EPFL

Numerical study of the influence of ion-induced electrons on the dynamics of electron clouds in gyrotron-like geometries

S. Guinchard[1], G. Le Bars[2]

January 13, 2023

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Physics Section (SPH), CH-1015 Lausanne, Switzerland

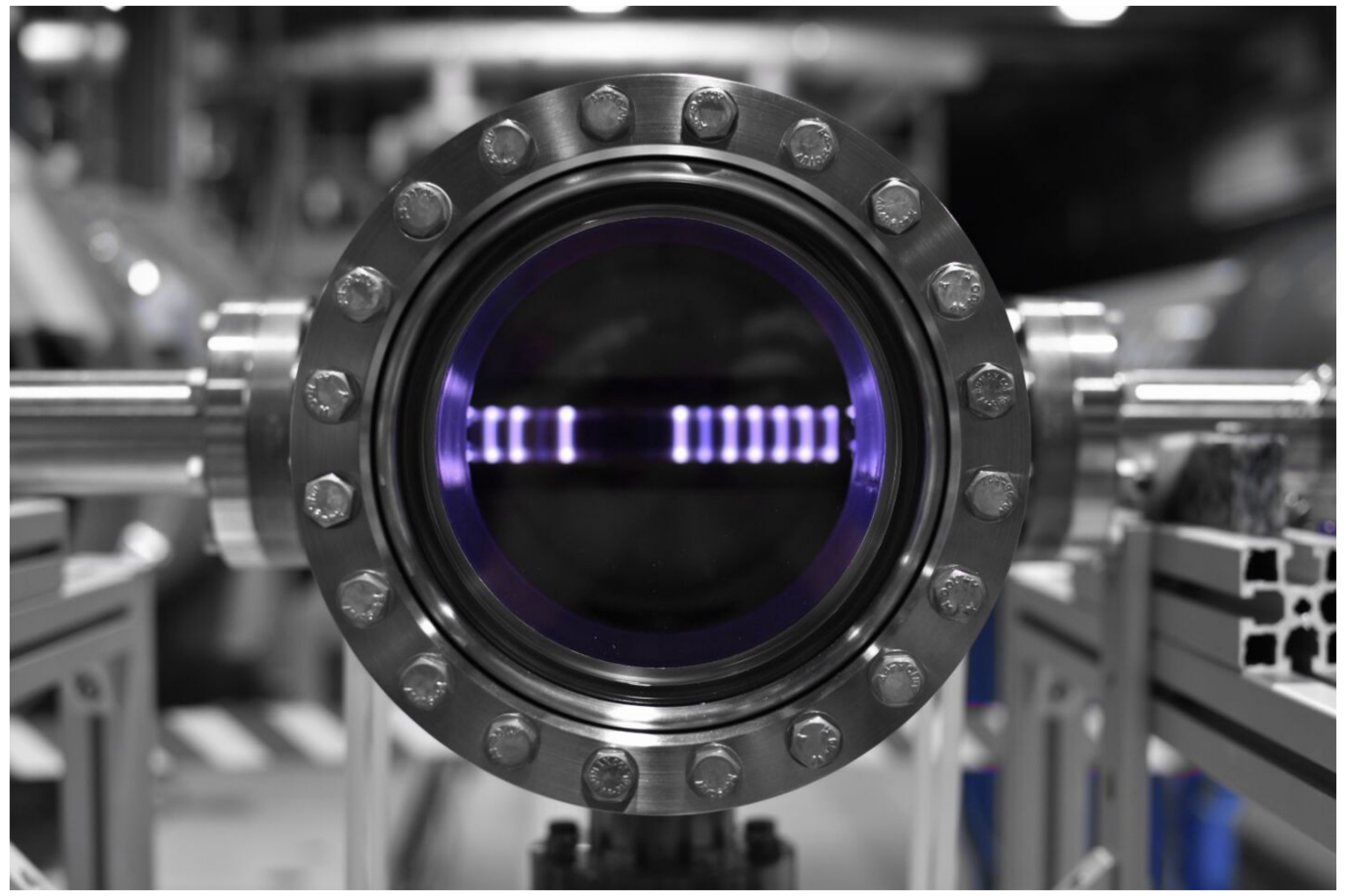
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

Swiss Plasma Center

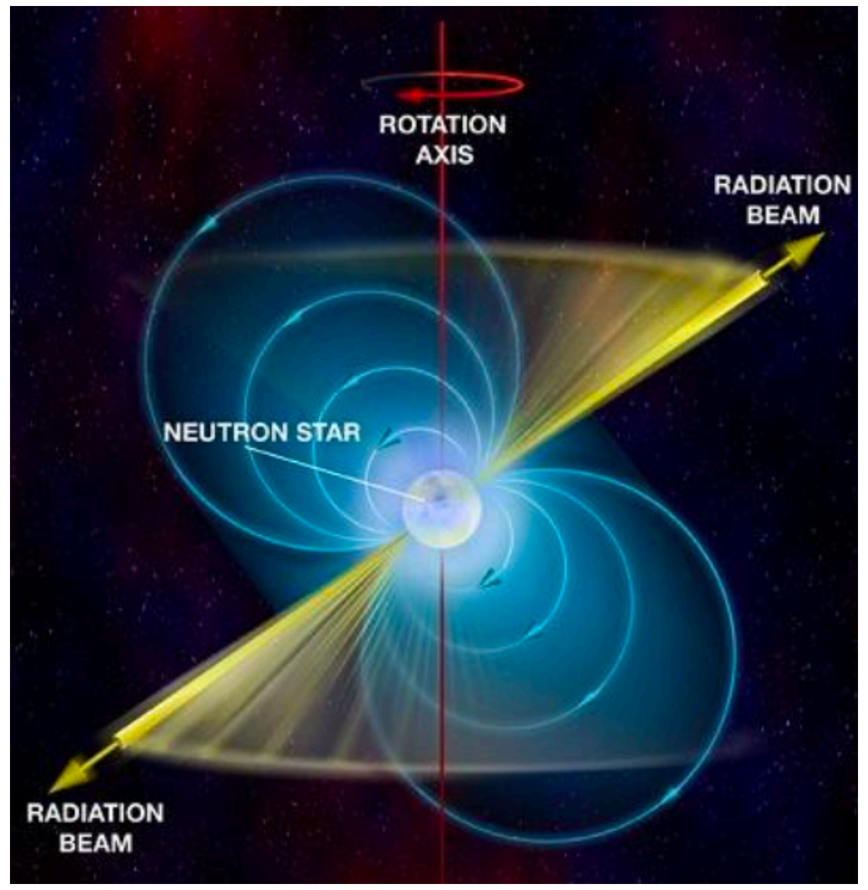
- Introduction
- II - Theory
    - Choosing a model
    - Implementation
- III - Results
    - Module testing
    - Cloud formation and dynamics
        - TREX *slanted*
        - TREX *extrude*
        - GT-170
- Conclusion

Introduction - Non neutral plasmas

- Collection of charged parts s.t. overall no charge neutrality [DS]
- Non-neutral plasmas relevant to many fields of physics: Astrophysics, atomic clocks, particle accelerators, surface engineering & **ECRH.**
- Electron Cyclotron Resonant Heating, for which **gyrotrons** are needed.



C sputtering in a plasma cell [Cern]

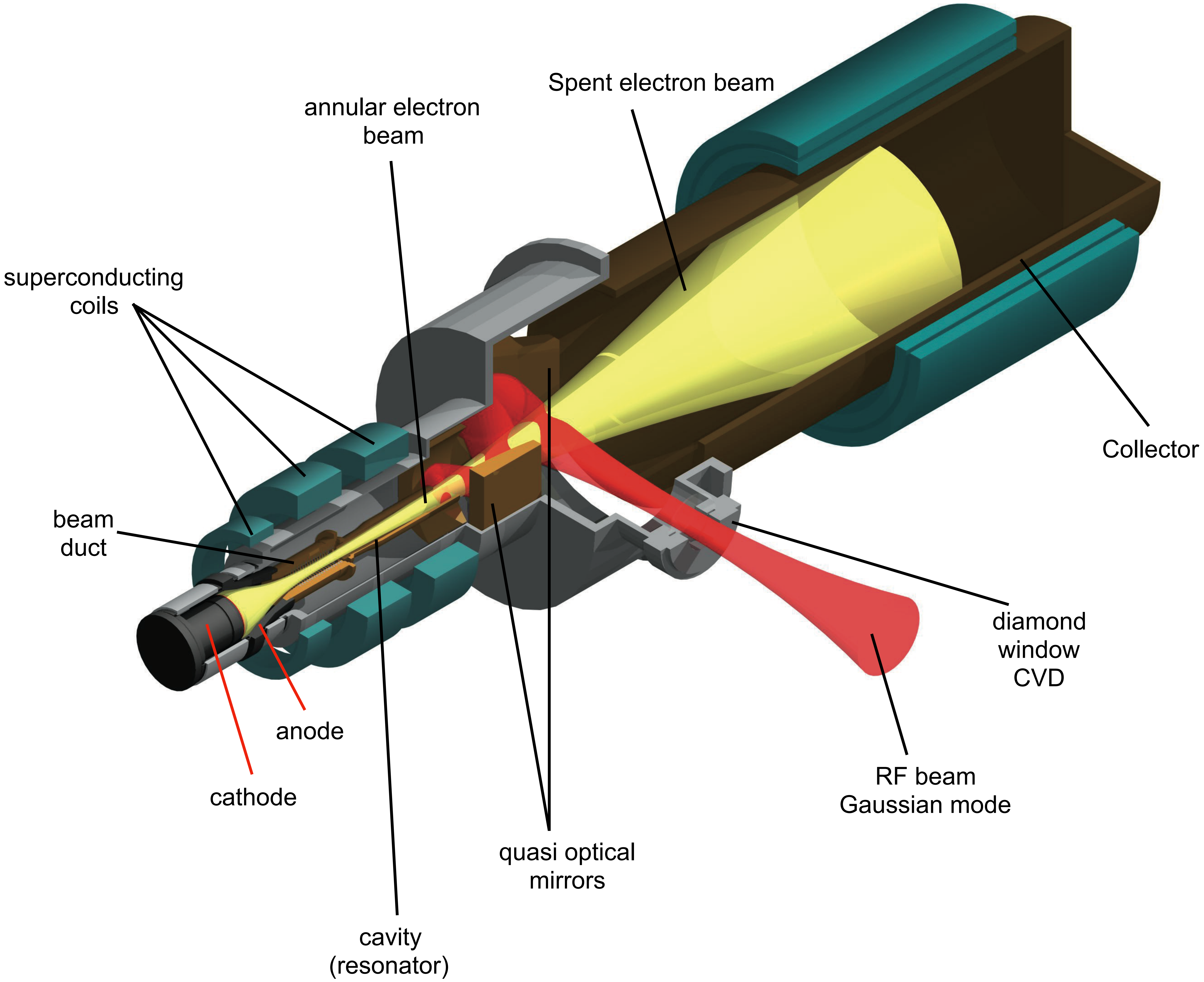


Neutron star magnetosphere

TCV gyrotron for ECRH

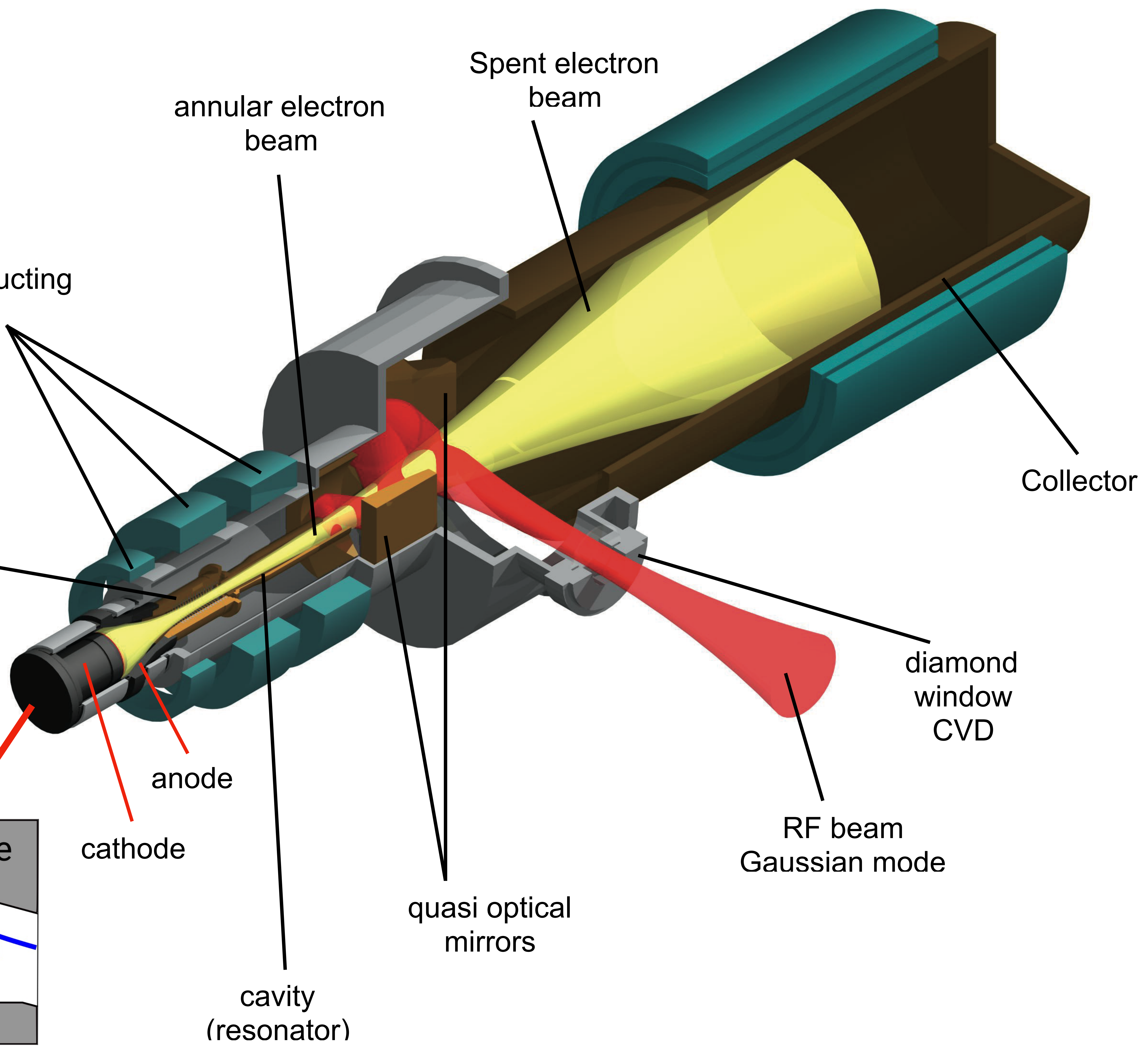
Introduction - The gyrotron as a high power mm wave source

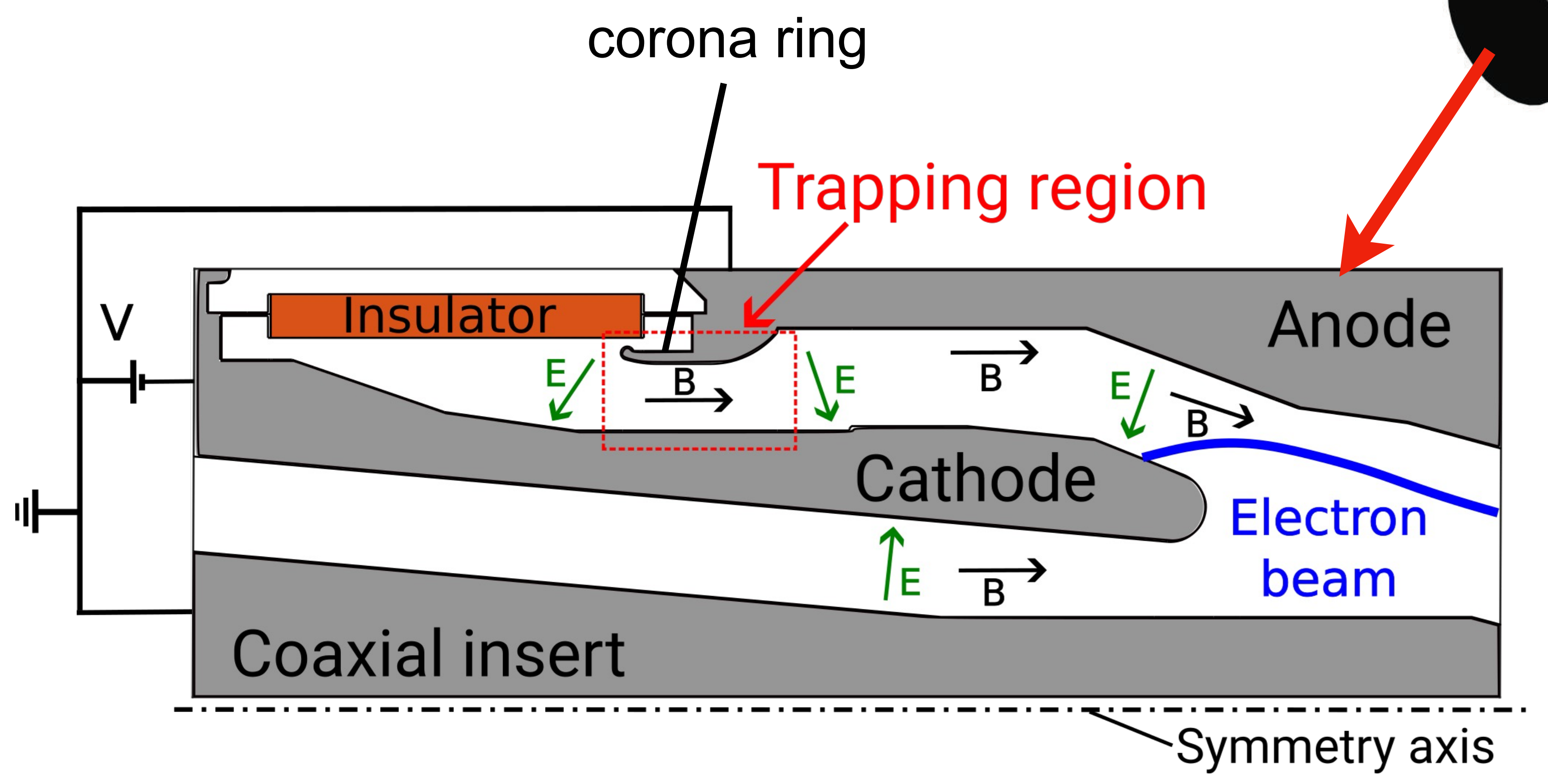
- Micro-waves for ECRH
- 1 MW, 170 GHz continuous beam
- 24 1MW gyrotrons for ITER ECRH



