The Effects of Extrinsic Low-Z Impurity Seeding in ICRF-heated Alcator C-Mod Plasmas

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JET - E1/E2 Task Force Meeting
September 20th, 2012

**OAK RIDGE INSTITUTE FOR
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Alcator
C-Mod

Is Low-Z Seeding Research Sufficient?

- cross-machine scaling [Eich – PSI 2012] predict the power exhaust channel will be narrow, ~1 mm, even in ITER
  - requires a partial-detached, impurity seeded divertor solution
  - ITER may operate initially with full tungsten divertor
- AUG, JET and C-Mod experiments show high-Z divertor tokamaks respond well to low-Z seeding, maintaining H_{98} ~ 1 w/ low $P_{O,DIV}$
- *these devices also show significant high-Z contamination in plasmas with substantial ICRF heating*

Do current NBI+ECRH scenarios provide sufficient confidence that low-Z seeding will work in ITER/DEMO which expect to rely on the use of ICRH?

Alcator C-Mod features all metal (Mo) PFCs and investigates high-confinement regimes with ICRF-heating

High-Z Contamination Has a Variety of Causes

Intrinsic impurities result from one of the following interactions

SPUTTERING & TURBLENT TRANSPORT

"The cost of doing business"

- Ohmic plasmas
- standard sheath-induced sputtering
- turblent/blobby edge plasma to transport impurities past LCFS

RF-ENHANCED SOURCES AND TRANSPORT

"The cost of making it work"

- ICRF, ECH, LHRF heated plasmas
- rf-rectified sheaths,
- ExB convective cells
- fast-ion & electron losses

MELTING/INJECTIONS DUE TO PFC DAMAGE

"The cost of doing it poorly"

- injections from dust/PFC flaking
- injections from melted leading edges
- evaporation from hot/melting surfaces

Which of these can low-Z seeding mitigate?

Do we win replacing a high-Z impurity with low-Z?

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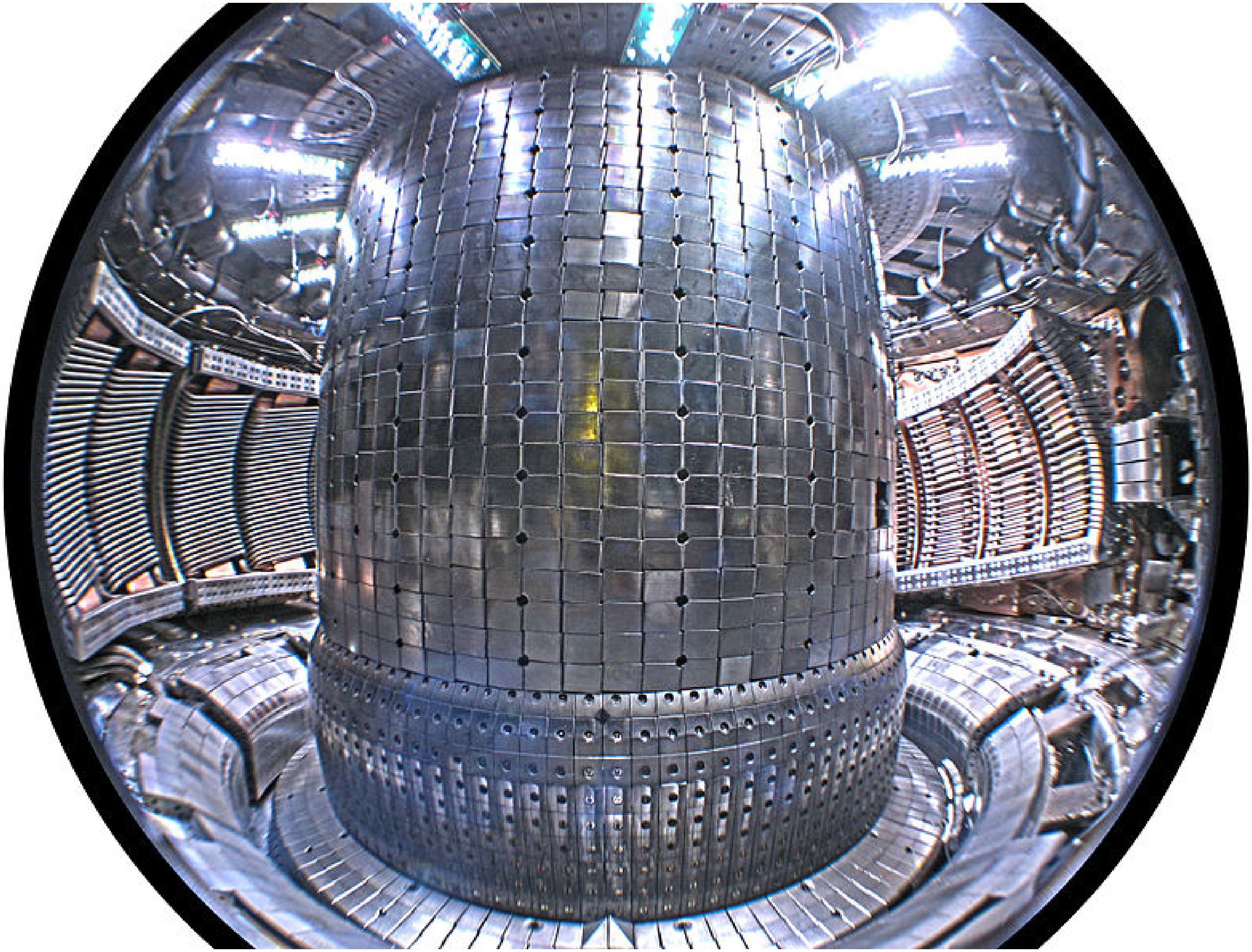
Are JET, AUG and C-Mod seeing the same phenomenology?
Is there one explanation or multiple PFC/impurity problems?

Outline

- overview of Alcator C-Mod tokamak and tools for seeding
  - intrinsic/extrinsic impurities and seeding techniques
  - diagnostics used to monitor core impurities and PFC sources
- low-Z seeding is not a panacea for all impurity problems
  - cannot replace the positive effects of boronization
  - cannot impact impurity sources driven by fast-e^- & fast-ion loss
- low-Z seeding is compatible with high confinement regimes
  - increase the reliability of the ICRF heating
  - lead to a decrease in $P_{RAD,CORE}$ by reducing molybdenum
  - drop $P_{O,DIV}/P_{IN}$ to < 10% while maintaining H_{98} ~ 1 in EDA H-mode
  - impact of neutral and low-Z seeding on pedestal physics

The Alcator C-Mod Tokamak

A high field, $B_t < 8$ T, compact, R_o=0.68 [m] a=0.205 [m] tokamak with all solid metal (Mo) plasma facing components



http://en.wikipedia.org/wiki/File:Alcator_C-Mod_Tokamak_Interior.jpg

$n_{e,0} < 1.0\times10^{21}$ m^{-3}
$T_{e,0} < 9$ keV

Primary Auxiliary Heating is ICRF < 6 MW (8 MW source)

single chord (radial) VUV/SXR spectroscopy for B→Ne and Ti → Cu

spatially-resolved SXR spectroscopy for Ar, Mo

multiple vis. periscopes to view of PFC sources

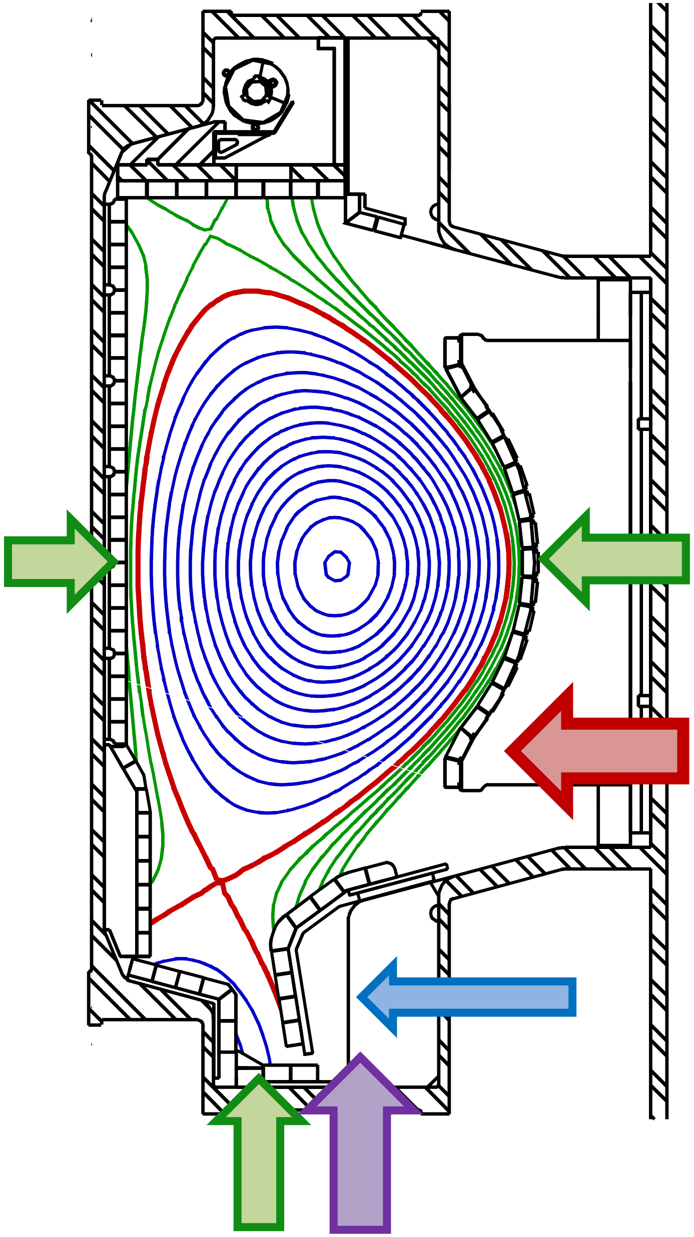
A Wide Range of Impurities Seen in C-Mod

KEY: steady-state *injections* **primary** **extrinsic**

Helium	gas puff imaging of edge turbulence, D(^{3}He) heating
Boron	boron-coated tiles, periodic boronization
Carbon	seen after vessel entry, prior to first boronization
Oxygen	unknown but seems to tied to limiter
Nitrogen	seeding for heat flux mitigation and ICRF performance
Fluorine	assumed to come from teflon coated/jacketed cables
Neon	seeding for heat flux mitigation and ICRF performance
Argon	for use with X-ray imaging crystal spectroscopy (T_i, rotation)
Calcium	injected using laser blow-off for impurity transport studies
Titanium	TiC-coated rods in Faraday screen
Iron	stainless-steel* in-vessel structures
Nickel	Inconel antenna structures
Copper	copper-coated ICRF antenna straps
Molybdenum	limiters and divertors
Tungsten	Langmuir probes and remnants from melted outer divertor

(*occasionally see other traces from metal processing like S, Cl, Mn, Cr)

Extrinsic Seeding From Multiple Locations



Neutral INJection Apparatus

Many toroidal/poloidal locations, but slow response

Main Chamber

Puffed into horizontal port, wide “footprint” at plasma

Divertor Chamber

Puffed into vertical port, slow response to divertor

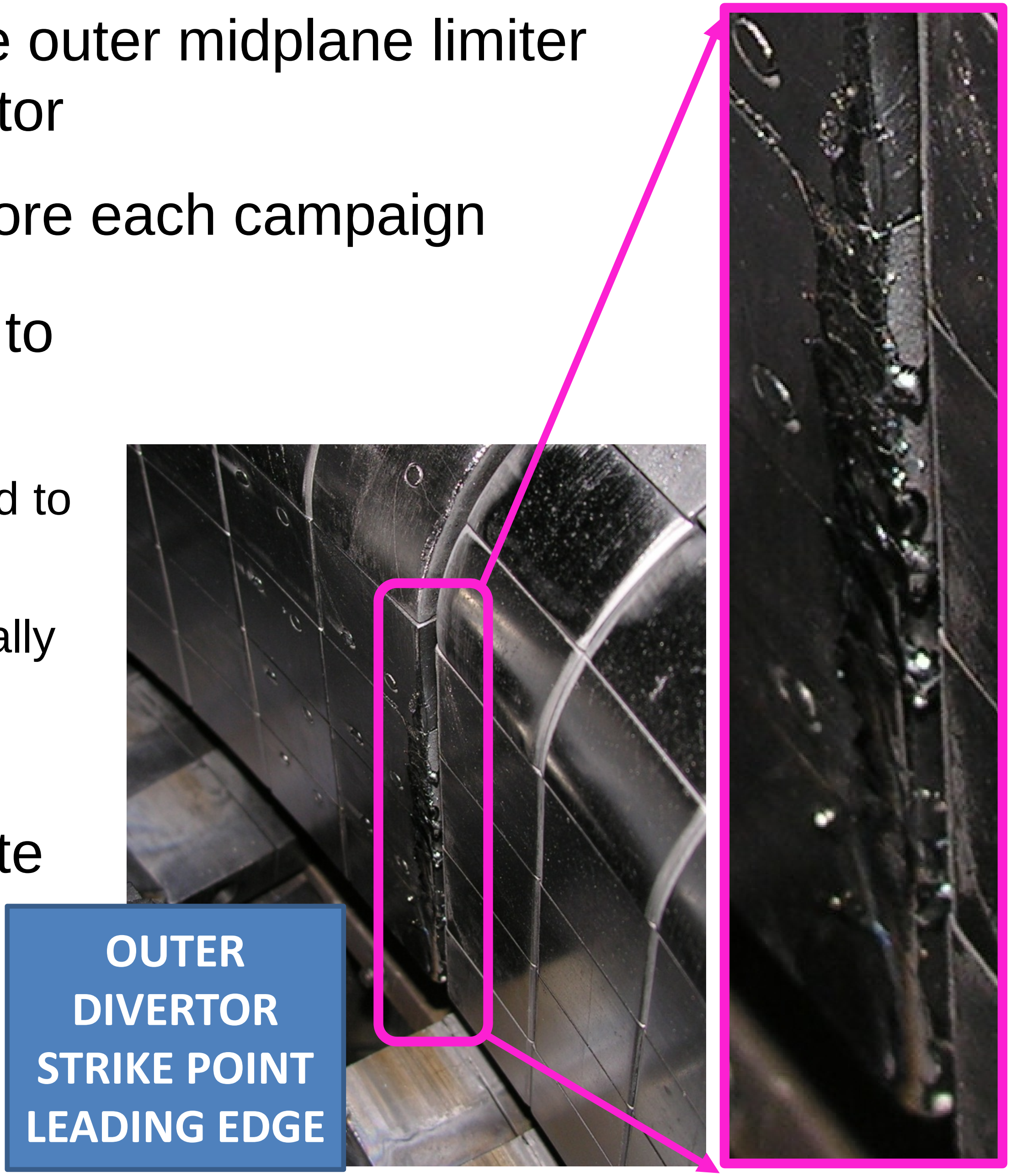
Localized Divertor

High throughput, direct injection into the divertor

- used for many experiments featuring high power ICRF (H-mode & I-mode)
- neon seeding is preferred over nitrogen
  - N V emission with B V line used for CXRS
  - shot-to-shot build-up of nitrogen contaminates subsequent experiments

C-Mod Regularly Operates With Melted PFCs

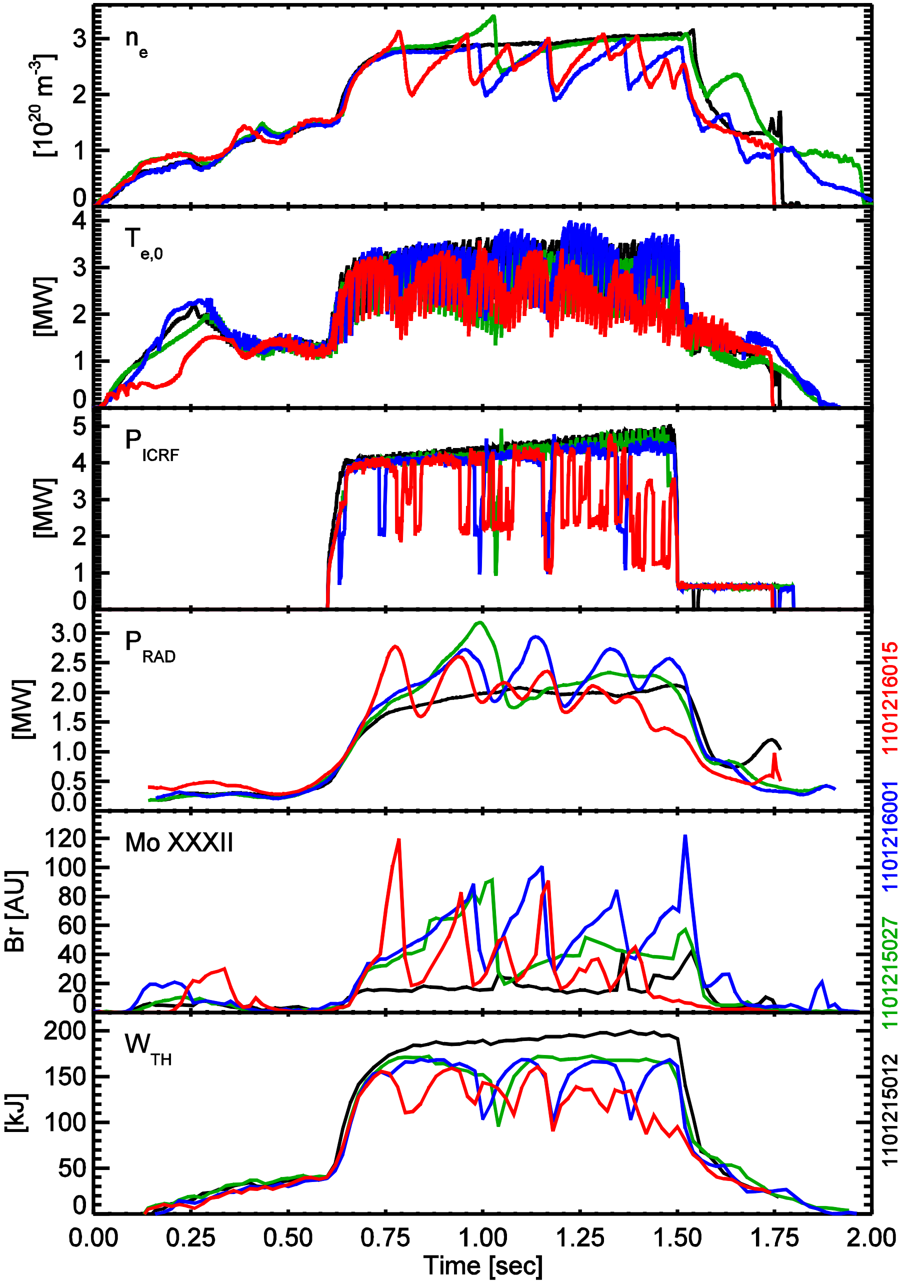
- over the campaign we melt the outer midplane limiter and leading edges in the divertor
- tiles are repaired/replaced before each campaign
- divertor melting demonstrated to impact core via injections
  - FY09/10 tungsten melting localized to divertor still impacted core
  - C-Mod is working on a new toroidally continuous divertor
- toroidally/polodially localized source hard to monitor/correlate



What fraction of core molybdenum originates from these melted PFCs?

