EX/7-2: Impurity Seeding on JET to Achieve Power Plant like Divertor Conditions

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Acknowledgements

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**See the Appendix of F. Romanelli et al., Proc. 25th IAEA FEC 2014, St Petersburg, Russian Federation*

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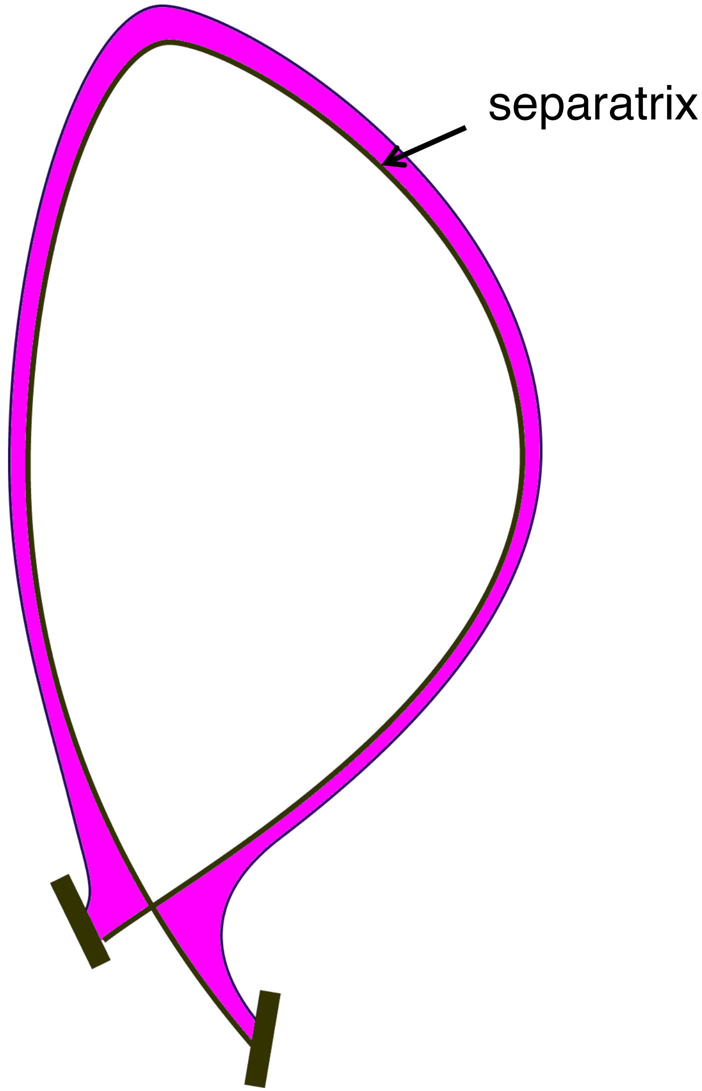
Boundaries for power exhaust

- Limit on acceptable erosion:
  - With impurity seeding and higher charged states enhancing erosion: $T_e < 2 - 5$ eV
- Expected power handling limit of actively cooled DEMO divertor component < 10MW/m^2:
  - limit on particle flux to limit power deposition by surface recombination (15.8 eV per ion – electron pair)

- Power handling limit combined with erosion limit
  ➔ ***completely detached divertor***

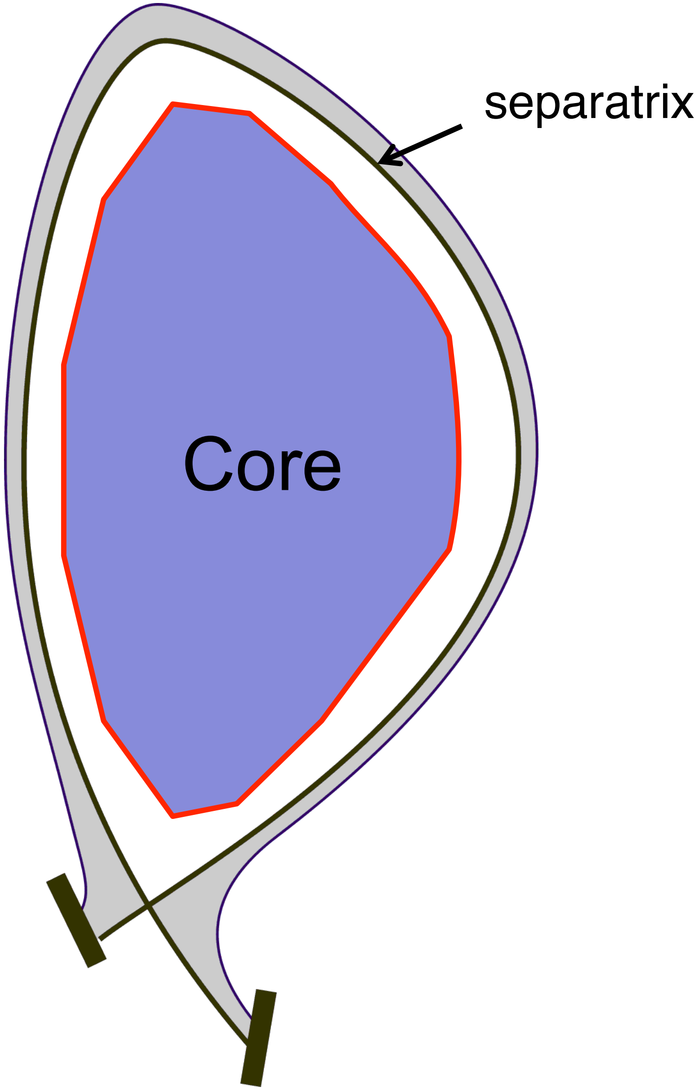
Radiation in DEMO divertor similar to ITER



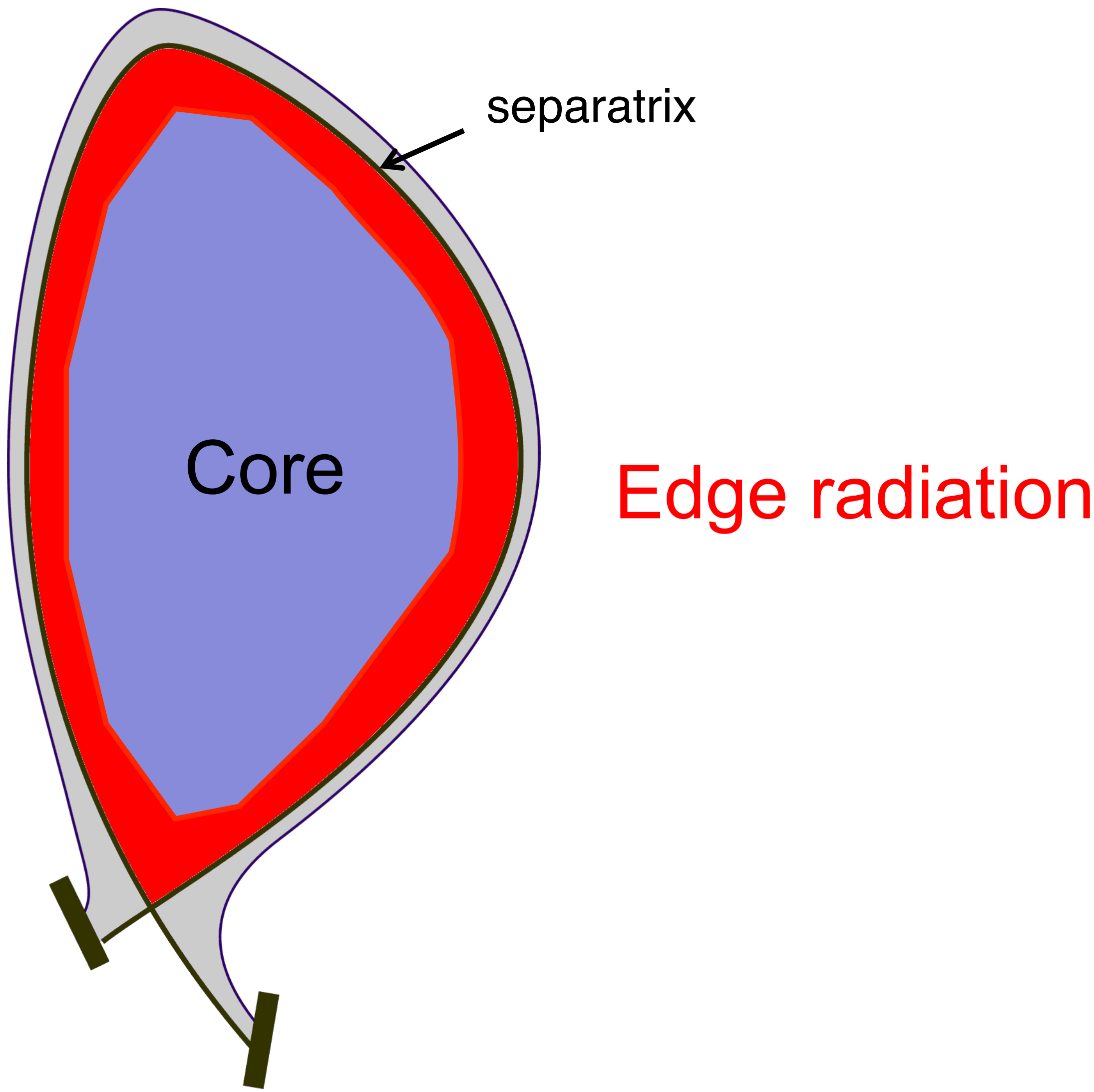
ITER to DEMO:

Similar volume and size of divertor ➔ similar absolute amount of radiation in SOL and divertor (ITER ~ 60% – 70% of P_{SOL}=120MW ➔ 70MW)

