Max-Planck-Institut für Plasmaphysik

The role of impurity transport and temperature in MGI induced runaway dynamics

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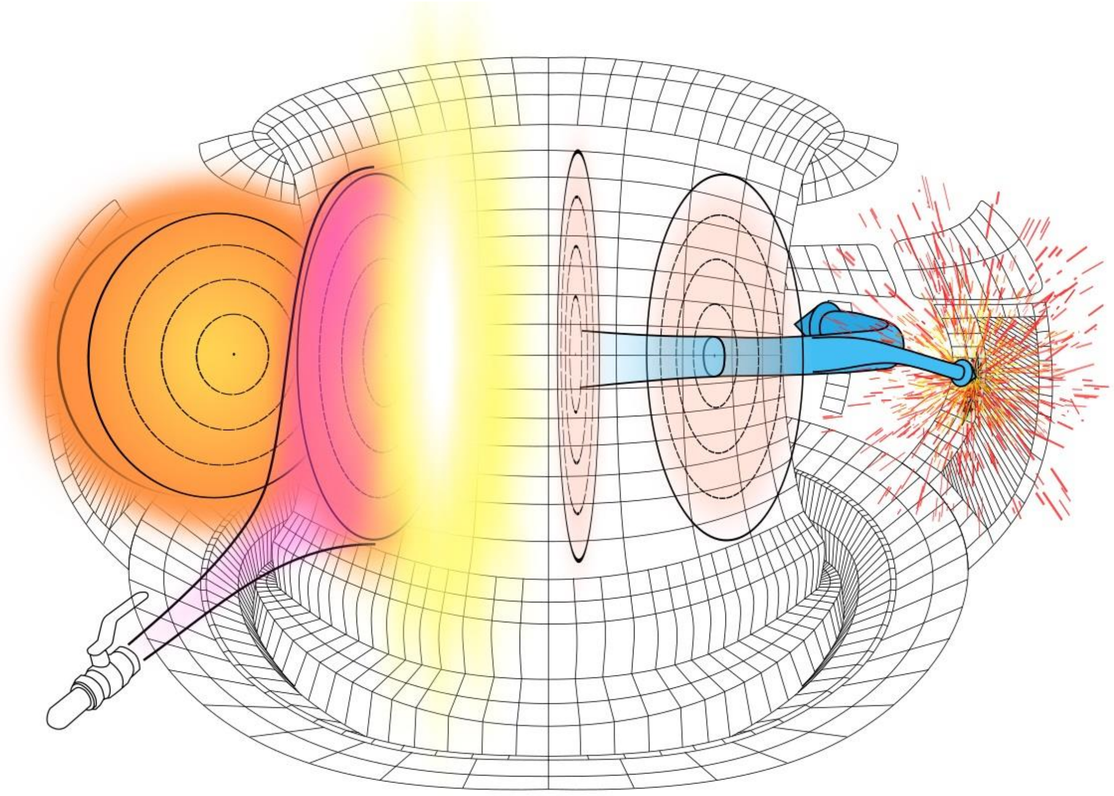
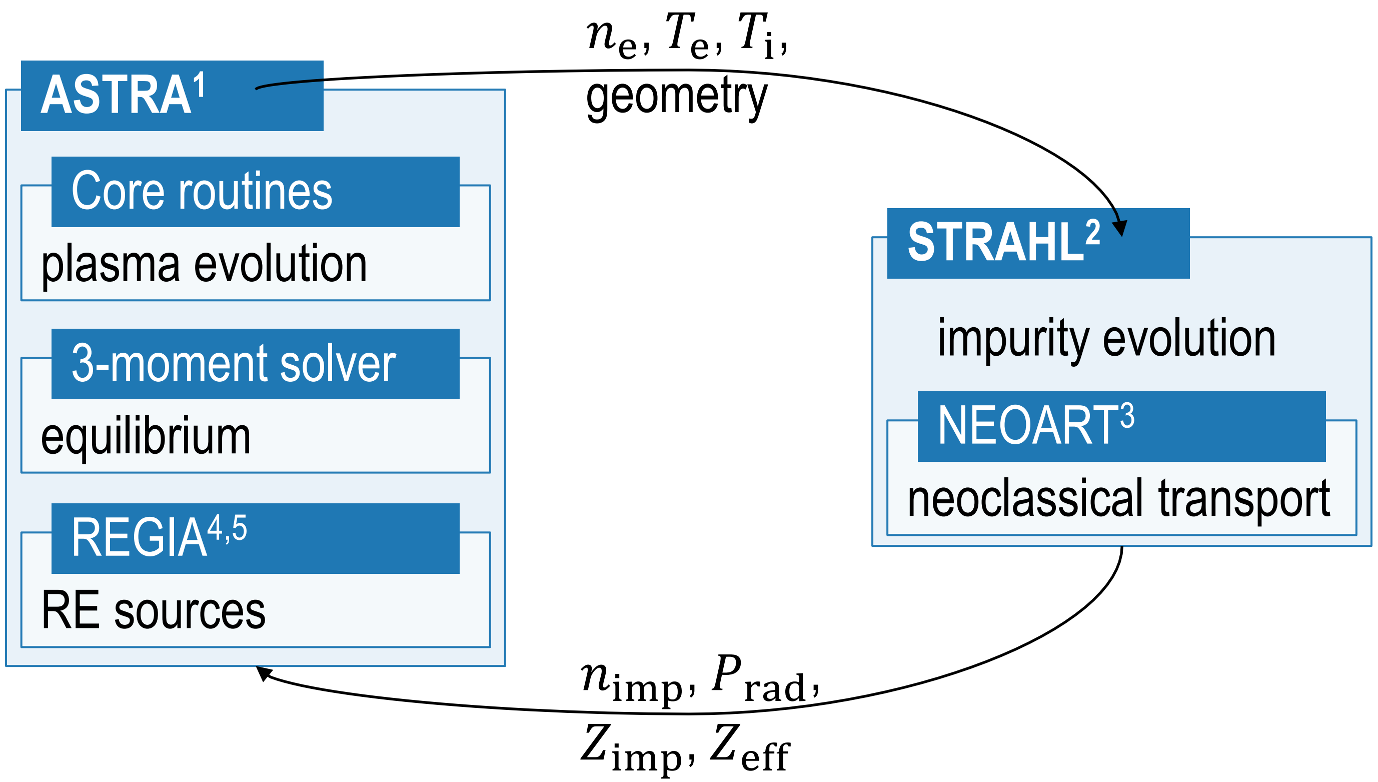
Outline

1. The transport model ASTRA-STRAHL
2. ASDEX Upgrade runaway electron experiments
3. Simulating ASDEX Upgrade #33108
    a. Runaway electron generation
    b. The role of impurity transport
    c. Impact of pre-disruption temperature
4. Conclusions



ASTRA-STRAHL: the coupled transport codes



[1] Fable et al. *Plasma Phys. Control. Fusion* **55**, 074007 (2013)
[2] Dux et al. *Nucl. Fusion* **39**, 1509 (1999)
[3] Peeters. *Phys. Plasmas* **7**, 268 (2000)
[4] Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
[5] Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)

ASTRA-STRAHL: background plasma evolution with ASTRA

Evolution of plasma quantities Y through macroscopic transport equation[1]

$$\frac{1}{V'}\frac{\partial}{\partial t}(V'Y) = \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle(\nabla\rho)^2\rangle\left[D\frac{\partial Y}{\partial \rho} - vY\right]\right) + \sum_i S_i$$

Temperatures T_e, T_i

- Ohmic heating
- Impurity radiation
- Electron-to-ion heat exchange
- Rapid transport during breakup of magnetic surfaces[2,3]
  (more on this later)

Poloidal flux Ψ

- Influenced by RE generation
- j_p profile flattened during TQ onset

Electron density n_e

- From quasineutrality

[1] Fable et al. *Plasma Phys. Control. Fusion* **55**, 074007 (2013)
[2] Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
[3] Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)

ASTRA-STRAHL: impurity evolution with STRAHL

Evolution of plasma quantities Y through macroscopic transport equation

$$\frac{1}{V'}\frac{\partial}{\partial t}(V'Y) = \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle(\nabla\rho)^2\rangle\left[D\frac{\partial Y}{\partial \rho} - vY\right]\right) + \sum_i S_i$$

Impurity densities

- Charge state resolved
- Atomic processes: electron-impact ionization and recombination (coefficients from ADAS[1])
- Neoclassical transport from NEOART[2]
- Neutral gas propagation at speed of sound
- Rapid transport during breakup of magnetic surfaces[3,4]
  (more on this later)
- Impurity radiation from line radiation, continuum radiation and ionization losses

[1] Summers. The ADAS User Manual, version 2.6.
[2] Peeters. *Phys. Plasmas* **7**, 268 (2000)
[3] Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
[4] Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)

ASTRA-STRAHL: Runaway Electron Generation In ASTRA (REGIA)

Evolution of plasma quantities Y through macroscopic transport equation

$$\frac{1}{V'}\frac{\partial}{\partial t}(V'Y) = \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle(\nabla\rho)^2\rangle\left[D\frac{\partial Y}{\partial \rho} - vY\right]\right) + \sum_i S_i$$

Runaway electron current density

- Runaway sources S_i from standalone Fortran module (github.com/o-linder/runawayelectrongeneration)
- Separate populations of RE due to different generation mechanisms
- Average velocity $\langle v_{\mathrm{RE}}\rangle = c$
- No RE losses
- Feed-back on Ψ evolution

Fortran module[1]

- **Dreicer generation**
  - Classical model by Connor & Hastie[2]
  - CODE neural network by Hesslow *et al*[3]
- **Hot-tail generation**
  - Model by Smith & Verwichte[4]
- **Avalanche generation**
  - Classical model by Rosenbluth & Putvinski[5]
  - High-Z model by Hesslow *et al*[6]
- **Nuclear generation**: not implemented
  (Recall, application to ASDEX Upgrade)

[1] Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
[2] Connor et al. *Nucl. Fusion* **15**, 415 (1975)
[3] Hesslow et al. *J. Plasma Phys.* **85**, 475850601 (2019)
[4] Smith et al. *Phys. Plasmas* **15**, 072502 (2008)
[5] Rosenbluth et al. *Nucl. Fusion* **37**, 1355 (1997)
[6] Hesslow et al. *Nucl. Fusion* **59**, 084004 (2019)

