Multi-machine SOLPS-ITER comparison of impurity seeded H-mode radiative divertor regimes with metal walls

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Goals

- Check the possibility of partially detached divertor solutions at high divertor neutral pressure on ITER for baseline burning plasmas with both neon (Ne) and nitrogen (N) low Z seeded impurity. Ne is preferred on ITER in DT plasmas to avoid impact on machine duty cycle due to the formation of tritiated ammonia
- Understand observations on smaller devices, such as ASDEX-Upgrade (AUG), in which Ne compression is reduced in comparison with N, pedestal plasma performance is compromised
- Predictive modeling for high power JET ITER-like experiments with N and Ne
- Understanding the fundamental controlling physics responsible for different behavior, in particular the impact of scale size as well, as other parameters

Factors that determine impurity redistribution

- Relative role of ExB and grad B drifts is smaller for larger machines, both for main plasma and impurity redistribution between outer and inner divertors
- Distribution of ambient D^+ poloidal flows, in particular role of reversal flows away from the divertor which depend on the machine size
- First ionization potential (FIP) effect - elements with higher ionization potential are more effectively extracted from the divertor towards upstream, so that N is kept better than Ne in the divertor region
- Position of ionization front - in larger machines ionization of neutral particles is shifted closer to plates. In smaller devices ionization source inside the separatrix changes impurities distribution considerably

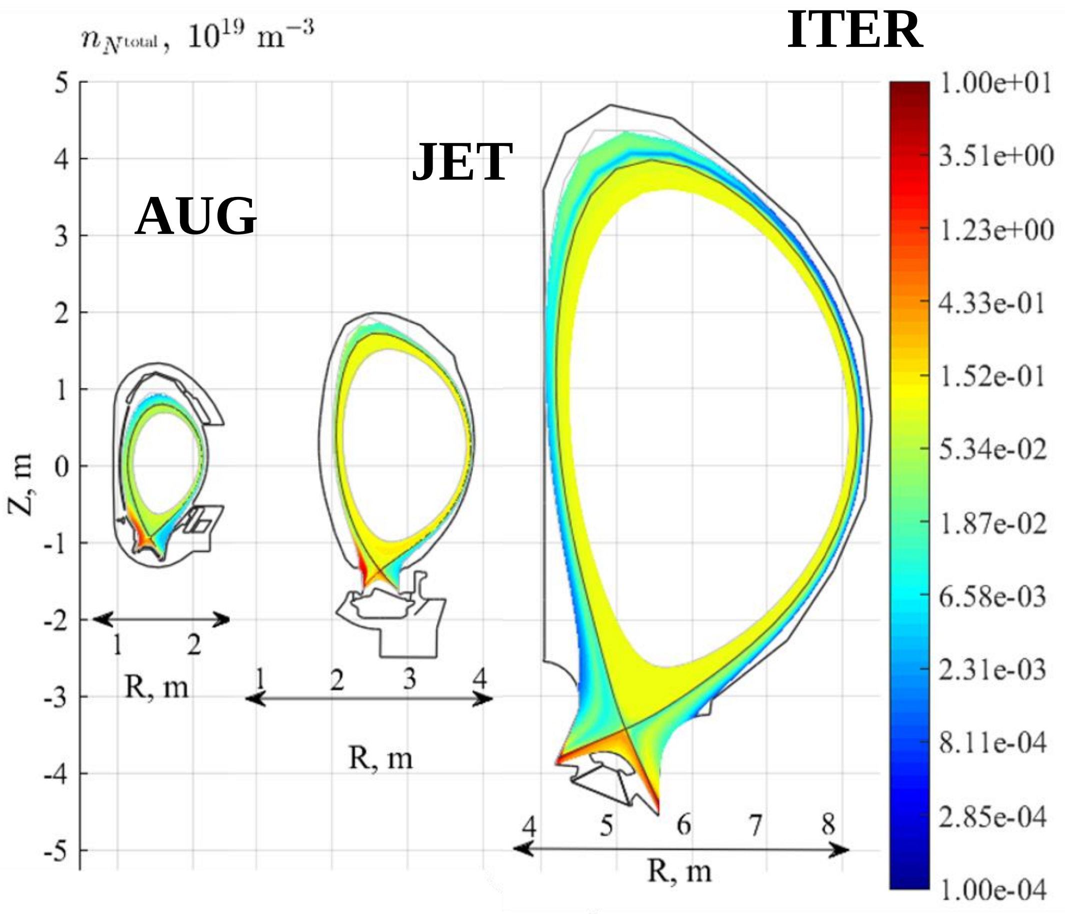
SOLPS-ITER simulations

- Modeling with full drifts and currents switched on
- AUG, JET and ITER were simulated
- Each tokamak with Ne and N
- Three semi-detached cases were chosen for detailed comparison
- Scan in radiator seeding gas puff to understand dependences on detachment degree for different scales machines-each point result of full modeling
- Databases for three tokamaks were created
- Modelling parameters for AUG and JET are inspired by existing experimental results

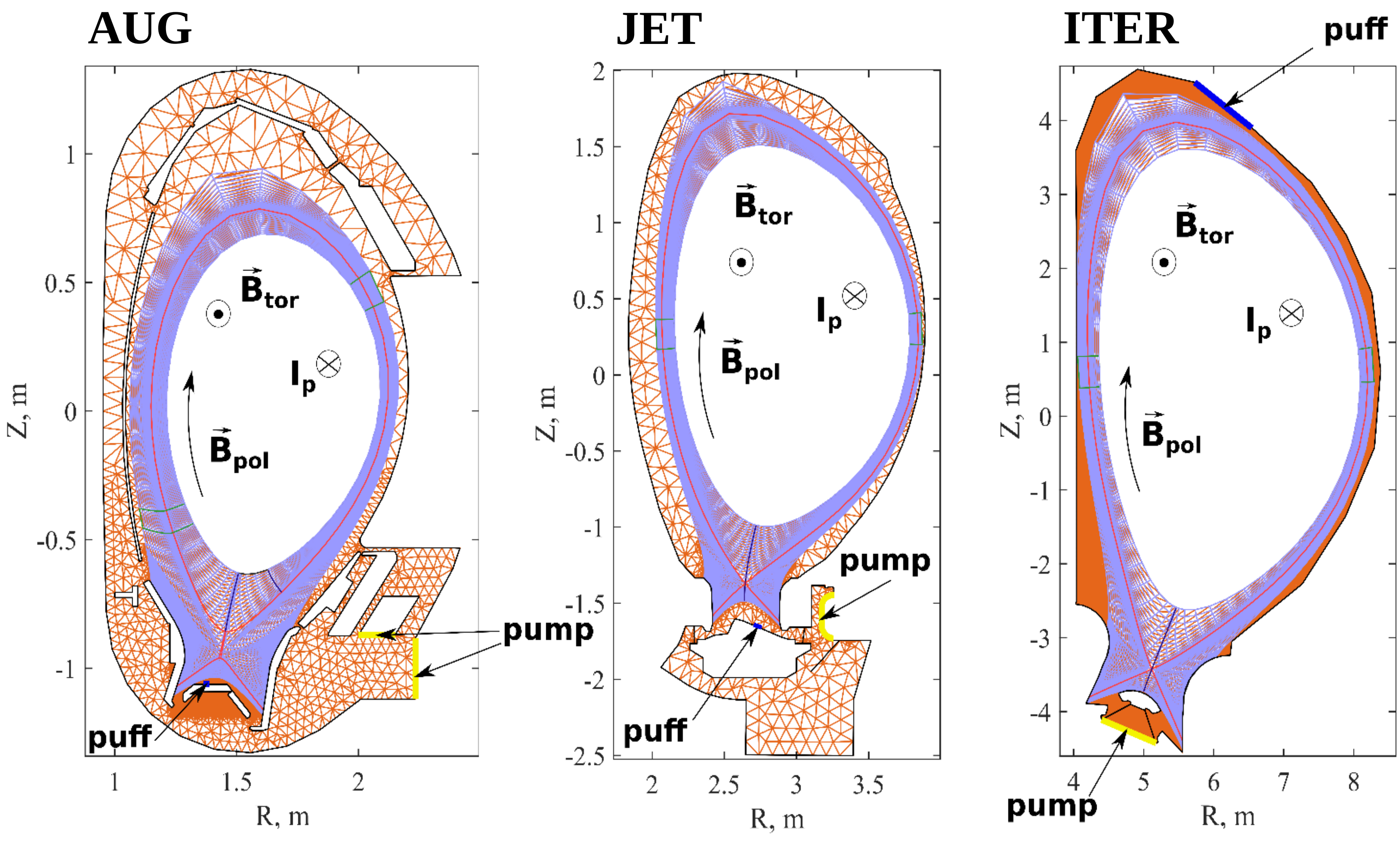
- see posters 1186 by R.Pitts, 977 by C. Giroud

