Use of Impurity Injection for Improved Performance in the DIII-D and JET Tokamaks

42nd DPP/APS Meeting, Oct. 2000, Poster HP1-057

G L Jackson 1), M Brix 3), R Budny 4), M Charlet 2), I Coffey 2),T.E. Evans 1),G Cordey 2),
P Dumortier 5), S K Erents 2), C.M. Greenfield 1), N C Hawkes 2), M von Hellermann 6),
D L Hillis 8), J Hogan 8), A.W. Hyatt 1), L C Ingesson 6), S Jachmich 3), A Kallenbach 7),
H R Koslowski 3), K D Lawson 1), A Loarte 9), G P Maddison 2), G F Matthews 2),
G.R. McKee 1), A Meigs 2), A M Messiaen 4), F Milani 2), P Monier-Garbet 10), P Morgan 2),
M Murakami 1,8), M F F Nave 11), J Ongena 5), M E Puiatti 12), E Rachlew 13), J Rapp 3),
C.L. Rettig 1), S Sharapov 2), G M Staebler 1), M Stamp 2), J D Strachan 4), G Telesca 12),
M Tokar 3), B Unterberg 3), M Valisa 12), K-D Zastrow 2),
& EFDA-JET 2000 workprogramme contributors*

1) DIII-D National Fusion Facility, San Diego, CA 92 186-5698, USA
2) EURATOM/UKAEA Fusion Association, Culham, UK
3) IPP, Forschungszentrum Juelich GmbH, EURATOM Association, D-52425 Juelich, Germany[a]
4) Princeton Plasma Physics Laboratory, Princeton University, NJ 08543, USA
5) LPP, Association EURATOM-Belgian State, ERM-KMS, B-1000 Brussels, Belgium[a]
6) FOM-IVP, EURATOM Association, Postbus 1207, NL-3430 BE Nieuwegein, Netherlands[a]
7) Max-Planck IPP, EURATOM Association, D-85 748 Garching, Germany
8) ORNL, Oak Ridge, TN 3783 1-8072, USA
9) EFDA-CSU, D-85 748 Garching, Germany
10) CEA Cadarache, F-13 108 St Paul lez Durance, France
11) CFN, EURATOM-IST Associac o,1096 Lisbon, Portugal
12) Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy
13) Association Euratom-NFR, KTH, Stockholm, Sweden

[a] Partners in the Trilateral Euregio Cluster (TEC).

Use of Impurity Injection for Improved Performance in the DIII-D and JET Tokamaks

Abstract

Injection of non-intrinsic impurities, e.g., neon, has produced enhancements in the energy confinement time, τ_E, and the neutron yield, S_{nn}, in the DIII-D and JET tokamaks. Comparing effects of impurity seeding in both tokamaks is important in establishing scaling relations extrapolating these scenarios to larger devices such as fusion reactors. Values of H_{89P} up to 2.0 with simultaneous reduction of turbulence in DIII-D and 1.7 in JET were obtained in diverted neon seeded discharges with an L-mode edge with significant radiation ($P_{rad\ tot}/P_{in}$ = 0.5--0.8). We will discuss similarities and differences between DIII-D and JET discharges including gyrokinetic simulations of turbulent growth rates. Effects of impurity injection in inner wall limited DIII-D discharges will also be discussed.

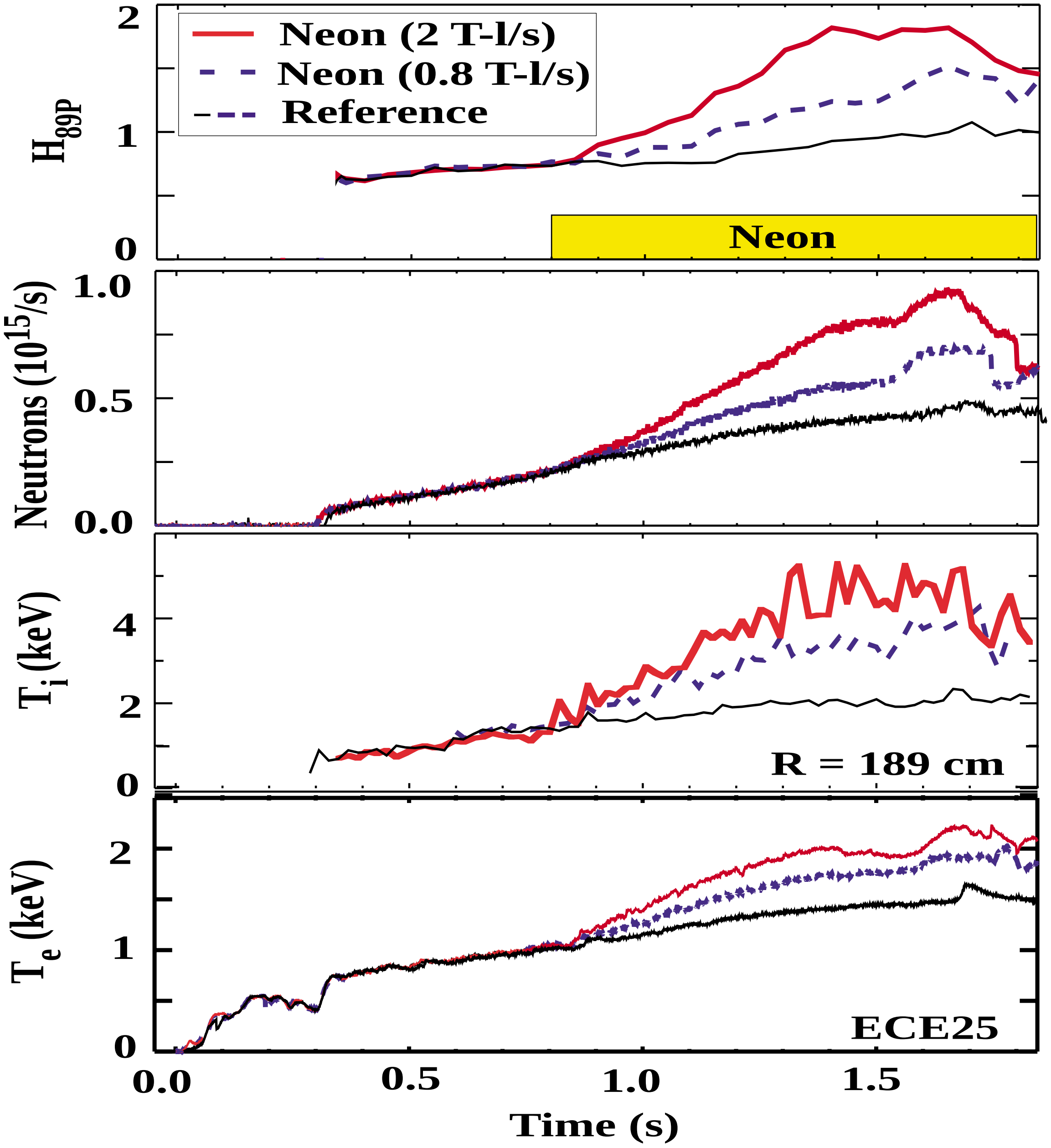
EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

MOTIVATION

- Radiating mantle discharges may provide attractive reactor s
  - High density operation near the Greenwald density limit
  - A large radiating power fraction, reducing peak heat fluxes to f
  - An L–mode edge, eliminating transient heat pulses such as ELMS
  - Enhanced confinement, above L–mode scaling, reducing auxiliary p for ignition
- Although enhanced confinement with impurity seeding has been many tokamaks (e.g., ISX-B, TEXTOR, ASDEX-U, and DIII–D), ac performance on larger devices is a critical step in evaluati such an approach
- Comparison of the effects of impurity seeding in different d important in order to
  - Obtain an understanding of the common physical mechanisms
  - Provide size scaling for extrapolation to reactor devices

