STUDY OF CURRENT SPIKE IN ASDEX UPGRADE WITH SIMULATIONS

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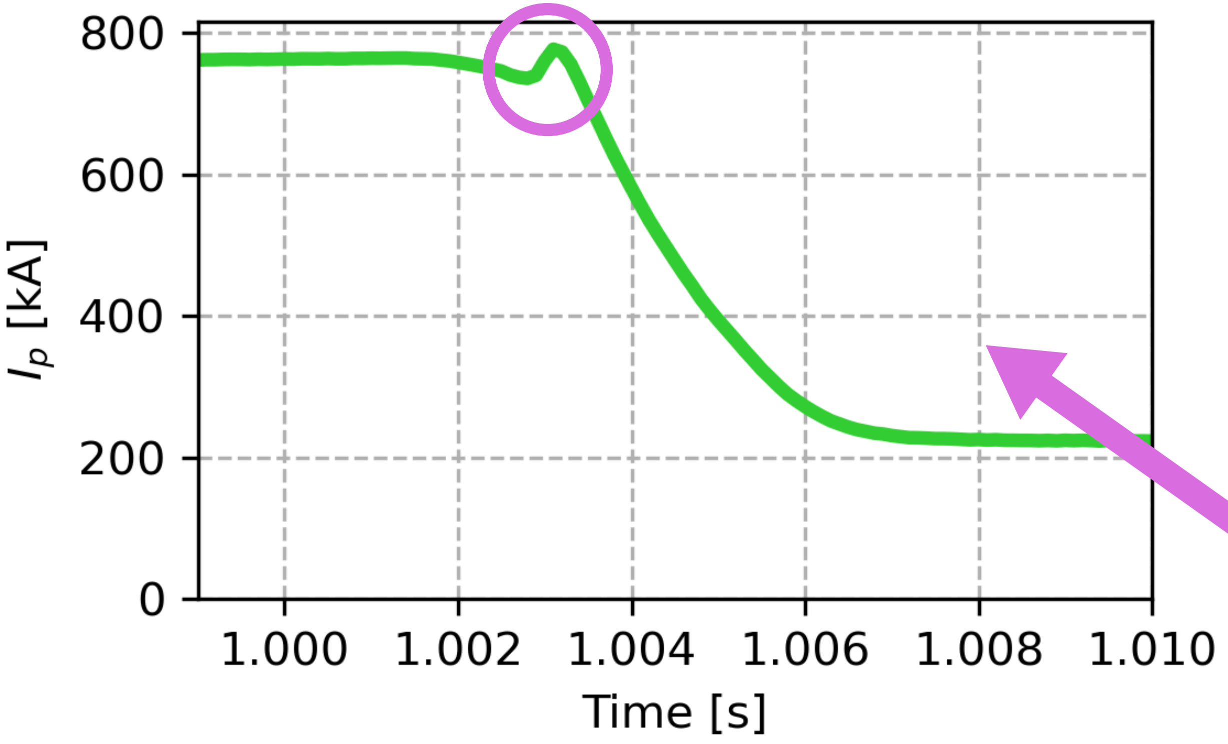
MŰEGYETEM 1782

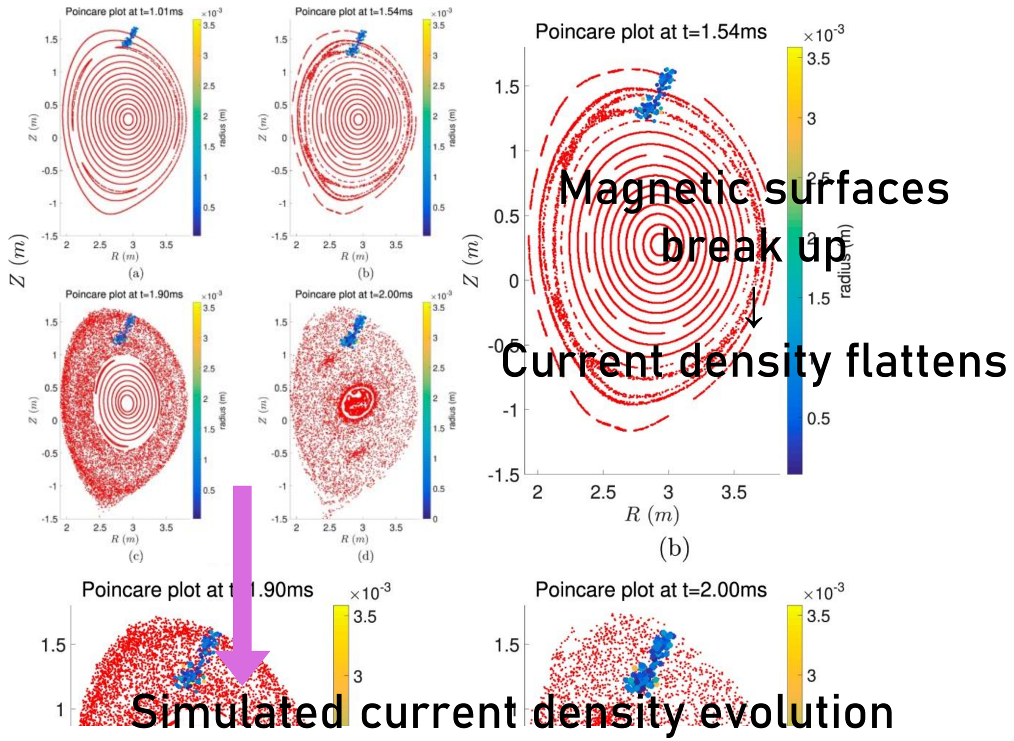
CHALMERS

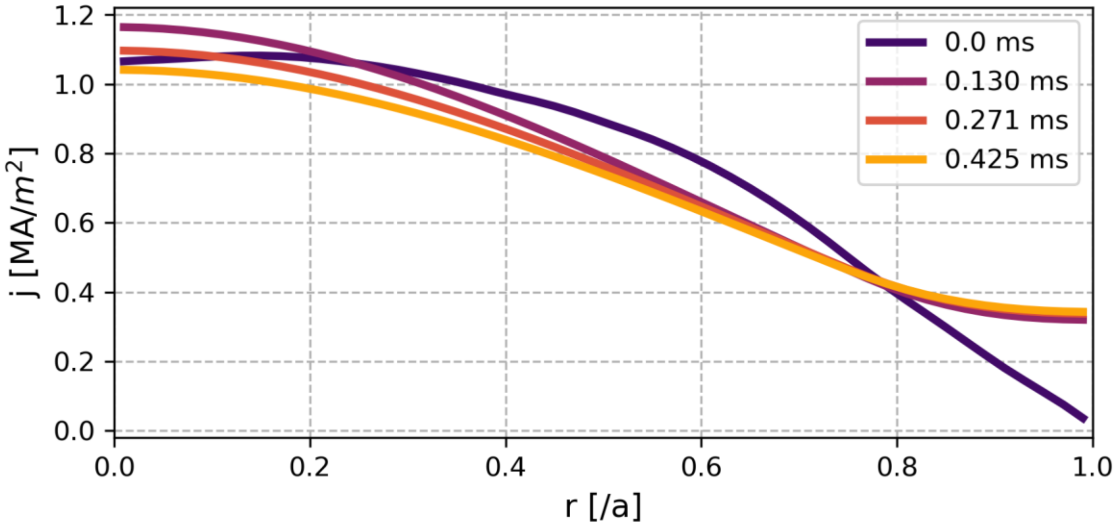
REM meeting 2023.06.19.