Source: Courtesy of S. Alberti

EPFL Introduction - The gyrotron as a high power mm wave source



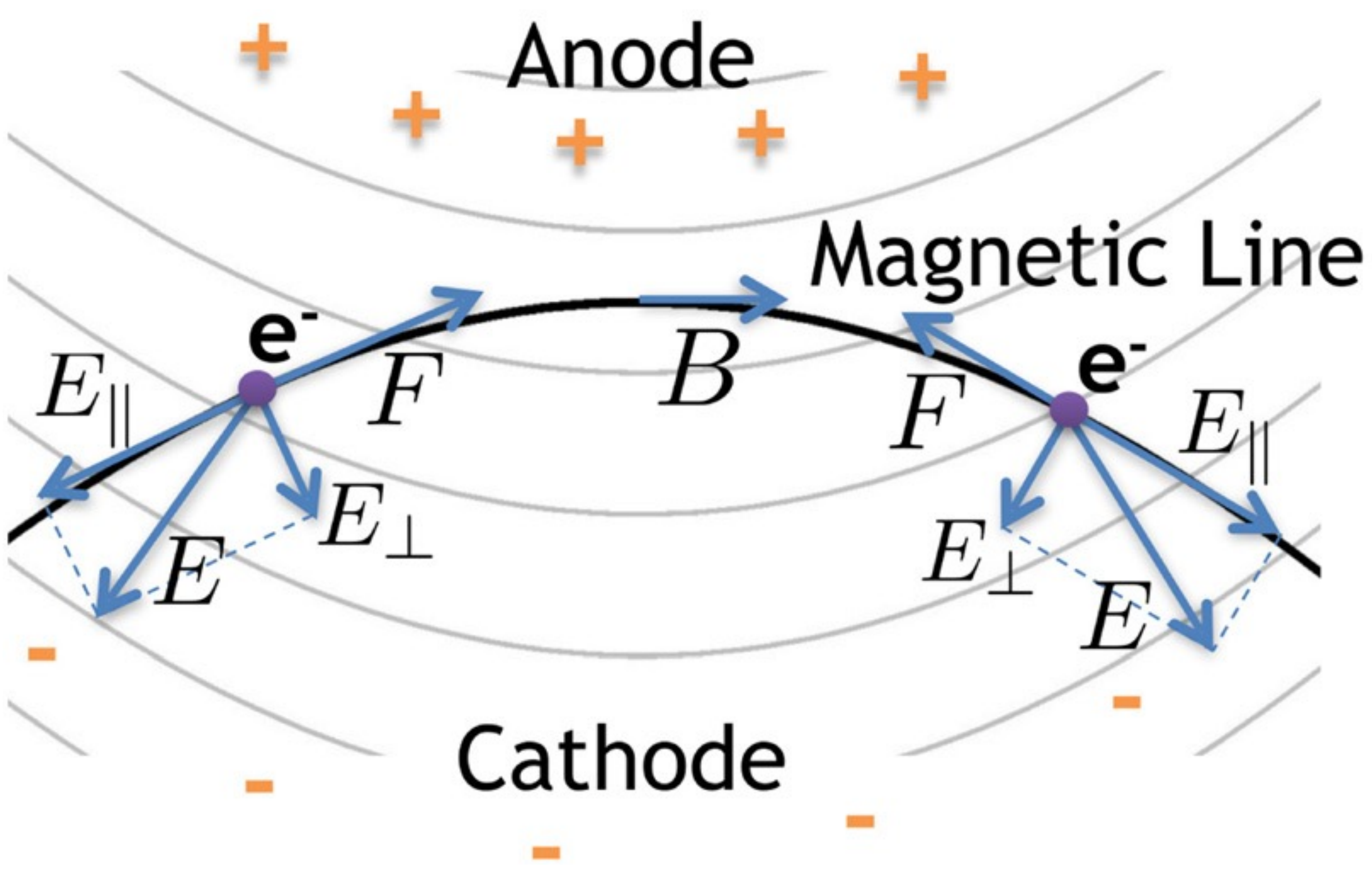


Region of interest

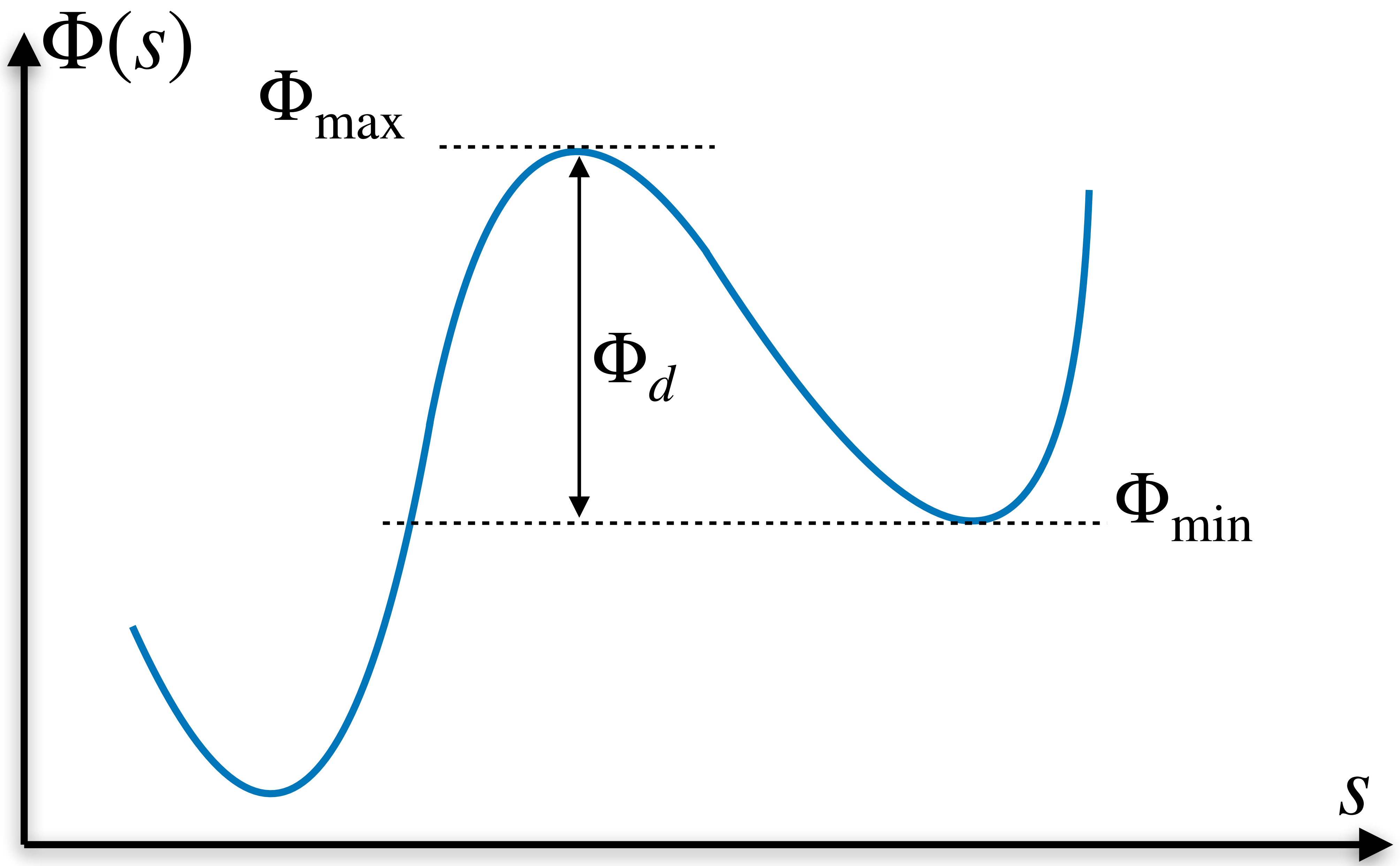
About the problem of trapping

- Due to **magnetic** and **electric** fields topology, some magnetic potential **wells** can form.
- Magnetic field line crosses twice an equipotential.
- Directional force keeps electrons **in the well** while they drift **azimuthally**.

$$F_{||} = -e \cdot E_{||}$$



Config leading to magnetic well [PPZ+16]

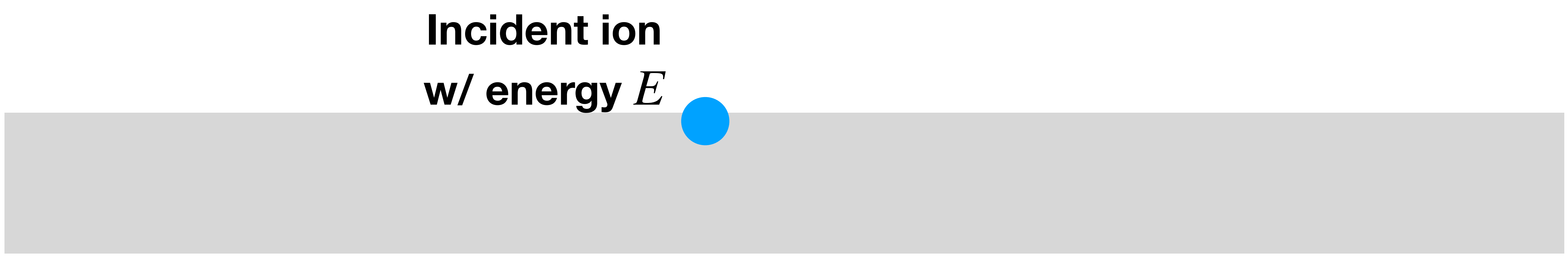


Theory: Choosing a model for IIEE

- We seek an expression for γ, the **electron yield per incident ion**.

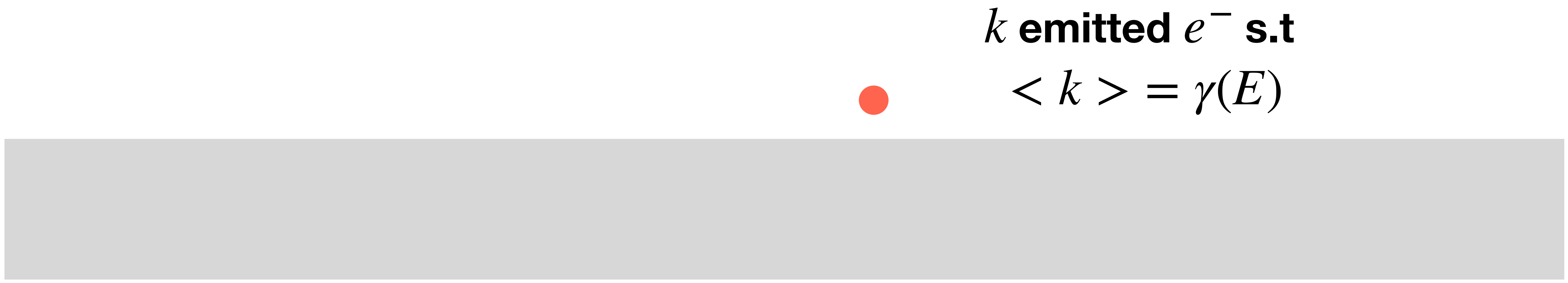
Theory: Choosing a model for IIEE

- We seek an expression for γ, the **electron yield per incident ion**.



Theory: Choosing a model for IIEE

- We seek an expression for γ, the **electron yield per incident ion**.



Theory: Choosing a model for IIEE

- We seek an expression for γ, the **electron yield per incident ion.**
- γ is expected to depend on the **incident particle energy**, some **material parameters** (target density, transport phenomena for produced electrons).
- Semi-empirical (kinetic) model: *Schou* - 1988 [DH]

$$\gamma = \Lambda \cdot \beta \cdot \left.\frac{dE}{dx}\right|_i ,$$

where Λ contains the **cross-sections** dependence for energy deposition, β accounts for **energy transport** of the produced electrons, and $\left.\frac{dE}{dx}\right|_i$ corresponds to the **energy loss** of ions in the solid, per unit distance.

Theory: Choosing a model

- For ions like H^+, H_2^+, the product $\Lambda \cdot \beta$ has been measured indep. of the metal and of approx. 10^{-3} **cm/MeV** $= 10^{-6}$ **cm/keV.**

- Hence our kinetic model reads $\gamma(E) = 10^{-6} \cdot \left.\frac{dE}{dx}\right|_i$, with $E \in [1{,}50]$ keV.

- Potential emissions: $E \in [0{,}1]$ keV, we need another model

- *Hagstrum* - 1954 [Kis73]:

$$\gamma \sim \frac{0.2}{\epsilon_F}\left(0.8 \cdot E_i - 2\phi\right),$$

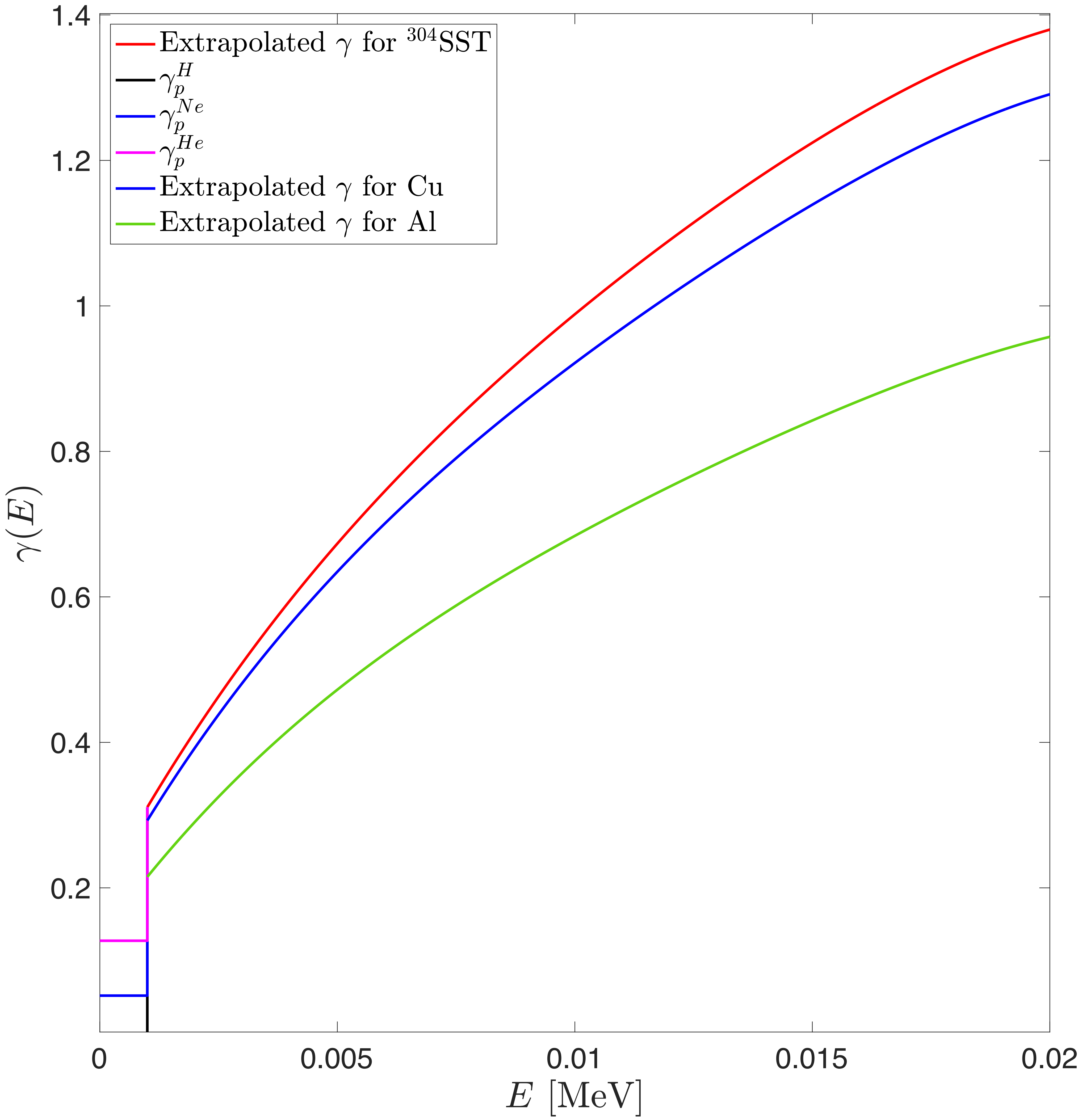
where ϵ_F denotes the **Fermi** energy of the solid, E_i the energy to produce the **incident ion**, and ϕ the **work function** of the metal.