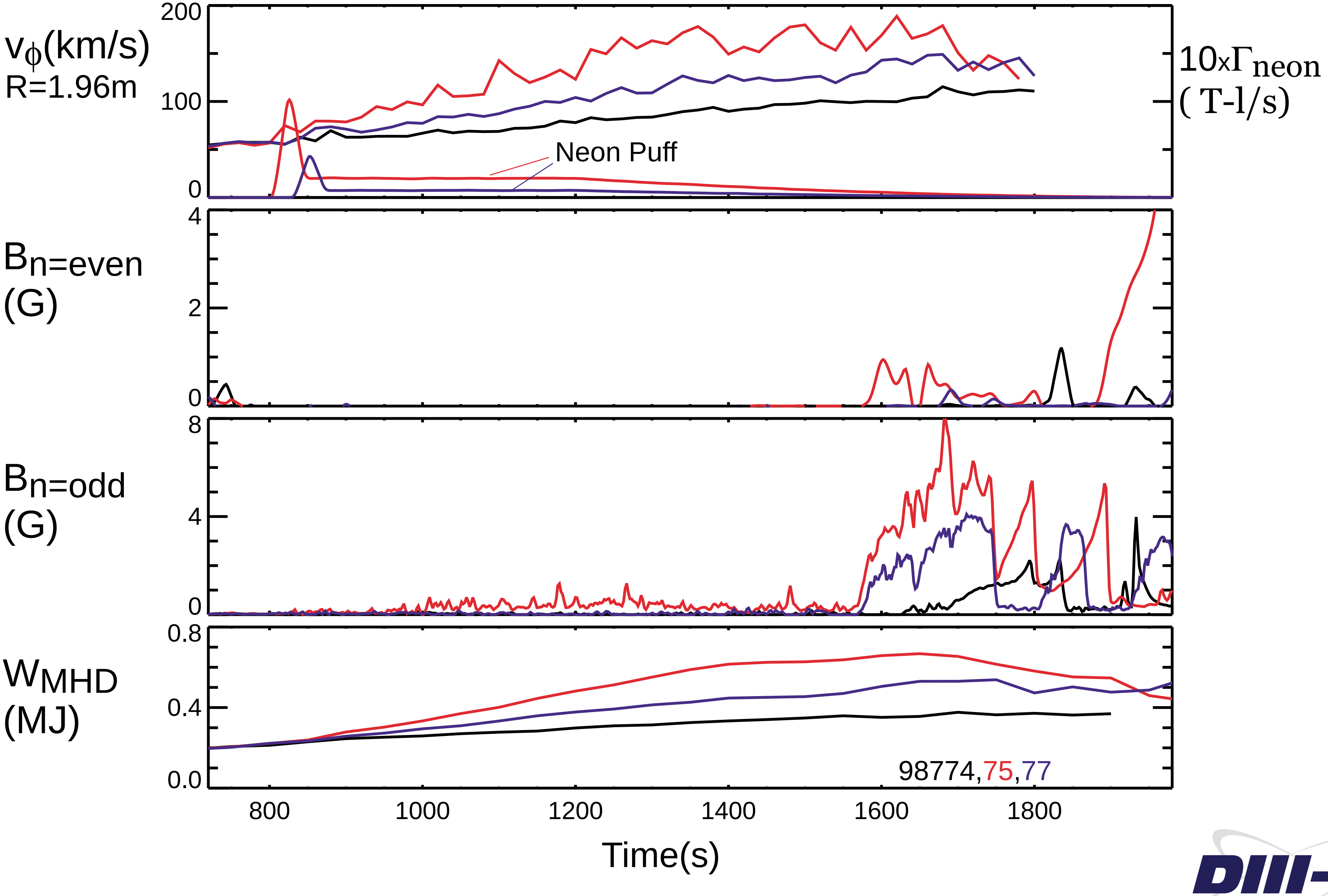
NEON SEEDED L-MODE DIVERTED DISCHARGES HAVE EXHIBITED ENHANCED CONFINEMENT, H_{89P} UP TO 2, AND A DOUBLING OF THE NEUTRON RATE COMPARED TO REFERENCE DISCHARGES WITHOUT NEON.



GLJackson aps00 f3

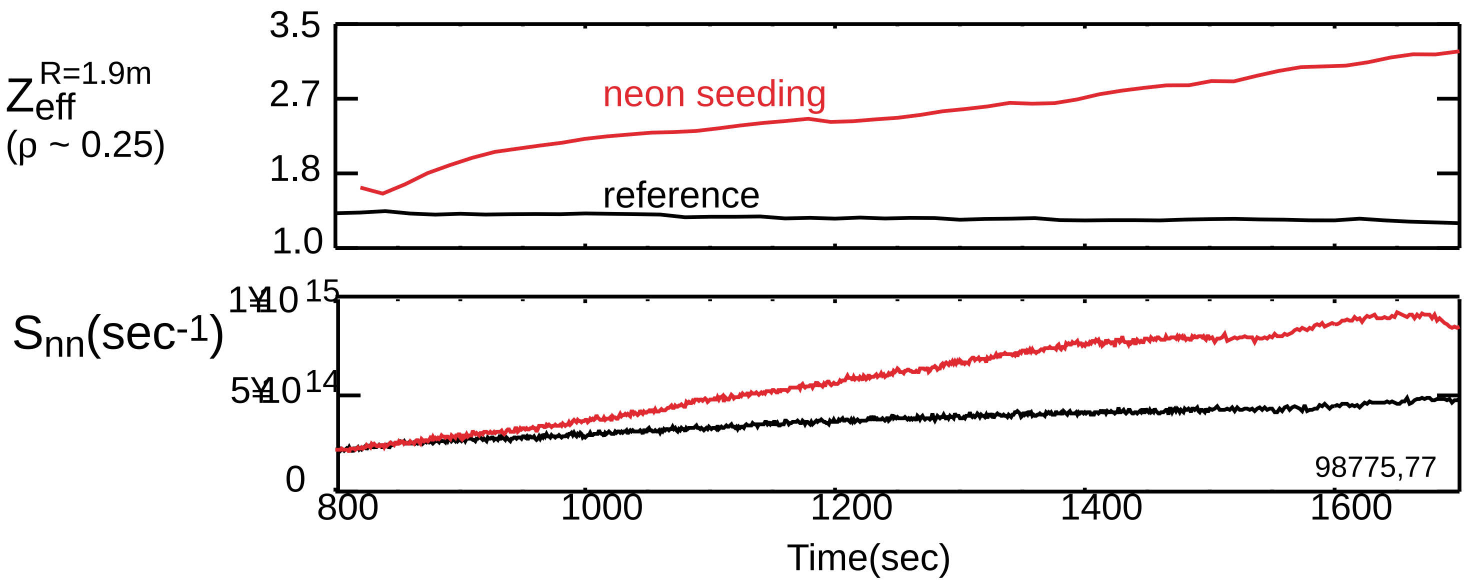
INCREASED TOROIDAL ROTATION IS OBSERVED IN DIII-D AFTER IMPURITY SEEDING

BOTH W_{MHD} AND v_{ϕ} DECREASE AFTER THE ONSET OF MHD (USUALLY m/n=3/2 or SAWTEETH)



GLJackson aps00 f3A

IN DIII-D DISCHARGES, Z_{eff} INCREASES WITH NEON INJECTION, BUT THIS IS OFFSET BY HIGHER T_i AND n_e, PRODUCING A LARGER NEUTRON YIELD THAN REFERENCE DISCHARGES



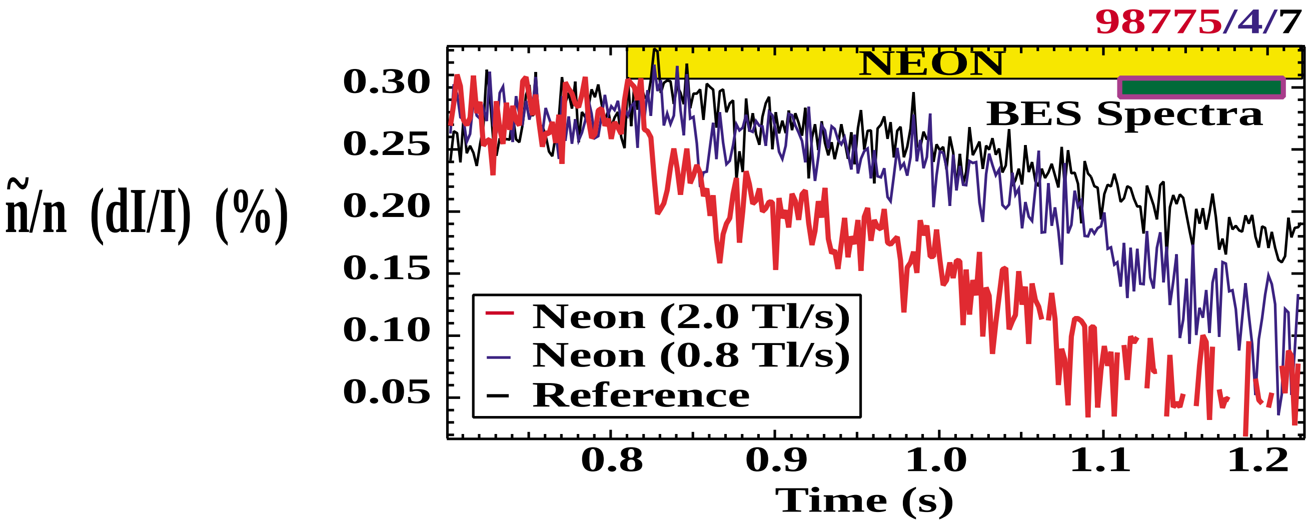
EVEN WITHOUT IMPROVED CONFINEMENT, HIGHER Z_{imp} PRODUCES THE SAME NEUTRON YIELD AT HIGHER Z_{eff}, THUS FUSION REACTORS WITH IMPURITY SEEDING MAY OPERATE AT HIGHER Z_{eff} THAN THE ITER BASELINE VALUE OF 2.0.

