Effect of Higher-Z Impurity Seeding on Divertor Plasma

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1. Impurity seeding is necessary for ITER and DEMO

The steps from present devices to ITER, and then towards Demo are big

• Substantial increases in

	Best achieved	ITER	DEMO
Fusion power (MW)	16 (JET)	350	3000
Heating power (MW)	40 (JT-60U)	140	654
Stored plasma energy (MJ)	12.9 (JET)	290	1215

• But relative small change in

Major radios (m)	3.56 (JT-60U)	6.35	6.5

adapted from Mukhovatov, V., et al., Nucl. Fusion 47 (2007) S404

• Future beryllium wall and tungsten divertor will abandon carbon as the main radiator.

→ High radiation fraction scenarios with high energy confinement
→ Higher-Z impurity seeding

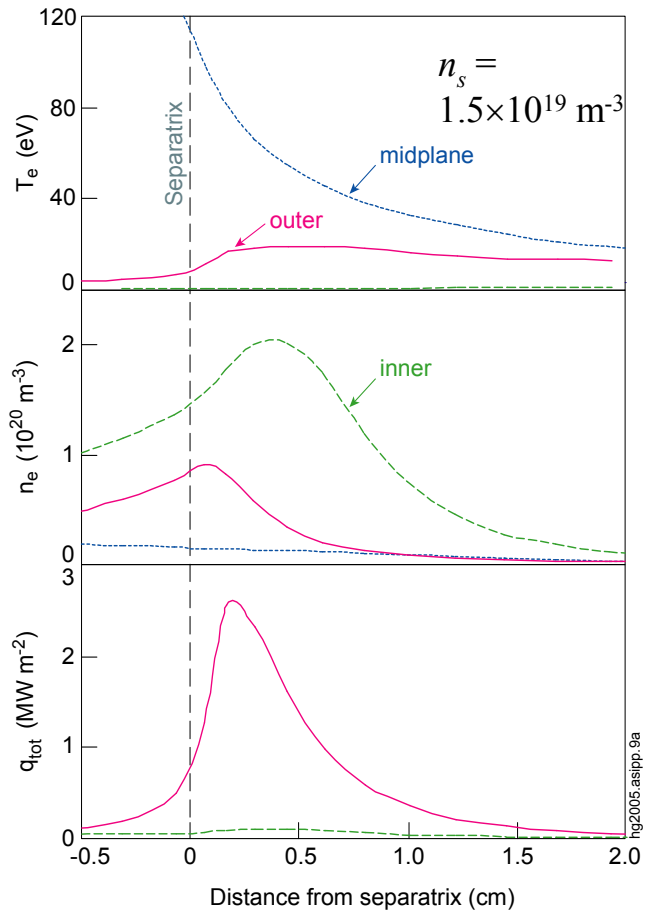
2. Reduction and in-out asymmetrymitigation of divertor power load through impurity seeding

Toroidal geometry + poloidal drifts
→ Strong asymmetries in the in-out divertor power deposition, favouring the outer target.

Simulation for the EAST CDN shows:
- Plasma is fully detached from inner target.
- Most of the outer divertor plasma still remains attached.

▪ Full plasma detachment at inner target may lead to confinement degradation.

▪ It is undesirable to have substantial power flux going to the outer target for long pulse operation, particularly at high power.



