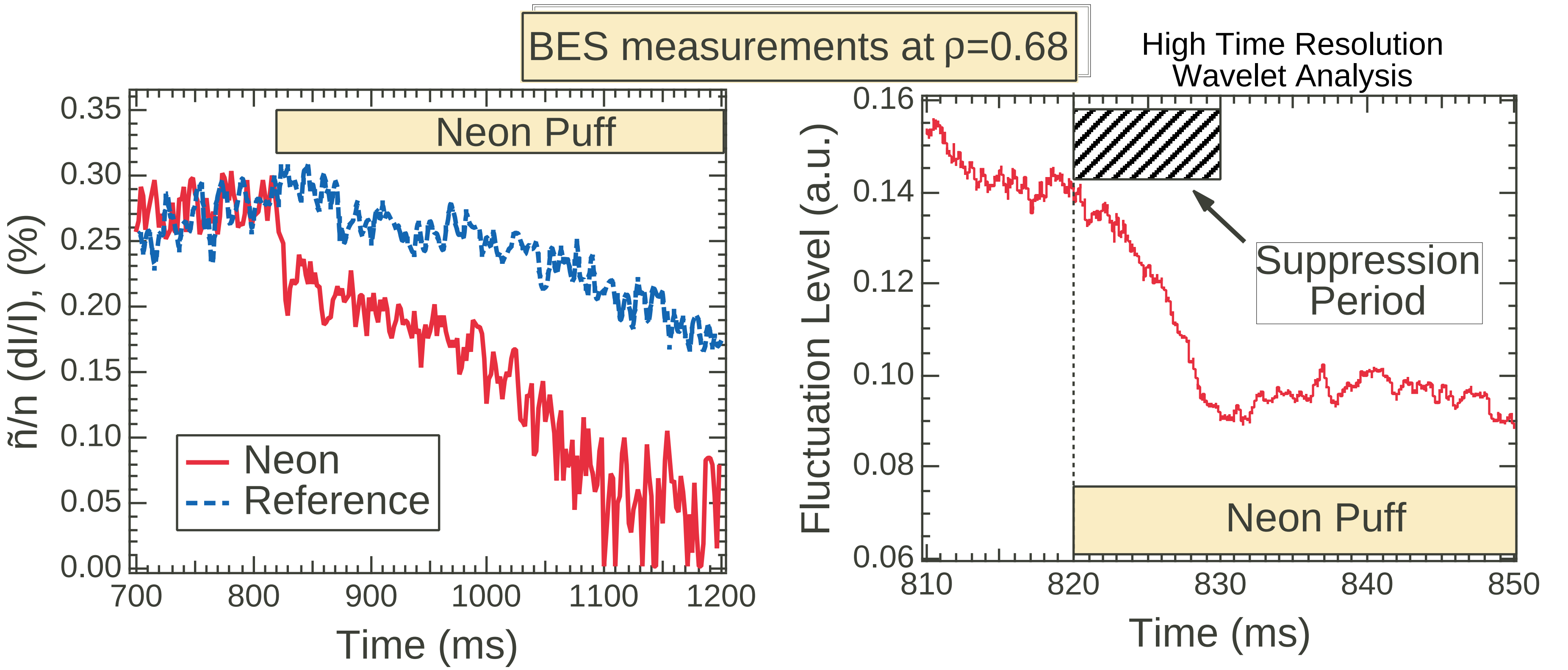
- Data obtained at ρ=0.68 with Beam Emission Spectroscopy (BES), long wavelength fluctuations, $0 \leq k \leq 2.5\ cm^{-1}$ [R. Fonck, Wed. morning, JI1.02]





- Suppression of turbulence and associated anomalous transport believed to be at least partially responsible for global confinement increase

