IAEA Technical Meeting on Plasma Disruptions and their Mitigation
20th - 23rd July 2020

Max-Planck-Institut für Plasmaphysik

Validation of state-of-the-art runaway electron generation models in simulations of ASDEX Upgrade disruptions

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Brief remark: RE modeling beyond this talk

More details and analyses on this topic can be found in the following publication:

IAEA nuclear fusion

ACCEPTED MANUSCRIPT

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

Oliver Linder[1], Emiliano Fable[1], Frank Jenko[1], Gergely Papp[1] and Gabriella Pautasso[2]

Accepted Manuscript online 17 June 2020 •

What is an Accepted Manuscript?

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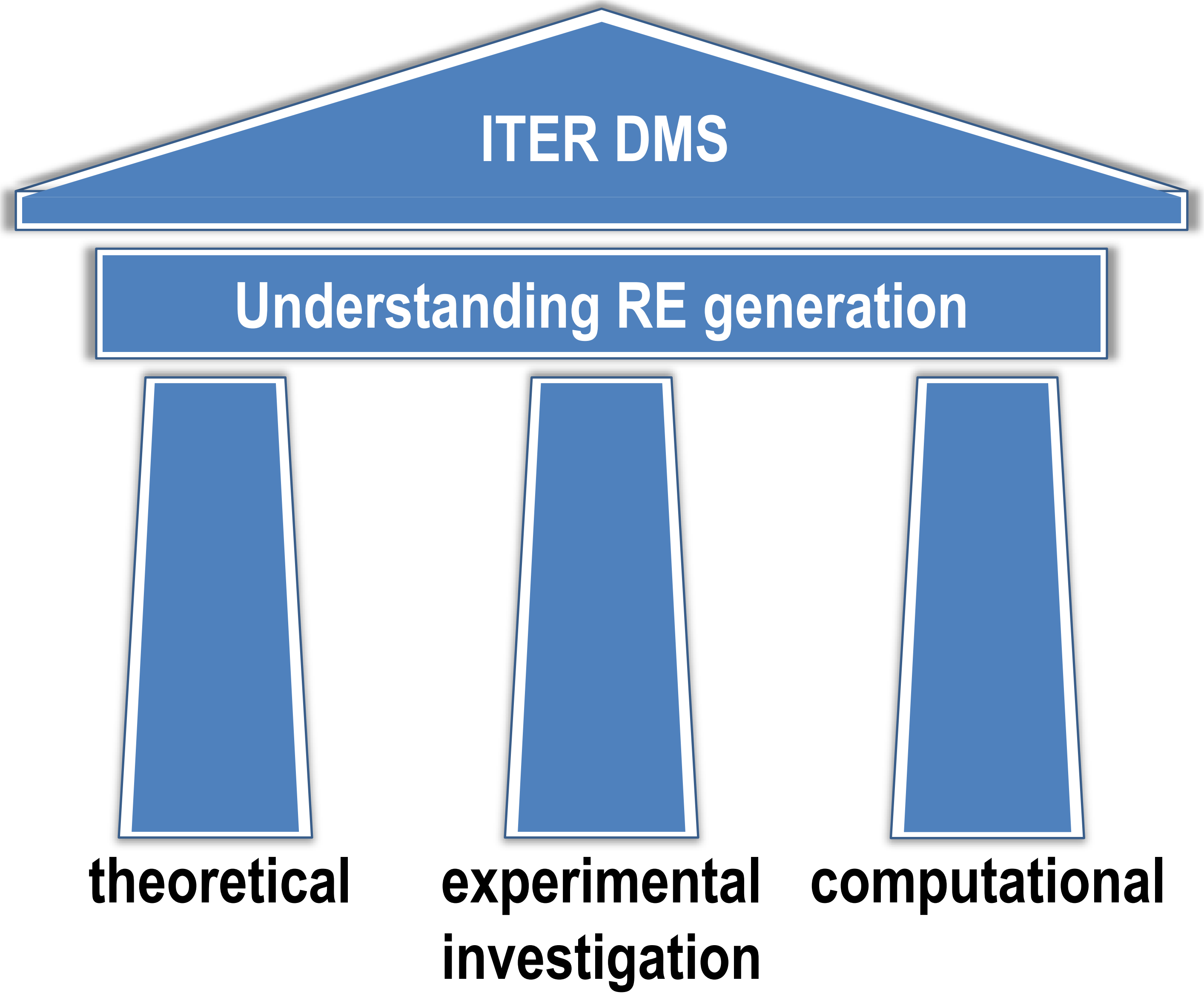
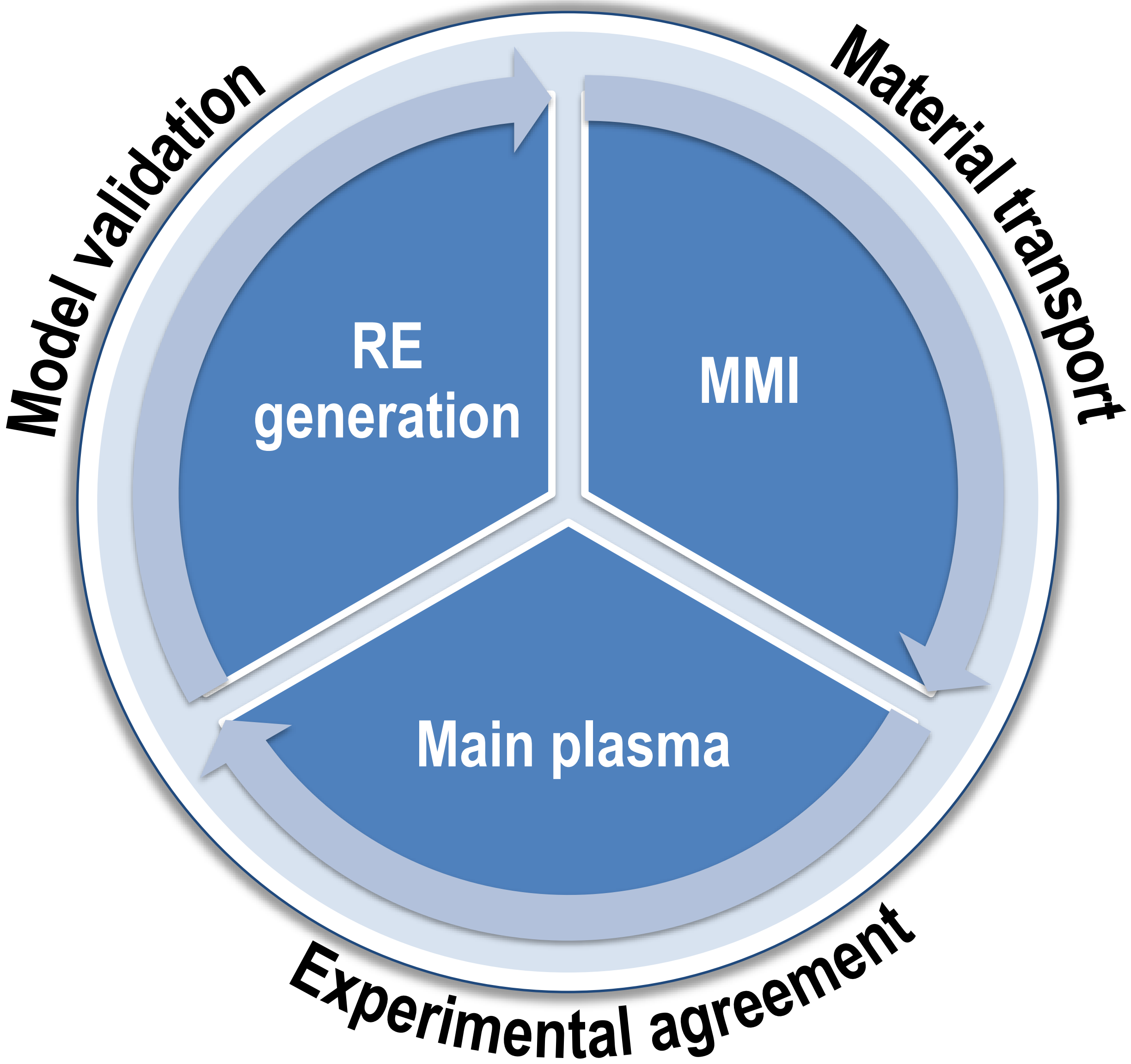
Towards understanding RE generation