Dimensions of three tokamaks

Color bar corresponds to typical nitrogen density distribution



Computational meshes for three machines

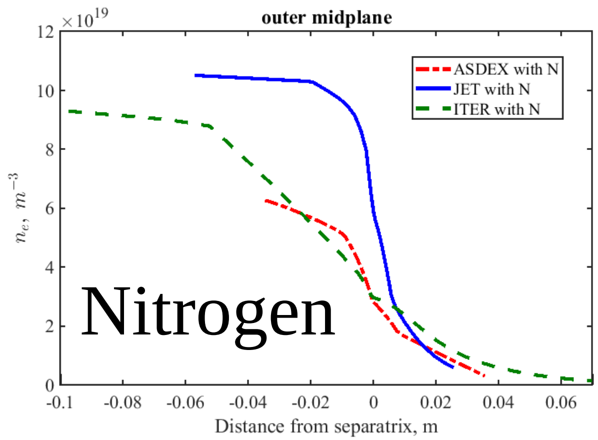


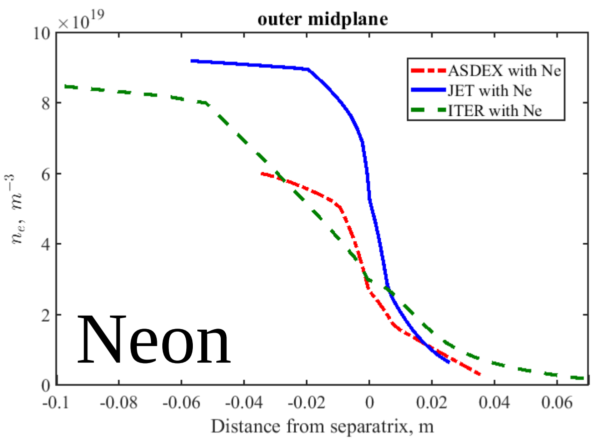
Three semi-detached cases for detailed comparison, 50% energy radiated.

	ITER, 100MW Ne	N	JET, 16 MW Ne	N	ASDEX-Upgrade, 5MW Ne	N
Separatrix power/ major radius, MW/m	16.1		5.3		3	
Btor	5.3		2.7		2.5	
λq(e),mm	3	3	3	3	1.6	1.4
q(e) max outer X-point, per target area (MW/m2)	34	37	19	13	14	19
q max outer target, MW/m2	7	7	3.3	3.4	2.3	2.9
Average impurity separatrix concentration, %	1.1	3	1.2	1.2	2.3	1.4
outer divertor radiation/separatrix power, %	26	26	16	15	13	10

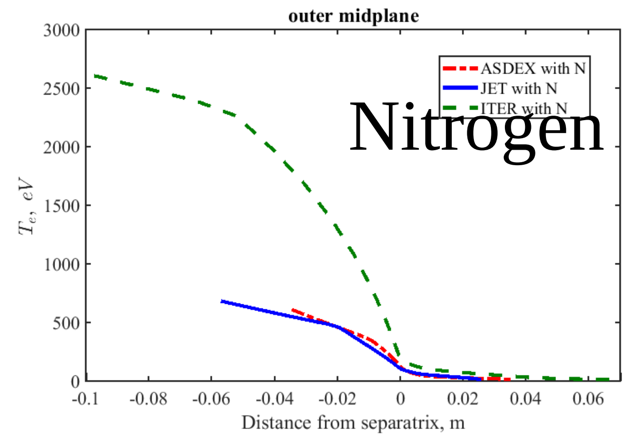
Outer midplane radial profiles.

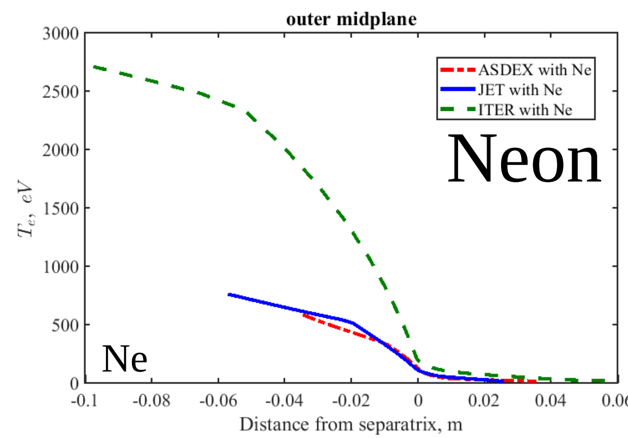
Electron density





Electron temperature





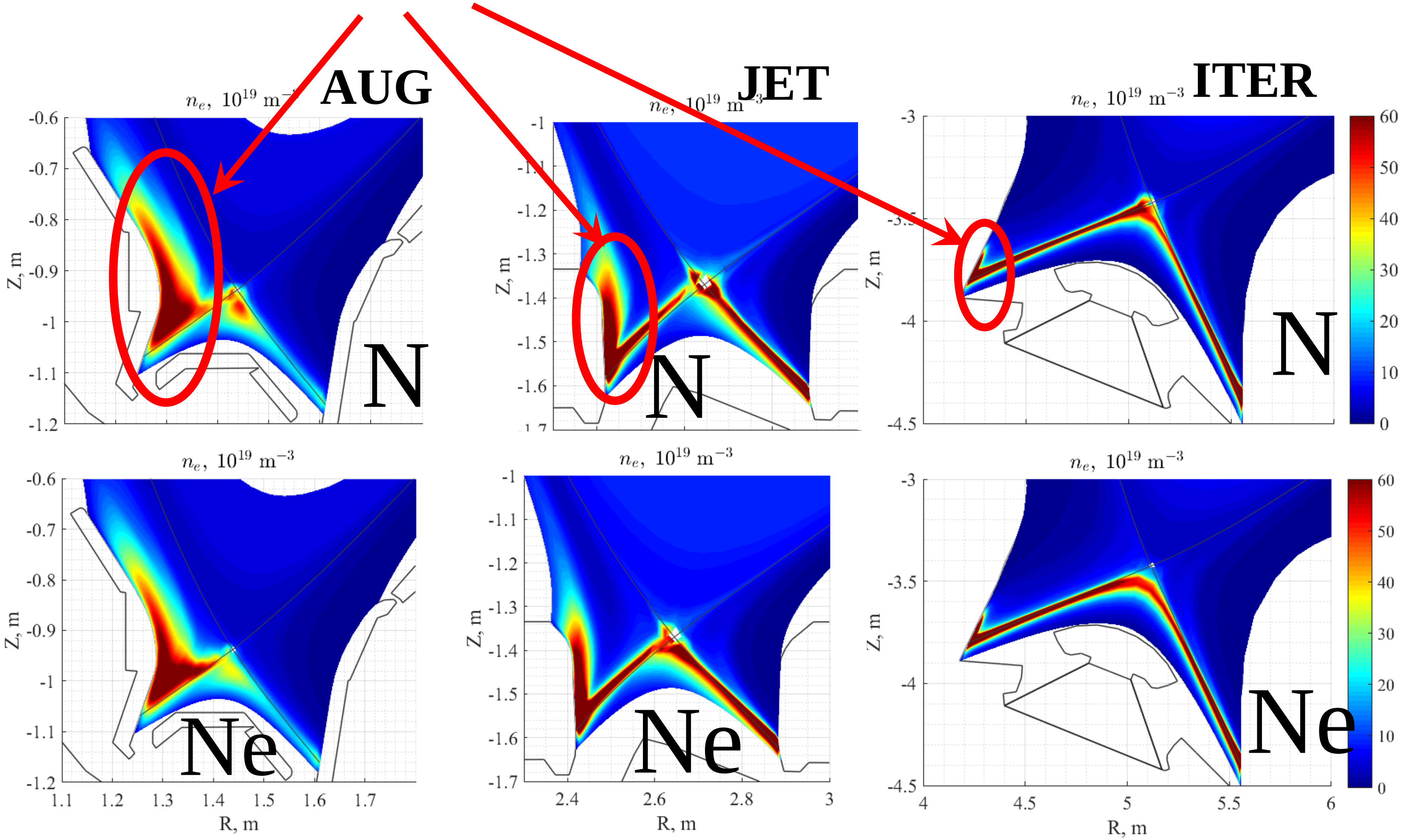
Ambient particle fluxes and divertor asymmetry

- Relative role of ExB and grad B drifts is smaller for larger machines, both for main plasma and impurity redistribution between outer and inner divertors

- Distribution of ambient D^+ poloidal flows, in particular role of reversal flows away from the divertor depends on the machine size

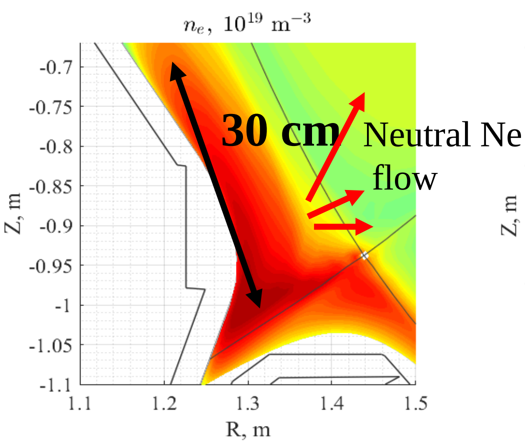
Electron density.

