Modeling of tungsten and beryllium dust impact on ITER-like plasma edge

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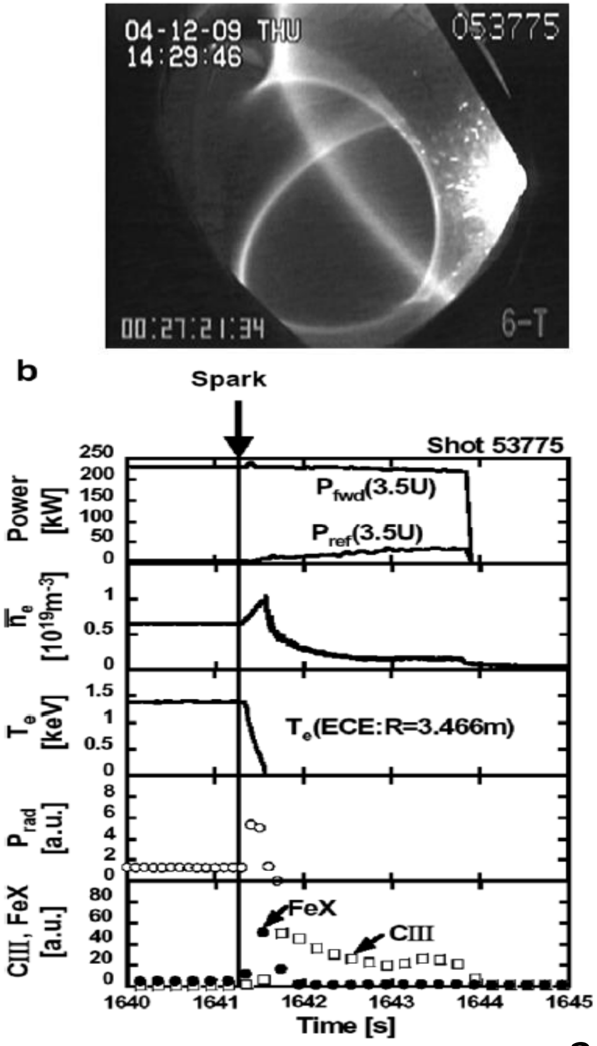
Outline

- Introduction
- DUSTT/UEDGE modeling of dust transport
- Impact of W dust on edge plasma in ITER
  - Impurity radiation and core content
  - Significance of dust vapor shielding
  - Impurity radiation induced plasma oscillations
- Differences in Be dust impact on ITER edge plasma
- Conclusions

Introduction

- High heat fluxes to PFCs in next generation tokamaks can lead to damage and ejection of PFC material into plasma
- Recent experiments suggest that ejected material, especially high-Z, can significantly impact plasma performance in fusion devices
- Recent QSPA-Kh50 experiments [2] suggest W dust production rate by ELMs in ITER of up to **1g/s!**
- What impact ejected PFC material (W, Be) will have in ITER?

"Spark" event in LHD [1]



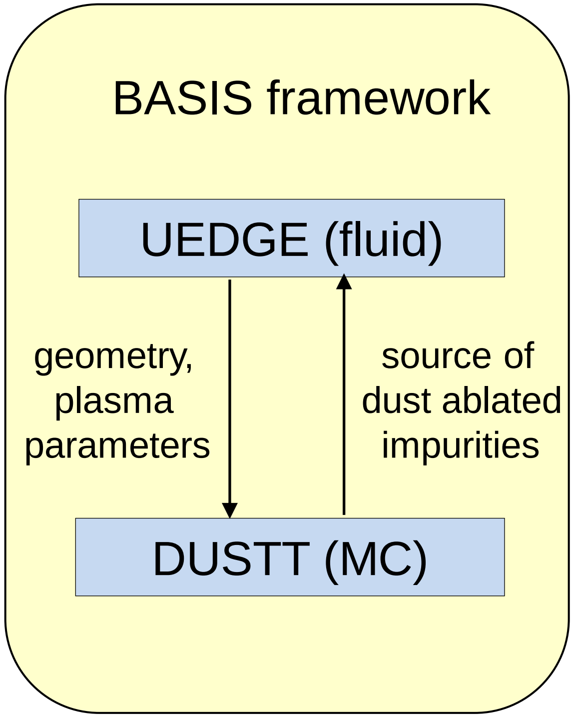
[1] K. Saito, et al., *J. Nucl. Mater.* **363-365** (2007) 1323

[2] V.A. Makhlaj, et al., *J. Nucl. Mater.* **438** (2013) S233

DUSTT-UEDGE coupled code

- To asses self-consistently an impact of high-Z material dust we use DUSTT-UEDGE package [3,4]
- DUSTT solves dust dynamics equations (motion, charging, heating, ablation) coupled with plasma parameters simulated using multi-fluid edge plasma transport code UEDGE
- DUSTT/UEDGE code was validated using dust trajectories measured on NSTX

DUSTT/UEDGE coupled code



BASIS framework

UEDGE (fluid)

geometry, plasma parameters

source of dust ablated impurities

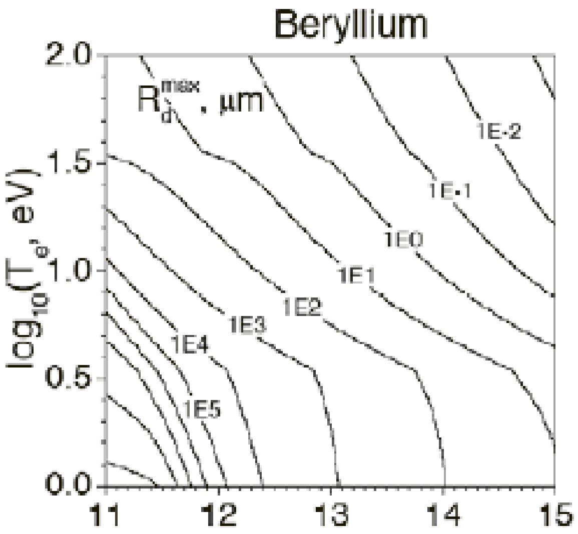
DUSTT (MC)

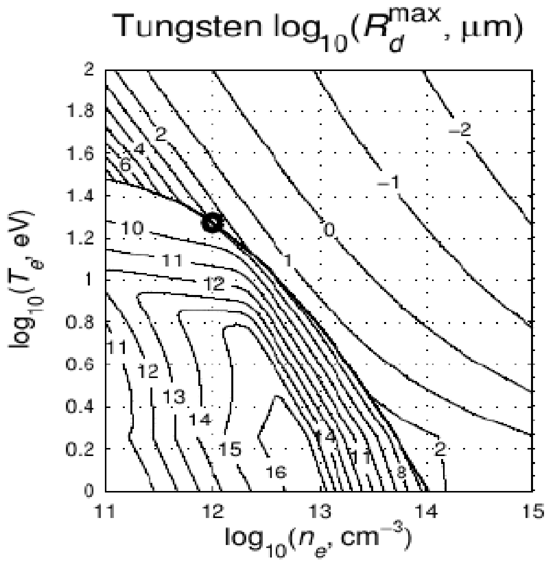
[3] R.D. Smirnov et al., *PPCF* **49** (2007) 347