Radiation: minimize in core



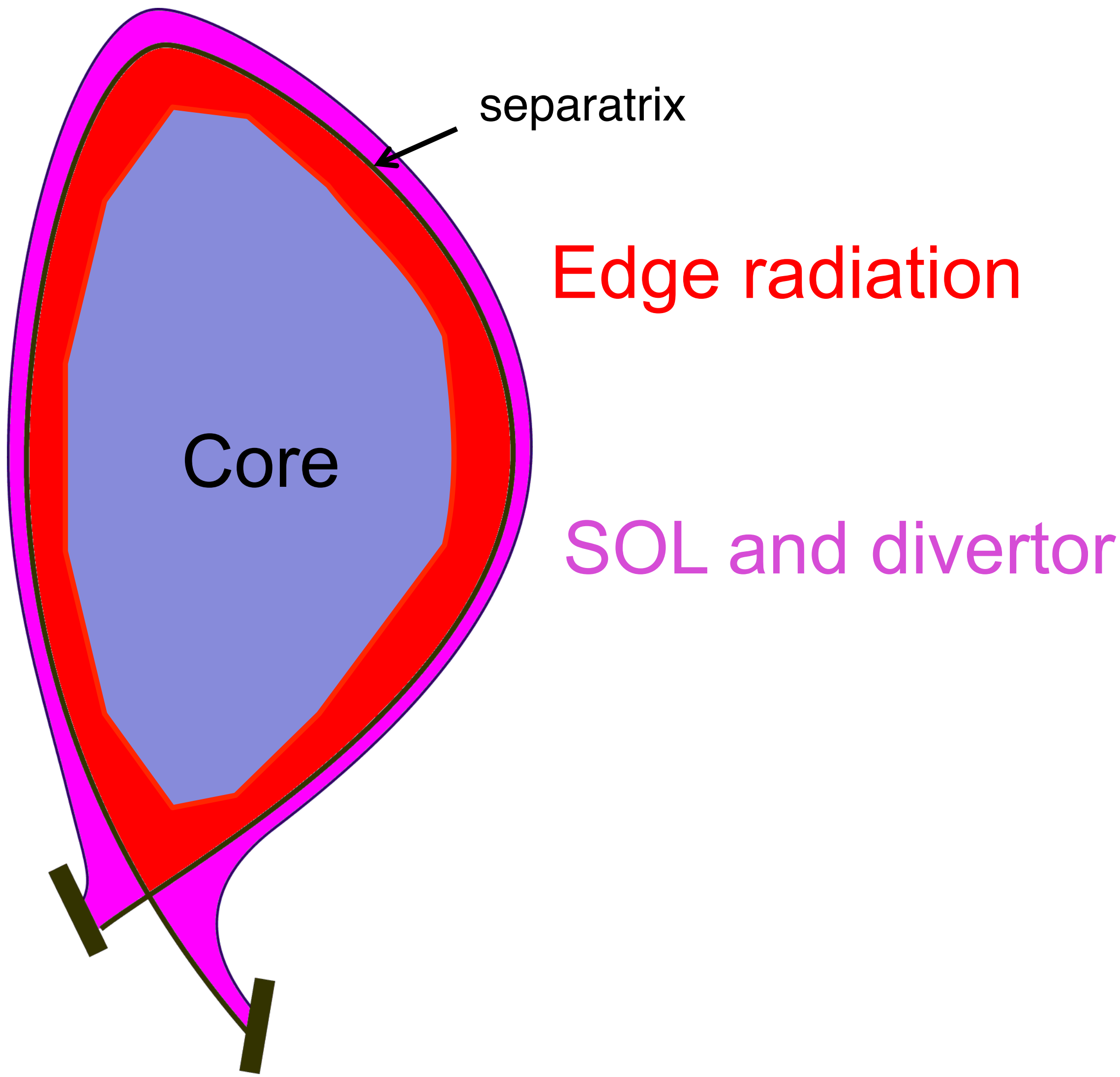
Radiation: minimize in core & optimize edge



Divertor power dissipation in DEMO similar to ITER

➔ Edge + core > 70% radiation

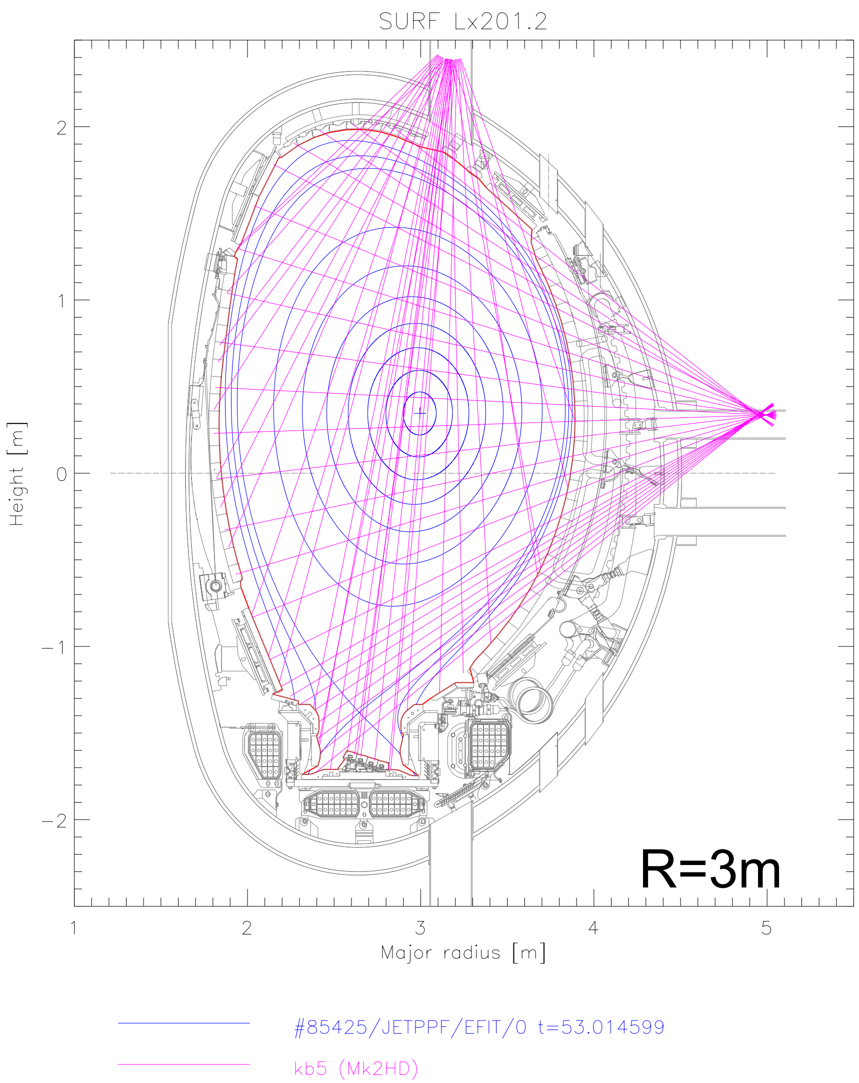
DEMO requires > 90 – 95% radiation



➔ Total radiation required sums to > 90% - 95% of P_{heat}

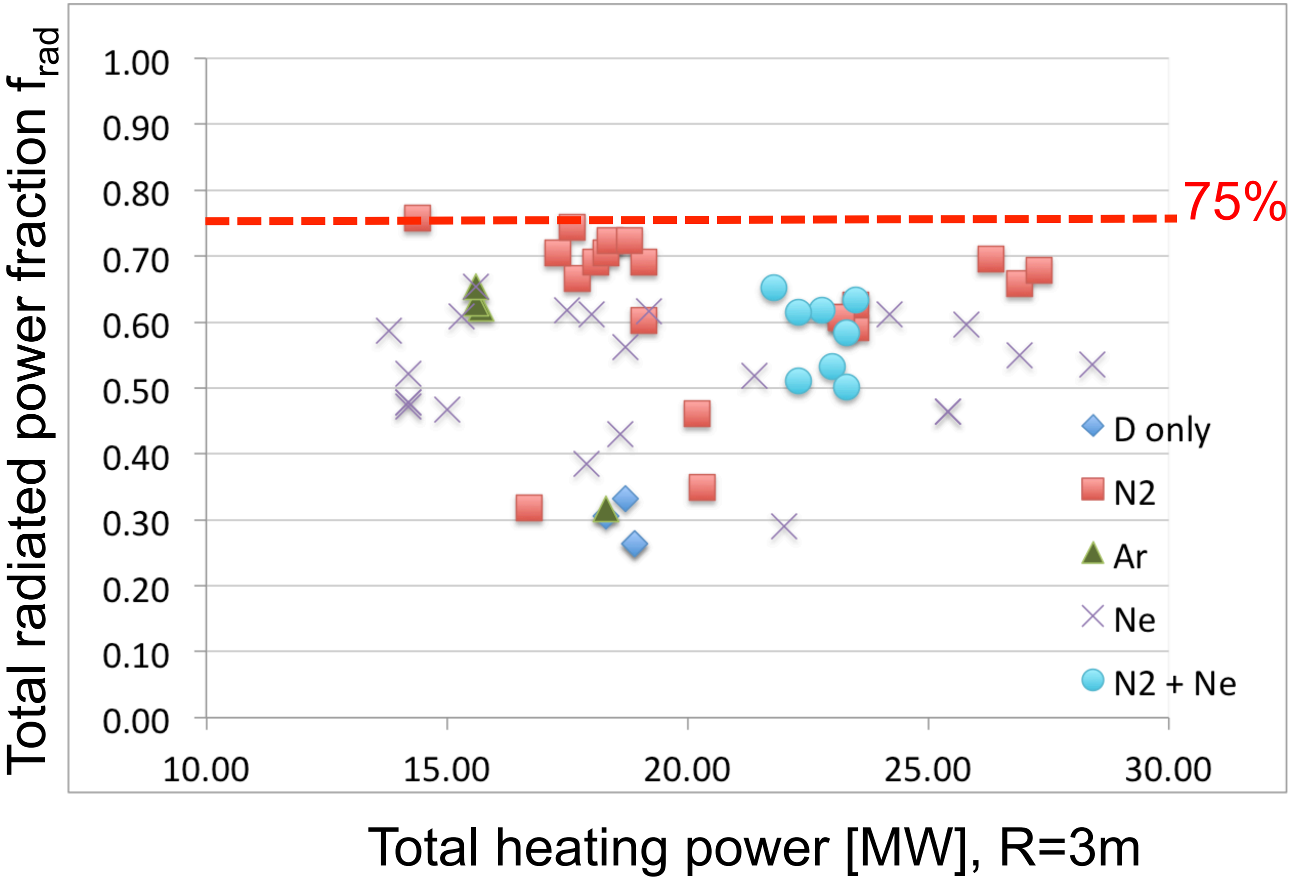
➔ Maximize radiation in EDGE and SOL → main guidance

Vertical target geometry



B_T=2.7T
I_P=2.5MA
δ=0.22 (low triangularity)
q_{95}=3.3
P_{heat}= P_{IN}-dW/dt (14-28MW)
P_{heat}/R ~ 5 – 9
P_{sep}/R ~ 3 - 6