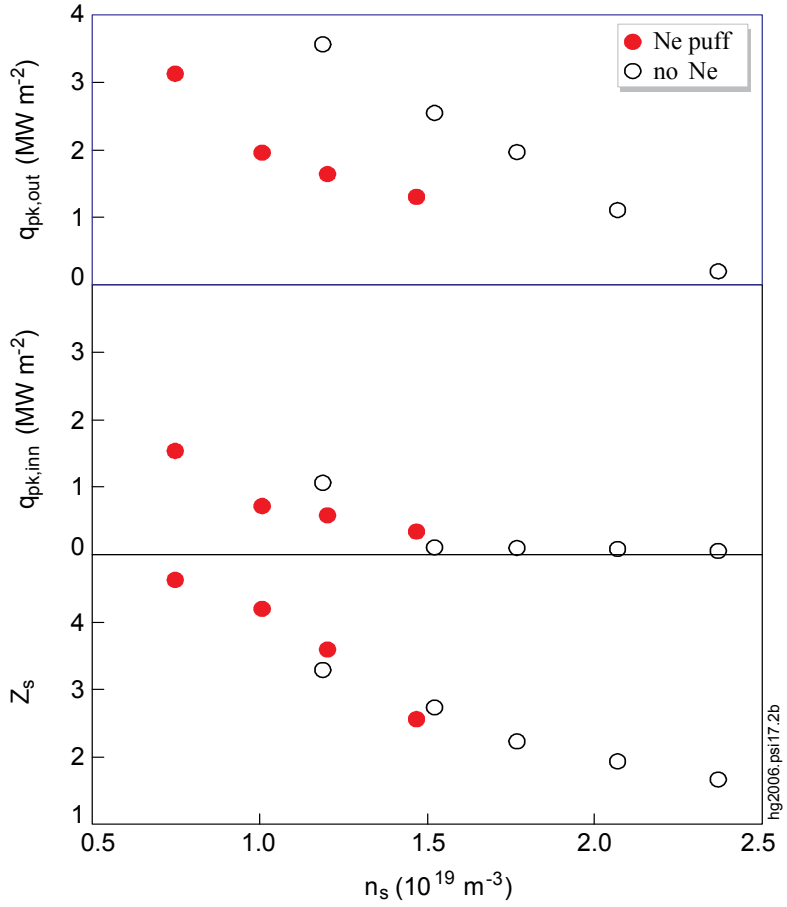
Reduction and in-out asymmetry mitigation of divertor power load through impurity seeding

Ne seeding is simulated for the EAST CDN configuration with a puff rate of $10^{20}s^{-1}$, and *Ych* =2%.

1. Dramatically reduces the heat fluxes to the outer divertor target plates.

2. Mitigates the degree of the in-out divertor power load asymmetry.

3. Does not appear to affect much the edge impurity content under these modeled conditions.



JET experimental results: divertor energy deposition profile in neon seeding case

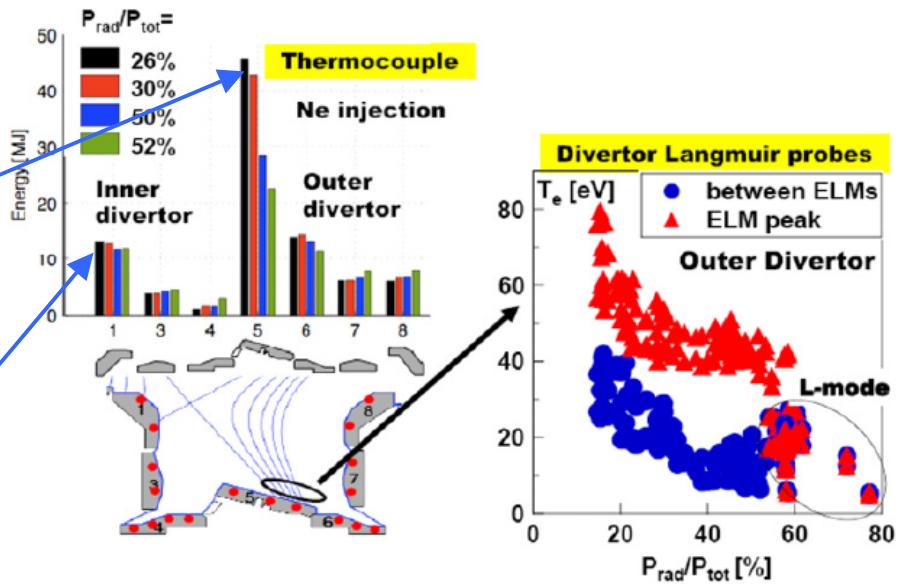
The energy deposition profile is more uniformly distributed as P_{rad}/P_{tot} increased.

The energy at the outer divertor strike point is reduced by more than a factor of 2.

The energy flowing to the inner divertor strike point is only slightly reduced as P_{rad}/P_{tot} increased.