[4] R.D. Smirnov et al., *J. Nucl. Mater.* **415** (2011) S1067

Dust vapor shielding effects

- Dust grain quickly heats and evaporates in fusion plasmas, producing ablation cloud that shields heat flux to the grain and affects dust propagation into fusion plasma
- Dust vapor shielding is due to plasma-vapor collisions, ionization, and radiation losses
- We found [5,6] that shielding effects become important for grain size larger that R_d^{max} , which for edge plasma conditions ~10μm





[5] B.T. Brown, et al., *Phys. Plasmas* **21** (2014) 024501

[6] S.I. Krasheninnikov and R.D. Smirnov, *Phys. Plasmas* **16** (2009) 114501

Dust vapor shielding (continued)

- First principles theory of dust vapor shielding is being developed (see poster S.I. Krasheninnikov, #21 Tuesday, this conference)
- In present modeling *ad hoc* shielding factor is introduced for sufficiently large dust grains

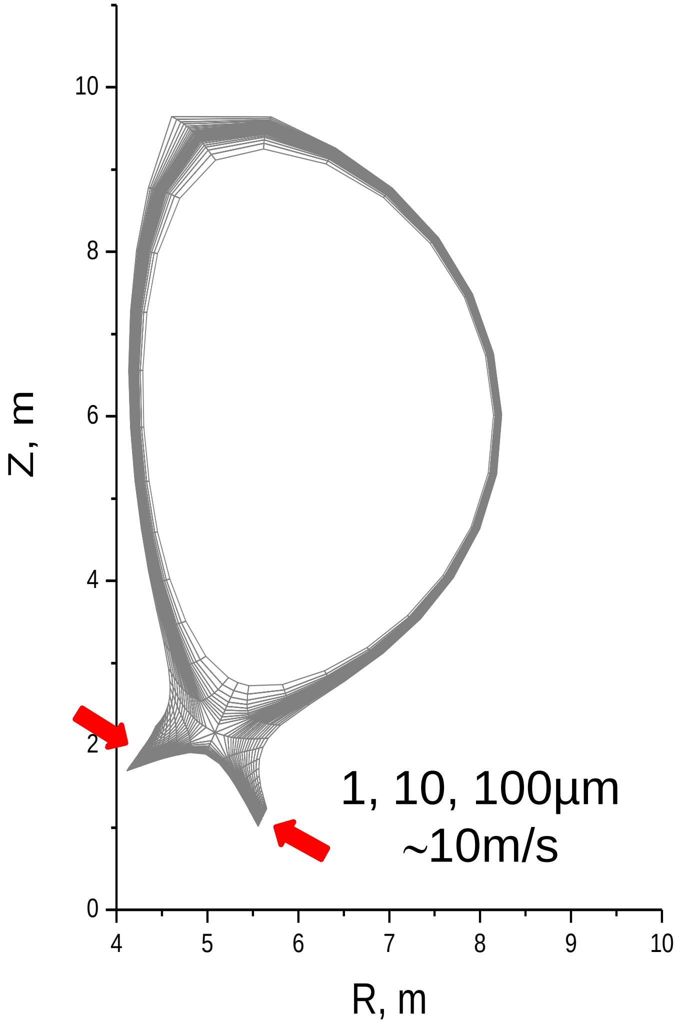
$$\gamma = \frac{ablation\ rate\ with\ shielding}{ablation\ rate\ without\ shielding}$$

- The theoretical estimates give $\gamma \sim 0.1$ for 10μm W dust

Simulation model

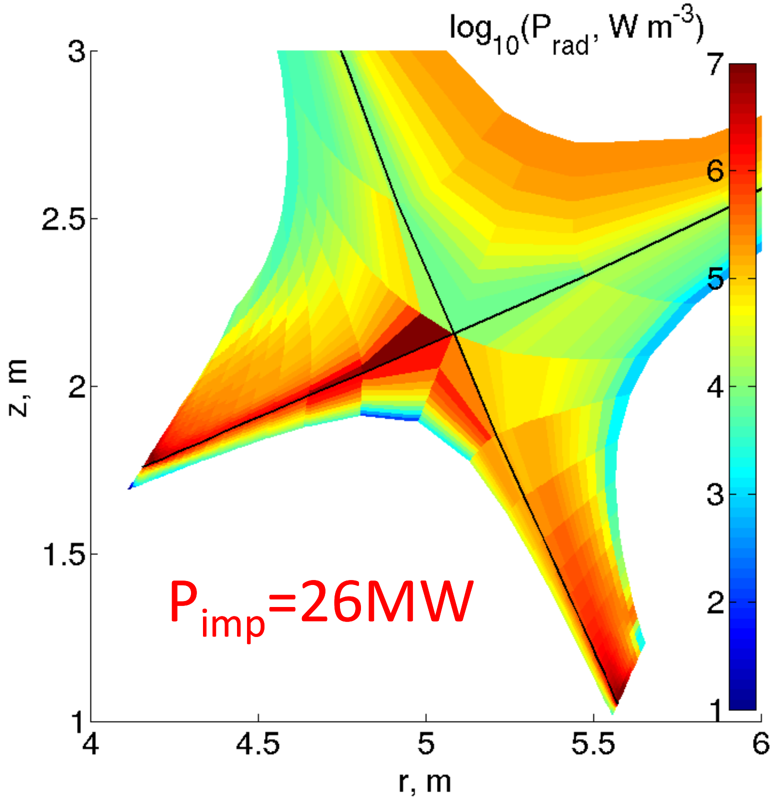
- Computational domain included SOL, divertor, private flux region, and core plasma up to $\Psi_{norm}=0.95$
- Dust grains of $R_d=1$, 10, and 100µm with the mass rate up to S=300mg/s were injected from divertor targets
- W dust particle flux was proportional to the power load to the targets
- Cosine angular distribution with respect to the normal direction to the surface and averaged speed 10m/s (Maxwellian distribution)