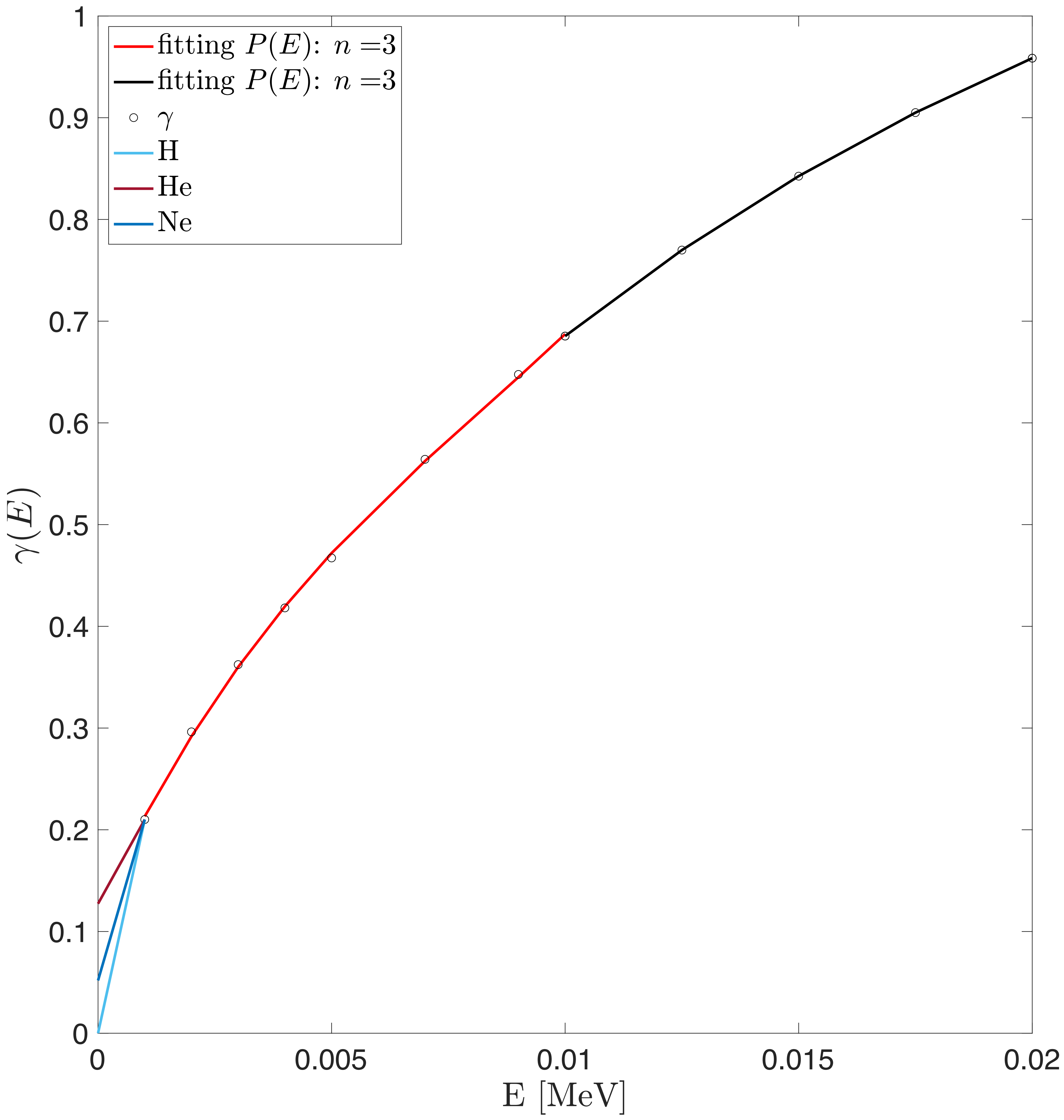
Choosing a model: remarks

- Schou's model: **kinetic**, holds for $E \in [1{,}50]$ keV
- Hagstrum's model: **potential**, holds for $E \in [0{,}1]$ keV, constant γ
- **Transition between the two models** ? Linear interpolation between bottom of kinetic region and constant γ, so the yield is decreasing continuously on the whole range.

Theory: Implementation

- Yield curve obtained by interpolating the points with cubic polynomials
- Right plot shows transition between Hagstrum's and Schou's model





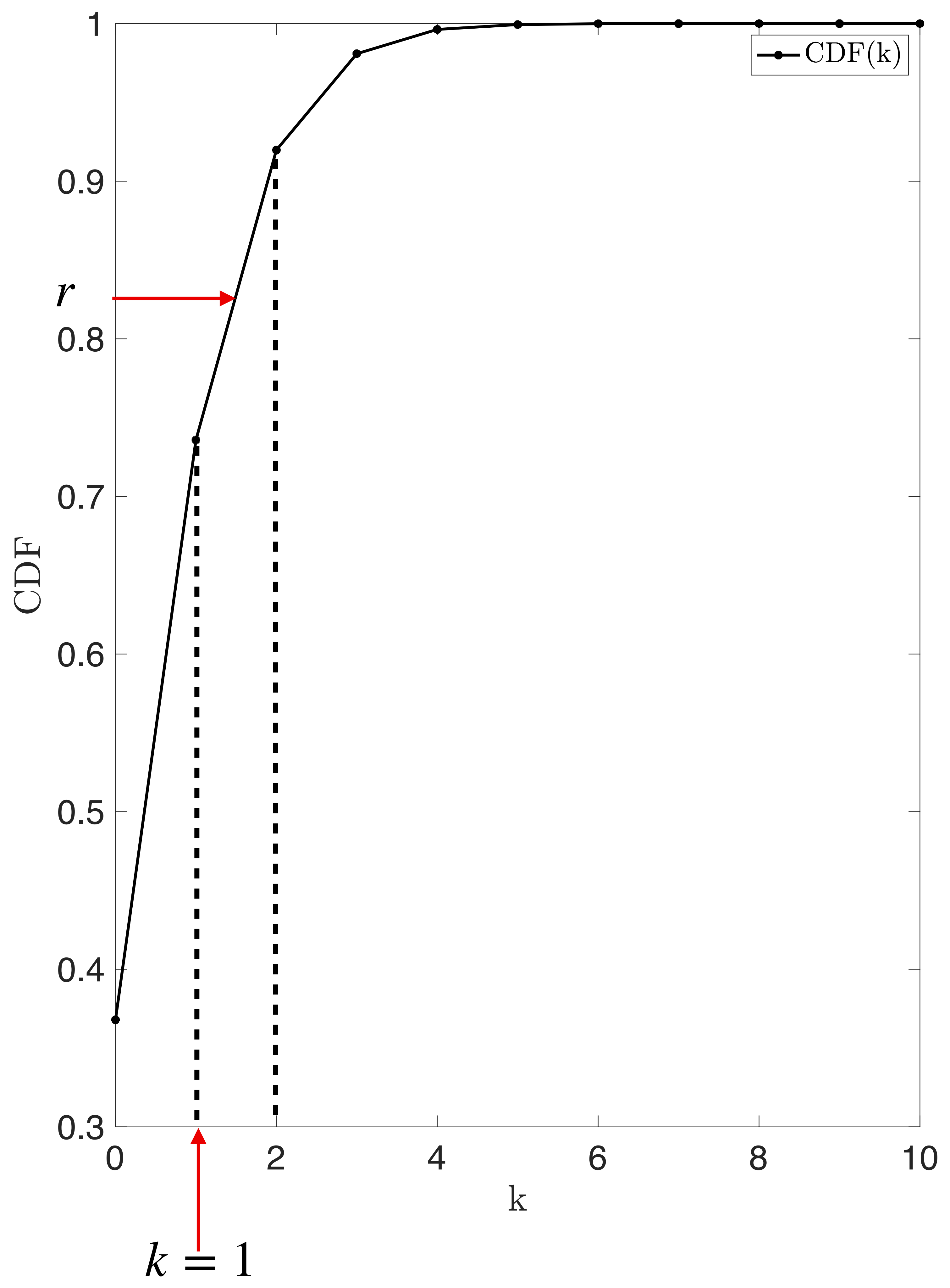
Implementation: electron generation

- Electron generation: discrete 'rare' events $\Longrightarrow$ **Poisson** distribution for the number of electrons generated per incident ion (parameter λ)

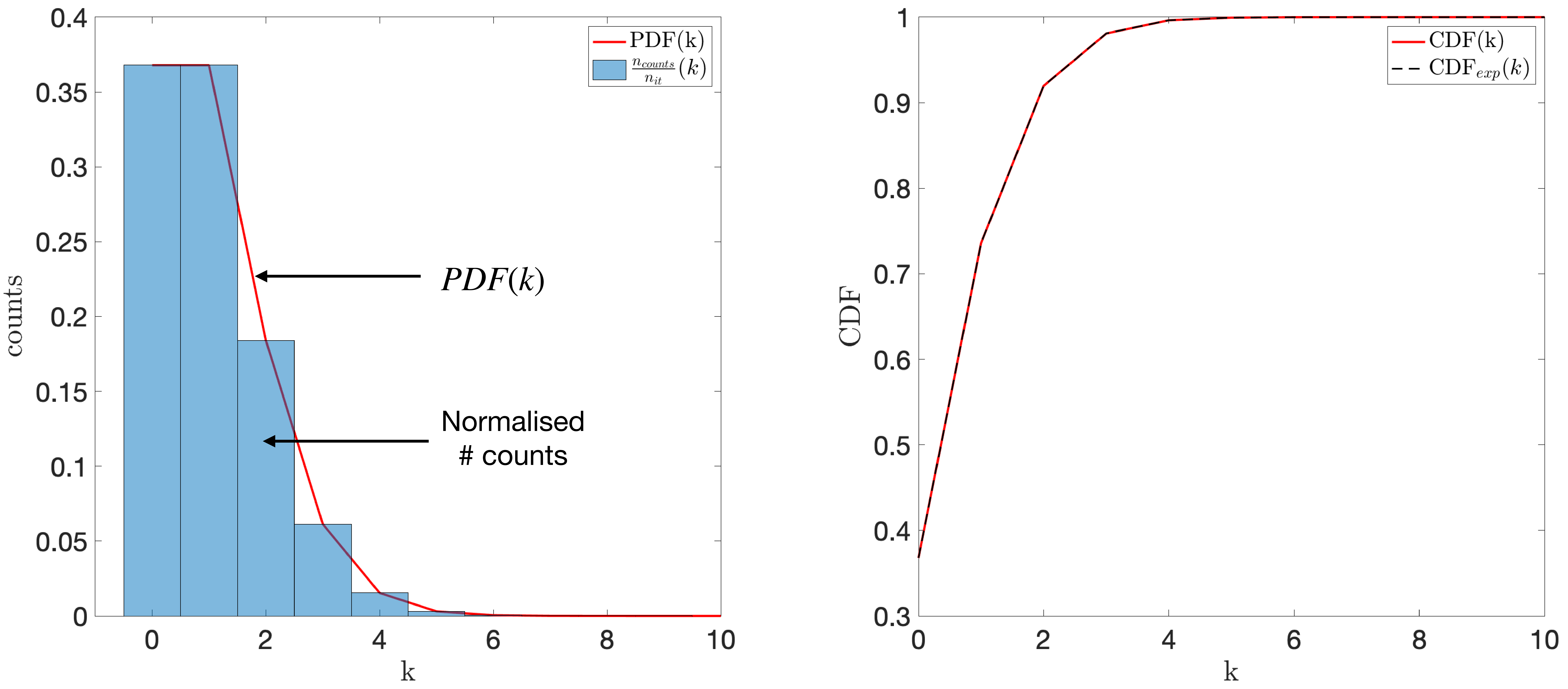
- Poisson s.t. $\lambda(E) = \gamma(E)$

- $P(k) = \dfrac{e^{-\gamma(E)}}{k!}$, and CDF: $C(k) = \displaystyle\sum_{j=0}^{\lfloor k \rfloor} \dfrac{\gamma(E)^j}{j!}$

- Procedure:
  - Generate a random number uniformly in $[0,1[$
  - Evaluate C with $\lambda = \gamma(E)$
  - If $r \in [C(\tilde{k}), C(\tilde{k}+1)[$ then $k = \tilde{k}$.



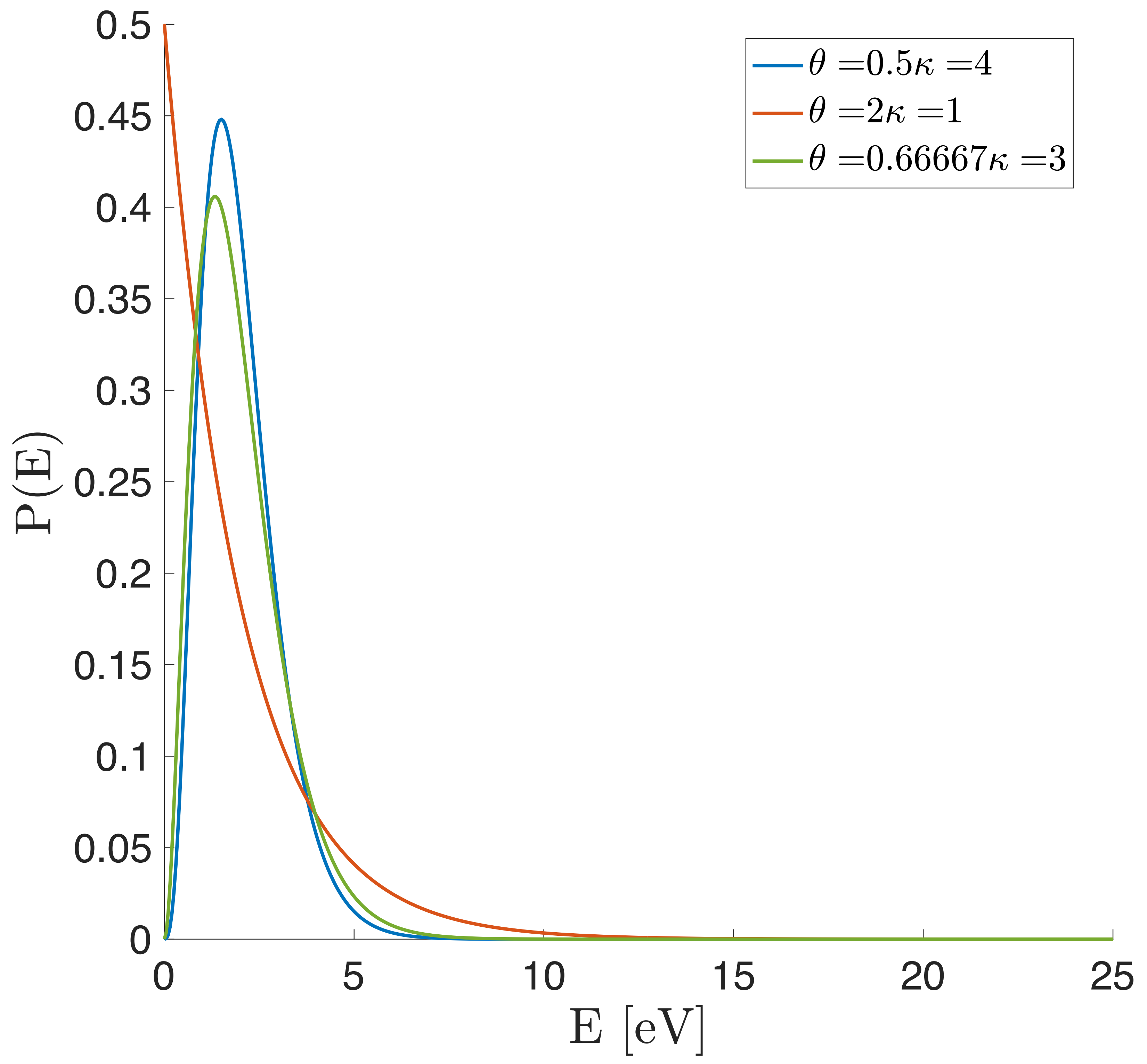
Electron generation - Test of Poisson generator

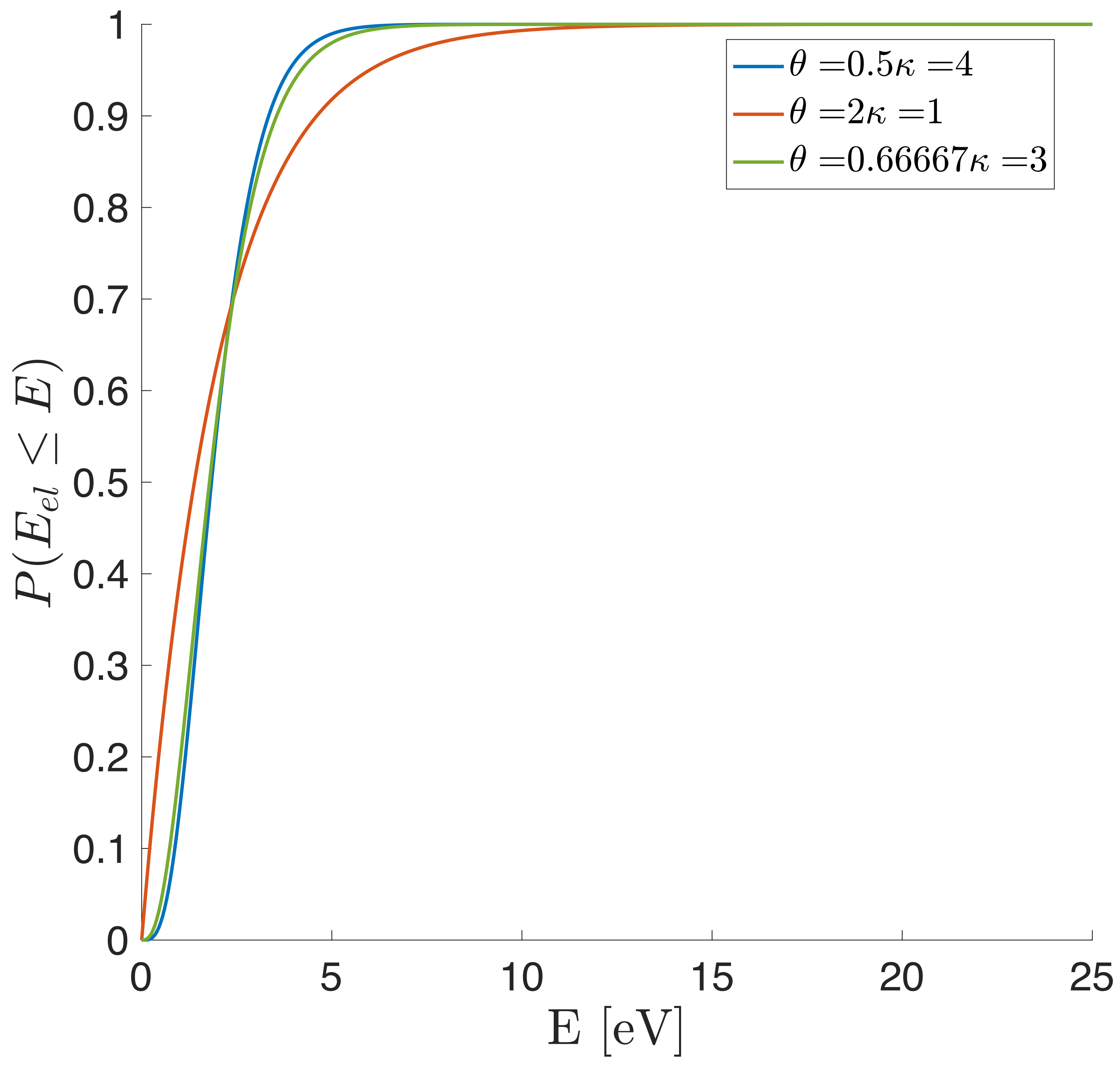


Implementation: Energy distribution of emitted electrons

- According to [DH] and [PPZ+16]: follows a gamma distribution that averages at 2 eV.