CURRENT SPIKE

#33108 ASDEX Upgrade





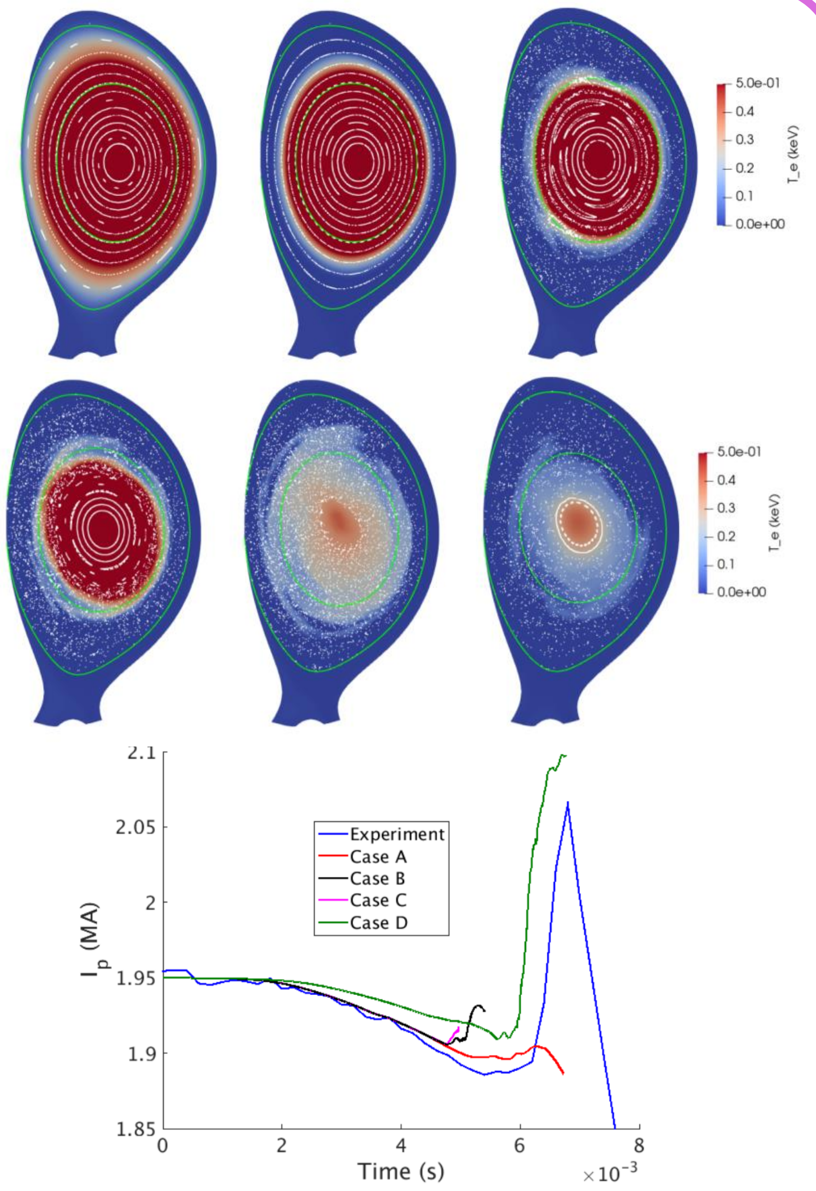


[Pusztai, JPP 2022]
[Boozer, Nucl. Fus. 2018]
[Nardon, Plasma Phys. Control. 2021]

CURRENT SPIKE

Current density rearrangement
Complicated 3D process:

JOREK simulations



[Nardon, Nucl. Fusion 2023]

Mean-field approximation
[Boozer, JPP 1986]

1D Radial transport

$$\frac{\partial L(\psi_t) I(\psi_t)}{\partial t} = 2\psi_t \frac{\partial}{\partial \psi_t}\left(\mathcal{R}\frac{\partial I(\psi_t, t)}{\partial \psi_t} - \frac{\partial}{\partial \psi_t}\psi_t \Lambda \frac{\partial^2 I}{\partial \psi_t^2}\right)$$

4th order spatial derivative.
Hyper-diffusion coefficient: $\Lambda(r,t)$.

[Pusztai, JPP 2022]
[Boozer, Nucl. Fus. 2018]

GOAL

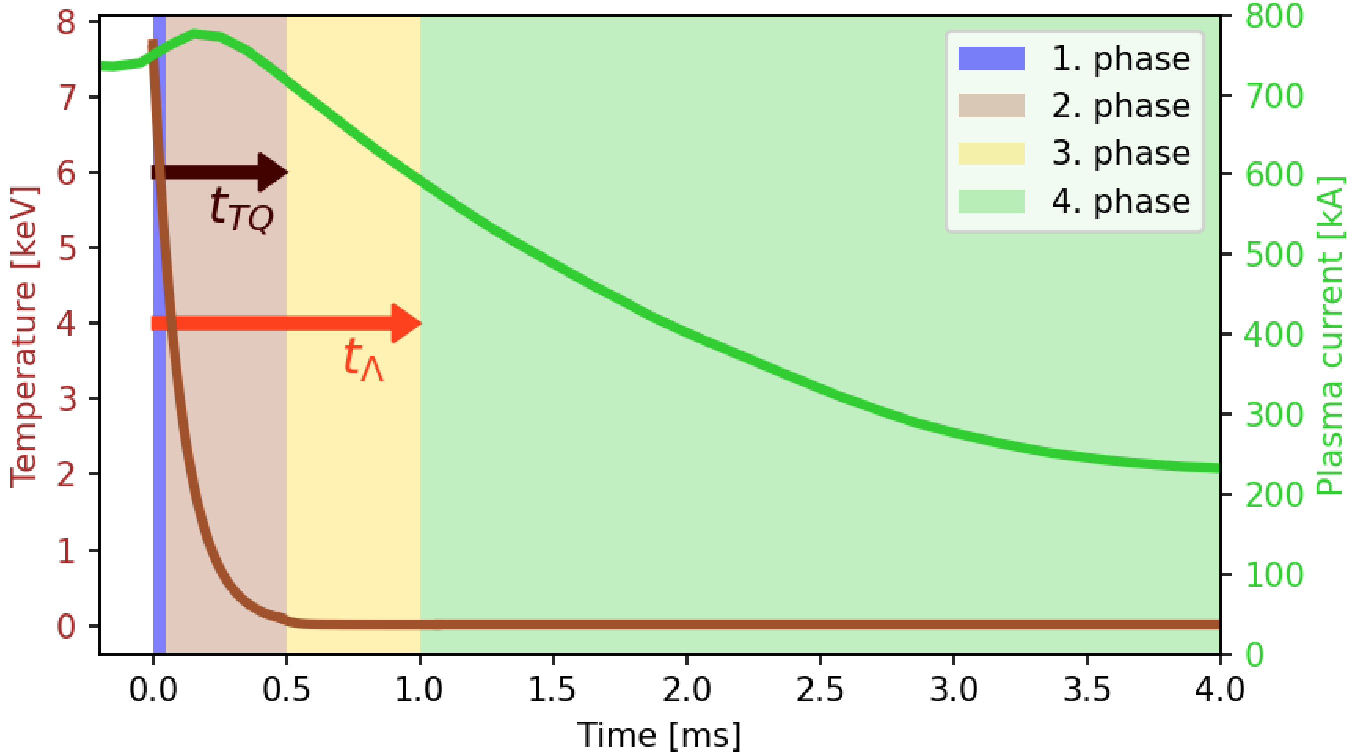
- Build self-consistent model required to reconstruct the current spike at the beginning of disruptions.
- Constrain free parameters appearing in the model, through optimization.
- Refine the evolution of plasma parameters that are relevant for the runaway electron model.

INITIAL MODEL

Experiment: ASDEX Upgrade #33108

Disruption:

- Induced by Massive Gas Injection



Model:

1. Assimilation phase: Argon injection. Constant argon density. Number of assimilated argon atoms in the plasma: $N_{Ar} \cdot \boldsymbol{q_{Ar}}$.
   Hyperresistivity is active: $\Lambda(r,t) = \boldsymbol{\Lambda} \cdot \theta(\boldsymbol{t_\Lambda} - t)$.
2. Thermal quench: $T_e(r,t) = T_f(r) + [T_i(r) - T_f(r)] \cdot e^{-t/\boldsymbol{\tau_{TQ}}}$.
3. Hyperresistivity is active, temperature evolution is self consistent. Duration of phase: $\boldsymbol{t_\Lambda}$.
4. Magnetic surfaces heal, hyperresistivity is not active.