Problems Even Low-Z Seeding Can’t Solve

Seeding Cannot Replace Boronization



- historically degradation of the BZN is correlated with the integrated ICRF input energy
  [S. Wukitch APS/IAEA 2010]

- indications that low-Z seeding could extend/avoid BZNs
  - seeded: sustained H_{98} = 1.0 @ 75 MJ
  - unseeded: isolated $0.8 < H_{98} < 0.9$

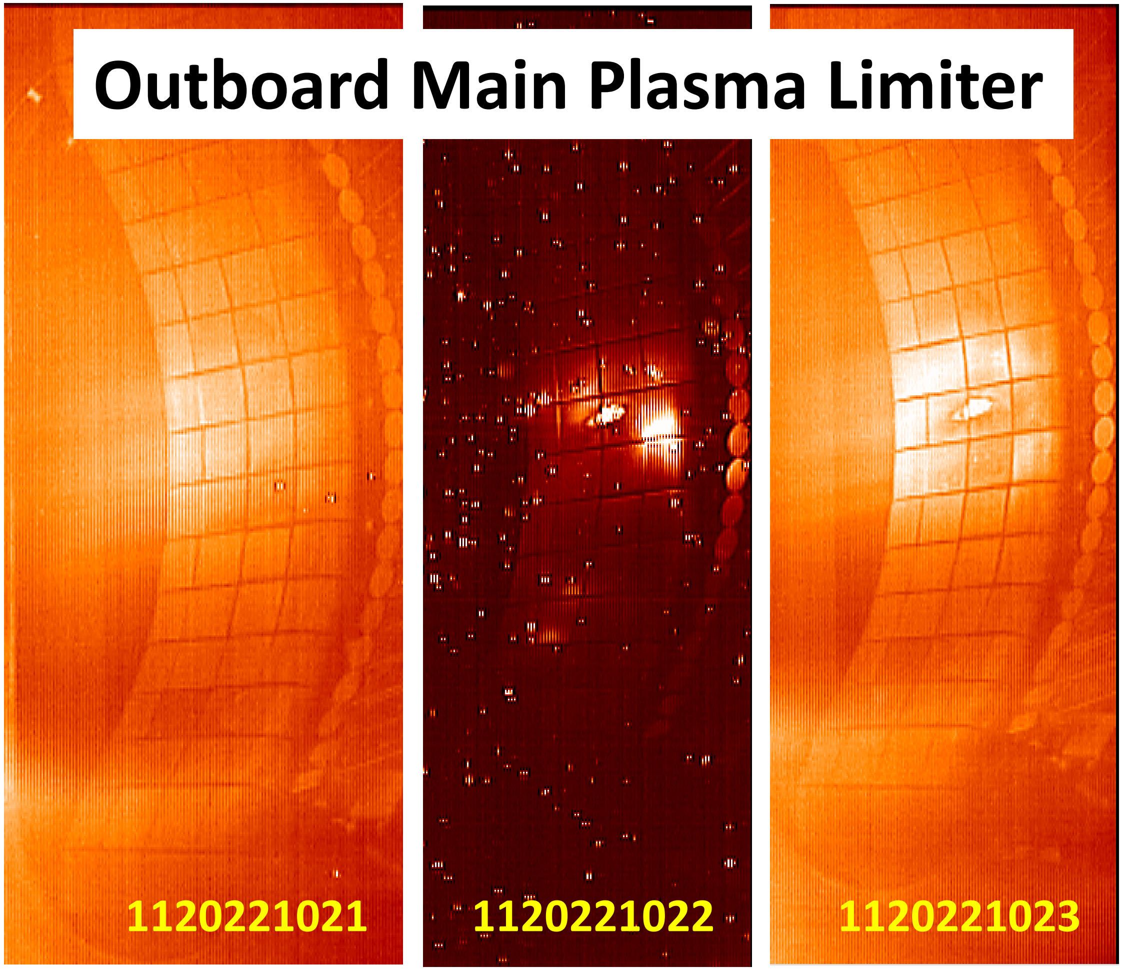
- over a two-day experiment using Ne and N_2 seeding a fiducial shot was repeated (5.4 T, 0.9 MA)

ICRF INPUT [MJ]: **26** **68** **71** **112**

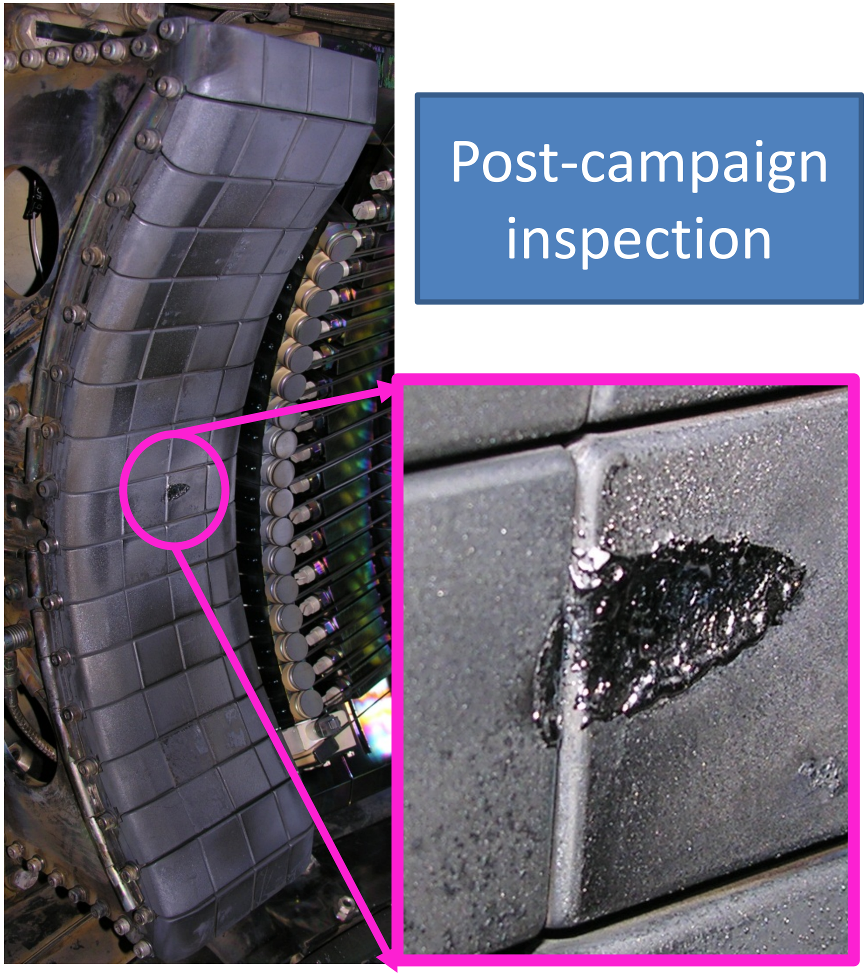
- could recover H_{98} ~ 1 by lowering the I_p to 0.7 MA

Limiter Melting Due Runaway e^- at Startup

- in FY09, instituted a runaway shutdown in plasma control system based on hard X-ray signal
- not 100% effective and recently have direct obs. of melt event

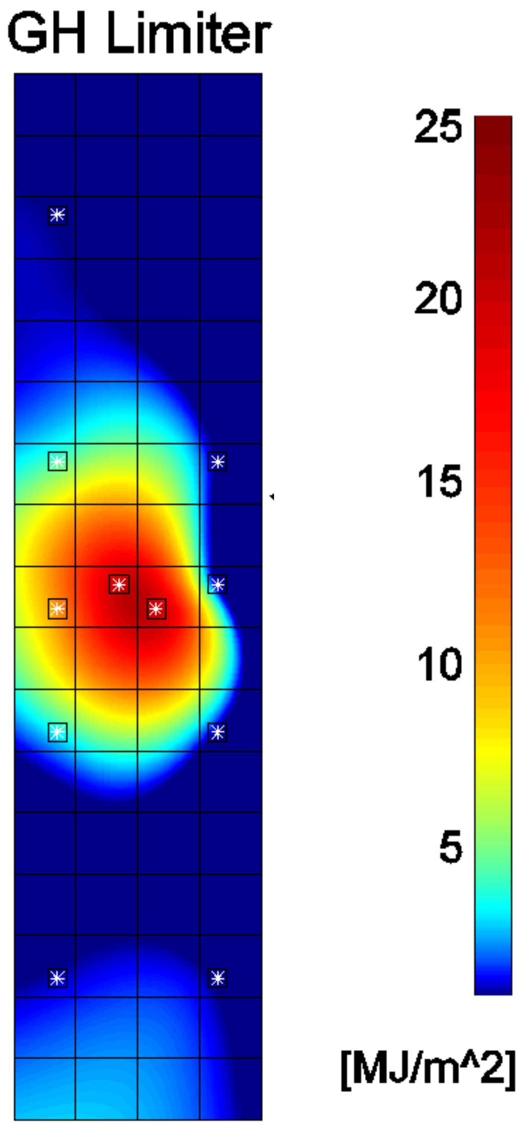


Outboard Main Plasma Limiter



Post-campaign inspection

Possible Limiter Melting Due to Fast-Ion Losses

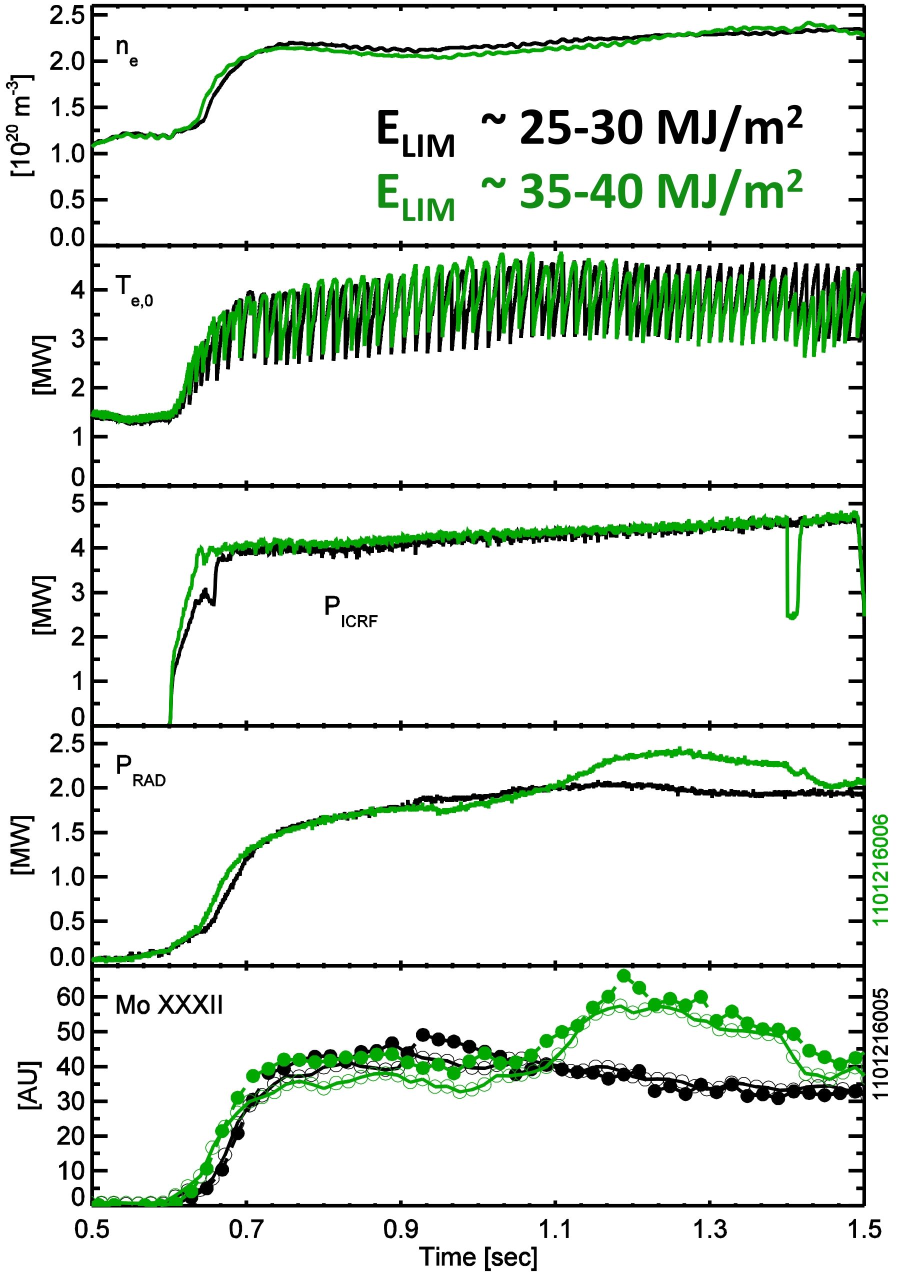


- observe large energy flux to the midplane of the outboard limiter during some ICRF-heated plasmas
- correlated with drives for fast-ion loss
  - increases with P_{RF}/n_e, exhibits a threshold
  - increases as plasma current is lowered
  - increases as D(H) resonance layer moves to LFS but not when moved to HFS
- energy flux near level of melting of flat surface (40-50 MJ/m^2 over 1 second)

Possible Two-Step Process Leading to Damage

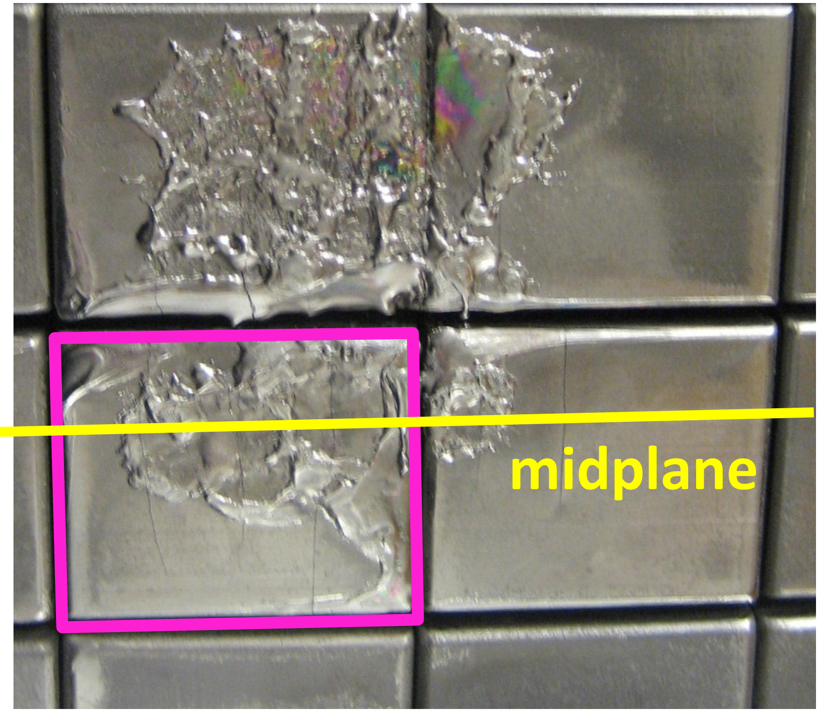
1) **initial surface deformation due to fast e^-**
2) **fast ion energy flux grows the melt layer**

Low-Z Seeding Cannot Mitigate the Limiter Source



- for N_2 seeded, low current (700 kA), observe strong **limiter** energy flux
- in repeated plasmas, increase in P_{RAD} due to molybdenum as tile approaches melting limit

