Self-consistent modelling of runaway electrons during tokamak startup

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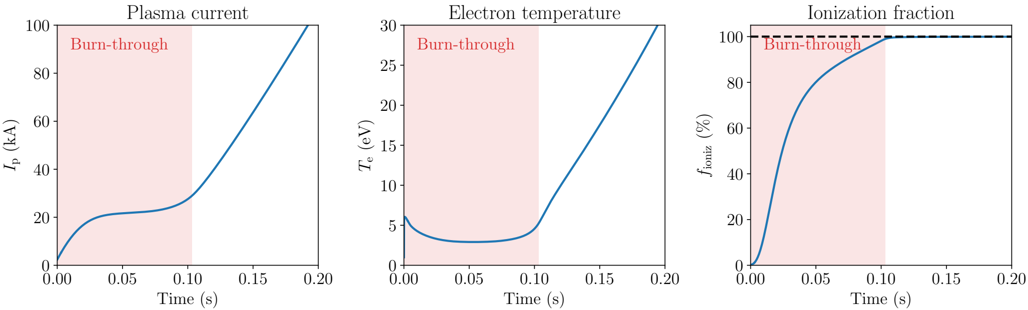
Outline

1. Tokamak burn-through
2. STREAM
3. Runaway electrons during startup
   - Conditions for existence
   - With gas fuelling
4. Conclusions

Tokamak burn-through

Burn-through: reaching a fully ionized plasma

- **Goals**
  - Raise temperature to reach full ionization
  - Raise current to form closed flux surfaces
- Struggle between heating and radiation losses
- Time scale in ITER: $\sim 100\,\mathrm{ms}$ after breakdown

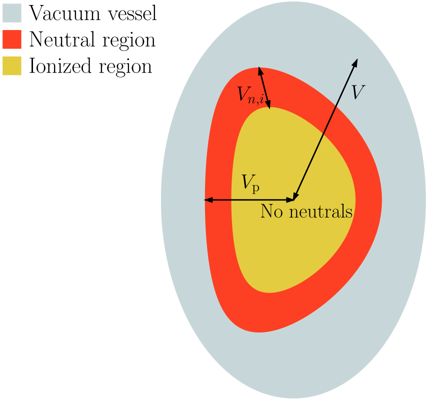


STREAM

STREAM: the STartup Runaway Electron Analysis Model

- Uses the DREAM libraries
- 0D model containing
  - Electric field/current evolution
  - Energy balance
  - Ion charge states
  - Runaway electron fluid
- Implements some additional physics
  - Neutral screening effect
  - Transition from open $\rightarrow$ closed flux surfaces
  - Electron cyclotron heating

STREAM: the neutral screening effect



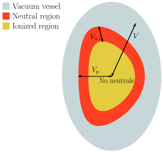
- Ionized plasma core screens out neutrals
- Neutral region determined via mean-free path for species i:

$$\lambda_i = \frac{v_{i,\mathrm{th}}}{n_e I_i^{(0)}}$$

- **Neutrals:**
  - In ⬜ vacuum vessel and 🟥 neutral region
- **Ions:**
  - In 🟥 neutral region and 🟨 ionized region

$\Longrightarrow$ …must account for different volumes

STREAM: Particles and heat



$V_i^{(j)}$ = total volume occupied by particles ⬜ + 🟥 or 🟥 + 🟨,

$\hat{V}_i^{(j)}$ = volume inside the plasma 🟥 (+ 🟨),

Particle balance

$$
\begin{aligned}
V_i^{(j)} \frac{\mathrm{d}n_i^{(j)}}{\mathrm{d}t} &= \hat{V}_i^{(j-1)} I_i^{(j-1)} n_e n_i^{(j-1)} - \hat{V}_i^{(j)} I_i^{(j)} n_e n_i^{(j)} && \text{(Ionization)}\\
&+ \hat{V}_i^{(j+1)} R_i^{(j+1)} n_e n_i^{(j+1)} - \hat{V}_i^{(j)} R_i^{(j)} n_e n_i^{(j)} && \text{(Recombination)}\\
&+ \hat{V}_\star^{(0)} n_\star^{(0)} \left(R_{i\star,\mathrm{cx}}^{(j+1)} n_i^{(j+1)} - R_{i\star,\mathrm{cx}}^{(j)} n_i^{(j)} \right) + S_i^{(j)} && \text{(CX + Transport/PWI)}
\end{aligned}
$$