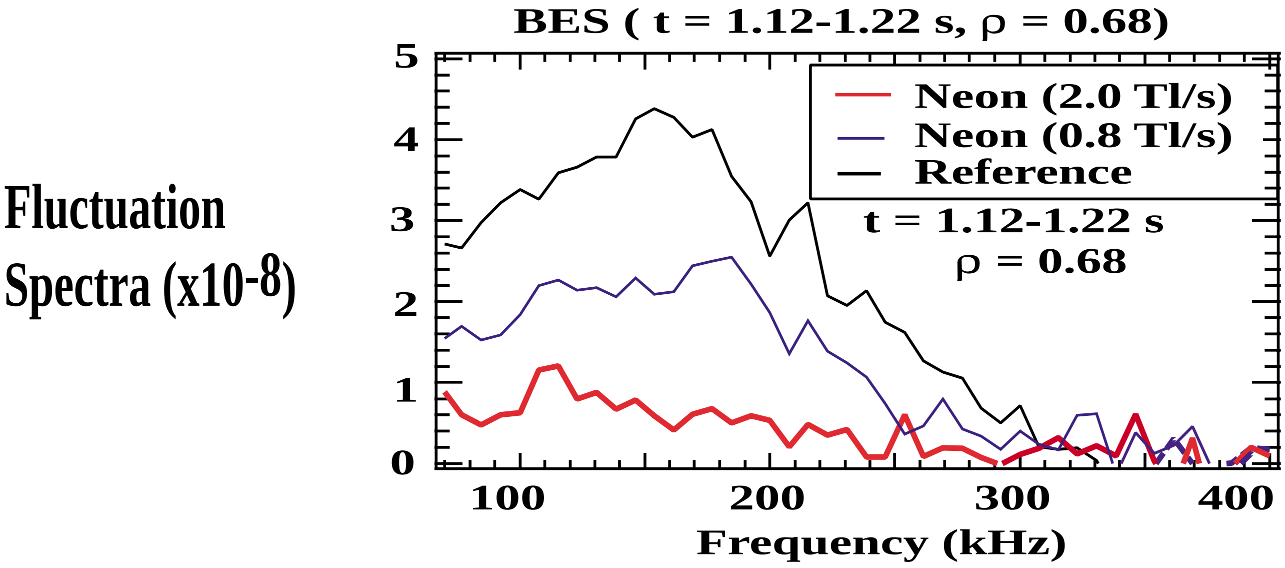
$$P_{fus} \sim \left[\frac{n_e(Z_{imp}-Z_{eff})}{(Z_{imp} - 1)}\right]^2$$

For example, $Z_{eff}^{carbon} = 2.0$ (ITER baseline) has the same fusion yield as $Z_{eff}^{neon} = 2.8$ or $Z_{eff}^{krypton} = 8.0$ (assuming single specie Z_{imp} and other parameters held fixed).