- Recall the two parameters: **shape** param. κ and **scale** param. θ s.t average $m = \kappa \cdot \theta$

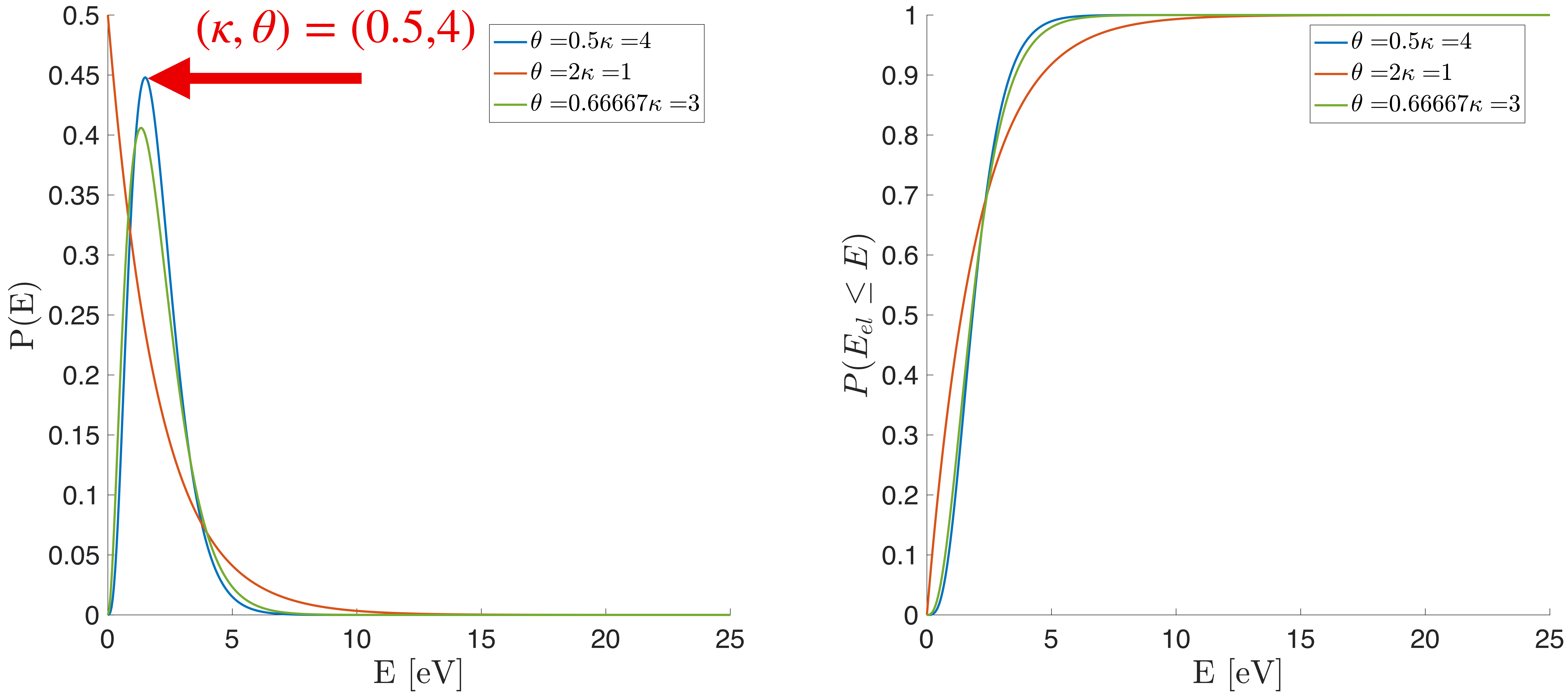




Implementation: Energy distribution of emitted electrons

- According to [DH] and [PPZ+16]: follows a gamma distribution that averages at 2 eV.

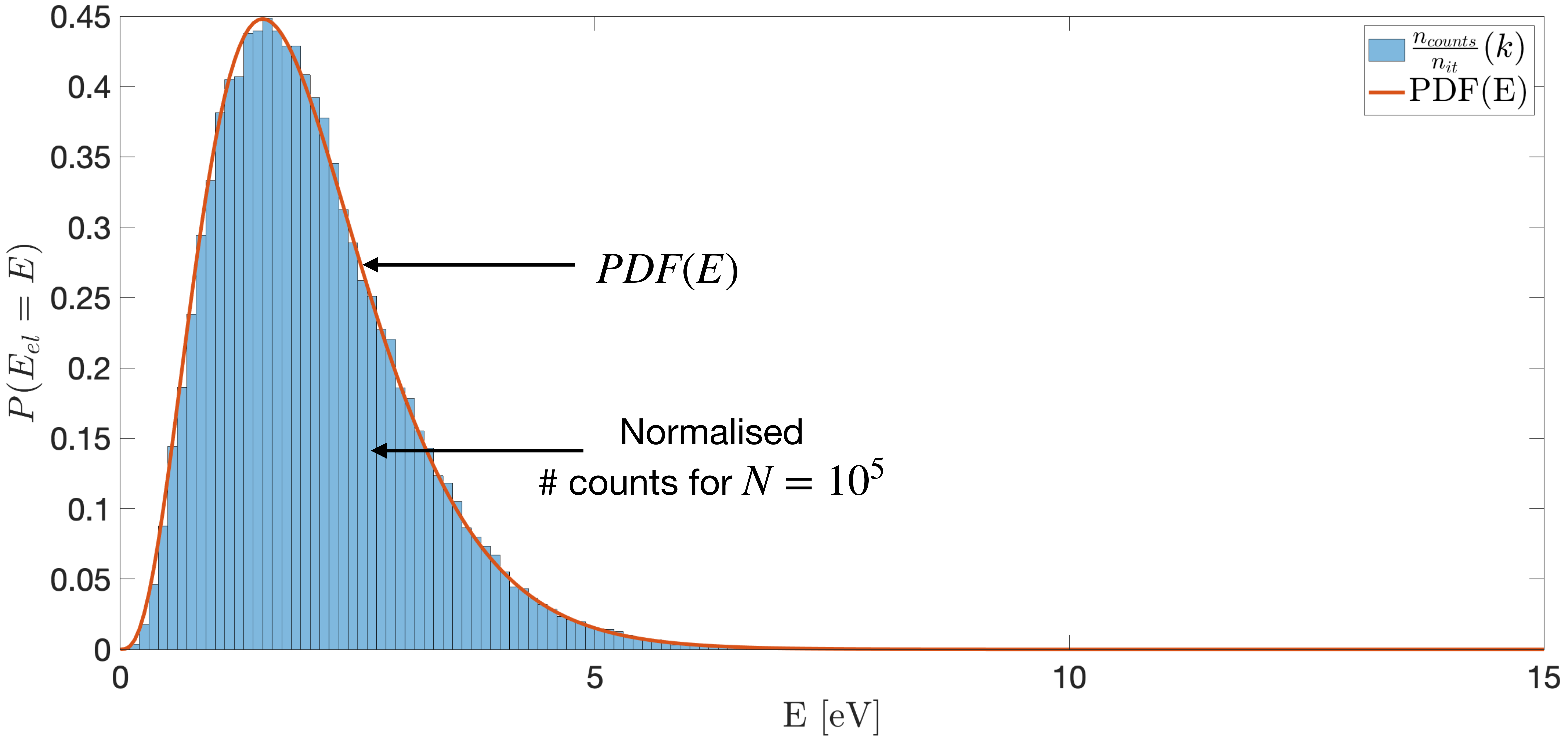
- Recall the two parameters: **shape** param. κ and **scale** param. θ s.t average $m = \kappa \cdot \theta$



- Chose $(\kappa, \theta) = (0.5, 4)$ so that peak prob closer to 2

Energy distribution of emitted electrons

- Procedure: generate a random number r uniformly in $[0,1[$
- Evaluate the CDF in the range $[0,15]$ eV with $N = 500$ points
- Take E as $E := \min_{\tilde{E}} | r - C(\tilde{E}) |$



Implementation - summary

- Identify each ion disappearing, evaluating the geometric weight (see [LB22])

Implementation - summary

- Identify each ion disappearing, evaluating the geometric weight (see [LB22])
- Energy E evaluated $\implies \gamma(E)$ can be used in the random generation of $k\ e^-$ for which add. memory has been allocated.

Implementation - summary

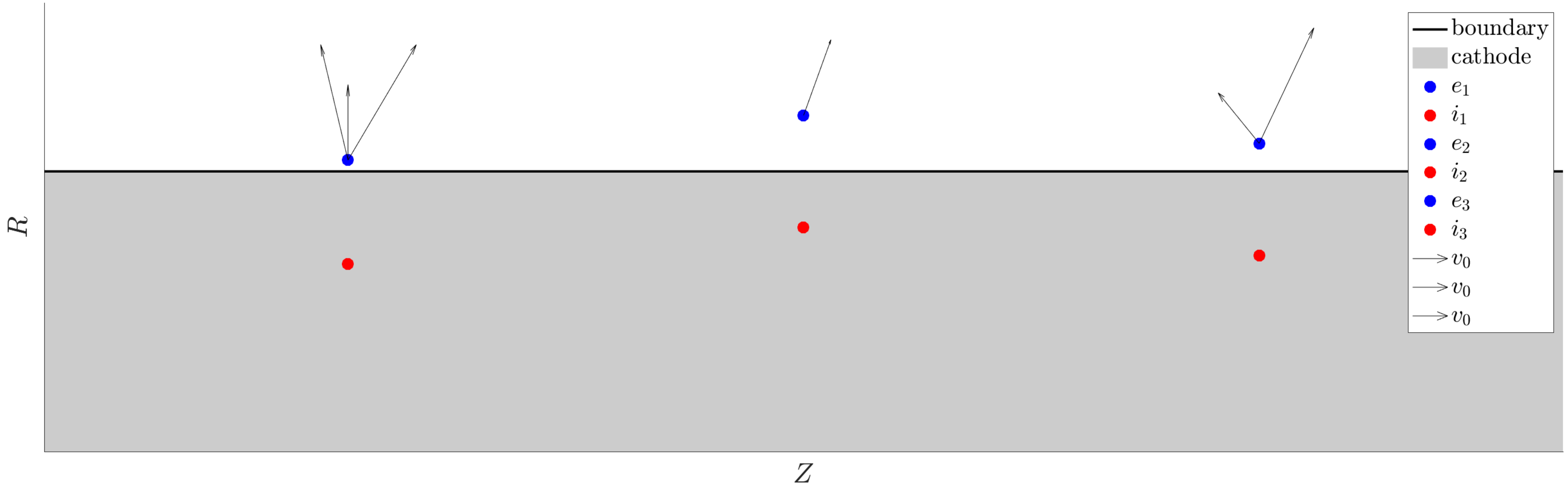
- Identify each ion disappearing, evaluating the geometric weight (see [LB22])
- Energy E evaluated $\implies \gamma(E)$ can be used in the random generation of $k\ e^-$ for which add. Memory has been allocated.
- e^- placed at the last position **inside** the domain + given an energy randomly gamma distr.

Implementation - summary

- Identify each ion disappearing, evaluating the geometric weight (see [LB22])
- Energy E evaluated $\implies \gamma(E)$ can be used in the random generation of $k\ e^-$ for which add. Memory has been allocated.
- e^- placed at the last position **inside** the domain + given an energy randomly gamma distr.
- Ion safely removed from the simulation

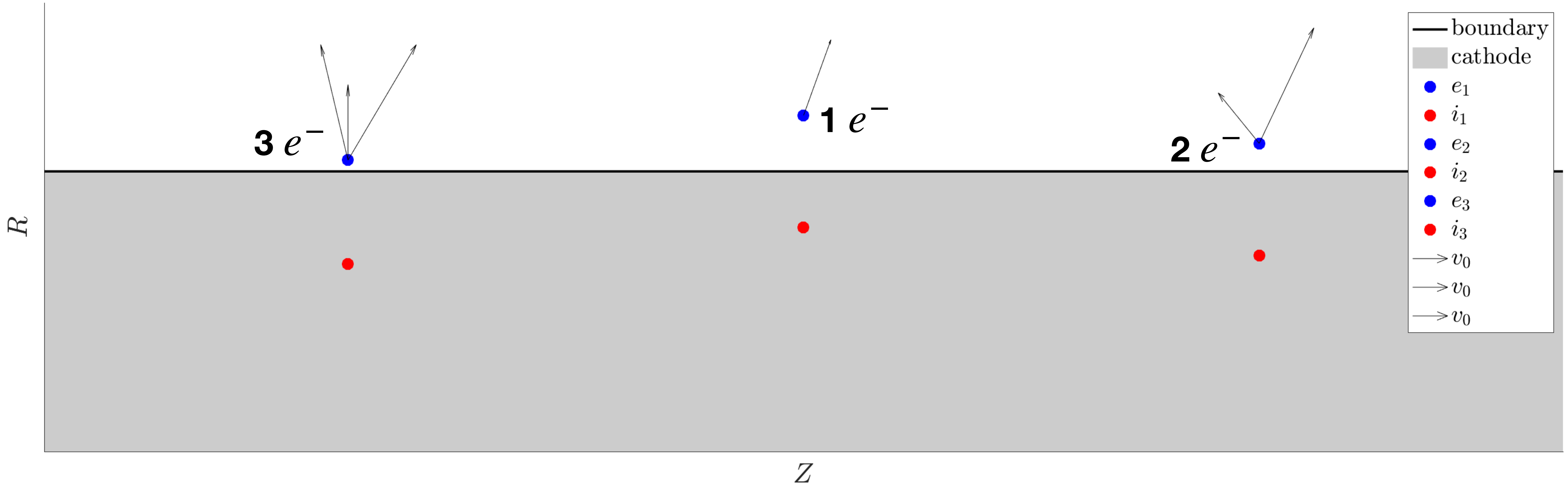
Implementation - summary

- Identify each ion disappearing, evaluating the geometric weight (see [LB22])
- Energy E evaluated $\Longrightarrow \gamma(E)$ can be used in the random generation of $k\ e^-$ for which add. Memory has been allocated.
- e^- placed at the last position **inside** the domain + given an energy randomly gamma distr.
- Ion safely removed from the simulation



Implementation - summary

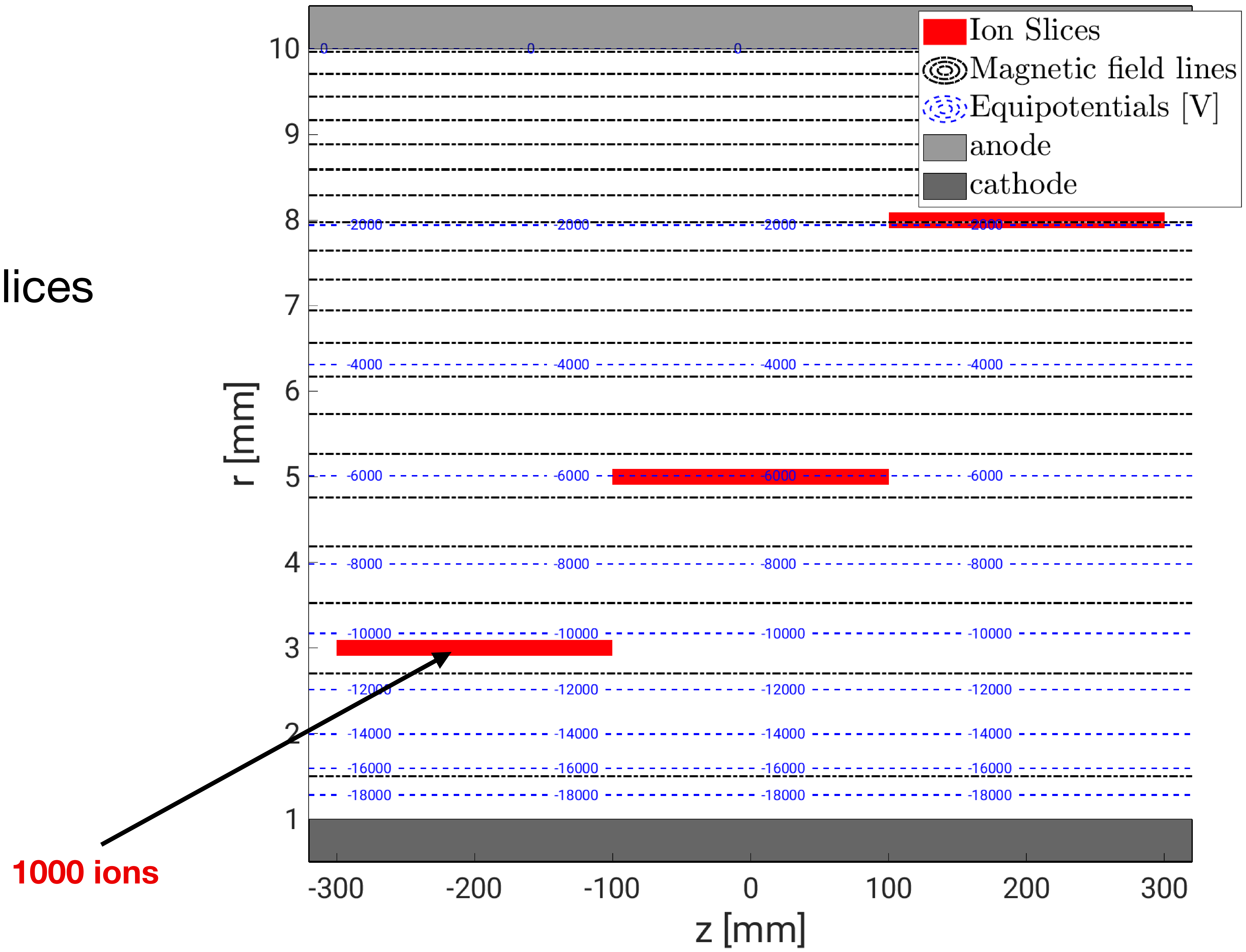
- Identify each ion disappearing, evaluating the geometric weight (see [LB22])
- Energy E evaluated $\Longrightarrow \gamma(E)$ can be used in the random generation of $k\ e^-$ for which add. Memory has been allocated.
- e^- placed at the last position **inside** the domain + given an energy randomly gamma distr.
- Ion safely removed from the simulation