Energy balance

$$
\frac{\mathrm{d}W_e}{\mathrm{d}t} = j_\Omega E_\parallel - n_e \sum_i \sum_{j=0}^{Z_i} \frac{\hat{V}_i^{(j)}}{V_i^{(j)}} n_i^{(j)} L_i^{(j)} - \sum_i Q_{ei} - \frac{W_e}{\tau_e}, \qquad \text{(Electrons)}
$$

$$
\frac{\mathrm{d}W_i}{\mathrm{d}t} = \sum_k Q_{ik} - \frac{3}{2} \frac{V_\star^{(0)}}{V_\mathrm{p}} n_\star^{(0)} \left(T_i - T_0 \right) R_{i,\mathrm{cx}}^{(1)} n_i^{(1)} - \frac{W_i}{\tau_i}, \qquad \text{(Ions)}
$$

$$S_i^{(j)} = \begin{cases} \Gamma_{i,\mathrm{in}}^{(0)} / V_i^{(0)}, & j = 0, \\ -n_i^{(j)} / \tau_i, & j \geq 1, \end{cases}$$

Plasma-wall interaction (PWI)

$$\Gamma_{i,\mathrm{in}}^{(0)} = V_\mathrm{p} \sum_k \sum_{l \geq 1} \frac{Y_k^i n_k^{(l)}}{\tau_k}$$

Confinement time

At early times

$$\tau_{i,\parallel} = \frac{L_\mathrm{f}}{C_s},$$

$$L_\mathrm{f} = \frac{3a}{4} \frac{B_\phi}{B_z\left(I_\mathrm{wall}\right)} \exp\left(\frac{I_\mathrm{p}}{I_\mathrm{ref}}\right),$$

At late times (turbulence)

$$\tau_{i,\perp} = \frac{a^2}{2D_\mathrm{Bohm}},$$

STREAM: Electric field

While DREAM solves the Ampère-Faraday equation, STREAM must solve the same set of circuit equations as DYON:

$$
\begin{aligned}
2\pi R_0 E_{\|} + L_{\mathrm{p}}\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}t} + M\frac{\mathrm{d}I_{\mathrm{wall}}}{\mathrm{d}t} &= V_{\mathrm{loop,ext}},\\
V_{\mathrm{loop,wall}} + L_{\mathrm{wall}}\frac{\mathrm{d}I_{\mathrm{wall}}}{\mathrm{d}t} + M\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}t} &= V_{\mathrm{loop,ext}},
\end{aligned}
$$

Pros

- Generalized wall model

Cons

- No poloidal flux

Generation

$$\frac{\mathrm{d}n_\mathrm{re}}{\mathrm{d}t} = \gamma_\mathrm{Dreicer} + n_\mathrm{re}\Gamma_\mathrm{ava} + \dots$$

Confinement

Parallel transport (dominant before closed flux surfaces)

$$\tau_\mathrm{re}^{\|} = \frac{m_\mathrm{e}c}{eE_\|}\sqrt{\left(\frac{eE_\| L_\mathrm{f}}{m_\mathrm{e}c^2}+1\right)^2 - 1} \approx \sqrt{\frac{2m_\mathrm{e}L_\mathrm{f}}{eE_\|}}$$

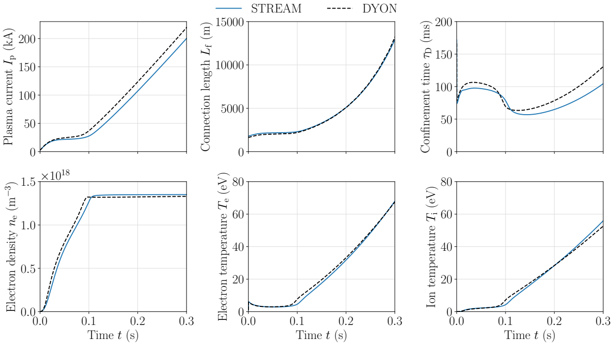
Drift losses (dominant at later times, but very small)

$$\tau_\mathrm{re}^\mathrm{drifts} = \frac{R_0}{10a}\frac{I_\mathrm{p}\,[\mathrm{MA}]}{E_\|\,[\mathrm{V/m}]}$$