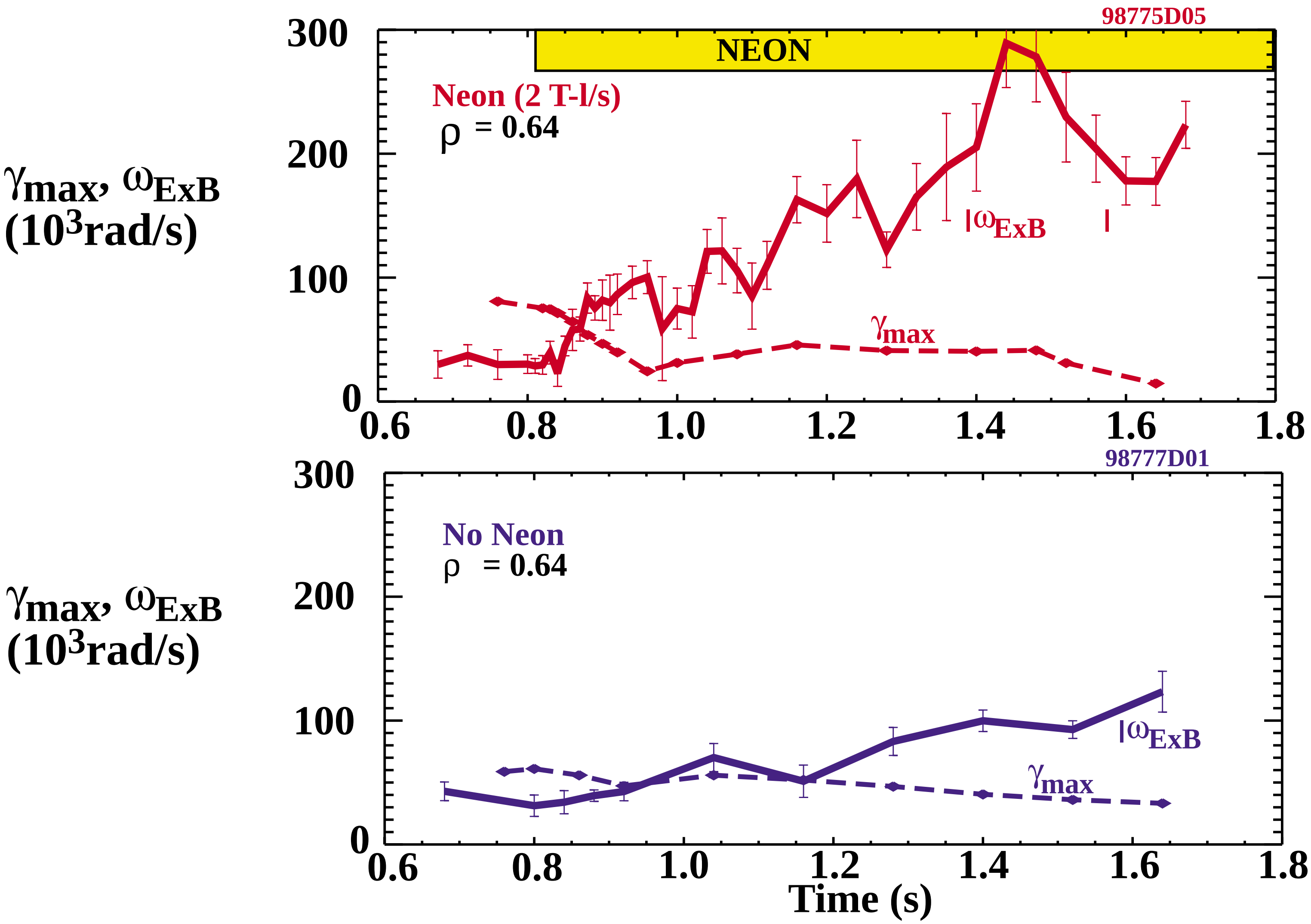
GLJackson aps00 f4

DENSITY FLUCTUATIONS PROMPTLY DROP AFTER NEON INJECTION (r > 0.5), THEN EXHIBIT A LONGER TERM DECLINE





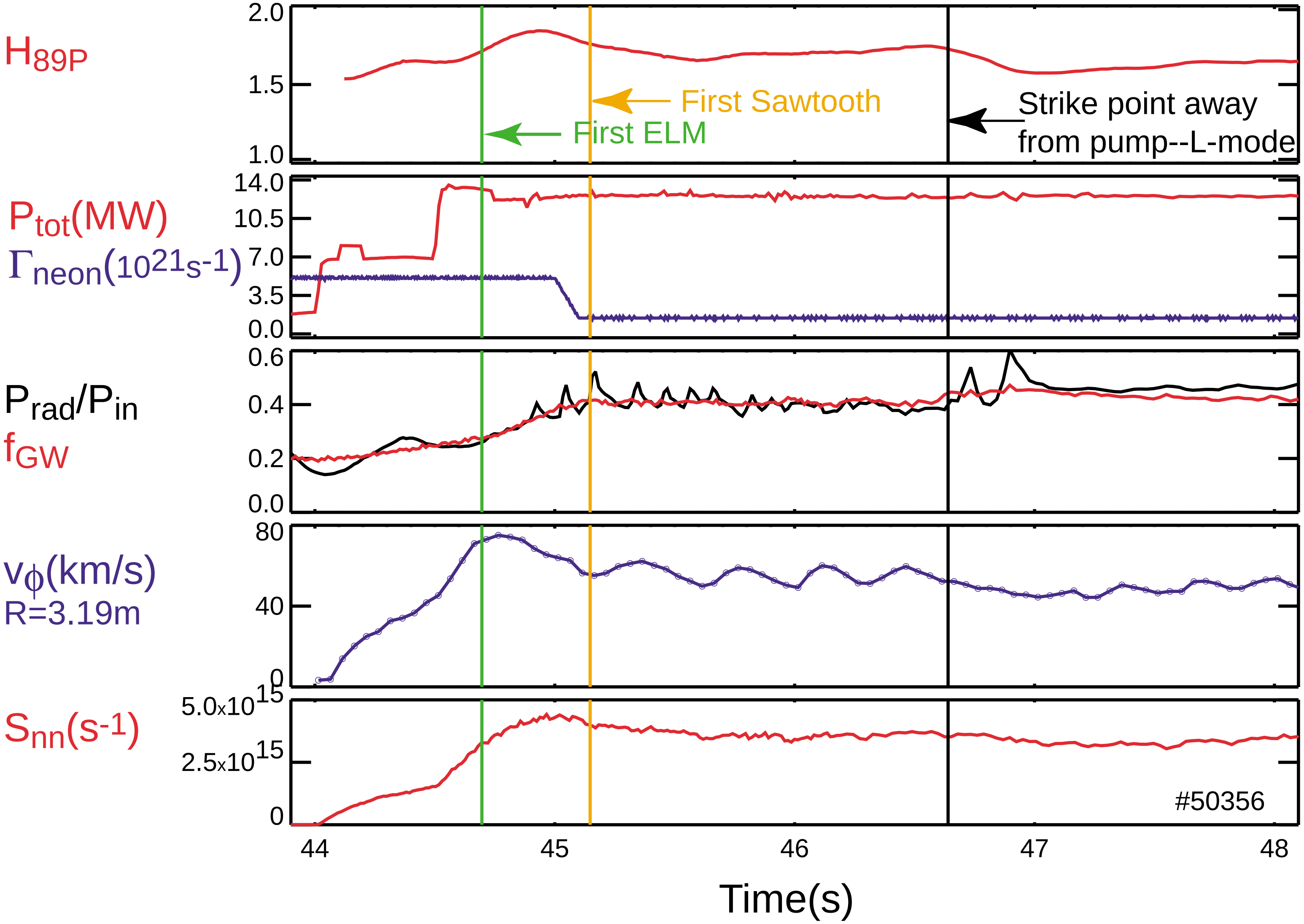
WITH NEON, REDUCED DENSITY FLUCTUATIONS ARE ACCOMPANIED BY AN INCREASE IN THE ExB SHEARING RATE



GLJackson aps00 f6

IMPROVED CONFINEMENT WITH NEON SEEDING HAS BEEN OBSERVED IN JET.

HOWEVER THE RAPID ONSET OF ELMS OR SAWTEETH LIMIT THE DURATION OF THE HIGHEST PERFORMANCE PHASE.