Outboard Main Plasma Limiter

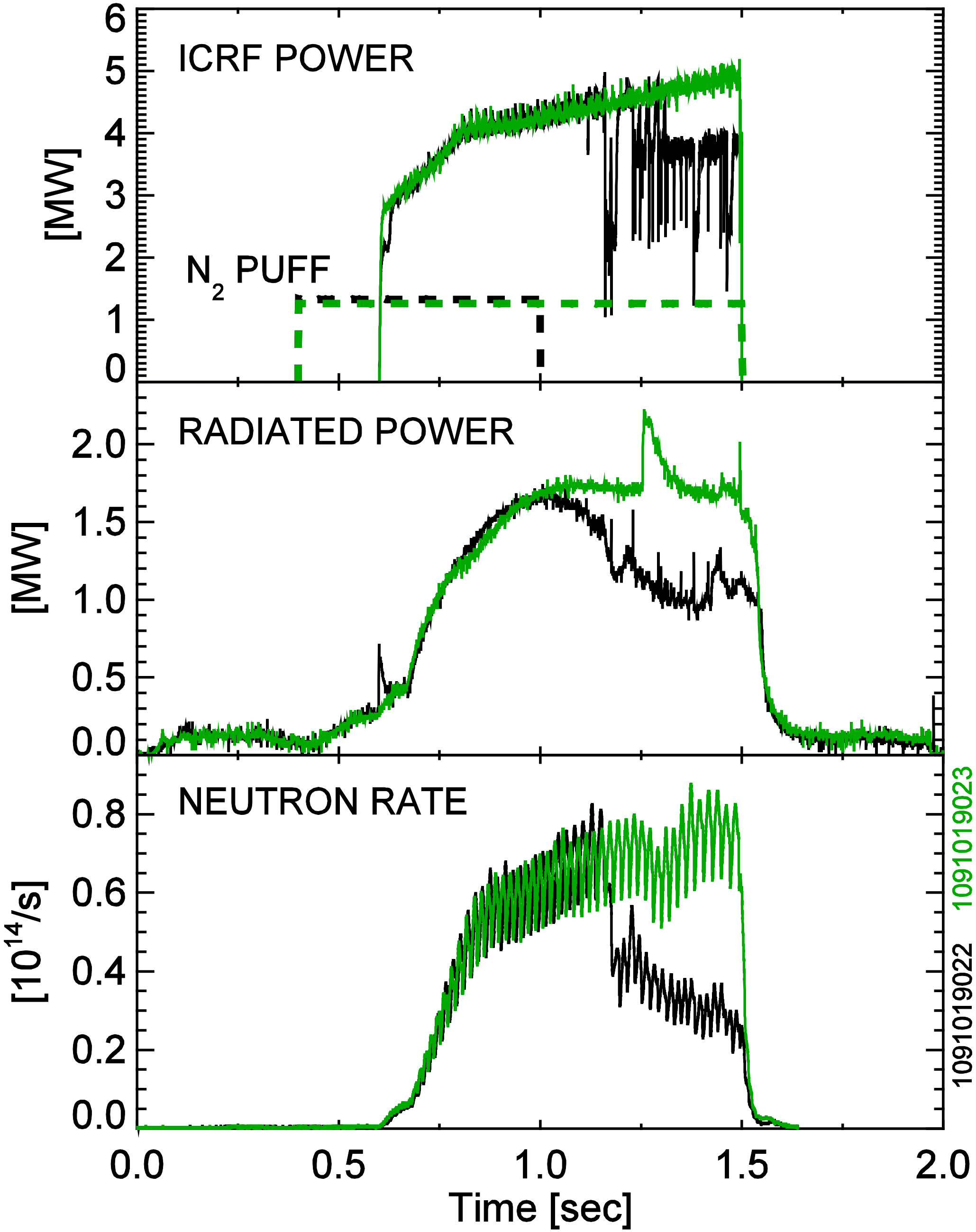


Operational Advantages to Low-Z Seeding

Low-Z Seeding Enhances ICRF Reliability

- initial 2009 impurity seeding experiments suggested favorable impact of low-Z seeding on ICRF performance

terminating N_2 seeding during the ICRF pulse leads to “trips” and reduced input power



Low-Z Seeding Enhances ICRF Reliability

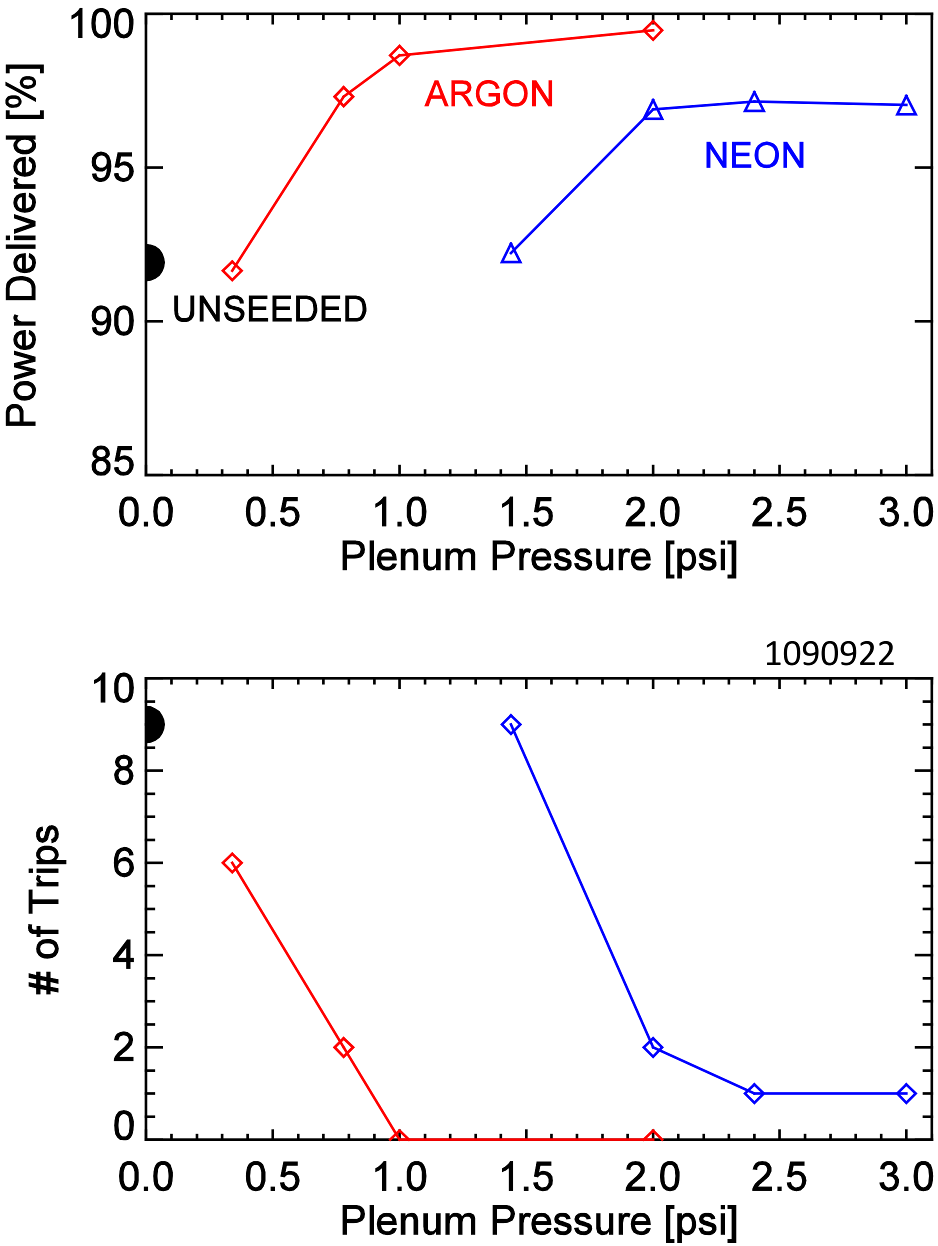
- initial 2009 impurity seeding experiments suggested favorable impact of low-Z seeding on ICRF performance

effects saturate after a small amount of low-Z impurities injected via main-chamber

- observe an increase of ~10% in the net energy delivered versus requested energy

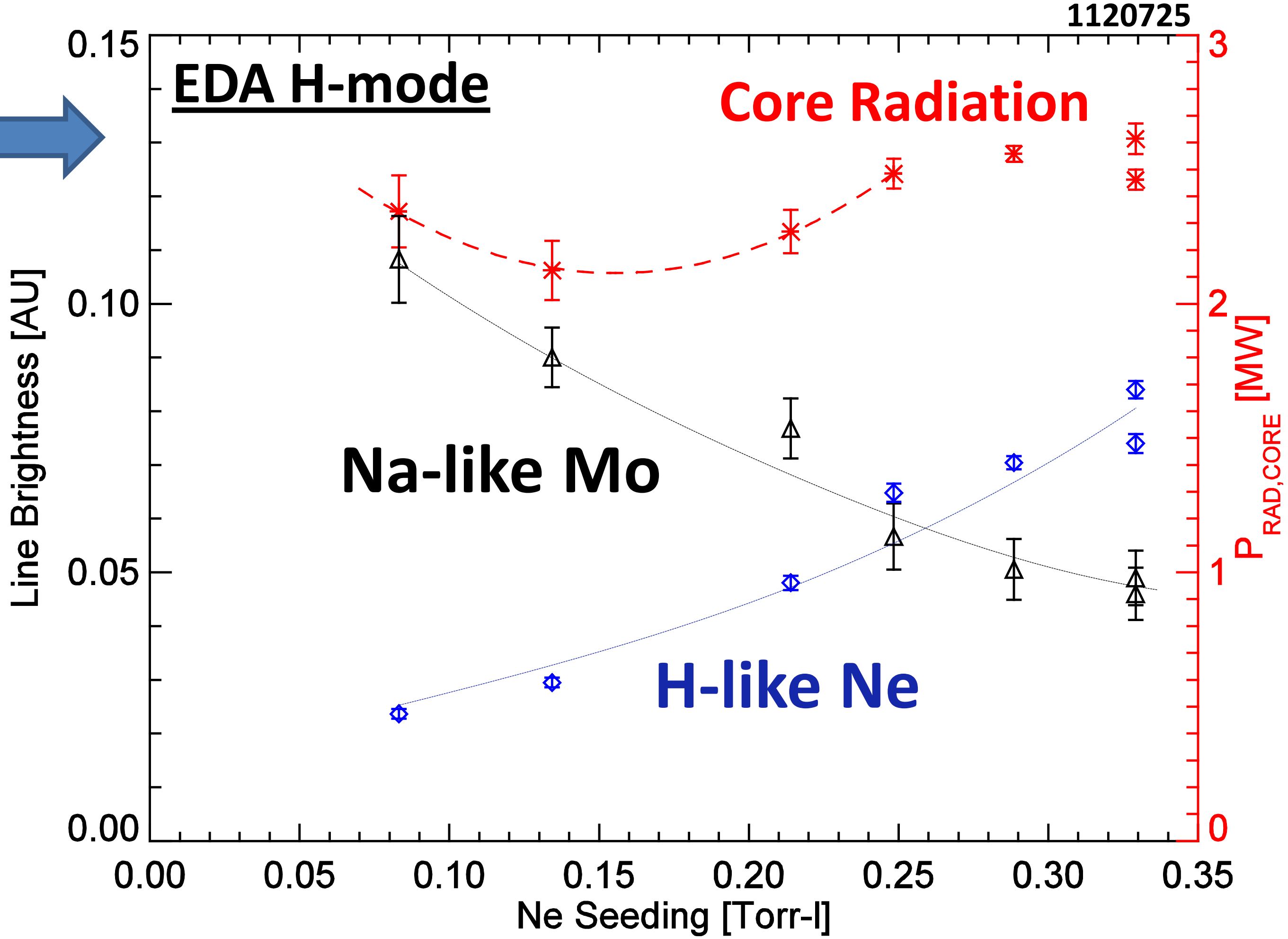
- reduce "trips" which can lead to confinement transitions

effects are easily reproducible and low-Z seeding now regularly used to aid ICRF performance



Low-Z Seeding Reduces Core Molybdenum

- **Mo** level drops steadily as **Ne** seeding is increased
- find a minimum in the **radiated power**
- observed in Ohmic plasmas and some I-mode plasmas
- demonstrated with both Ne and N_2



Seeding also reduces injections from divertor

- known/observed leading edges of molybdenum tiles
- tungsten Langmuir probes at attached inner strike point in rev.-field operation

Clues to a Major Source of Molybdenum?

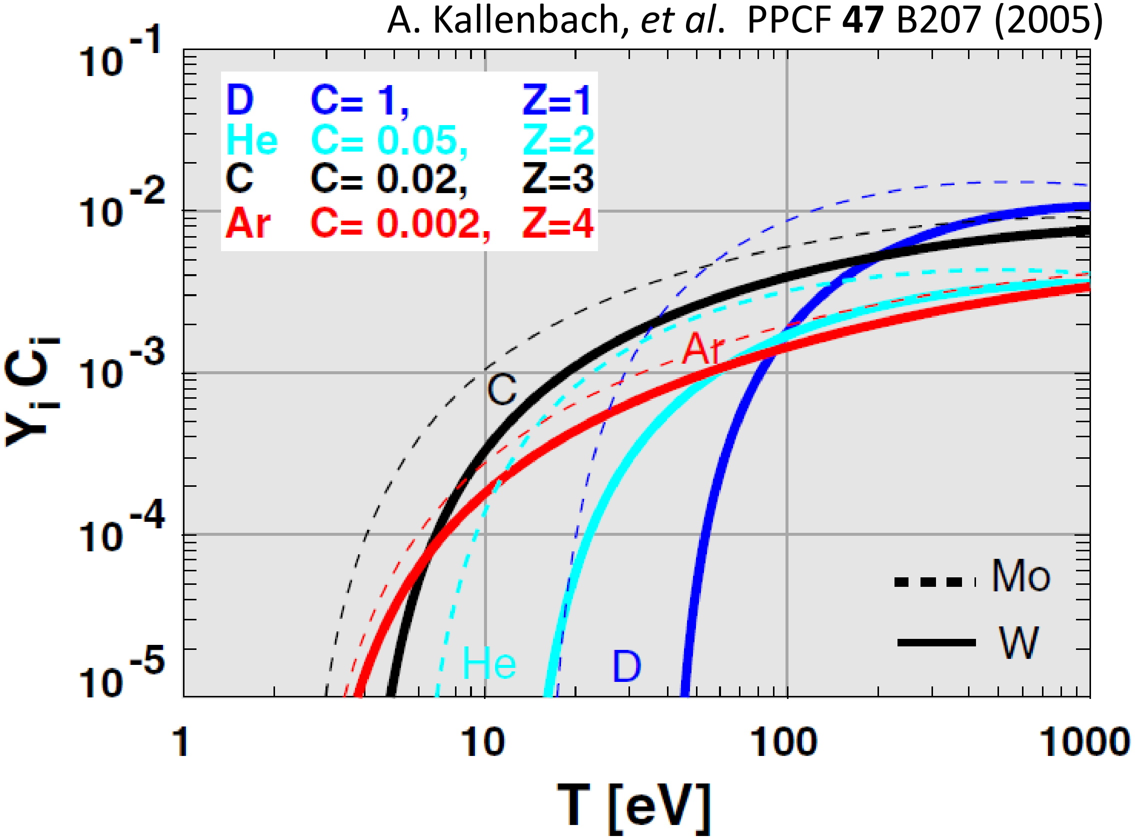
melting/evap. responds directly to P_{IN}-P_{RAD}

standard sheath-induced sputtering responds to seeding

- impurity radiation lowers T_e, but dilution increases ⟨Z⟩ of ions
- sputtering yield drops quickly with T_e, turn down/off sputtering

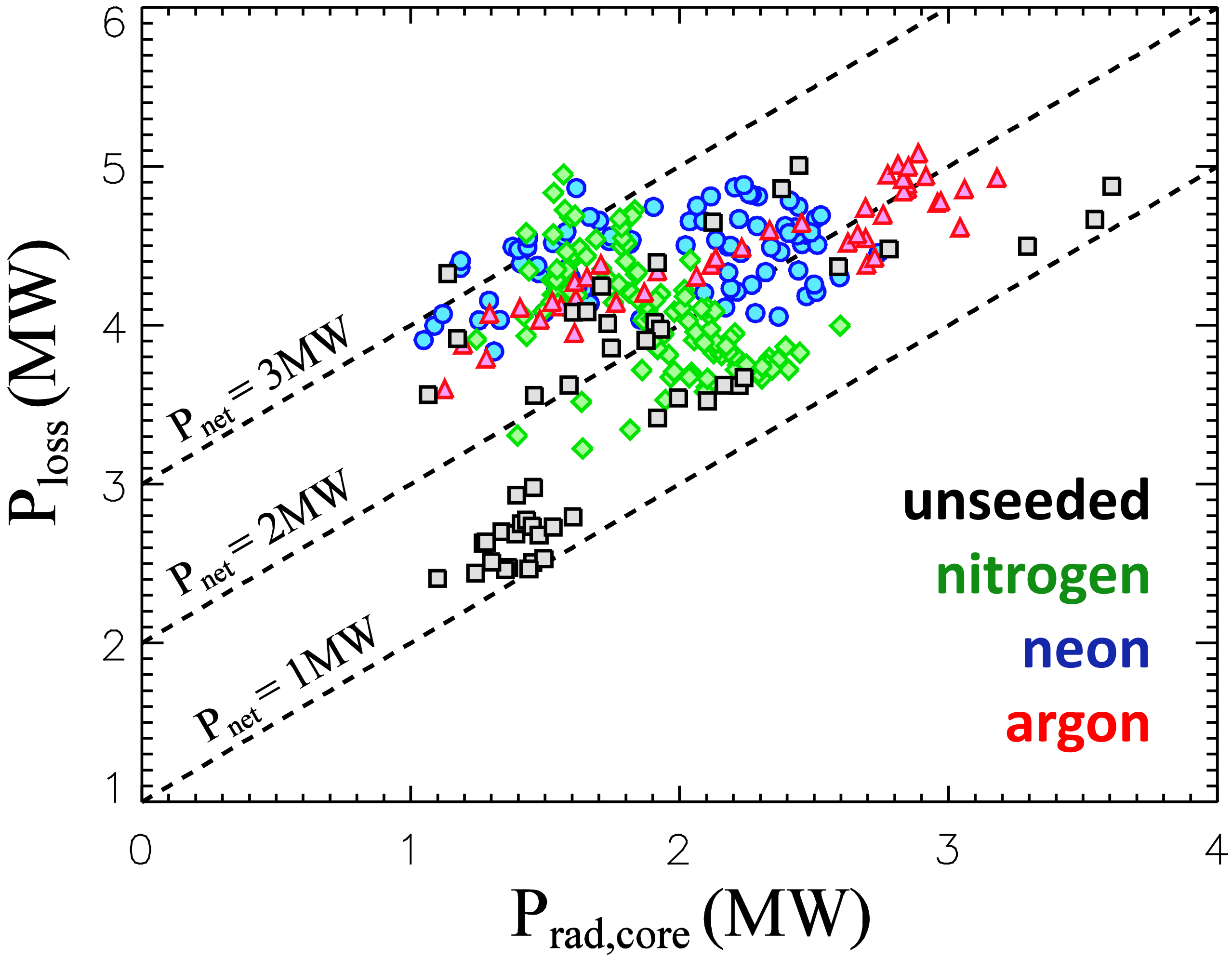
how do rf-induced sheaths & convective cells respond to low-Z impurities?