Maximum f_{rad} independent of P_{heat}

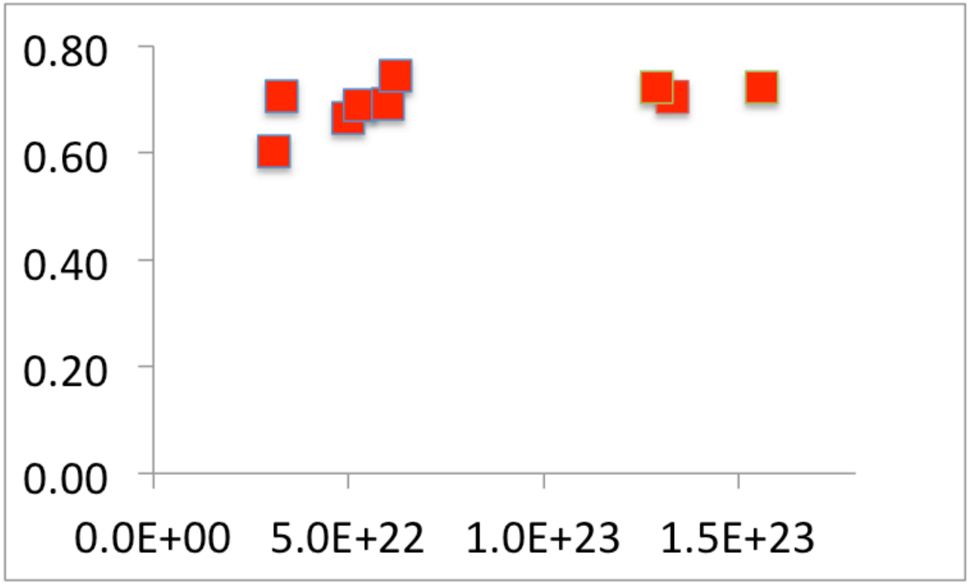


- ~70% f_{rad} at maximum P/R ~ 9
- Highest f_{rad} with only N_2 seeding
- Performance of N2 + Ne seeding evolves qualitatively very similar to pure Ne seeding
- ASDEX Upgrade reaches f_{rad}>85% but higher c_W (W from MCW)

Maximum f_{rad} increases with seeding

P_{heat}: 18 – 20 MW

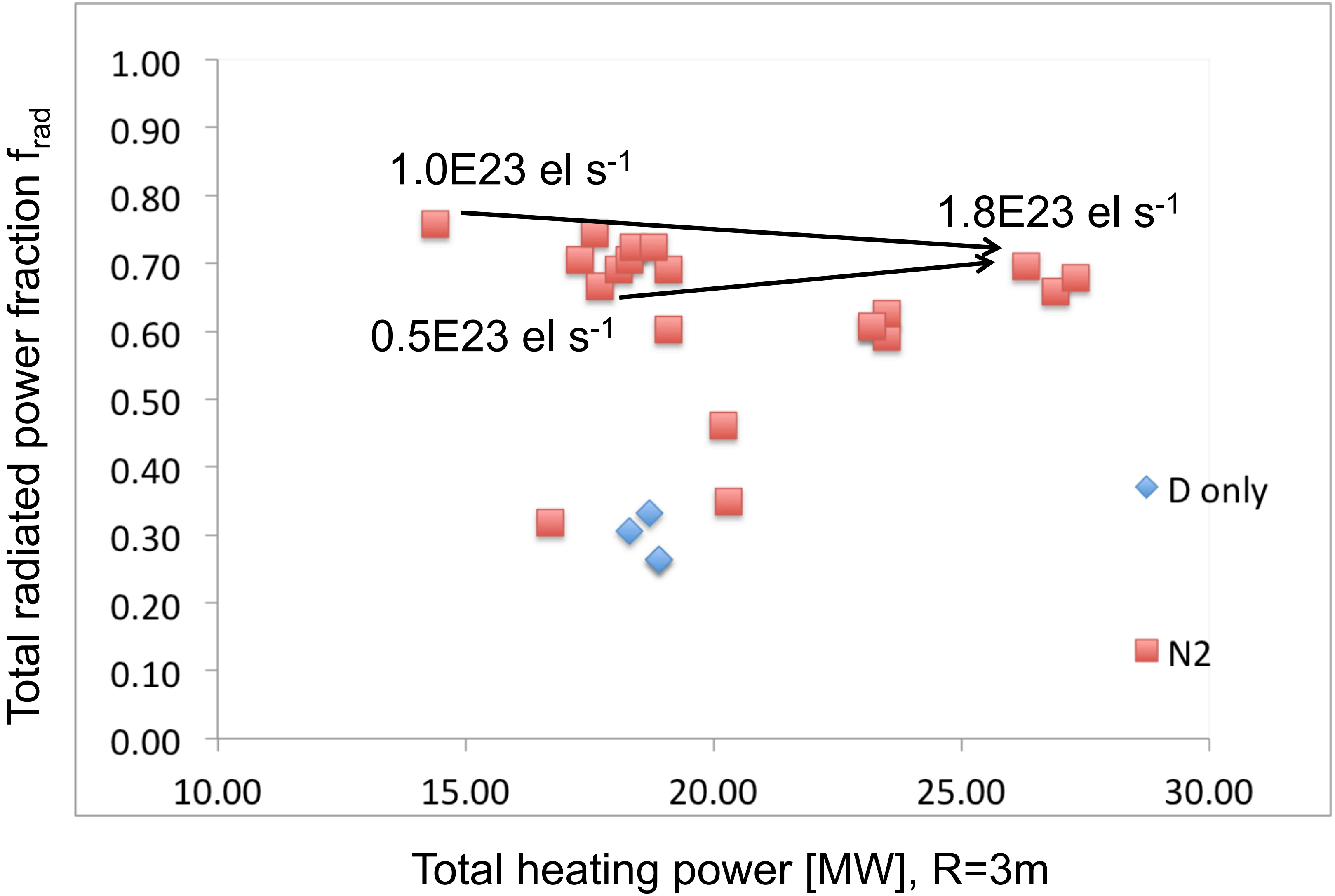
f_{rad}



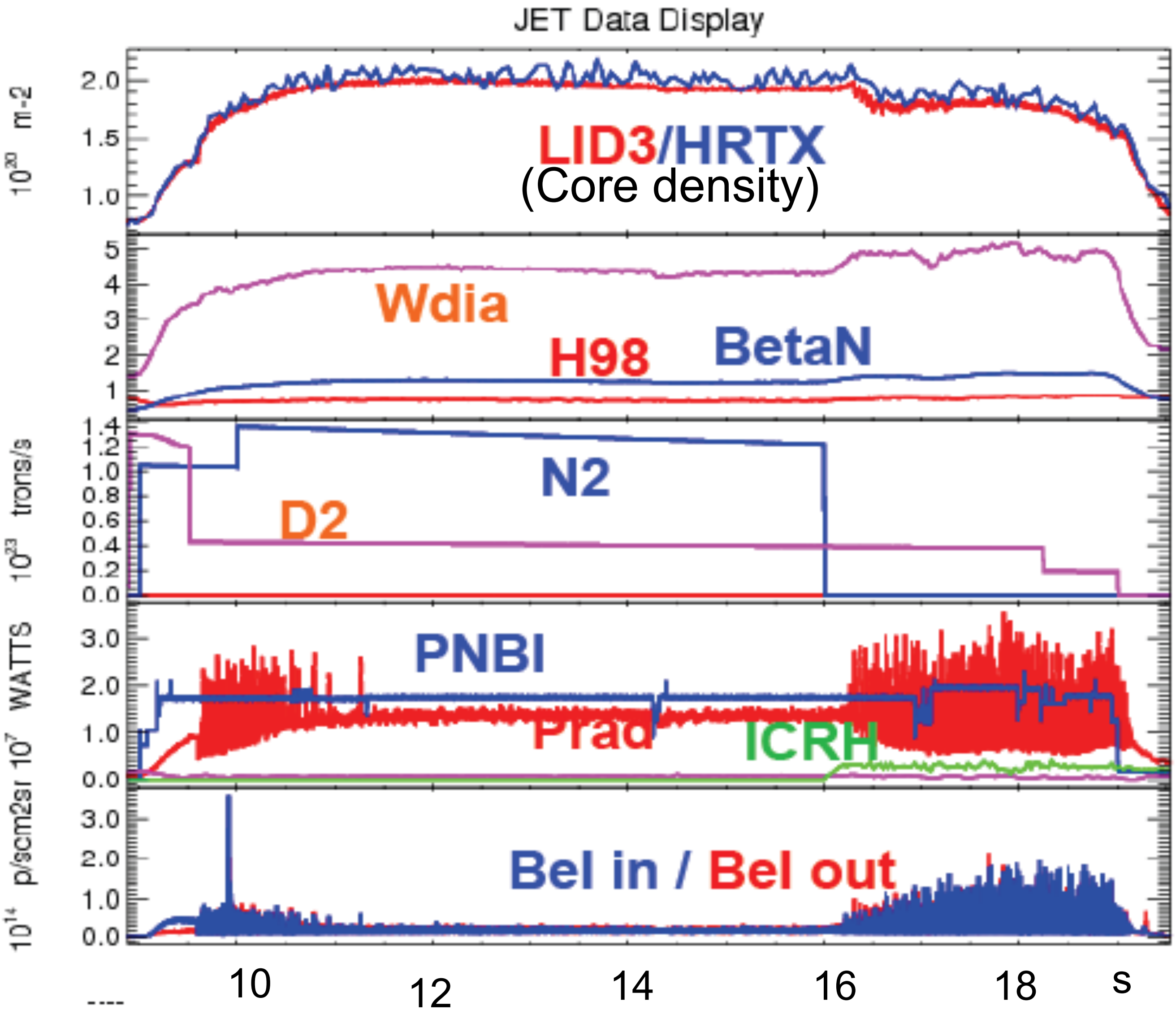
Nitrogen seeding rate [el s^{-1}]

- Close to maximum: f_{rad} low efficiency of seeding on f_{rad}

Higher P_{heat} → higher seeding for f_{rad}



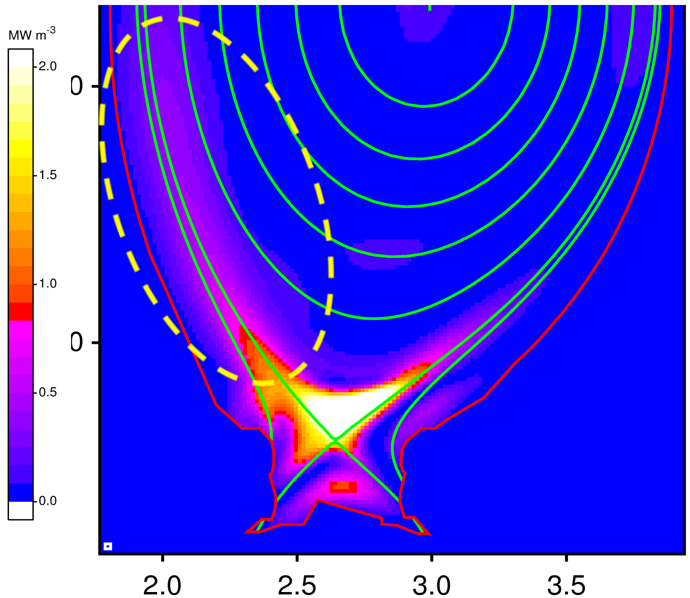
N_2 seeding into H-Mode plasma: stable radiation of 75%