EUROPEAN FUSION DEVELOPMENT AGREEMENT

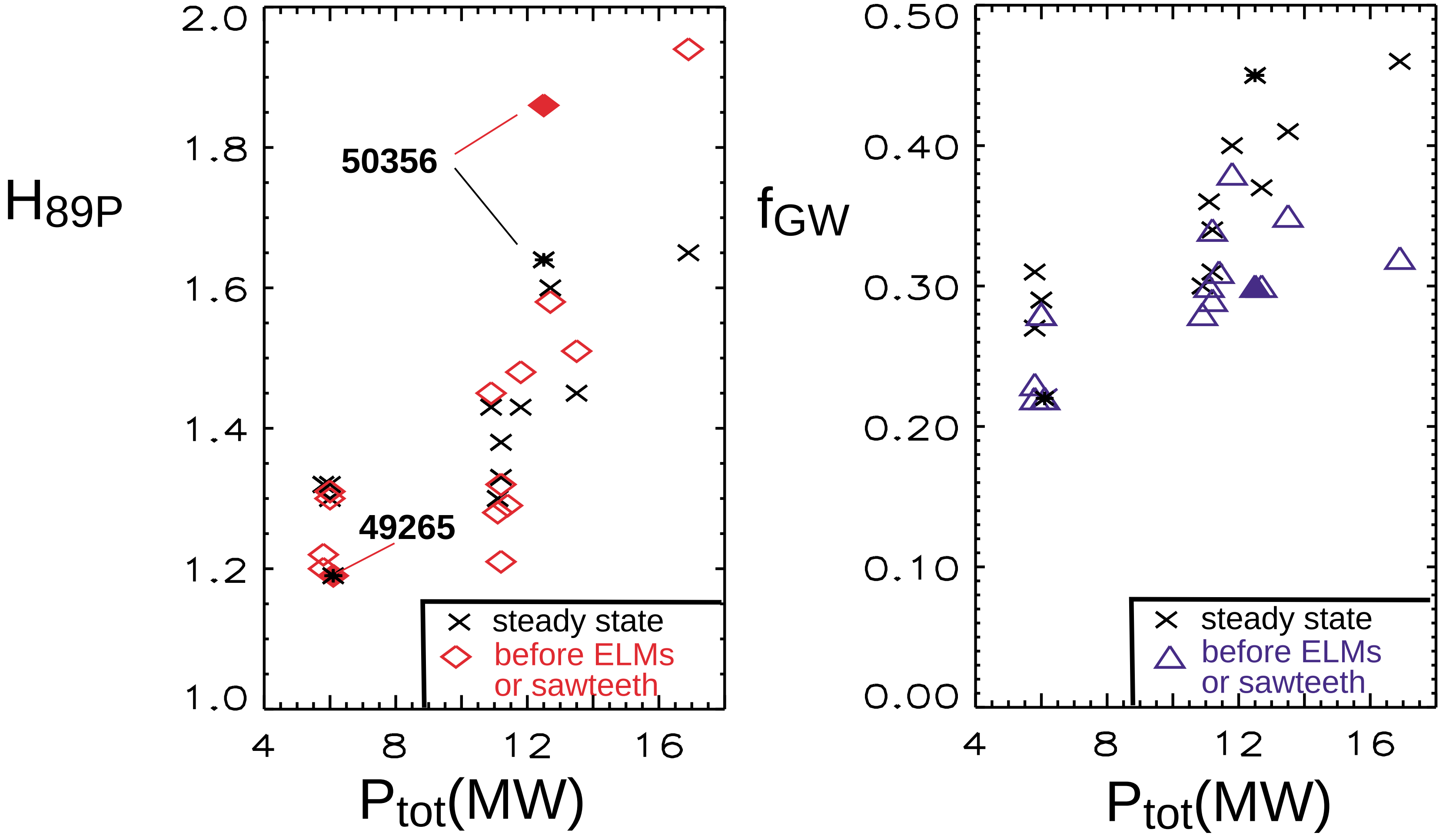
GLJackson aps00 f7

JET L-MODE IMPURITY SEEDED DISCHARGES EXHIBIT BEST PERFORMANCE AT HIGHEST POWER

- ELMS OR SAWTEETH LIMIT THE HIGH PERFORMANCE PHASE

- NORMALIZED DENSITY ALSO INCREASES WITH POWER

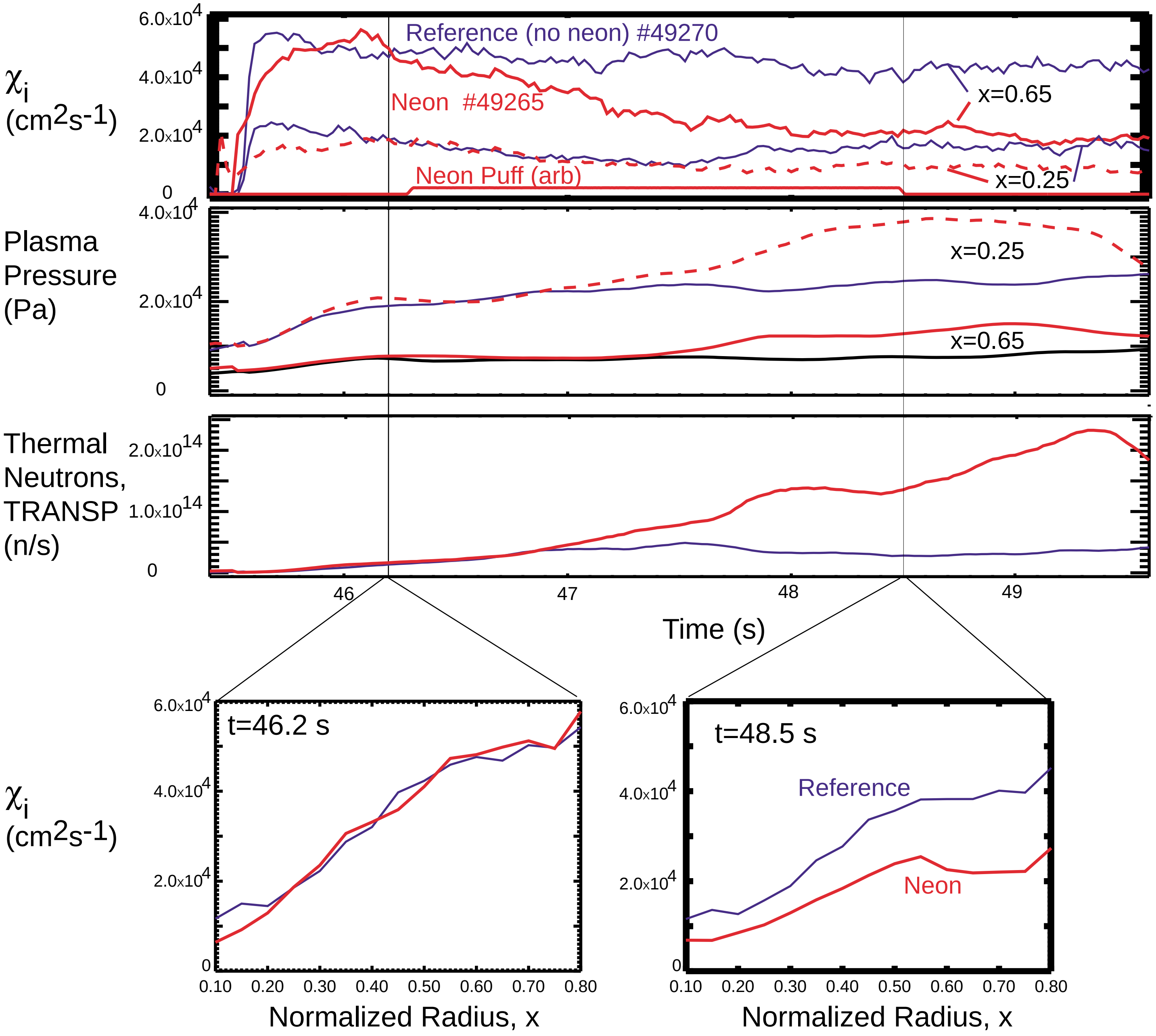
(Neon injection, "Corner" divertor configuration)



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

GLJackson aps00 f8

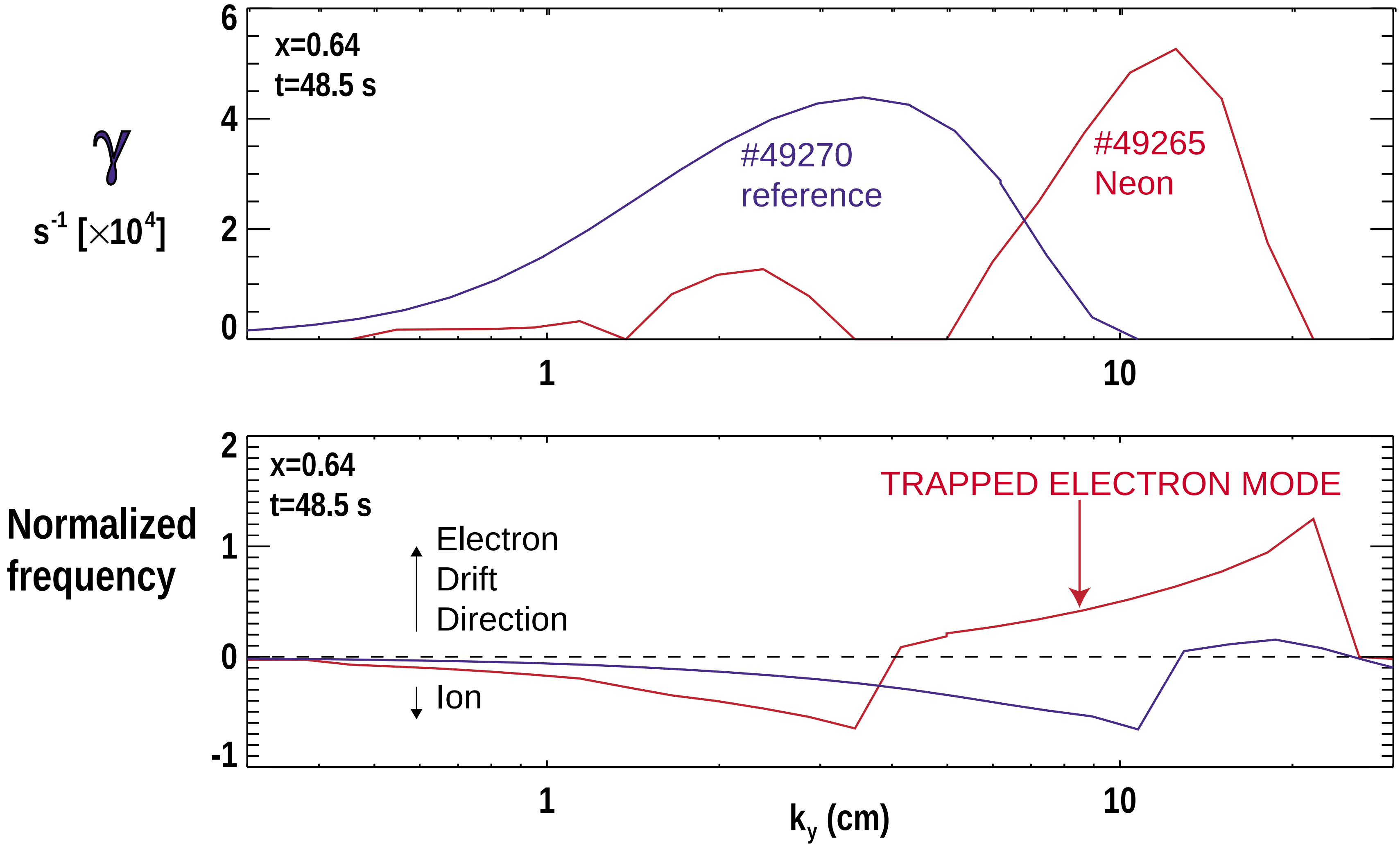
TRANSP ANALYSIS SHOWS χ_i DECREASING WITH NEON WHILE BOTH PLASMA PRESSURE AND THE THERMAL NEUTRON RATE INCREASE.