A. Kallenbach, *et al.* PPCF **47** B207 (2005)



Confinement Studies in Impurity Seeded EDA H-mode Plasmas

Wide Parameter Space Covered at Fixed I_p,B_t



Investigate confinement versus P_{LOSS} and $P_{NET}=P_{LOSS}-P_{RAD}$

Work described in more detail in:

Reinke – J. Nucl. Materials 2011

Hughes – Nucl. Fusion 2011

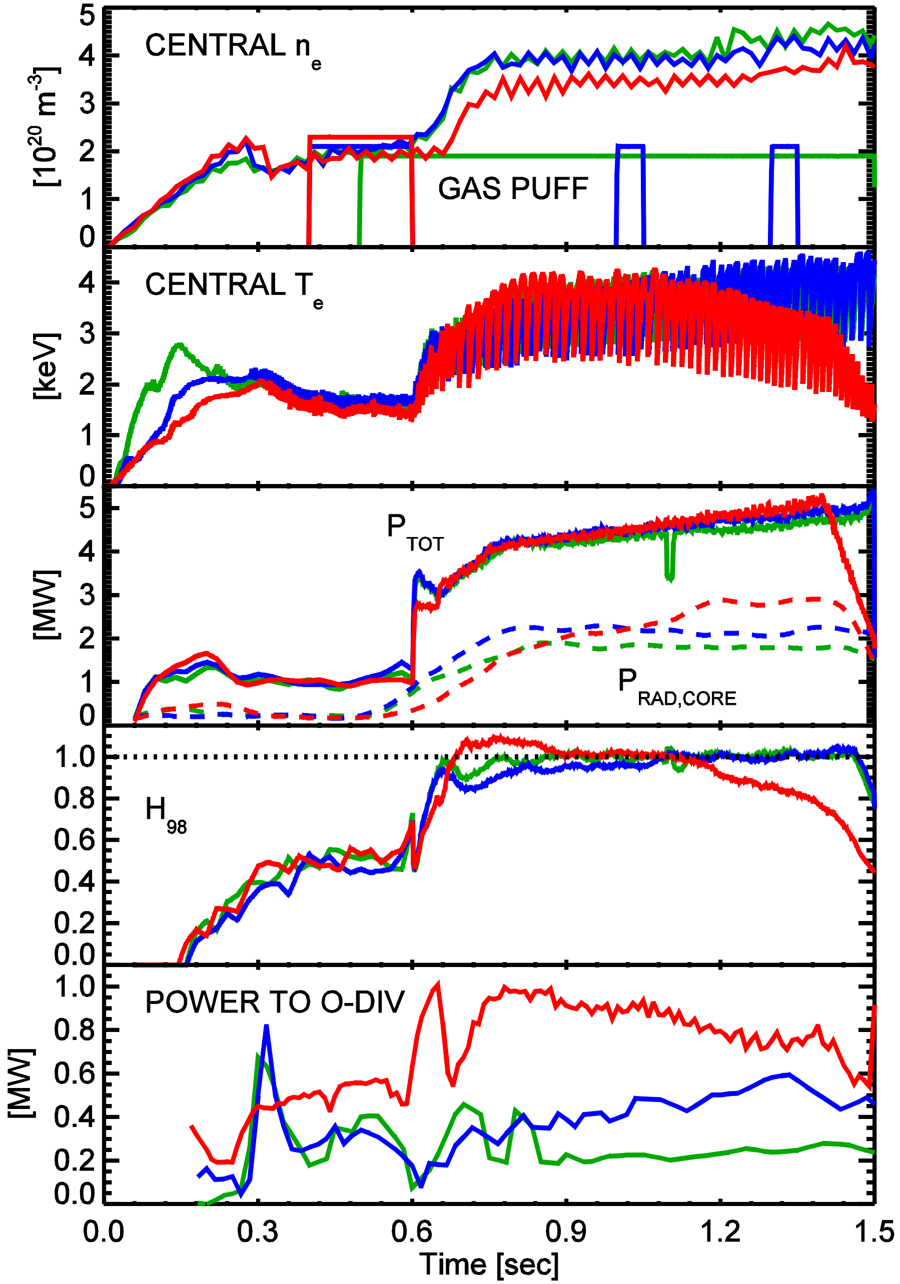
Loarte – Phys. Plasmas 2011

$$P_{LOSS} = P_{OHM} + f_{RF}P_{ICRF} - dW_{th}/dt$$

$$P_{NET} = P_{OHM} + f_{RF}P_{ICRF} - P_{RAD,CORE} - dW_{th}/dt$$

$P_{RAD,CORE}$ = the radiated power estimated to be inside the LCFS

Example Time Traces of Seeded Discharges



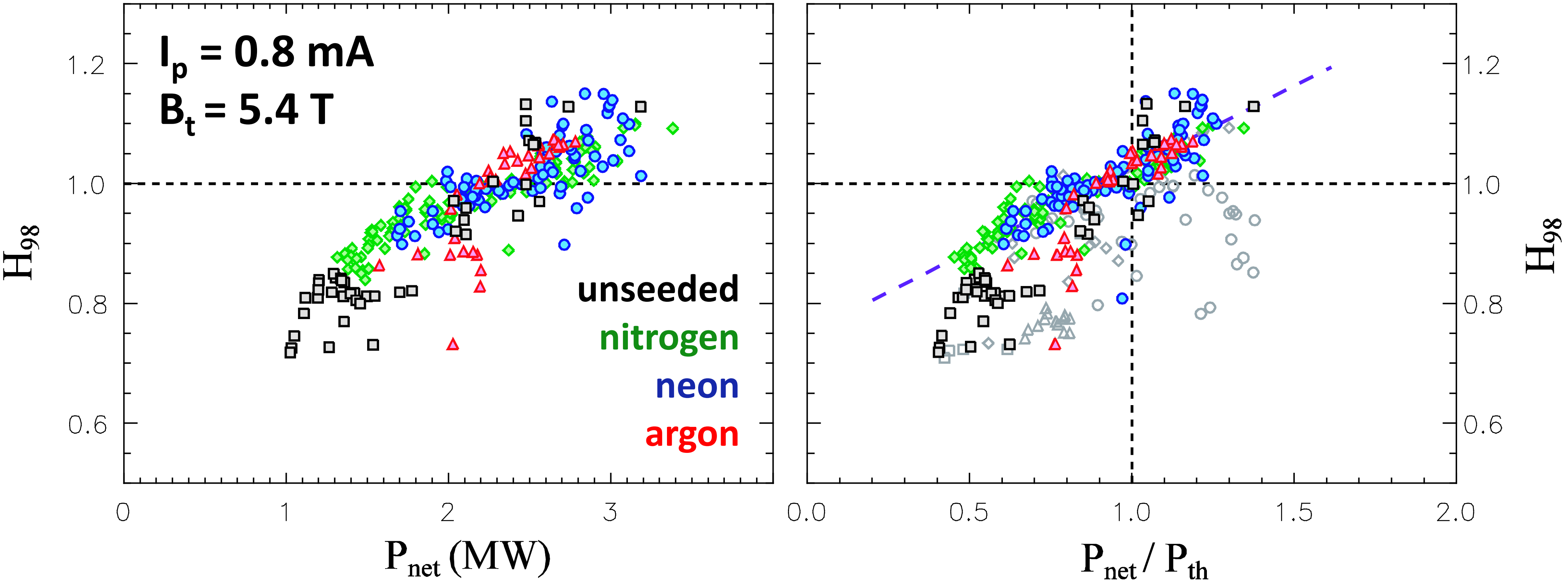
Scanned ICRF input power in EDA H-mode plasmas seeded with

ARGON NEON NITROGEN

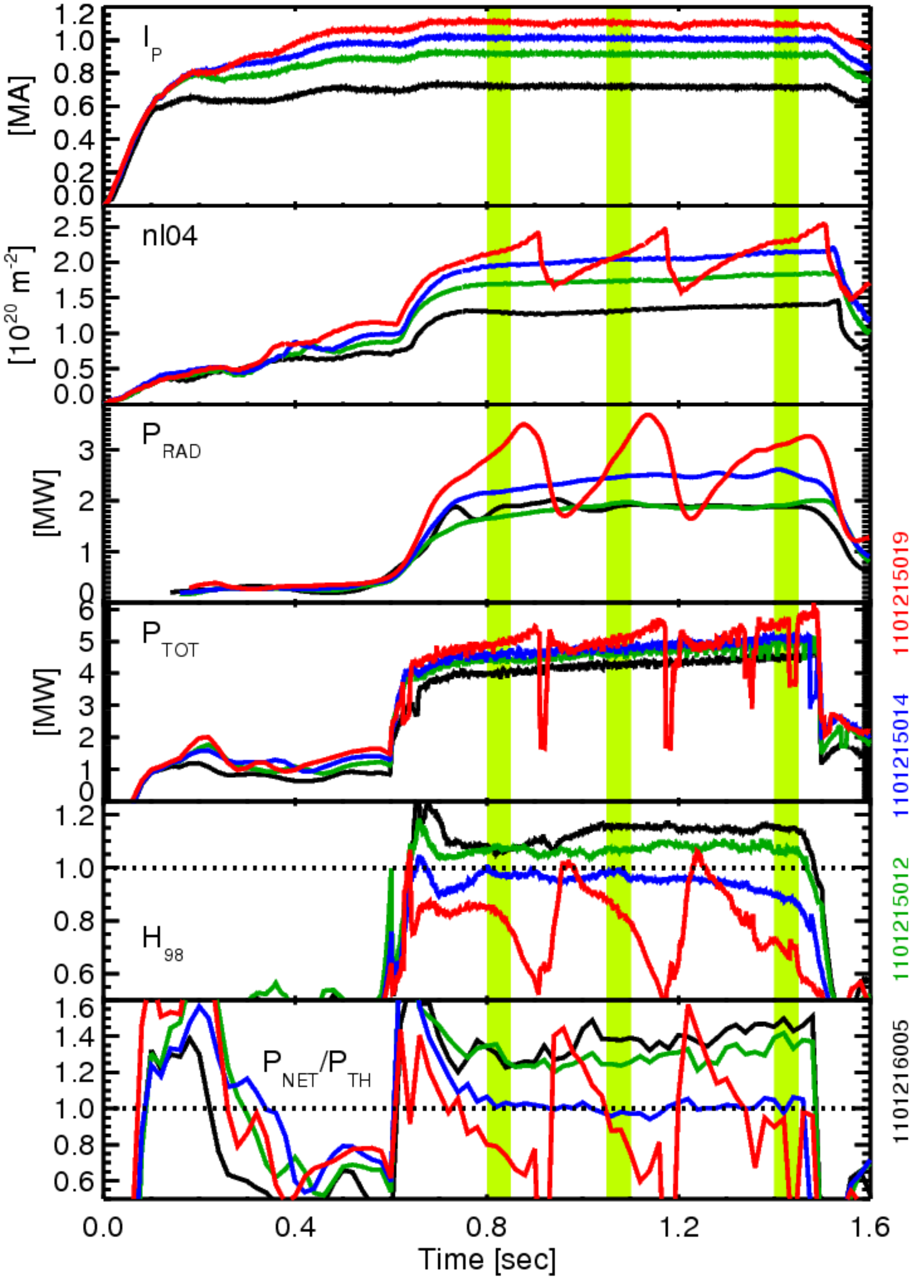
- impurity fueling initiated before the application of ICRF and the L/H transition
- using all three impurities, H_{98} ~ 1 plasmas were obtained
- lowest heat flux measured for nitrogen seeding
- H_{98} very sensitive to higer-Z (Ar) impurity levels, quickly leading to reduced confinement

Results Show H_{98} Correlated with P_{NET}

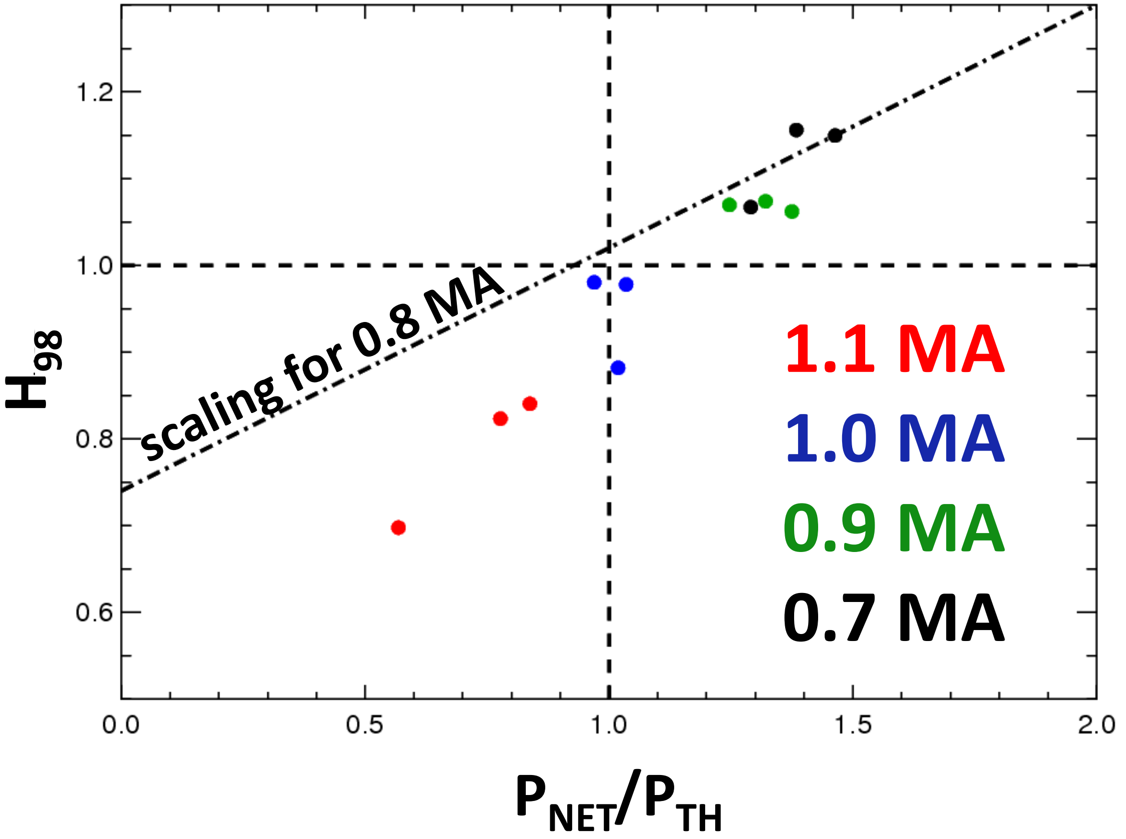
- Regardless of seeded impurity, confinement organized to **$P_{NET} = P_{IN} – P_{RAD,CORE} – dW/dt$**
- H_{98} ~ 1 occurs at P_{NET}/P_{TH} ~ 1 [P_{TH} – Y. Martin scaling]
- This differs with JET results [Giroud – 2012] in ELMy H-mode showing H_{98} correlated with ELM regime (Type I > Type III)