PROMPT SUPPRESSION IN FLUCTUATION AMPLITUDE AT PUFF; GRADUAL REDUCTION AFTERWARDS

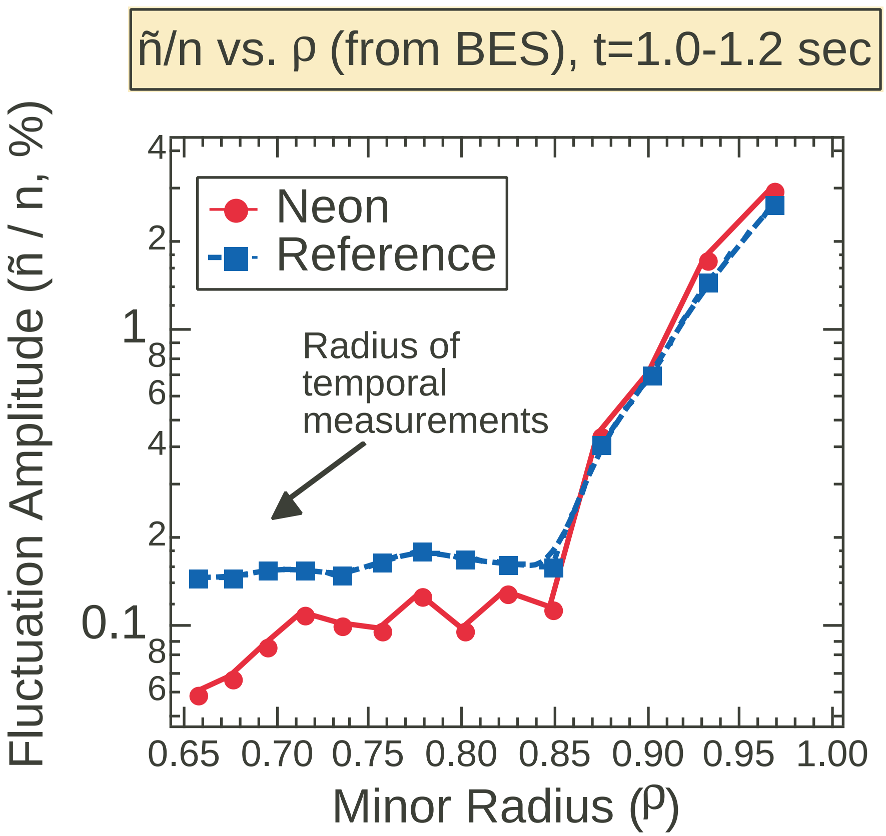


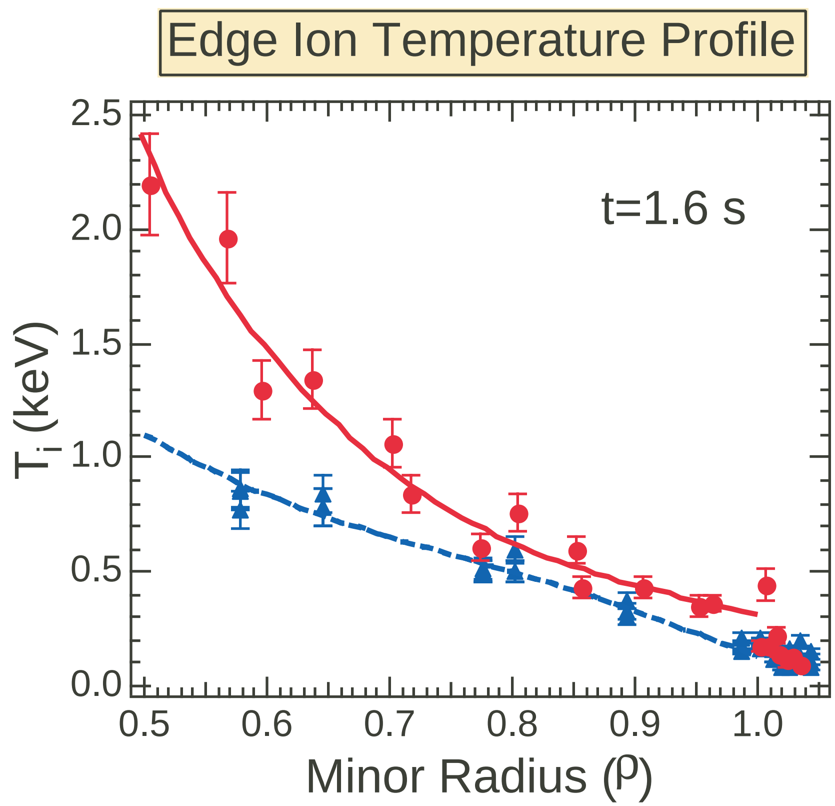
- Fast initial response (25% drop in 10 ms) suggests impurity-induced turbulence suppression preceeds subsequent confinement improvements

- Slower response (~200 ms) may result from induced profile changes and increase in resulting ExB shearing rate