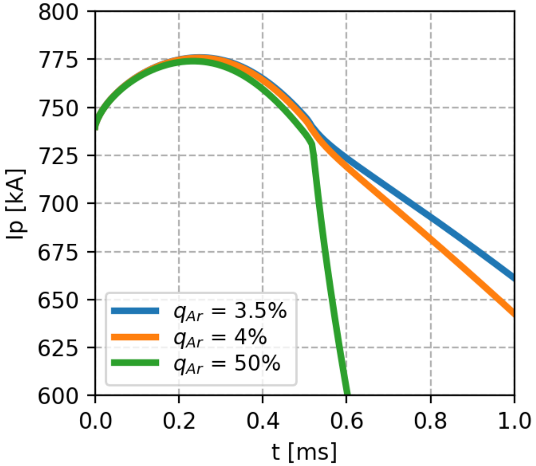
MANUAL OPTIMIZATION

DREAM

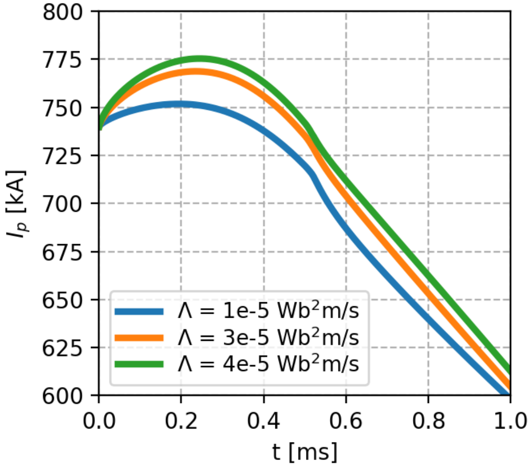
1D, fluid

Free parameters:

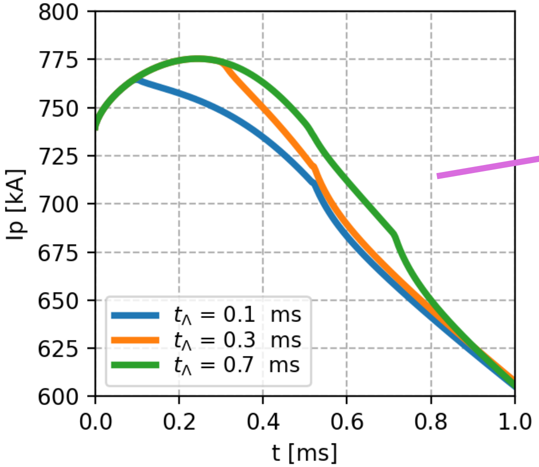
q_{Ar}



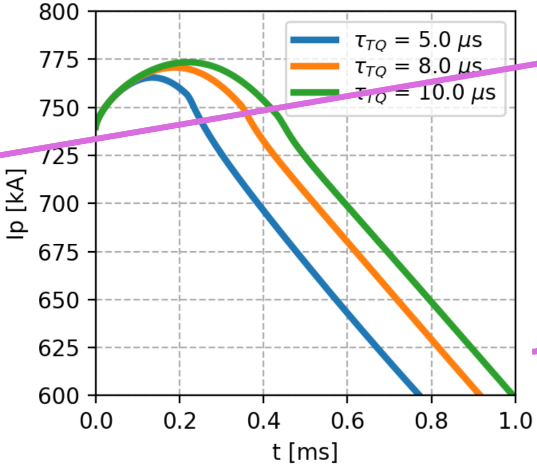
Λ



t_Λ



τ_{TQ}

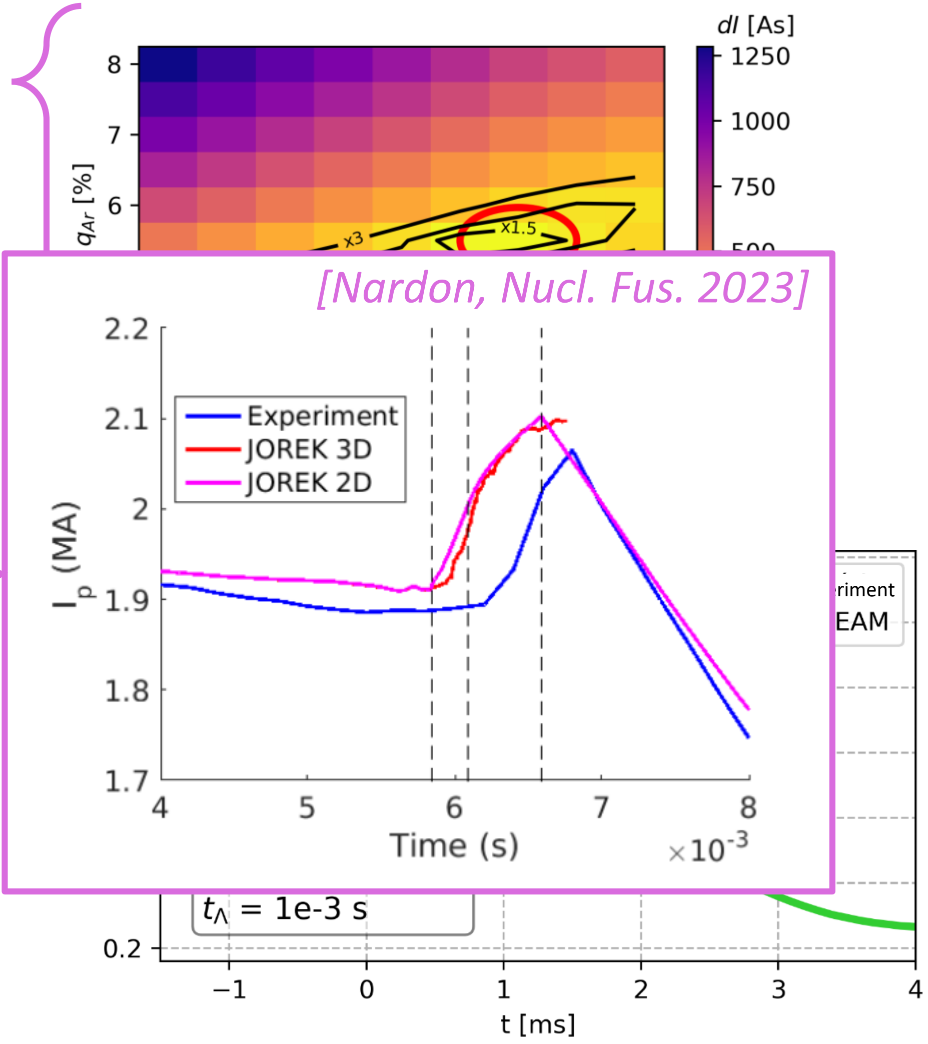


MANUAL SCAN

+

PHYSICAL UNDER-STANDING

=



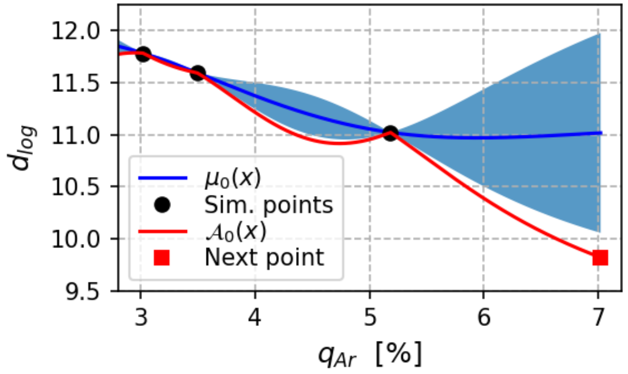
BAYES-OPTIMIZATION

Objective function

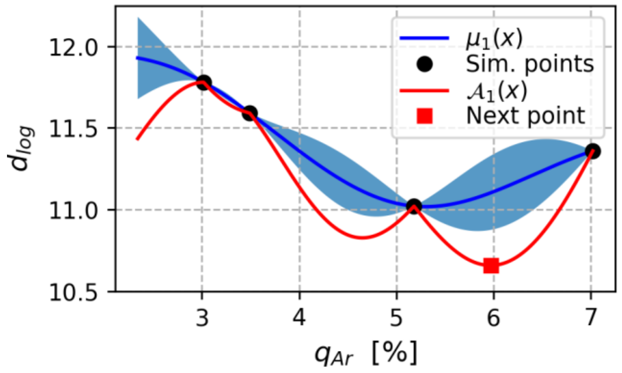
$$d_{log}(\boldsymbol{X}) = \log\left(\sqrt{\int (I_{EXP}(t) - I_{DREAM}(\boldsymbol{X},t))^2 \, dt}\right)$$