Formation of HFSHD region caused by radial ExB drifts.

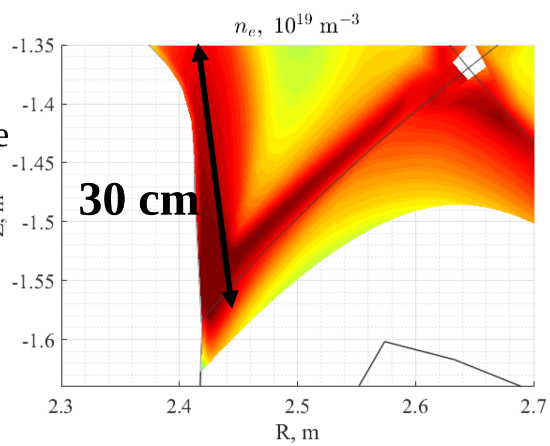


Electron density. Formation of HFSHD region caused by radial ExB drifts. Better resolution.

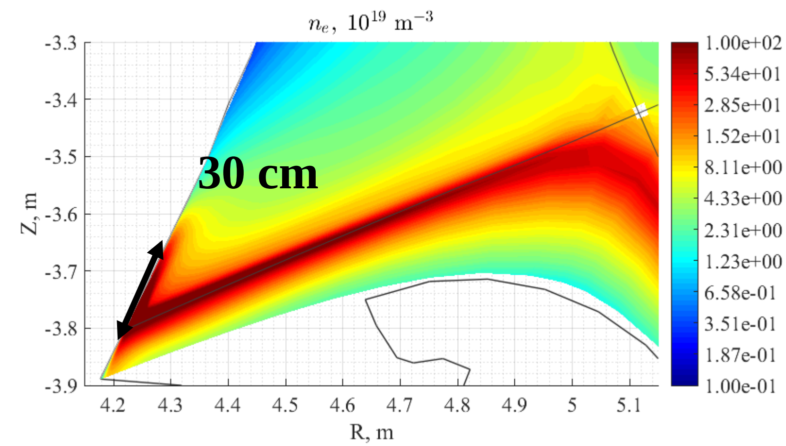
AUG with Ne



JET with Ne



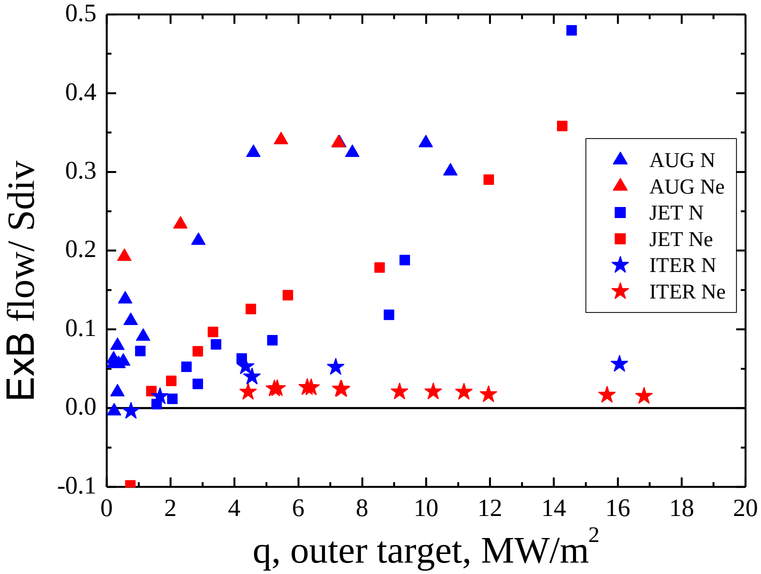
ITER with Ne



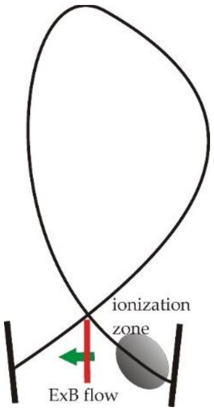
- **Dense and cold region expansion is of same dimension in three machines**
- **Distance from cold zone to X-point is smallest in AUG**
- **Better penetration of neutral Ne to pedestal region**

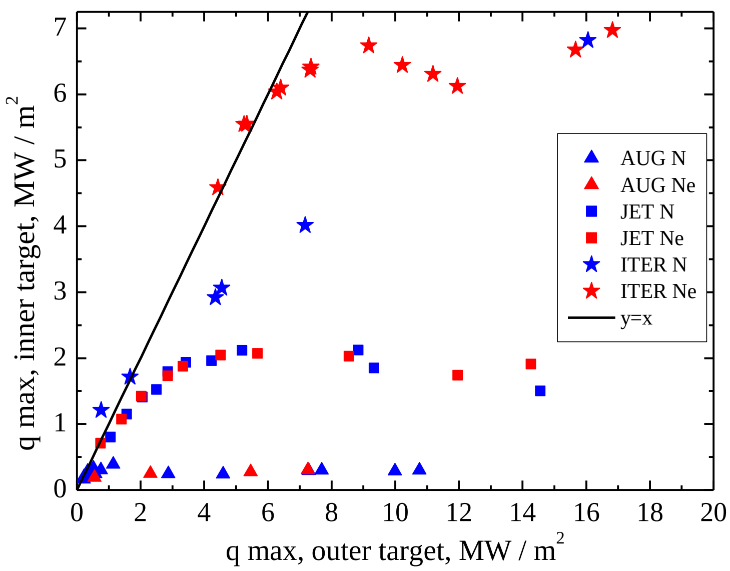
ExB drift and divertor asymmetry

- Relative role of ExB flow through PFR decreases with machine size and magnetic field increase
- Divertor asymmetry decreases with machine size and magnetic field increase
- Inner divertor is more detached and outer divertor is less detached for smaller machines



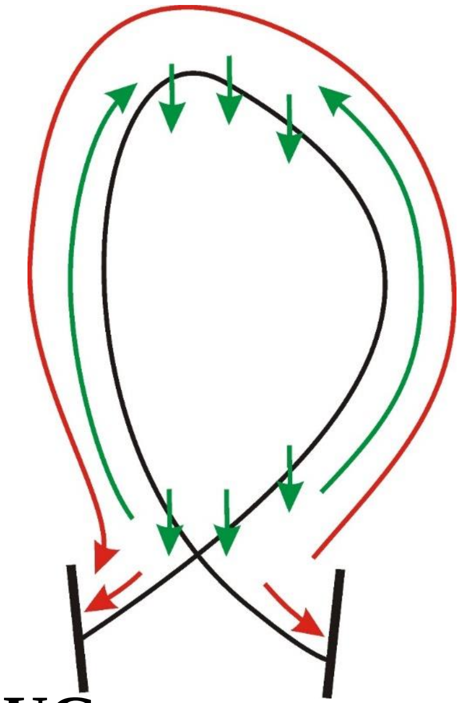
Ratio of ExB drift flow through PFR to ionization in outer divertor as function of maximal outer target heat load.

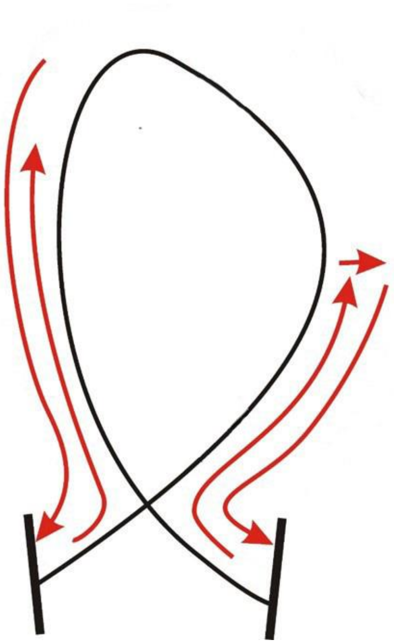




Maximal inner target heat load as function of maximal outer target heat load.

Poloidal projections of parallel ambient flows.





AUG:

Green arrows – Pfirsch-Schlueter (PS) flows and grad B flows in near SOL;

Red arrows – parallel flows caused by ionization, which is bigger in outer divertor.

ITER :

Role of PS and drift flows is reduced in large machines.

Red arrows – radial diffusion at outer midplane and poloidal flows closing it with zones of exceeding ionization in strike-point vicinity.