George McKee, APS 1999

FLUCTUATION SUPPRESSION INSIDE OF ρ=0.85; EDGE TURBULENCE AMPLITUDE UNCHANGED





- Ion Temperature profile bifurcates near region of turbulence suppression

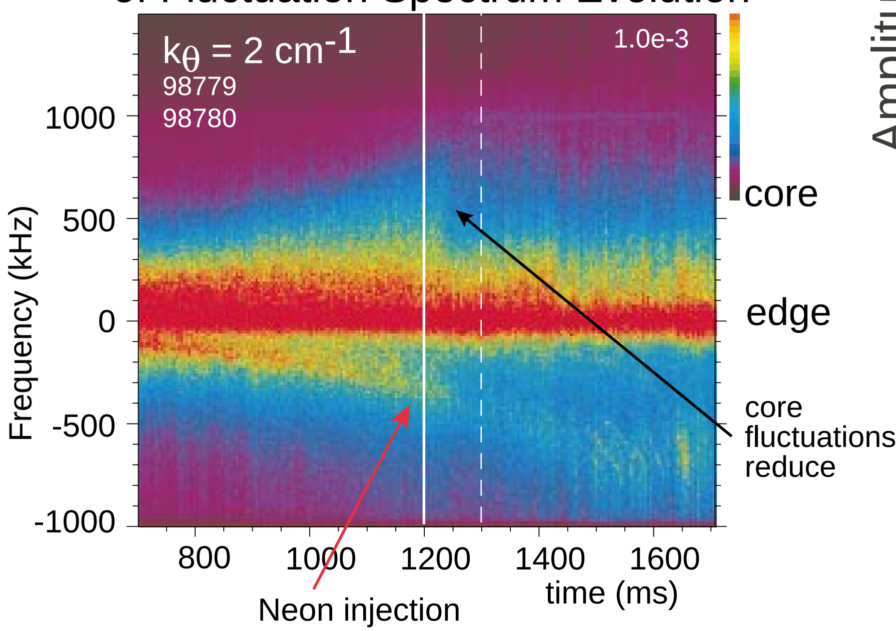
George McKee, APS 1999

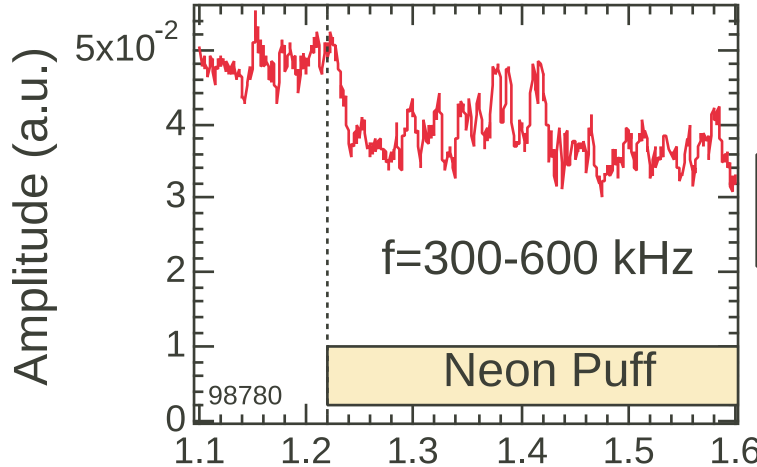
Department of Engineering Physics

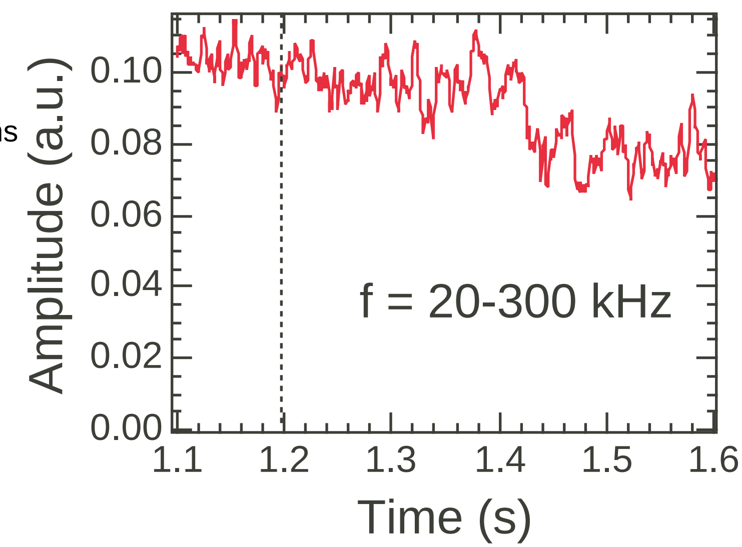
FAR INFRARED SCATTERING FLUCTUATION MEASUREMENTS SHOW PROMPT REDUCTION IN CORE

$k_\theta = 2\ cm^{-1}$

Color Enhanced Contour Plot of Fluctuation Spectrum Evolution







- Edge shows little change at beginning of gas puff

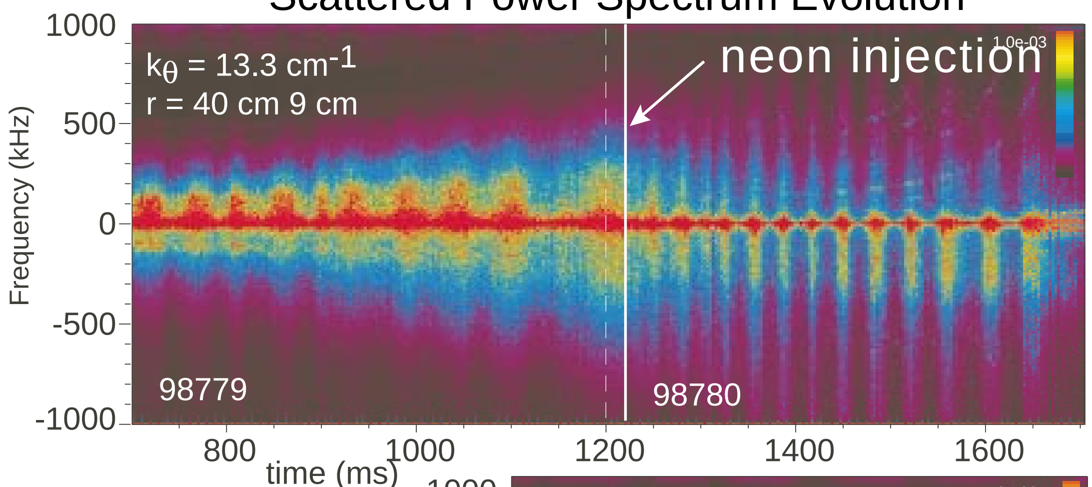
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

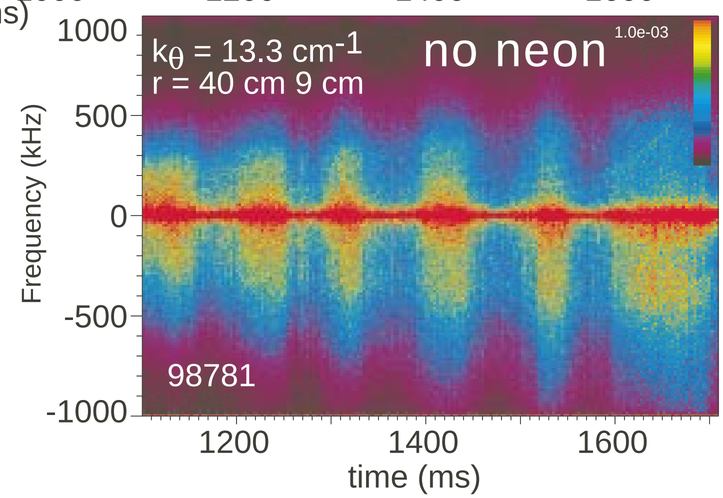
UCLA

SHORT WAVELENGTH FIR SCATTERING FLUCTUATION MEASUREMENTS DECREASE IN BURSTY FASHION

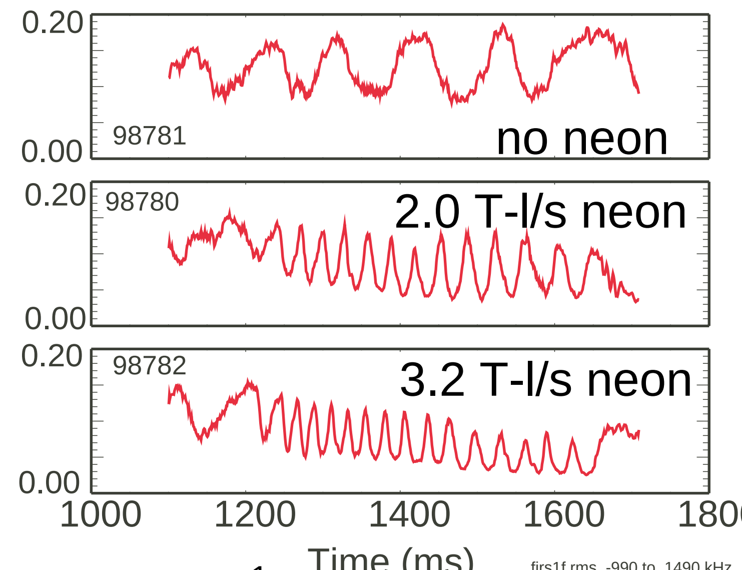
- Measurements in range $0.5 < \rho < 0.8$, k_θ=13.3 cm^{-1}
- Burst frequency increases with neon quantity, appears correlated with reduced electron energy transport

Color Enhanced Contour Plot of Scattered Power Spectrum Evolution





Frequency Integrated Fluctuation Level



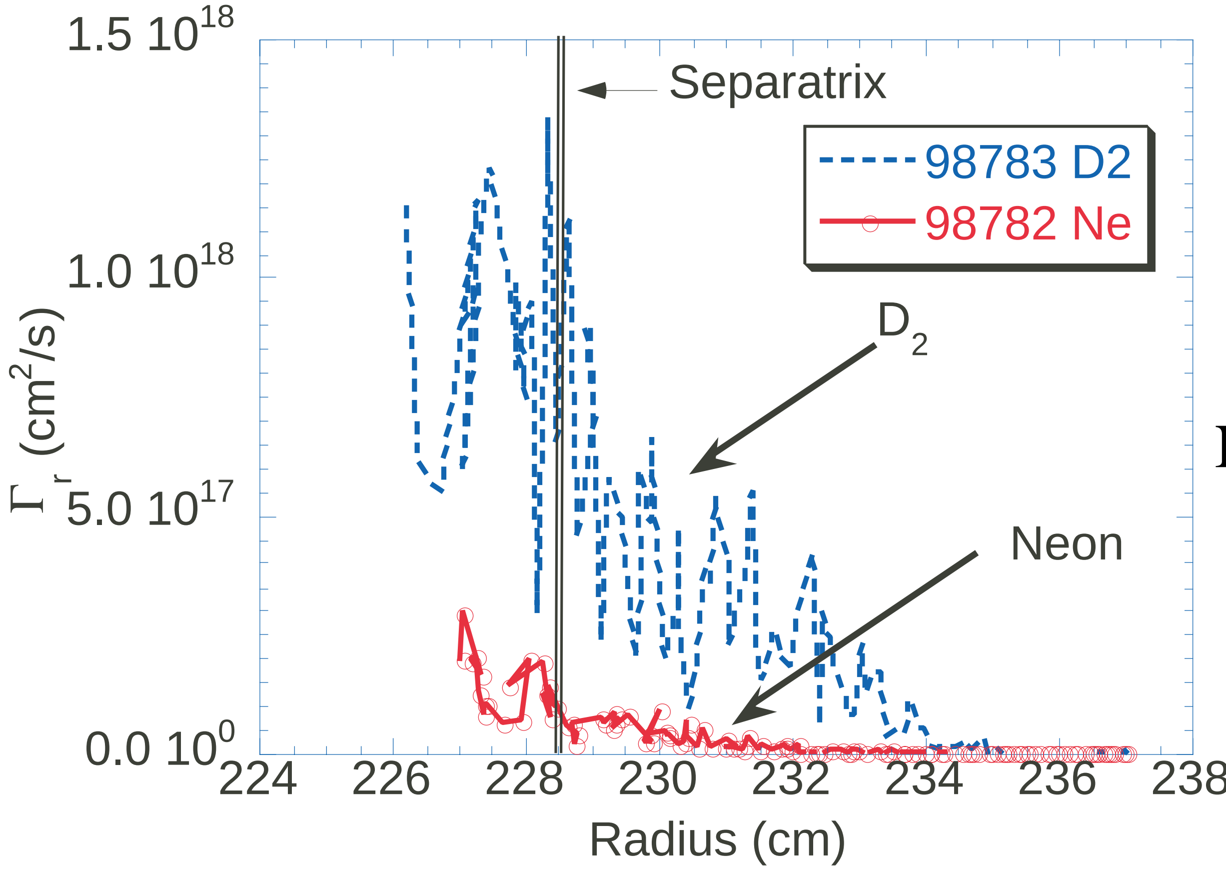
k_θ = 13.3 cm^{-1}
R = 40 cm 9 cm

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

UCLA

EDGE TURBULENT PARTICLE FLUX REDUCED WITH IMPURITY INJECTION

- Langmuir probe measurements of density, potential, cross-phase and net particle flux in plasma edge and scrape-off layer