Integrated simulations with the transport codes ASTRA-STRAHL



The model: main plasma & impurity evolution

Solving transport equation

$$\frac{\partial Y}{\partial t} = \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle(\Delta\rho)^2\rangle\left[D\frac{\partial Y}{\partial \rho} - v\,Y\right]\right) + \sum_j S_j$$

ASTRA[1]

- For arbitrary quantity Y; here:
  - Poloidal magnetic flux Ψ
  - Electron temperature T_e
  - Ion temperature T_i
  - RE current density j_RE
- Flux-surface average; toroidally symmetric
- Magnetic geometry:
  - 3-moment solver
  - SPIDER[2]

STRAHL[3]

- For individual ion charge states (incl. neutrals) ($n_\mathrm{e}(t)$ from quasineutrality)
- Transport coefficients D & v:
  - From NEOART[4]
  - Externally provided
- Atomic processes (sources S_j) from ADAS[5]
- Impurity radiation for $T_\mathrm{e}(t)$

[1] E Fable *et al.* *Plasma Phys. Control. Fusion* **55**, 074007 (2013)
[2] A A Ivanov *et al.* 32nd EPS Conference on Plasma Physics 2005, P5.603
[3] R Dux *et al.* *Nucl. Fusion* **39**, 1509 (1999)
[4] A G Peeters. *Phys Plasmas* **7**, 268 (2000)
[5] H P Summers. The ADAS User Manual, version 2.6. http://www.adas.ac.uk

The model: RE generation mechanisms

Primary generation	Secondary generation

Primary generation

- Dreicer mechanism:
  - Classical formula by Connor & Hastie[1]
  - Neural-network version of kinetic solver CODE[2] by Hesslow *et al*[3] incl. impact of partially ionized impurities
- Hot-tail mechanism:
  - Model by Smith & Verwichte[4] to be implemented
- Nuclear sources not considered (tritium β^--decay, Compton γ)
  - Irrelevant for AUG

Secondary generation

- Avalanche mechanism:
  - Classical formula by Rosenbluth & Putvinski[5]
  - Formula with partially ionized impurities by Hesslow *et al*[6]

[1]J W Connor and R J Hastie. *Nucl. Fusion* **15**, 415 (1975)
[2]A Stahl *et al. Nucl. Fusion* **56**, 112009 (2016)
[3]L Hesslow *et al. J. Plasma Phys.* **85**, 475850601 (2019)
[4]H M Smith *et al. Phys. Plasma* **15**, 072502 (2008)
[5]M N Rosenbluth and S V Putvinski. *Nucl. Fusion* **37**, 1355 (1997)
[6]L Hesslow *et al. Nucl. Fusion* **59**, 084004 (2019)

The model: RE implementation

Dreicer generation

- Classical formula by Connor & Hastie
- CODE-NN by Hesslow *et al*

Avalanche generation

- Classical formula by Rosenbluth & Putvinski
- Updated formula by Hesslow *et al*

Fortran module + wrapper for ASTRA

(https://github.com/o-linder/runawayelectrongeneration)

- Incl. calculation of auxiliary quantities (e.g. E_D, E_c, $E_\mathrm{c}^\mathrm{eff}$, $p_\star$, $\bar{\nu}_\mathrm{D}$, $\bar{\nu}_\mathrm{s}$)

Formulae w/ partially ionized impurities

- **Applied throughout this work**
- Implementation verified against MATLAB versions by Hesslow *et al*

Classical formulae

- **Applied to assess impact of partially ionized impurities**
- Implementation verified against disruption code GO[1] (exp. T_e-decay for AUG plasmas)

[1] G Papp *et al. Nucl. Fusion* **53**, 123017 (2013)

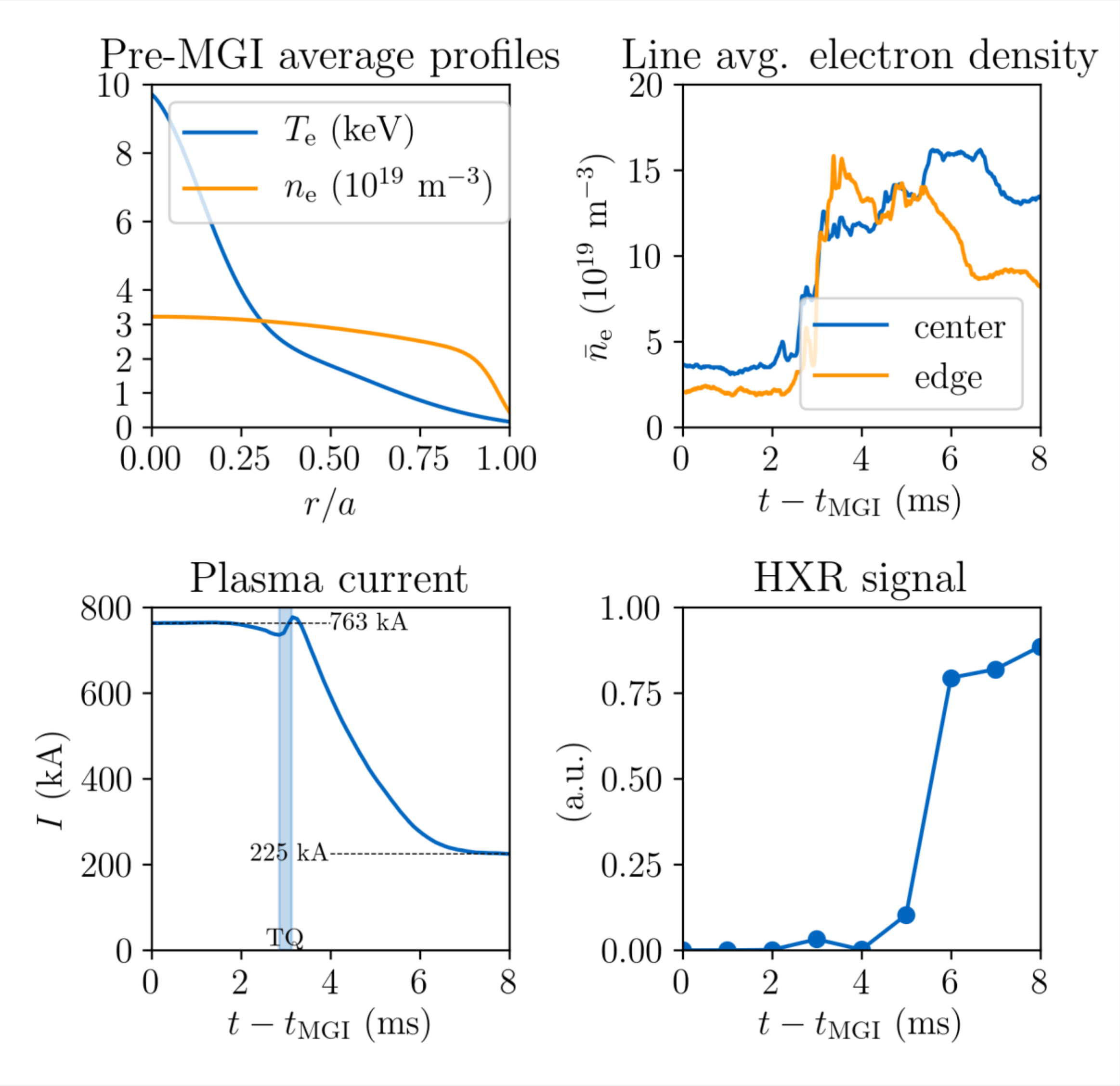
Experimental scenario: ASDEX Upgrade #33108

