What Can be Learned From ASDEX Upgrade on Gas Assimilation and Its Interaction with Runaway Electrons(*)?

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(*) generated during current quench
Introduction

- ASDEX Upgrade (AUG) carries out “bona fide” disruption mitigation studies for ITER
- MGI (noble gases) on AUG has been used to study thermal quench (divertor load and forces) mitigation, and runaway electron (RE) generation and dissipation
- Impurities in plasma are powerful radiators: exp. and modelling works from many devices suggest that thermal load and force mitigation in ITER disruptions is feasible
- In what follows: focus on assimilation of injected gas and RE dissipation by collisions with gas (data analysis, basis for code benchmark) because

Whether MMI suppression and or dissipation of REs is feasible in ITER disruptions depends on $\Delta n_e(t, \psi)$

- **Ultimate questions:**
  - Is $\Delta n_e(t, \psi)$ physically achievable?
  - Is an injection scheme able to assure needed $\Delta n_e(t, \psi)$ technically feasible?
  - (→ should AUG pursue disruption mitigation experiments further? Or concentrate on modelling? Or invest mainly on plasma control algorithm?)

Caveat: small device compared to ITER
Which $\Delta n_e(t, \psi)$?

- $n_c > 10^{22} - 10^{23} / m^3$ (ITER Physics Basis, Nuclear Fusion 1999)
- 2$^{nd}$ argon injection into RE beam: $n_{Ar} > 10^{22} / m^3$ needed to induce RE current decay … *but too late* (S. Konovalov, IAEA 2016)
- Ar/D$_2$ injection to suppress seed and avalanche (= slow down CQ); within ~10 ms injection of 14 kPa m$^3$ → $n_e \sim 4 \times 10^{21} / m^3$ (J.R. Martin-Solis, Nuclear Fusion 2017)

(I believe we should keep considering all three schemes)
AUG: Mitigation valves, relevant diagnostics and coils

2017 valves, 5 bar \times 1 each

+ SXR, magnetics, gamma spectrometer, thermography
+ fast camera with filter, halo current, strain gauges
RE beam generation: 1\textsuperscript{st} injection

- First exp.s in 2014 (~ 80 discharges by now)

- RE beam (I_{RE} < 400 kA for < 500 ms) is generated with argon puff and mostly reproducible

- typically: circular plasma, I_p = 0.8 MA, B_t ~ 2.5 T, low n_e, P_{ECRH} > 2 MW,

- plasma has been vertically stable and w/o MHD activity; often vertically unstable in 2017

- RE current after 1\textsuperscript{st} Ar injection can follow reference I_p; faster or slower depending on argon injected; → E_ϕ from OH system adds to self-inductance
RE beam suppression by 2nd gas (argon and neon) injection

- relevant for injection schemes (1) and (2)
- argon and neon (not shown) effectively suppress RE beam
- \( N_{\text{inj}} \leq 2 \times 10^{22} \) argon atoms; \( N_{\text{inj}} \leq 4.3 \times 10^{22} \) neon atoms
Density and REs

- Electron density is measured by COO
  - can follow fast transients but noisy; only 2 chords
  - and DCN diagnostics
  - can follow slow transients, 5 chords, 1 toroidal position; correct ~ 50 ms after injection
Density and REs

discussion of 1st injection, RE beam and 2nd injection phases
1\textsuperscript{st} argon injection – to create RE beam

- argon MGI in AUG not documented in literature → shown here
- small argon amount injected – to avoid suppressing the REs
- → argon assimilation is not small
- \(\Delta n_e / (N_{\text{inj}}/V) = 50 \pm 15\%\) from V-1 (averaged 5 ms after TQ); but
  - argon ionization stage not known; recombination possible
  - line integrated \(n_e\) decays in RE beam also because V-1 chord length decreases
**n_e in RE plateau**

- DCN density (→ profile reconstruction) and spectroscopic measurements (→ mostly argon; $T_e \sim 1.7$ eV) available in RE plateau
- density outside of LCFS → large diffusion coefficients
- $n_e \sim 6-9 \times 10^{19} / m^3$ ~ weak $f(I_{RE})$;
  why this (not a larger or smaller) density?