W dust injection in ITER

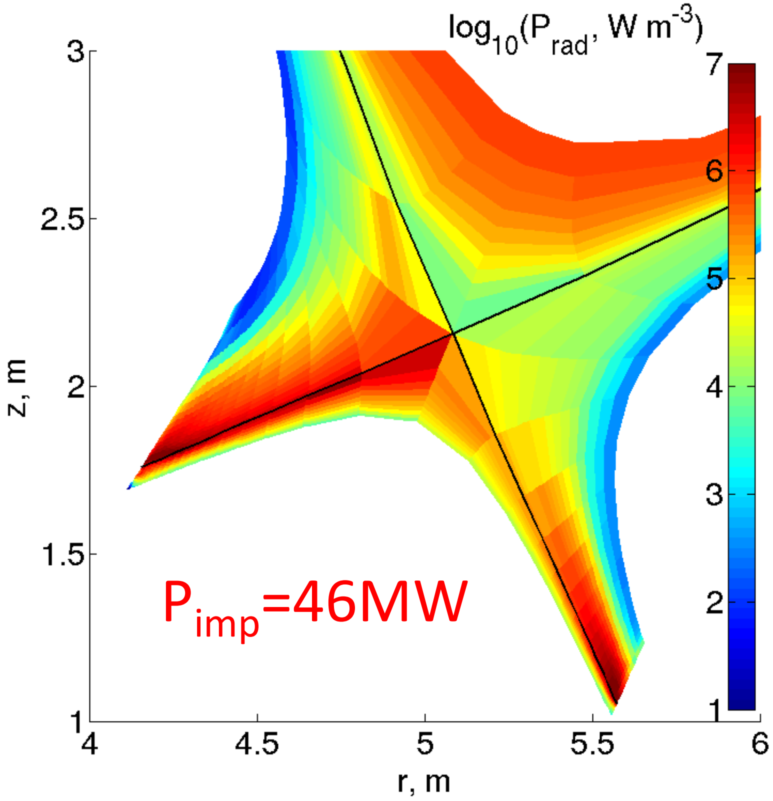


Impurity radiation profiles

10µm, 60mg/s, non-shielded



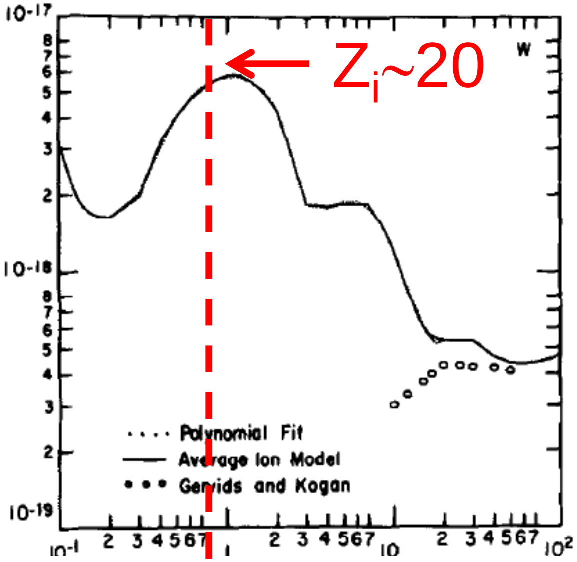
10µm, 60mg/s, shielded

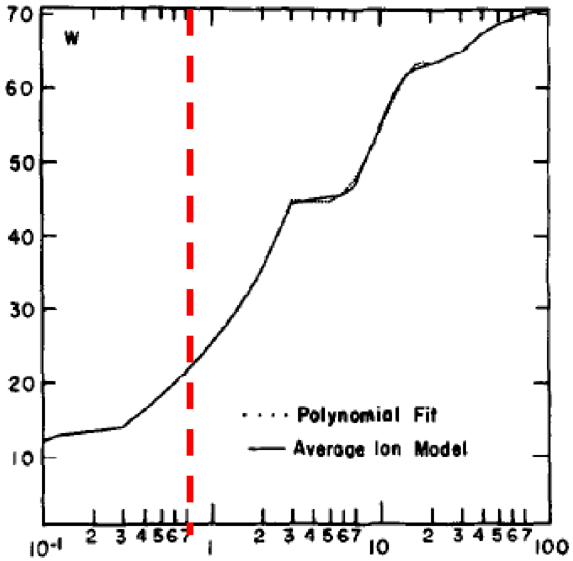


- Vapor shielding effects allow dust to propagate deeper into plasma, leading to stronger impurity radiation especially in the core region

Simulation model (continued)

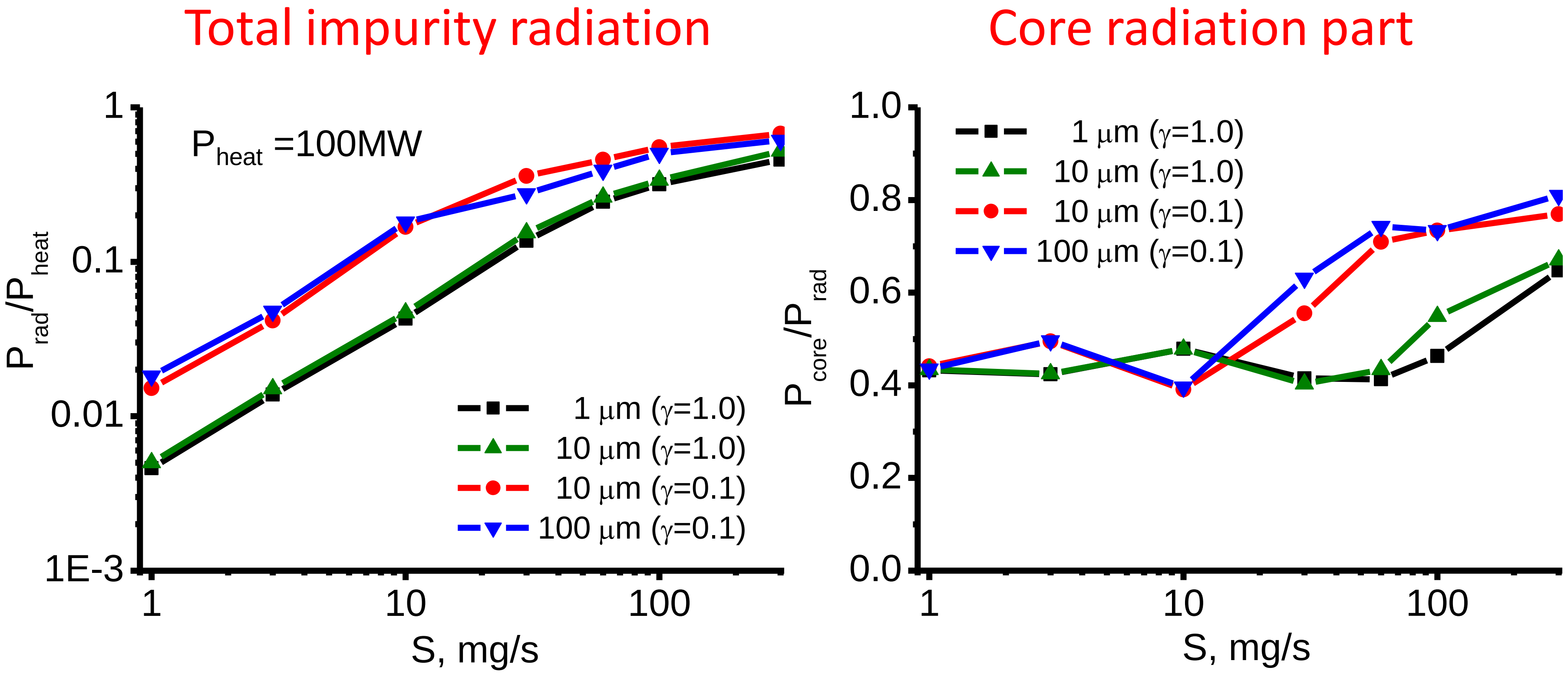
- No shielding was assumed for R_d=1μm (γ=1); for R_d=100μm, according to our shielding model, γ=0.1; and for R_d=10μm we have run the cases with (γ=0.1) and without shielding effects (γ=1)
- We have followed the evolution of W ions with the charges $Z_i \leq 20$, close to corona radiation maximum [7]
- It was assumed that there is no flux of W ions into the core through the boundary Ψ_{norm}=0.95 that gives us low limit of impurity radiation