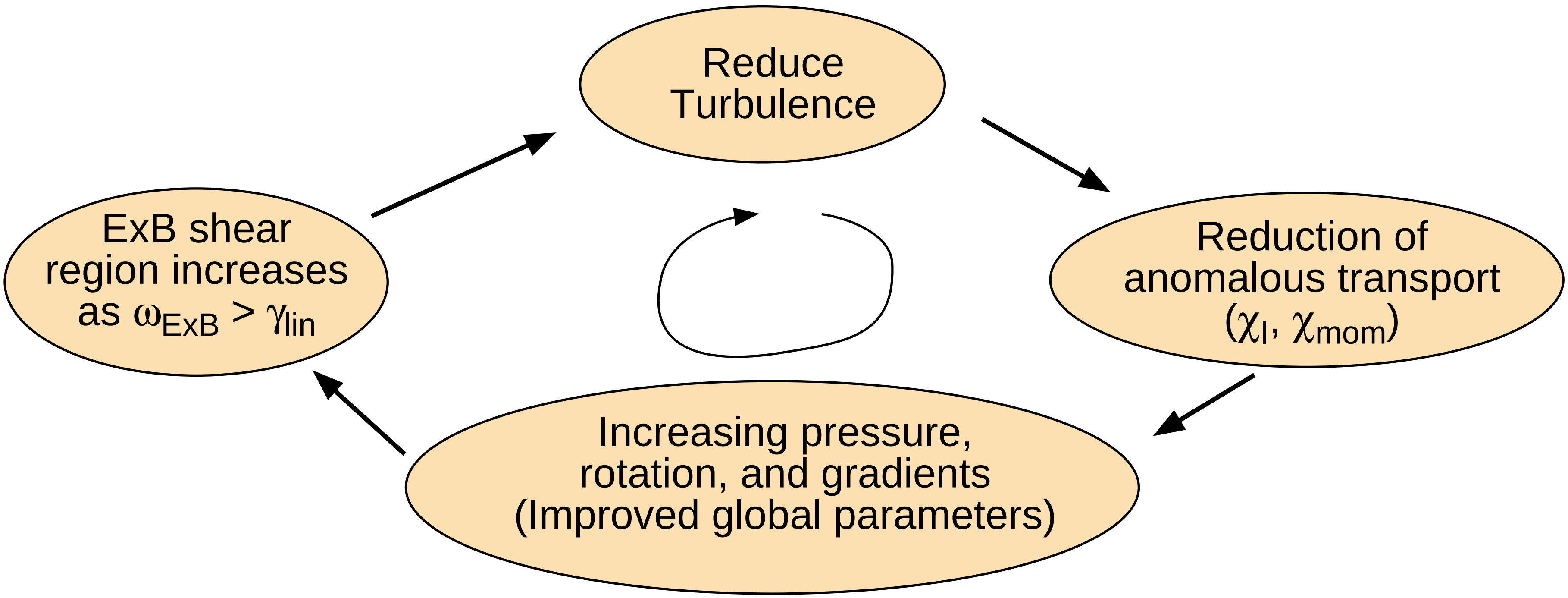
$$\Gamma_r = \langle \tilde{n} (\tilde{E}_\theta / B_t) \rangle$$

- Consistent with reduction in recycling

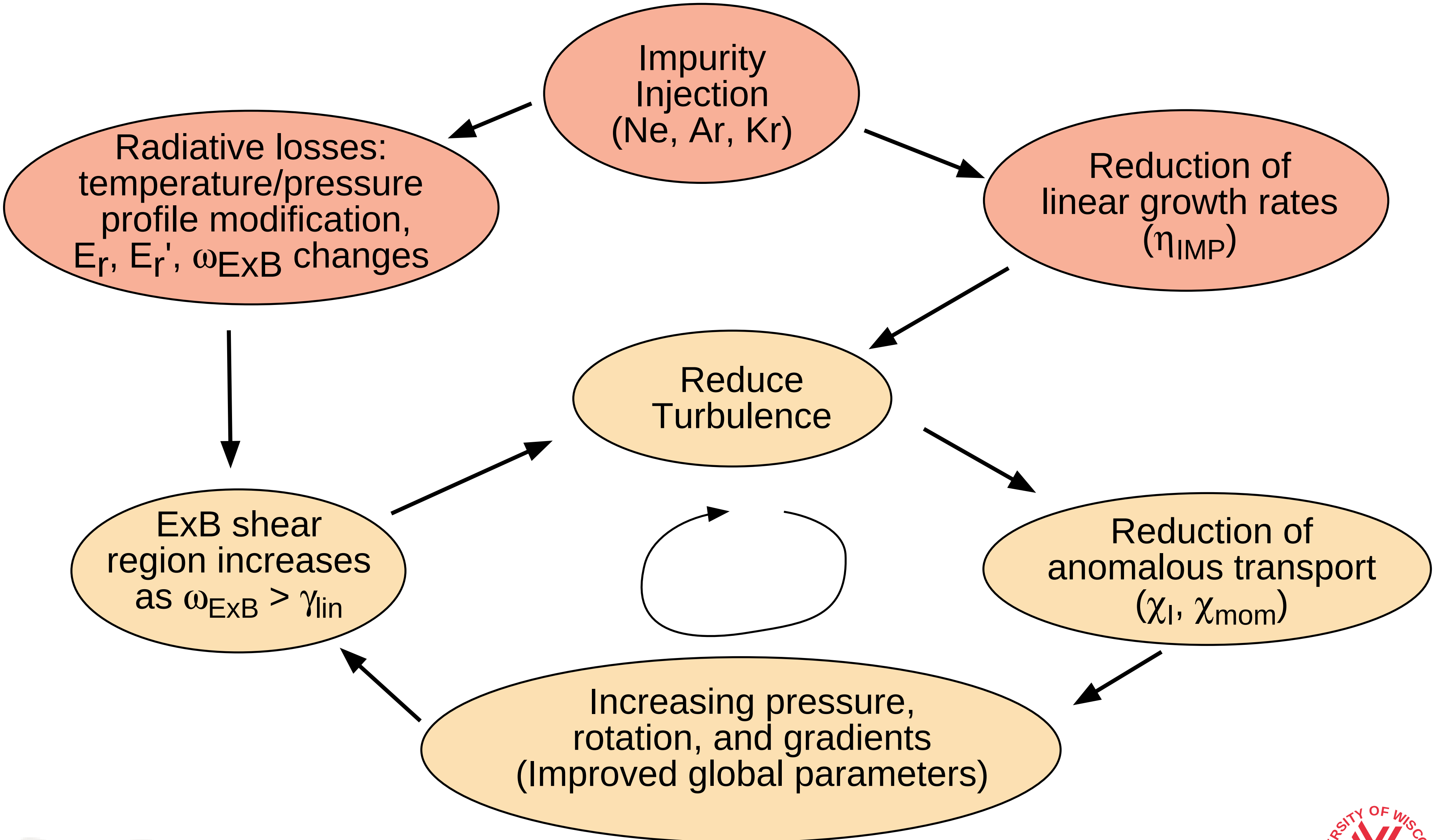
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