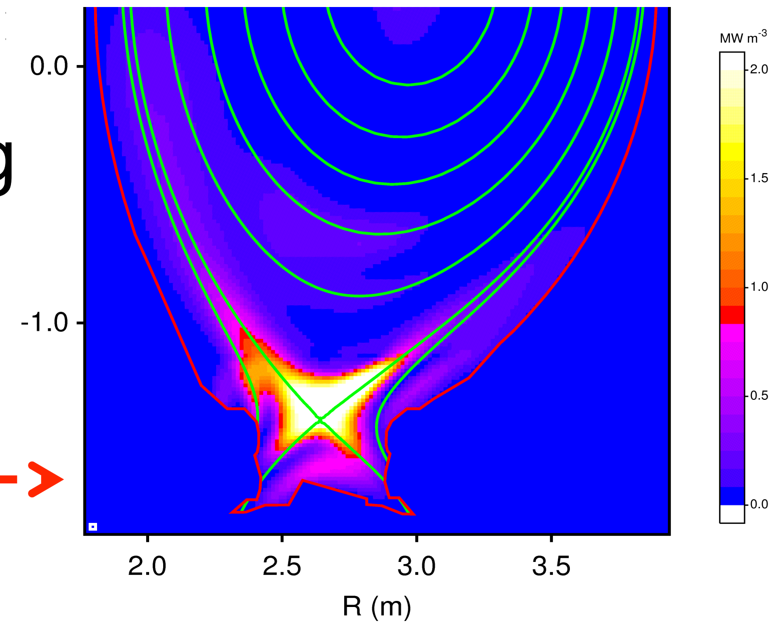
- N_2 → leads to ELM mitigated H-mode with f_{rad} of ~75%
- ELM mitigated phase with magnetic activity similar to M-Mode (E. Solano et al., EPS 2013)
- c_W in core at detection limit ($<10^{-5}$)

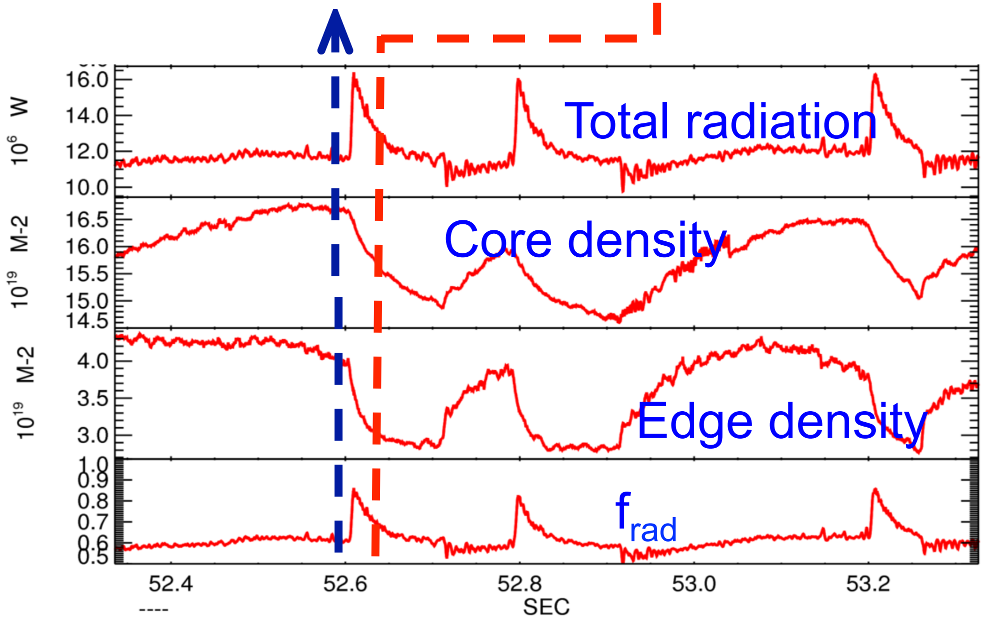
A. Huber et al. EPS 2014,
M. Wischmeier PSI 2014

Poloidal radiation at highest f_{rad}



Ne seeding

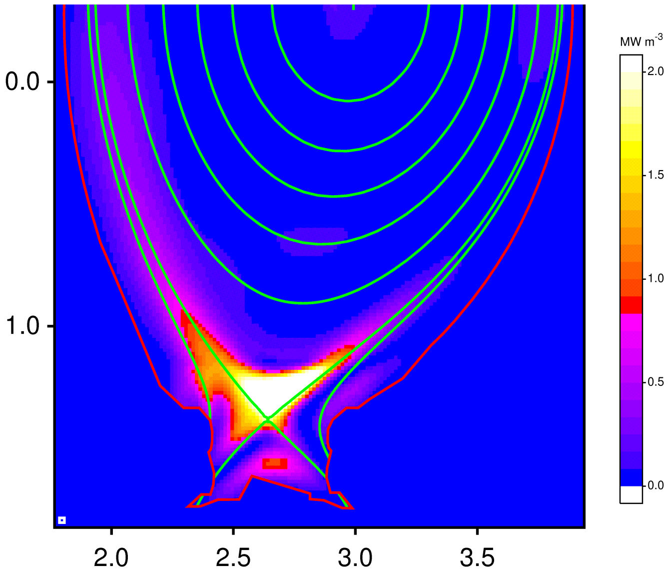




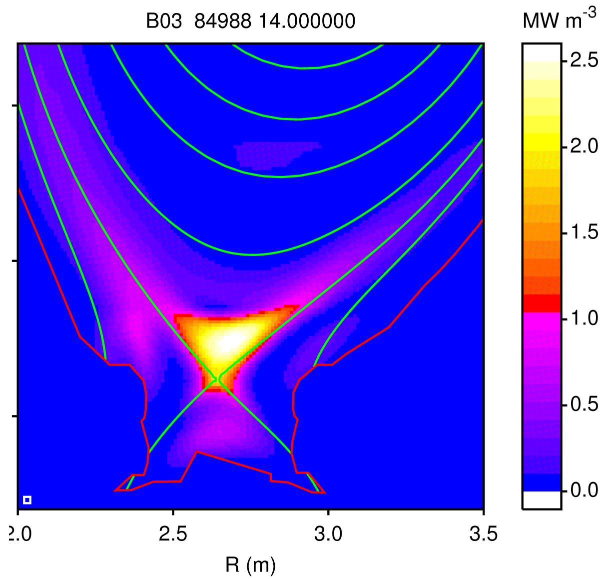
Radiative instabilities with transient f_{rad} of up to 90%

Poloidal radiation at highest f_{rad}

Ne seeding



Ar seeding

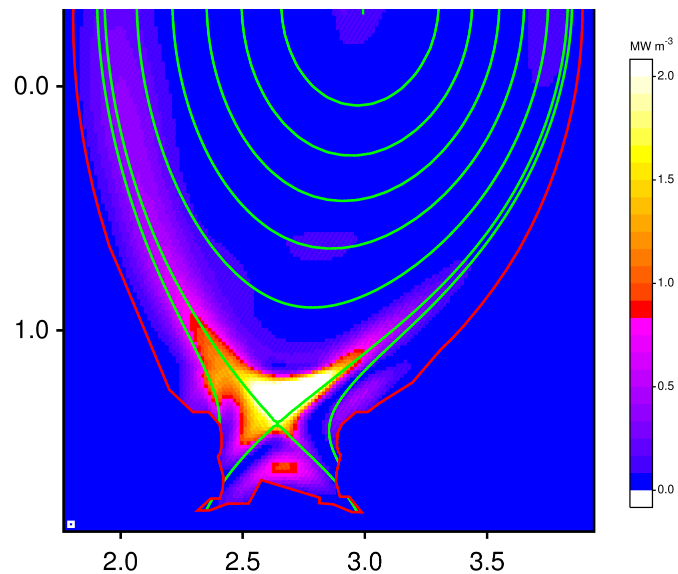


Radiative instabilities with transient f_{rad} of 90%

Maximum f_{rad} ~60%

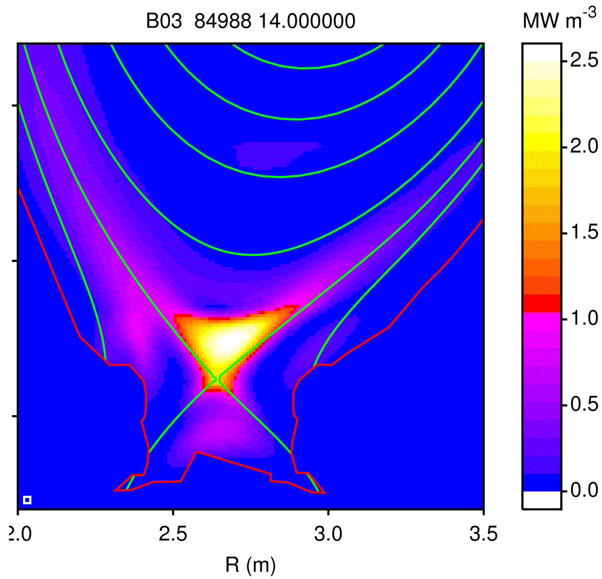
Poloidal radiation at highest f_{rad}

Ne seeding



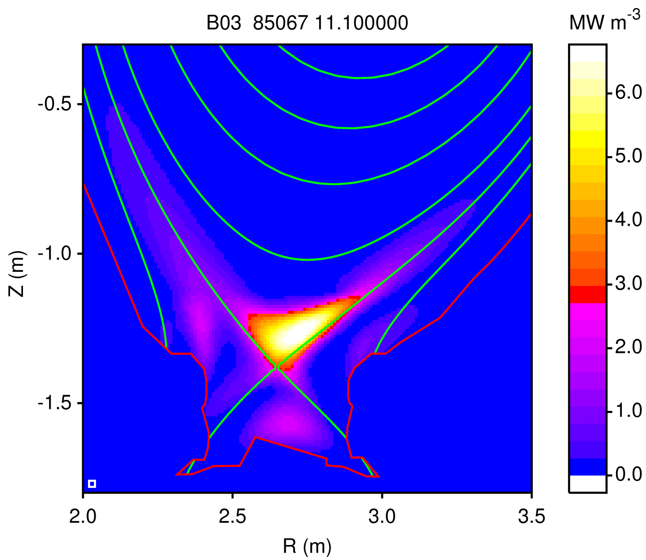
Radiative instabilities with transient f_{rad} of 90%