Startup runaways

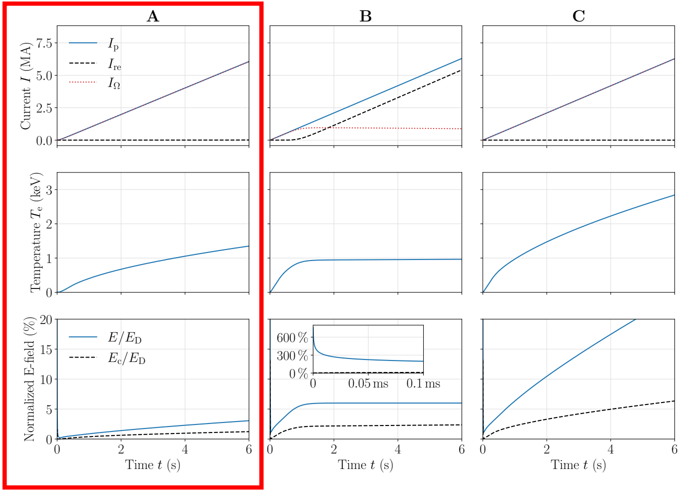
Baseline scenario: ITER

- Prefill pressure: $0.8\,\mathrm{mPa}$
- Initial ionization: 0.2%
- Vessel volume: $1000\,\mathrm{m}^3$
- Temperature (e/i): $1/0.026\,\mathrm{eV}$
- Plasma current: $2.4\,\mathrm{kA}$
- $R_0 = 5.65\,\mathrm{m}$
- $B_\mathrm{T} = 2.65\,\mathrm{T}$
- No impurities
- No conducting structures
- No PWI



Startup runaways

- Case A – baseline
  - $p_{\text{prefill}} = 0.8\,\text{mPa}$



Startup runaways

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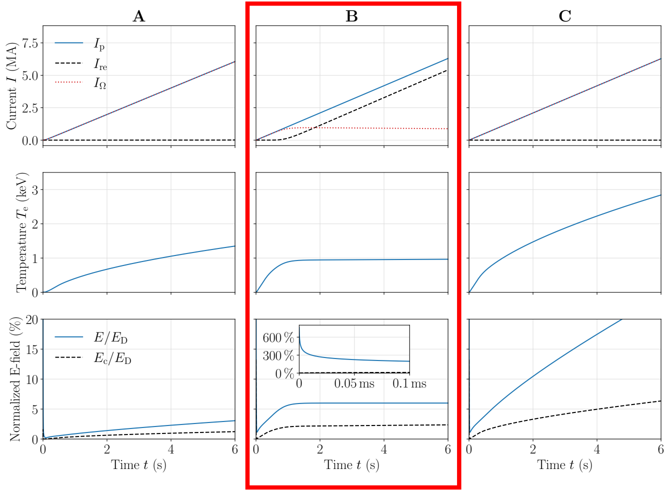
- Case B – low prefill
  - $p_{\mathrm{prefill}} = 0.08\,\mathrm{mPa}$