→ Better symmetry of the in-out divertor power load for neon seeding

Litaudon, X., et al.,
Plasma Phys. Control. Fusion 49 (2007) B529–B550

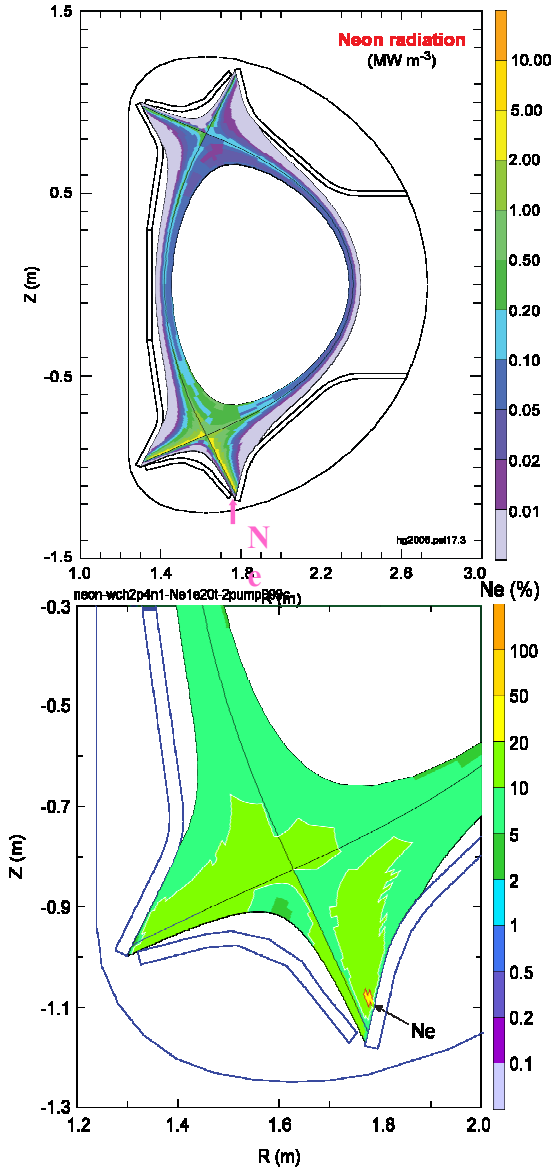


JET discharges Nos 69987, 69981, 70291, 70285

Neon radiation and concentration

The simulations of the Ne seeding for EAST indicate Ne radiation is well restricted to the vicinity of the lower divertor due to:

- Strong divertor/SOL screening at sufficiently high densities.

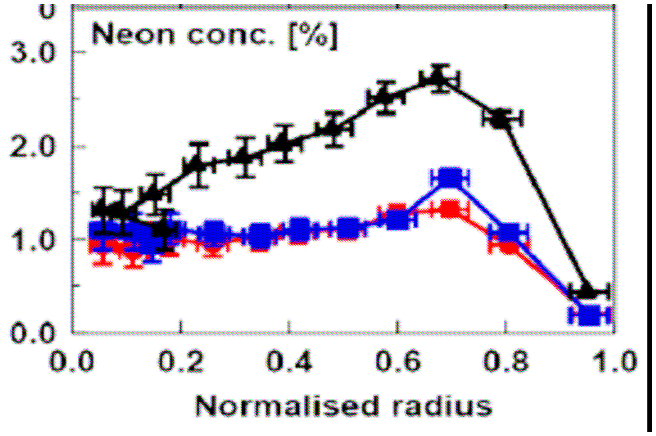


Experimental results: Neon concentration

Litaudon, X., et al.,
Plasma Phys. Control. Fusion 49 (2007) B529–B550

The neon concentration profile is hollow with a concentration of about:

- 1% in the core
- Rising to~2.5% at a normalized radius of 0.7.



JET discharges Nos 69091 ($Ne+D_2$), 69092 ($Ne+D_2$), 69093 (mainly Ne)