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

GKS CALCULATIONS SHOW THE LARGEST GROWTH RATES SHIFT TO HIGHER k WITH IMPURITY SEEDING

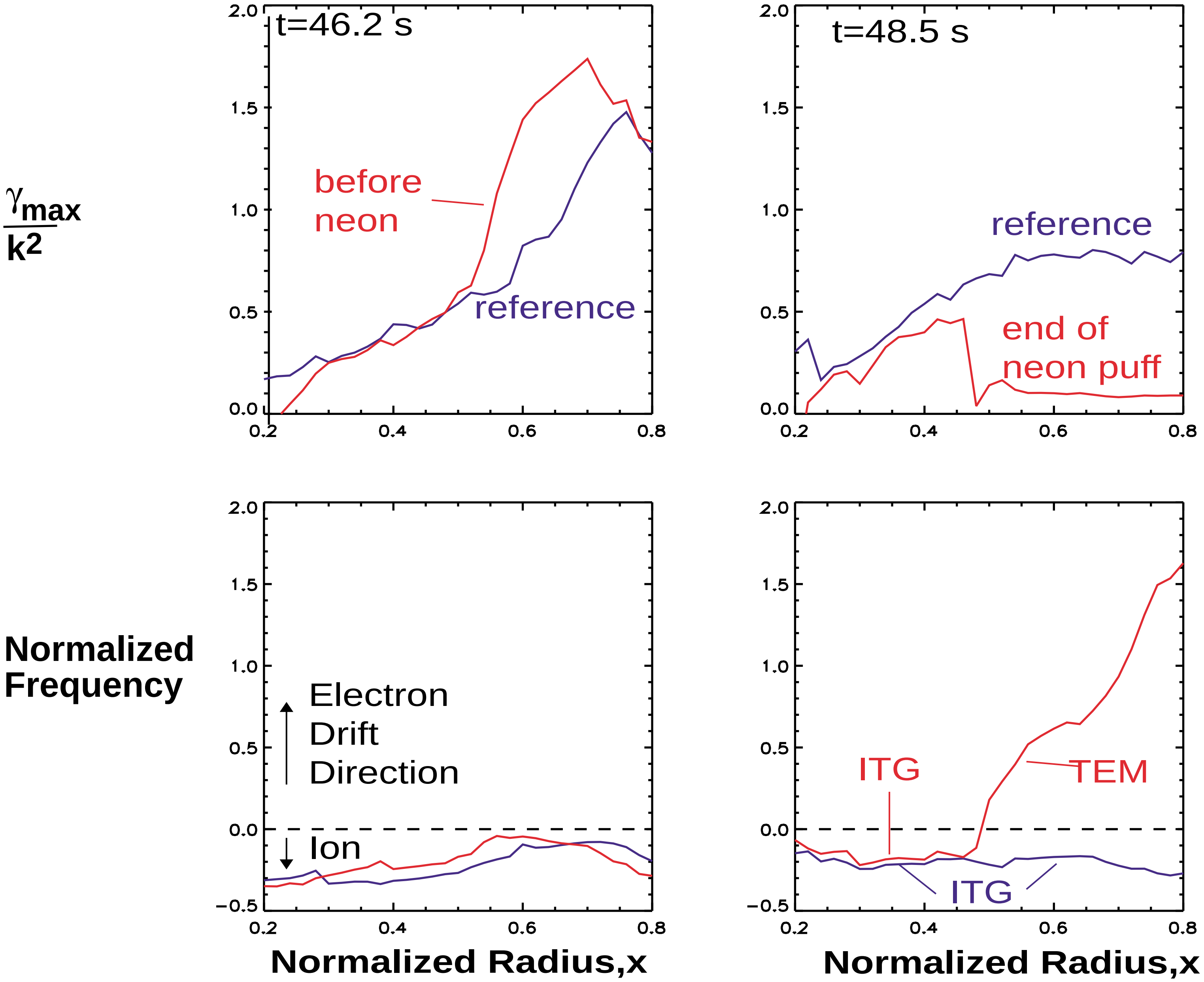
WITH NEON, FREQUENCY AND k RANGE INDICATE TRAPPED ELECTRON MODES AT LARGEST GROWTH RATE. HOWEVER, ITG GROWTH RATES ARE REDUCED (k < 5).



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

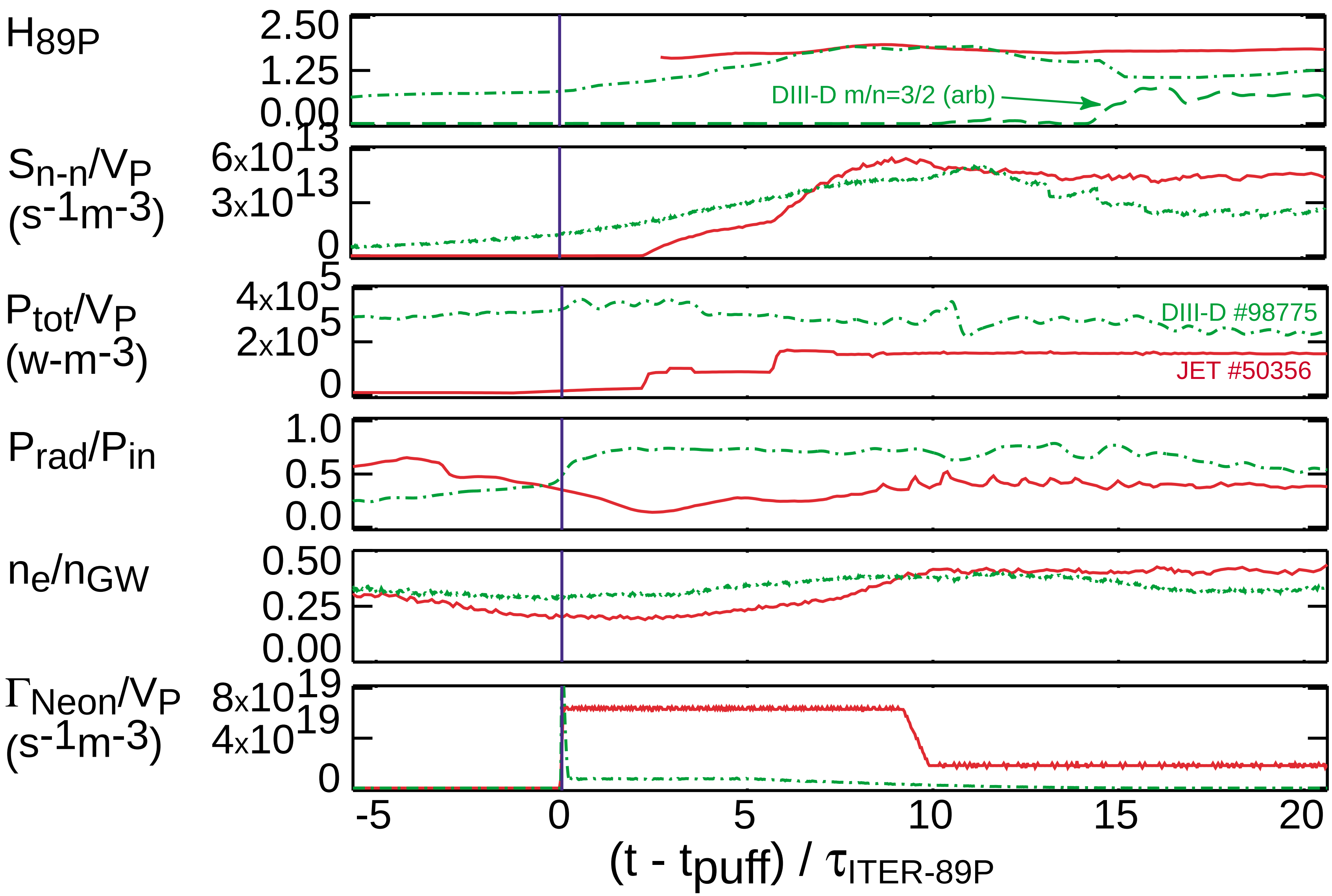
GYRO-KINETIC SIMULATION (GKS) MODELING SHOWS THE TRAPPED ELECTRON MODE (TEM) HAS THE LARGEST GROWTH RATE (for x > 0.5) WITH IMPURITY SEEDING IN JET

THE TEM IS NOT OBSERVED IN THE REFERENCE DISCHARGE (BLUE).



EUROPEAN FUSION DEVELOPMENT AGREEMENT

DIII-D(green) and JET(red) DISCHARGES EXHIBIT SOMEWHAT DIFFERENT TEMPORAL BEHAVIOR BUT REACH SIMILAR VALUES OF H_{89P} AND n_e/n_{GW}.



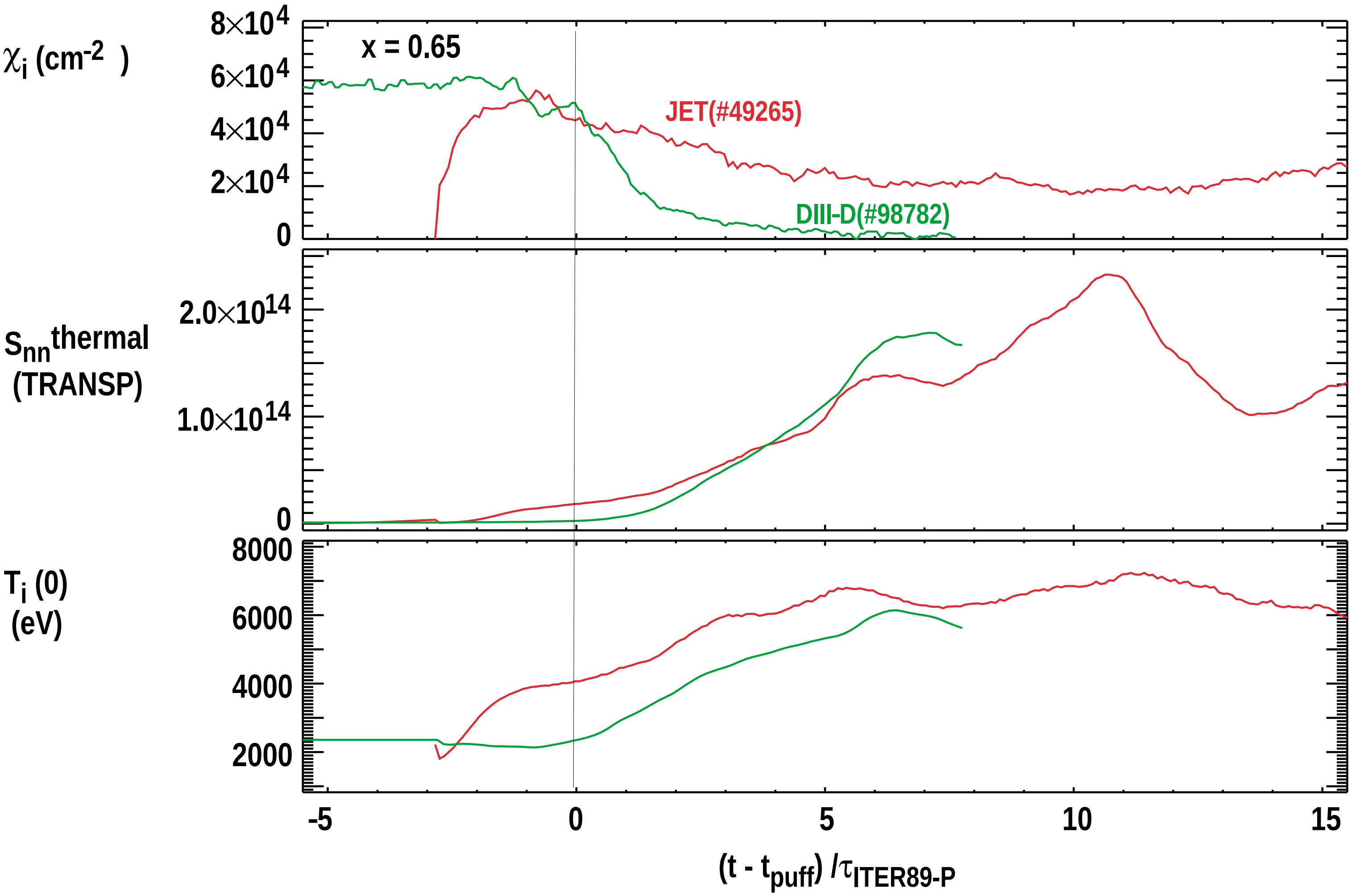
EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GLJackson APS00 F13