Higher I_p Requires Inc. P_{NET}/P_{TH} to get H_{98} ~ 1

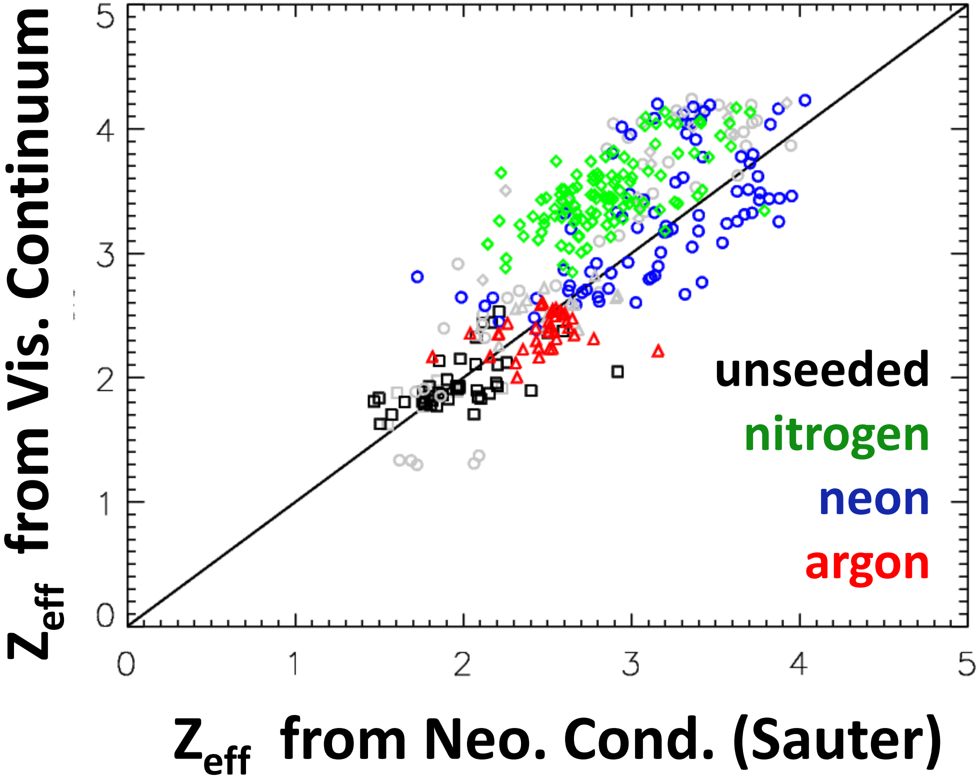


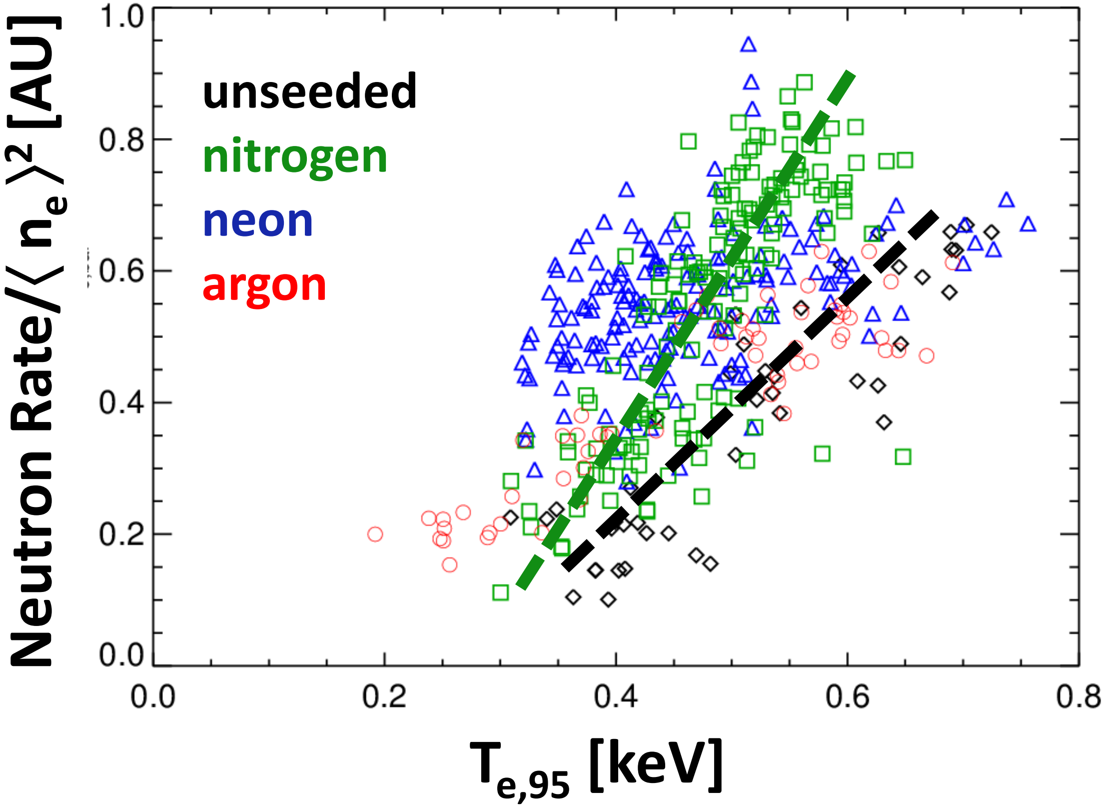
- confinement below 0.8 MA scaling as current is increased
- work under IOS 1.2 obtained EDA H-modes at 1.3 MA (q95 ~ 3.3) but are underpowered



Z_{eff} is High, but so is Fusion Reactivity?

- two estimates of Z_{eff} averaged over the plasma agree
- Ne and N_2 seeded plasmas with low $P_{O,DIV}$ have $Z_{eff} > 3$





At same $T_{e,95}$, low-Z seeded plasmas have higher neutron rate

Effect could be the result of

1) **change in T_i vs. T_e profile**
2) **hollow imp. density profiles**

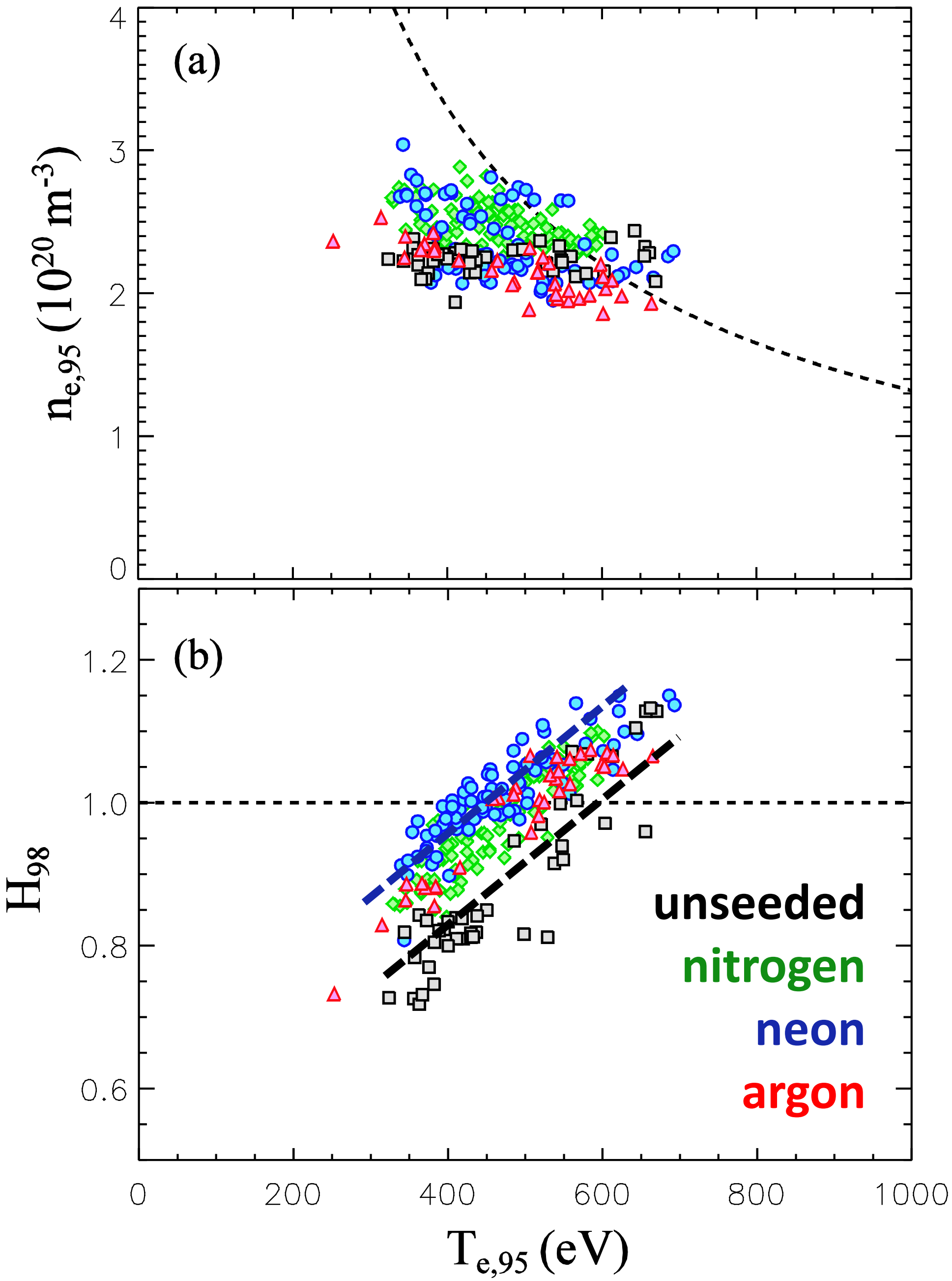
Enhanced Confinement Due to Pedestal Changes

H_{98} scales with pedestal temperature, $T_{e,95}$

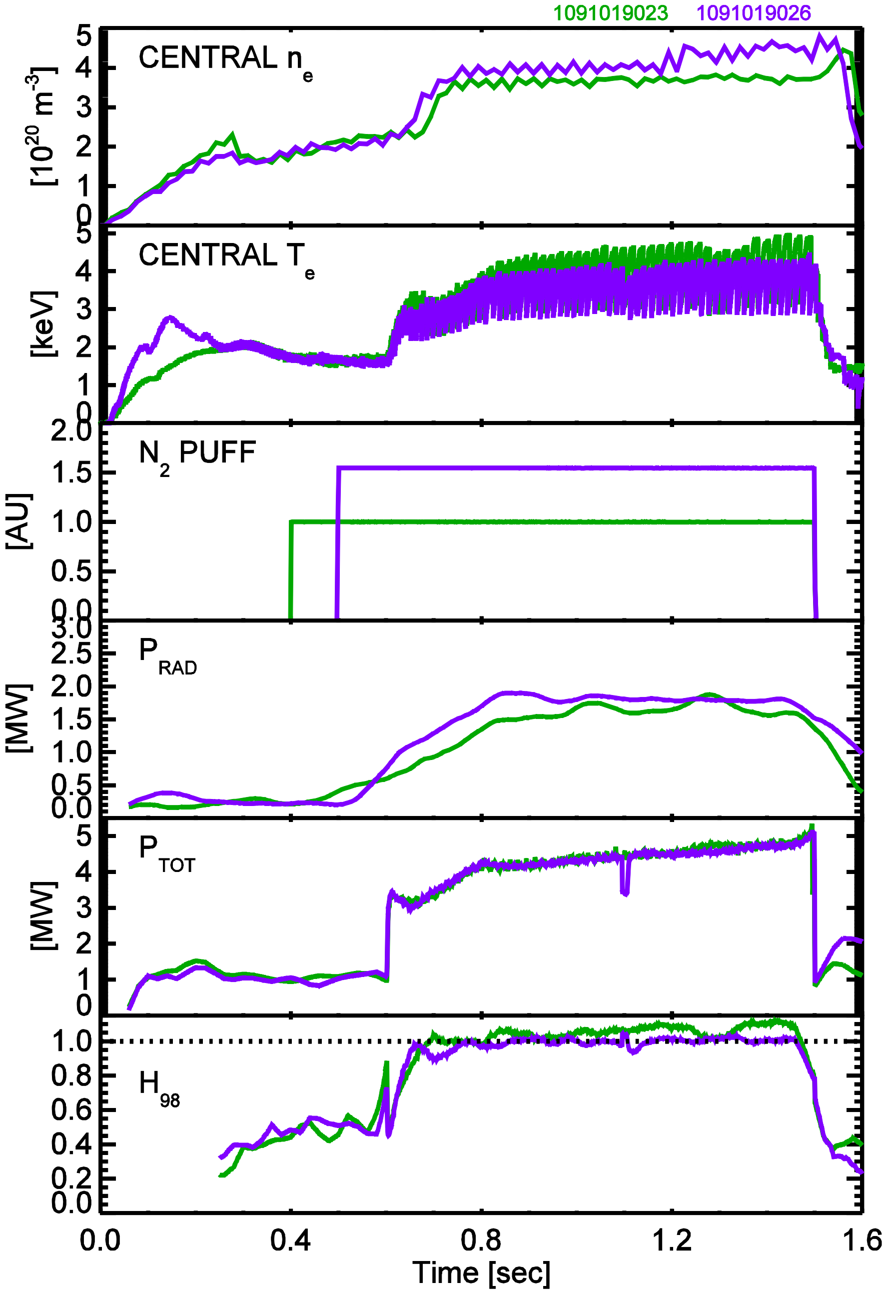
- no significant change in L_{ne}, Lte observed in seeded plasmas
- consistent with profiles stiffness

Small difference in H_{98} at fixed $T_{e,95}$ for different impurities

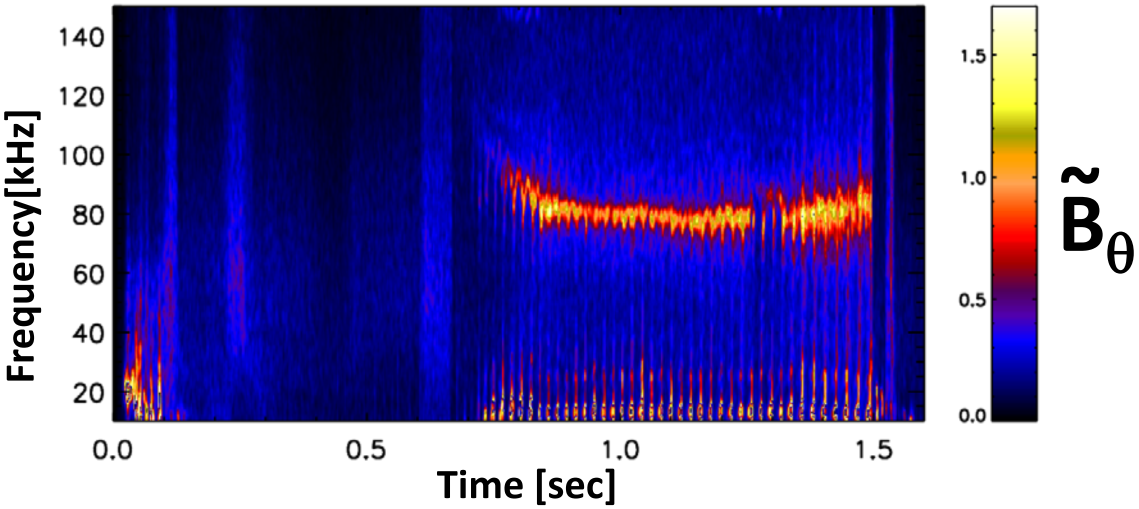
- low-Z seeded shots higher H_{98} compared to unseeded plasmas
- low-Z shots have slightly higher pedestal density



Nitrogen Seeding Effects Quasi-Coherent Mode



- in the EDA H-mode, the pedestal is relaxed continuously via the Quasi-Coherent Mode (QCM)
- in similar, repeated plasmas see large qualitative change in QCM
- for H_{98} ~ 1 and **moderate seeding**, the QCM is strong and located frequencies < 100 kHz