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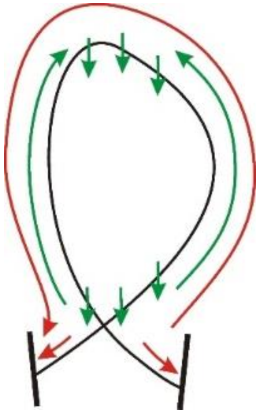
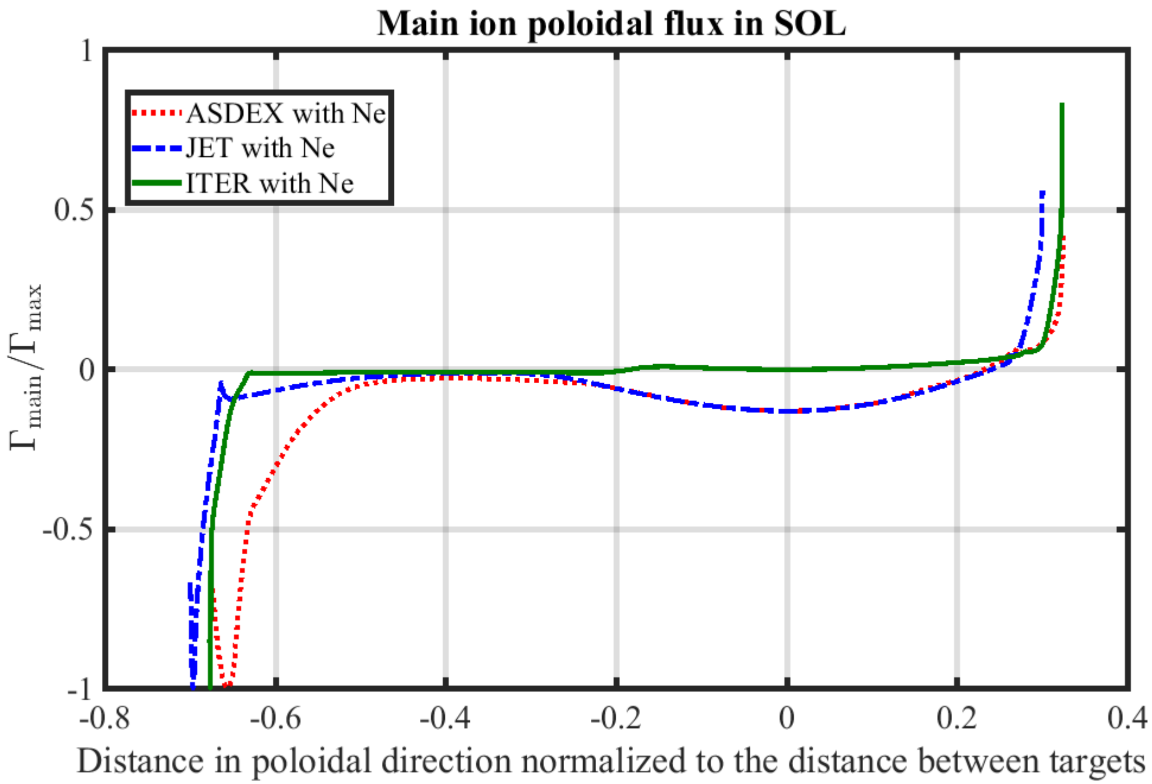
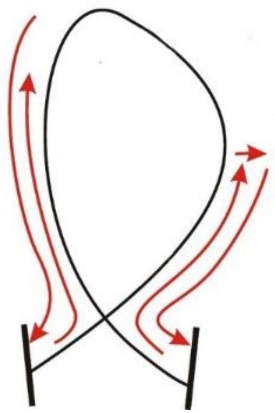
Integral poloidal flows in SOL from outer to inner divertor:

- are reduced with increase of machine size
- are modulated poloidally by Pfirsch-Schlueter flows
- bigger divertor asymmetry for smaller machine



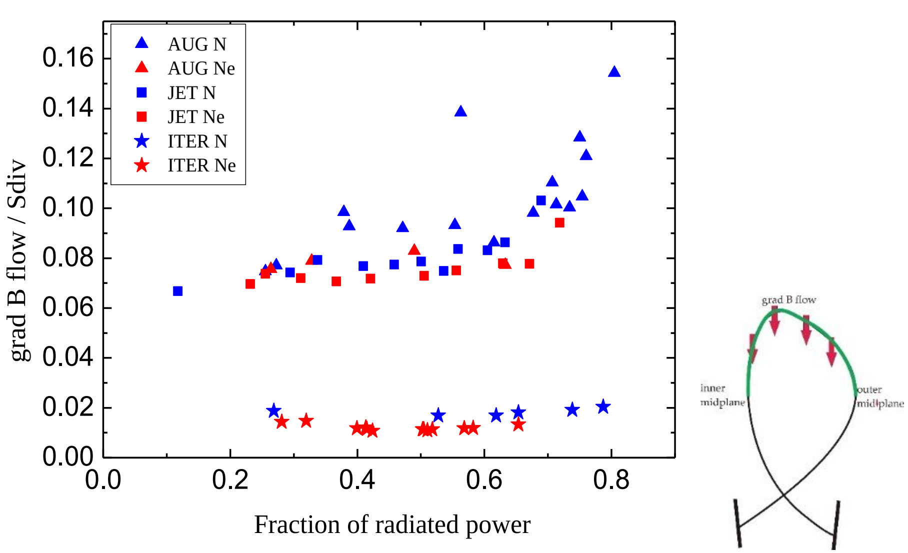




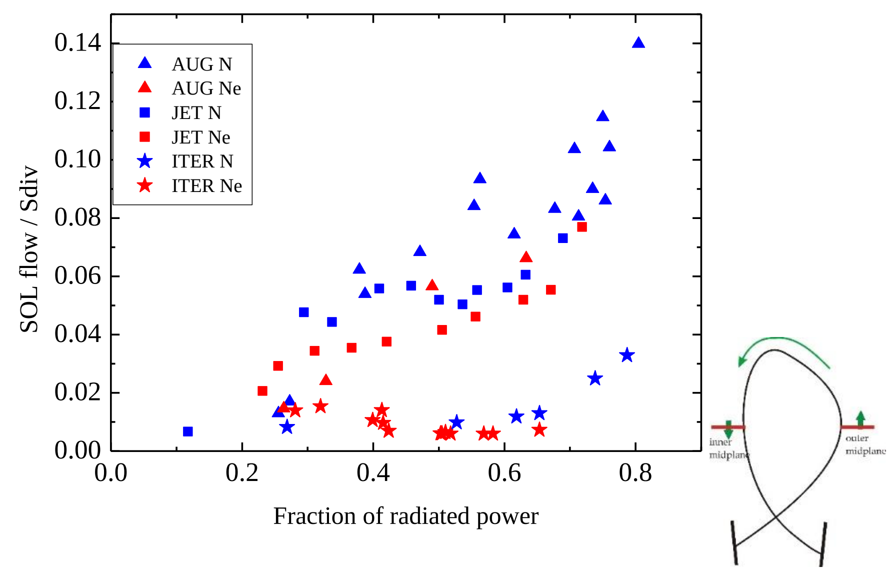
SOL flow patterns in big tokamaks are not seen on integral flow distribution

Integral relative importance of poloidal flows from outer to inner divertor in SOL and of grad B drift through database:

- Grad B drifts are reduced with increase of machine size
- Bigger flows between divertors through SOL for smaller machines
- bigger divertor asymmetry for smaller machines