Scenario

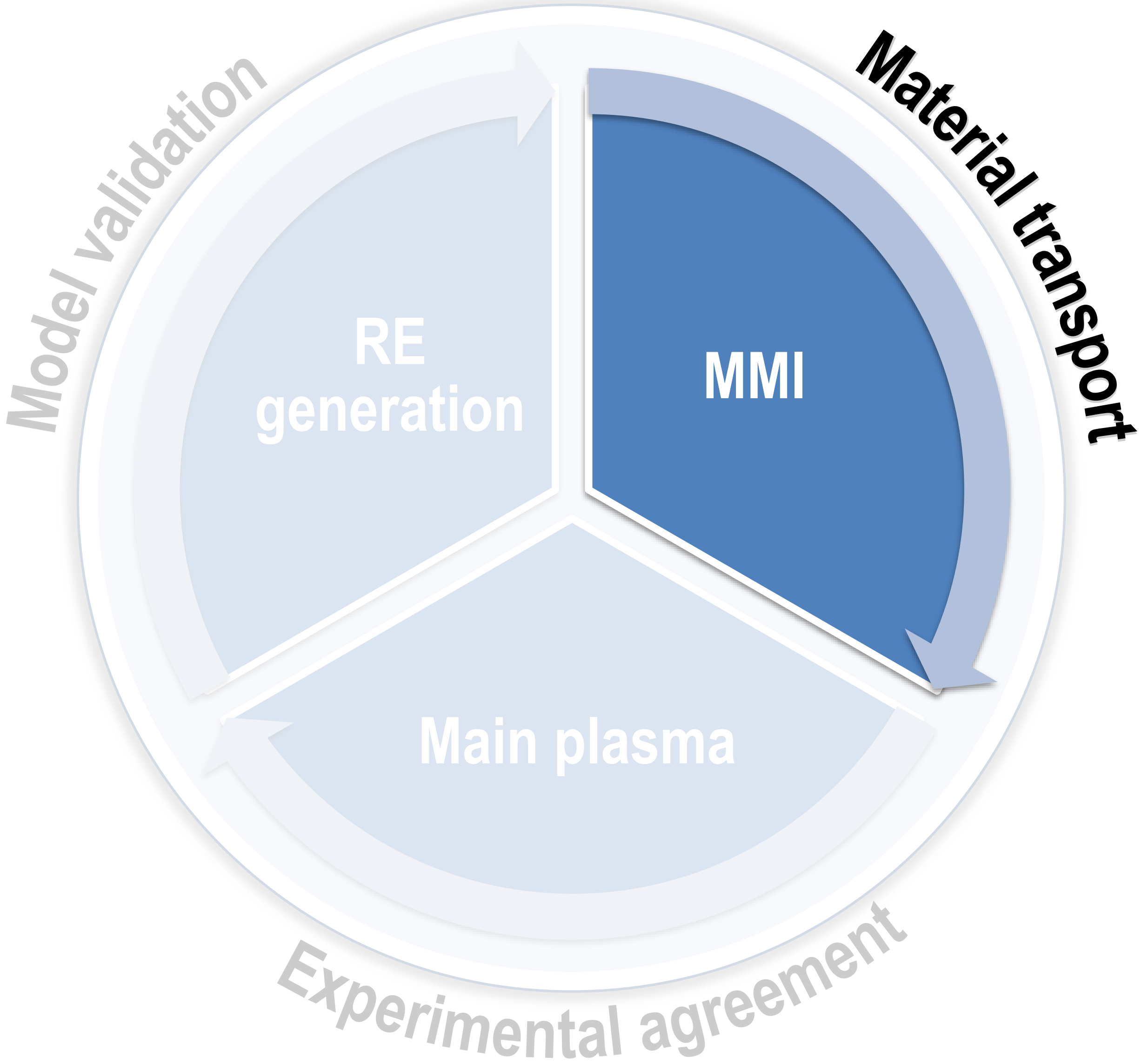
- Circular L-mode limiter plasma
- Low density $\langle n_e \rangle = 2.8 \times 10^{19} \mathrm{m}^{-3}$
- High temperature $T_e(\rho = 0) \approx 10$ keV

Evolution

- Ar MGI at $t_{\mathrm{MGI}} = 1.0$ s
- Thermal quench (TQ):
  $$2.85 \text{ ms} \leq t - t_{\mathrm{MGI}} \leq 3.13 \text{ ms}$$
- Final (RE) current: 763 kA → 225 kA



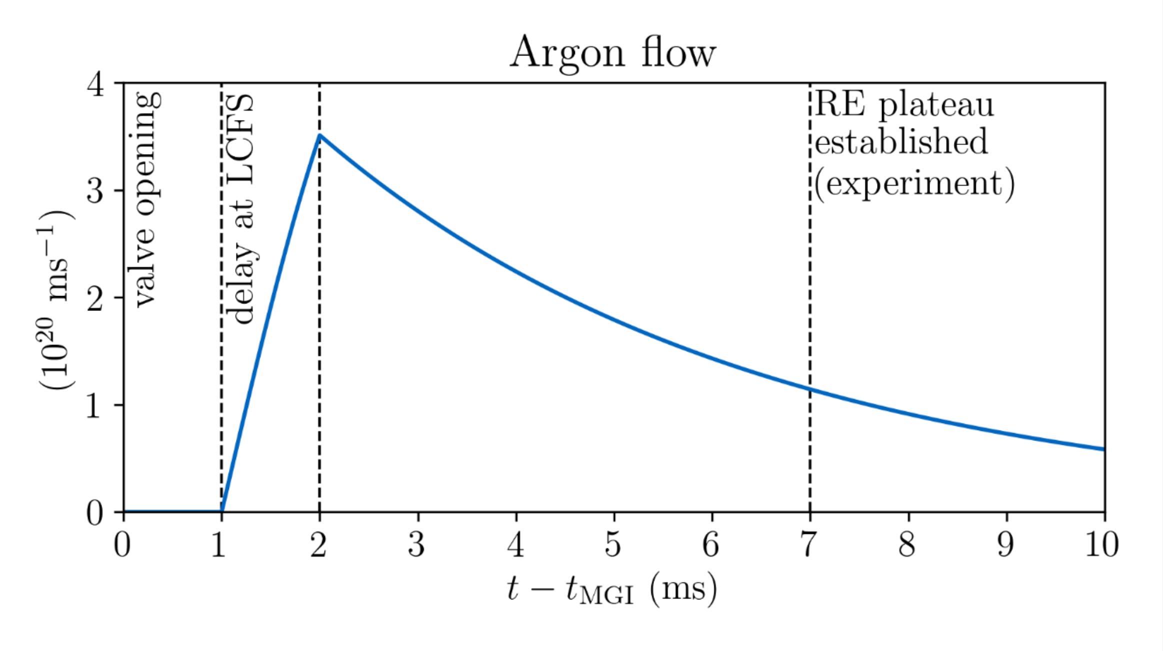
Material transport



Material transport: deposition

Outflow from gas valve described by continuity equation[1]

$$\frac{\mathrm{d}N_{\mathrm{Ar}}}{\mathrm{d}t} = -v_{\mathrm{Ar}}\, N_{\mathrm{Ar}} \frac{A_{\mathrm{v}}(t)}{V_{\mathrm{v}}(t)}$$