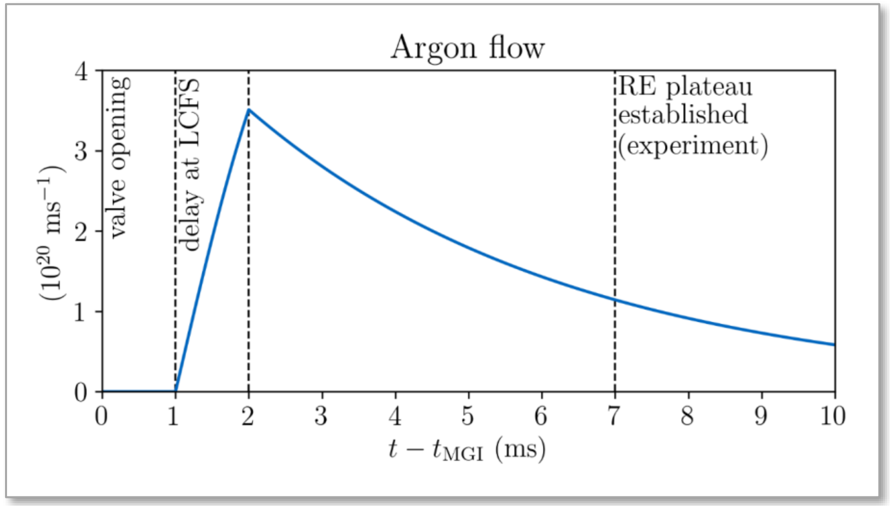
ASTRA-STRAHL: Description of MGI and TQ

Massive gas injection

- Outflow from gas valve described by continuity equation[1]
- Inward propagation with thermal velocity (for Ar):

$$v_{\mathrm{th}} = \sqrt{T/m} = 246\ \mathrm{m/s}$$

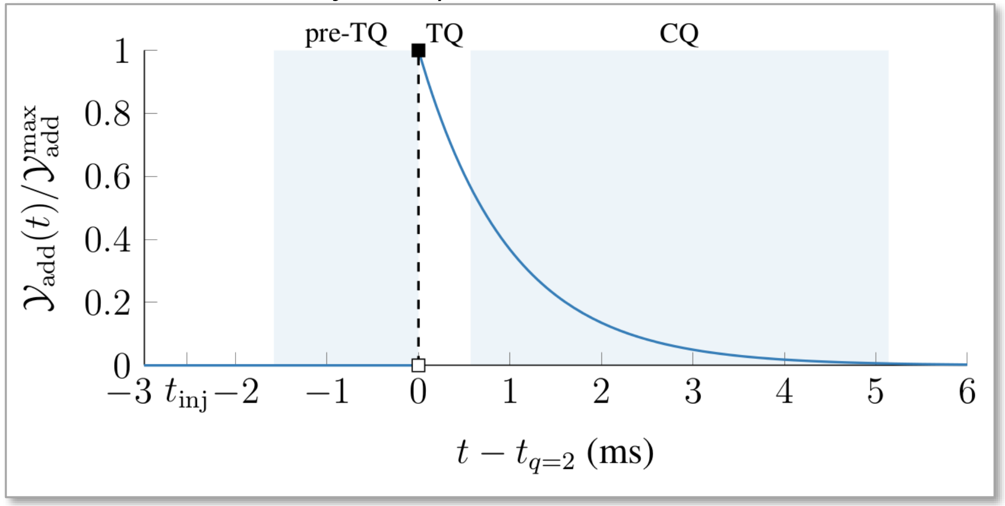
- In AUG: valve opens within 1 ms
- In ASTRA: source located 1 cm outside LCFS
  $\rightarrow$ 1 ms delay
  (no need to model propagation from valve to LCFS)



Break-up of magnetic surfaces / onset of TQ

- Cold gas front reaches $q = 2$ surface, triggers $(m, n) = (2,1)$ MHD modes (+ higher harmonics)
- In experiment: flattens j_{p} profile, drop in l_{i}, I_{p} spike
- In ASTRA[2,3]: j_{p} flattened when $\left|\frac{\mathrm{d}j_{\mathrm{p}}}{\mathrm{d}\rho}\frac{1}{j_{\mathrm{p}}}\right| > 50$ at $q = 2$
- Additional transport: $\mathcal{Y}_{\mathrm{add}}(t) = \mathcal{Y}_{\mathrm{add}}^{\max} \exp\left(-\frac{t - t_{q=2}}{\tau_{\mathrm{add}}}\right)$

  (more on the necessity later)



[1] Pautasso et al. *Nucl. Fusion* **47**, 900 (2007)
[2] Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
[3] Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)

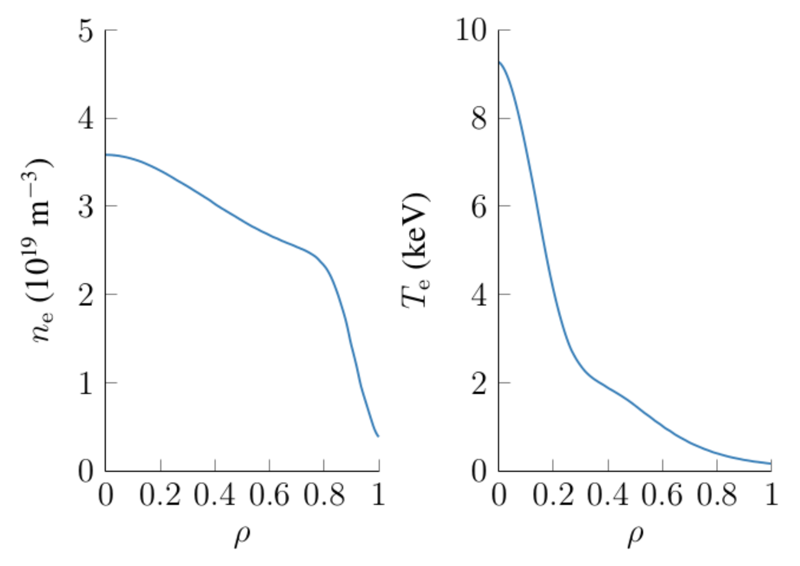
ASDEX Upgrade runaway electron experiments[1-3]

MGI in AUG #33108

- Circular L-mode limiter plasma
- Low density ($3 \times 10^{19}\ \mathrm{m}^{-3}$), high temperature ($9\ \mathrm{keV}$)
- Central ECRH ($2.6\ \mathrm{MW}$)
- Argon injection ($0.73\ \mathrm{bar} \times 100\ \mathrm{cm}^3 \sim 7\ N_\mathrm{D}$)

Application

- Used as base case for simulations
- Similar discharges selected for comparison of simulations with experimental trend
  (impact of T_e)



Quantity	AUG #33108	similar shots
$I_{\mathrm{p},0}$ (MA)	0.76	0.60 – 0.90
p_{Ar} (bar)	0.73	0.60 – 0.85
B_{tor} (T)	2.50	2.30 – 2.70
q_{95}	3.79	3.50 – 4.10

[1] Pautasso et al. *Nucl. Fusion* **55**, 033015 (2015)
[2] Pautasso et al. *Plasma Phys. Control. Fusion* **59**, 014046 (2017)
[3] Pautasso et al. *Nucl. Fusion* **60**, 086011 (2020)