χ_i DECREASES MORE RAPIDLY IN DIII-D THAN IN JET, BUT EVOLUTION OF THE THERMAL NEUTRON FLUX AND T_i ARE QUALITATIVELY SIMILAR

(NORMALIZED TO ITER-89P CONFINEMENT TIME)



APS00 GLJackson F14

COMPARISON OF DIII-D AND JET L-MODE DISCHARGES WITH NEON

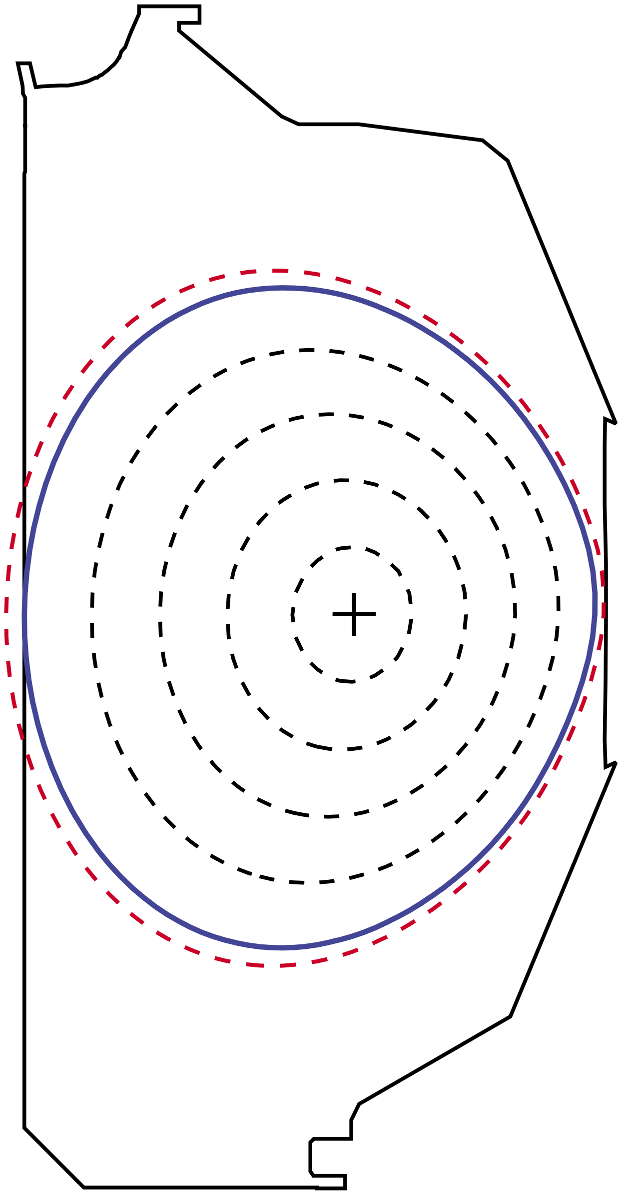
	DIII-D	JET(1999)	EFDA/JET(2000)
Configuration	USN	LSN	LSN
$\nabla B \times B$ drift direction	Away from X-point	Toward X-point	Toward X-point
B_T (typ)	1.6 T	3.0 T	1.8-2.2 T
q_{95} (typ)	3.6	4.0	3.3-4.4
H_{89P} (max)	2.0	~1.4 (in L-mode)	1.9 (in L-mode)
n_e/n_{GW}	0.5	0.25	0.46
P_{rad}/P_{in}	0.7 (typ)	0.6 (max)	0.6 (max)
V_ϕ increase after neon?	Yes	No	yes
Z_{eff}	2.5-3.5	4-6	5-6
Termination of high performance	m/n=3/2 or sawteeth	sawteeth	ELMs or sawteeth
Largest reduction in thermal diffusivity	ions	ions	ions

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D INNER WALL LIMITED DISCHARGES (SHAPE SIMILAR TO TEXTOR) HAVE BEEN USED TO COMPARE TEXTOR RI-MODE TO DIII-D AND TO EXPLORE POSSIBLE SIMILAR PHYSICAL MECHANISMS

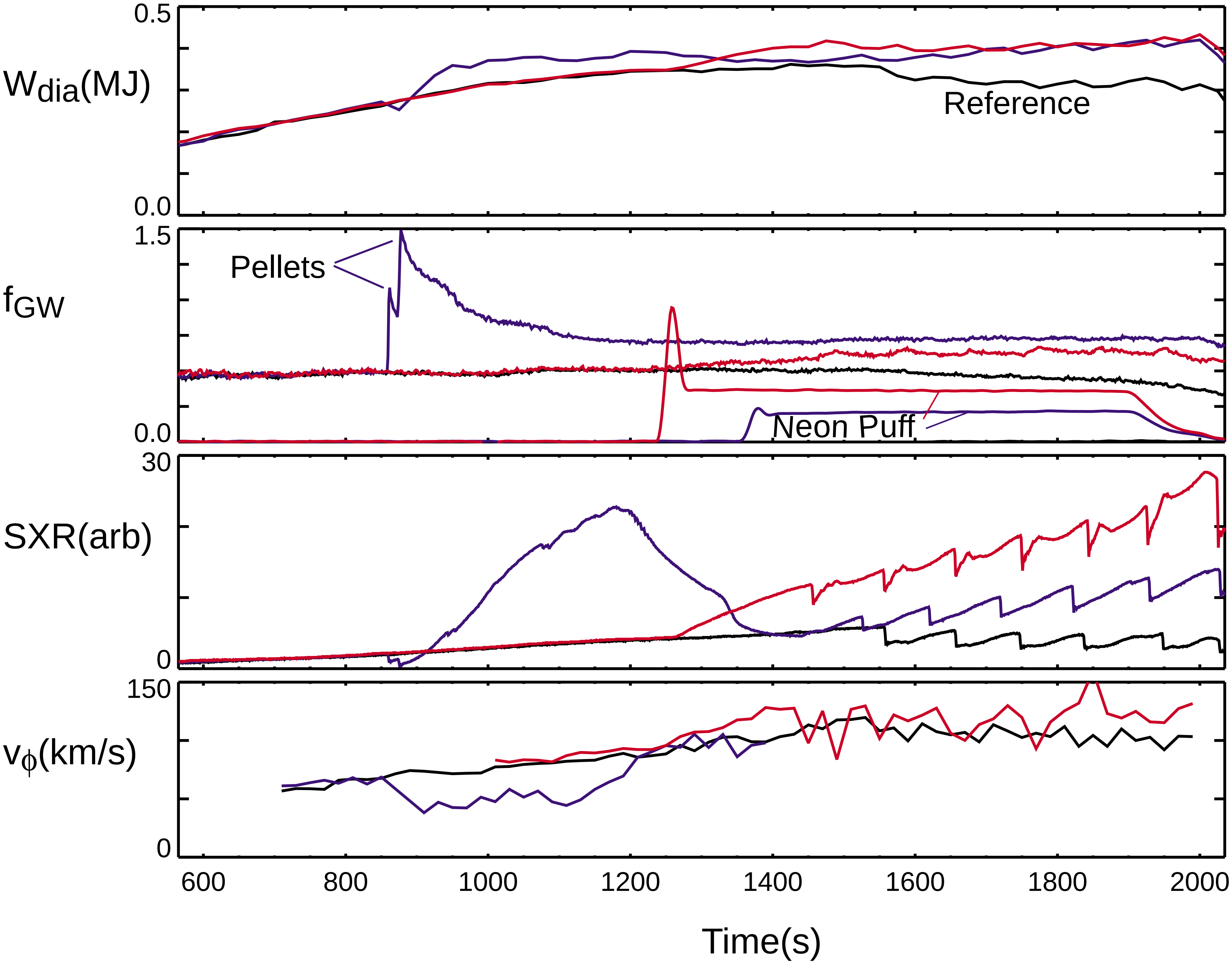
elong	1.155
Li	1.058
q95	3.085
BT(0)(T)	-1.599
Ipfit(MA)	0.904
gapout(m)	0.025