Experimental constraints

- $N_{\mathrm{Ar}}(t = 0) = 1.75 \times 10^{21}$ Ar atoms
- v_{Ar}: inward propagation with thermal velocity

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

- A_{v}: valve opens within 1 ms
- In simulation located 1 cm outside LCFS ⟶ 1 ms delay
  (no need to model propagation from valve to LCFS)

[1]G Pautasso *et al. Nucl. Fusion* **47**, 900 (2007)

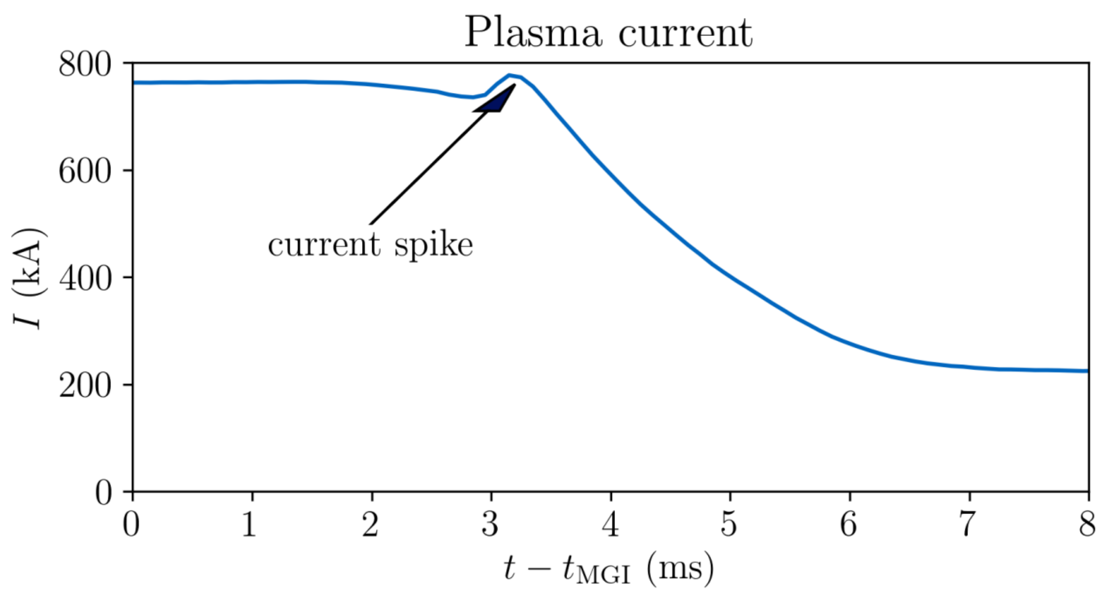
Material transport: rapid redistribution

MHD effects

- Currently missing
- Evidence: current spike
- Hypothesis: gas triggers $(m, n) = (2,1)$ mode upon reaching $q = 2$ surface[1]
- Mimic rapid redistribution through exponential decay at $\rho \leq \rho(q = 2)$:

$$D_{\mathrm{add}}(t) = D_{\mathrm{add}}^{\mathrm{max}} \exp\left(-\frac{t - t_{q=2}}{\tau_{\mathrm{add}}}\right) \cdot \Theta(t - t_{q=2})$$

$$v_{\mathrm{add}}(t) = v_{\mathrm{add}}^{\mathrm{max}} \exp\left(-\frac{t - t_{q=2}}{\tau_{\mathrm{add}}}\right) \cdot \Theta(t - t_{q=2})$$

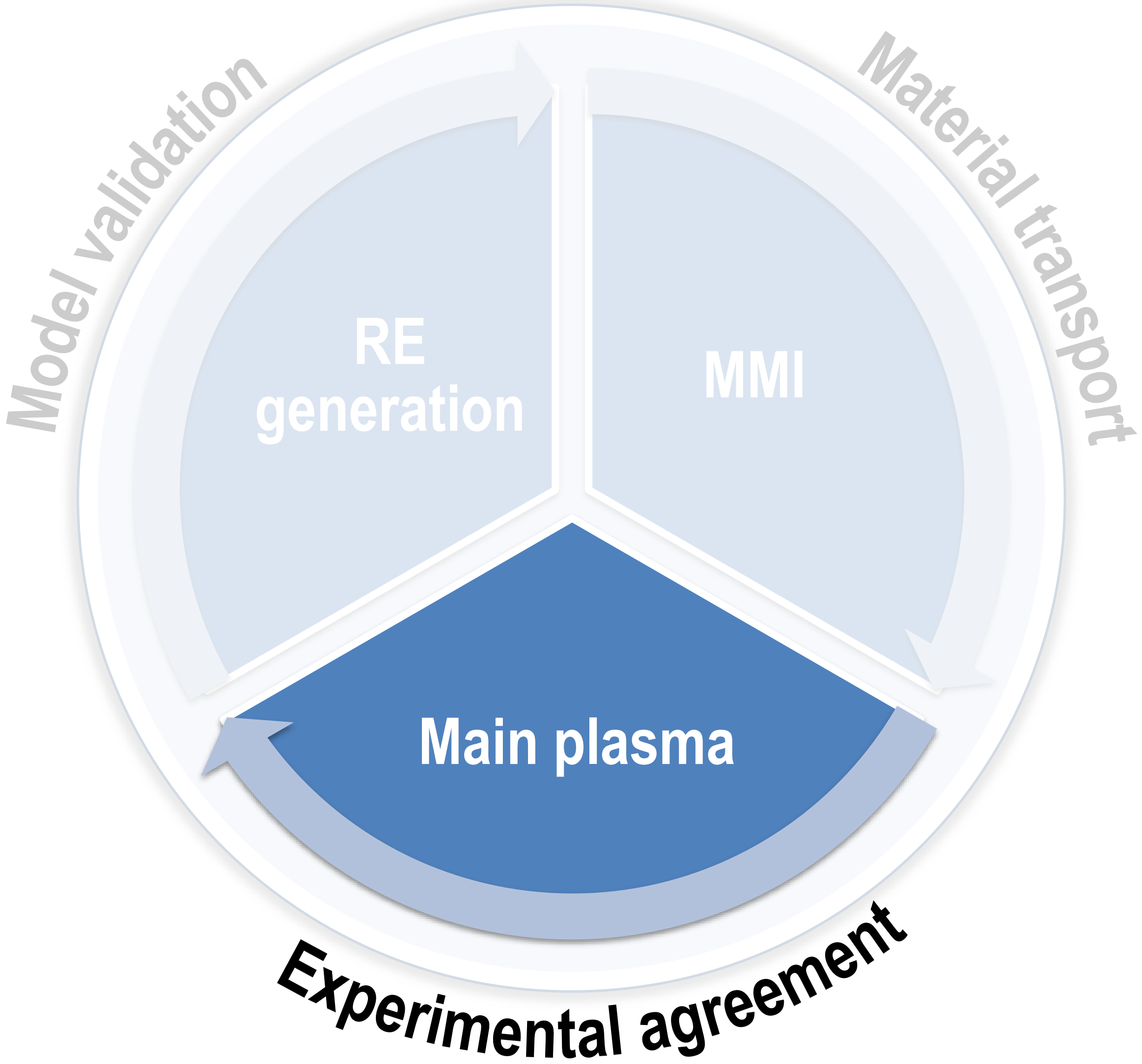


$D_{\mathrm{add}}^{\mathrm{max}}$ (m^2/s)	$v_{\mathrm{add}}^{\mathrm{max}}$ (m/s)	τ_{add} (ms)
100	−200	1.0