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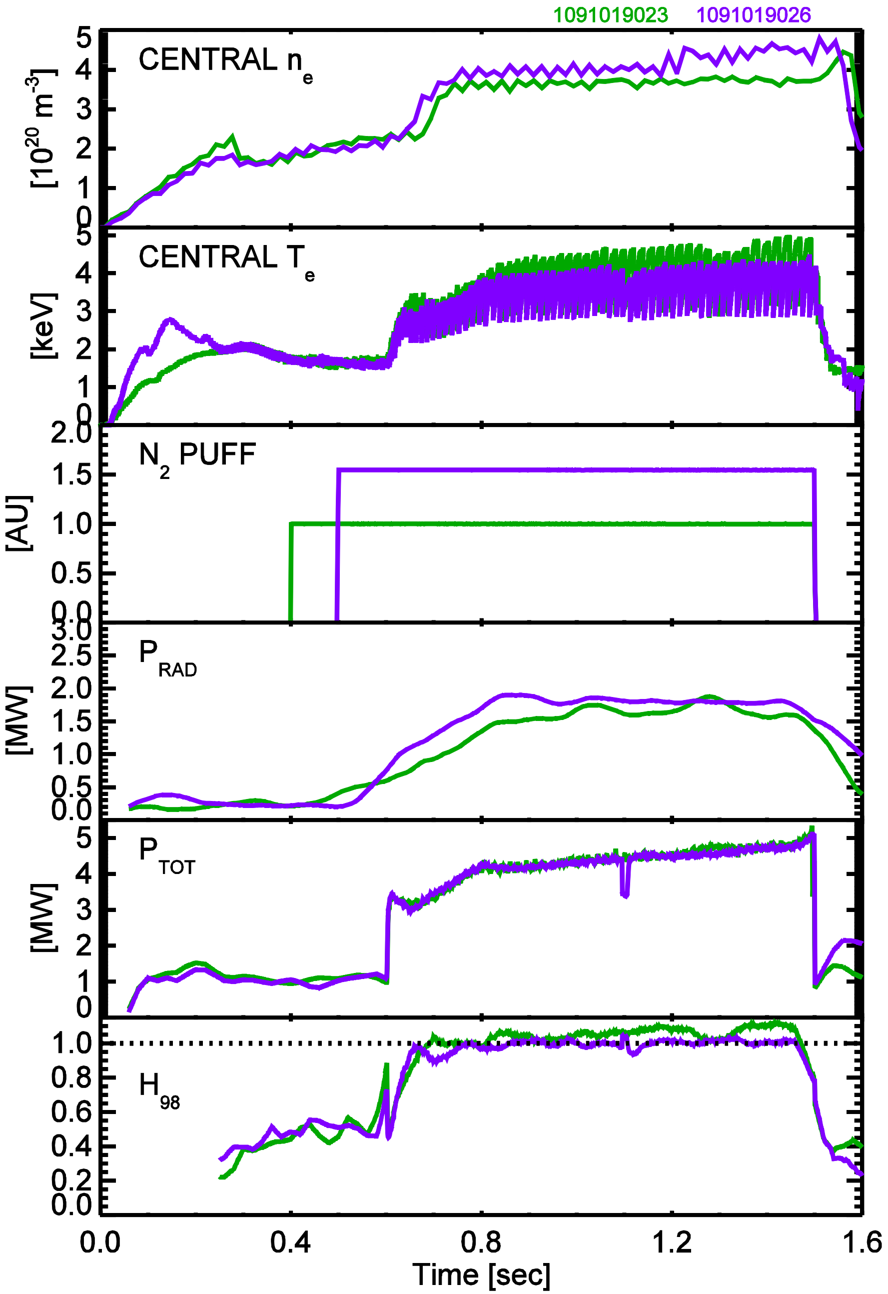
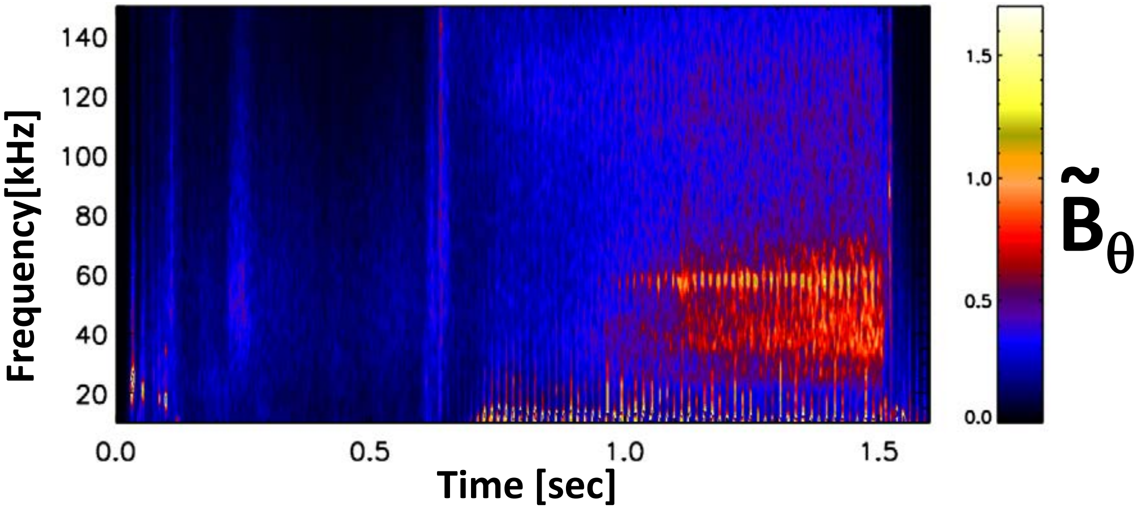
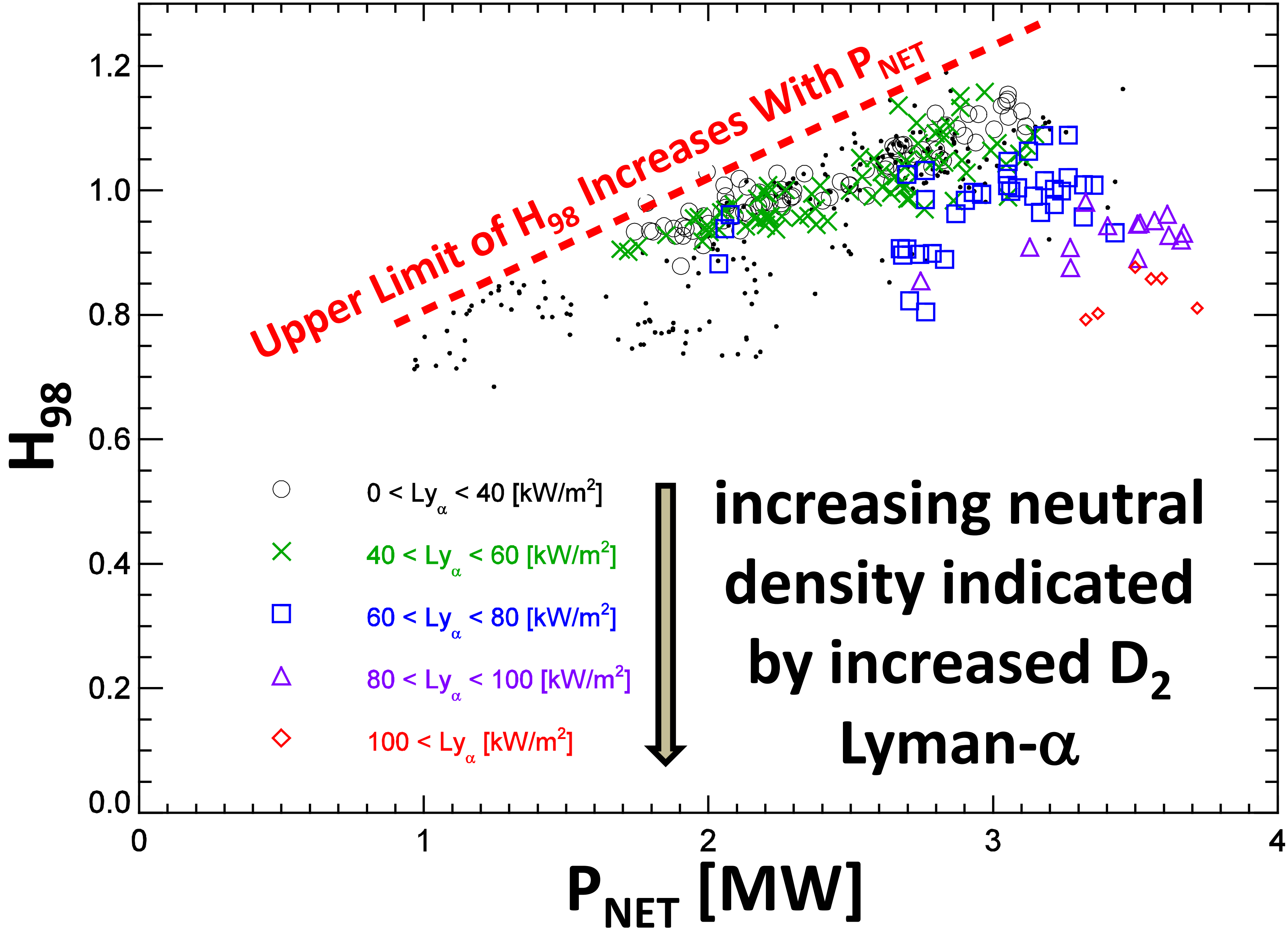


- in the EDA H-mode, the pedestal is relaxed continuously via the Quasi-Coherent Mode (QCM)
- in similar, repeated plasmas see large qualitative change in QCM
- for H_{98} ~ 1 and **heavy seeding**, the QCM weakens, upshifts and lower frequency fluctuations appear



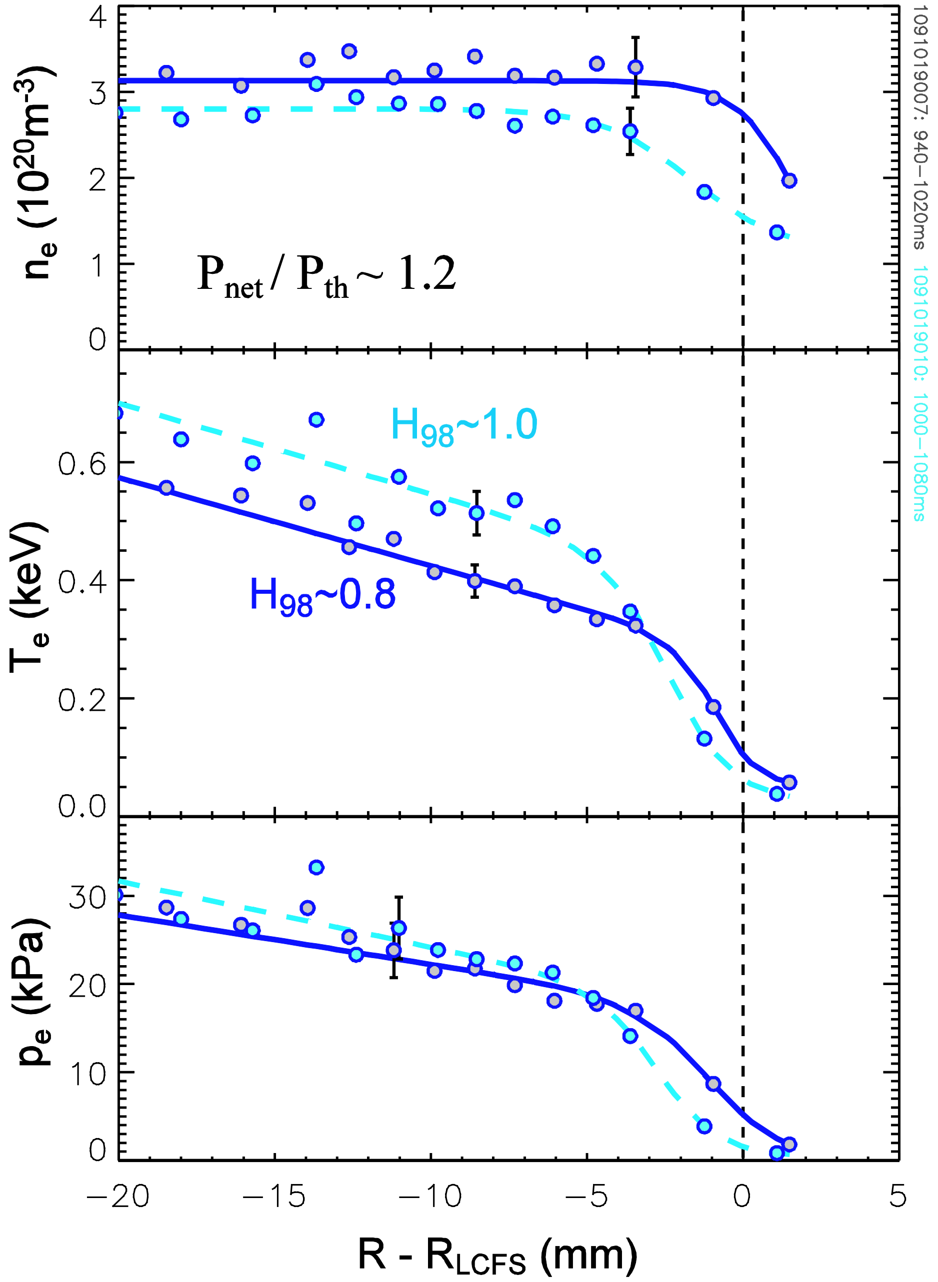
Increased Neutral/Edge Density Drops H_{98}



increasing neutral density indicated by increased D_2 Lyman-α

Increased Neutral/Edge Density Drops H_{98}

- C-Mod has not completed “matrix-scans” of Γ_Z and Γ_i like JET
- prior work [Hughes Nucl. Fusion 2007] shows active neutral puffing at EDA H-mode reduces $T_{e,95}$
- observe natural background changes in neutral density due to PFC outgassing following BZN
- shots with similar pedestal densities but enhanced seperatrix densities have reduce $T_{e,95}$ and H_{98}

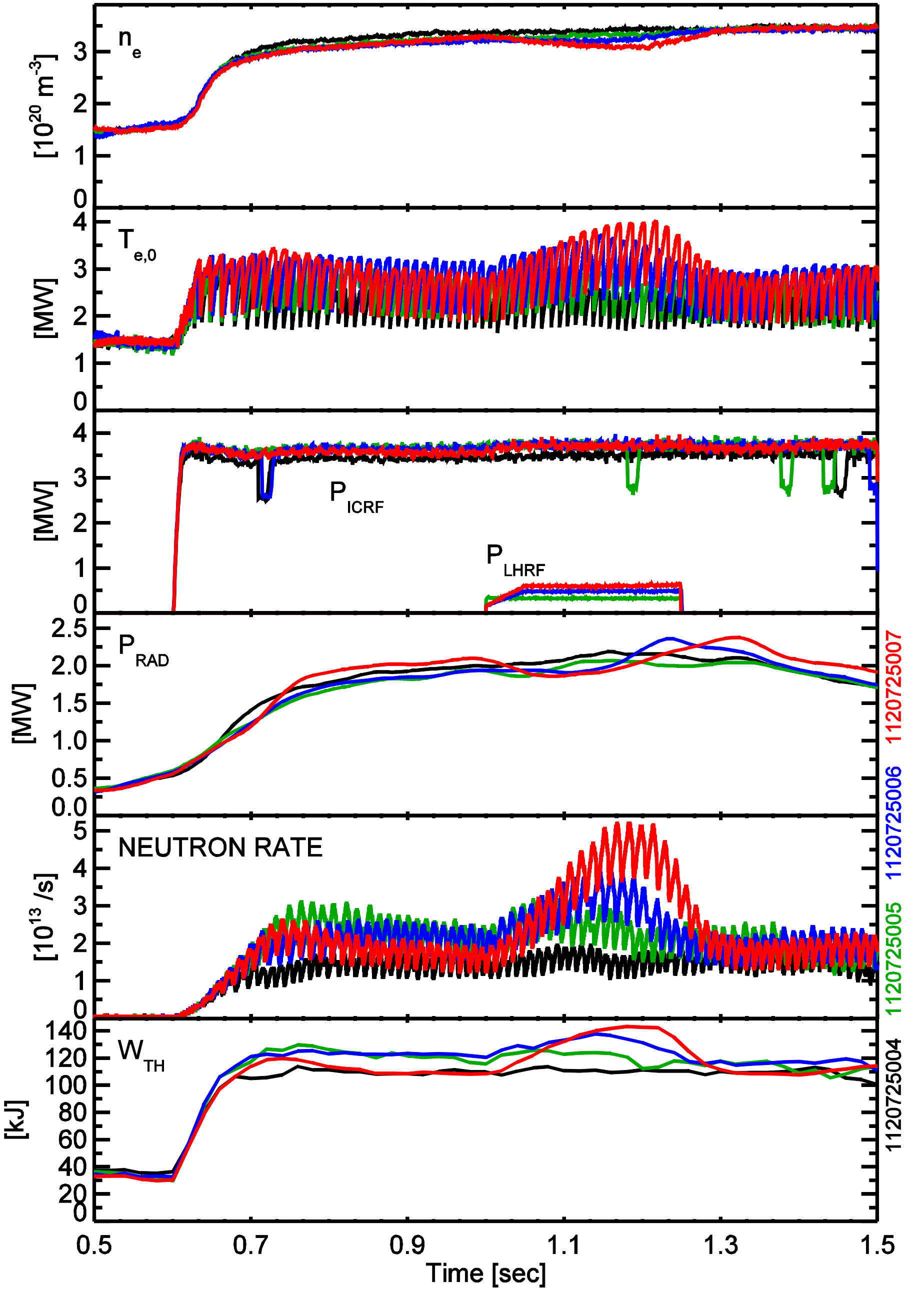


<u>What is the mechanism at work?</u>

1) **Energy loss from charge-exchange**
2) **Stiff particle transport removing heat**