[7] D.E. Post, et al., *Atom. Data Nucl. Data Tables* **20** (1977) 397

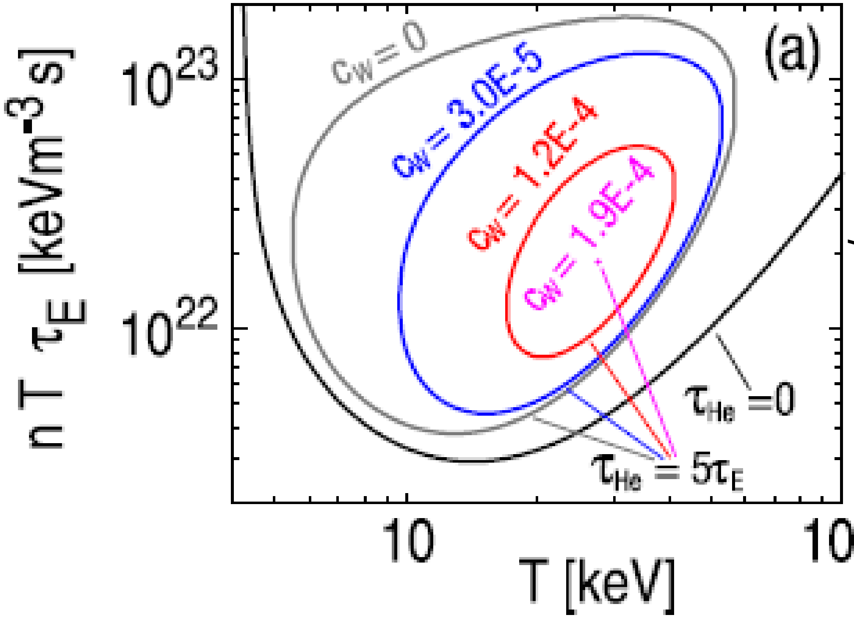
Impurity radiation vs. dust mass rate



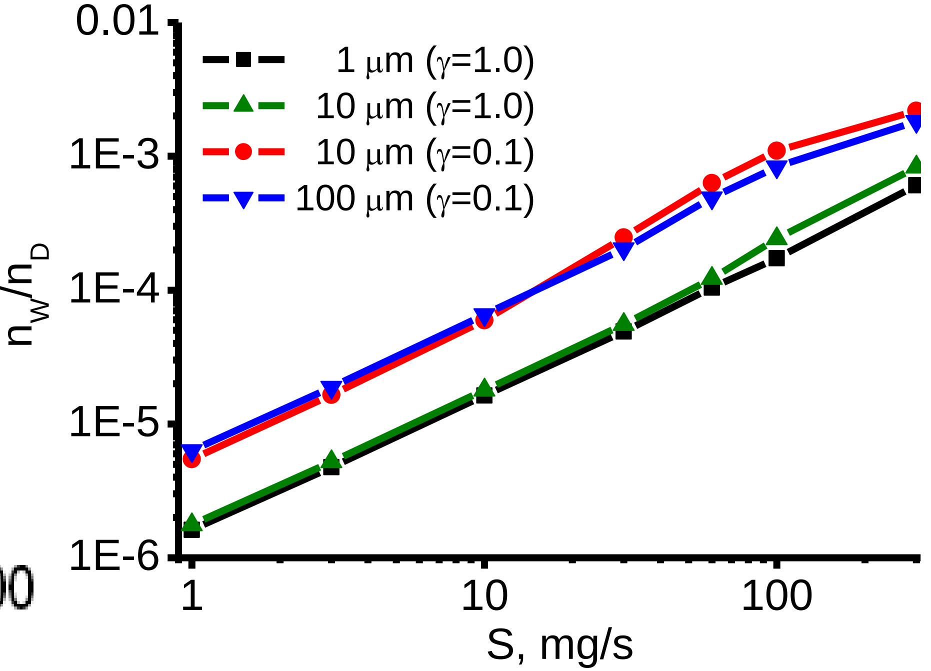
- Strong dust shielding effect for 10μm grains
- Relatively small impact of 100μm dust is due to incomplete grain ablation
- Core radiation part grows for the large mass rates as SOL cools and dust propagates deeper into plasma

Core impurity contamination

ITER ignition curves [8]



Relative core W concentration



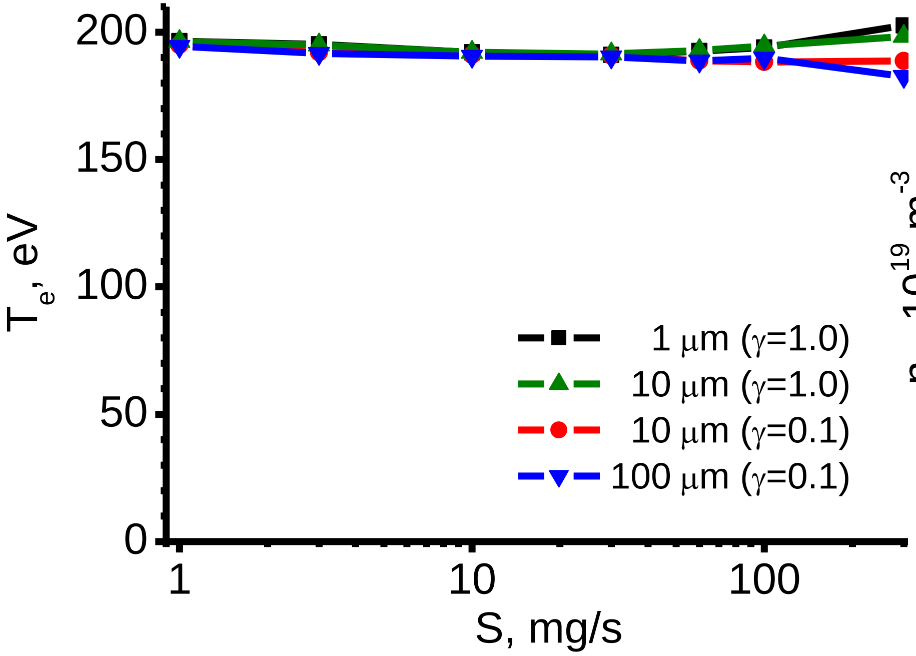
- Even very low core W relative concentrations significantly limit ITER operational regimes to the point of no ignition possible