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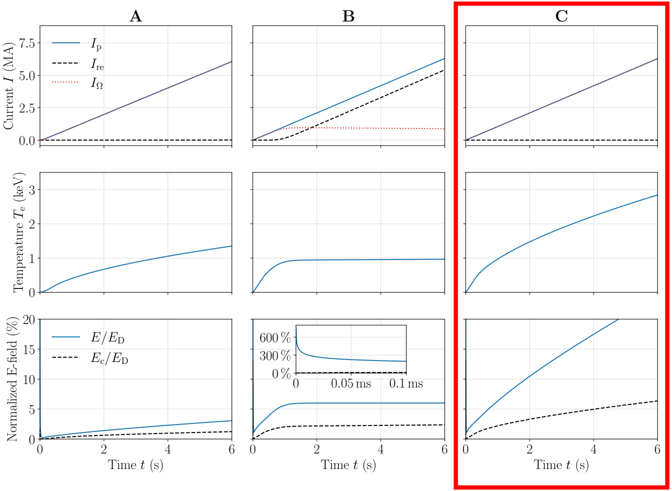
- Case C – no runaways
  - $p_{\mathrm{prefill}} = 0.08\,\mathrm{mPa}$
  - $\mathrm{d}n_{\mathrm{re}}/\mathrm{d}t = 0$



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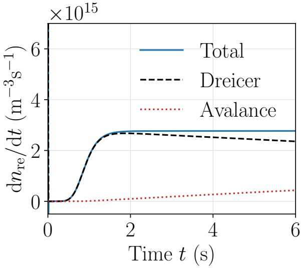

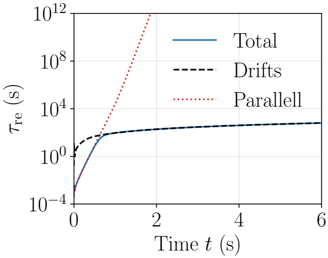

Startup runaways: effect of gas fuelling

Idea

Start with low density to achieve burn-through, then raise density to prevent runaway generation.

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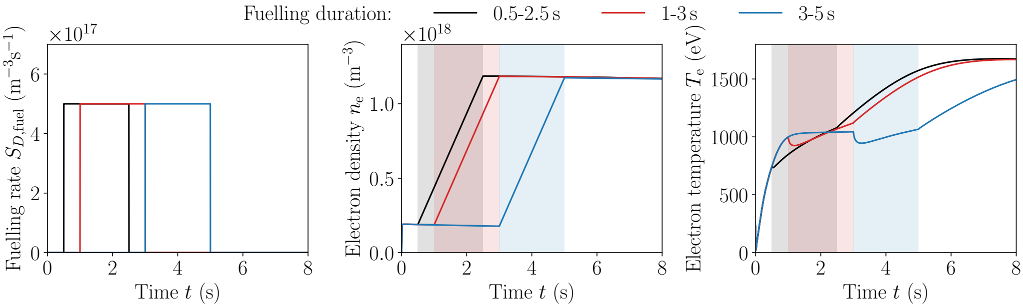
- Baseline ITER case (with $p_{\mathrm{prefill}} = 0.08\,\mathrm{mPa}$)
- Inject neutral D for 2 seconds, constant rate



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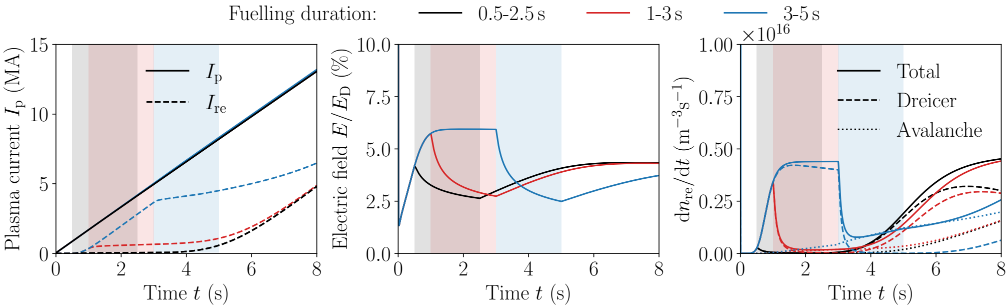

Conclusions

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- Runaway electron generation occurs *after* burn-through
- Runaways can prevent further (Ohmic) heating
- Gas fuelling after burn-through could be effective in suppressing Dreicer seed

Outlook

- Include basic ECH model
- Couple to Fokker–Planck equation
  - Superthermal electrons
  - Effect of runaways on heating and ionization

Paper on arXiv

Hoppe, Ekmark, Berger and Fülöp, *Runaway electron generation during tokamak startup*. arXiv:2203.09900