Ar seeding



Maximum f_{rad} ~60%

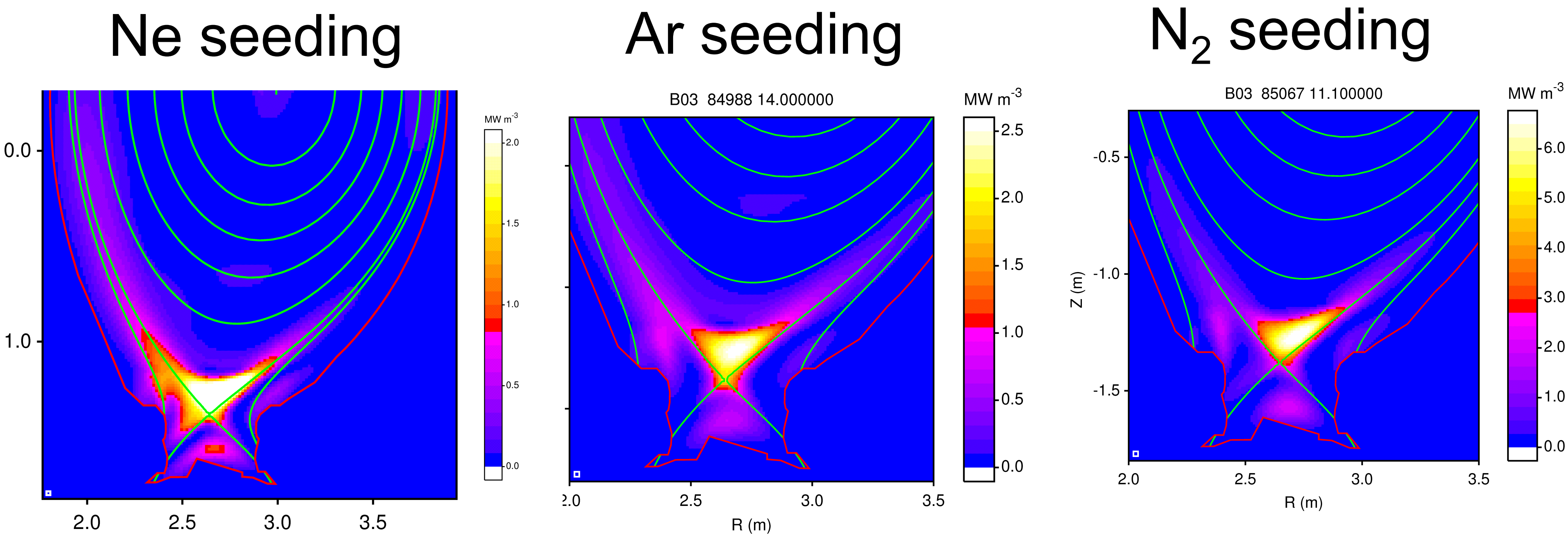
N_2 seeding



Maximum f_{rad} ~75%

Concentrated around X-point

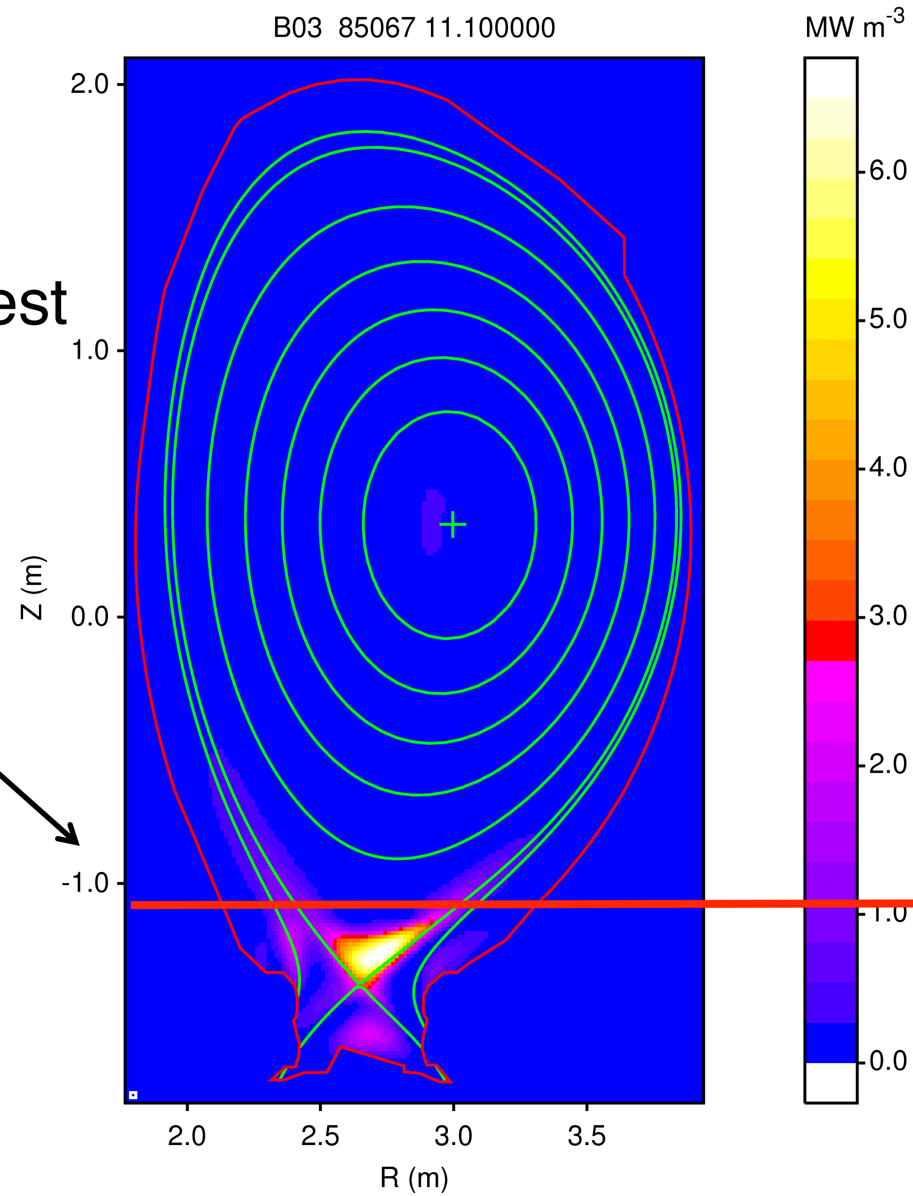
Radiation concentrated at X-point independent of seeding species



- ➢ Peaking of radiation density (W/m³) varies with seeding species as well as poloidal extent
- ➢ No radiating belt formed

Definition of radiation distribution

- According to reconstruction at highest f_{rad} this accounts for largest part of edge & SOL radiation



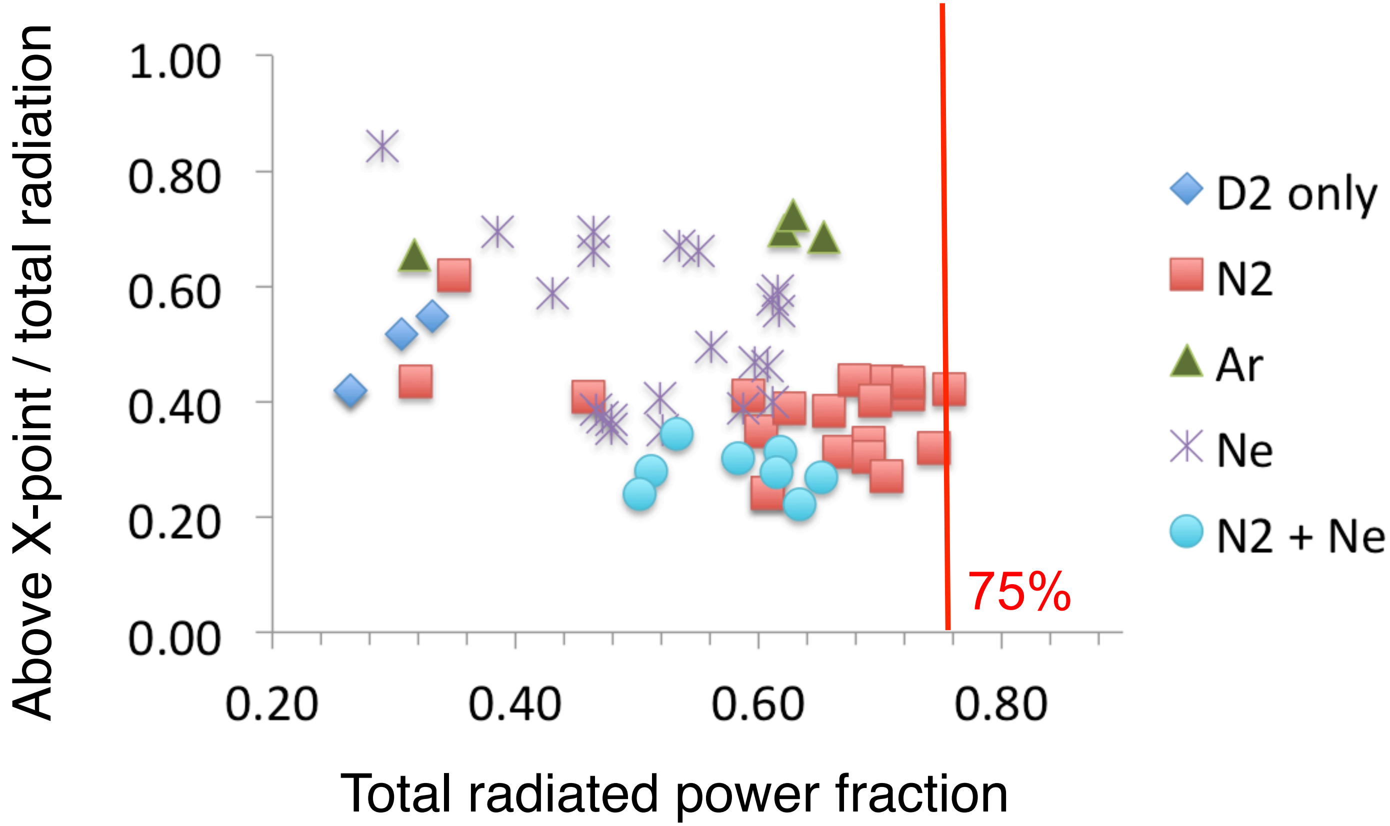
Above X-point ~ inside LCFS excluding X-point ➔due to poloidal distribution ~ core radiation