- W impurity relative concentration of $\geq 10^{-5}$ is reached at ~1mg/s mass rate for large (≥10μm) dust grains!
- Recall 1g/s estimate for ITER

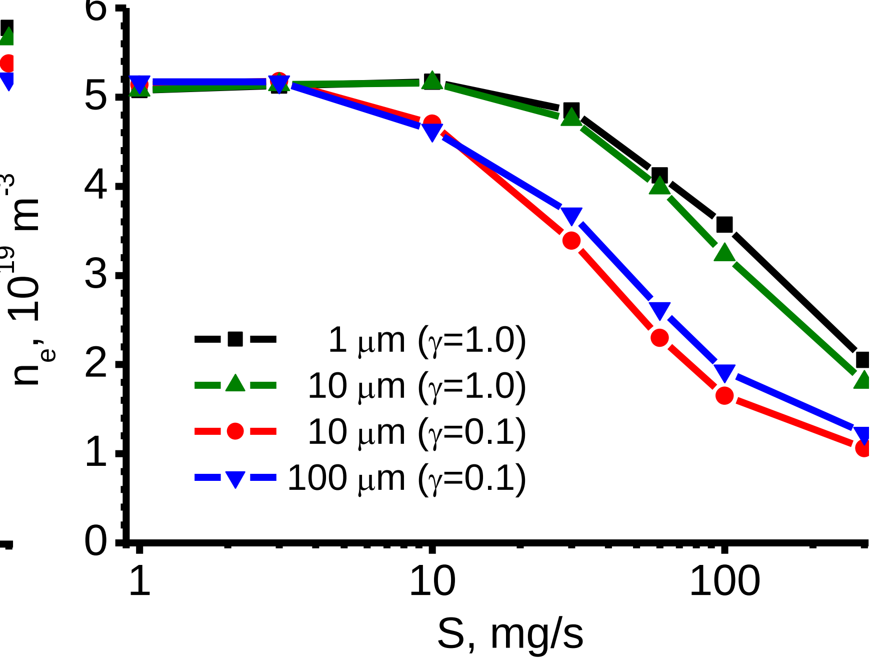
[8] T.Pütterich, et al., *Nucl. Fusion* **50** (2010) 025012

Impact on plasma at separatrix

Electron temperature



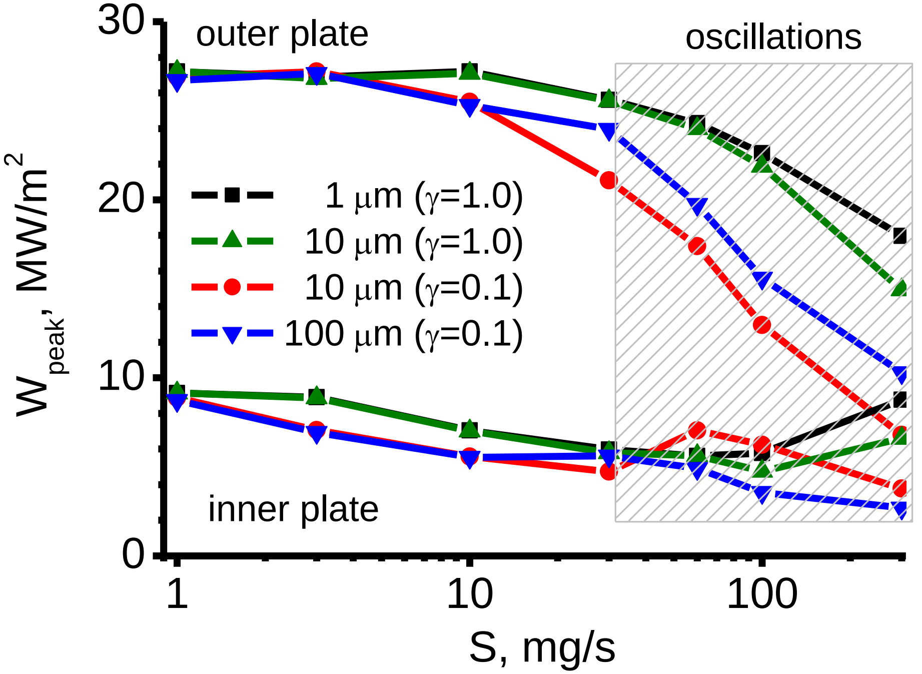
Electron density



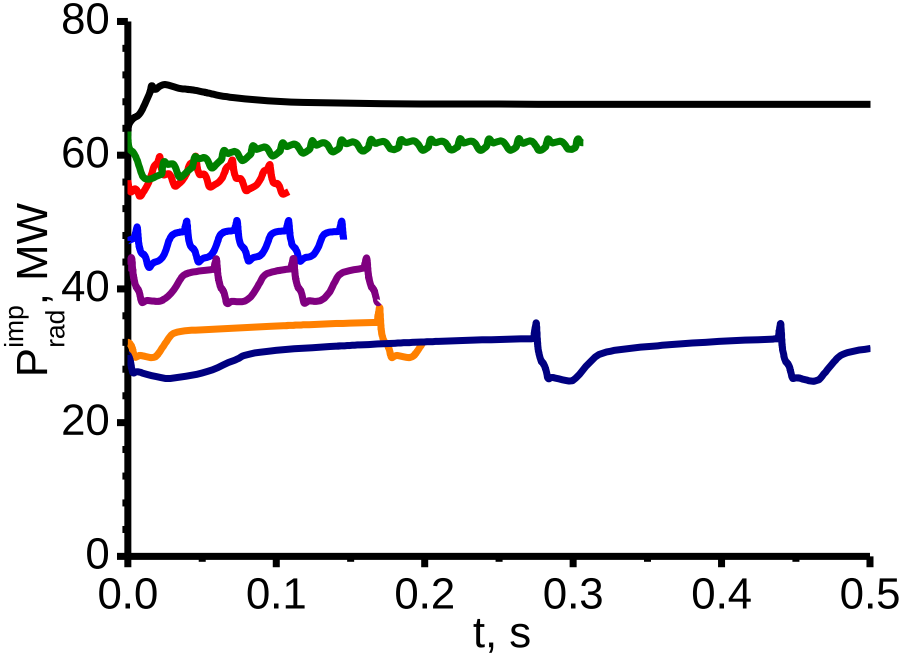
- Temperature is almost unchanged at up to 300mg/s dust mass injection rate as it is weakly dependent on plasma heat flux
- Substantial edge plasma density and pressure reduction starting at ~10-30mg/s due to radiative cooling