EPFL

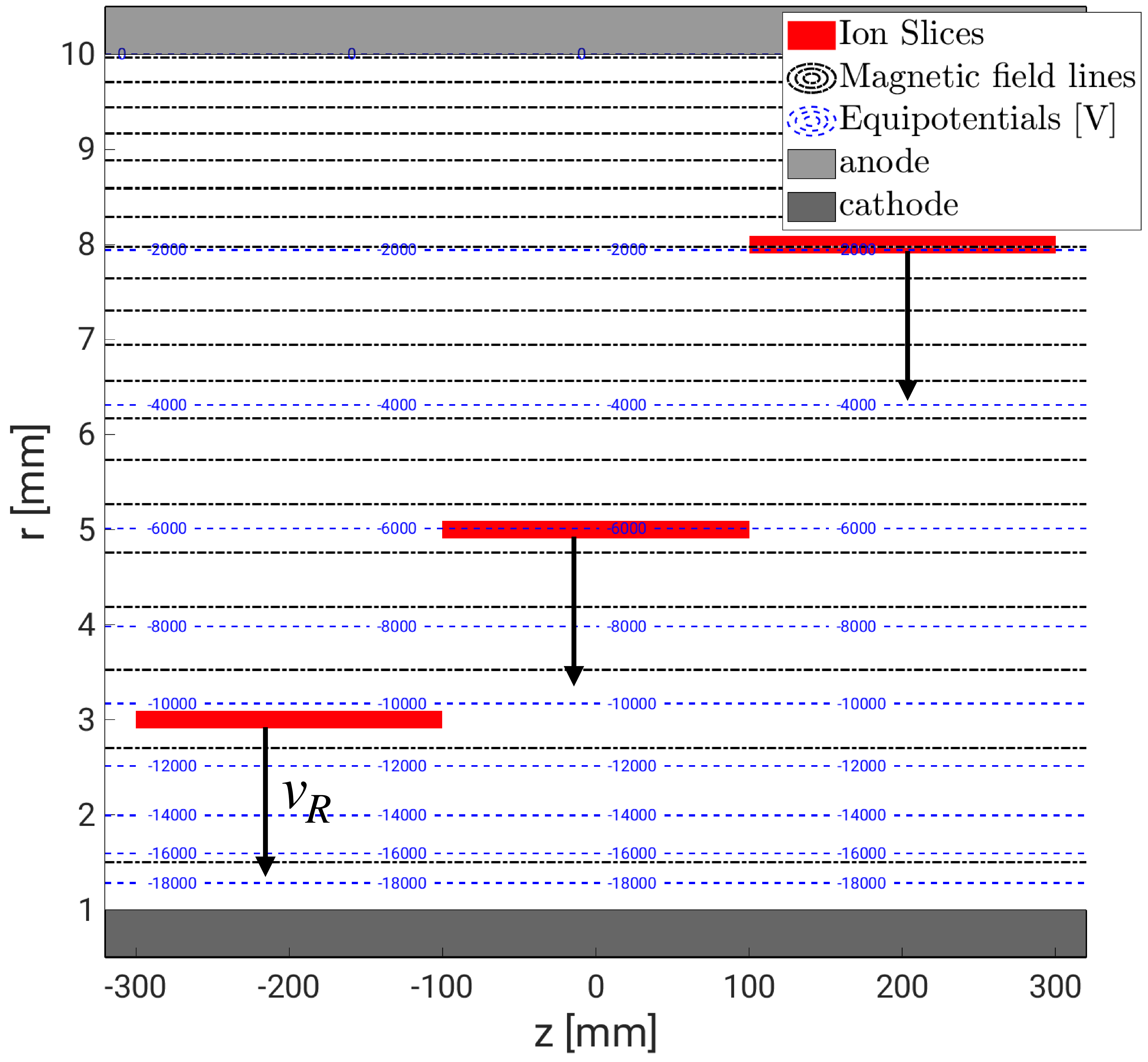
Results - Testing the module (statistics)

- Initial configuration: 3 horizontal slices of H_2^+ ions - SS, Al and Cu.
- $\Delta\Phi = 20$ kV. $B = 0.21$ T.
- $r_a = 10^{-3}$ m , $r_b = 10^{-2}$ m

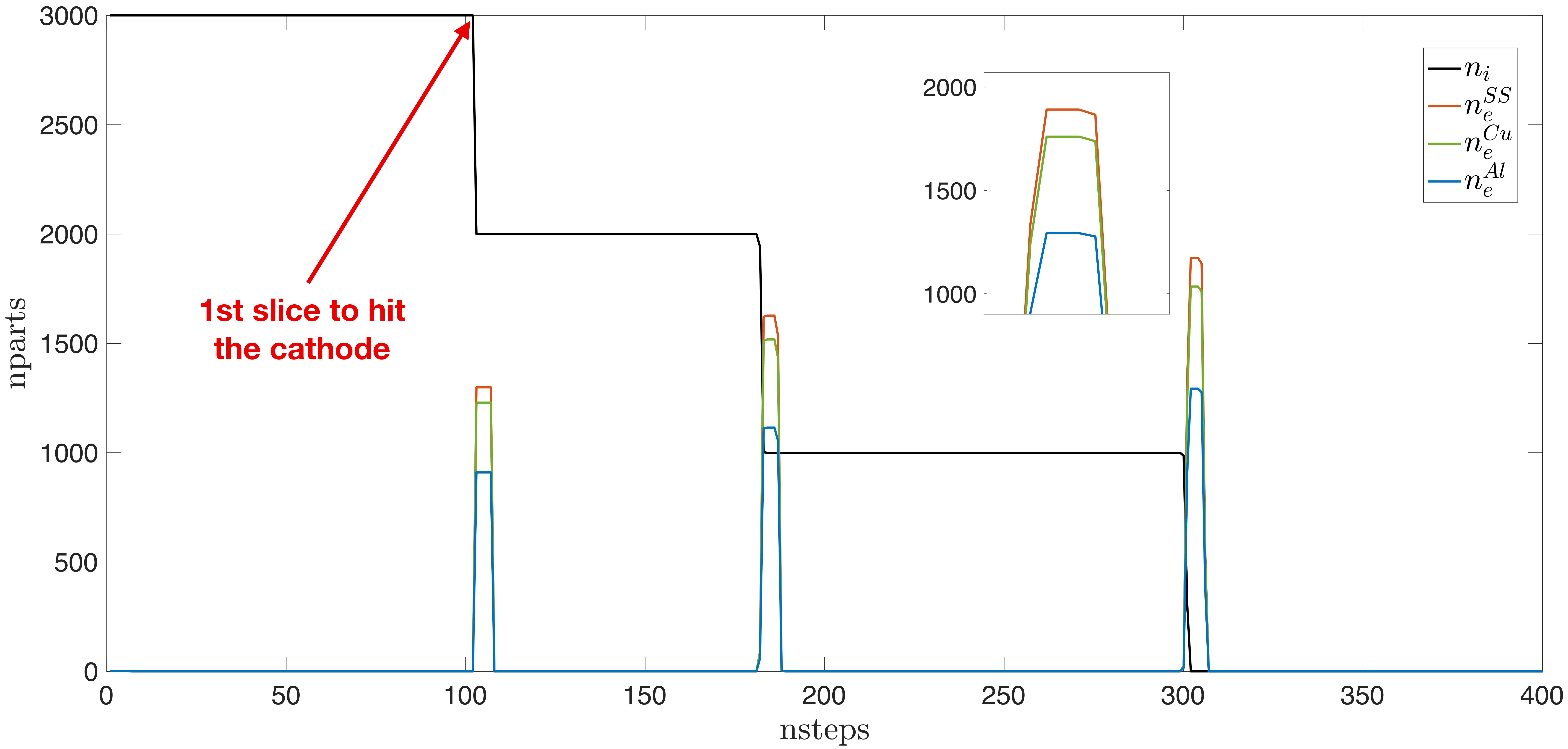


Results - Testing the module (statistics)

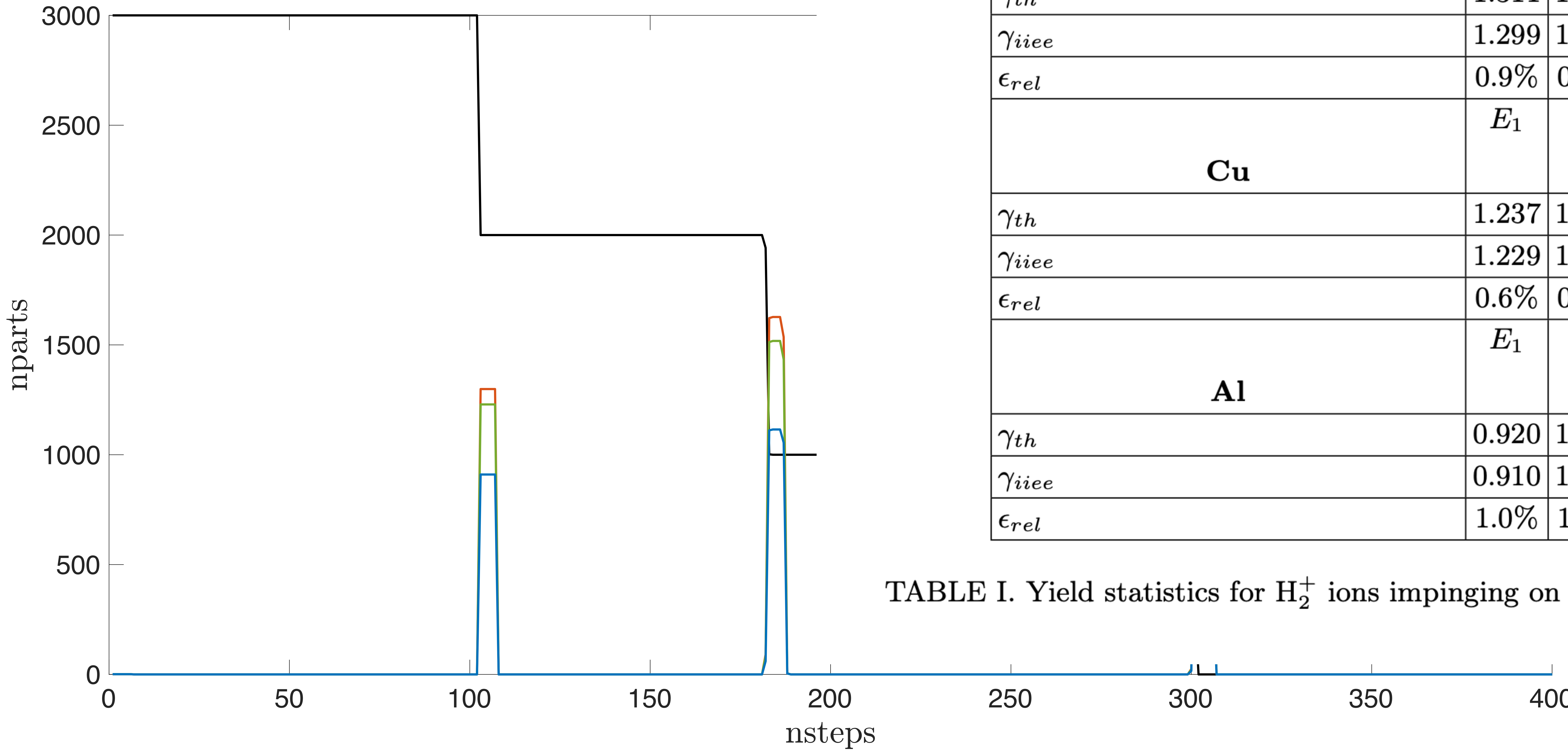
- Initial configuration: 3 horizontal slices of H_2^+ ions - SS, Al and Cu.
- $\Delta\Phi = 20$ kV. $B = 0.21$ T.
- $r_a = 10^{-3}$ m , $r_b = 10^{-2}$ m



Testing the module (statistics)



Testing the module (statistics)

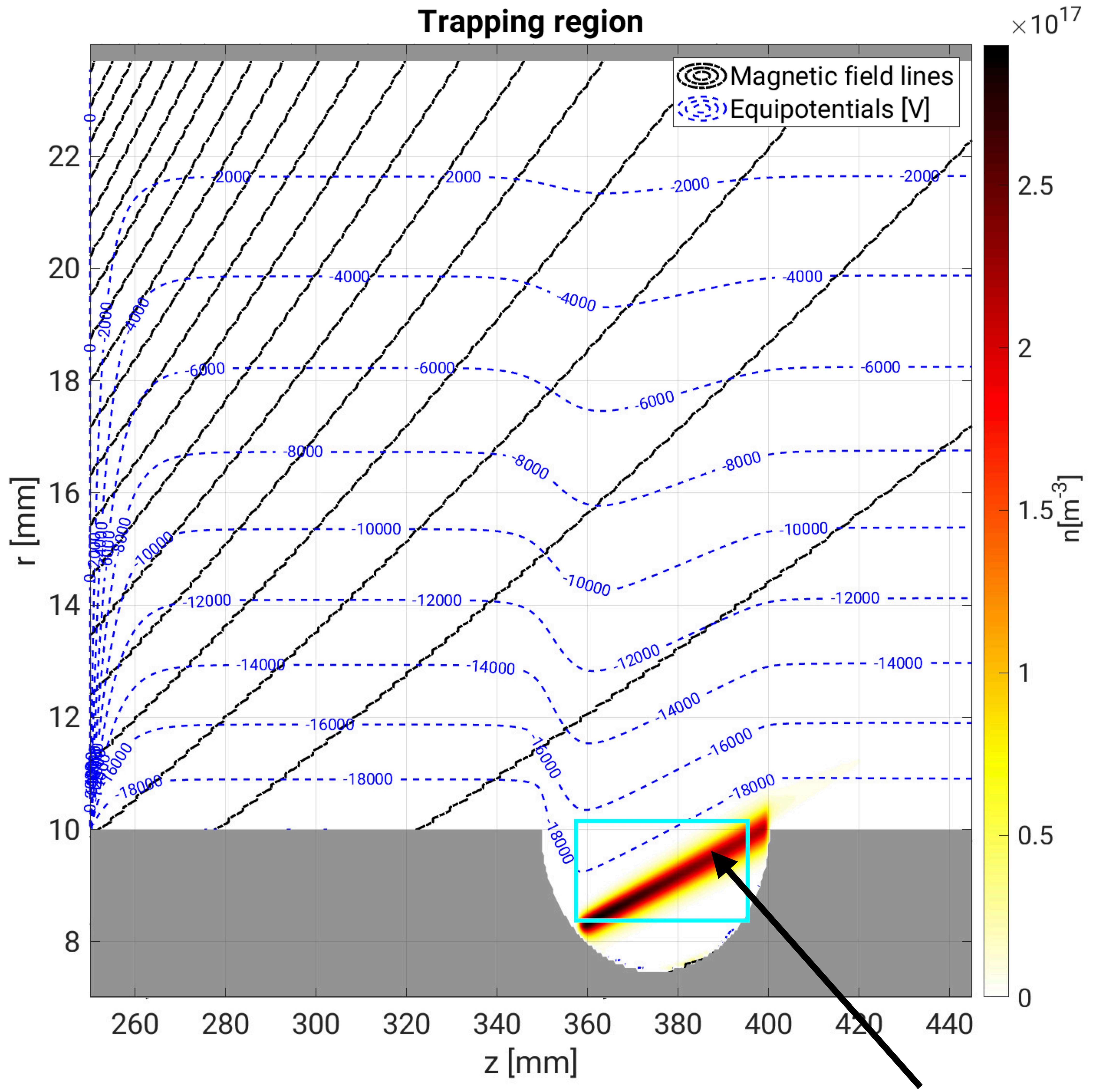


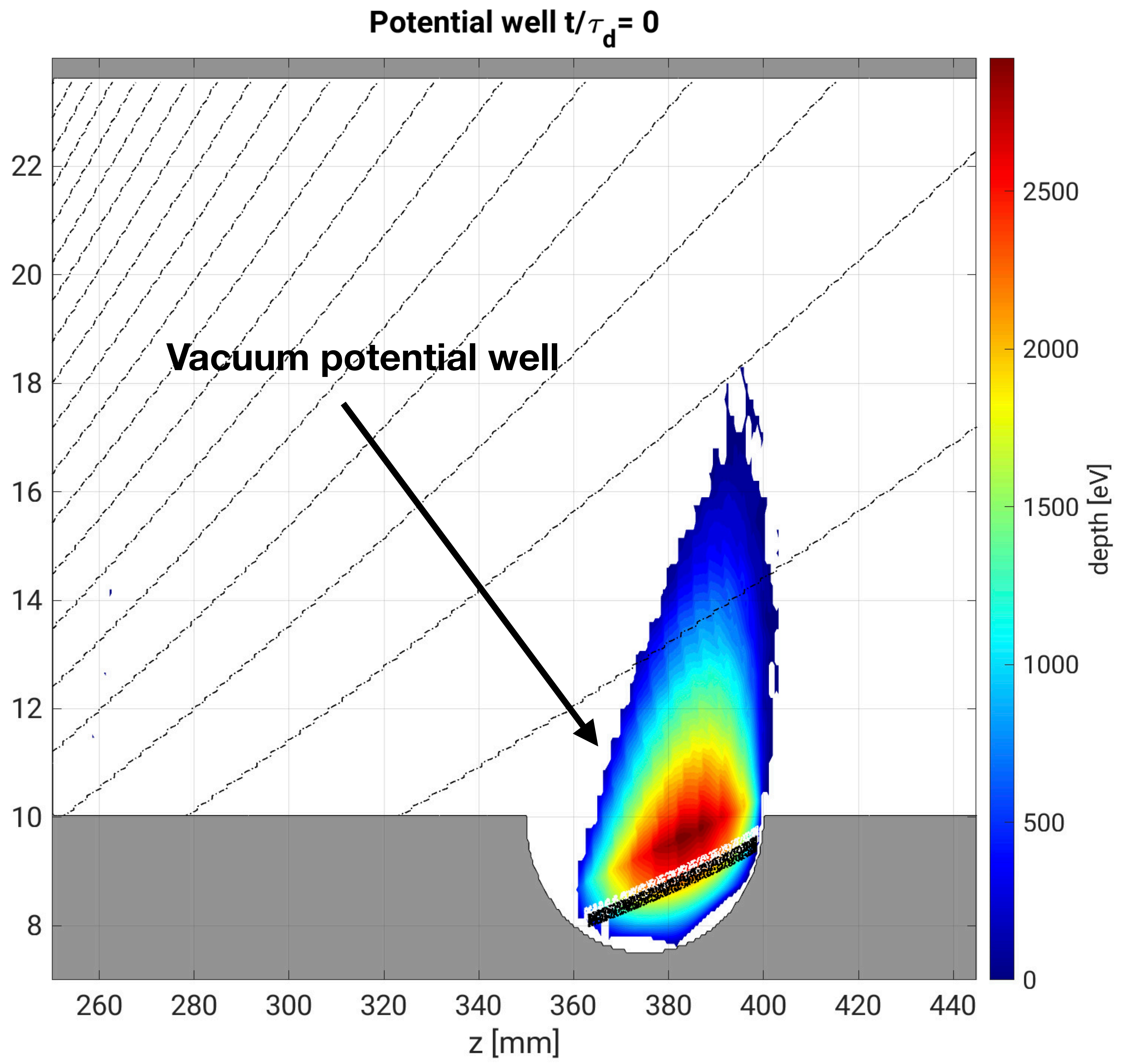
	E_1	E_2	E_3
^{304}SS			
γ_{th}	1.311	1.623	1.870
γ_{iiee}	1.299	1.627	1.891
ϵ_{rel}	0.9%	0.2%	1.1%
Cu	E_1	E_2	E_3
γ_{th}	1.237	1.522	1.746
γ_{iiee}	1.229	1.518	1.760
ϵ_{rel}	0.6%	0.3%	0.8%
Al	E_1	E_2	E_3
γ_{th}	0.920	1.133	1.297
γ_{iiee}	0.910	1.115	1.293
ϵ_{rel}	1.0%	1.6%	0.3%