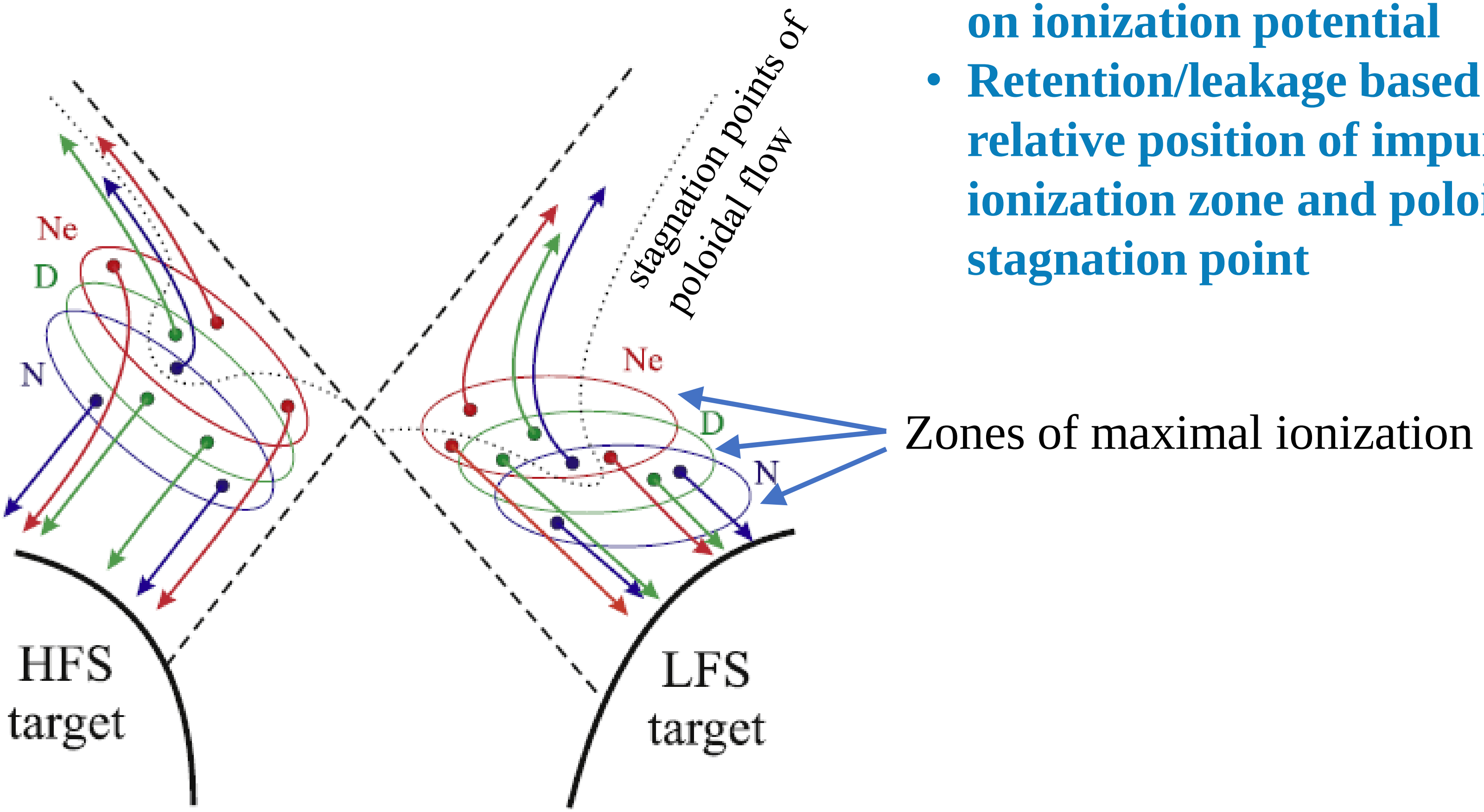


Grad B flow through the upper part of separatrix (above midplane) ratio to ionization in both divertors as a function of radiated power relative to input power



Flow through the SOL as half-sum of radially integrated flows at outer and inner midplanes. Positive direction towards inner target.

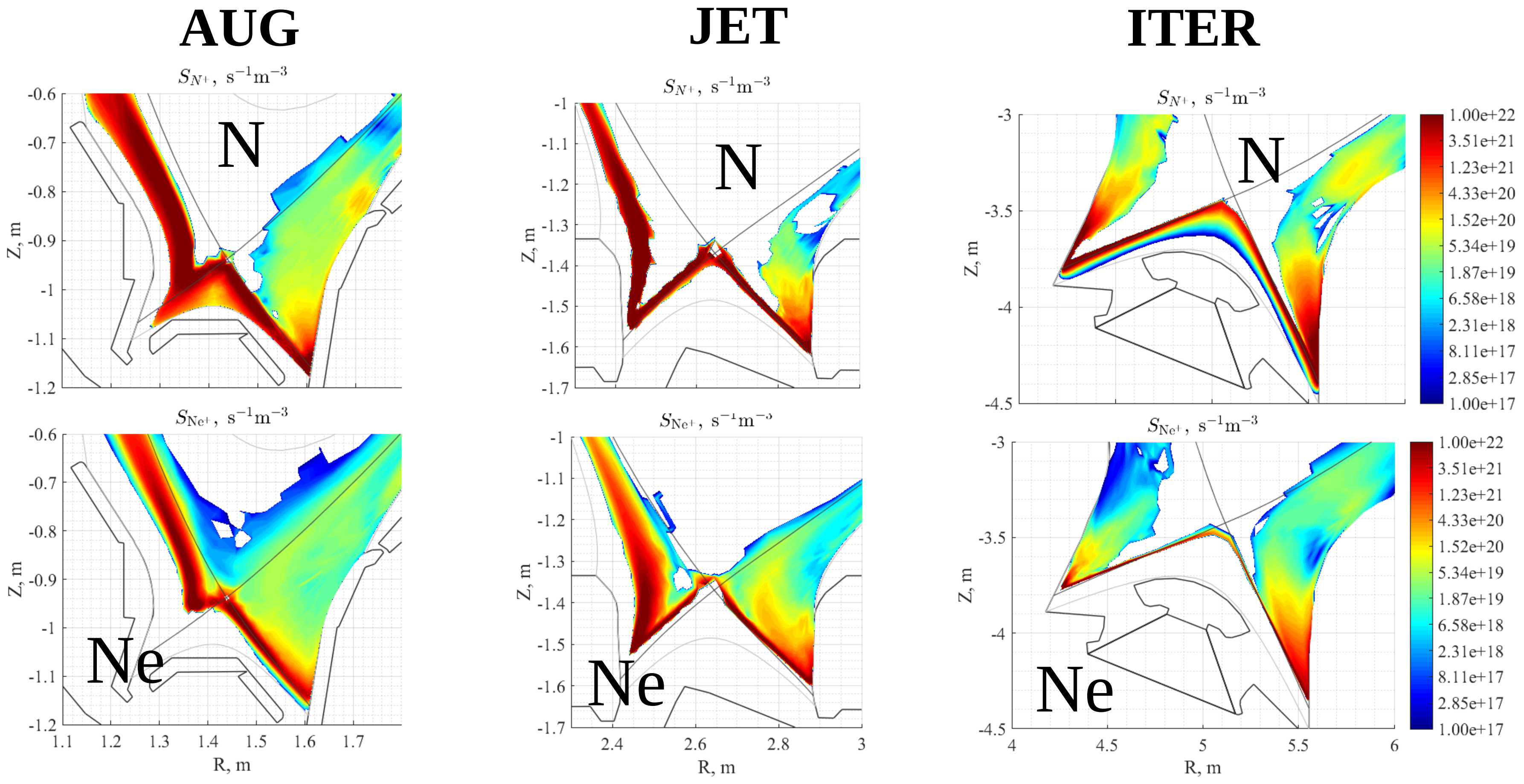
First ionization potential effect



- **Dependence of ionization zone on ionization potential**
- **Retention/leakage based on relative position of impurity ionization zone and poloidal flow stagnation point**

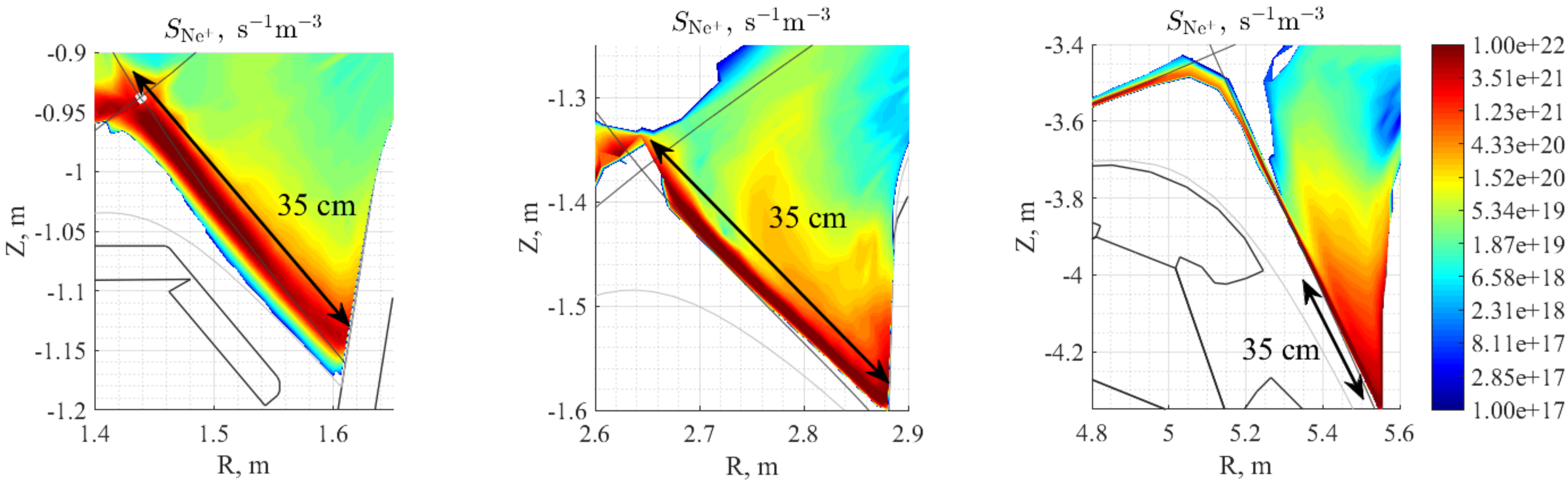
Ionization source for impurities:

- is situated higher upstream for Ne than for N
- reaches separatrix for Ne in AUG ; is situated in divertor for Ne in ITER

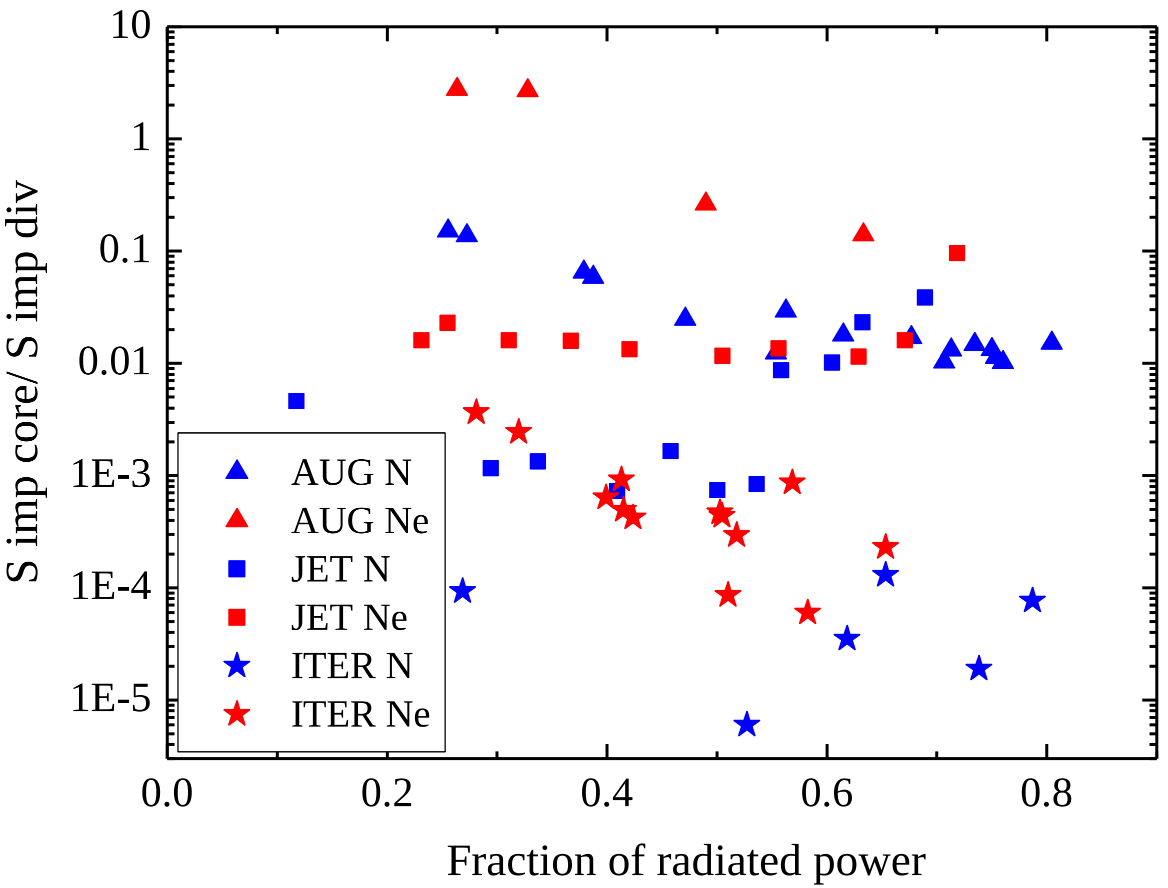


Ionization source for Ne has the same dimension in three machines

AUG with Ne **JET with Ne** **ITER with Ne**

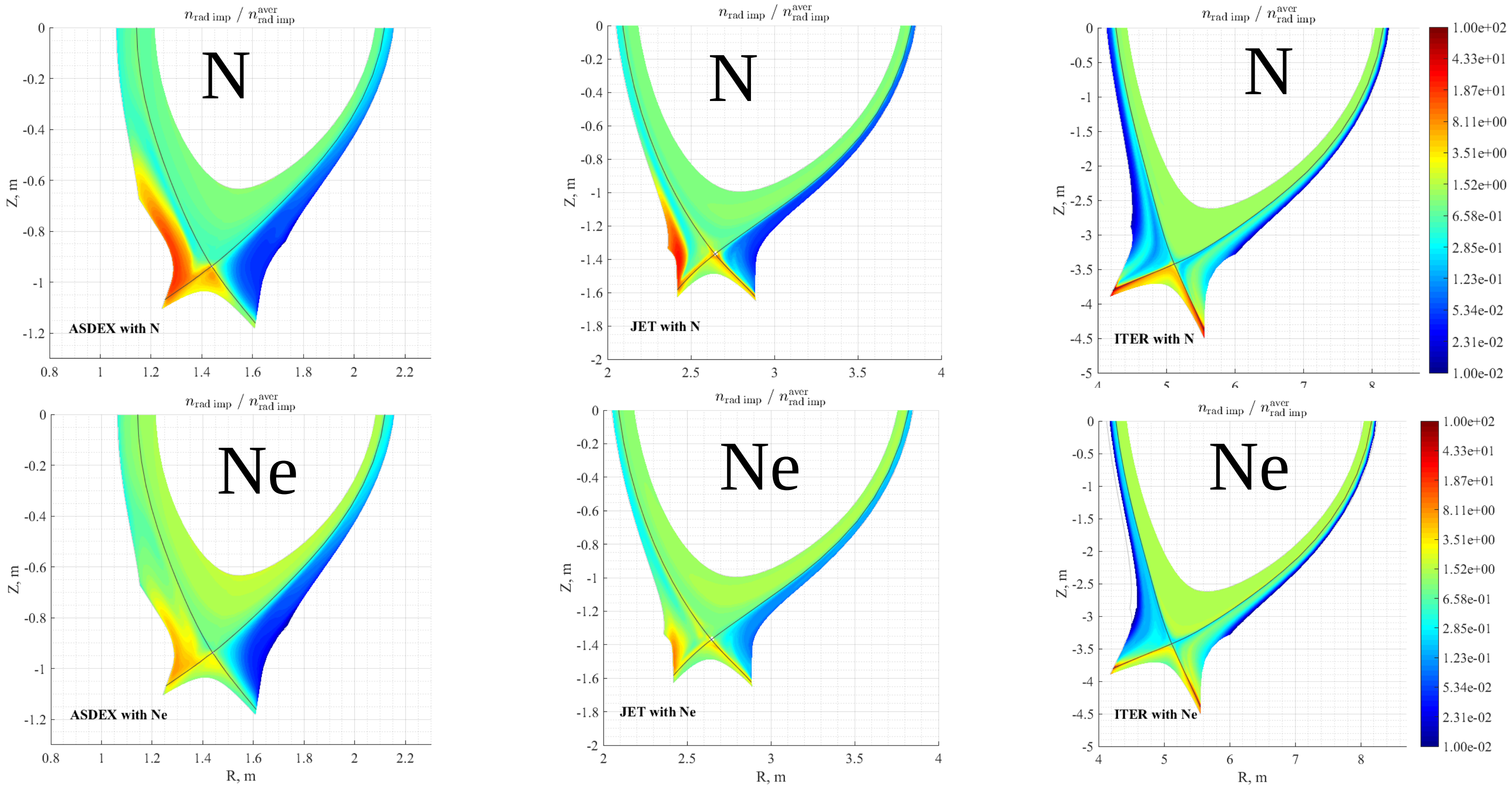


Ratio of impurity ionization in the core to that in both divertors.
AUG – significant Ne ionization in the core.