![Density profiles in RE beam](image-url)
2\textsuperscript{nd} argon injection – to dissipate RE beam

- argon \parallel velocity \sim 5 \text{ m / 1ms} (vertical diode cameras, $\Delta \varphi = 2\pi$)
- slow density rise \sim gas penetration, consistent with perp. classical ion diffusion (but also gas flow)

\begin{itemize}
  \item \begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{argon_injection.png}
  \caption{argon injection - to dissipate RE beam}
  \end{figure}
\end{itemize}
2\textsuperscript{nd} argon injection – to dissipate RE beam

- $\Delta n_e$ averaged within 10 ms after 2\textsuperscript{nd} argon injection shows no significant increase
- $\max n_e$ versus $N_{\text{inj}} / V$ (plasma volume) after 2\textsuperscript{nd} inj.: up to 10 % increase
- $\max n_e$ versus $N_{\text{inj}} / V_{\text{vessel}}$ (vessel volume) after 2\textsuperscript{nd} inj. (100 %; meaning?)
2\textsuperscript{nd} argon injection – to dissipate RE beam

\[ E_\varphi \propto \frac{dI_p}{dt} \frac{l_i}{2} \]
\[ l_i = 4 \]
\[ n_{Ar} = 3-6 \times 10^{21} /m^3 \]
becomes interesting for ITER

10 times larger than in AUG
At large neon-$N_{\text{inj}}$:

- $F_{\text{eff}}$ decreases
- large poloidal density asymmetry = cold ions, low mobility
- + $F_{\text{eff}}$ degradation at large thermal energy (?)
D₂ pellets in RE beam

- Small contribution to animated discussion on ITER DMS and RE suppression
- *I (GP) do not know of similar exp.s*
- Shot 34183: 15 pellets, $1.9 \times 1.9 \times 2.0$ mm³ → $15 \times 5 \times 10^{20}$ D₂
- 400 ms of RE beam ramped down by control system; Uloop $\leq 0$ → “clean” plasma; spectroscopic measurement underway
- 0-D energy balance calculations: pellet should sublimate at “edge” of RE beam
  Q: how to show it? Important for modelling and more
- diode bolometer measurements seem to confirm calculations
- density decays probably because Te not large enough to ionize D
D$_2$ pellets in RE beam

- $I_p$ (MA)
- $U_{loop}$ (V)
- Line integrated radiation through plasma core (kW/m$^2$)
- COO and DCN line integrated density ($10^{20}$/m$^2$)
Pellet in “hot” thermal plasma (cartoon)

Pellet in RE beam
pellet in thermal plasma; horizontal (left) and vertical (right) diode bolometer background subtracted
pellet in RE beam; horizontal (left) and vertical (right) diode bolometer background subtracted

\[ \Delta t = 2 \text{ ms} \]
Why D does not refuel the plasma?

- radiating region in plasma core needs input power from RE beam (left)
- radiation from pellet-plasma interaction starts at edge of RE beam (right)
- small $P_{\text{rad}}$ and $n_e$ decay $\rightarrow$ neutral Ds crosse plasma w/o ionizing (hypothesis)
Summary

- Relatively large argon assimilation after 1\textsuperscript{st} injection (~50 \%)
- Density rather constant in the RE beam phase (no clear dependence on current)
- Up to 10 \% argon assimilation after 2\textsuperscript{nd} injection; probably radial diffusion coefficient can be inferred
- Just trowing mass into plasma does not help (D\textsubscript{2} pellets)
- Understand whether RE suppression/dissipation is feasible with MMI means understanding particle and energy (which \(T_e\)?) transport in these plasmas
- Plenty of experimental data to benchmark models
Additional slides
Pre-TQ time

- pre-TQ lasts > 2 ms (variables behind scatter data not yet identified
Equilibrium, density profile

Series of equilibria; beam position confirmed by SXR

Density profiles in RE beam
RE suppression with argon

Line integrated density after 1\textsuperscript{st} and 2\textsuperscript{nd} argon injection (70 ms apart)

RE beam lifetime versus argon $N_{\text{inj}}$
Several known mechanisms of RE losses

Only inelastic collisions RE–electrons considered (energy losses)

Formally:

$$\frac{1}{\tau_{RE}} = \frac{d I_{RE}}{dt} \frac{1}{I_{RE}} = \frac{e(E_{\Phi} - E_c)}{p_{RE}}$$

$$E_{\Phi} = \frac{V_{loop}}{2\pi R}$$

$$E_c = \frac{e^3 n_e \ln(\Lambda_{e,free})}{4\pi \epsilon m_e c^2}$$

$$n_e = n_{e,free} + \frac{\ln(\Lambda_{e,bound})}{\ln(\Lambda_{e,free})} n_{e,bound}$$

$E_c$ depends on plasma composition (atomic species and ionization state)
E_c versus E_\phi

Several spectrometers configured to measure Ar-I, Ar-II, C-II and C-III line emission; allow to determine T_e, n_{Ar} and n_C (n_e is known)

line radiance: \[ L = \frac{1}{4\pi} \int n_e n_z f_z X_{\text{eff}} \, dl \]

X_{\text{eff}}: photon emissivity coefficients calculated with a collisional radiative model and ADAS208-code (R. Dux)

f_z: fractional abundance

comparison of line radiance of C-II and C-III with (f_z X_{\text{eff}}) suggests \( T_e < 2 \text{ eV} \) and \( n_{Ar} / n_e \approx 100 \%

\[ \rightarrow E_c > E_\phi \]

(uncertainties in atomic data for argon)