TABLE I. Yield statistics for H_2^+ ions impinging on the three materials

EPFL

Testing the module (trapping)

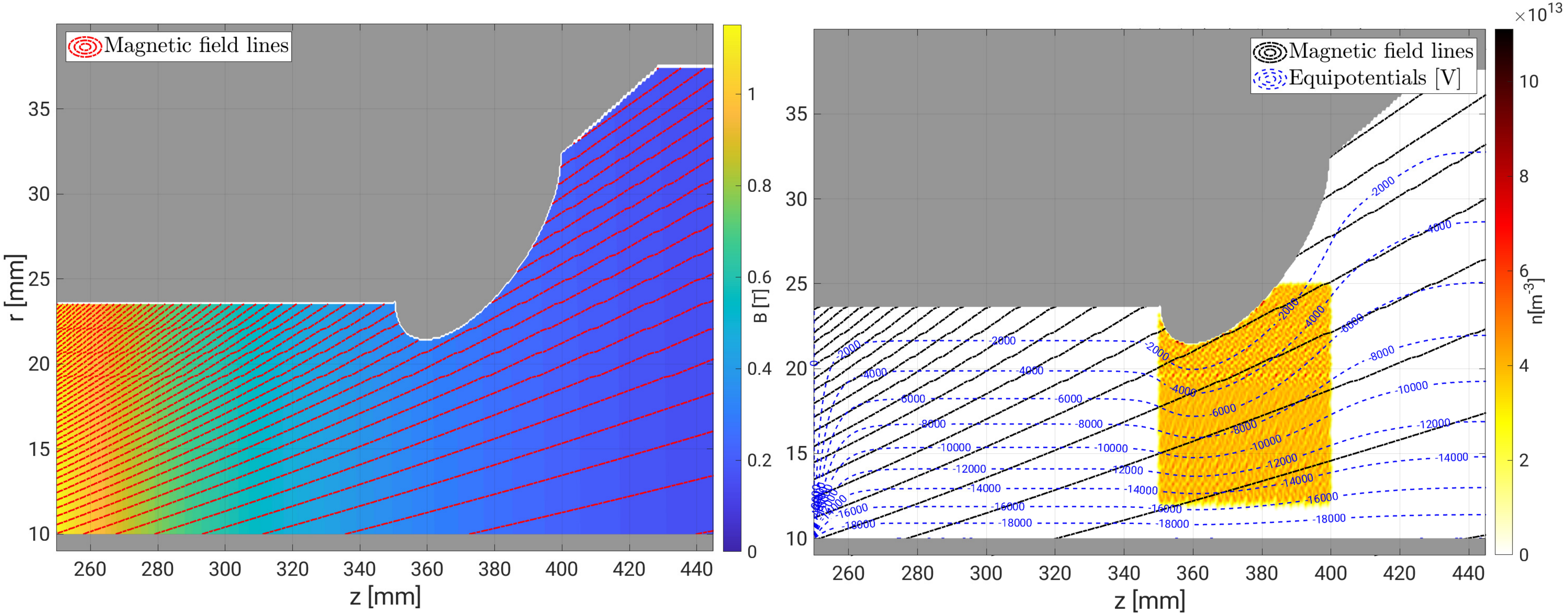




Cloud to emphasize trapping region

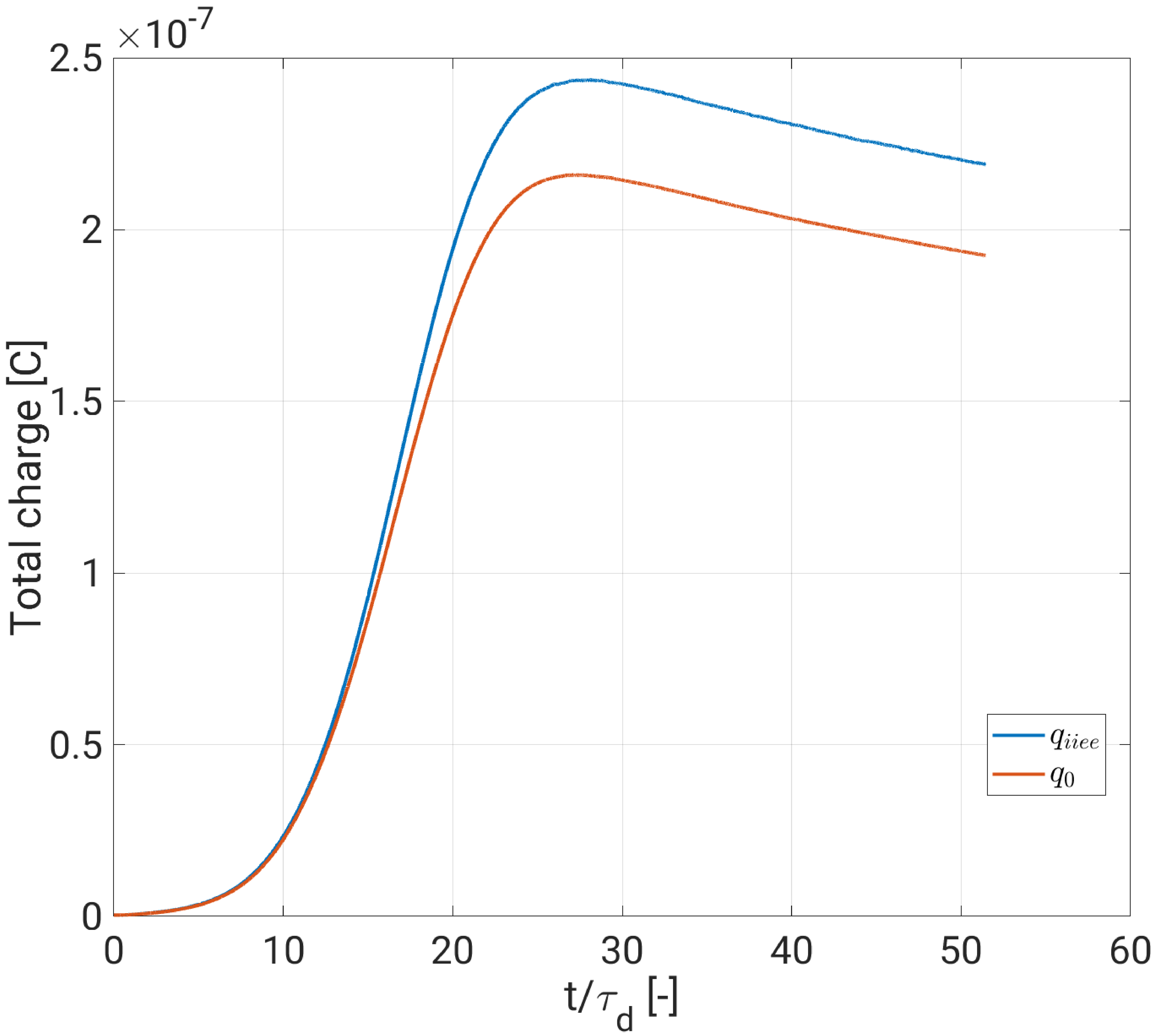
Cloud formation and dynamics: The case TREX (slanted)

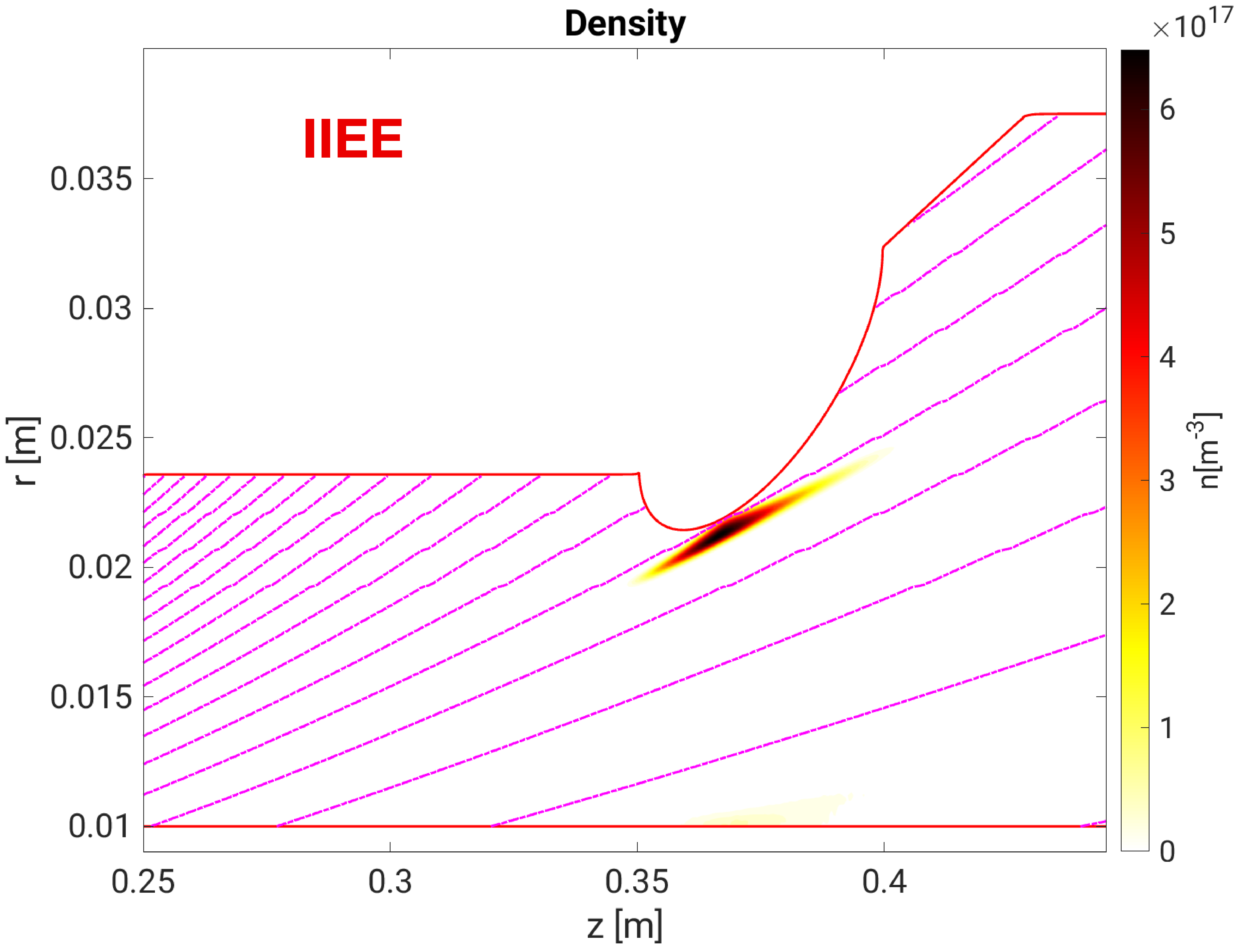
- **Physical/numerical parameters**
  - $\Delta\Phi = 20$ kV
  - Neutral pressure $P_n \sim 2 \cdot 10^{-2}$ mbar



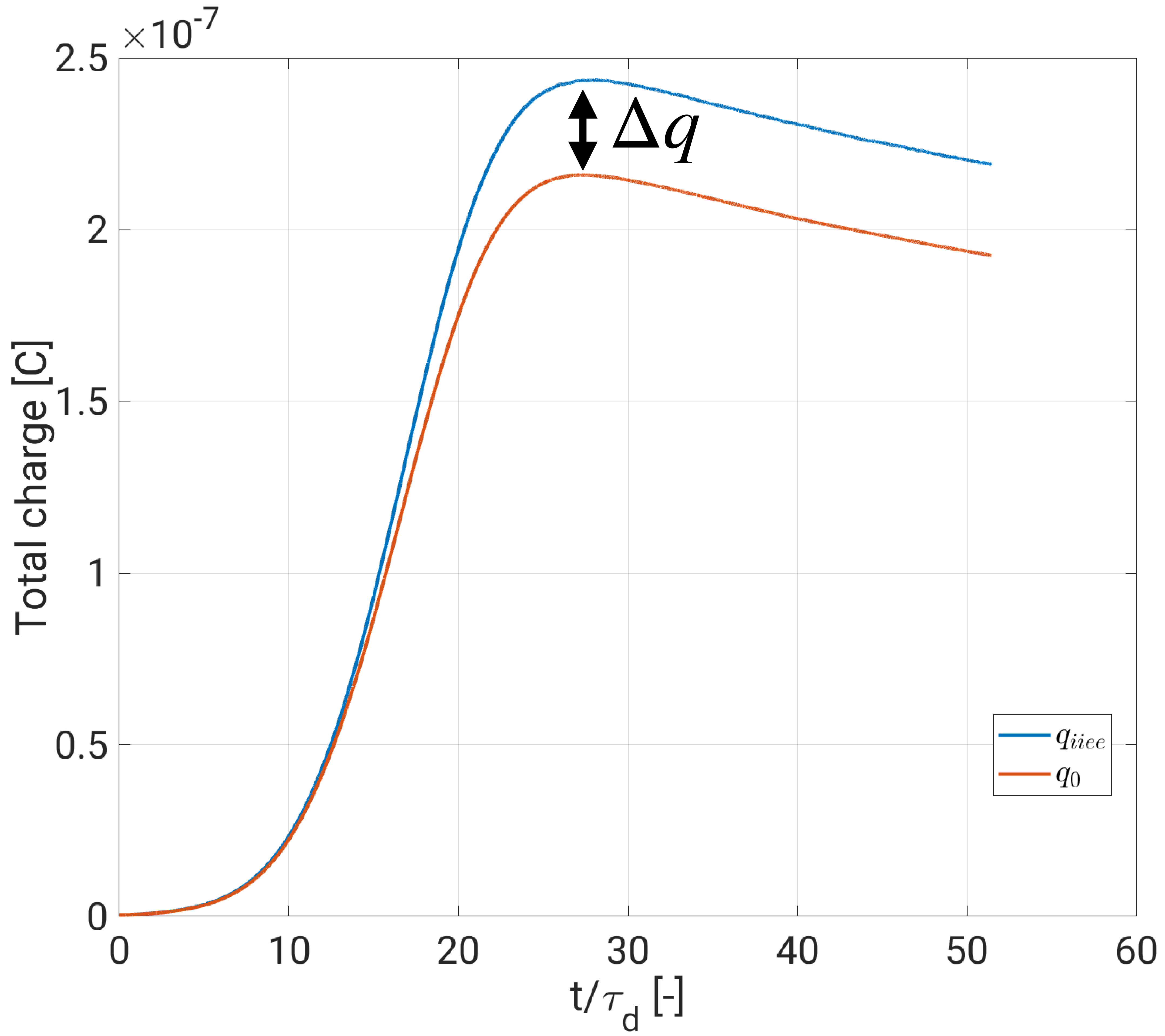
Swiss Plasma Center

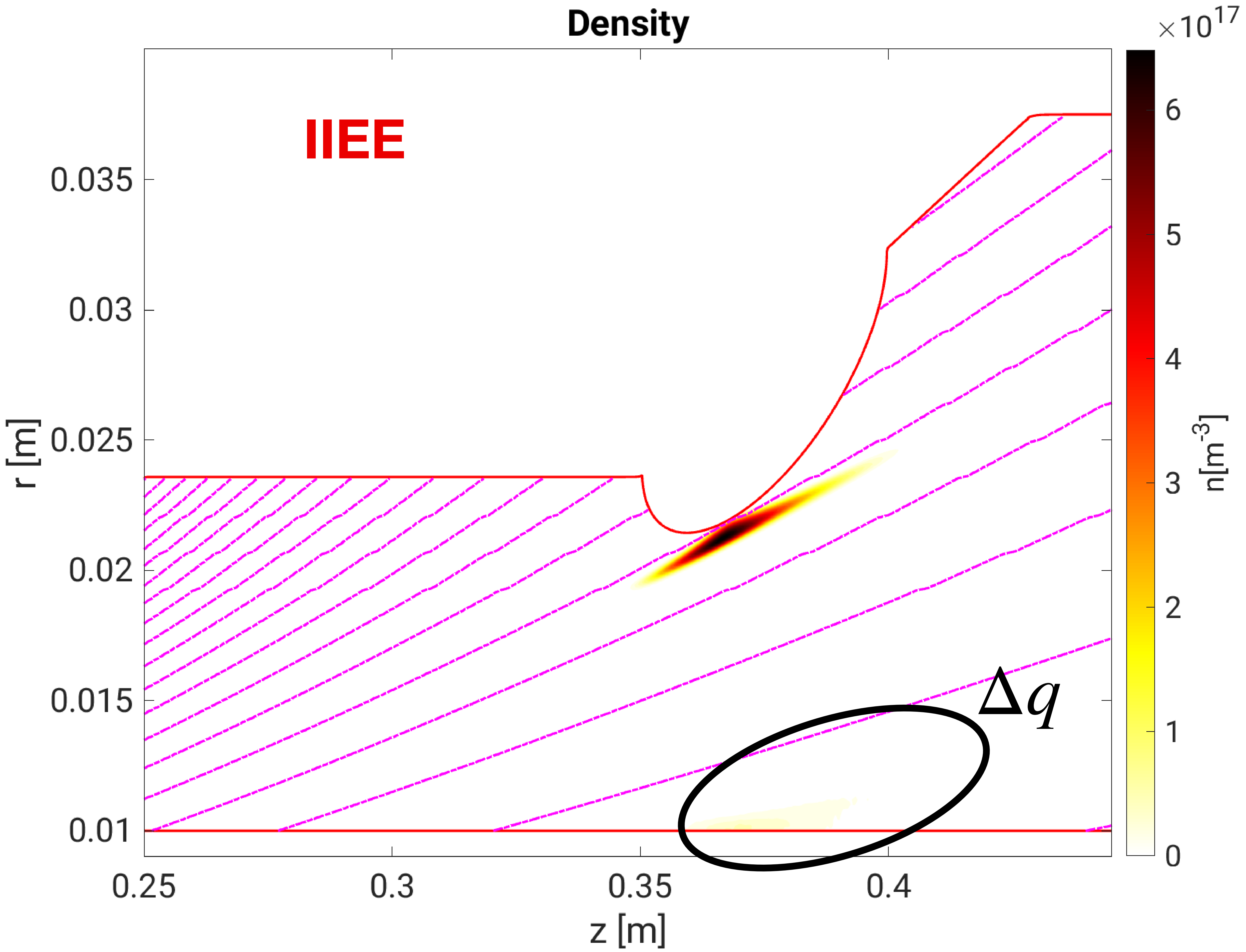
Cloud formation and dynamics: TREX slanted geometry