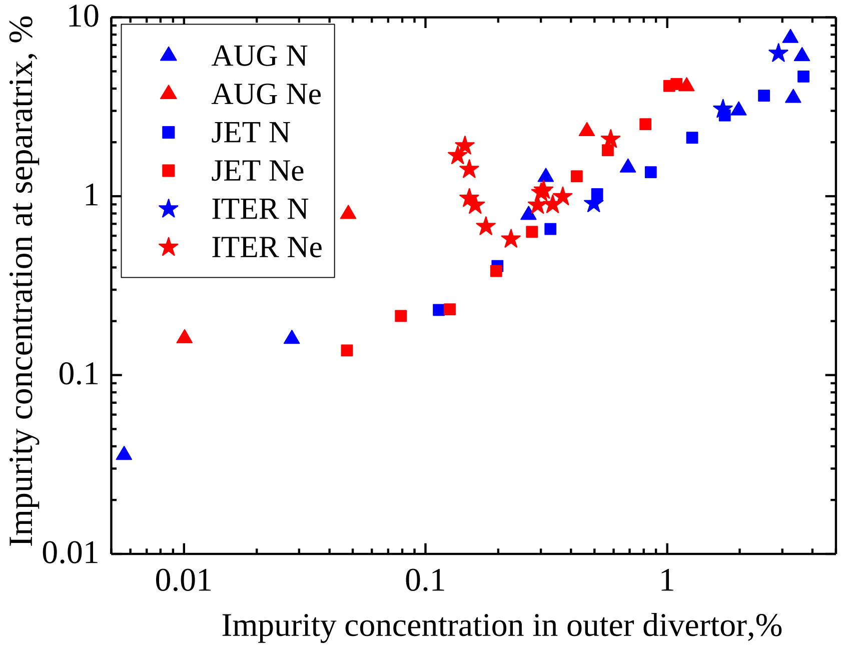


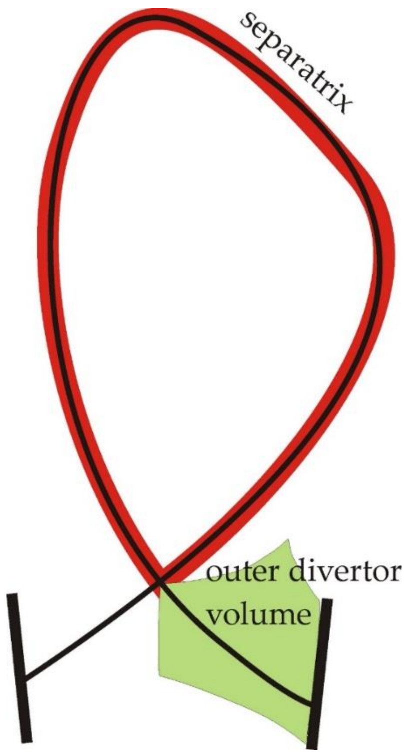
Impurity distribution(normalized to average) – more symmetric for bigger machine
N is better retained in divertor than Ne

AUG **JET** **ITER**



Impurity concentration at the separatrix and in outer divertor

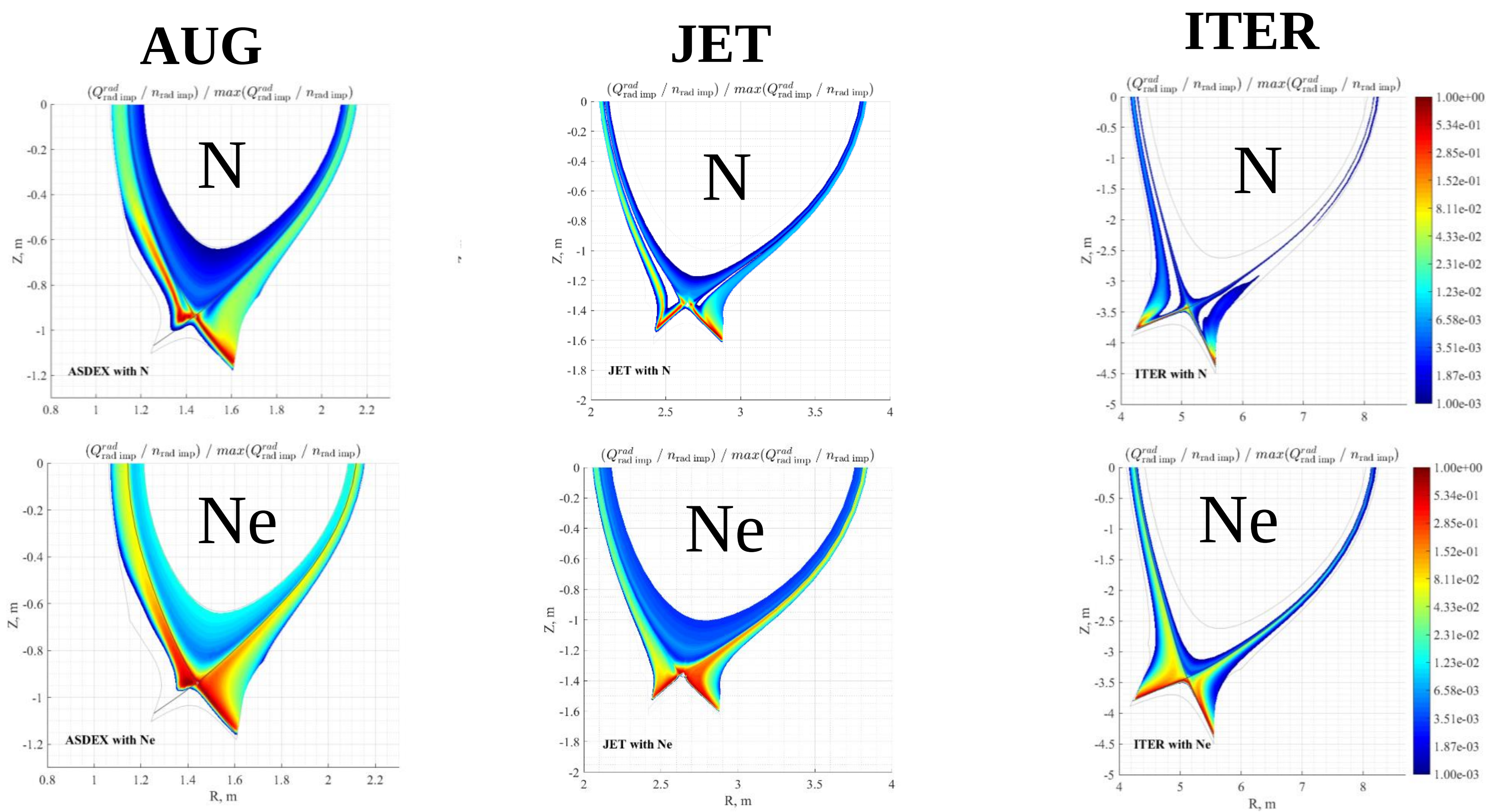




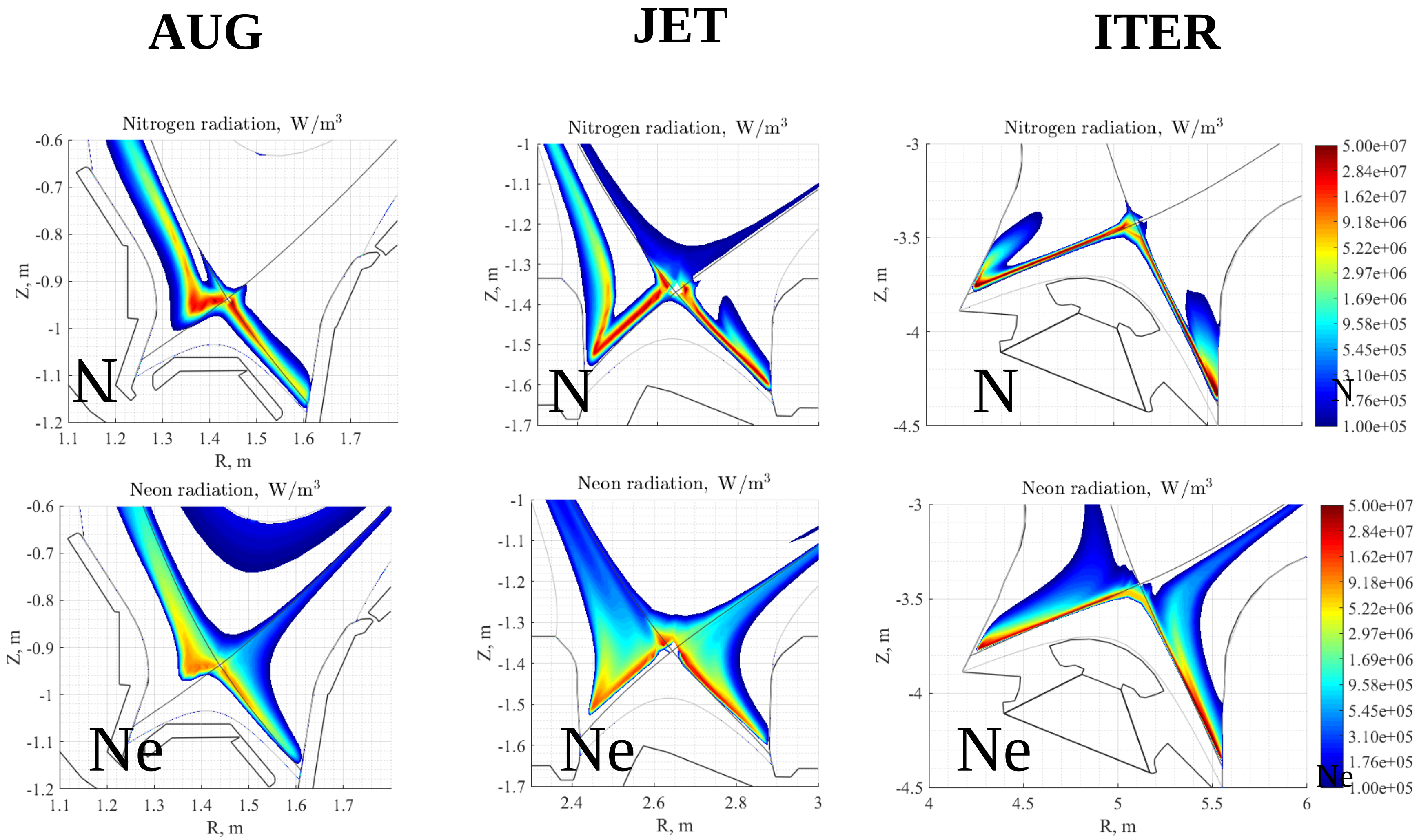
- **In small machines impurities are ionized further upstream and are dragged to separatrix by Pfirsch-Schlueter flows**
- **In bigger machines impurities are ionized in divertor and dragged upstream by flow produced by excessive ionization in near SOL**
- **Retention of impurities in divertor is comparable in different scales machines**