Divertor and X-point

A. Huber et al. EPS 2014

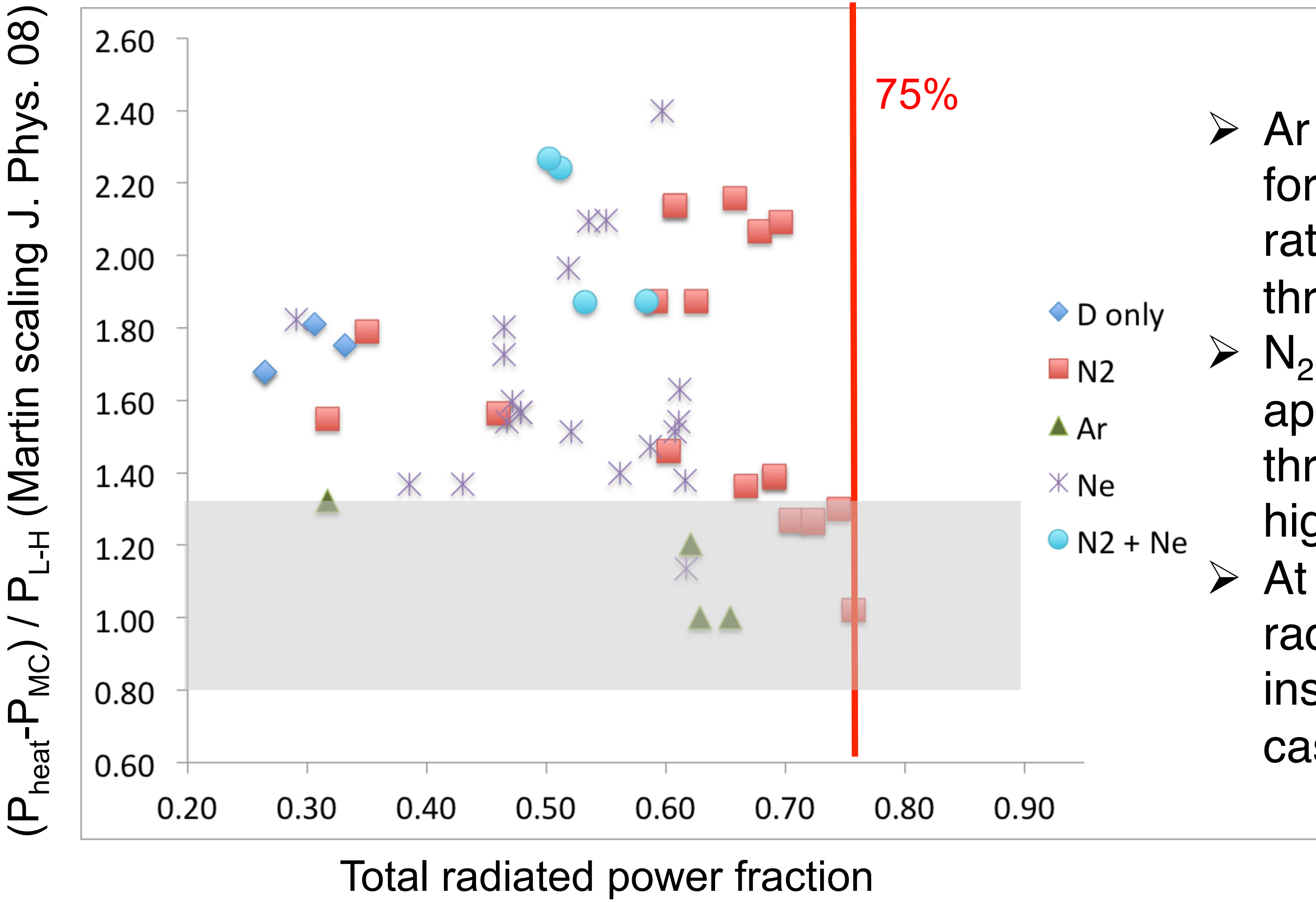
M. Wischmeier et al. PSI 2014

Limit of radiation above X-point for N_2



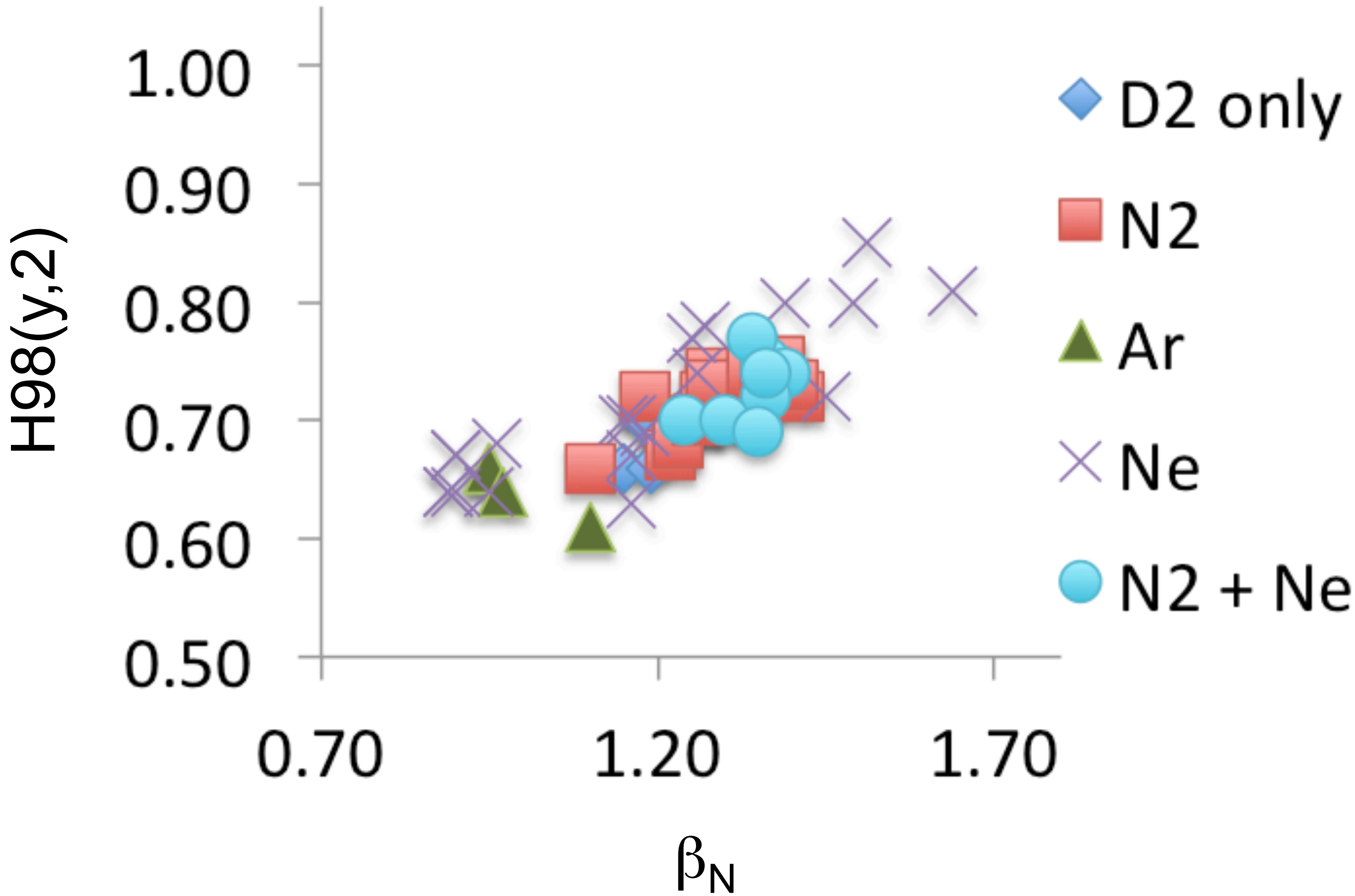
- Lowest fraction of above X-point radiation for seeding that includes N_2
- Fraction of experimental radiation above X-point not directly comparable to requirements for DEMO

Above f_{rad} of 70% close to L-H threshold



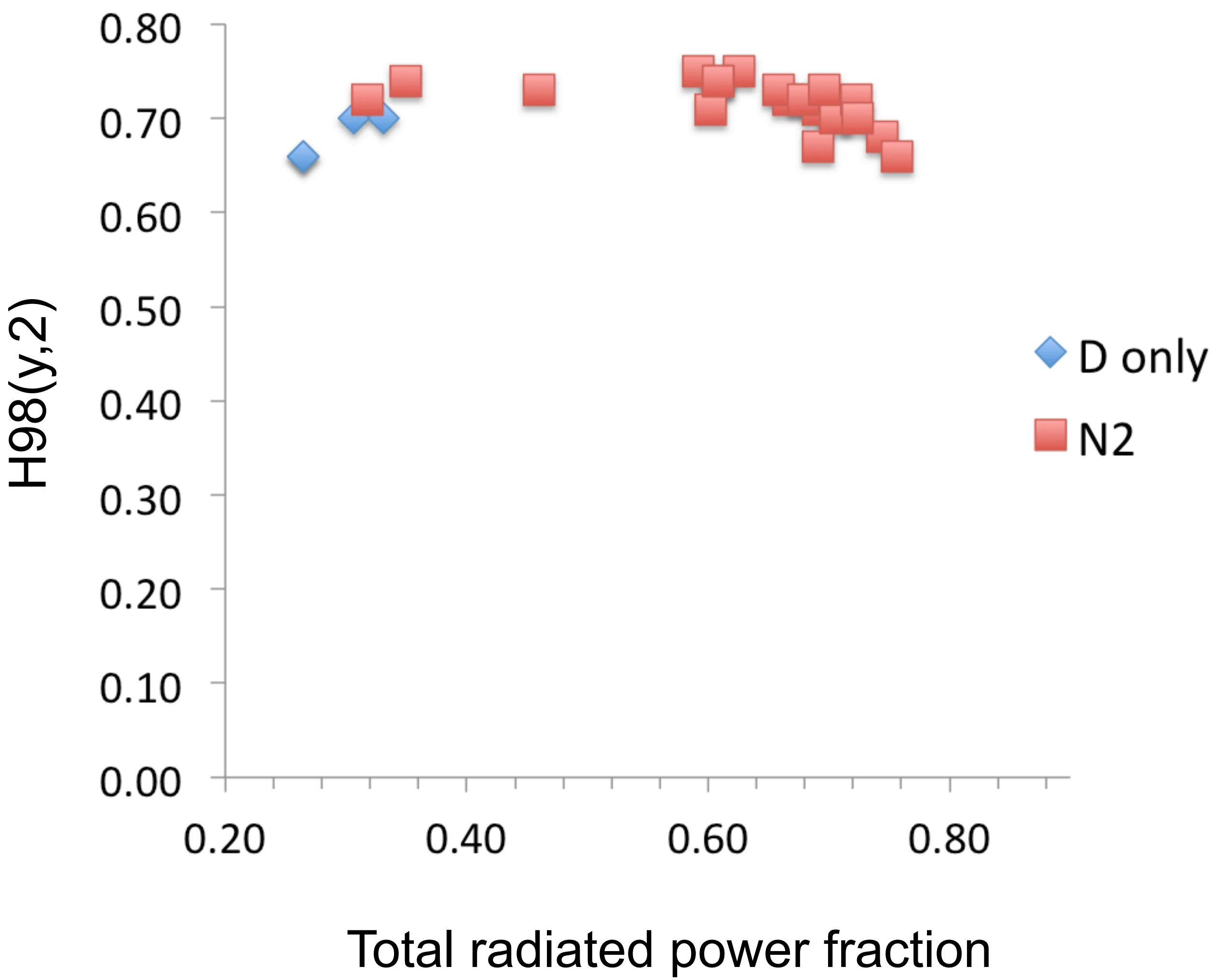
- Ar seeding even for low seeding rates close to L-H threshold
- N_2 seeding approaches threshold for highest f_{rad}
- At low ratios radiative instabilities in case of Ne