3. Effect of impurity seeding on ELM mitigation

- Unmitigated ELMs on ITER would correspond to ~20MJ/ELM

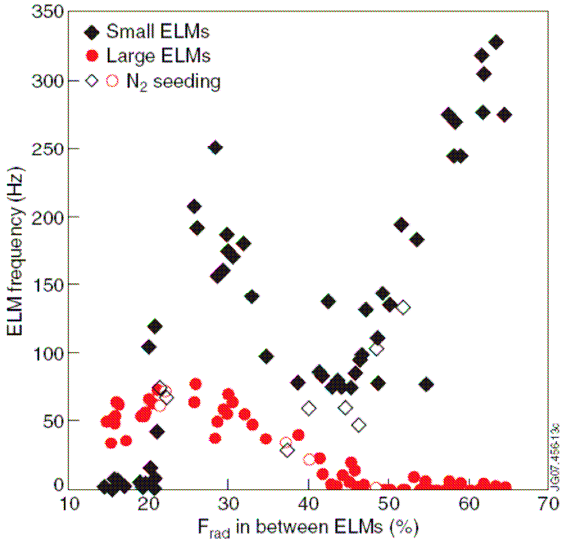
- But an incident energy impulse of ~1MJ
  - → ablate or melt divertor materials
  - → potentially degrade the purity of ITER plasmas
  - → greatly reduce the lifetime of the ITER divertor.

→ A need to reduce the energy loss by a factor of ~20, even at the cost of a partial loss of confinement.

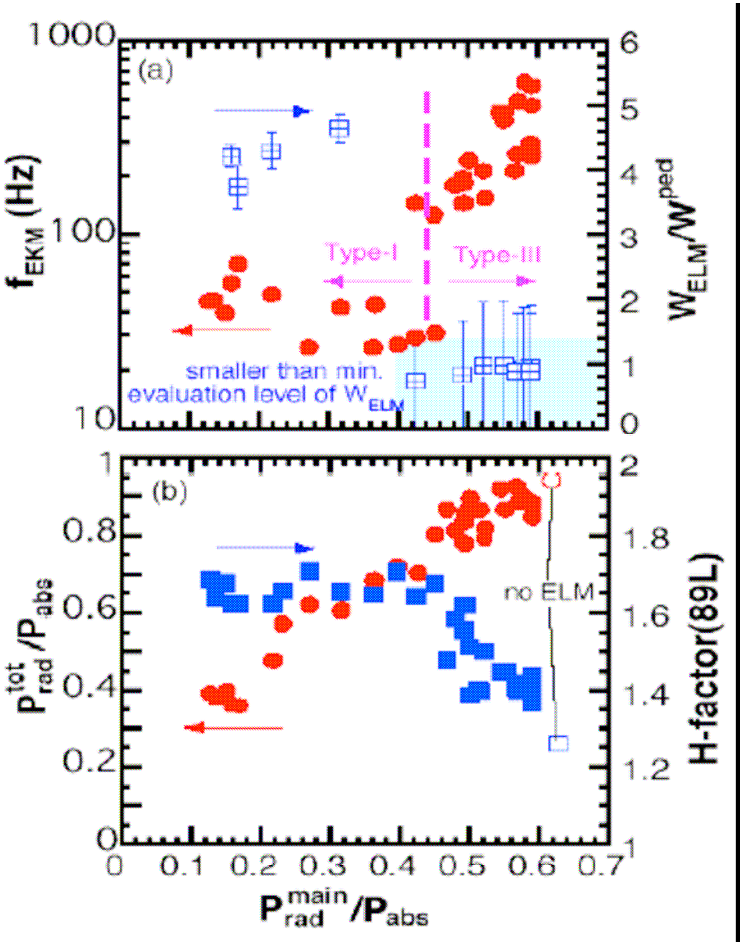
- Active control of Type-I ELM
  - Radiating divertors (Impurity seeding)
  - Magnetic triggering (“vertical kicks”)
  - Pellets pacing making
  - Edge ergodization / external edge resonant magnetic perturbation fields