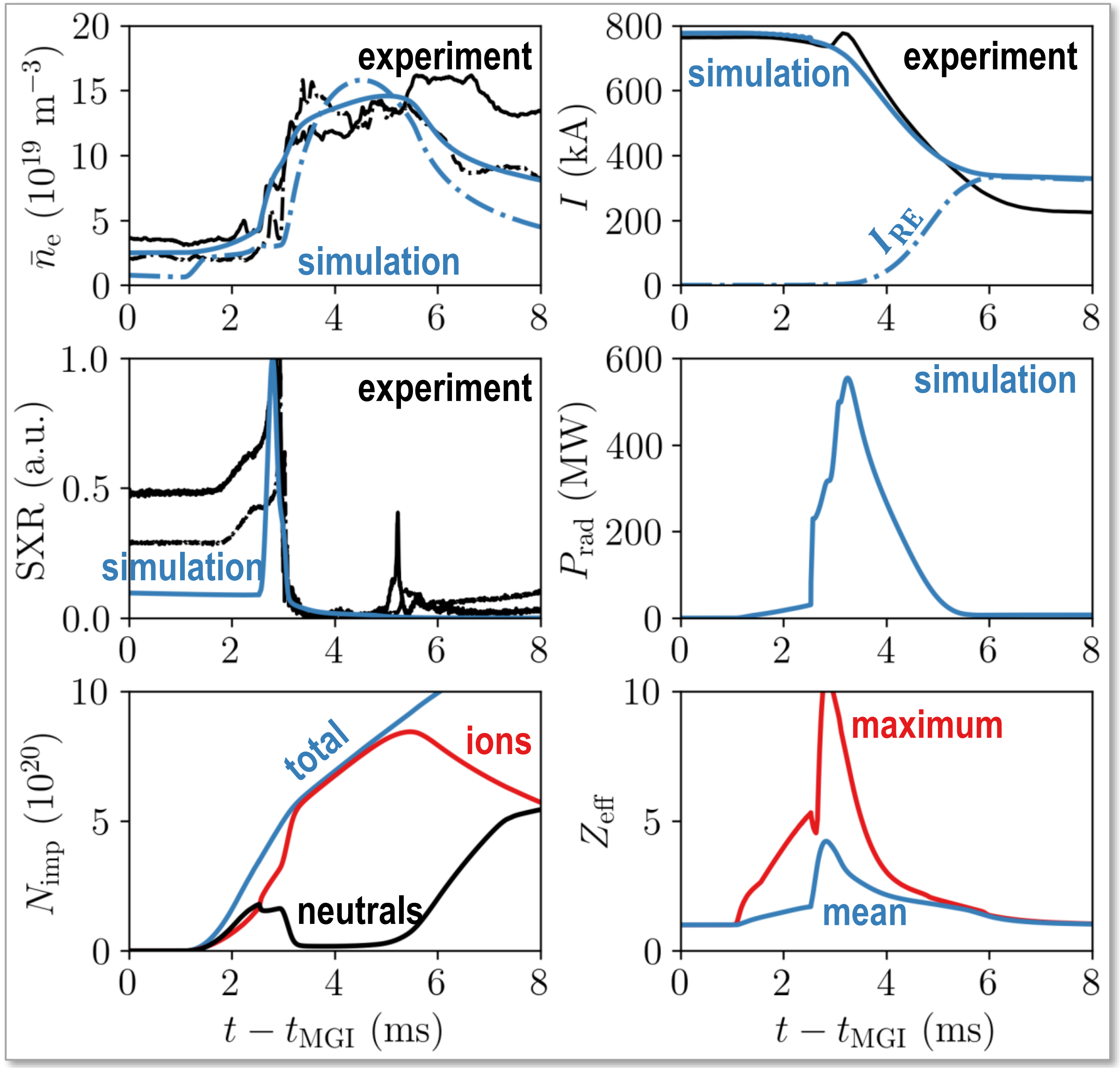
Simulating ASDEX Upgrade #33108

Key experimental observations reproduced

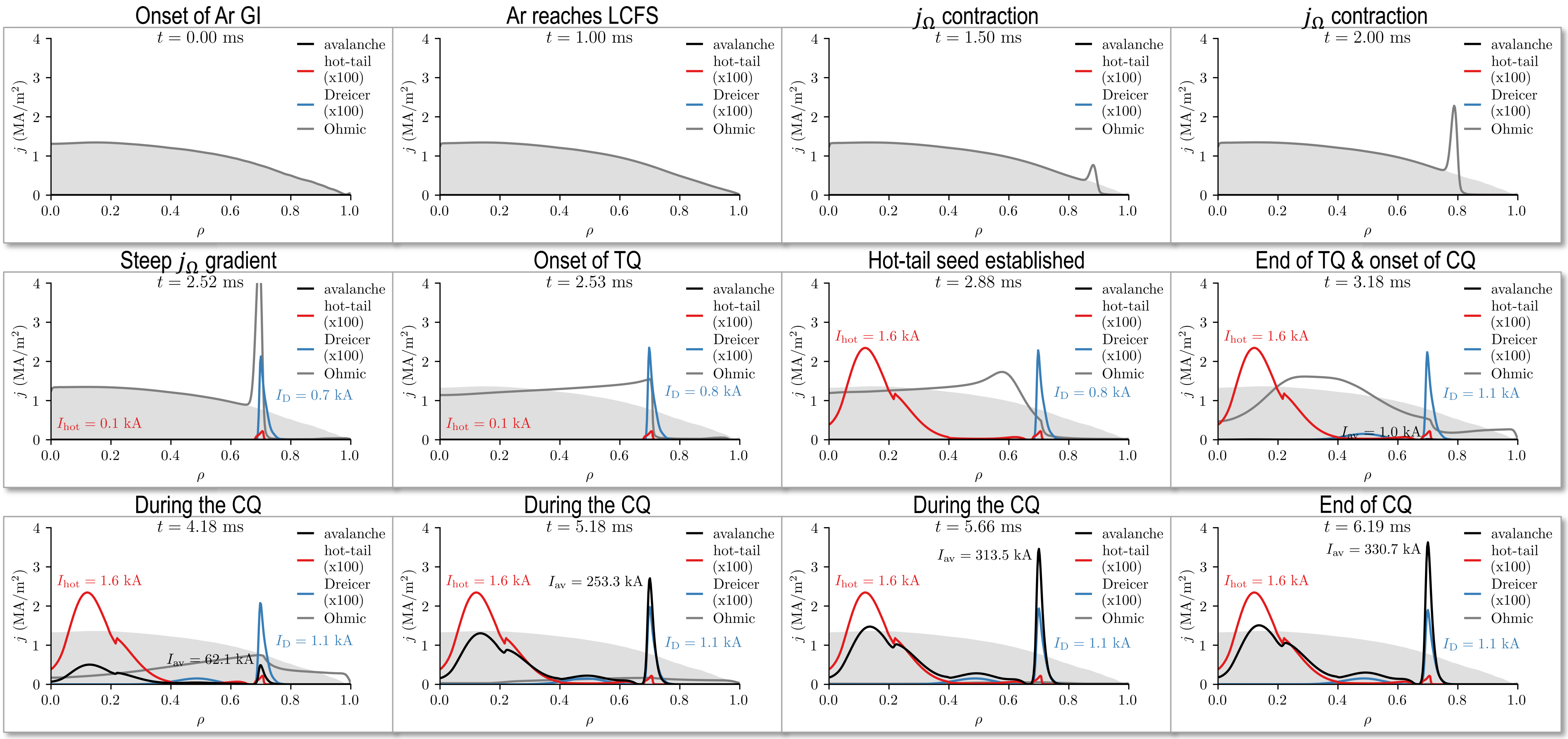
- Increase of electron density $\bar{n}_\mathrm{e}$
- Decay of plasma current I_p
- Occurrence of TQ

Simulation features

- Density increase reproduced
  $\longrightarrow$ current decay reproduced
- Density increase requires additional transport
  $D = 100\ \mathrm{m}^2/\mathrm{s}, \qquad v = -1000\ \mathrm{m/s},$
  $\tau = 1.0\ \mathrm{ms}$
- Thermal energy dissipated by impurity radiation
- Ohmic heating during CQ → prolonged radiation
- Distinct phases of disruption covered
  (pre-TQ, TQ, CQ)



Runaway electron generation: current evolution



Runaway electron generation: contributions

Seed generation

- Only a few kA
- Similar contributions by hot-tail & Dreicer mechanisms

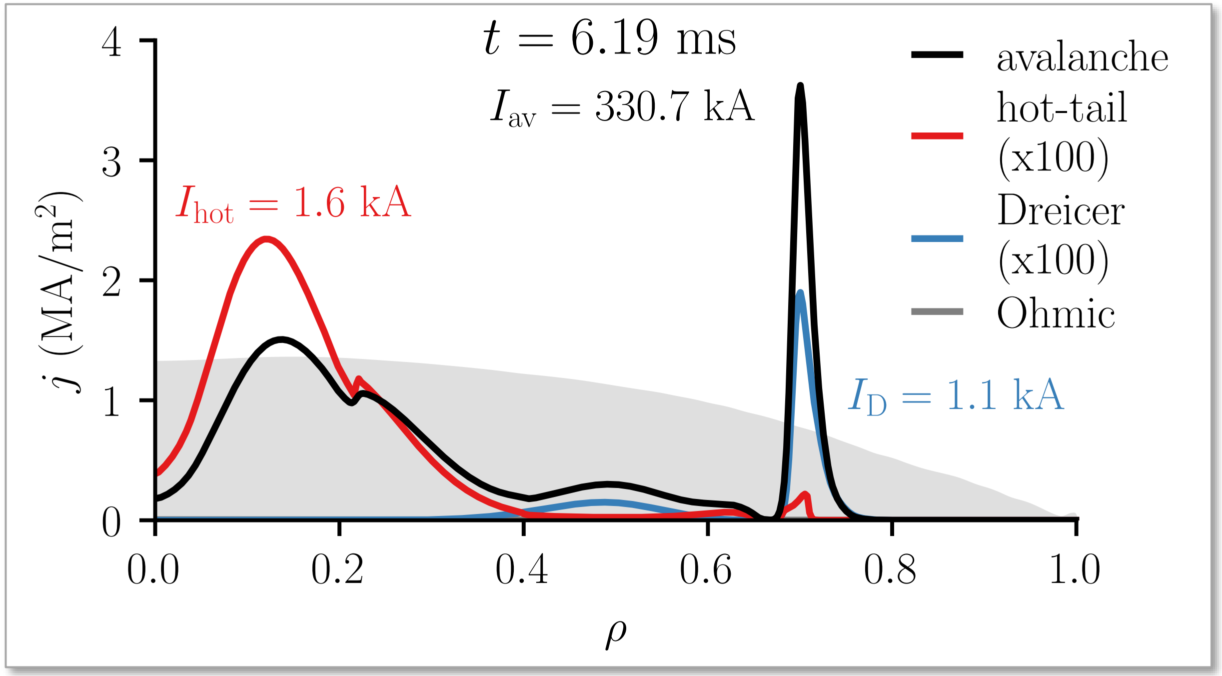
Avalanching

- Seed multiplication
- Generates 331 kA of REs
- Final RE beam avalanche dominated

→ RE seed of minor importance
(varying strength & composition)

Experimental comparison

- Higher I_{RE} simulated due to absence of RE losses



Runaway electron generation: impact of the RE seed

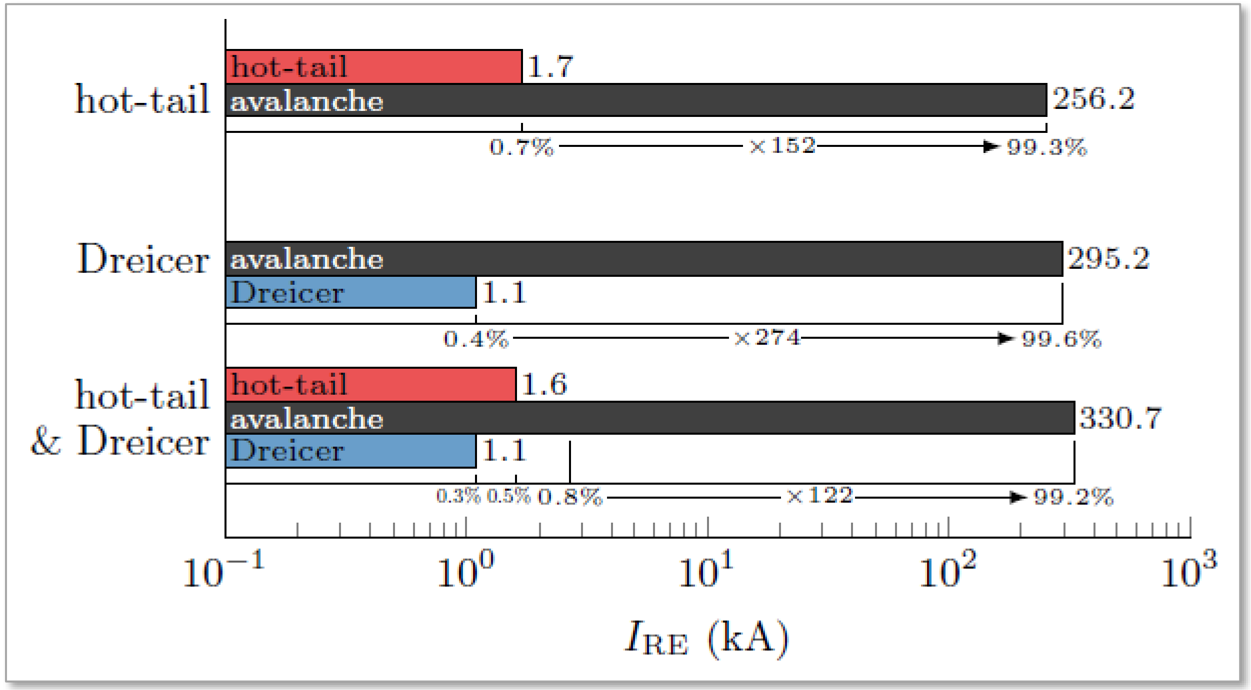
Comparison with only one seed mechanism used