Impact on divertor operation

Peak heat load



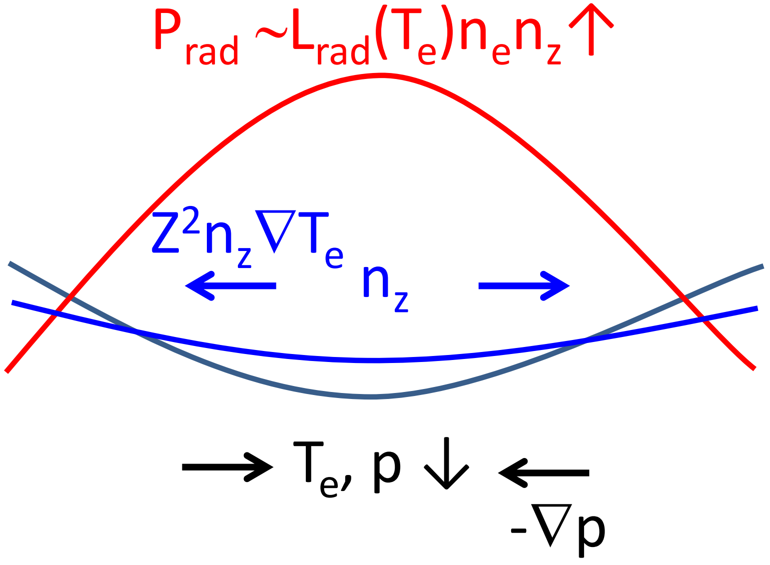
Impurity radiation



- At rates >30mg/s peak heat load to plates is significantly reduced and starts to oscillate in time
- Recall that we have no impurity seeding except W

- Staring at 30mg/s we observe strong plasma parameters oscillations leading to variation of divertor heat load