Applied parameters

[1] E Fable *et al.* *Nucl. Fusion* **56**, 026012 (2016)

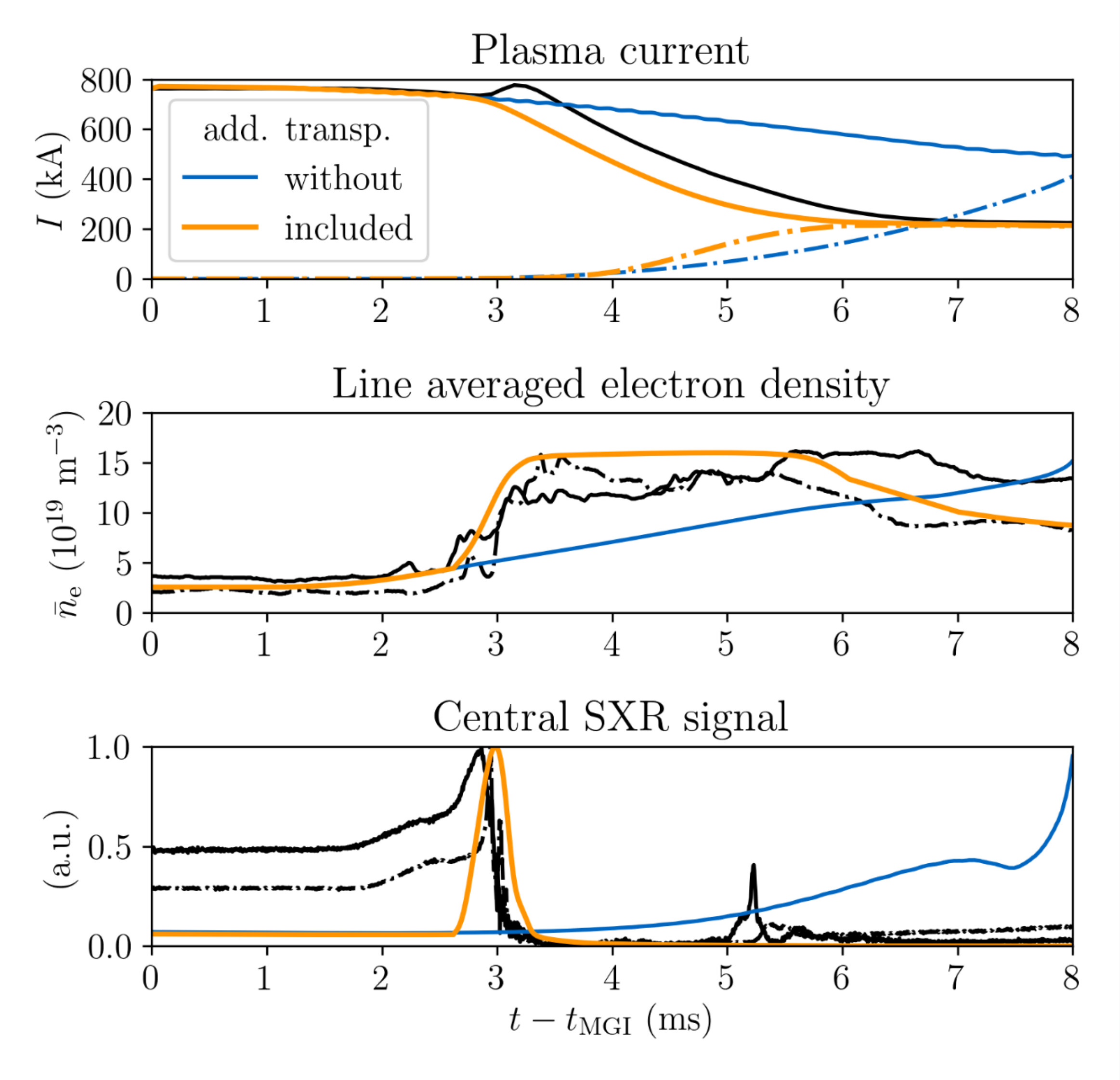
Experimental agreement



Experimental agreement: key parameters

- **Key observations reproduced:**
  - **plasma current**
  - **electron density**
  - **TQ occurrence**
- Distinct phases of disruption covered
  (pre-TQ, TQ, CQ)
- Rapid density increase requires additional transport
  (increased neutral propagation velocity does not help)
- Density increase reproduced → current decay reproduced
  (conductivity $\sigma \propto Z_{\mathrm{eff}}^{-1}$)

→ **1D approach suitable for modeling MGI**



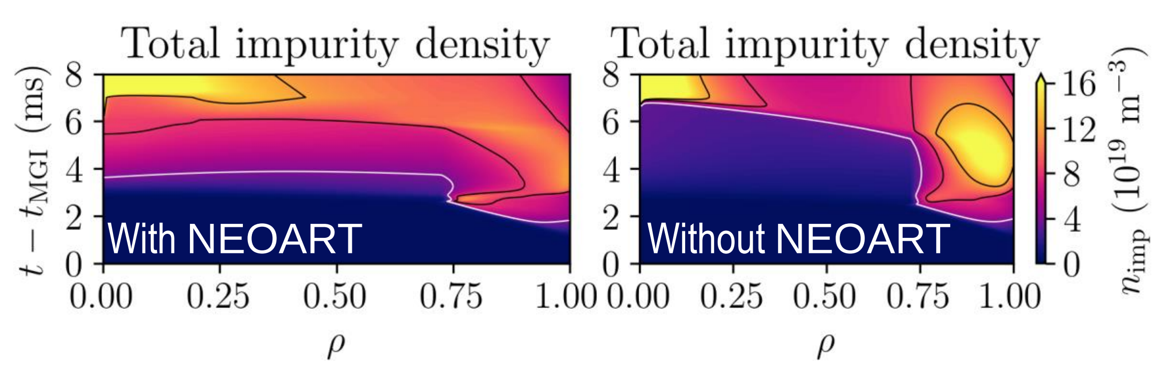
Experimental agreement: neoclassical transport