- Reduction of $I_{\mathrm{RE}}^{\mathrm{seed}}$ does not affect RE multiplication with equal weight:

  hot-tail: $-37\%\ I_{\mathrm{RE}}^{\mathrm{seed}} \rightarrow -23\%\ I_{\mathrm{av}}$

  Dreicer: $-59\%\ I_{\mathrm{RE}}^{\mathrm{seed}} \rightarrow -11\%\ I_{\mathrm{av}}$

- Decay of I_{Ω} at similar time scales, avalanche multiplication time determines post-CQ I_{RE} *(feedback on Ψ-evolution)*



→ **Exact strength of RE seed is of secondary importance due to dominating avalanche generation**

Runaway electron generation: impact of partially ionized impurities

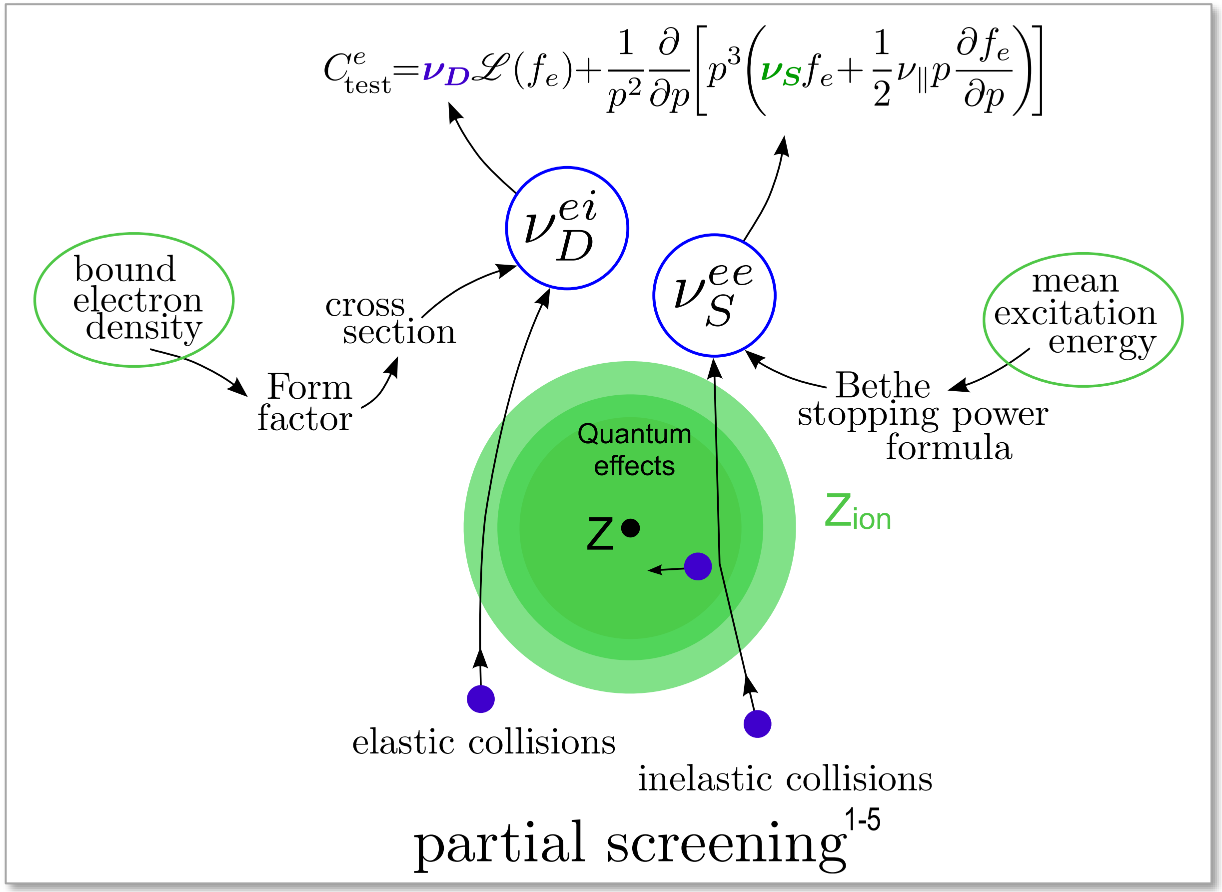
Impact of partially ionized impurities[1-5]

- Increased electron-ion friction → hinders runaway
- Relevant in MGI scenarios
- Classical formulae[6-7] assume full ionization
- Effects considered in state-of-the-art models[4-5]

ASTRA-STRAHL simulations[8]

- Assess importance of partial screening in self-consistent simulations:

  state-of-the-art[4-5] ↔ classical[6-7]



[1] Hesslow *et al.* *Phys. Rev. Lett.* **118**, 255001 (2017)
[2] Hesslow *et al.* *Plasma Phys. Control. Fusion* **60**, 074010 (2018)
[3] Hesslow *et al.* *J. Plasma Phys.* **84**, 905840605 (2018)
[4] Hesslow *et al.* *Nucl. Fusion* **59**, 084004 (2019)
[5] Hesslow *et al.* *J. Plasma Phys.* **85**, 475850601 (2019)
[6] Connor *et al.* *Nucl. Fusion* **15**, 415 (1975)
[7] Rosenbluth *et al.* *Nucl. Fusion* **37**, 1355 (1997)
[8] Linder *et al.* *Nucl. Fusion* **60**, 096031 (2020)

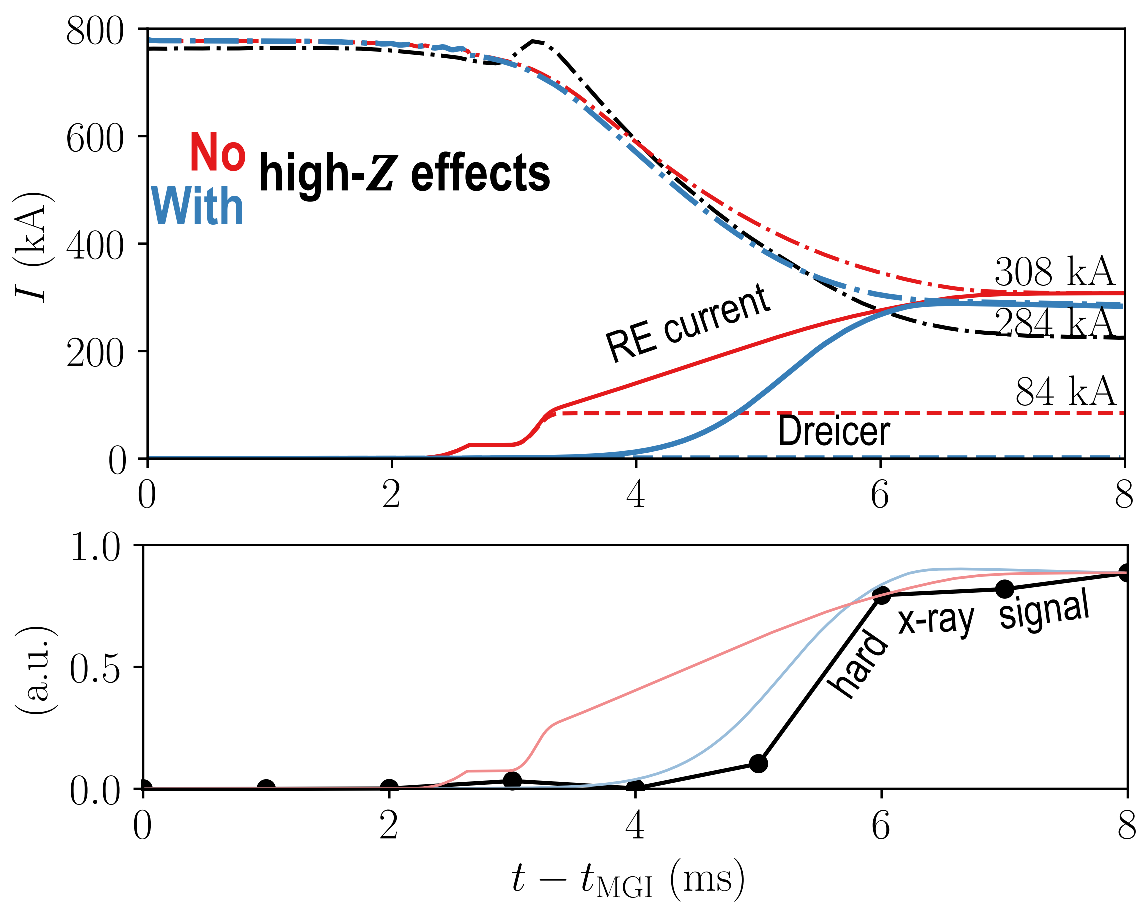
Runaway electron generation: model validation

Absence of high-Z effects

- Dreicer generation overestimated
  (earlier onset & stronger, 84 kA)
- Avalanche multiplication reduced
  (slower rise of RE current during CQ)
- Decay of total current slowed down
  → less Ohmic heating, less radiation
- Final I_{RE} similar, but different composition
- Hard x-ray signal: High I_{RE} only at end of CQ