Radiation-condensation oscillations



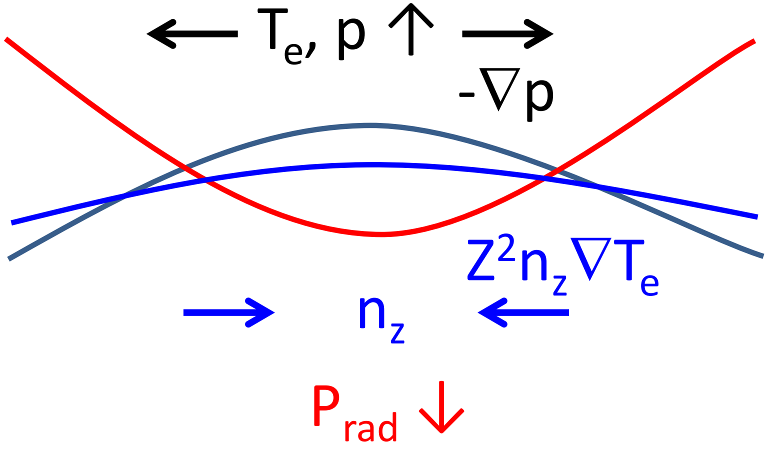
$P_{rad} \sim L_{rad}(T_e)n_e n_z$ ↑

$Z^2 n_z \nabla T_e$

← n_z →

→ T_e, p ↓ ←

$-\nabla p$



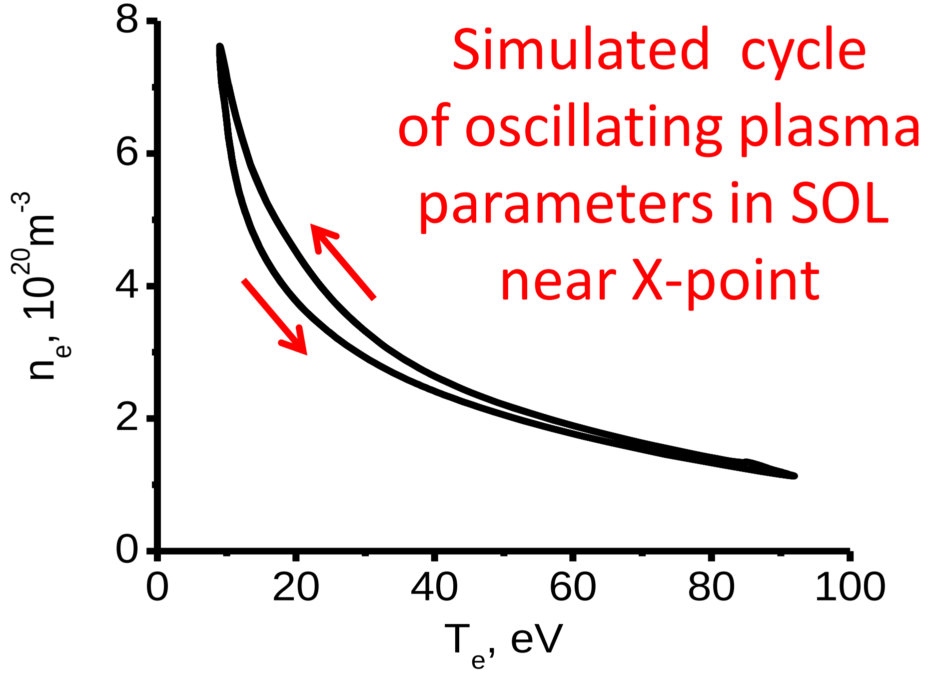
← T_e, p ↑ →

$-\nabla p$

$Z^2 n_z \nabla T_e$

→ n_z ←

P_{rad} ↓



Simulated cycle of oscillating plasma parameters in SOL near X-point

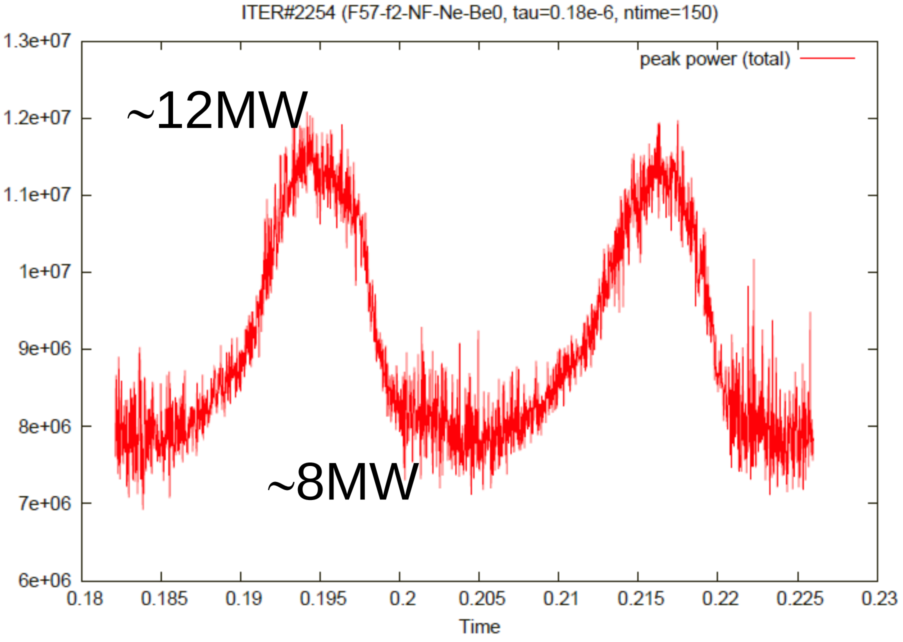
$$\omega \sim i\nu_{RC} \pm \left[\alpha\, Z^2 \frac{\nu_R}{\nu_{Ii}} (k_\parallel c_{sI})^2 - \nu_{RC}{}^2\right]^{\frac{1}{2}}$$

$$\nu_{RC} = \nu_R \left[2 - \frac{d(\ln \nu_R)}{d(\ln T_e)} - \frac{\varkappa_\parallel k_\parallel{}^2}{\nu_R}\right]$$

Implications of oscillations

- Detailed SOLPS simulations with Ne seeded divertor [9] show ~30% divertor peak heat flux variation
- Varying heat load can cause divertor plate material cracking and dust production even with no ELMs
- The self-sustained oscillations are driven by interplay of plasma and impurity transport
- How to mitigate the macroscopic plasma oscillations ?

Variation of divertor peak heat power in ITER [9]

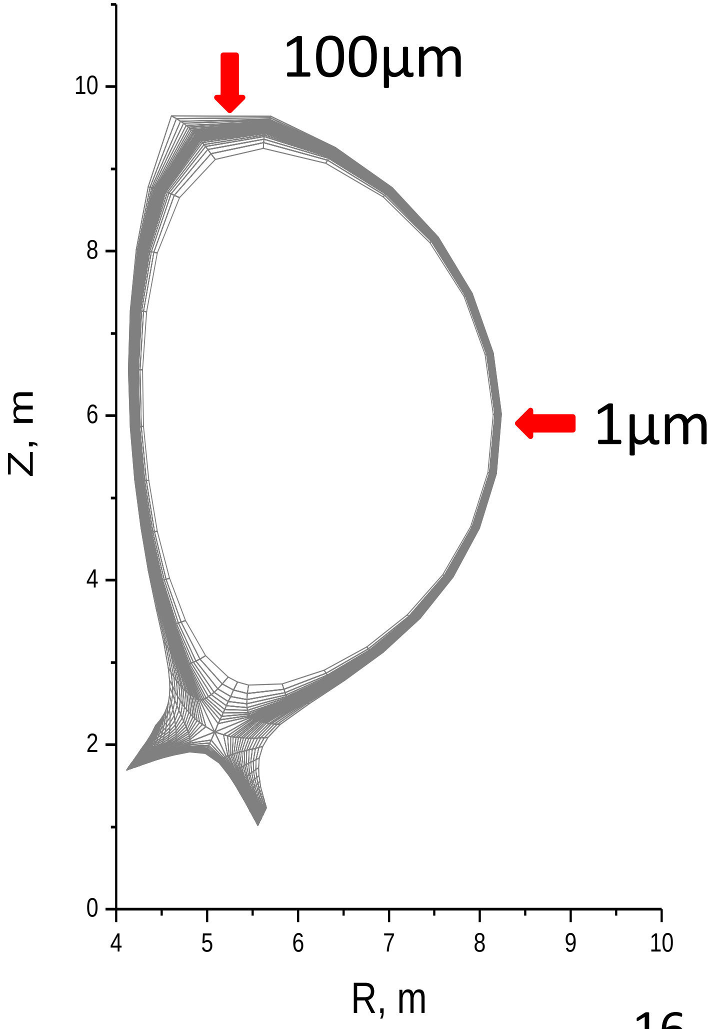


[9] A. Kukushkin (private communication, 2014)

Be dust simulations in ITER

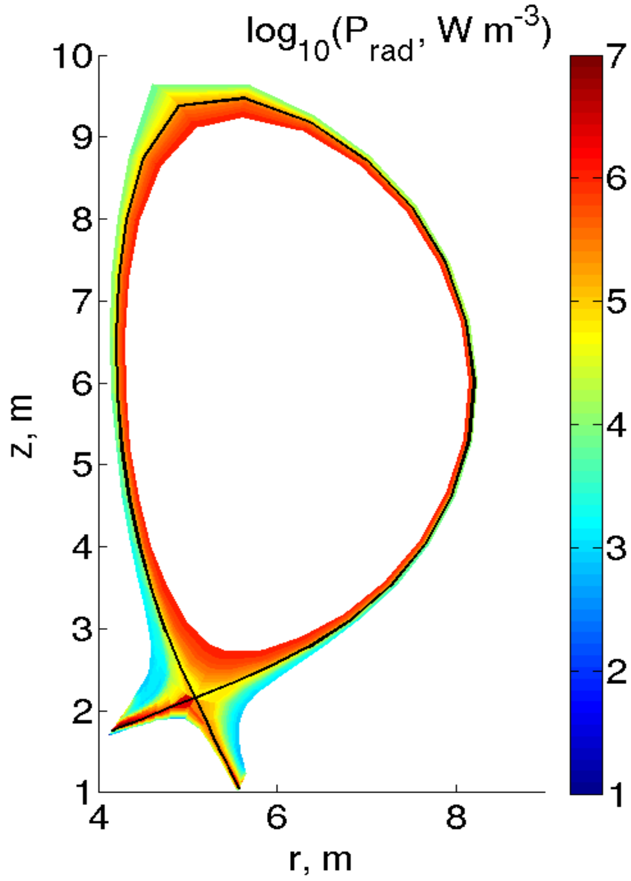
- Same geometry and initial plasma conditions as for W dust injection
- 1 and 100µm Be dust injected from the outer mid-plane and top poloidal locations with mean speed 10-100m/s
- All Be ionization states are modelled (Be^0 … Be^{+4})
- Be impurity ion recycling coefficient ~0.2
- No Be ion flux to/from core