102115.01600

GLJackson aps00 f16

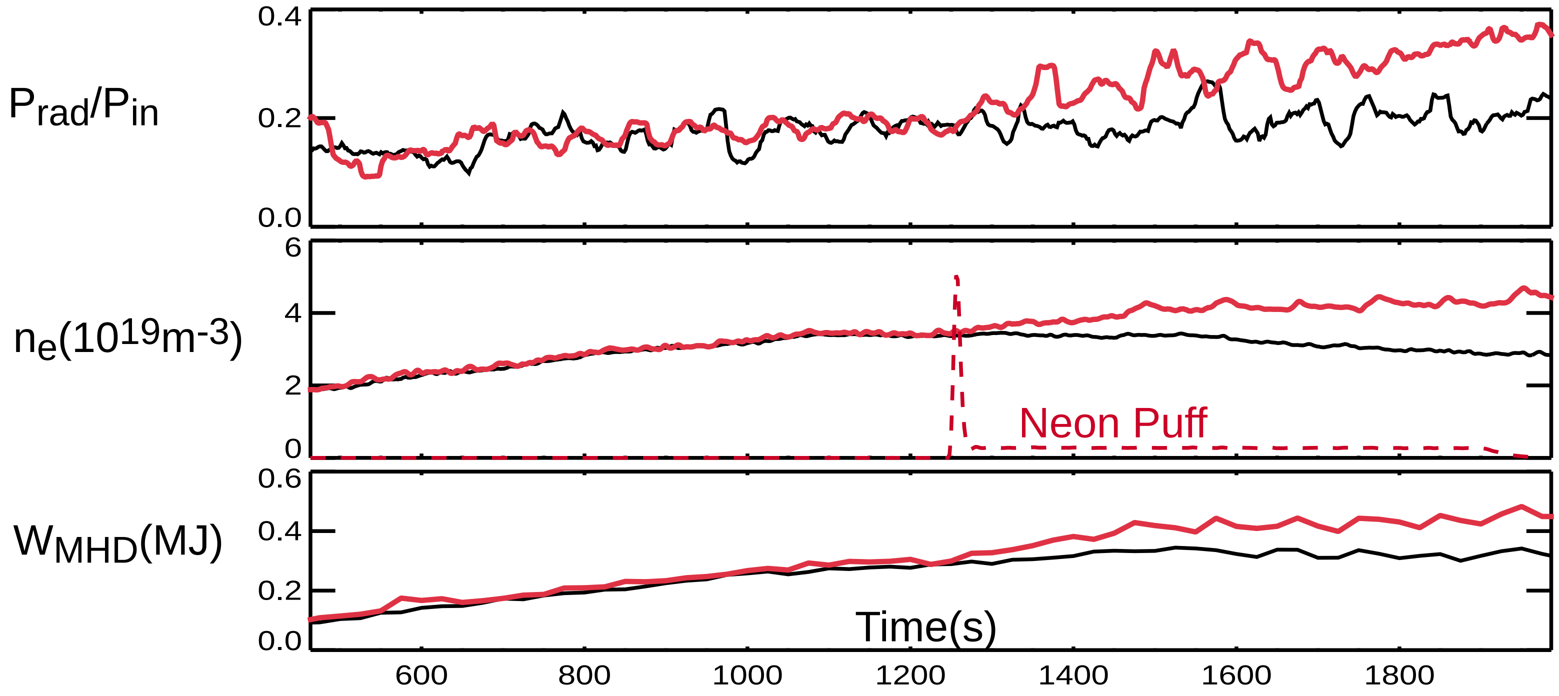
DIII-D NEON SEEDED LIMITED DISCHARGES EXHIBIT ENHANCED CONFINEMENT AND HIGHER DENSITY THAN A REFERENCE DISCHARGE (BLACK), EVEN AFTER THE ONSET OF SAWTEETH.

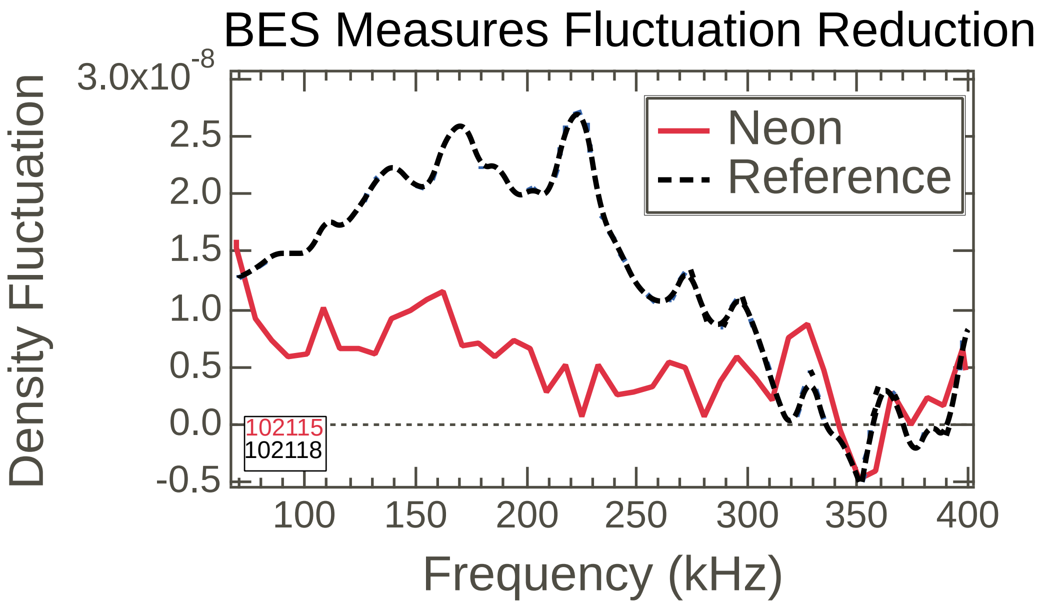


GLJackson aps00 f17

DIII-D INNER-WALL LIMITED (TEXTOR-LIKE) RI-MODE REPRODUCED

(Reductions in density fluctuations (DIII-D IWL) are similar to DIII-D diverted discharges)





- Similar turbulence suppression mechanism appears to be at work

- Improvement persists during sawtoothing phase

- Density peaking is not a necessary condition for improved confinement

CONCLUSIONS

O APPLICATION OF IMPURITY SEEDING HAS LED TO L-MODE ENHANCED CONFINEMENT,H_{89P} UP TO ~ 2, IN BOTH THE DIII-D AND JET TOKAMAKS

O IN DIII-D, IMPURITY DISCHARGES, FLUCTUATION MEASUREMENTS AND DETAILED MODELING INDICATE THAT ITG TURBULENCE IS SUPPRESSED, RESULTING IN REDUCED THERMAL DIFFUSIVITIES

O IN JET IMPURITY DISCHARGES (L-MODE), H_{89P} INCREASES WITH INPUT POWER. BEST PERFORMANCE IS LIMITED BY EARLY ELMS AND/OR SAWTEETH. GKS MODELING SHOWS THAT GROWTH RATES OF LOW k MODES ARE REDUCED

O INNER WALL LIMITED DIII-D DISCHARGES EXHIBIT SIMILAR BEHAVIOR TO DIVERTED DISCHARGES AND TO THE TEXTOR RI-MODE

O THESE OBSERVATIONS SUGGEST A COMMON PHYSICAL MECHANISM FOR THE EFFECT OF IMPURITIES IN JET, DIII-D, AND TEXTOR, NAMELY A REDUCTION ITG TURBULENCE ALLOWING LOWER THERMAL DIFFUSIVITIES, LEADING TO ENHANCED CONFINEMENT