→ **Simulations consistent with experiment only when considering high-Z effects**

→ **High-Z interactions important for runaway!**



The role of impurity transport: impact of transport mechanisms

Mechanisms considered

- Rapid redistribution
  (MHD effects due to breakup of magnetic surfaces)
- Neoclassical effects

Absence of rapid redistribution

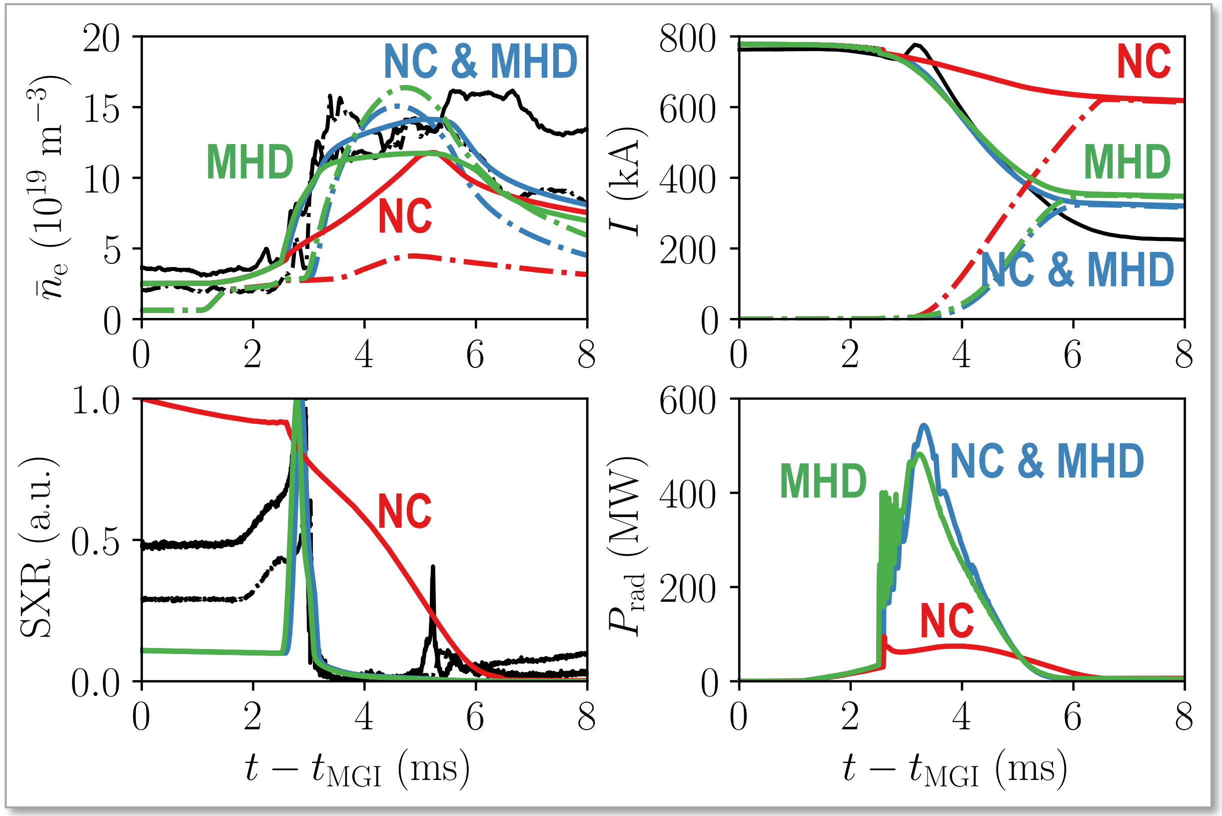
- Impurity propagation driven by neutral gas
- Increase of electron density $\bar{n}_\mathbf{e}$ not matched

→ **Much slower TQ!**

Absence of neoclassical effects

- Inward transport less effective

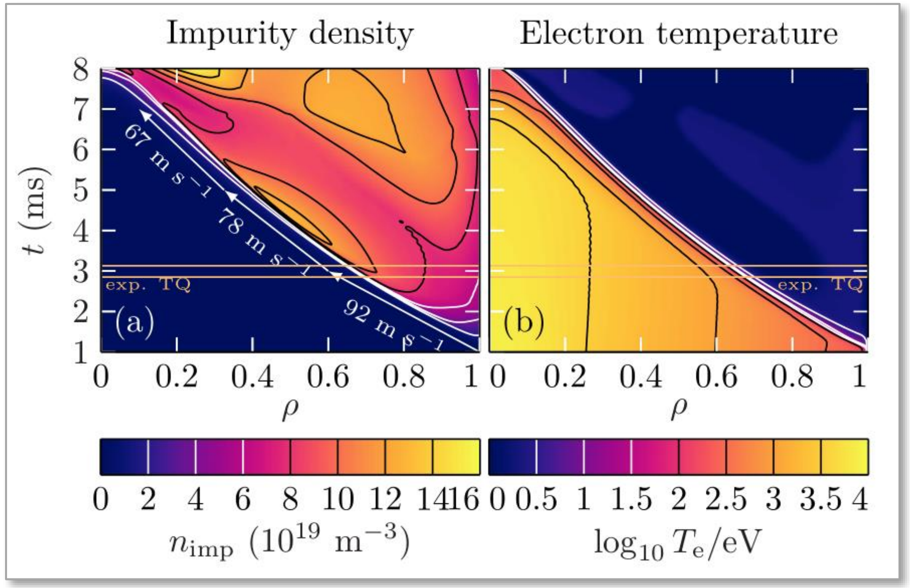
→ **Rapid redistribution & neoclassical effects relevant for impurity transport**



The role of impurity transport: rapid redistribution

Absence of rapid redistribution

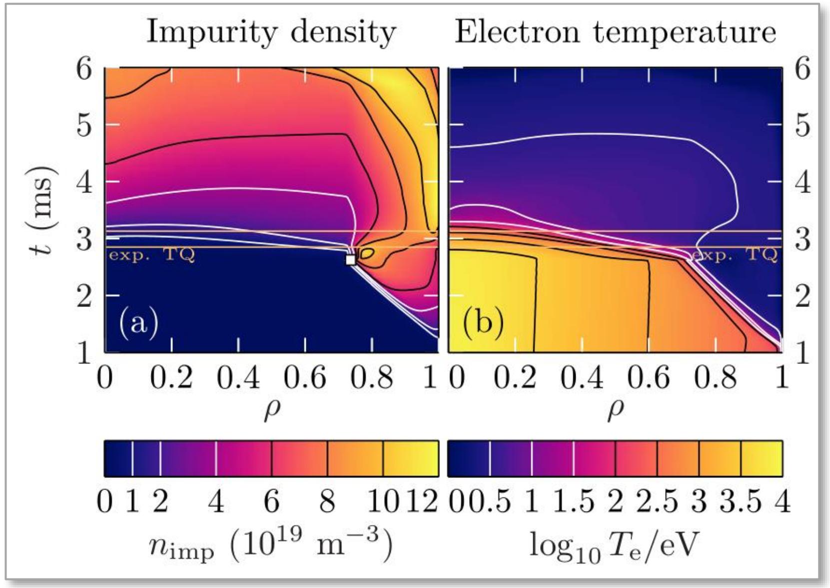
- Impurity propagation driven by neutral gas
- Slow TQ over several ms



Considering rapid redistribution

- Central impurity density increases during CQ
- TQ on experimental sub-ms time scales
- Note, only order of magnitude values used:
  $D = 100\ \mathrm{m^2/s}, \qquad v = -1000\ \mathrm{m/s},$
  $\tau = 1.0\ \mathrm{ms}$

(variation by around 50% describes experiment adequately)



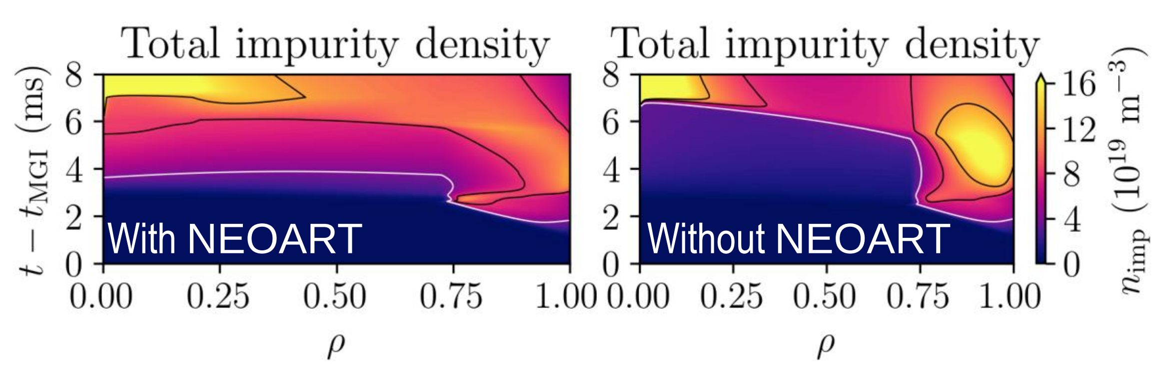
The role of impurity transport: neoclassical transport