Example: 1D problem

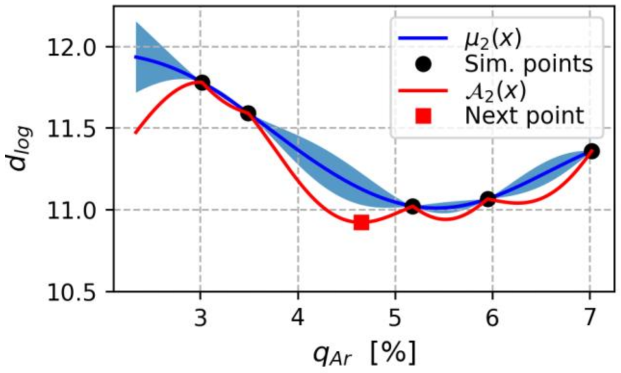
Initialization



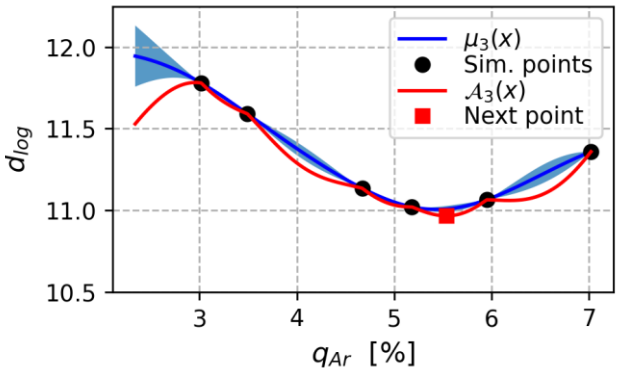
1. iteration



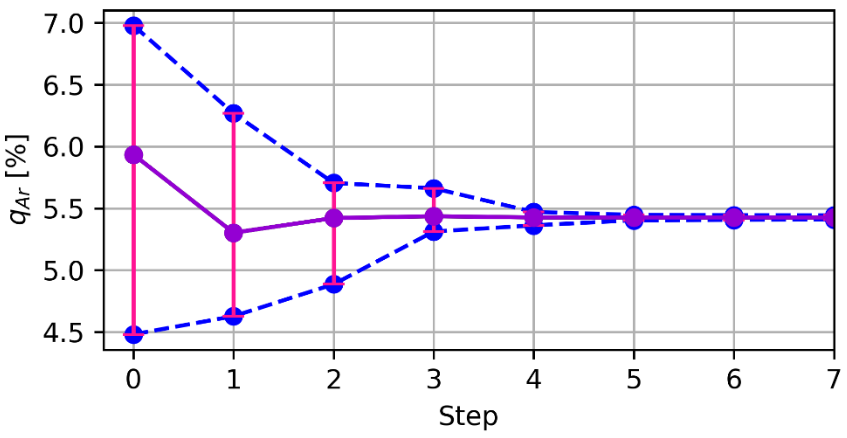
2. iteration

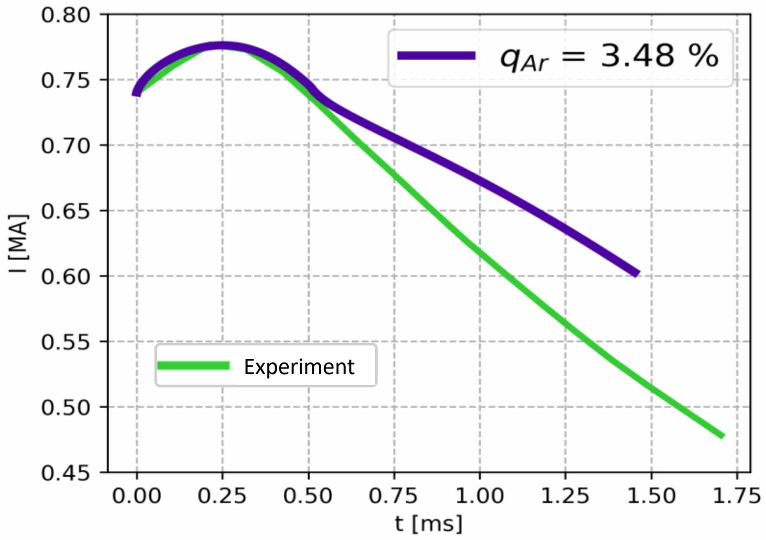


3. iteration



Steps in each iteration:
1. Runs the simulation with the selected values.
2. Updates the estimate of the objective function and its uncertainty.
3. Selects the next sampling point.