University of California San Diego

ExB SHEAR TURBULENCE SUPPRESSION MODEL USED TO DESCRIBE IMPROVED CONFINEMENT



POSSIBLE FEEDBACK LOOP RESULTING IN IMPURITY-INDUCED CONFINEMENT IMPROVEMENTS



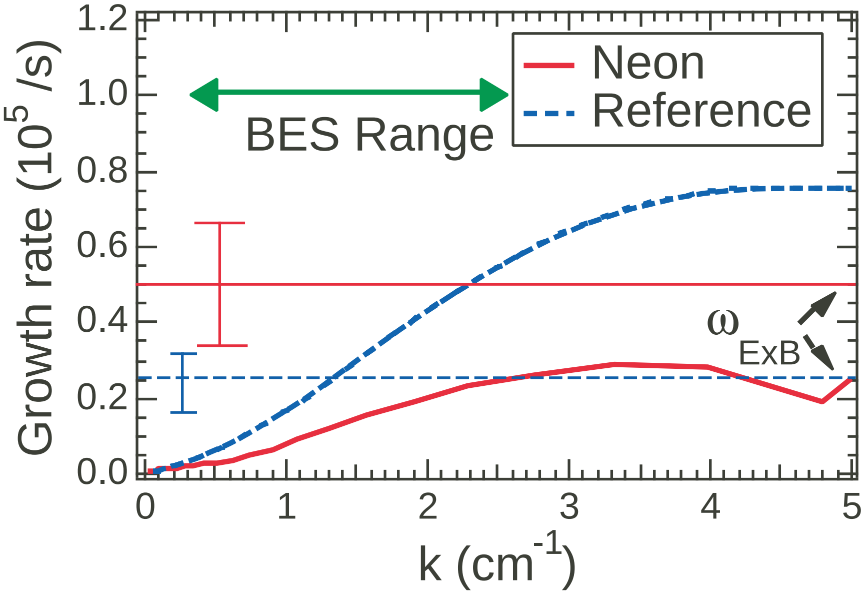
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

George McKee, APS 1999

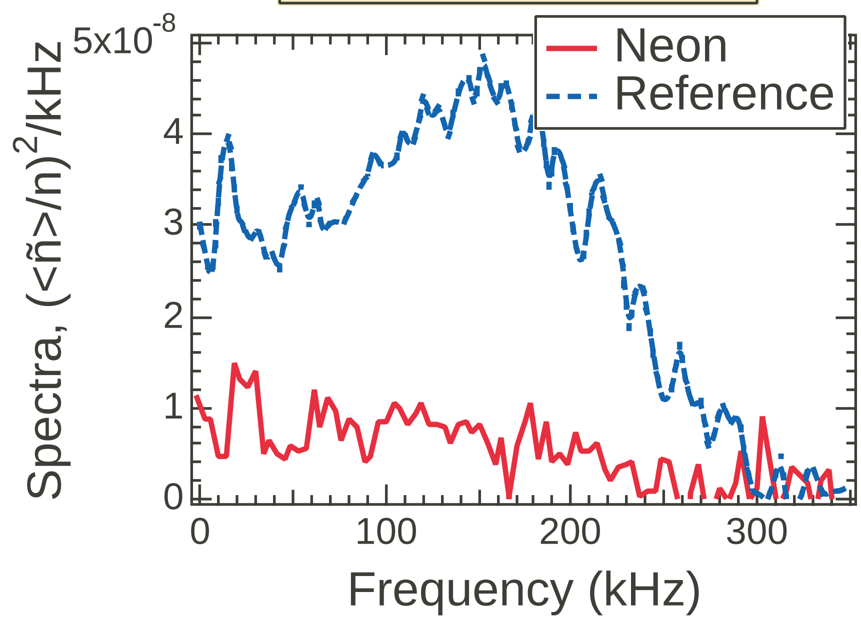
UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

GKS CALCULATIONS OF LINEAR STABILITY GROWTH RATES SHOW SIGNIFICANT REDUCTION AT LOW-k

Growth rates at ρ=0.7, t=1160 ms, BES (low-k) Region



Measured Fluctuation Spectra



- ExB shearing rates exhibit opposite behavior, increasing in neon shot, further suppressing turbulence:

Neon: $\gamma_{lin} < \omega_{ExB}$, Reference: $\gamma_{lin} > \omega_{ExB}$

George McKee, APS 1999

Department of Engineering Physics

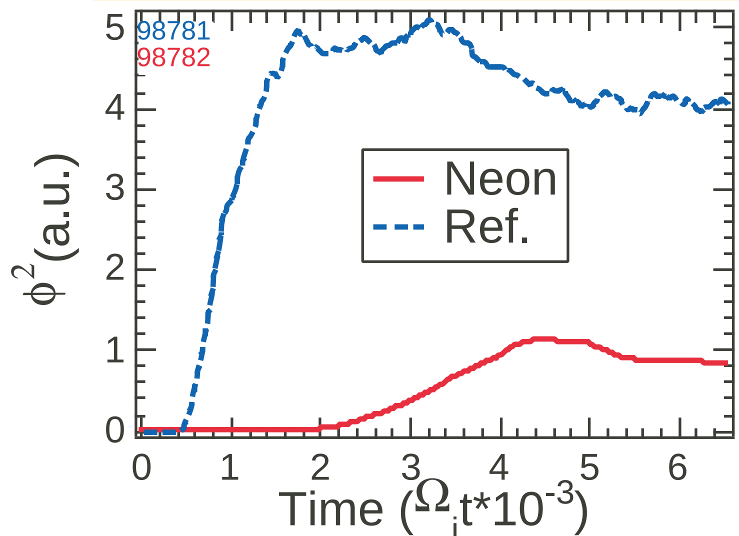
NONLINEAR GYROKINETIC SIMULATIONS EXHIBIT REDUCED SATURATED TURBULENCE LEVELS

- 3D gyrokinetic particle simulation code calculates nonlinear mode amplitude:

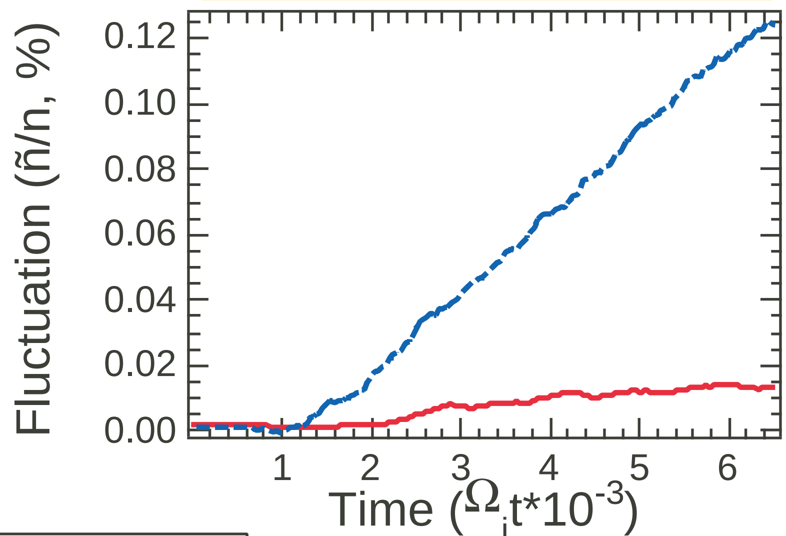
  - *fully kinetic ion dynamics (Ion Temperature Gradient modes)*
  - *adiabatic electrons*
  - *electrostatic modes*
  - *measured plasma profiles and magnetic equilibrium*

- Provide basis for direct, quantiative comparisons of simulations to measuremetns

Spatially Integrated Electrostatic Potential Fluctuation Saturates



Local Density Fluctuation, ρ=0.7



See R. Sydora, UP1.51 Friday

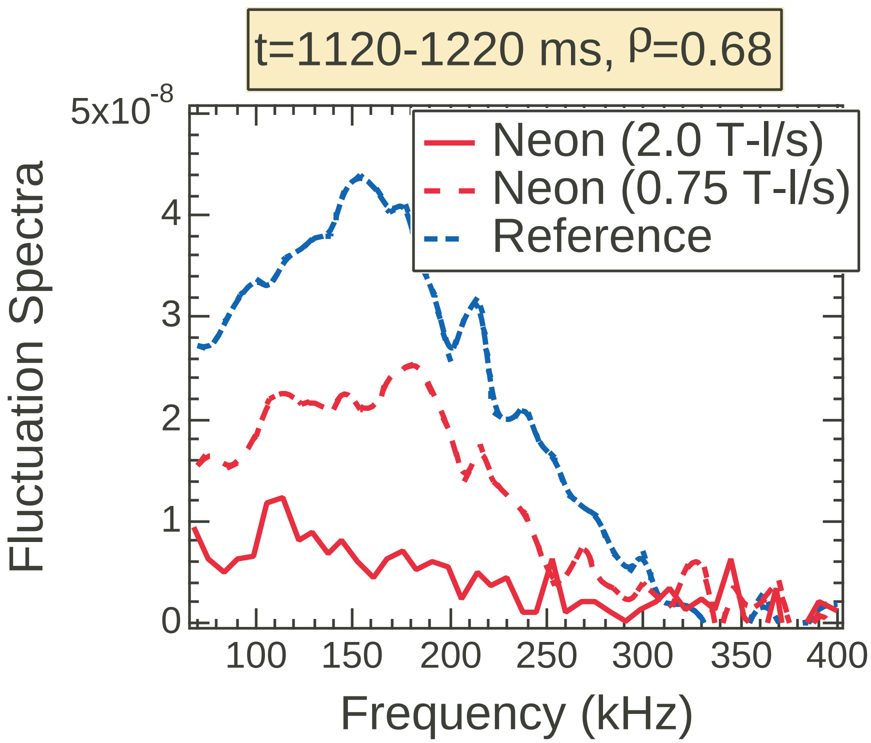
Department of Engineering Physics

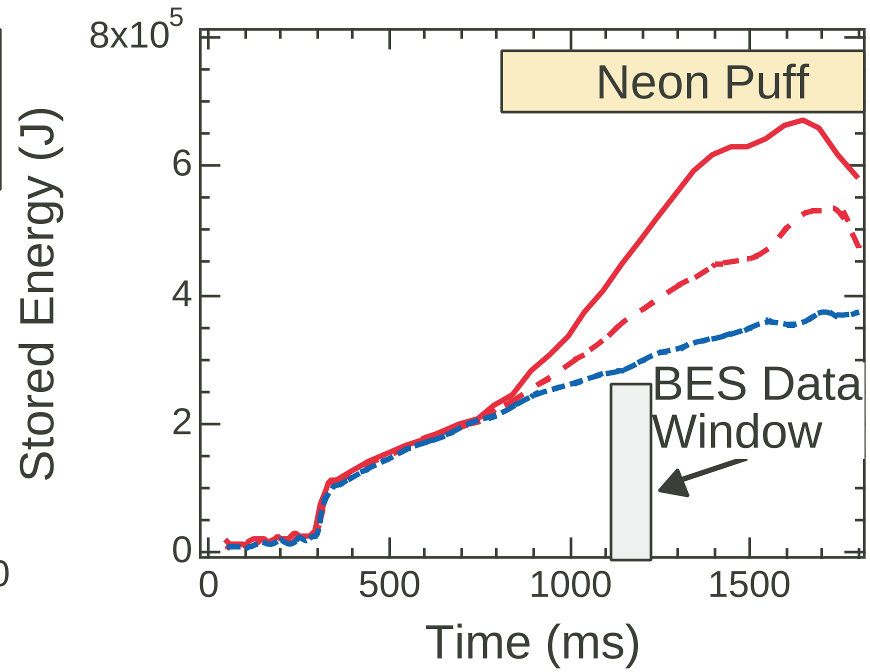
Summary & Conclusions

- Turbulence is strongly suppressed after impurity injection (Ne, Ar, Kr) into L-mode NCS plasma
- Improves confinement and reduces transport in ion and electron channel:
  - Higher stored energy, more peaked density profile
  - Higher fusion reactivity
- Zone of improved confinement moves out into positive shear region
- Neon produces stronger effect than Ar, Kr; increasing impurity quantity increases improvement (up to radiation limit)
- Gyrokinetic simulations show linear stability growth rates and nonlinear saturated levels are reduced for low-k (ion) turbulence
- Growth rate reduction acting synergistically with ExB shear suppression to reduce turbulence and transport
- These results suggest an operational regime that simultaneously achieves good particle and energy confinement (~2 H89, ~1 H93H) while maintaining a highly radiative, cool L-mode edge with lower carbon influx

DENSITY FLUCTUATION AMPLITUDE DECREASES WITH NEON QUANTITY, STORED ENERGY INCREASES

- Compare BES density fluctuation spectra at given spatial location and time as neon flow rate is varied from 0, 0.75, 2.0 Torr-liters/sec





- Yet higher neon quantities result in radiative collapse
- Argon flow rate scan yields qualitatively similar results