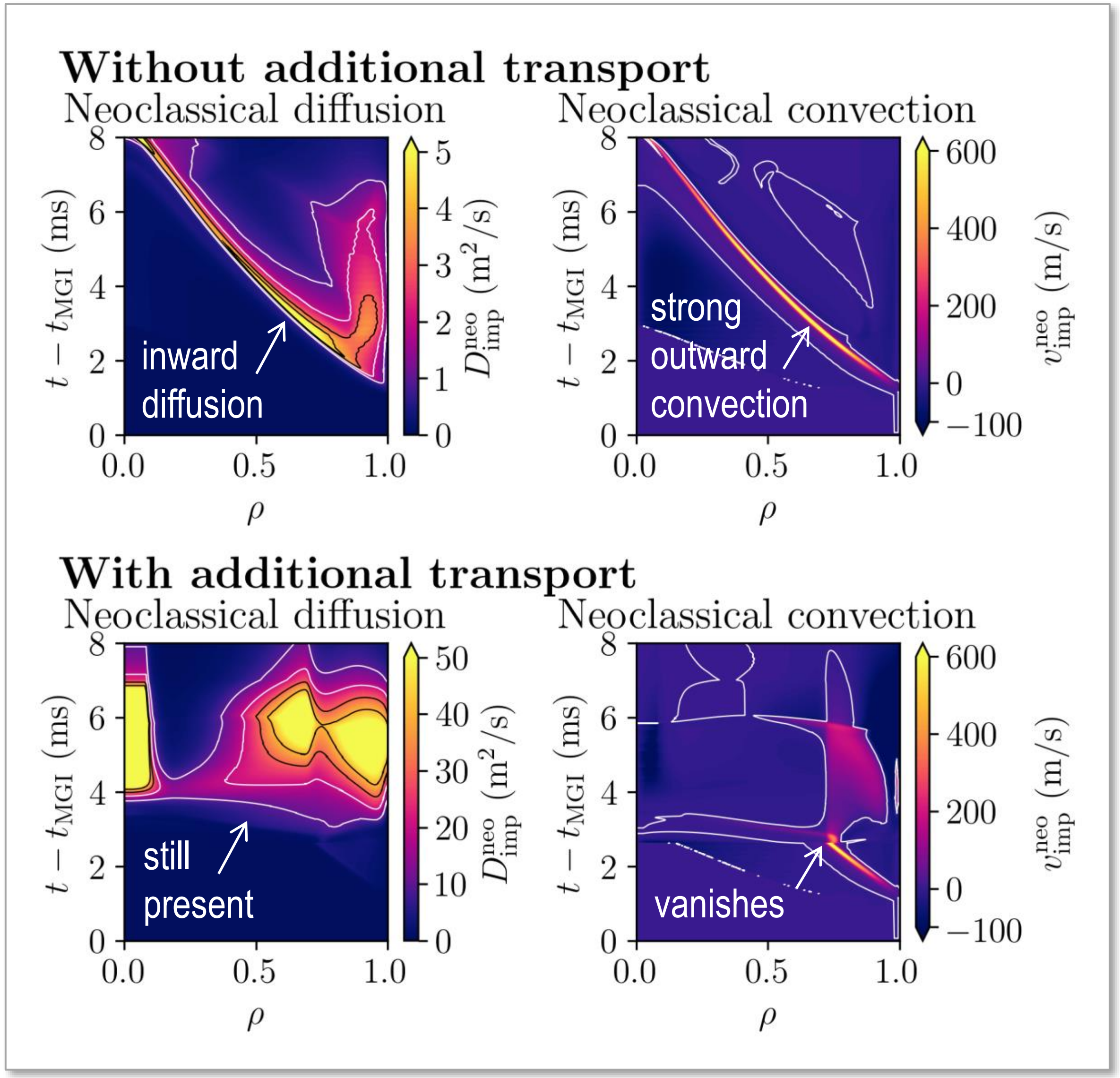
In absence of additional transport

- Diffusion & strong outward convection almost cancel
- Propagation driven by neutrals
- Slow inward propagation of material

With additional transport

- Outward convection vanishes; diffusion present
- Neoclassical transport contributes noticeably to inward transport
  (current decay too slow in absence of neoclassical effects)





Impact of pre-disruption temperature: simulation setup

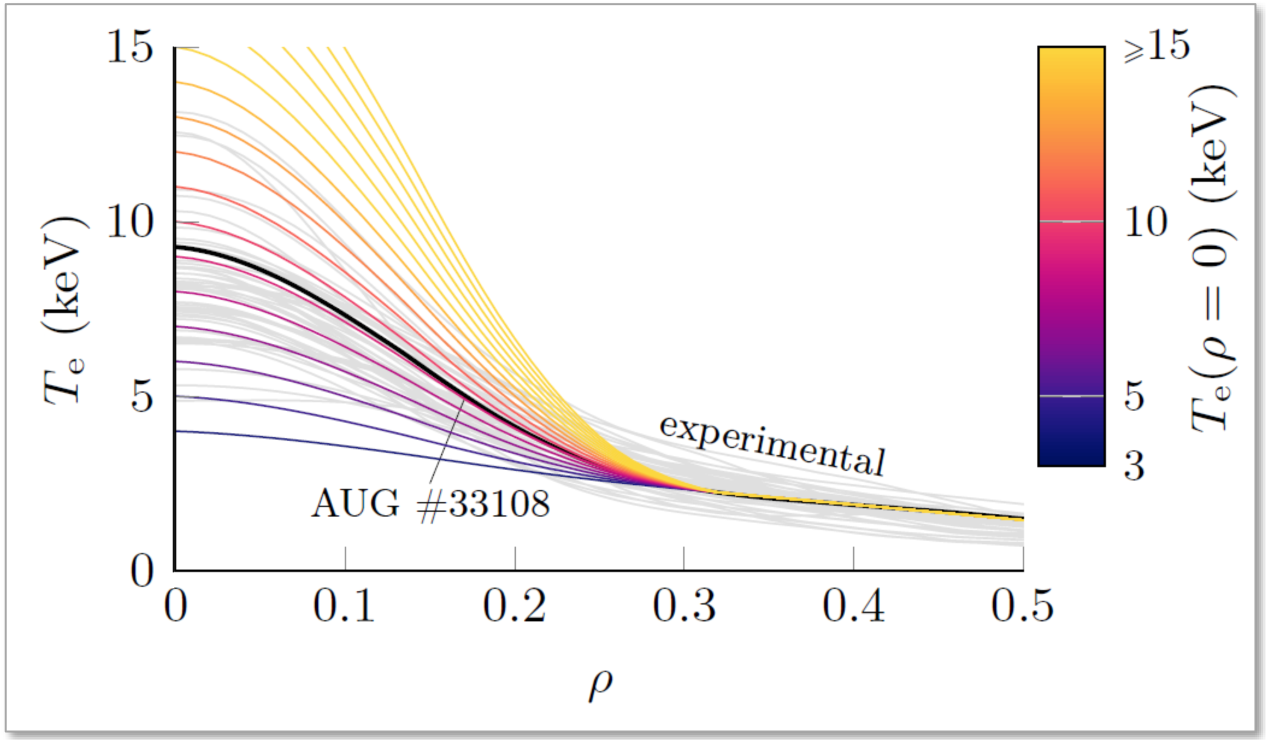
Setup

- In AUG experiments, on-axis ECRH during last $0.1\ \mathrm{ms}$ prior to MGI
- Scale ECRH contribution of $T_e(\rho)$ in AUG #33108

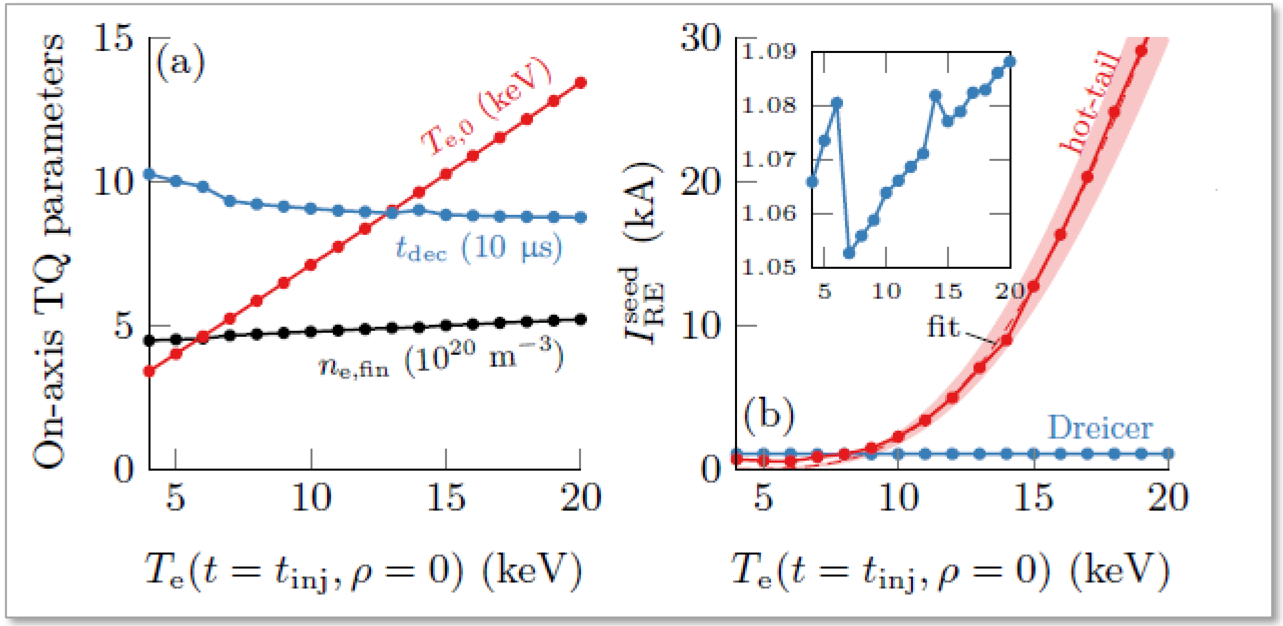
$$T_\mathrm{e}(\rho) = \frac{T_\mathrm{tar} - T_\mathrm{bg}(0)}{T_\mathrm{ECRH}(0)} T_\mathrm{ECRH}(\rho) + T_\mathrm{bg}(\rho)$$

target **back**g**round**

- Temperature unaffected for $\rho > 0.35$



Impact of pre-disruption temperature: the RE seed



Dreicer population

- Virtually unaffected: $I_D = 1.1$ kA
- No (significant) T_e change in region of strongest generation

Hot-tail population

- Grows exponentially
  I_{hot}: 0.6 kA → 33.7 kA
- Strongest increase above 10 keV
- Described by exponential

$$I_{hot}^{fit}(T_{e,0}(\rho = 0)) = (914 \pm 58) \exp\left(-4\left\{\frac{\tilde{\nu}\ln\Lambda(t_0)\,\langle n_{e,fin} t_{dec}\rangle}{T_{e,0}(\rho = 0)^{3/2}}\right\}^{2/3}\right)\ \text{kA}$$