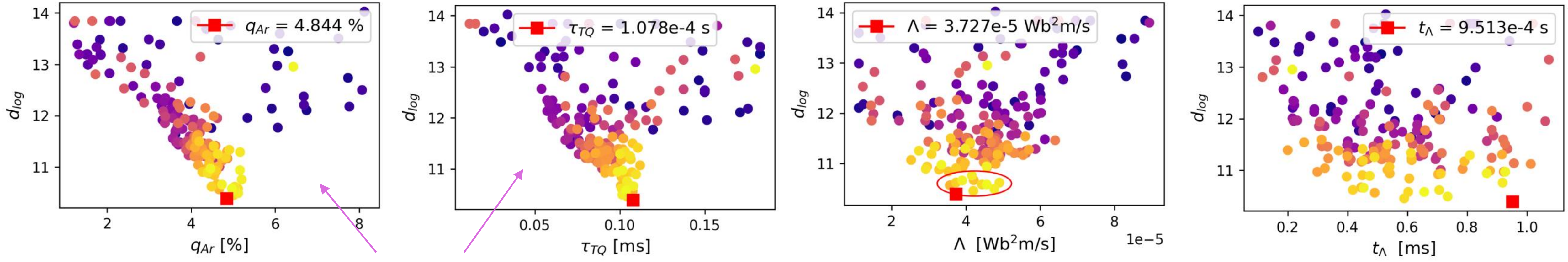




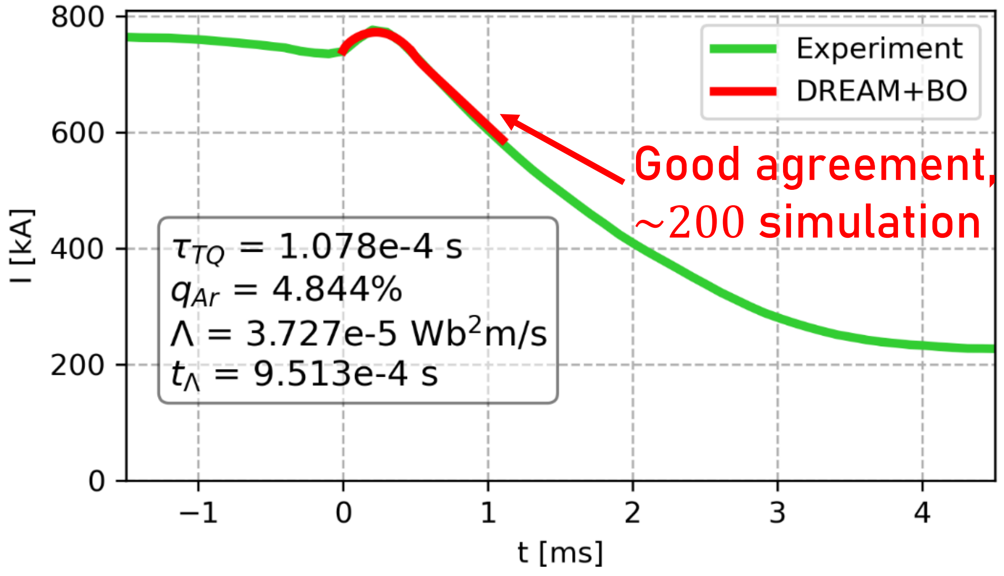
4D BAYES-OPTIMIZATION

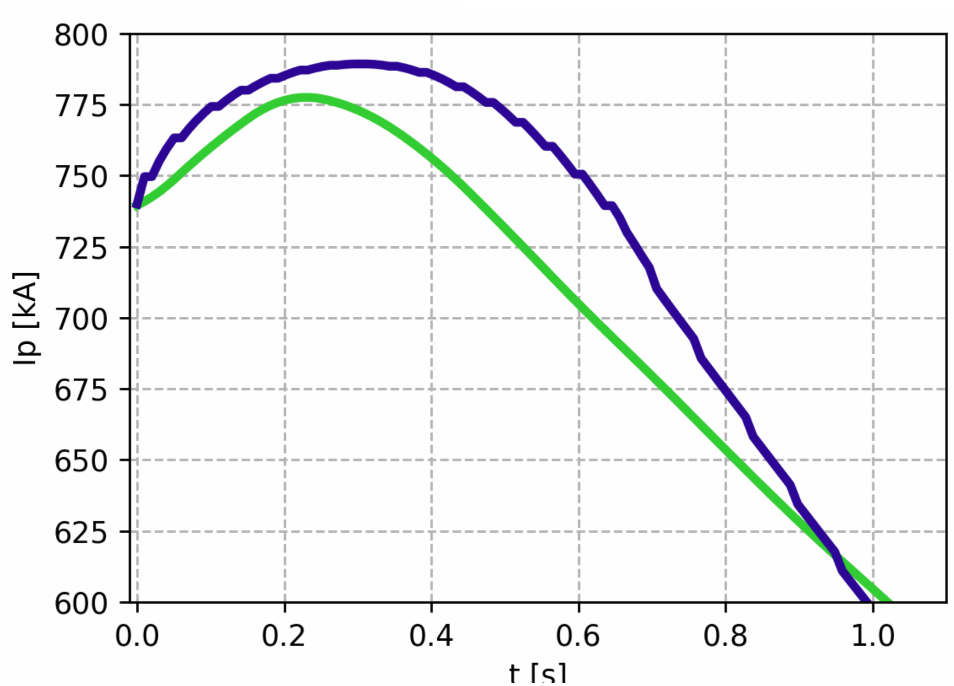
Objective function

$$d_{log}(\boldsymbol{X} \equiv \tau_{TQ}, q_{Ar}, \Lambda, t_{\Lambda}) = \log\left(\sqrt{\int (I_{EXP}(t) - I_{DREAM}(\boldsymbol{X}, t))^2 \, dt}\right)$$



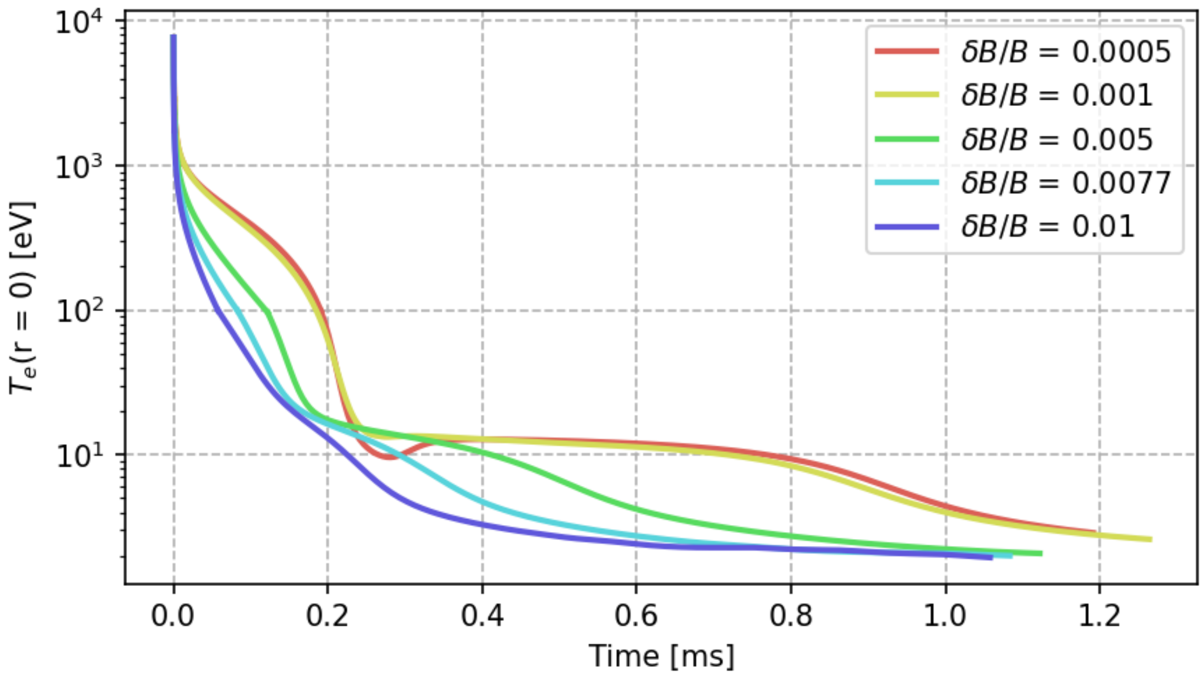
The current is more sensitive to these parameters

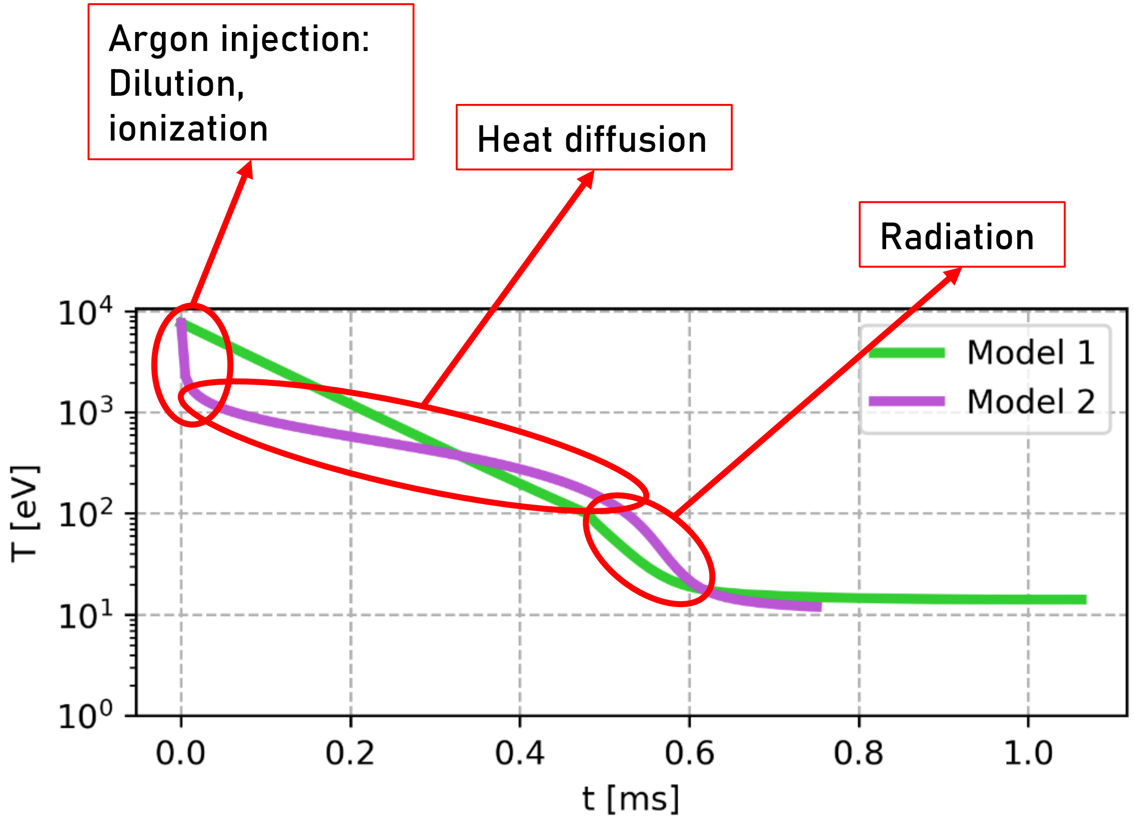




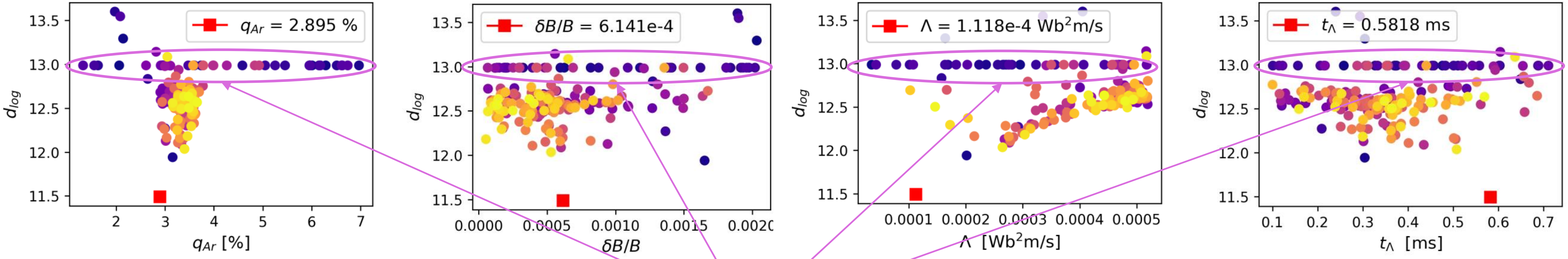
MODEL 2: SELF-CONSISTENT TQ

1. Assimilation: argon appears instantaneously, total number of assimilated argon atoms: $N_{Ar} \cdot \boldsymbol{q_{Ar}}$. Hyperresistivity: $\Lambda(r,t) = \boldsymbol{\Lambda} \cdot \theta(\boldsymbol{t_\Lambda} - t)$.
2. Self-consistent TQ: Heat diffusion modelled with Rechester & Rosenbluth model: $D_W = 2\sqrt{\pi} R v_{th} \left(\frac{\delta B}{B}\right)^2$.
3. Hyperresistivity is active, temperature evolution is self consistent. Duration of phase: $\boldsymbol{t_\Lambda}$.
4. Magnetic surfaces heal, hyperresistivity: $\Lambda(r,t) = 0$.