Mitigation of ELM peak heating load

JET Beurskens, M.N.A., et al., Nucl. Fusion 48 (2008) 095004



JT60-U Asakura, N., et al., 22nd IAEA FEC, (Geneva, Swiss) EX/4-4Ra 2008

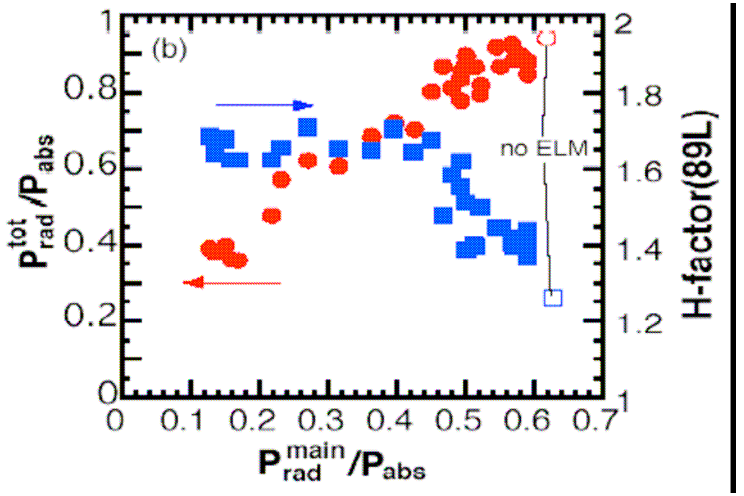


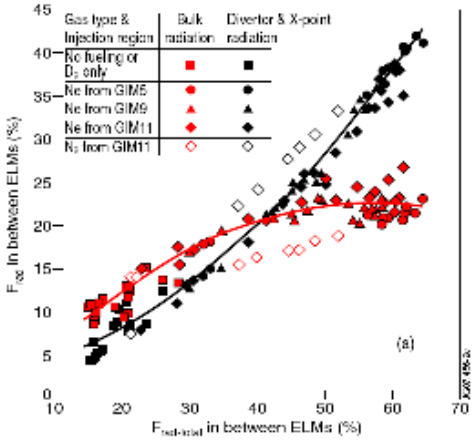
Changing the radiation fraction can mitigate ELM peak heating load with minimum degradation of the energy confinement.

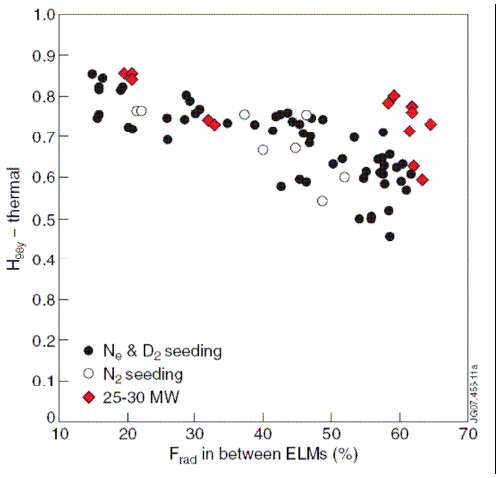
4. Effect of Impurity Seeding on H-factor

Beurskens, M.N.A., et al.,
Nucl. Fusion 48 (2008) 095004

Asakura, N., et al., 22nd IAEA FEC,
(Geneva, Swiss) EX/4-4Ra 2008







- There is a phase with relative constant confinement H-factor with type I ELM.
- The confinement is degraded at the transition from type I to type III ELMs.

5. Effect of impurity seeding on ITB sustainment

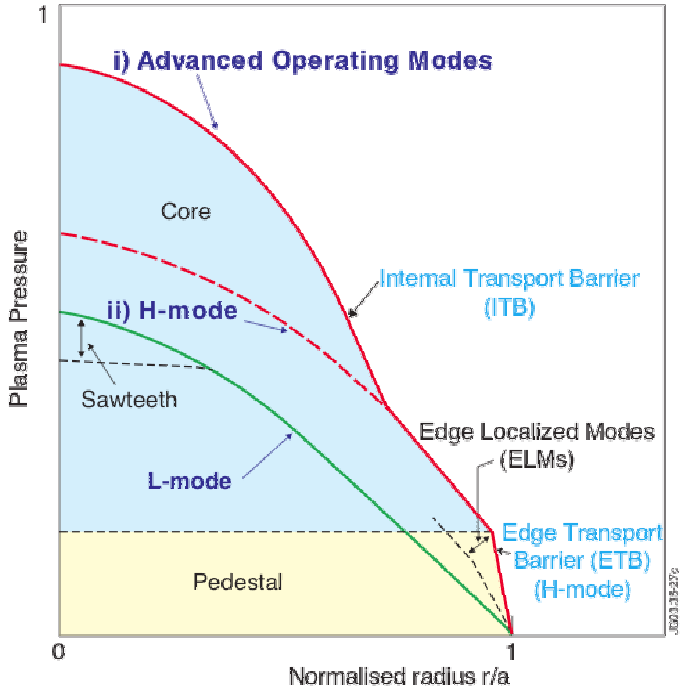
Advanced tokamak scenario is essential for establishing steady-state operation.