Impact of seeding on confinement scaling

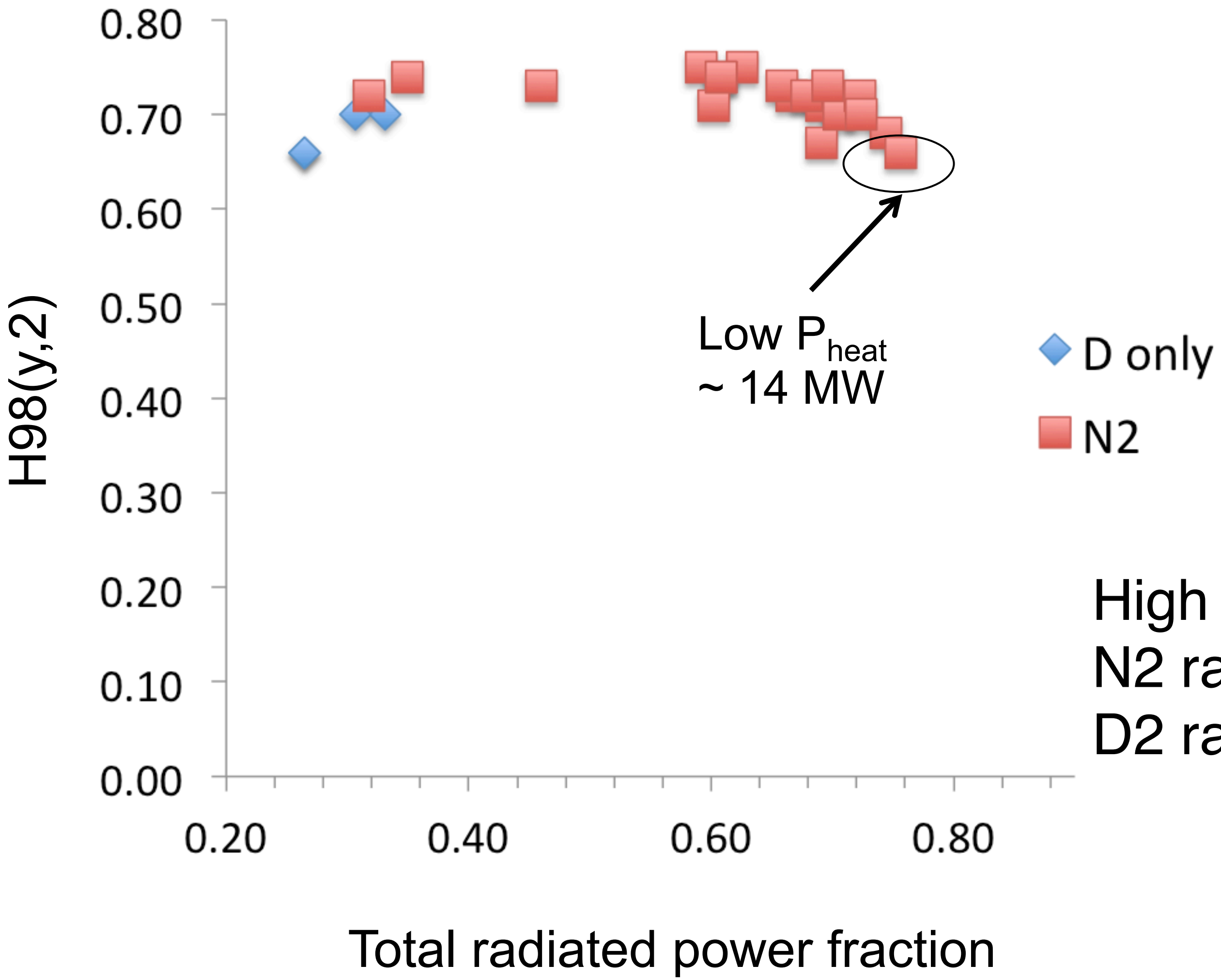


In highly seeded discharges H98(y,2) is function of β_N

Impact of N_2 seeding on confinement scaling



Impact of N_2 seeding on confinement scaling

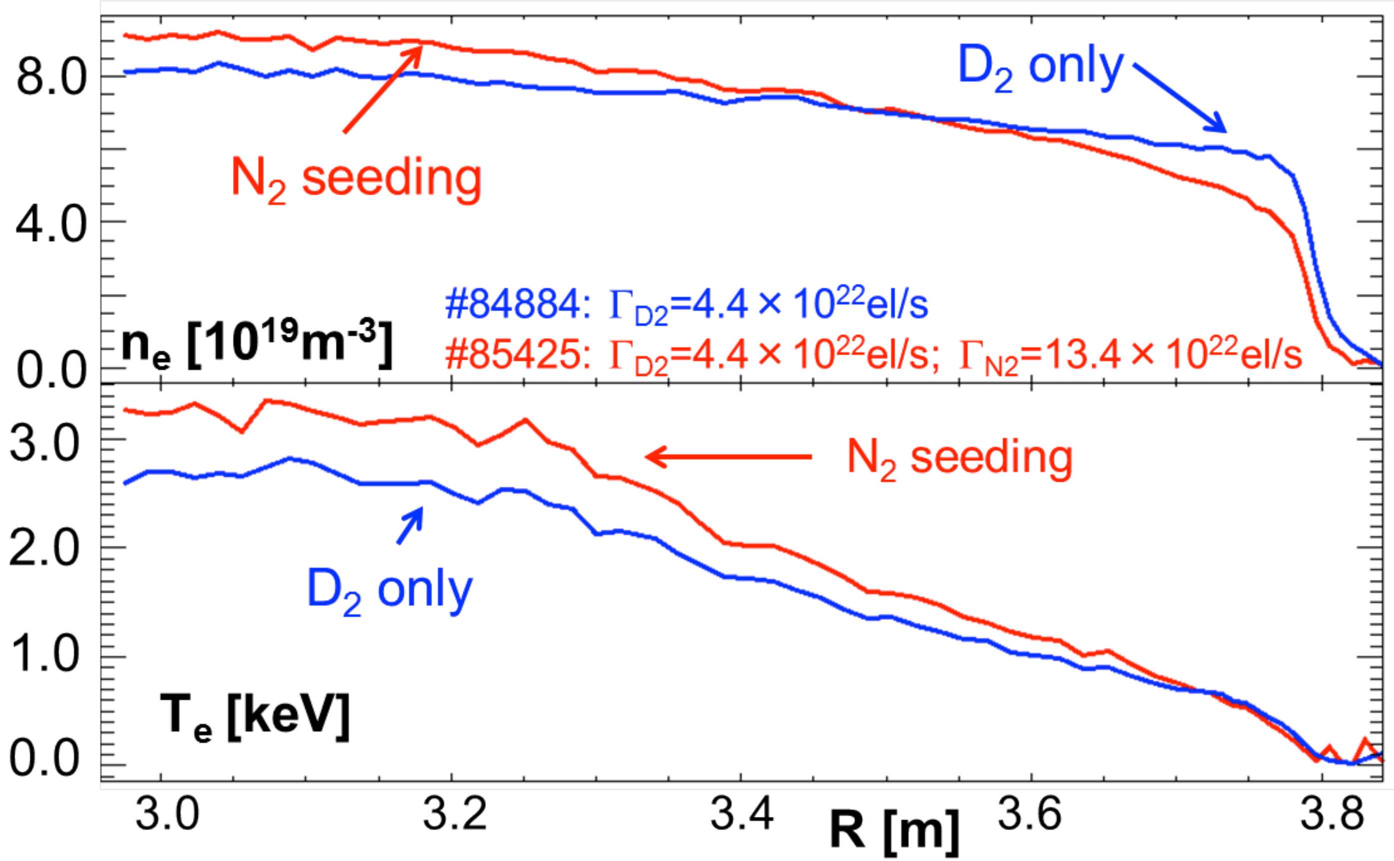


High fueling and seeding levels

N2 rate: 5 – 18 10^{22} el s^{-1}

D2 rate: 2 – 6.5 10^{22}el s^{-1}

Core & pedestal profiles at high f_{rad}



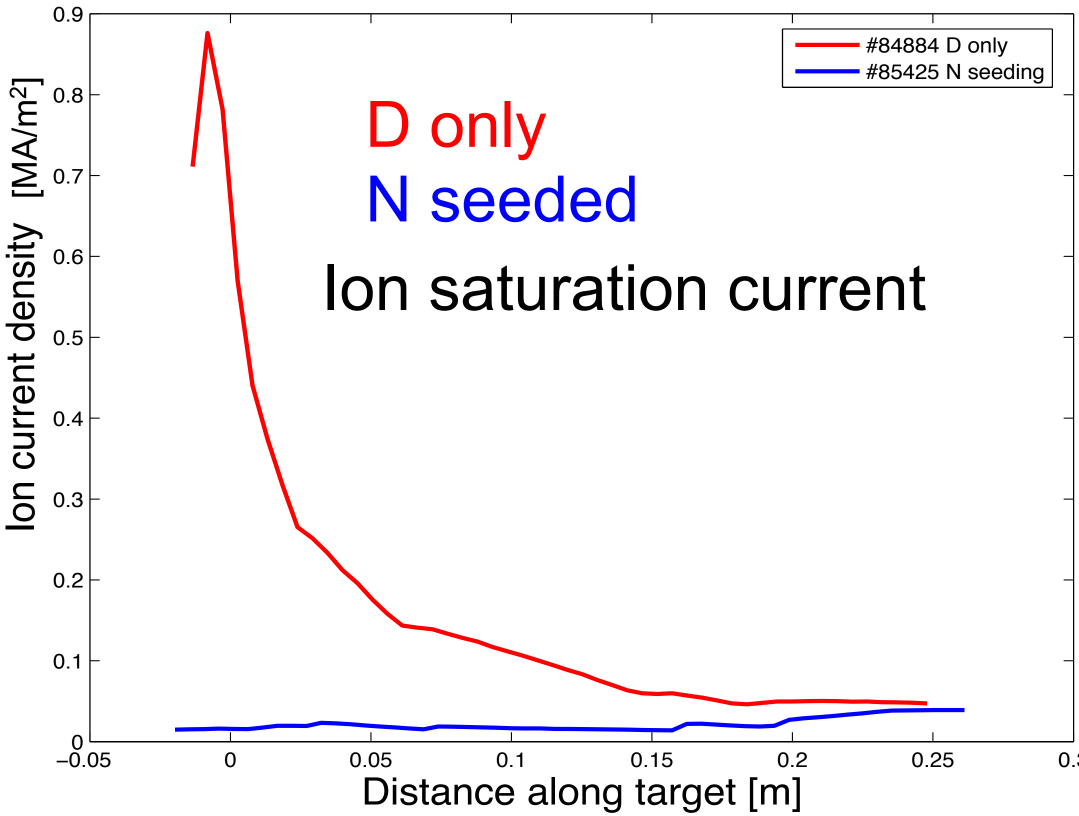
P_{heat} ~ 20MW

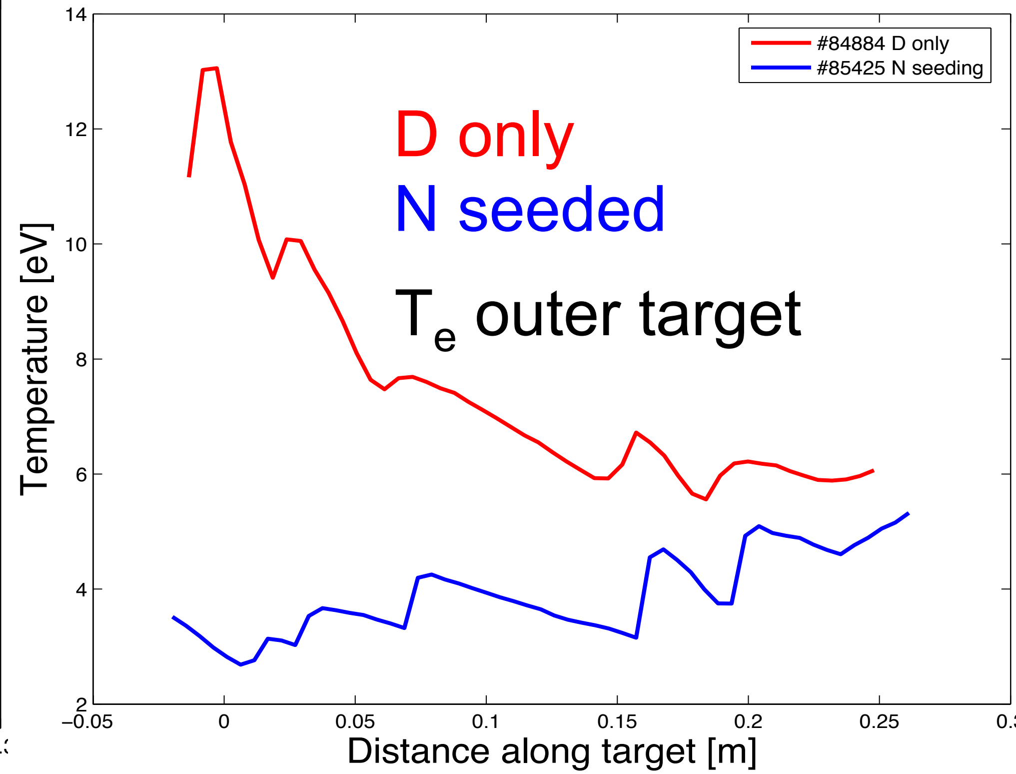
A. Huber et al. EPS 2014

- With N2 seeding mainly pedestal n_e depletes
- Profiles recover and surpasses unseeded values in core
- No reliable information on changes in SOL profiles yet

JET: Complete detachment with N_2

Time averaged outer target LP profiles for 12s -14s for #84884 and #85425





Distance along outer target [m]

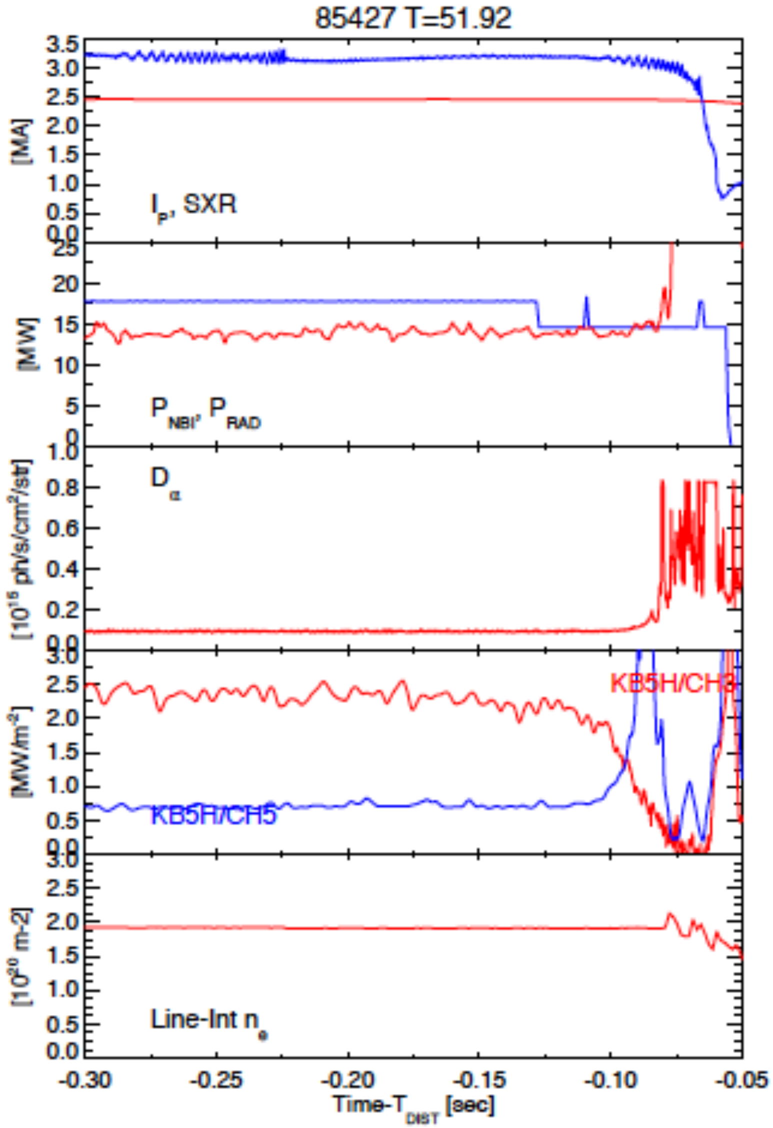
M. Wischmeier et al. PSI 2014

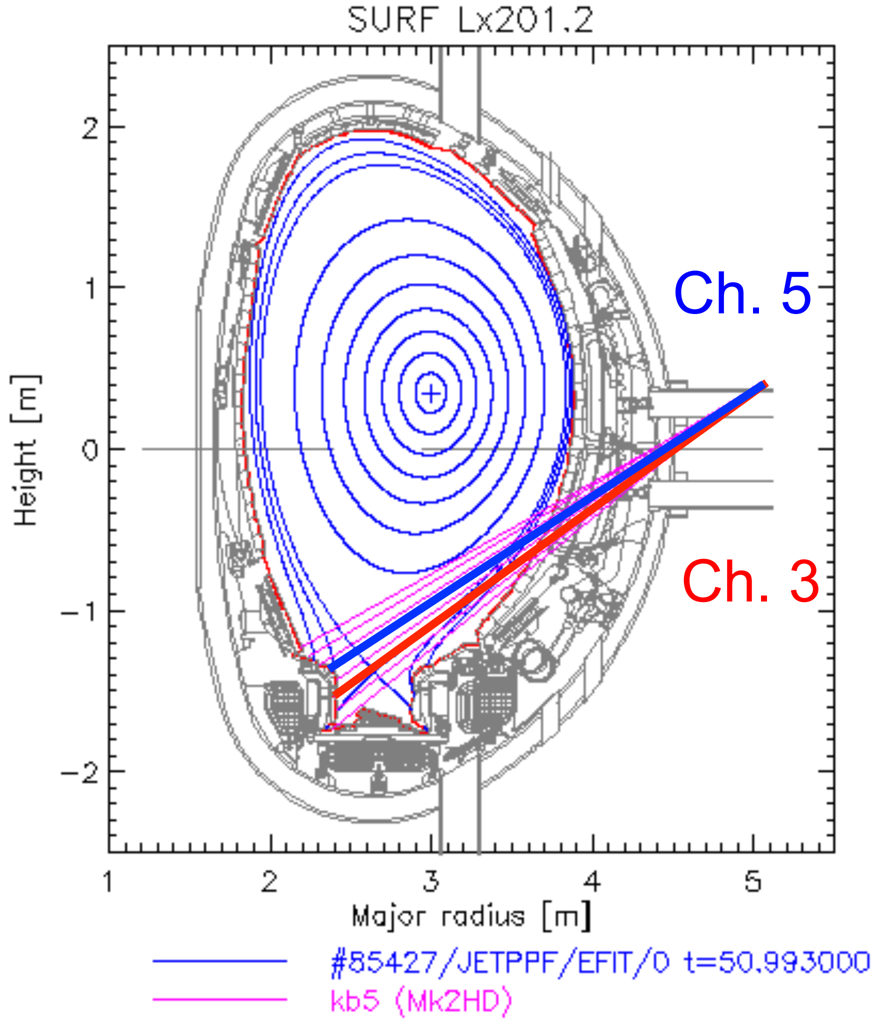
- Highest N_2 seeding evolves to complete detachment on outer and inner target
- Complete detachment coincides with strong radiation at X-point

Similar to ASDEX Upgrade (A. Kallenbach et al. EX/7-1, F. Reimold et al., subm. to Nucl. Fusion)

Operational stability of radiation

Loss of NBI power and no backup