Be dust injection in ITER

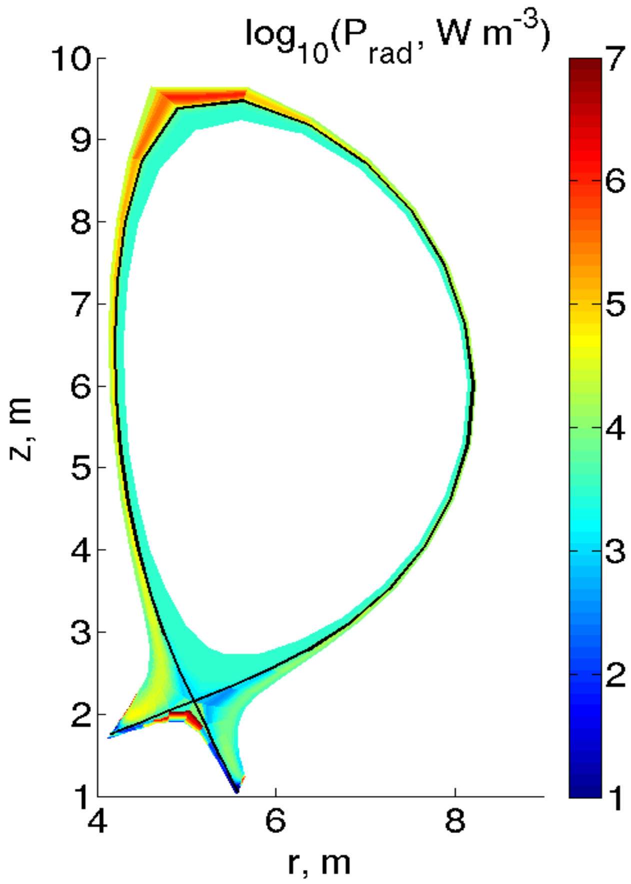


W and Be radiation patterns

W, 100μm, 300mg/s
P_{imp}=61MW



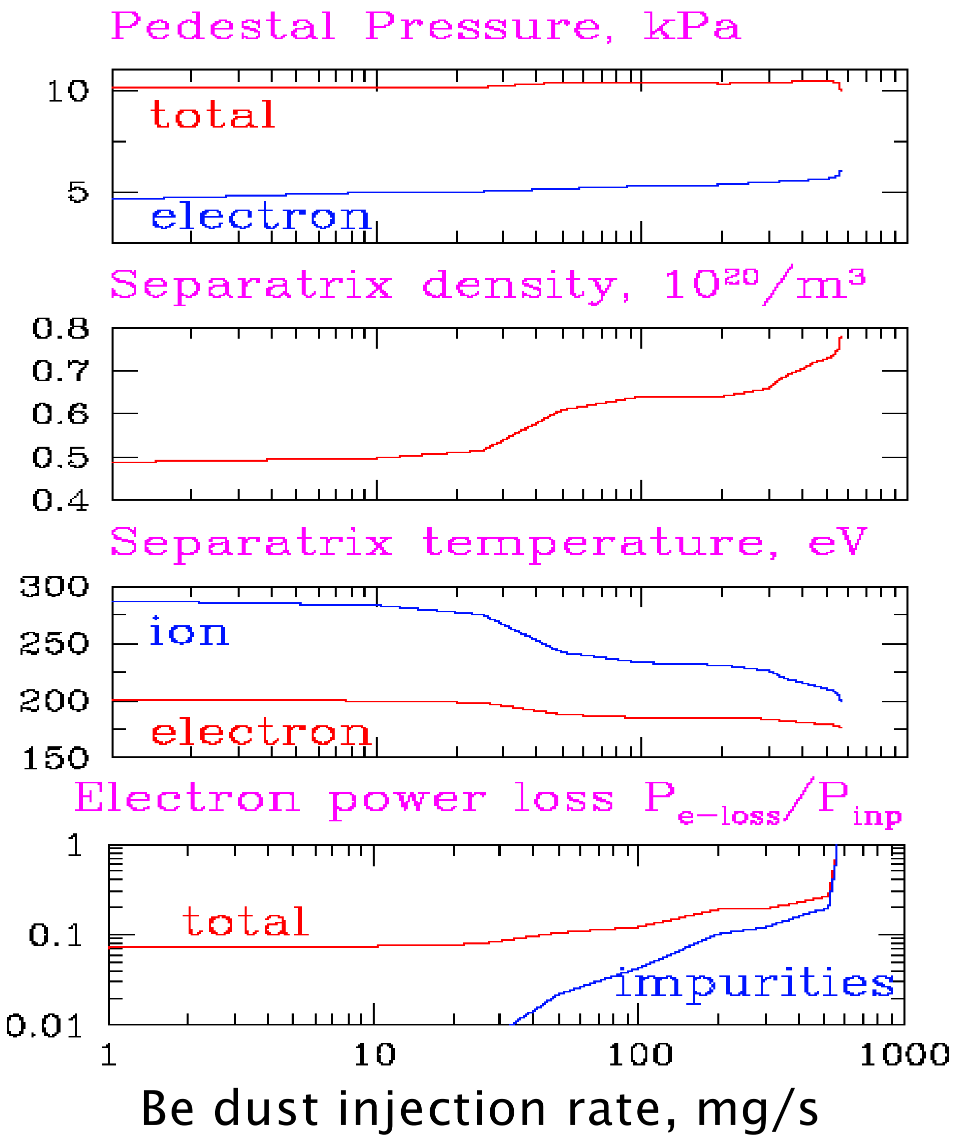
Be, 100μm, top 300mg/s
P_{imp}=19MW



- Unlike W, Be radiates mostly in SOL due to low-Z states

Impact of Be dust injection

- Unlike for W dust, p_{ped} is sustained, separatrix T_e decreases and n_e increases with increasing Be injection rate due to low Be core radiation
- Inner divertor detaches at 100mg/s; discharge collapses at 600mg/s
- Total impurity radiation power reaches ~30% of heating before collapse



Conclusions

- Modeling of W and Be dust injection in ITER shows that it can result in **dramatic impact on both core and edge plasma performance**:
  - W core concentration reaches potentially dangerous level $\geq 10^{-5}$ at the mass injection rate as low as ~1mg/s. Potential W dust production rate in ITER by ELMs is up to 1g/s**!**
  - W and Be dust injection with rates >100 and 600mg/s, respectively, can lead to thermal plasma collapse
  - Impurities can cause radiation-condensation plasma oscillations, due to which divertor heat load can vary by ~30% leading to PFCs thermal stresses and possible dust production
  - Shielding effects play important role in both dust grain penetration depth and impurity radiation loss for $R_d \geq 10\mu m$

Acknowledgements

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Thank you!