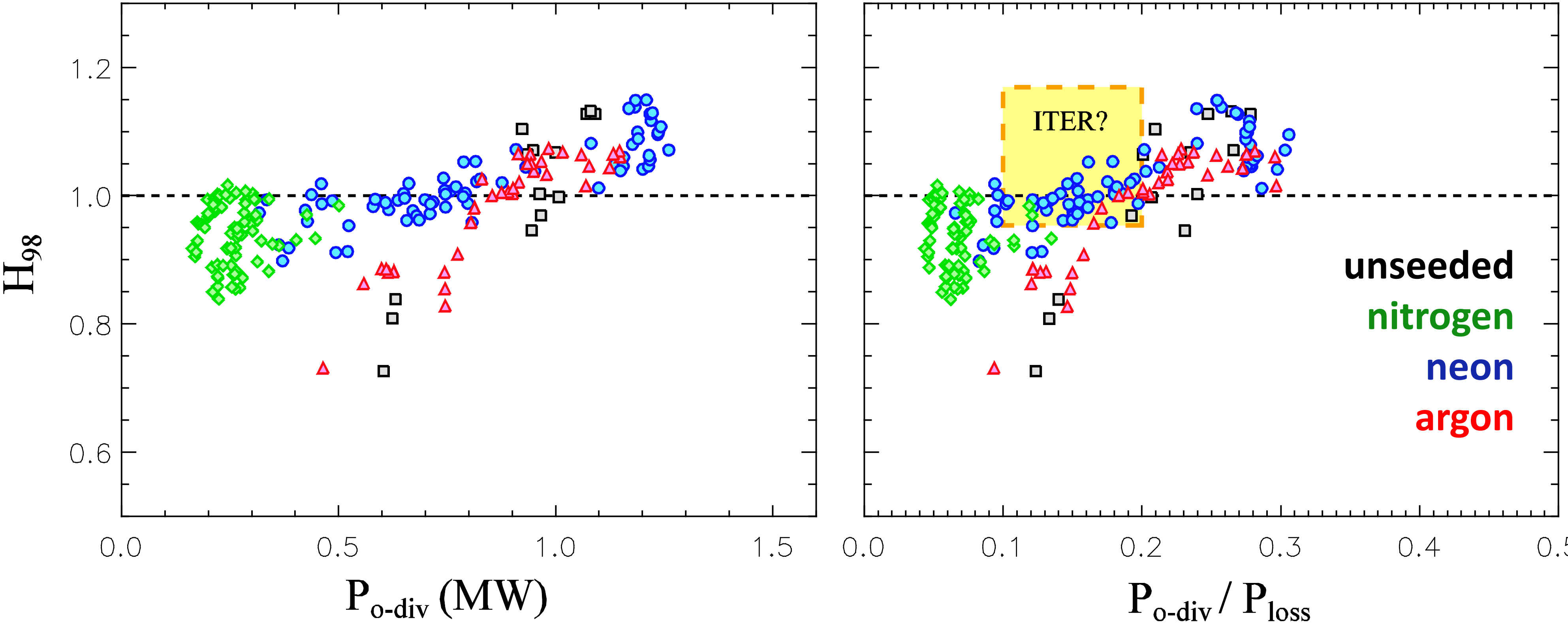
Edge Plasma Modified with LHRF Increases H_{98}

- previous research [Hughes NF – 2010] in 0.6 MA EDA H-modes demonstrated effect of a few 100 kW of LHRF
  - drop in core elec. density
  - increase in core elec. temperature
  - increase in pedestal T_e at fixed p_e
  - outward radial shift in neutral emission
- recently demonstrated this in 0.8 MA seeded EDA H-modes
  - increase in H_{98} from 0.7→0.9
  - no significant change in the core level of seeded impurity
  - strong change in edge turbulence observed, blobs “quieted”



Divertor Heat Flux Reduced at High H_{98}

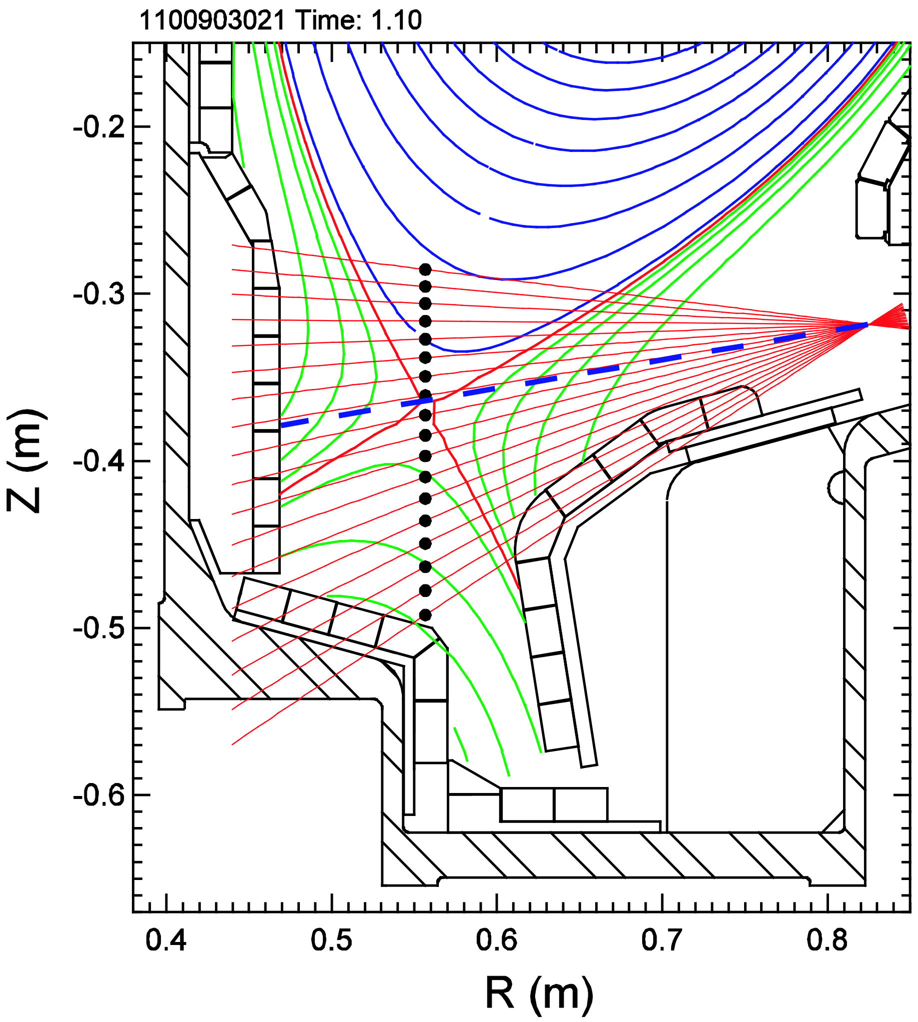
- outer divertor heat flux profile measured using IR imaging and surface/tile thermocouples [Terry – PSI 2010]
- can reach ITER-relevant levels of $P_{O\text{-}DIV}/(P_{IN}\text{-}dW/dt) < 10\%$
- only when using **Ne** or **N_2** can H_{98} ~ 1 be maintained

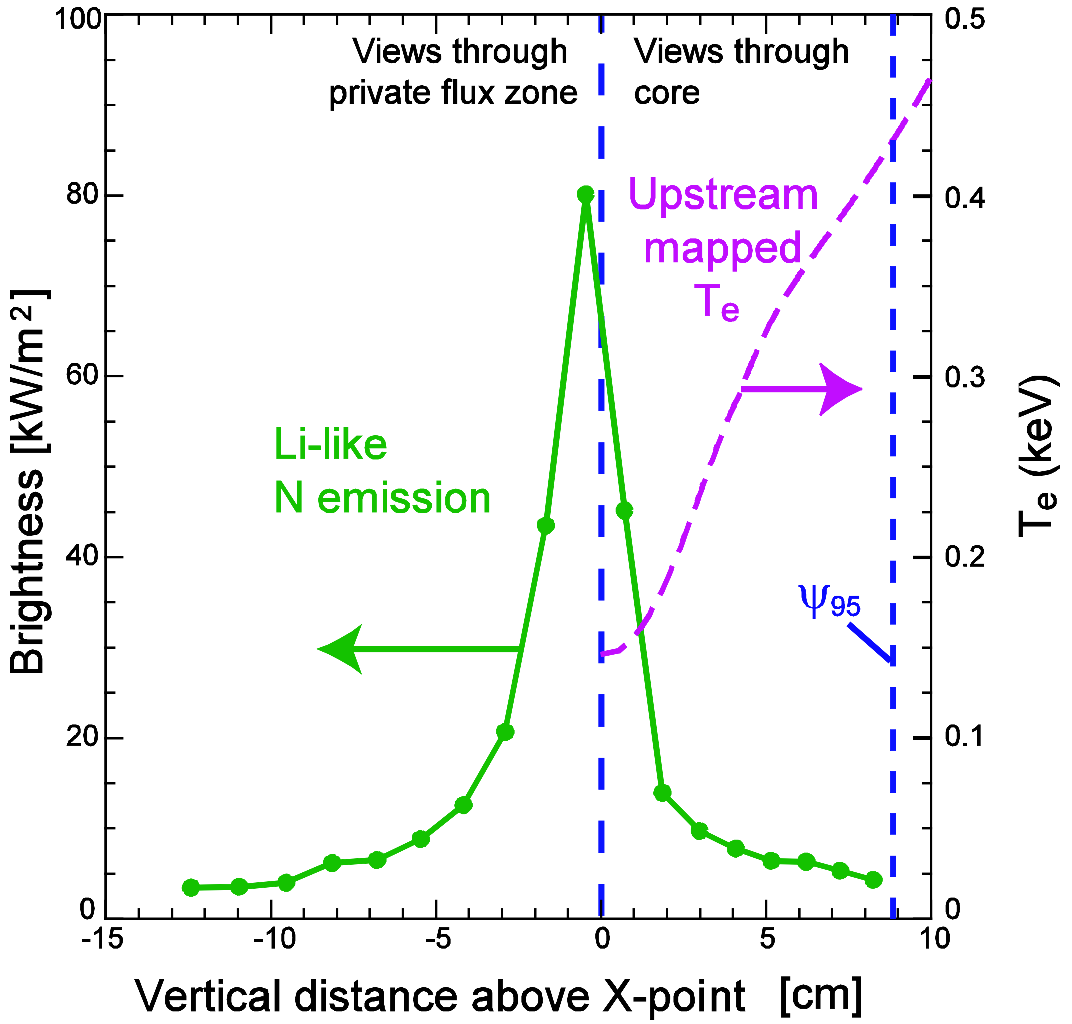


X-Point Radiation Comp. With High Confinement

measure the X-point profile of Li-like nitrogen (N V @ 123.9 nm)

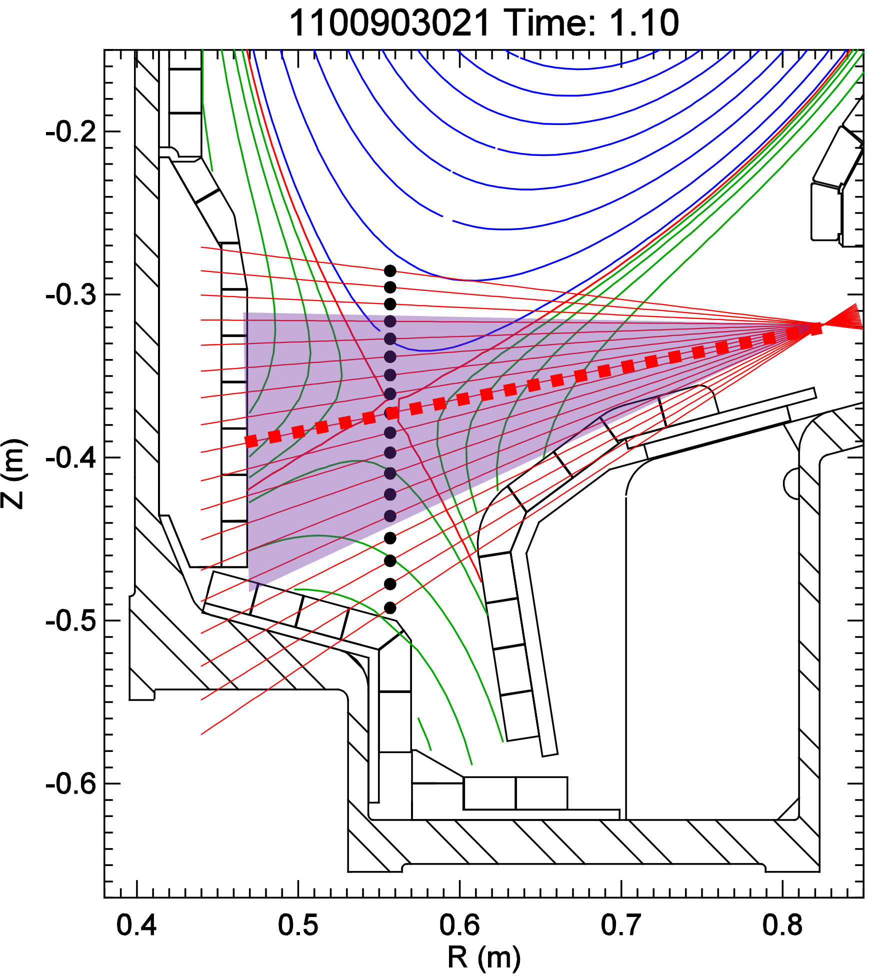
radiation inside LCFS but outside of pedestal





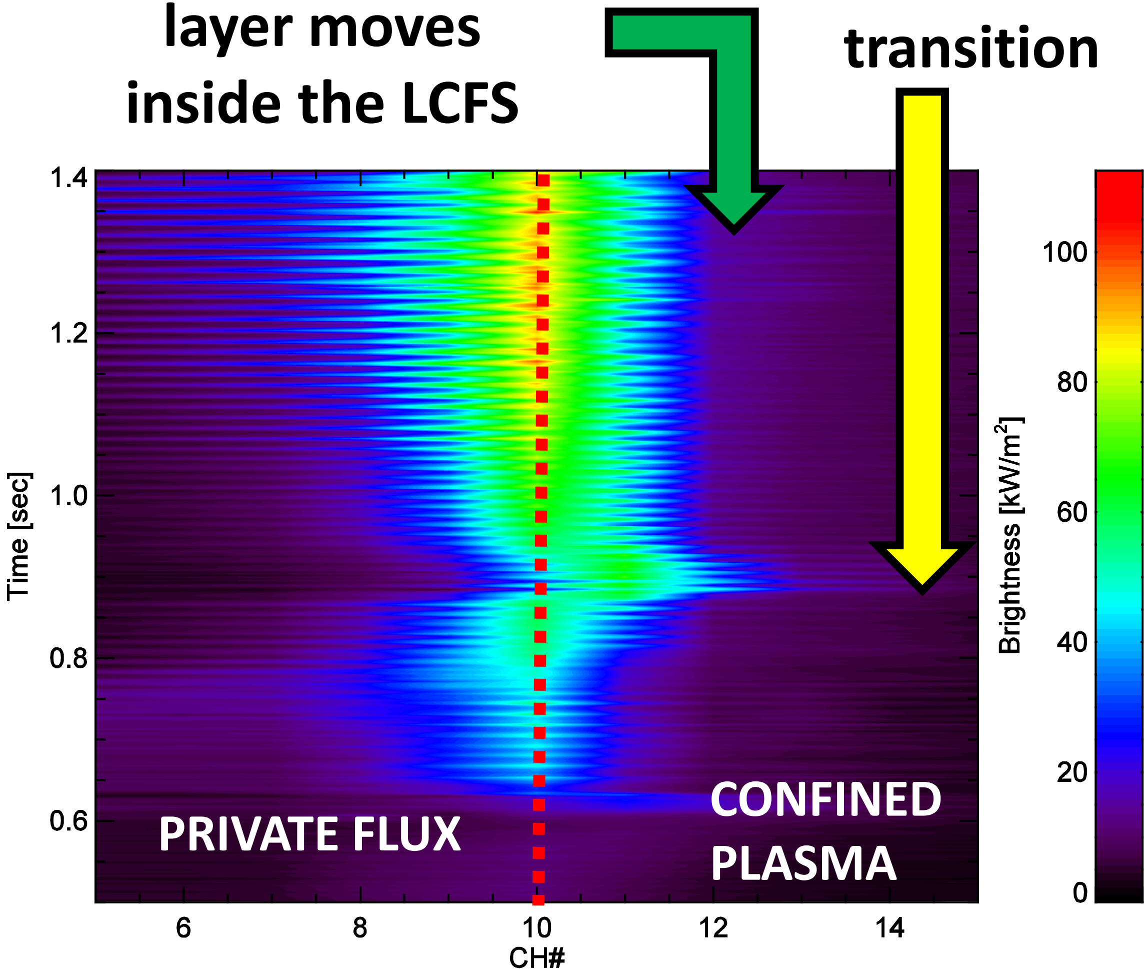
X-Point Radiation Candidate for Feedback Control

filtered photodiode array views x-point VUV emission with good space and time resolution – possible use for N_2 control