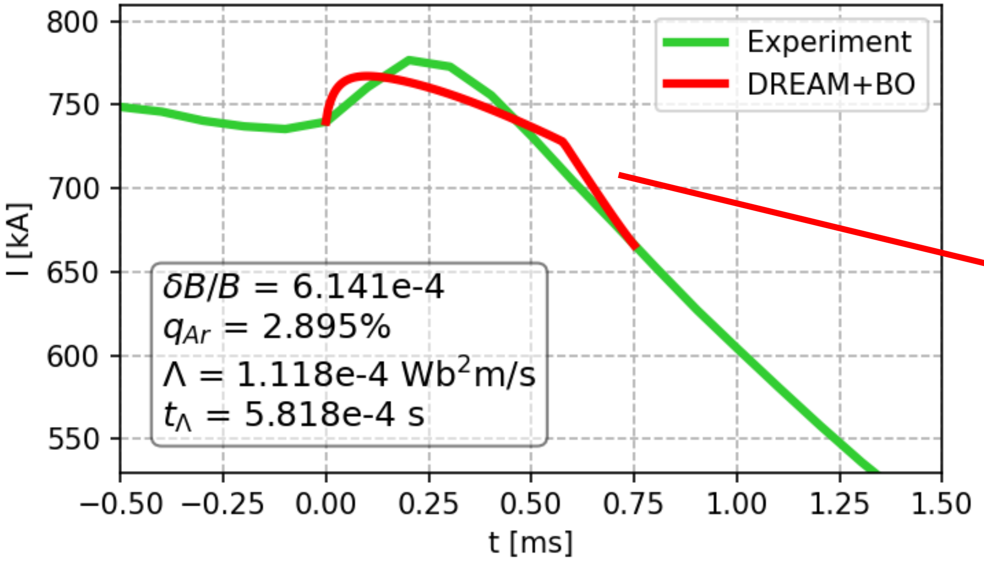




SELF-CONSISTENT TEMPERATURE EVOLUTION

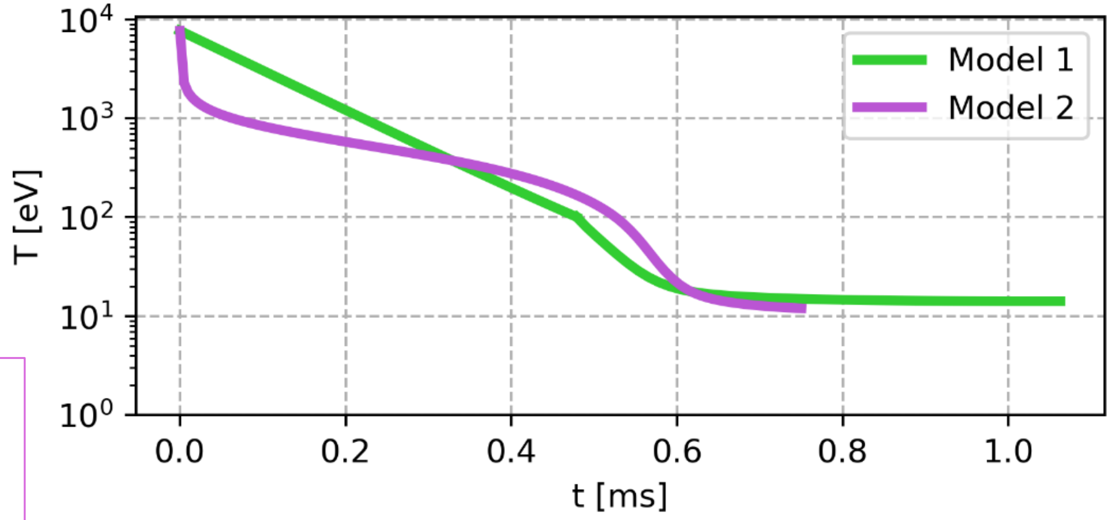


Failing simulation



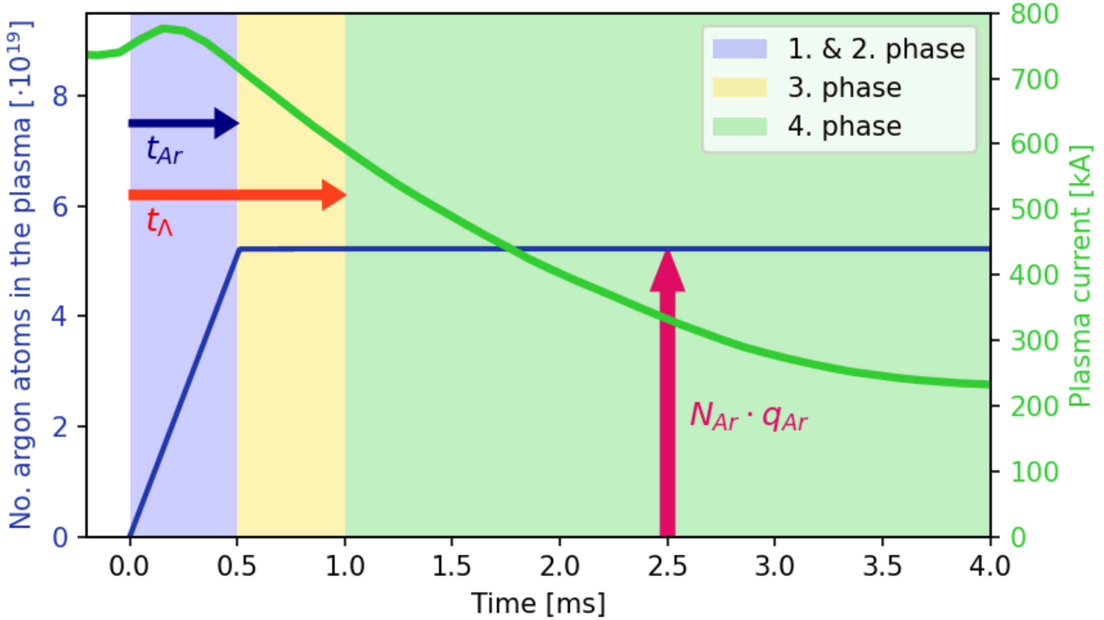
Poor agreement

Solution:
Slower increase in argon density
→ slower decrease in T_e

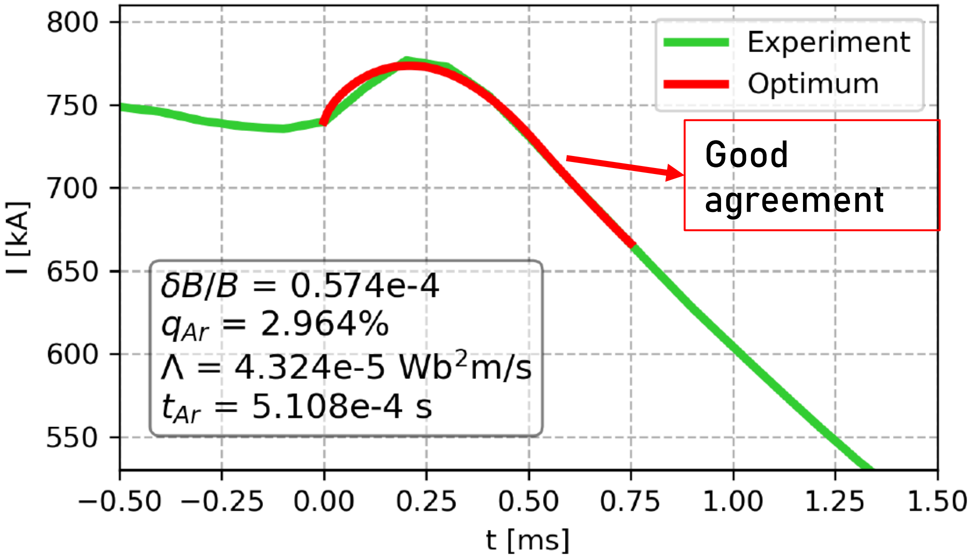


MODEL 3: ARGON INJECTION

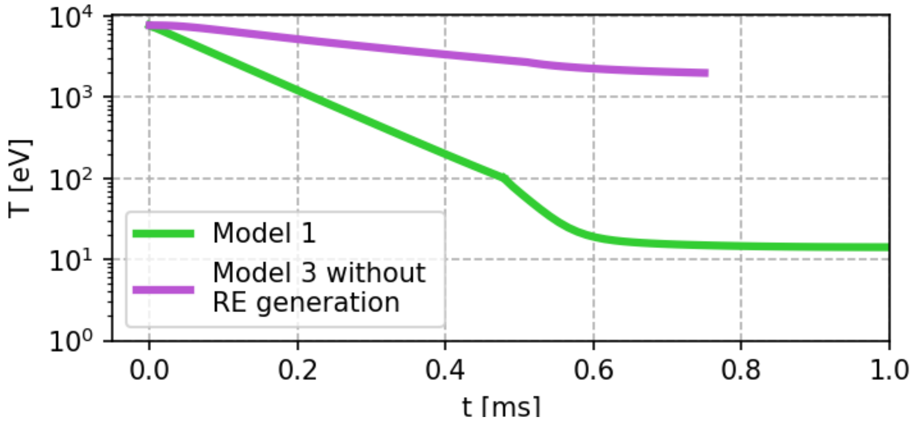
1. Assimilation: argon is introduced via source term: $\frac{dN}{dt} = N_{Ar} \cdot \boldsymbol{q_{Ar}} \frac{\Delta t}{\boldsymbol{t_{Ar}}}$, and high diffusion coefficient.
   Hyperresistivity: $\Lambda(r,t) = \boldsymbol{\Lambda} \cdot \Theta(\boldsymbol{t_\Lambda} - t)$
2. Self-consistent TQ: Model with Rechester & Rosenbluth model: $D_W = 2\sqrt{\pi} R v_{th} \left(\frac{\delta B}{B}\right)^2$.
3. hyperresistivity is active, temperature evolution is self consistent. Duration of phase: $\boldsymbol{t_\Lambda}$.
4. Magnetic surfaces heal, hyperresistivity: $\Lambda(r,t) = 0$.