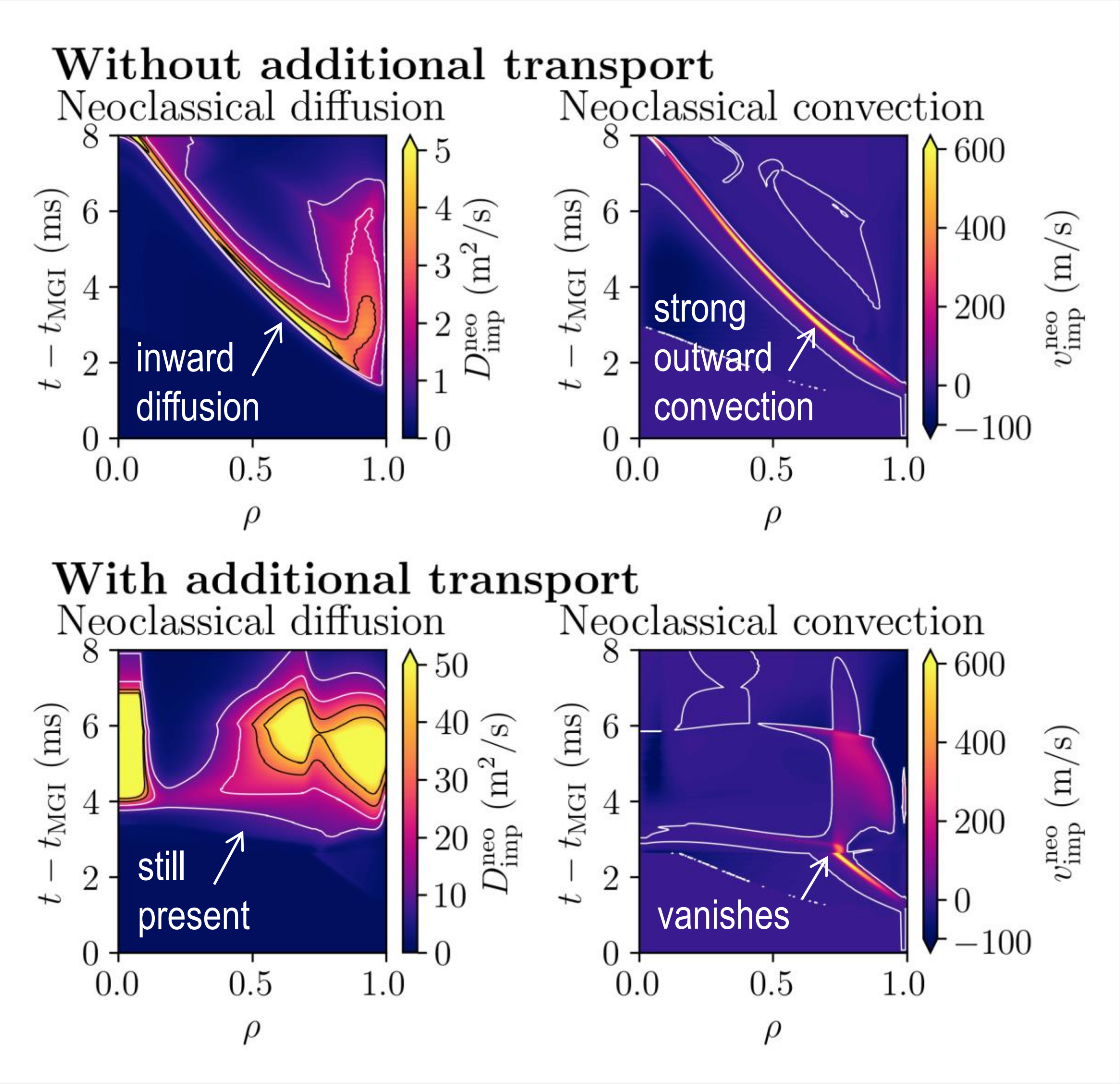
In absence of additional transport

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

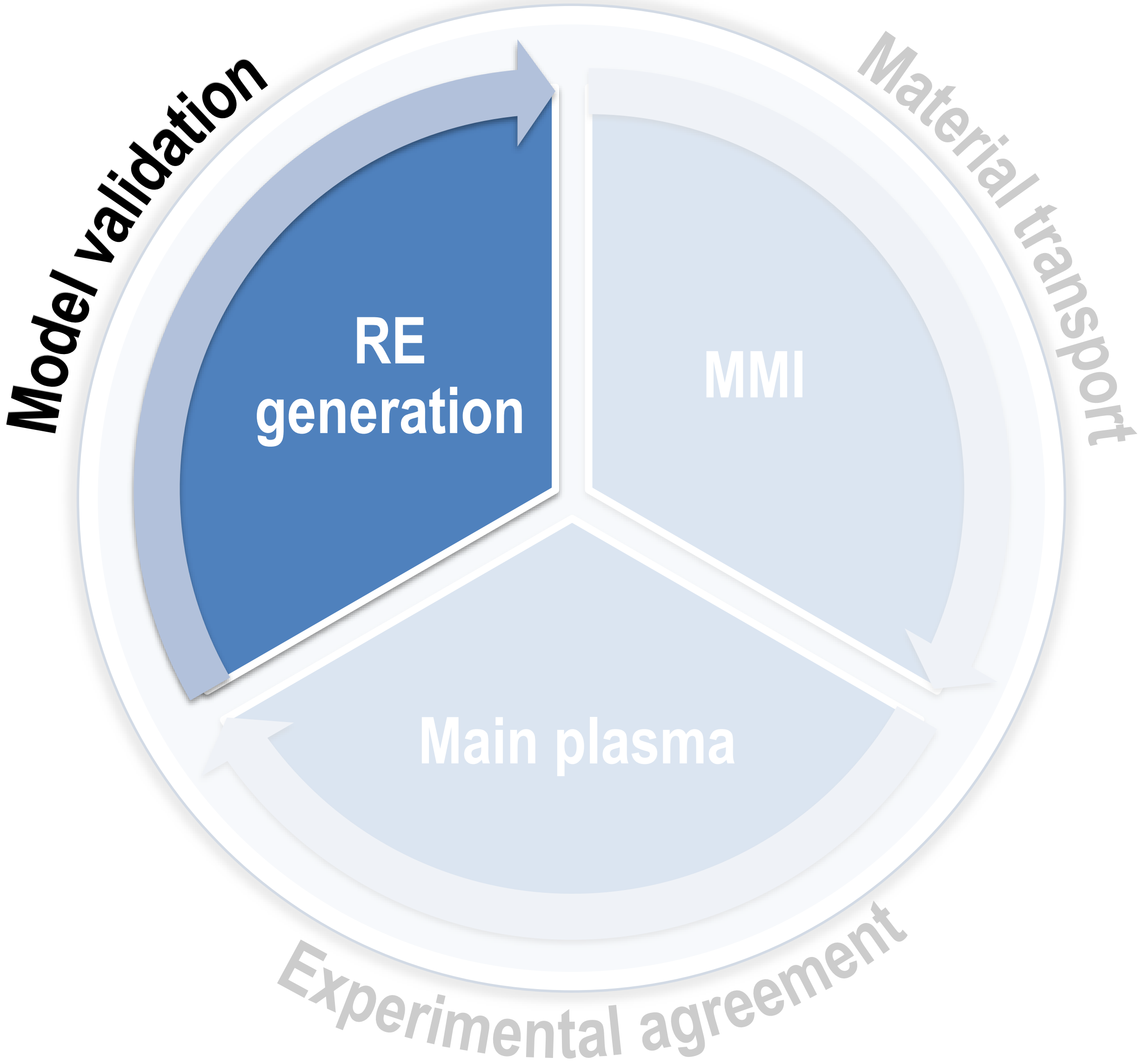
With additional transport

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



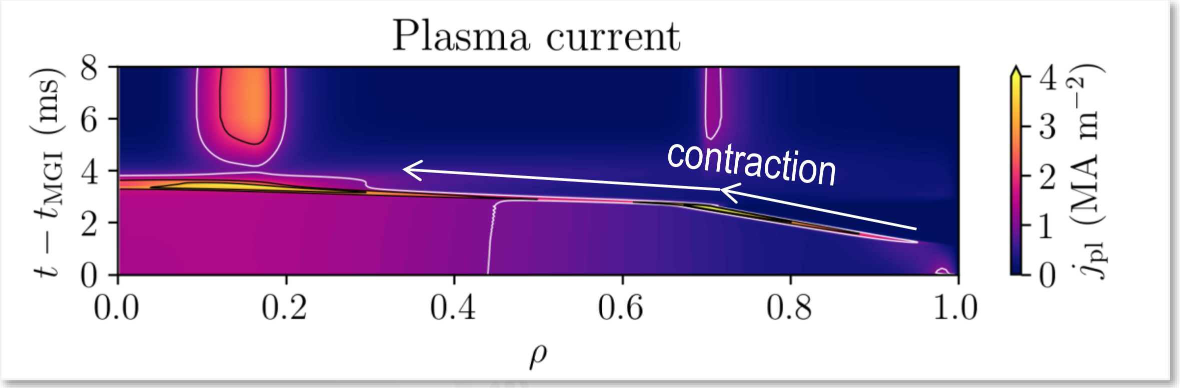


Runaway electron generation & model validation



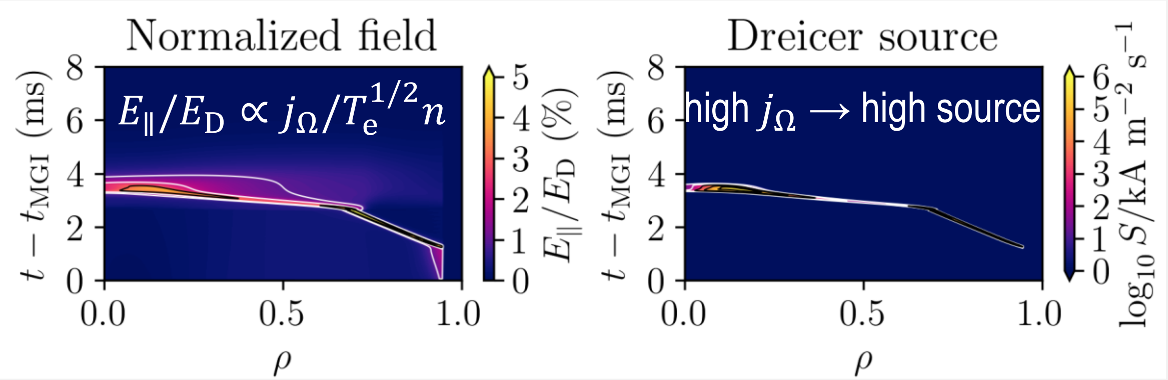
Runaway electron generation