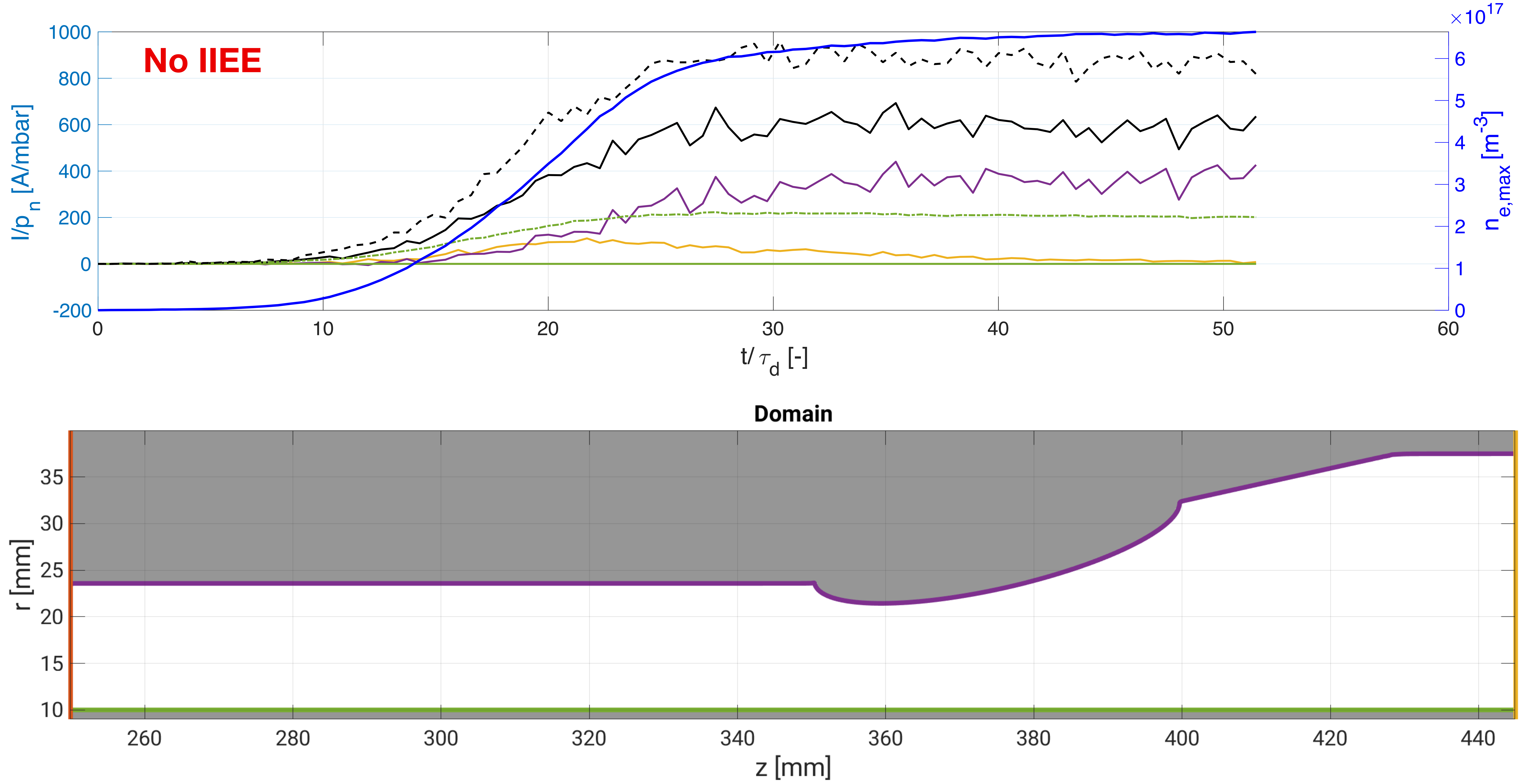
Cloud formation and dynamics: TREX slanted geometry





Swiss Plasma Center

TREX slanted - collected currents

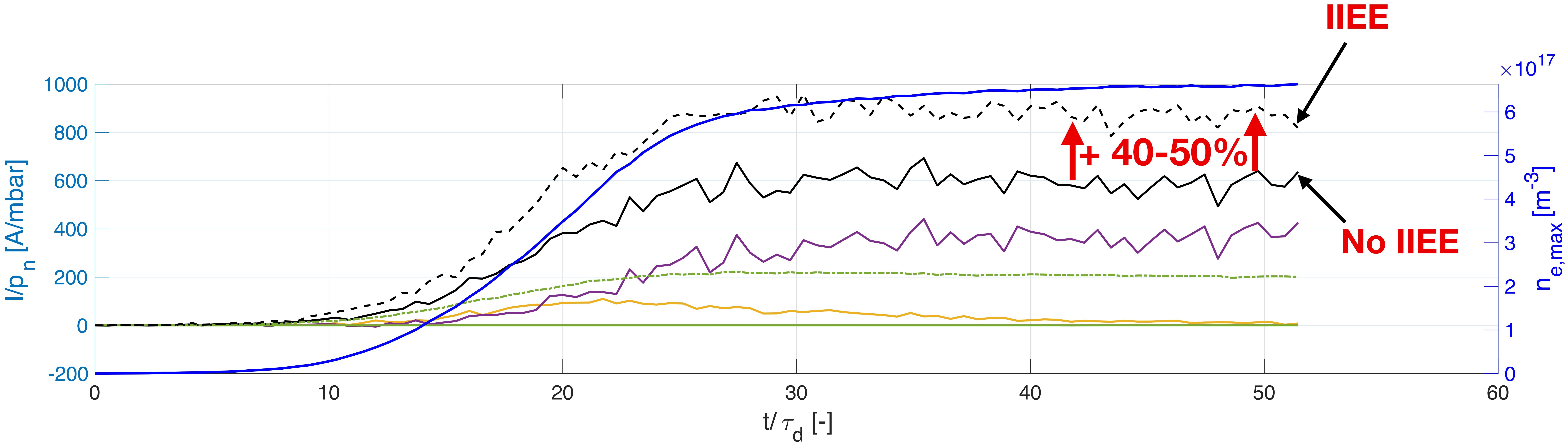


TREX slanted - collected currents

Center

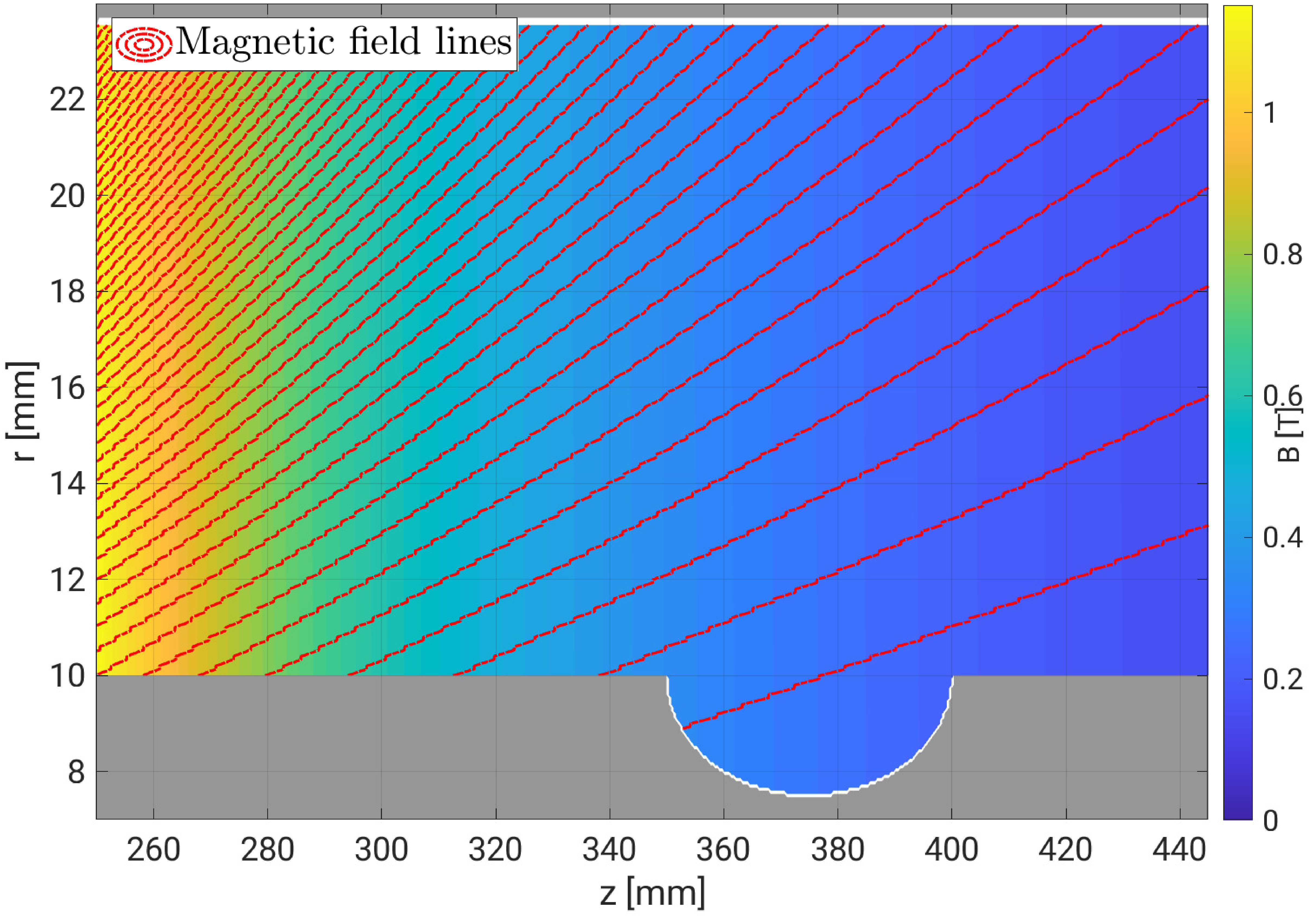
TREX slanted - SUMMARY

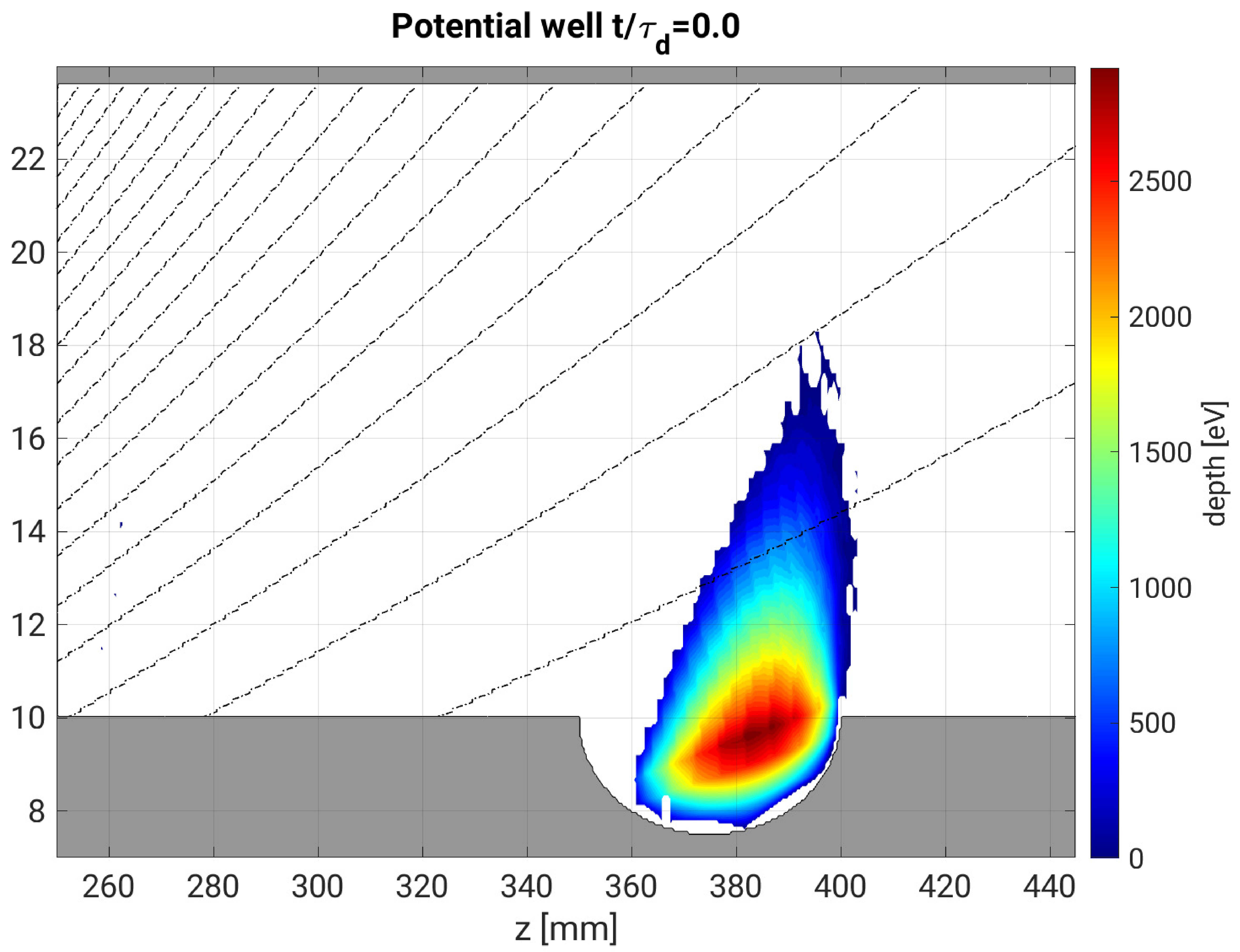
- Same cloud **densities**
- Same cloud **formation times**
- Current increased by ~ **40-50%**



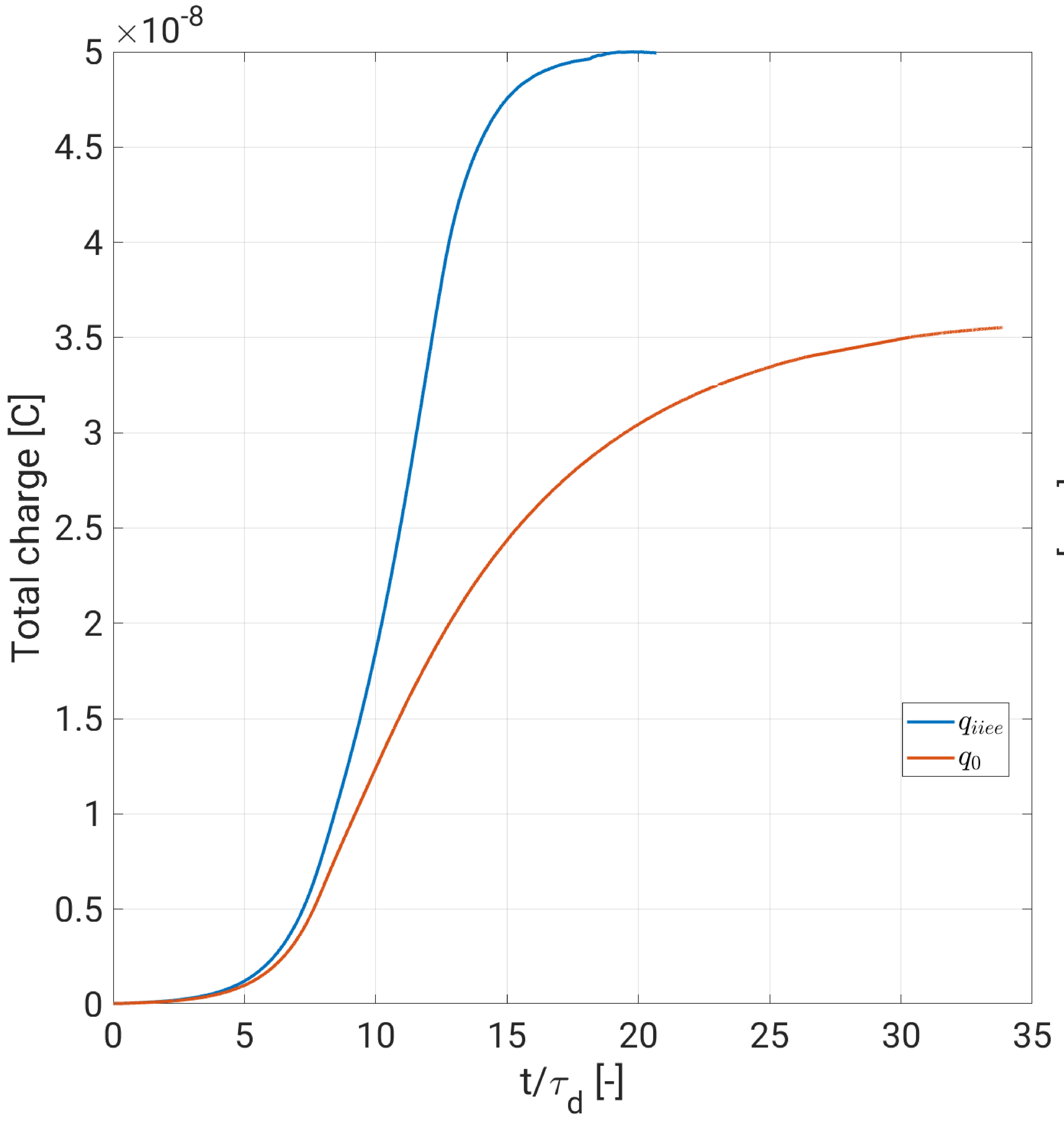
EPFL Cloud formation and dynamics: TREX extrude geometry