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

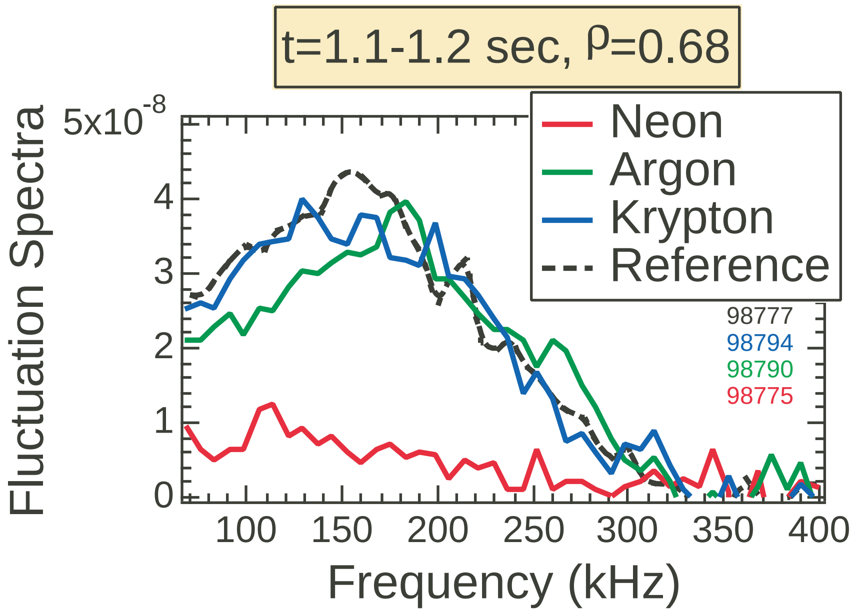
George McKee, APS 1999

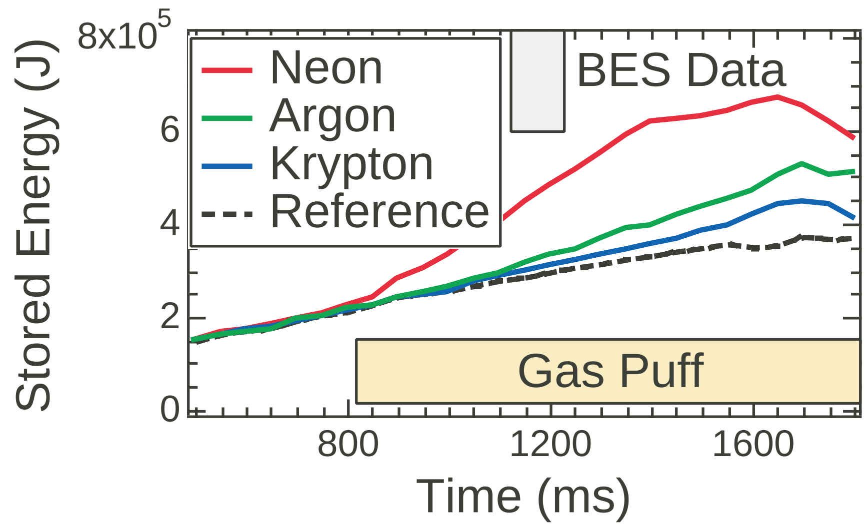
UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

Z-SCAN: LOWER-Z YIELDS LARGER, FASTER CONFINEMENT IMPROVEMENT (Ne, Ar, Kr)

- Neon improvement takes place most rapidly and achieves highest stored energy while higher-Z gases (Ar, Kr) yield more gradual improvement

- All gases achieve comparable radiation level (3.5 MW)





- Confinement improvement again exhbits inverse relation to amplitude of fluctuation spectra: Ne spectra has lowest amplitude, highest stored energy

- Stored energy saturates after 1.6 sec., as q_{min} falls below 1: MHD results

George McKee, APS 1999

Department of Engineering Physics

Impurities can impact stability of drift waves

• Ion Temperature Gradient (ITG) Modes and Trapped Electron modes (TEM) are unstable drift waves in the wavelength rages observed by BES.

ITG:

Impurity dilution and peaked impurity density profiles (or Zeff) are stabilizing for main ion ITG modes.

A hollow impurity density profile (or z_{eff}) is destabilizing.

If the impurity charge density is dominant (Z_I n_I/ne > 50%) the trends are reversed since the impurity ITG mode is the most unstable.

A nearly flat z_{eff} profile can generate a main ion particle pinch.

TEM:

Impurity dilution and z_{eff} peakedness are destabilizing.

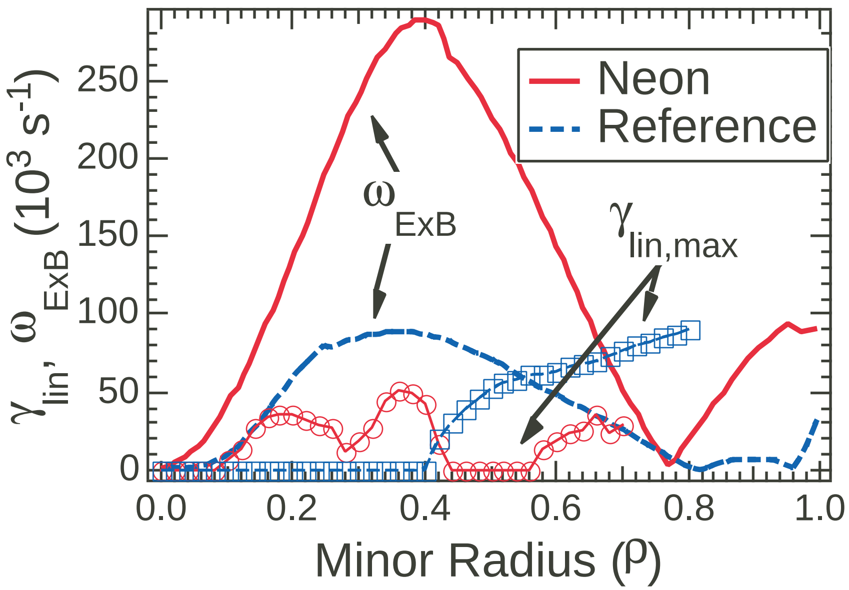
• ExB shear suppression can be more effectiv e at lower g rowth rates

º Summary of linear stability theory results for a single fully stripped impurity species.:

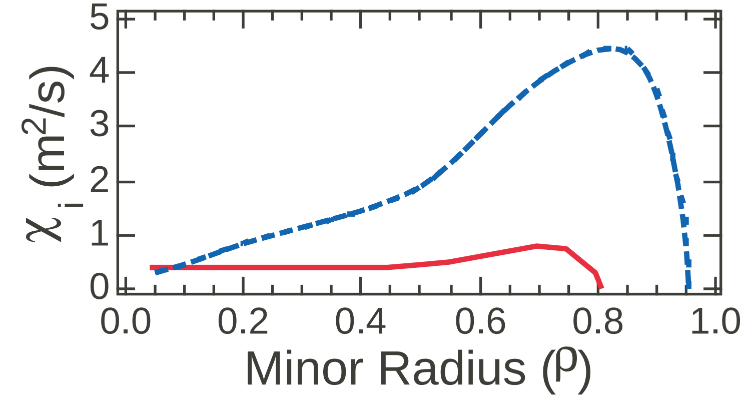
R. R. Dominguez, Nucl. Fusion 31 (1991) 2063.
R. R. Dominguez and G. M. Staebler, Nuclear Fusion 33 (1993) 51.
R. Sydora, Personal communication, TTF presentations