- Ohmic current contracts due to MGI
- Electric field (normalized) locally increases
  ($E_\parallel \propto j_\Omega T_e^{-3/2}$)



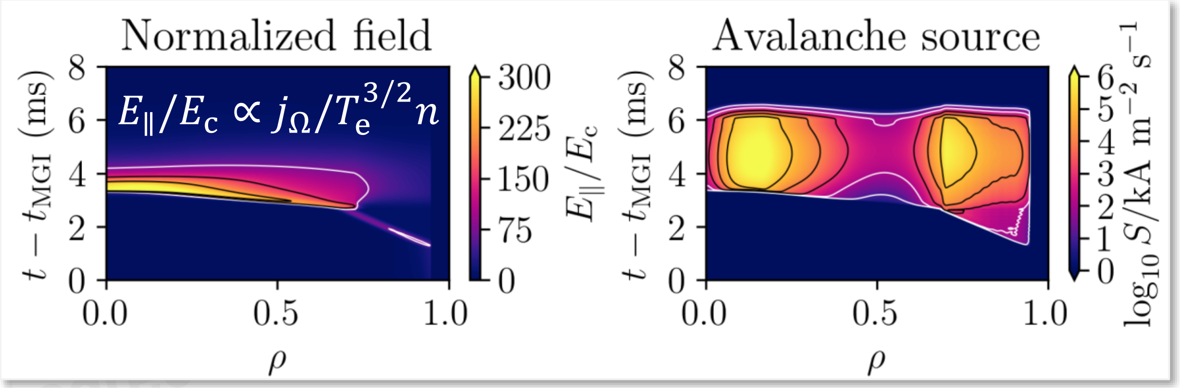
Dreicer generation

- Dreicer generation transiently at radii with high j_Ω
  → only small seed generated: $1.1\%\ I_{\rm RE,tot}$



Avalanche generation

- Multiplication over a few ms
  → RE current avalanche dominated: $98.9\%\ I_{\rm RE,tot}$