detect if radiation layer moves inside the LCFS

see H/L back transition



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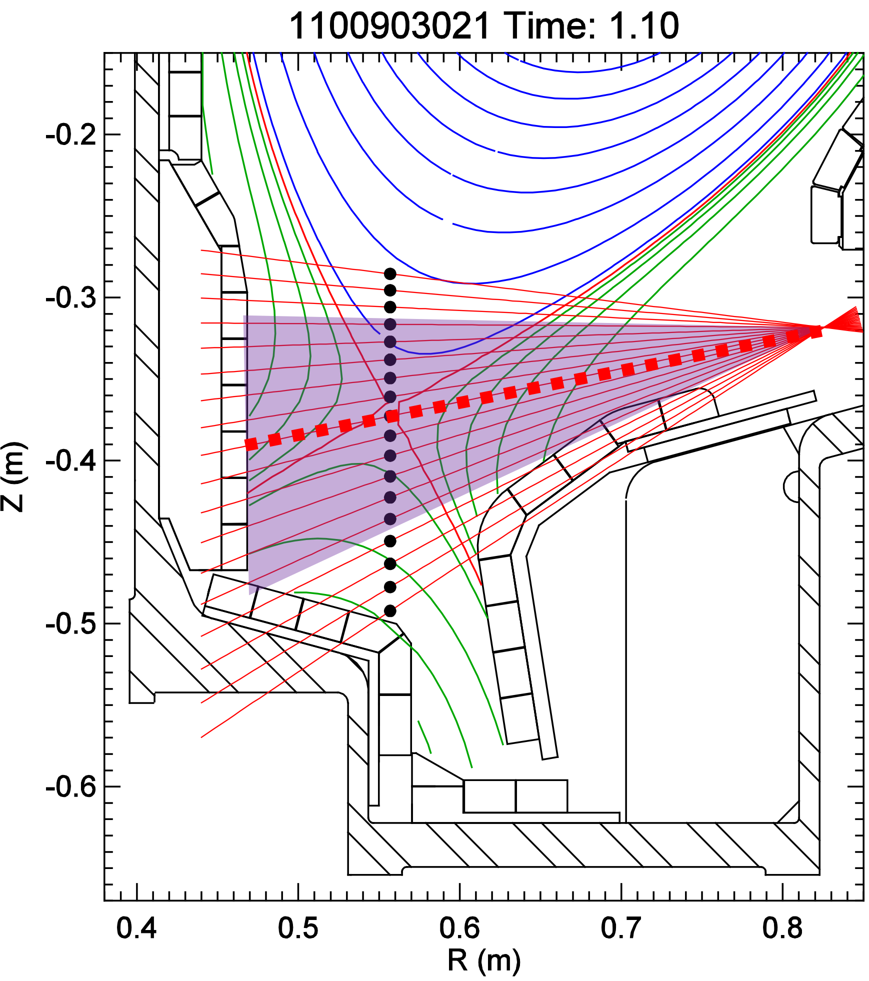
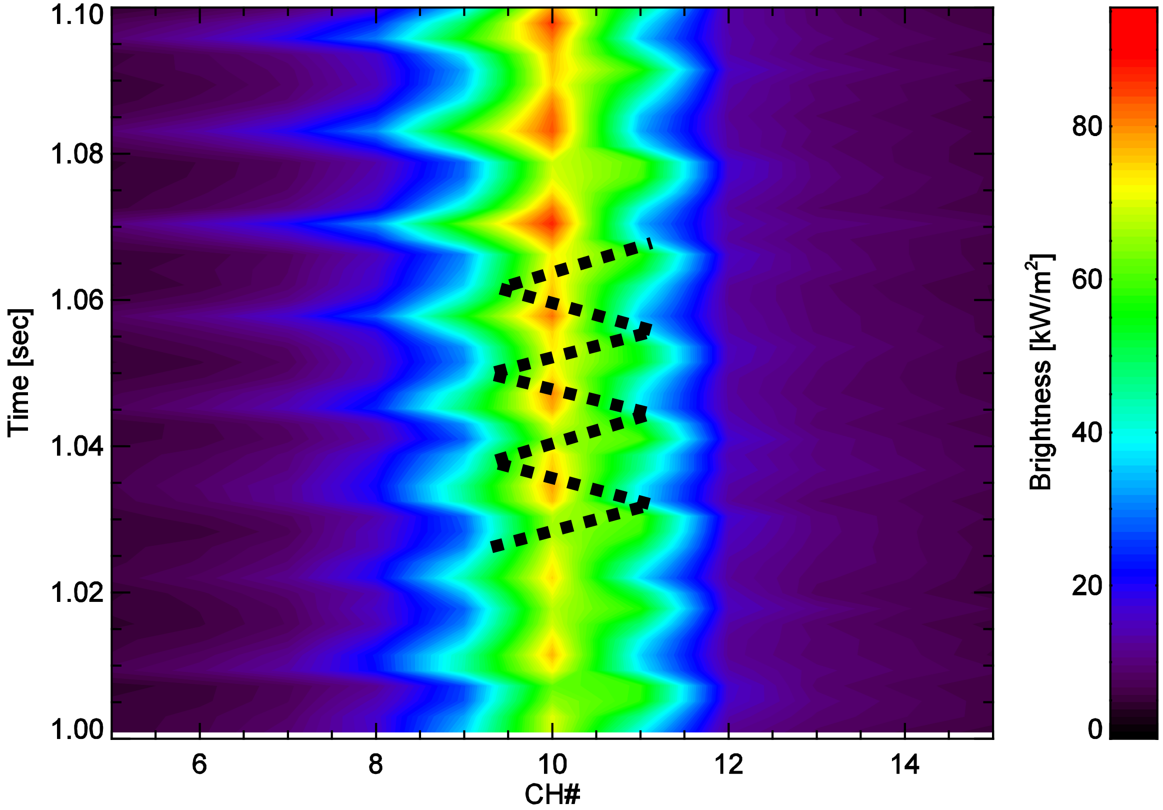


observe ~100 Hz motion of the radiation layer



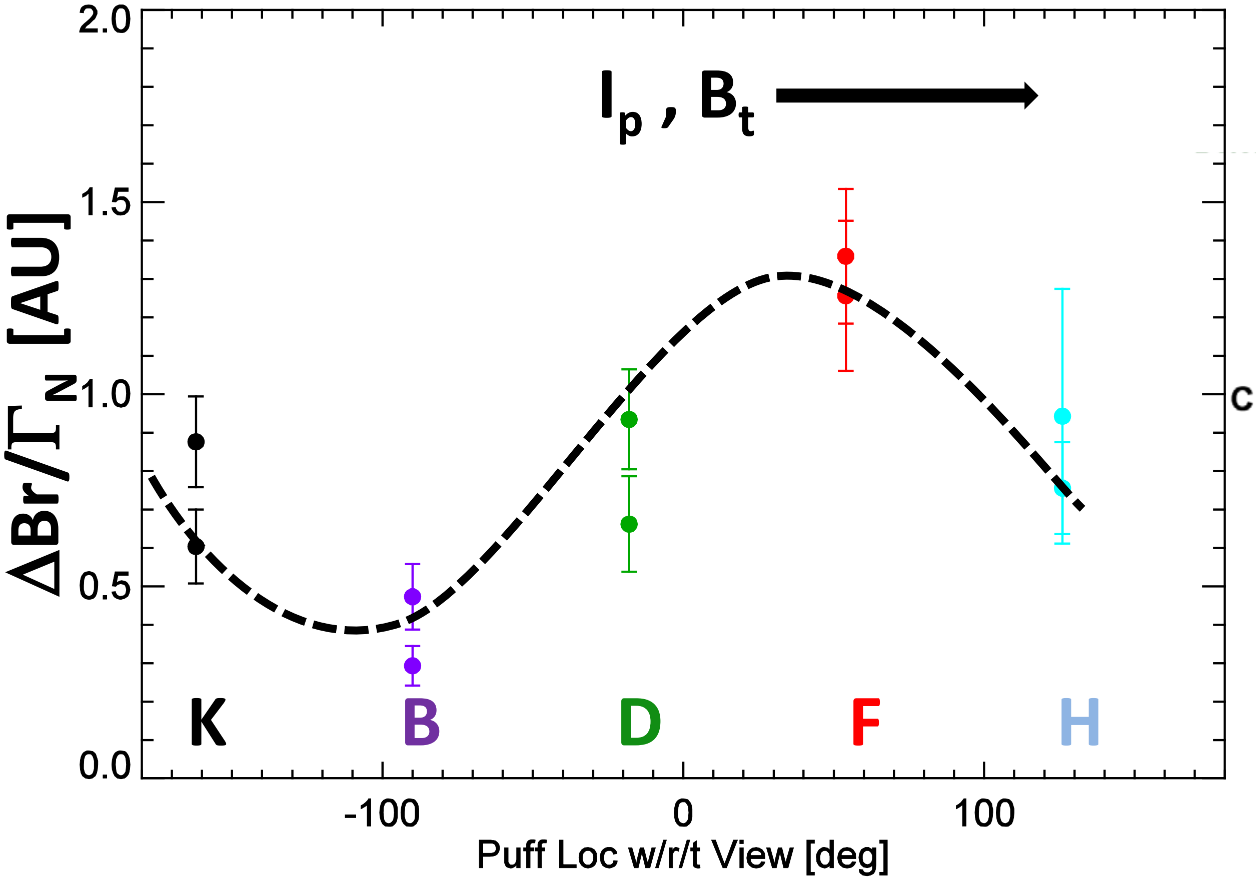
Summary

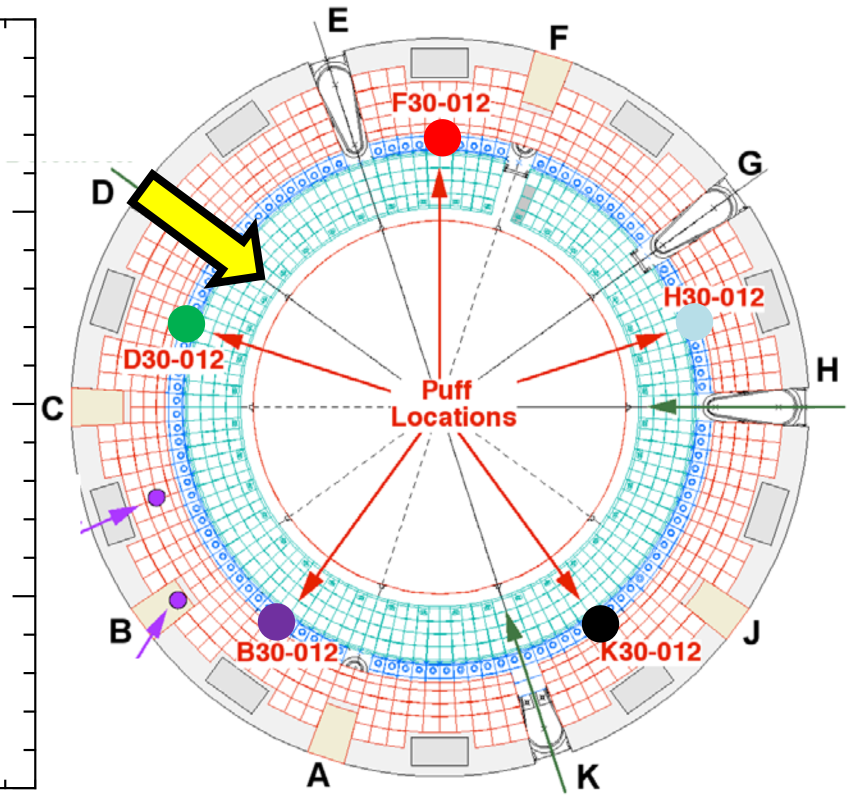
- Alcator C-Mod has demonstrated operations with low-Z seeding
  - low-Z seeding shown to improve ICRF performance
  - low-Z seeding shown to reduce core molybdenum content
- use of low-Z impurities cannot replace boronization or eliminate intrinsic impurity sources driven by fast particle losses
- C-Mod EDA H-mode studies demonstrate confinement, H_{98}, responds to $P_{NET} = P_{IN}\text{-}dW/dt\text{-}P_{RAD,CORE}$
  - response consistent with core profile stiffness accompanying change in pedestal temperature and density
- we are working to extend our contributions
  - relative role of high-Z source due to rf effects, sputtering and melting
  - improved physics understanding of seeding impact on pedestal
  - exploring ways to deploy feedback control of low-Z seeding

EXTRA SLIDES

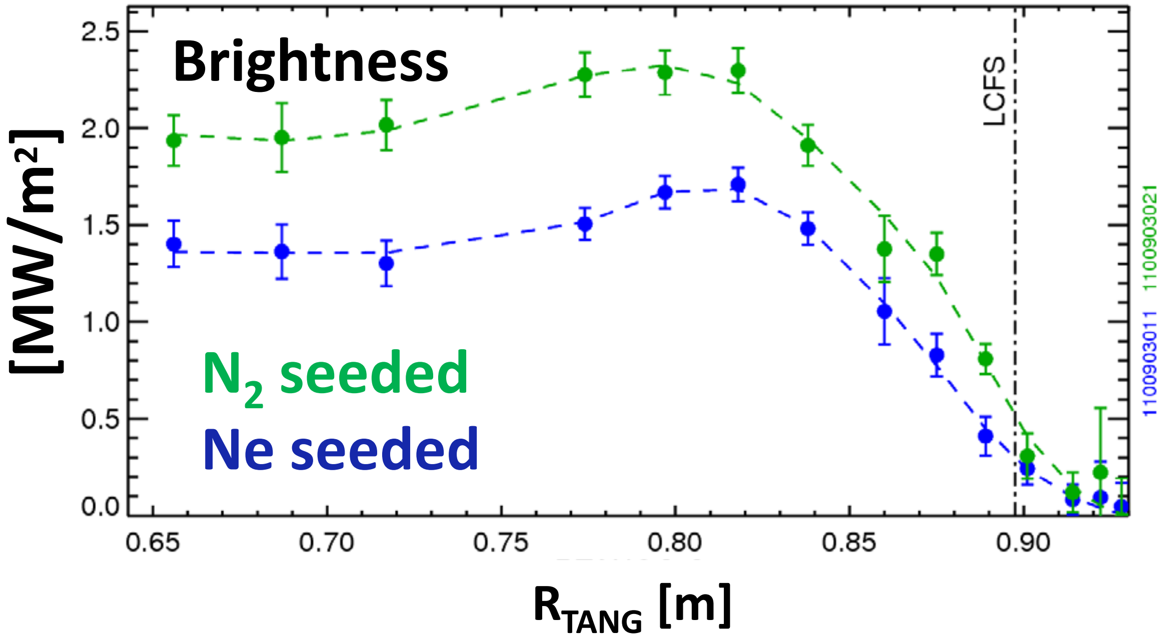
N_2 Seeding Found to Be Toroidally Asymmetric

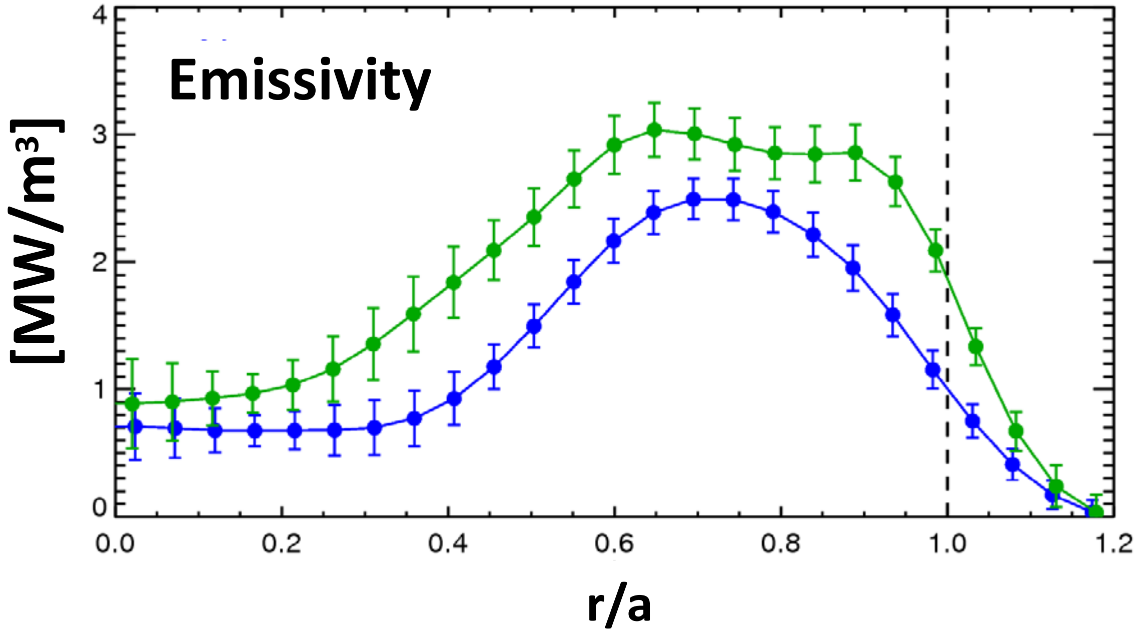
- toroidal non-uniformity of nitrogren puffing investigated at ITER’s request to inform the # and spacing of divertor gas puffs (R. Pitts)
- observe divertor P_{RAD} at fixed toroidal location & puff at others





Confinement Scaling for P_{RAD} and P_{IN}





Work described in more detail in:

Reinke – J. Nucl. Materials 2011

Hughes – Nucl. Fusion 2011

Loarte – Phys. Plasmas 2011

Impurities Observed Over Wide Spectral Range

XEUS+LoWEUS spectra

Soft X-ray (SXR) and vacuum ultraviolet (VUV) spectroscopy:

- X-ray imaging crystal spectroscopy for radial profiles of Ar, Ca and Mo (Dl < 0.1 Ang within 3 < l < 4 angstroms, with up to 5 ms time resolution [PPPL collaboration]
- two single cord, core-viewing flat-field spectrometers with 2 ms time resolution [LLNL collaboration]
    - 10 < l < 60 Ang for viewing H-like and He-like emission in 5 < Z < 10 (B to Ne)
    - 100 < l < 300 Ang for viewing Na/Mg-like Mo and Li/Be-like metal