Numerical modeling

- COREDIV: 1D core modeling and 2D slab geometry for SOL (G. Telesca et al. PSI2014)
  - For highest N2 seeding, radiation in divertor does not increase further due to low divertor T_e
  - Highest f_{rad} with X-point not accounted for due to 1D core (strong poloidal gradients in T_e and radiation)
- EDGE2D-EIRENE simulations demonstrate detachment achievable with N_2 seeding (TH/P5-34 A.E. Jarvinen et al.)
- Dedicated numerical modeling with full geometry pending
- SOLPS5.0 (w. EIRENE) simulations including activated drift terms for similar ASDEX Upgrade cases: complete detachment induced by loss of upstream pressure due to strong X-point radiation (EX/P3-16 P M. Wischmeier et al. , F. Reimold et al. PSI 2014)

Conclusions

- Stable discharges with radiation peaked around X-point for N_2, Ne, Ar and N_2+Ne
- Maximum radiation independent of heating power
  - Maximum radiation achieved 75% - DEMO requires > 90%
  - Physics reason not yet understood – link to maximum stable radiation in edge region?
  - ELM mitigation for marginal H-mode
- Stable completely detached outer and inner divertor achieved
- Pedestal profile degradation recovered by steeper core profiles
- Future: Combine seeding of higher Z at higher P_{heat} with N_2