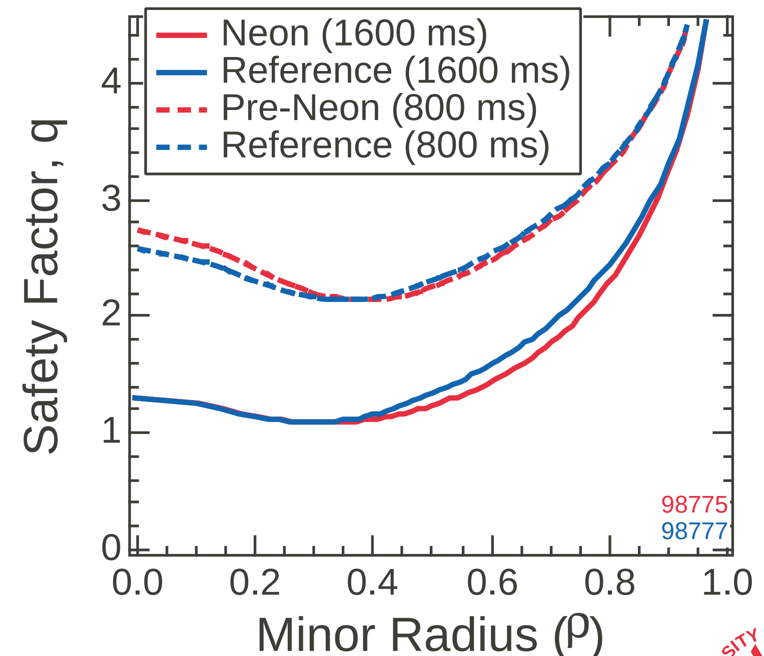
ExB SHEARING RATE CONTRIBUTES TO CONFINEMENT IMPROVEMENTS

Comparison of growth rate, γ_{lin}, and ω_{ExB} Shearing Rate, t=1.16 sec



Ion Thermal Diffusivity





- Turbulence and transport reduced when $\omega_{ExB} > \gamma_{lin}$ over much of the profile

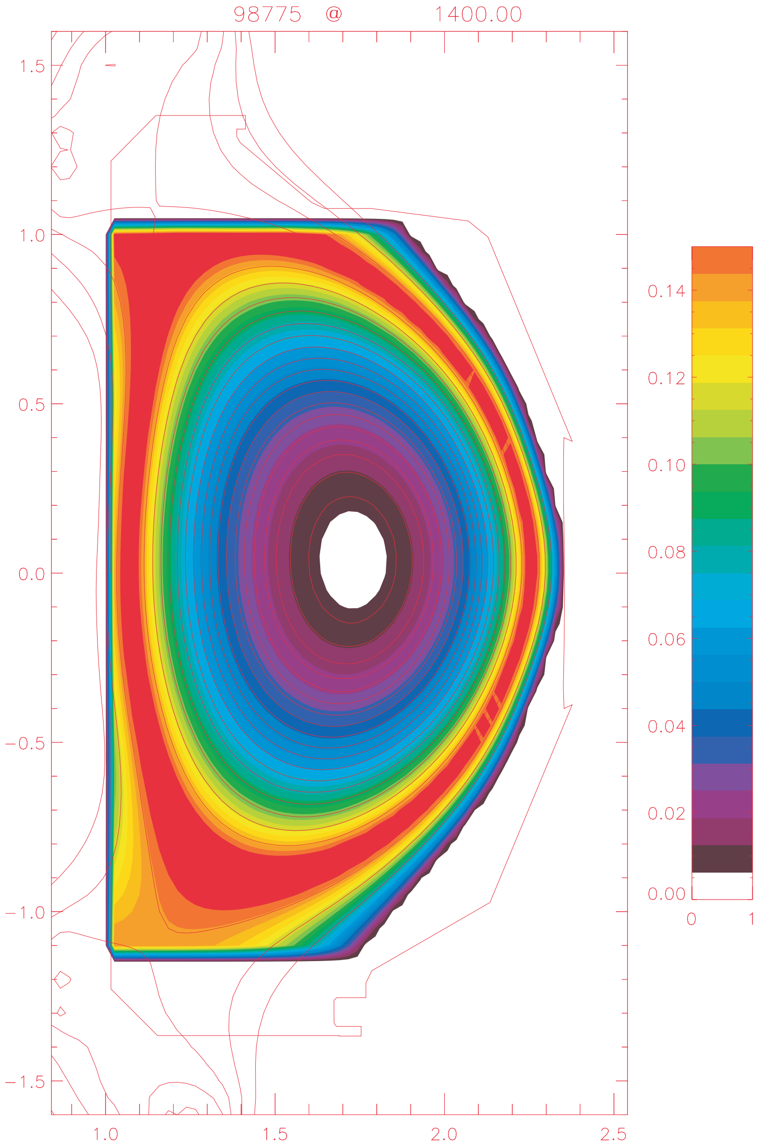
- High confinement region ($\rho \leq 0.7$) extends well beyond q_{min} ($\rho \approx 0.35$)

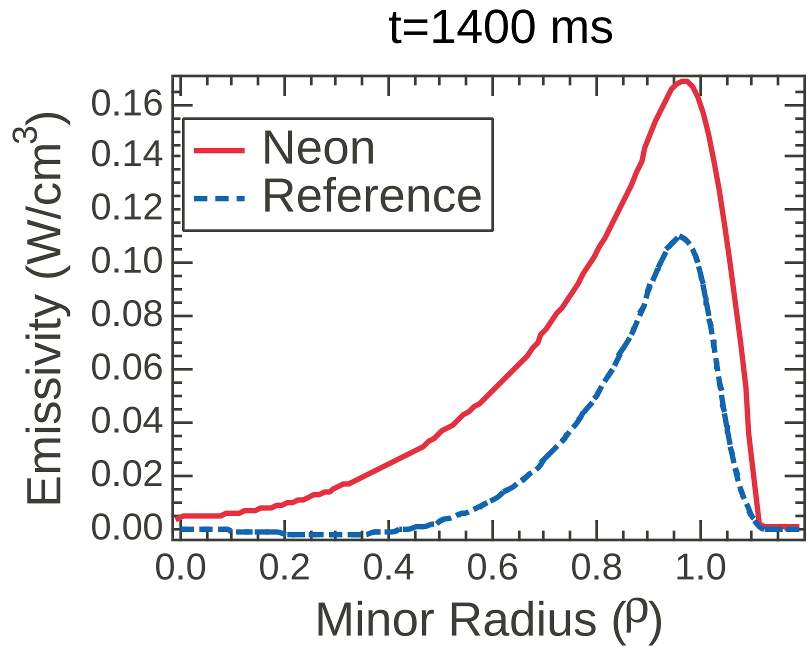
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

George McKee, APS 1999

UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics

RADIATIVE MANTLE PRODUCED WITH NEON





- Most of radiation from outside of r=0.7

George McKee, APS 1999

UNIVERSITY OF WISCONSIN MADISON

Department of Engineering Physics

DIII-D NATIONAL FUSION FACILITY SAN DIEGO