- Enhanced core confinement advanced scenarios - ITB
- Reduced edge transport H-mode - ETB

→ improved bootstrap current

→ steady-state operation

The foot of a high confinement ITB need to be located at a relatively large radius.

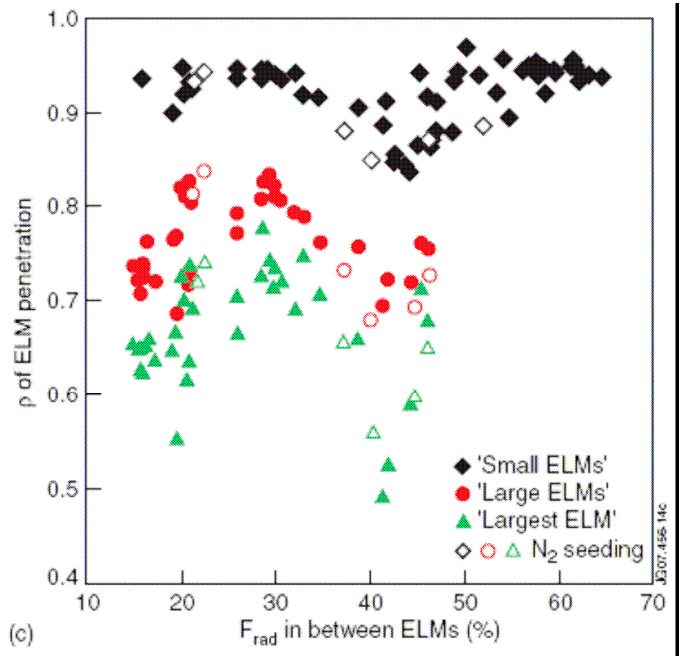


To limit the maximum ELM penetration depth

Beurskens, M.N.A., et al.,
Nucl. Fusion 48 (2008) 095004

Large periodic edge pedestal relaxations due to type I ELMs
→ the perturbation will penetrate deep into the plasma and reach the ITB location
→ cause a loss of ITB

Impurity seeding can possibly be used to limit the maximum ELM penetration depth and favor ITB sustainment.



6. Effect of impurity seeding on operating window

Pacher, H.D., et al., 18th Int. Conf. on Plasma-Surface Interactions (Toledo, Spain) O-27 2008
Pacher, G.W., et al., Nucl. Fusion 48 (2008) 105003

No C + 0.45% Ne

Higher radiation P_{rad}

→ Lower SOL power P_{SOL}

→ Unfavorable for LH transition limit P_{SOL} / P_{LH}

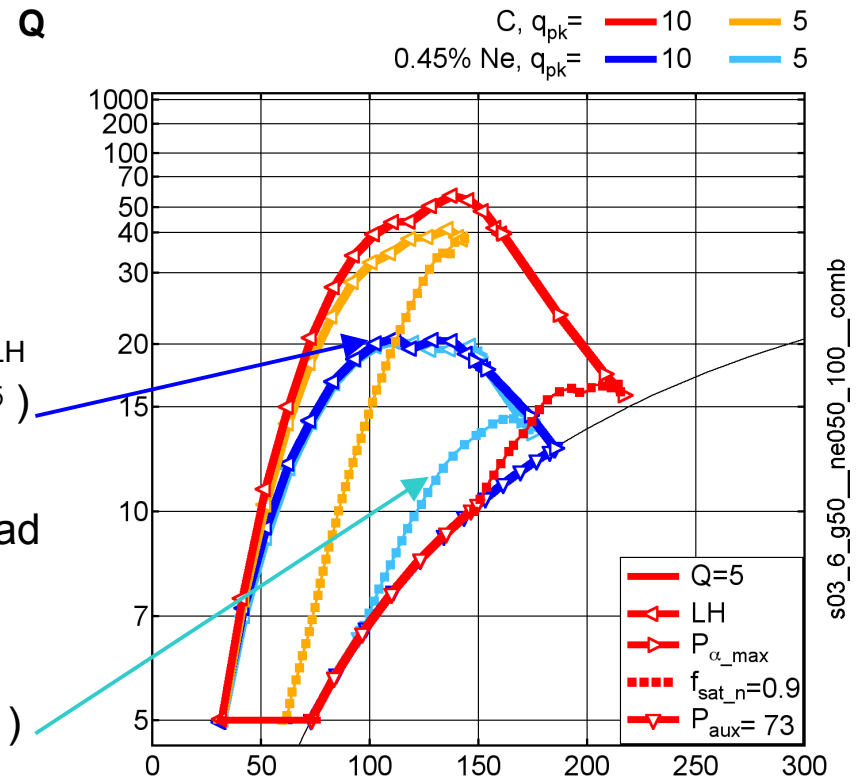
→ Reduction of the accessible Q (10 5)

