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

ASTRA\(^1\)
- Core routines
- Plasma evolution
- 3-moment solver
- Equilibrium
- REGIA\(^{4,5}\)
- RE sources

STRAHL\(^2\)
- Impurity evolution
- NEOART\(^3\)
- Neoclassical transport

\(n_e, T_e, T_i, \text{geometry}\)

\(n_{imp}, P_{rad}, Z_{imp}, Z_{eff}\)
### Evolution of plasma quantities $Y$ through macroscopic transport equation

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

<table>
<thead>
<tr>
<th><strong>Temperatures</strong> $T_e, T_i$</th>
<th><strong>Poloidal flux</strong> $\Psi$</th>
<th><strong>Electron density</strong> $n_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ohmic heating</td>
<td>• Influenced by RE generation</td>
<td></td>
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<tr>
<td>• Impurity radiation</td>
<td>• $j_p$ profile flattened during TQ onset</td>
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<td>• Electron-to-ion heat exchange</td>
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<td>• Rapid transport during breakup of magnetic surfaces$^{2,3}$</td>
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</tbody>
</table>

(\textit{more on this later})

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ASTRA-STRAHL: impurity evolution with STRAHL

Evolution of plasma quantities $Y$ through macroscopic transport equation

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

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

$^3$Linder et al. Nucl. Fusion 60, 096031 (2020)
ASTRA-STRahl: Runaway Electron Generation In ASTRA (REGIA)

Evolution of plasma quantities $Y$ through macroscopic transport equation

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

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 $\langle \nu_{RE} \rangle = c$
- No RE losses
- Feed-back on $\Psi$ evolution

For Fortran module:

- 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)
$^5$ Rosenbluth et al. Nucl. Fusion 37, 1355 (1997)
$^6$ Hesslow et al. Nucl. Fusion 59, 084004 (2019)
**ASTRA-TRAHL: Description of MGI and TQ**

### Massive gas injection
- Outflow from gas valve described by continuity equation\(^1\)
- Inward propagation with thermal velocity (for Ar):
  \[
  v_{th} = \sqrt{\frac{T}{m}} = 246 \text{ m/s}
  \]
- In AUG: valve opens within 1 ms
- In ASTRA: source located 1 cm outside LCFS → 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 \(\left| \frac{dj_p}{d\rho} \right| > 50\) at \(q = 2\)
- Additional transport: 
  \[
  Y_{\text{add}}(t) = Y_{\text{add}}^{\text{max}} \exp \left( -\frac{t-t_{q=2}}{\tau_{\text{add}}} \right)
  \]
  *(more on the necessity later)*

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ASDEX Upgrade runaway electron experiments\textsuperscript{1-3}

**MGI in AUG #33108**

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

**Application**

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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Quantity & AUG #33108 & similar shots \\
\hline
$I_{P,0}$ (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 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{1} Pautasso et al. *Nucl. Fusion* 55, 033015 (2015)  
\textsuperscript{3} Pautasso et al. *Nucl. Fusion* 60, 086011 (2020)
Simulating ASDEX Upgrade #33108

Key experimental observations reproduced

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

Simulation features

- Density increase reproduced → current decay reproduced
- Density increase requires additional transport $D = 100 \, \text{m}^2/\text{s}$, $v = -1000 \, \text{m/s}$, $\tau = 1.0 \, \text{ms}$
- 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

- Onset of Ar GI
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic

- Ar reaches LCFS
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic

- $j_\Omega$ contraction
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic

- $j_\Omega$ contraction
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic

- Steep $j_\Omega$ gradient
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 0.7$ kA
  - $I_{\text{hot}} = 0.1$ kA

- Onset of TQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 0.8$ kA

- Hot-tail seed established
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA
  - $I_{\text{hot}} = 1.6$ kA
  - $I_{\text{sat}} = 253.3$ kA

- End of TQ & onset of CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA
  - $I_{\text{hot}} = 1.6$ kA

- During the CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA

- During the CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA
  - $I_{\text{sat}} = 313.5$ kA

- During the CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA

- End of CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA
  - $I_{\text{hot}} = 1.6$ kA

- End of CQ
  - Avalanche
  - Hot-tail (x100)
  - Dreicer (x100)
  - Ohmic
  - $I_D = 1.1$ kA
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
Comparison with only one seed mechanism used

- Reduction of $I_{RE}^{seed}$ does not affect RE multiplication with equal weight:
  - hot-tail: $-37\%$ $I_{RE}^{seed} \rightarrow -23\% I_{av}$
  - Dreicer: $-59\%$ $I_{RE}^{seed} \rightarrow -11\% I_{av}$

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

$\rightarrow$ 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

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

ASTRA-STRAHL simulations

- Assess importance of partial screening in self-consistent simulations:
  - state-of-the-art ↔ classical
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
  \((MHD \text{ effects due to breakup of magnetic surfaces)}\)
- Neoclassical effects

Absence of rapid redistribution

- Impurity propagation driven by neutral gas
- Increase of electron density \(\bar{n}_e\) not matched
  \(\rightarrow\) Much slower TQ!

Absence of neoclassical effects

- Inward transport less effective

\(\rightarrow\) 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:
  \[ D = 100 \, \text{m}^2/\text{s}, \quad v = -1000 \, \text{m/s}, \quad \tau = 1.0 \, \text{ms} \]
  (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 ms prior to MGI
- Scale ECRH contribution of $T_e(\rho)$ in AUG #33108

$$ T_e(\rho) = \frac{T_{\text{tar}} - T_{\text{bg}(0)}}{T_{E\text{CRH}(0)}} T_{E\text{CRH}}(\rho) + T_{\text{bg}}(\rho) $$

  target background

- Temperature unaffected for $\rho > 0.35$
Impact of pre-disruption temperature: the RE seed

Dreicer population
- Virtually unaffected: $I_D = 1.1 \text{ kA}$
- No (significant) $T_e$ change in region of strongest generation

Hot-tail population
- Grows exponentially
  \[ I_{\text{hot}}: 0.6 \text{ kA} \rightarrow 33.7 \text{ kA} \]
- Strongest increase above 10 keV
- Described by exponential
  \[ I_{\text{hot}}^{\text{fit}}(T_e,0(\rho = 0)) = (914 \pm 58) \exp \left( -4 \left\{ \frac{\bar{\nu} \ln A(t_0) (n_{e,\text{fin}} t_{\text{dec}})}{T_e,0(\rho = 0)^{3/2}} \right\}^{2/3} \right) \text{ kA} \]
- Strong increase of temperature (by design), but density not at similar rate
  \[ \rightarrow \text{Strong increase of hot-tail runaway for hotter plasmas} \]
Impact of pre-disruption temperature: avalanche & total current

**Multiplication**
- Avalanche (\& total) RE current $\sim 330$ kA for $T_e < 9$ keV
- Between 9 keV and 17 keV, $I_{av}$ increases  
  (additional multiplication between 2 – 3)
- Avalanche current saturates for $T_e > 17$ keV at 356 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 $T_e > 9$ keV, grows linearly due to hot-tail contribution
- At $T_e = 20$ keV, hot-tail constitutes 9% $I_{RE}$
  → **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 $\sim$ 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:

Linder et al. Nucl. Fusion 60, 096031 (2020)  
https://doi.org/10.1088/1741-4326/ab9dfc

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


Appendix: Average runaway electron velocity

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

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

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

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

$\rightarrow$ 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

Simple estimate

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

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

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

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