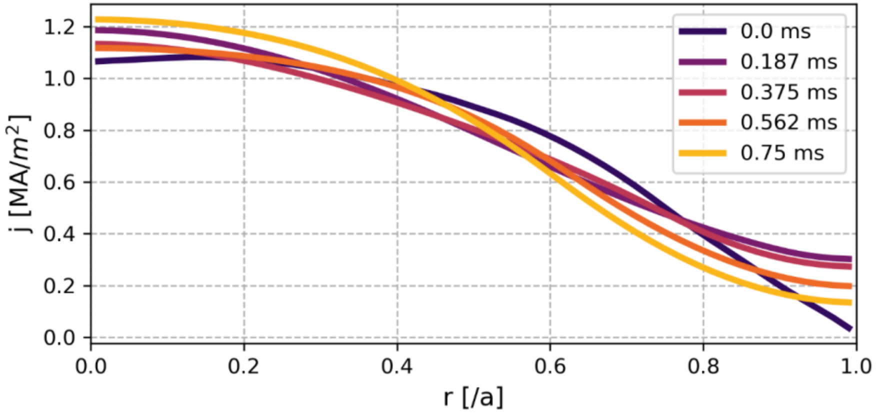
MODEL 3
NO RE GENERATION

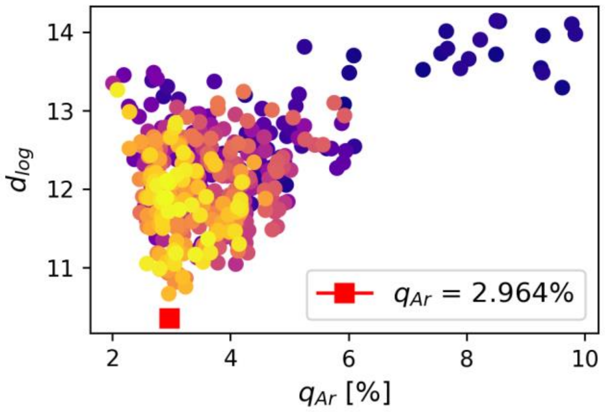


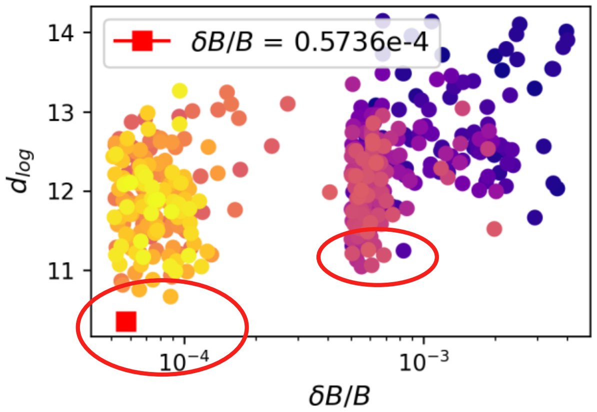
Temperature decreases more slowly

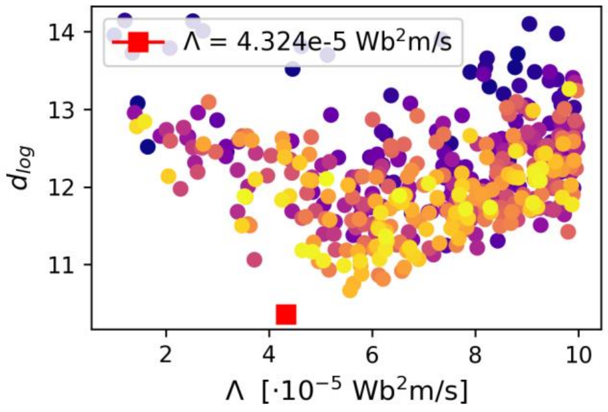


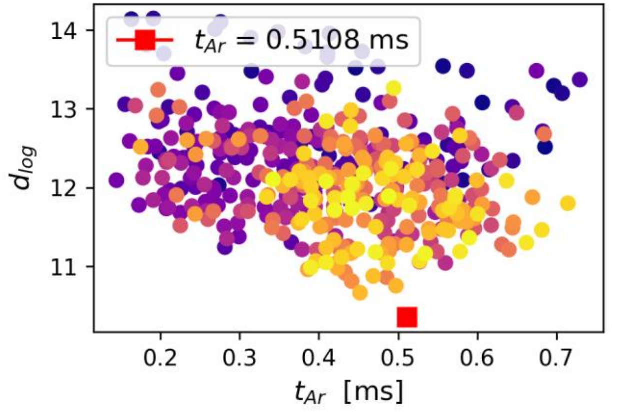
Current relaxation



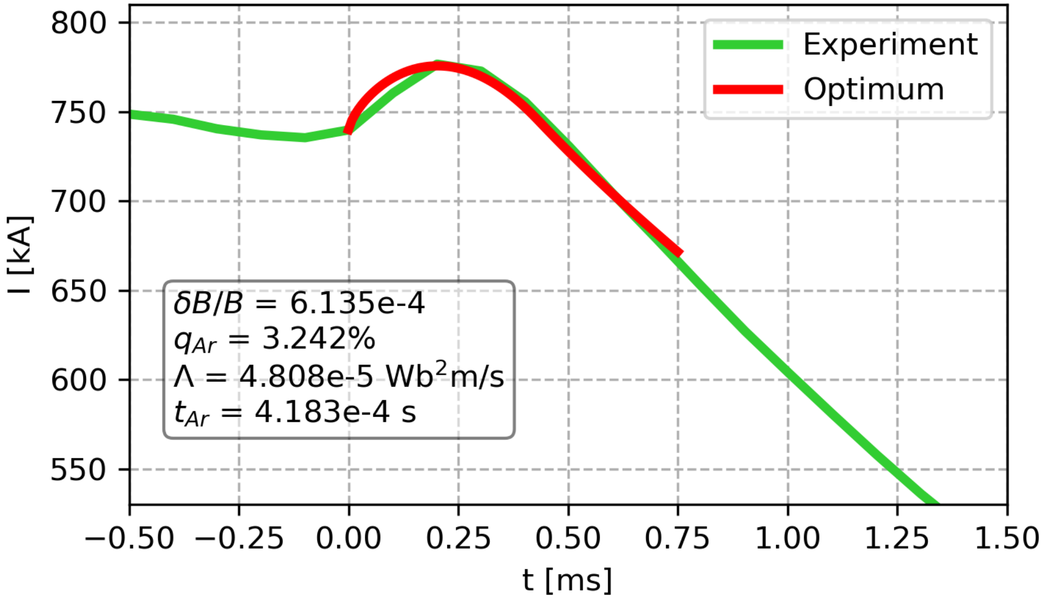




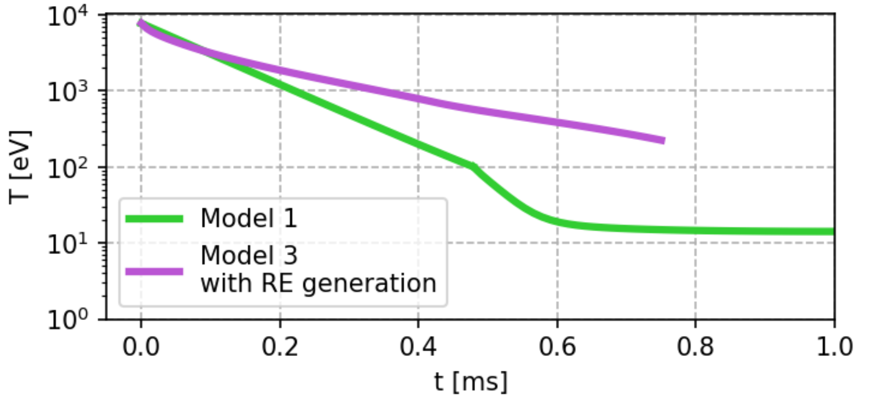




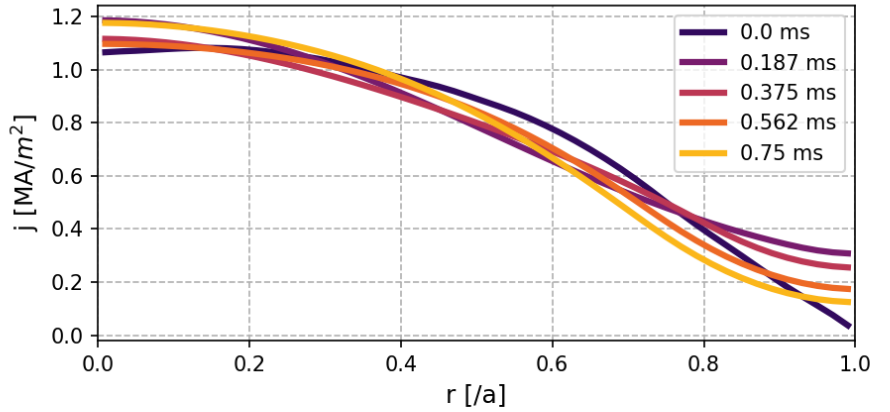
MODEL 3
RE GENERATION, NO RE TRANSPORT

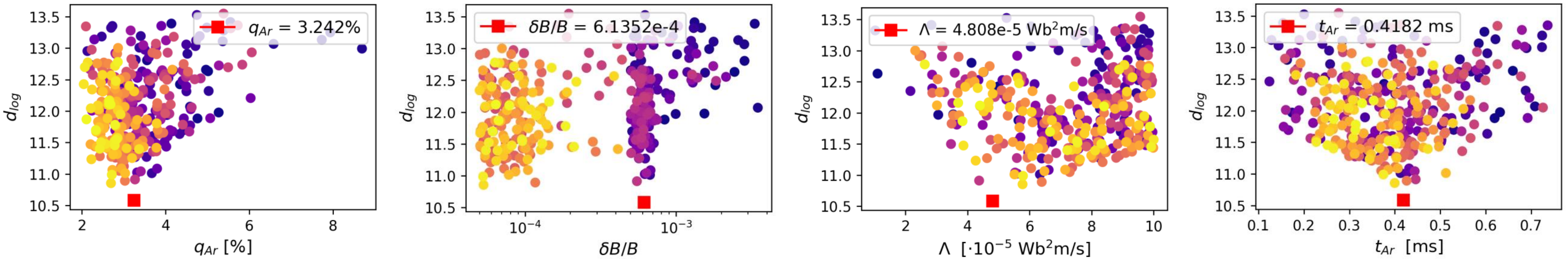


Temperature decreases more slowly



Current relaxation





SUMMARY

- Simulation of current spike during disruptions.
  - Prescribed TQ.
  - Self-consistent TQ.
  - Argon injection.

- Constraining parameters by Bayesian optimization.

- Time scale of current spike $\approx$ time scale of TQ $\approx$ time scale of argon assimilation.

OUTLOOK

- Analysis of more discharges.

- Additional parameters
  - Spatio-temporal evolution of hyperdiffusion coefficient.

- Using other measurements.

- RE generation modelling.

CURRENT RELAXATION

$$H^M = \int_V \mathbf{A}\cdot\mathbf{B}\, dV,$$

$$\Big/ \; \frac{d}{dt}(\,)$$

$$\frac{\partial \mathbf{A}\cdot\mathbf{B}}{\partial t} = (-\mathbf{E}+\nabla\varphi)\cdot\mathbf{B} + \mathbf{A}\cdot(-\nabla\times\mathbf{E}) = -2EB + \nabla\cdot(\varphi\mathbf{B}+\mathbf{A}\times\mathbf{E})$$

$$\frac{dH}{dt} = -2\int_V \mathbf{E}\cdot\mathbf{B}\, dV$$

$$\mathbf{E}+\mathbf{v}\times\mathbf{B} = \eta\mathbf{j} - \frac{\mathbf{B}}{B^2}\nabla\left(\lambda\nabla\frac{j_\parallel}{B}\right)$$

$$\frac{dH}{dt} = -2\eta\mu_0\int_V \mathbf{j}\cdot\mathbf{B}\, dV + \int\nabla\left(\lambda\nabla\frac{j_\parallel}{B}\right) dV$$

$$\int\nabla\left(\lambda\nabla\frac{j_\parallel}{B}\right) dV = \oint\lambda\left(\nabla\frac{j_\parallel}{B}\right)\cdot\nabla\psi_t\mathcal{J}\,d\theta d\varphi = \psi_t\Lambda_m\frac{\partial^2 I}{\partial\psi_t^2}$$

$$\frac{\partial}{\partial\psi_t}(\,)\;\Big/$$

$$H^M = -\frac{2}{(2\pi)^2}\int\psi_p\, d\psi_t$$

$$\frac{\partial\psi_p(\psi_t,t)}{\partial t} = \mathcal{R}_\psi\frac{\partial I(\psi_t,t)}{\partial\psi_t} - \frac{\partial}{\partial\psi_t}\left(\psi_t\Lambda\frac{\partial^2 I}{\partial\psi_t^2}\right)$$

$$\psi_p(\psi_t) = -\int\frac{L(\psi_t)I(\psi_t)}{2\psi_t}\, d\psi_t$$

$$\frac{\partial L(\psi_t)I(\psi_t)}{\partial t} = 2\psi_t\frac{\partial}{\partial\psi_t}\left(\mathcal{R}\frac{\partial I(\psi_t,t)}{\partial\psi_t} - \frac{\partial}{\partial\psi_t}\psi_t\Lambda\frac{\partial^2 I}{\partial\psi_t^2}\right)$$

[Brandenburg 2005]
[Boozer, Nucl. Fus. 1986]
[Boozer, Nucl. Fus. 2018]