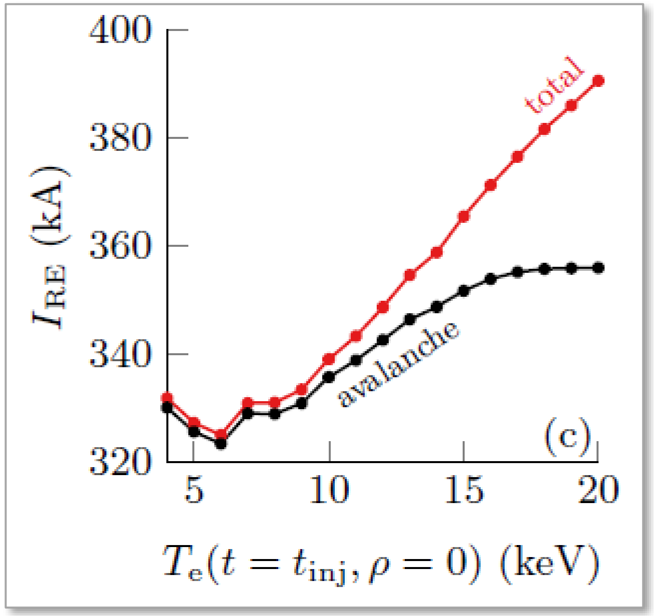
- Strong increase of temperature (by design), but density not at similar rate

→ **Strong increase of hot-tail runaway for hotter plasmas**

Impact of pre-disruption temperature: avalanche & total current

Multiplication

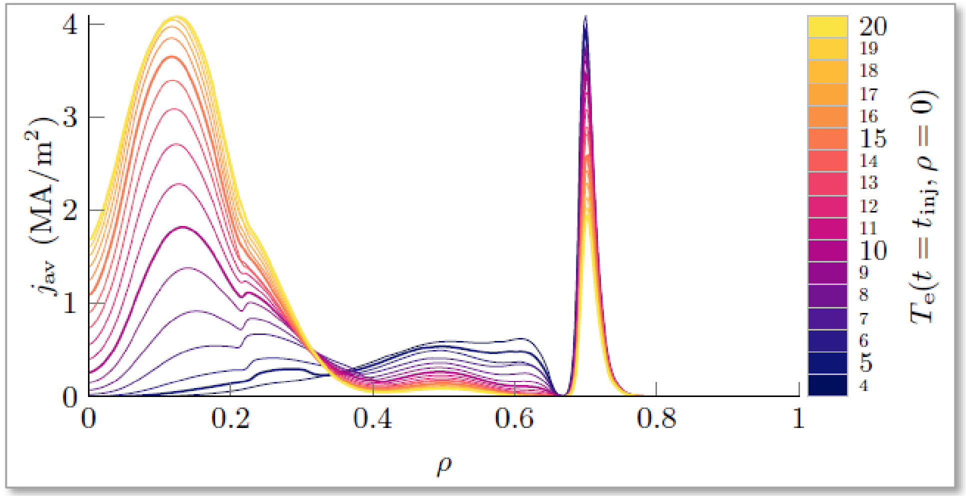
- Avalanche (& total) RE current $\sim 330\ \mathrm{kA}$ for $T_\mathrm{e} < 9\ \mathrm{keV}$
- Between $9\ \mathrm{keV}$ and $17\ \mathrm{keV}$, I_av increases
  (additional multiplication between $2 - 3$)
- Avalanche current saturates for $T_\mathrm{e} > 17\ \mathrm{keV}$ at $356\ \mathrm{kA}$
- Radial distribution of j_av changes (as hot-tail becomes more important): mid radius & $q = 2 \rightarrow \rho \sim 0.12$



Total current

- For $T_\mathrm{e} > 9\ \mathrm{keV}$, grows linearly due to hot-tail contribution
- At $T_\mathrm{e} = 20\ \mathrm{keV}$, hot-tail constitutes $9\%\ I_\mathrm{RE}$

→ **Relative importance of multiplication decreases due to finite poloidal magnetic flux available**
(less avalanching in ITER?)



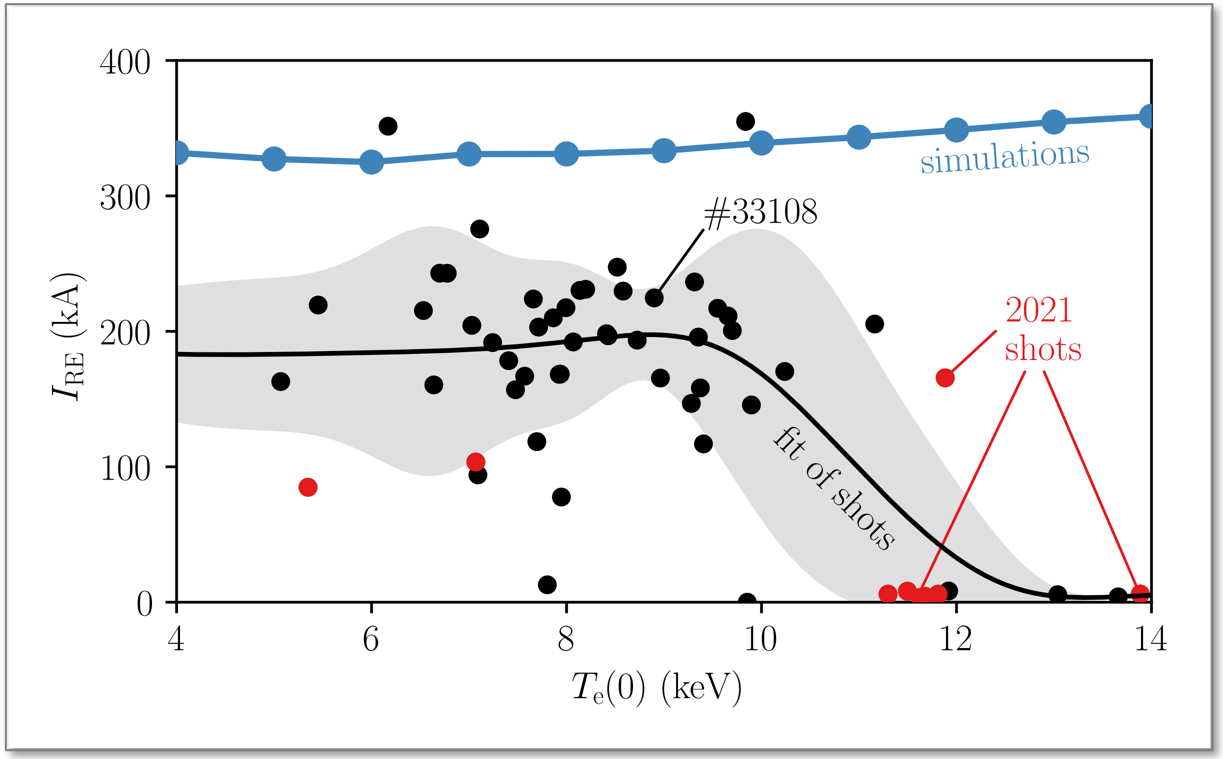
Impact of pre-disruption temperature: experimental comparison

For $T_e < 9$ keV

- **RE current ~ constant (experiment & simulation)**
- Simulated I_{RE} larger due to absence of RE losses

For $T_e > 9$ keV

- **In simulation, I_{RE} increasing (hot-tails)**
- **None in experiment at $T_e > 12$ keV**
- In 2021 campaign, one discharge with RE beam close to 12 keV
- Reason: Loss of RE seed during breakup of magnetic surfaces?



Further reading

More details on self-consistent ASTRA-STRAHL simulations of Ar MGI in ASDEX Upgrade #33108 are presented in the following publications:

IAEA nuclear fusion

PAPER

Self-consistent modeling of runaway electron generation in massive gas injection scenarios in ASDEX Upgrade

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Article PDF

Linder et al. *Nucl. Fusion* **60**, 096031 (2020)
https://doi.org/10.1088/1741-4326/ab9dcf

Journal of Plasma Physics

Electron runaway in ASDEX Upgrade experiments of varying core temperature

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O. Linder, G. Papp, E. Fable, F. Jenko, G. Pautasso, the ASDEX Upgrade Team and the EUROfusion MST1 Team

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Article contents

Abstract

The formation of a substantial postdisruption runaway electron current in ASDEX Upgrade material injection experiments is determined by avalanche multiplication of a small seed population of runaway electrons. For the investigation of these scenarios, the runaway electron description of the coupled 1.5-D transport solvers ASTRA-STRAHL is amended by a fluid model describing electron runaway caused by the hot-tail mechanism. Applied in

Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)
https://doi.org/10.1017/S0022377821000416

Conclusions

1. **Successful ASTRA-STRAHL simulations of RE dynamics on ASDEX Upgrade** (background plasma, MGI, RE generation)

2. **High-Z effects important for RE generation**

3. **Impurity transport due to MHD & neoclassical effects**

4. **Discrepancies w.r.t. experiment in high T_e scenarios suggest seed RE loss**

References

CONNOR, J.W. and HASTIE, R.J.. Relativistic limitations on runaway electrons. *Nucl. Fusion* **15**, 415 (1975)

DUX, R., PEETERS, A.G., GUDE, A. et al. Z dependence of the core impurity transport in ASDEX Upgrade H mode discharges. *Nucl. Fusion* **39**, 1509 (1999)

FABLE, E., ANGIONI, C., IVANOV, A.A. et al. Dynamical coupling between magnetic equilibrium and transport in tokamak scenario modelling, with application to current ramps. *Plasma Phys. Control. Fusion* **55**, 074007 (2013)

HESSLOW, L., EMBREUS, O., STAHL, A. et al. Effect of Partially Screened Nuclei on Fast-Electron Dynamics. *Phys. Rev. Lett.* **118**, 255001 (2017)

HESSLOW, L., EMBREUS, O., WILKIE, G.J. et al. Effect of partially ionized impurities and radiation on the effective critical electric field for runaway generation. *Plasma Phys. Control. Fusion* **60**, 074010 (2018)

HESSLOW, L., EMBREUS, O., HOPPE, M. et al. Generalized collision operator for fast electrons interacting with partially ionized impurities. *J. Plasma Phys.* **84**, 905840605 (2018)