Radiation per impurity nuclei (normalized to maximal value)

- Ne and N radiate effectively at different temperatures ➡ Ne radiates further upstream than N
- Ne radiation is not negligible in the core for AUG



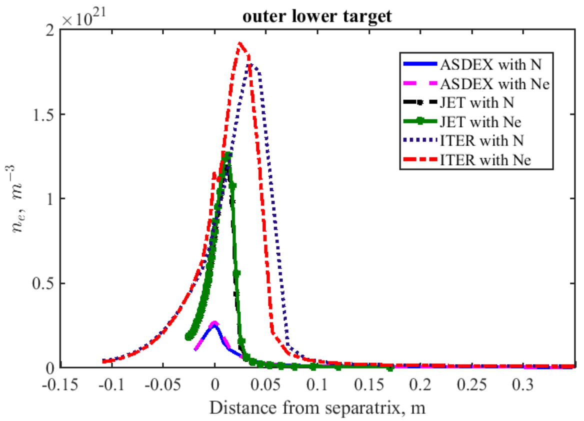
Radiation.

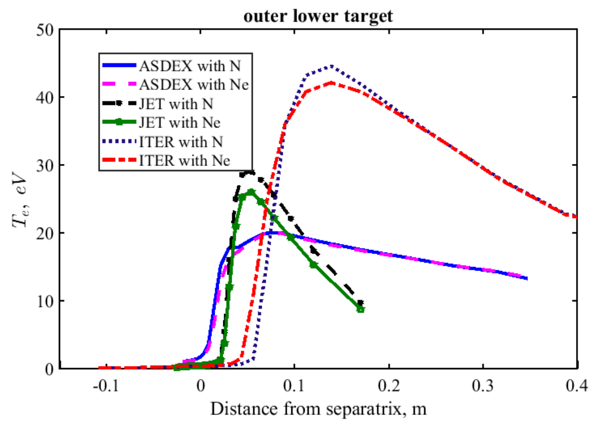

AUG
JET
ITER
Nitrogen radiation, W/m³
Neon radiation, W/m³
Z, m
R, m
N
Ne
5.00e+07
2.84e+07
1.62e+07
9.18e+06
5.22e+06
2.97e+06
1.69e+06
9.58e+05
5.45e+05
3.10e+05
1.76e+05
1.00e+05

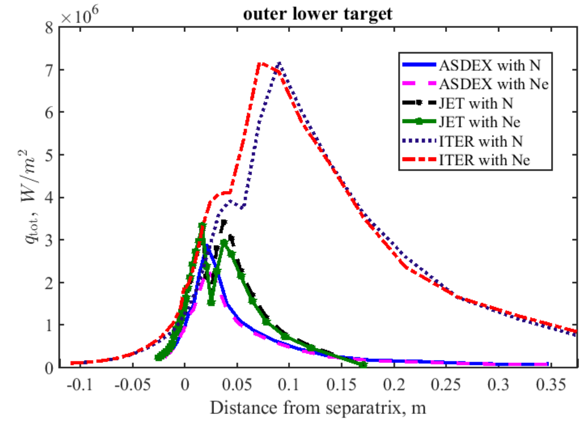
Radiation

- Impurity radiation in larger machines is more localized in the divertor
- On JET and ITER, this means that even though the strongly radiating region with Ne impurity is more extended than for N seeding at comparable radiated power, both are equally effective at power dissipation in divertor.
- On ITER Ne ions reaching pedestal region are fully stripped and cannot radiate reducing impact on pedestal
- On large tokamaks both N and Ne are effective in reduction of the power flow on the divertor plates, while on smaller machines like AUG Ne produces too strong radiation in the upstream and core, which leads to radiation collapse

N and Ne have similar effect on targets shielding for similar radiated power but…







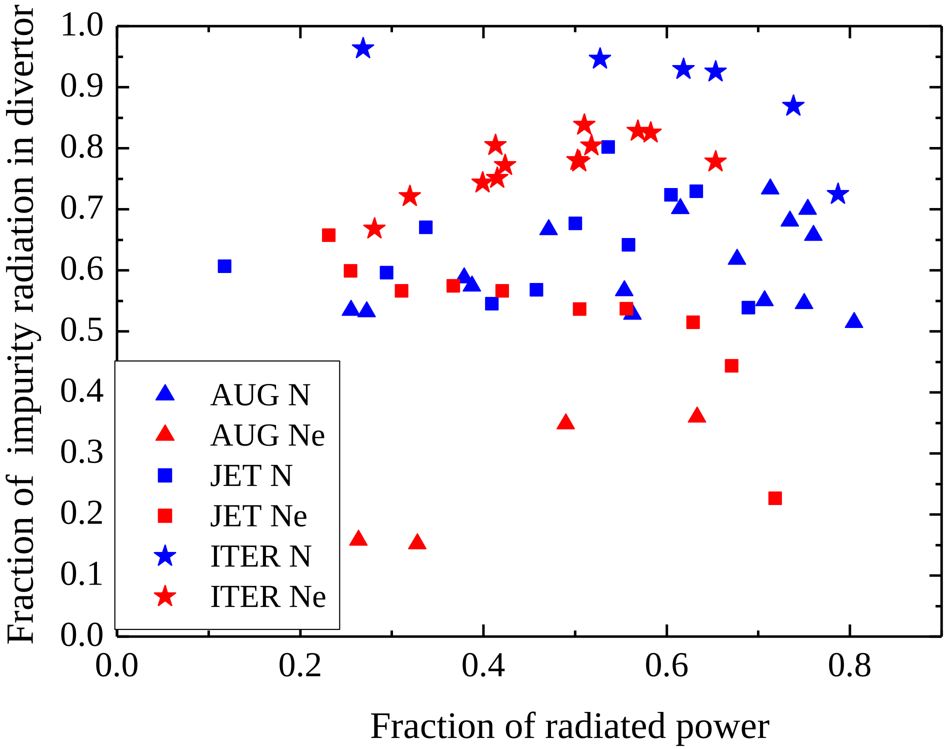
	ITER, 100MW		JET, 16 MW		ASDEX-Upgrade, 5MW	
	Ne	N	Ne	N	Ne	N
Average impurity separatrix concentration, %	1.1	3	1.2	1.2	2.3	1.4

For AUG similar radiation demands bigger Ne separatrix concentration
For ITER similar radiation demands bigger N separatrix concentration

Ratio of power radiated by impurity in the divertor to full power radiated by impurity as a function of ratio of radiated power to input power.

Modeling:

radiation of Ne in JET is more localized in divertor than in ASDEX-Upgrade but less localized in divertor than will be in ITER



Conclusions

- **Outer and inner divertors are more symmetric for larger machines and symmetry increases with seeding, i.e. for more detaches cases.**
- **Ambient plasma and impurity flow from outer to inner divertor both through upper SOL and PFR are more significant for smaller tokamaks like AUG and are less significant for larger machines.**
- **In larger machines ionization of neutral particles takes place closer to the plates and neutral impurities are better confined in the divertor.**
- **Impurities with higher ionization potential are more effectively extracted from the divertor towards upstream, so that N is kept better than Ne in the divertor region-FIP effect.**
- **Ne radiation is kept in divertor for big machines due to big temperature and big dimensions of the divertor as well as that of N. As a result, their protecting role for divertor targets shielding is comparable.**
- **According to modeling both gases can be used as radiators in JET and ITER.**