\+ Mitigated in-out asymmetry of divertor power load

→ Lower DT throughput required

→ Less constraint of edge density limit f_{sat_n}

→ Higher attainable alpha power P_{alpha} (5)



C vs. no C + 0.45% Ne, q_{pk}=5&10

7. Summary and discussion

• Reduction and in-out asymmetry mitigation of divertor power load can be obtained through impurity seeding.

• Changing the radiation fraction can mitigate ELM peak heating load with minimum degradation of the energy confinement.

• Impurity seeding can possibly be used to limit the maximum ELM penetration depth and favor ITB sustainment.

• To predict the impurity seeding scenarios of ITER and DEMO, we might need to consider:

- the effect of the seeded impurity on the SOL/divertor region.
- pedestal and ELM response to impurity seeding
- strong coupling between core plasma and divertor operation

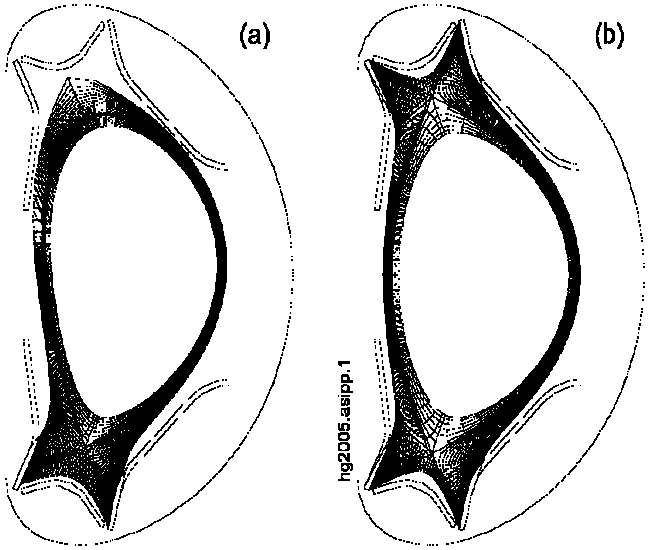
Summary and discussion

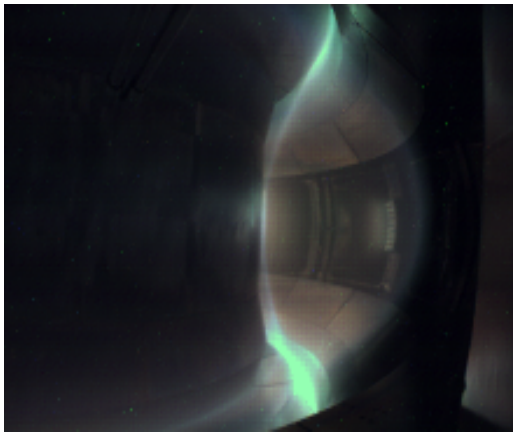
But

• Theory-based transport models self-consistently describing SOL, pedestal and core regions are not yet sufficiently mature.

• Due to the higher temperature and lower collisionality $\nu*$, the physics processes in ITER and DEMO plasma edge might differ significantly from those of present experiments.

EAST Divertor Configurations





	SN	CDN
Major radius, R (m)	1.94	1.94
Minor radius, a (m)	0.46	0.47
Elongation at separatrix, κ_s	1.69	1.76
Upper triangularity at separatrix, δ_{su}	0.32	0.56
Lower triangularity at separatrix, δ_{sl}	0.54	0.56
Plasma volume, V_p (m^3)	11.9	12.5