HESSLOW, L., EMBREUS, O., VALLHAGEN, O. et al. Influence of massive material injection on avalanche runaway generation during tokamak disruptions. *Nucl. Fusion* **59**, 084004 (2019)

HESSLOW, L., UNNERFELT, L. , VALLHAGEN, O. et al. Evaluation of the Dreicer runaway growth rate in the presence of high-Z impurities using a neural network. *J. Plasma Phys.* **85**, 475850601 (2019)

LINDER, O., FABLE, E., JENKO, F. et al. Self-consistent modeling of runaway electron generation in massive gas injection scenarios in ASDEX Upgrade. *Nucl. Fusion* **60**, 096031 (2020)

LINDER, O., PAPP, G., FABLE, E. et al. Electron runaway in ASDEX Upgrade experiments of varying core temperature. *J. Plasma Phys.* **87**, 905870301 (2021)

PAUTASSO, G., FUCHS, C.J., GRUBER, O. et al. Plasma shut-down with fast impurity puff on ASDEX Upgrade. *Nucl. Fusion* **47**, 900 (2007)

PAUTASSO, G., MLYNEK, A., BERNERT, M. et al. Assimilation of impurities during massive gas injection in ASDEX Upgrade. *Nucl. Fusion* **55**, 033015 (2015)

PAUTASSO, G., BERNERT, M., DIBON, M. et al. Disruption mitigation by injection of small quantities of noble gas in ASDEX Upgrade. Plasma Phys. Control. Fusion **59**, 014046 (2017)

PAUTASSO, G., DIBON, M., DUNNE, M. et al. Generation and dissipation of runaway electrons in ASDEX Upgrade experiments. *Nucl. Fusion* **60**, 086011 (2020)

PEETERS, A.G. Reduced charge state equations that describe Pfirsch Schluter impurity transport in tokamak plasma. *Phys. Plasmas* **7**, 268 (1999)

ROSENBLUTH, M.N. & PUTVINSKI, S.V. Theory for avalanche of runaway electrons in tokamaks. *Nucl. Fusion* **37**, 1355 (1997)

SMITH, H.M. & VERWICHTE, E.. Hot tail runaway electron generation in tokamak disruptions. *Phys. Plasmas* **15**, 072502 (2008)

SUMMERS, H.P. The ADAS User Manual, version 2.6. https://www.adas.ac.uk.

Appendix: Average runaway electron velocity

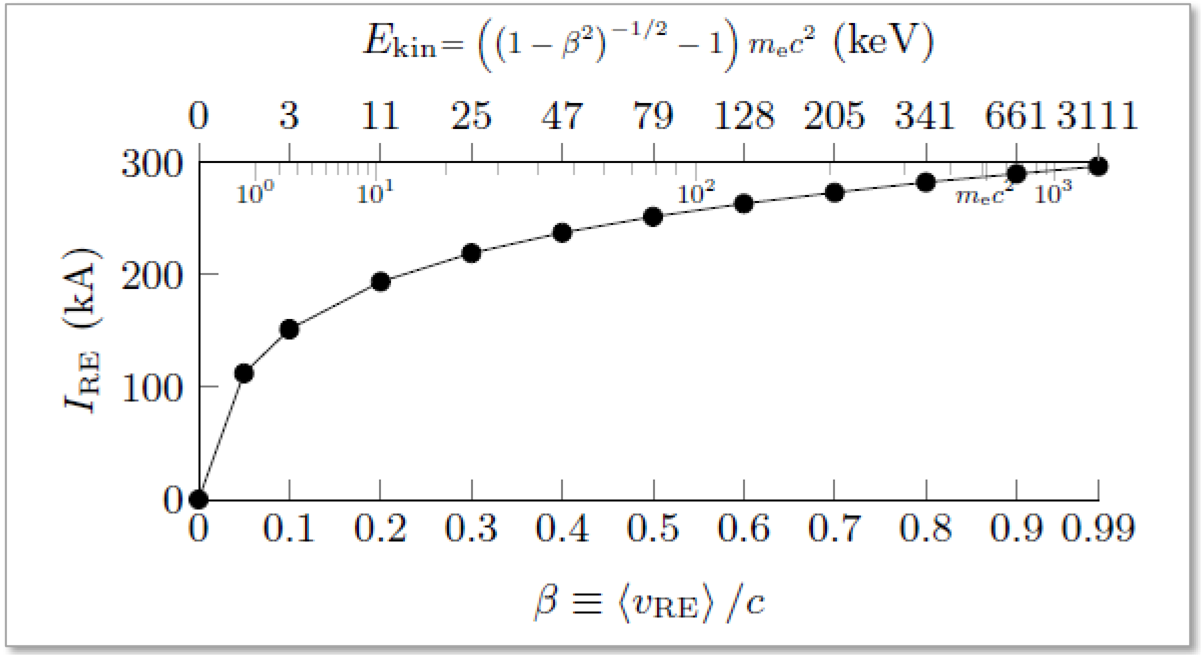
Impact of assumption $\langle v_{RE} \rangle = c$

- Valid for $E_{\text{kin}} \geq 3.1\ \text{MeV}$
  ($\lesssim 1\%$ deviation)
- Conditions not fulfilled during early stages
- Yet, reduction of $\langle v_{RE} \rangle$ to below c
  → slight decrease of I_{RE}
  (only assuming $E_{\text{kin}} \sim T_{\text{e,0}}$: strong decrease)
- Reduction of $\langle v_{RE} \rangle \equiv$ reduction of seed population!
  (*mathematically*)

$$\frac{\partial j_{\text{seed}}}{\partial t} = e \langle v_{\text{RE}} \rangle S_{\text{seed}} = e (c\beta) S_{\text{seed}} = ec (\beta S_{\text{seed}})$$

$$\frac{\partial j_{\text{av}}}{\partial t} = e \langle v_{\text{RE}} \rangle n_{\text{RE}} \tilde{S}_{\text{av}} = (j_{\text{av}} + j_{\text{seed}}) \tilde{S}_{\text{av}}$$

→ **Avalanche contribution not affected proportionally; total current only somewhat reduced**
(*same argument as before!*)



Appendix: Off-axis hot-tail density peaking

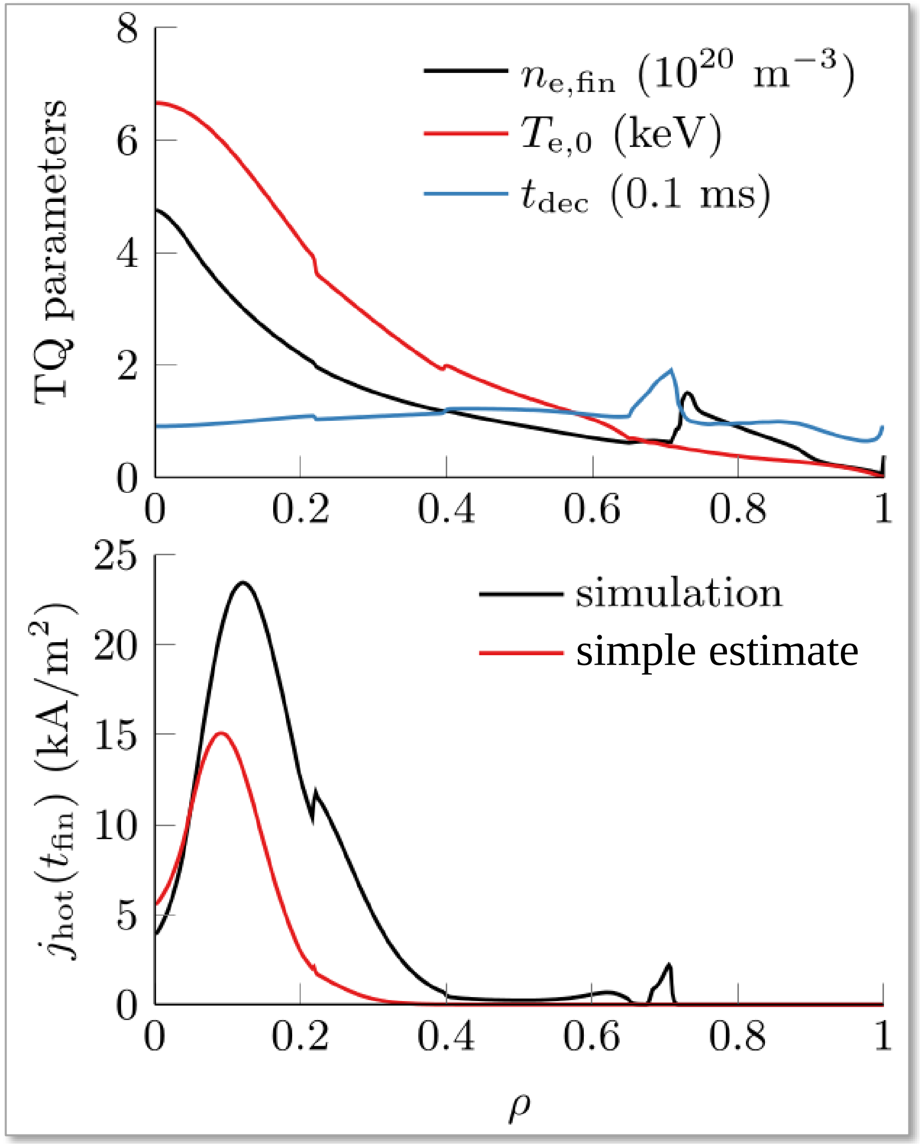
Important parameters for hot-tail generation[1]

Simple estimate[2]

$$n_{\text{hot}}^{\text{simple}}(t_{\text{fin}}) \propto n_{\text{e},0} \exp\left(-4\,\tilde{\nu}\,\frac{n_{\text{e,fin}}^{2/3} t_{\text{dec}}^{2/3}}{T_{\text{e},0}}\right)$$

- Pre-disruption temperature $T_{\text{e},0}$
- Decay time scale t_{dec}
- Post-disruption density $n_{\text{e,fin}}$

→ **Off-axis hot-tail peaking due to on-axis density peaking post-TQ**



[1] Smith et al. *Phys. Plasmas* **15**, 072502 (2008)

[2] Linder et al. *J. Plasma Phys.* **87**, 905870301 (2021)