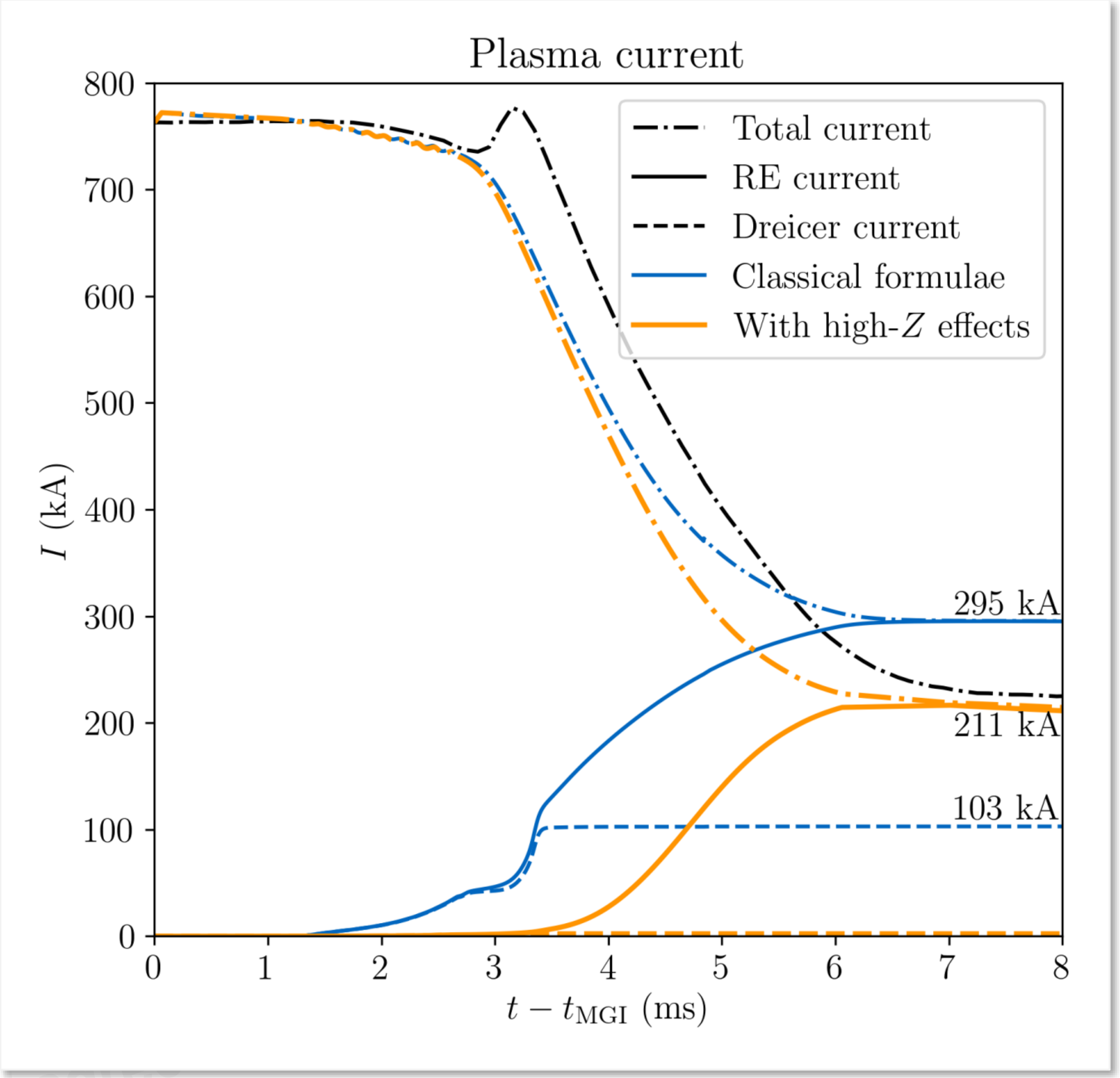


Model validation: impact of partially ionized impurities

Neglecting impact

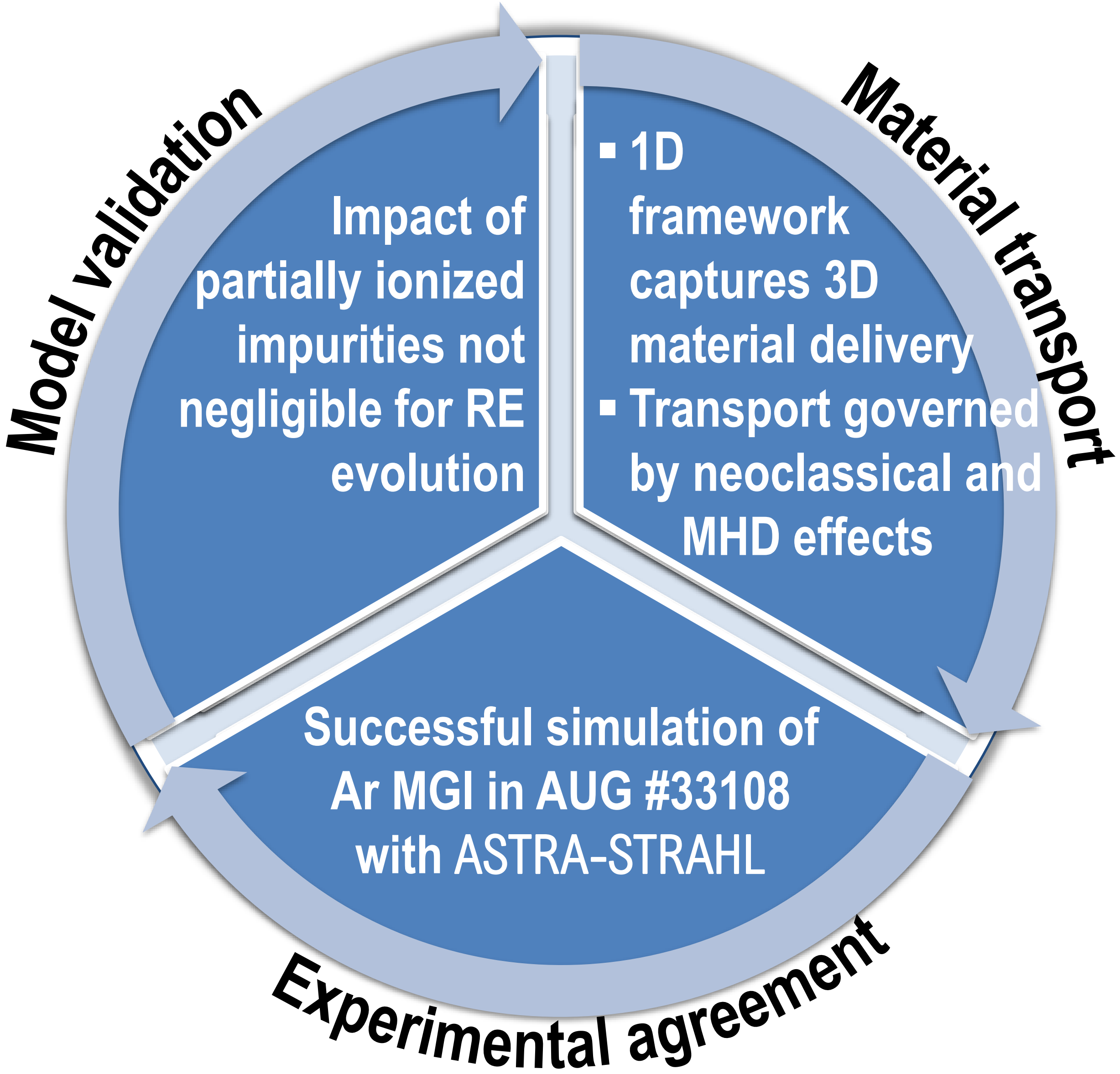
- Earlier & stronger onset of Dreicer source
- Weaker avalanching
  (similar I_{av} despite larger seed)
- Final RE current not too different, but evolution & composition is

→ **Impact or partially ionized impurities important for RE evolution**



Note: Agreement with all measurements cannot be re-obtained by adjusting $D_{\mathrm{add}}^{\mathrm{max}}$, $v_{\mathrm{add}}^{\mathrm{max}}$ and τ_{add}

Conclusion

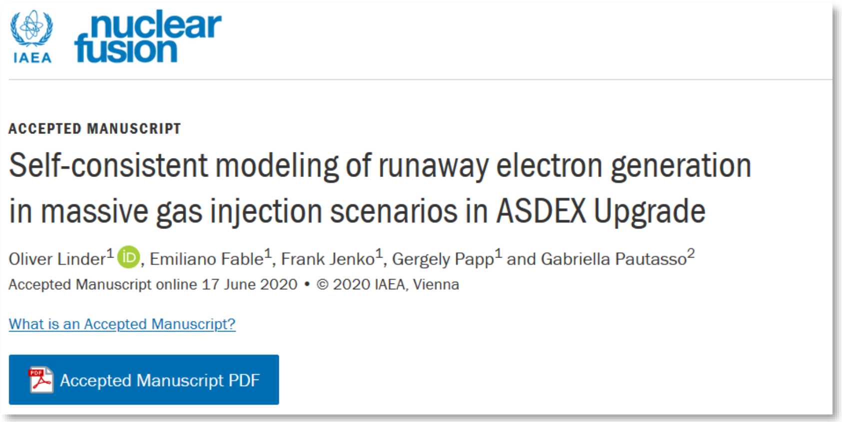

Model validation
Material transport
Experimental agreement
Impact of partially ionized impurities not negligible for RE evolution
▪ 1D framework captures 3D material delivery
▪ Transport governed by neoclassical and MHD effects
Successful simulation of Ar MGI in AUG #33108 with ASTRA-STRAHL

Further questions?

Send a mail to Oliver.Linder@ipp.mpg.de

Let's discuss during the *Consequences* session on Monday, 20th July

Look up the detailed article recently accepted for publication in Nuclear Fusion


IAEA nuclear fusion

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Accepted Manuscript PDF

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[6.2] A Stahl, O Embreus, G Papp, M Landreman and T Fülöp. Kinetic modelling of runaway electrons in dynamic scenarios. *et al. Nucl. Fusion* **56**, 112009 (2016)

[6.3] L Hesslow, L Unnerfelt, O Vallhagen, O Embreus, M Hoppe *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)

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[10.1] G Pautasso, C J Fuchs, O Gruber, C F Maggi, M Maraschek *et al*. Plasma shut-down with fast impurity puff on ASDEX Upgrade *Nucl. Fusion* **47**, 900 (2007)

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