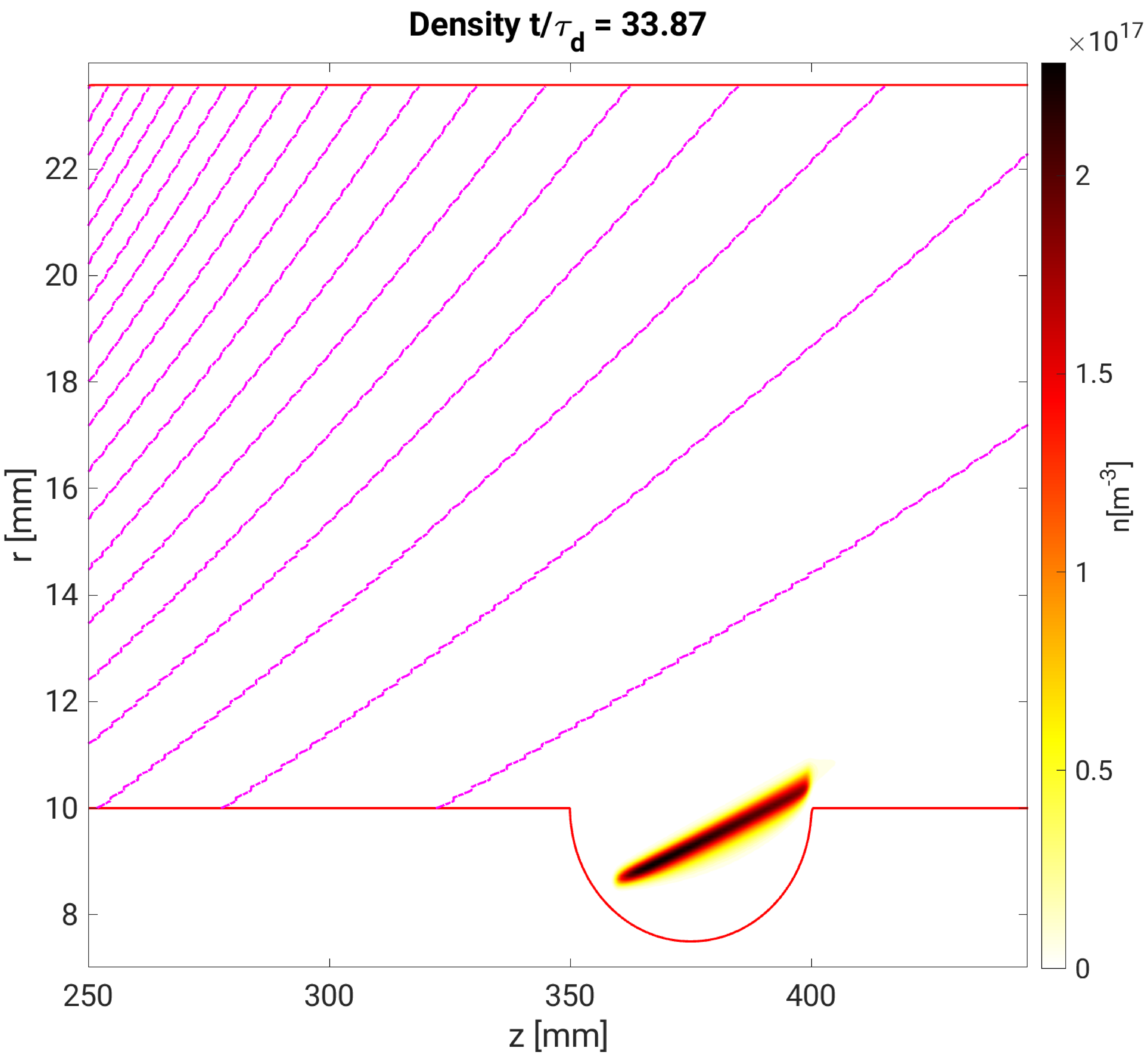
- **Physical/numerical parameters**
  - $\Delta\Phi = 20$ kV
  - Neutral pressure $P_n \sim 1 \cdot 10^{-2}$ mbar





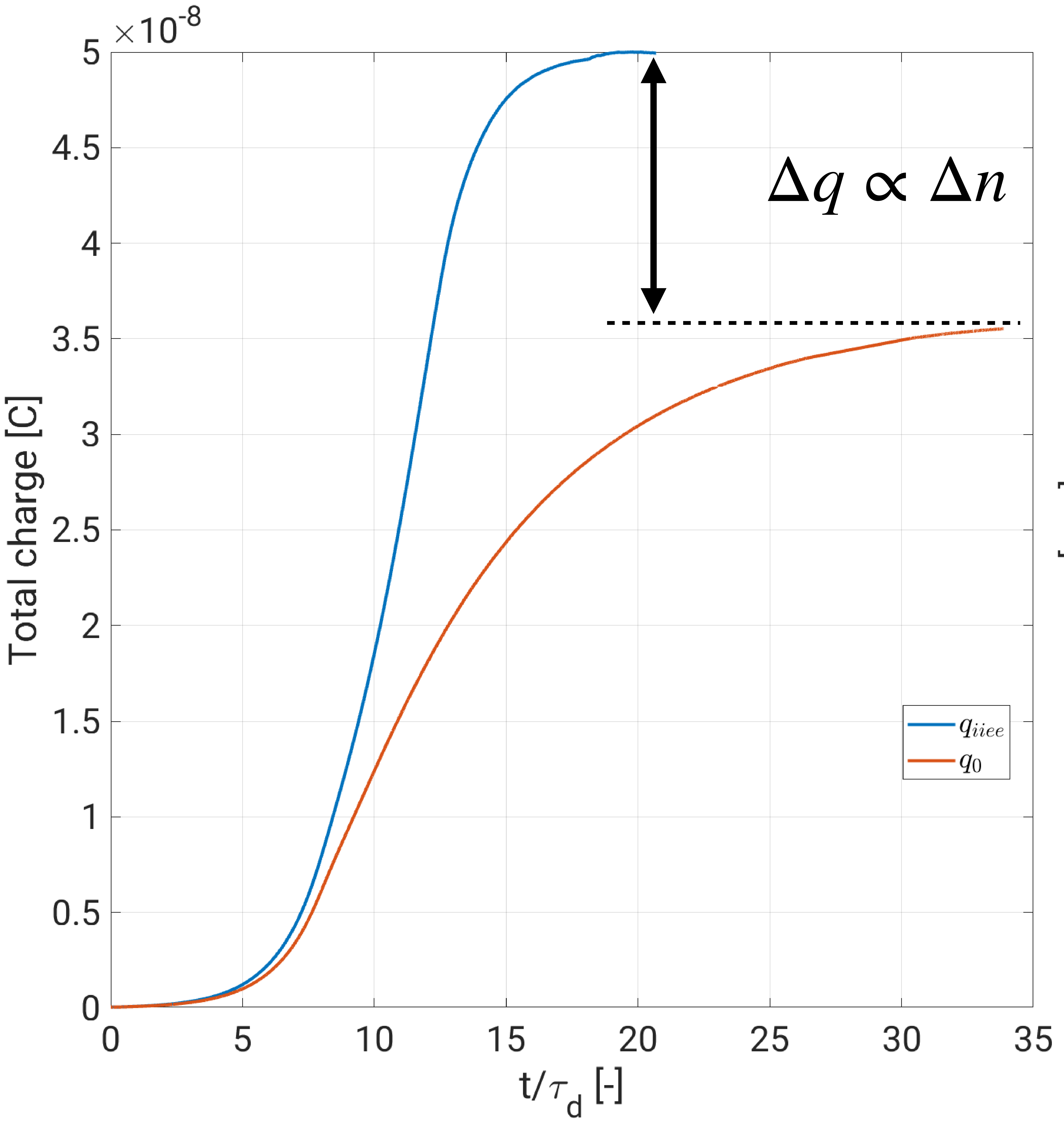
TREX extrude geometry - total charge and cloud formation

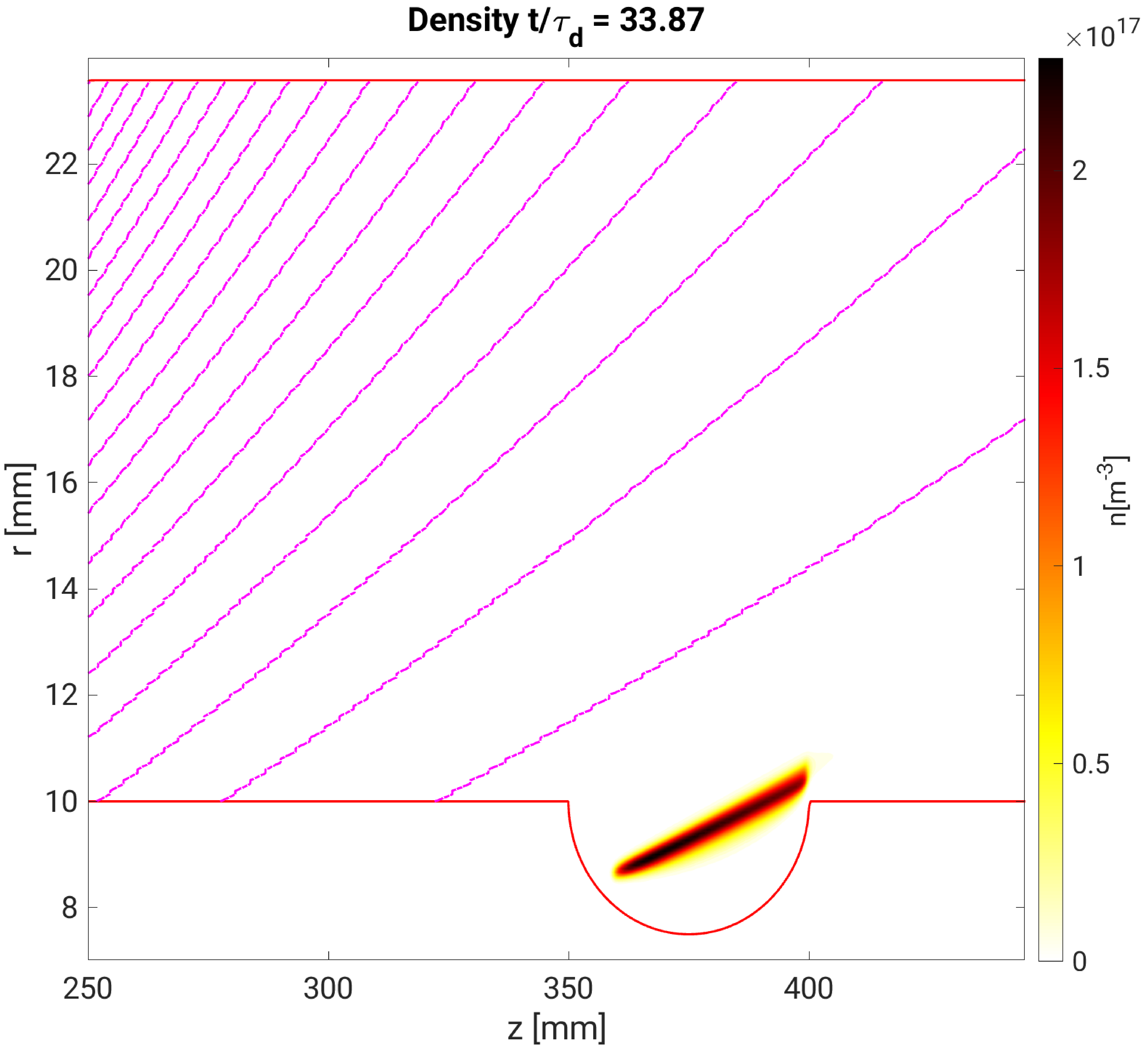




Plasma Center

TREX extrude geometry - total charge and cloud formation

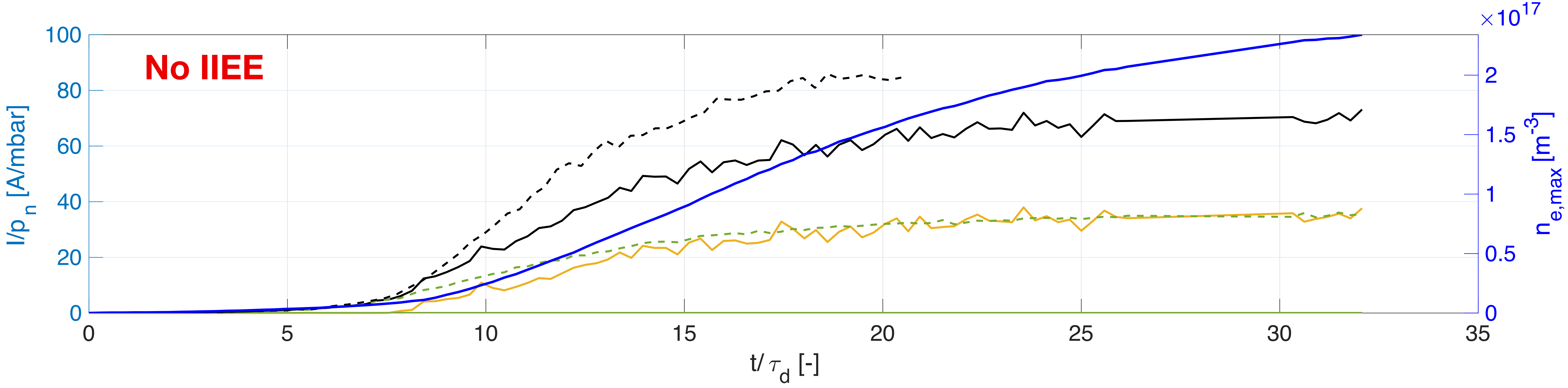


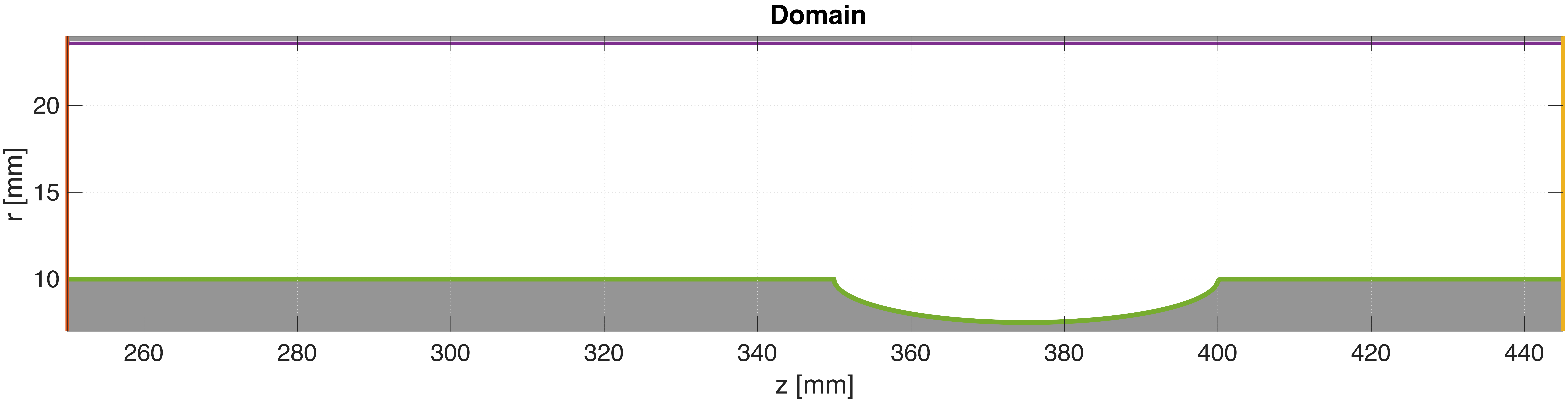


TREX extrude geometry - total charge and cloud formation

Swiss Plasma Center

TREX extrude - collected currents



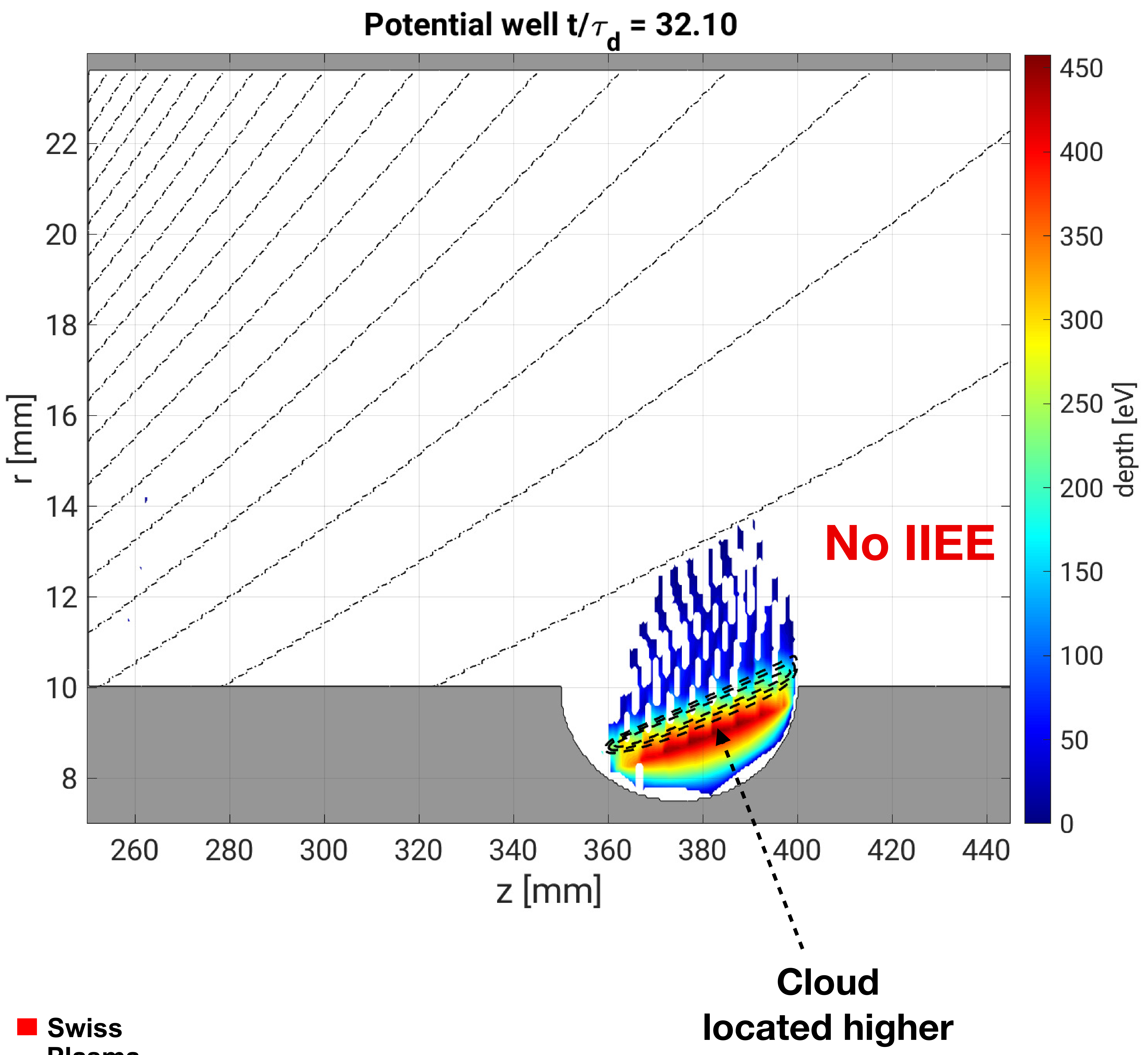


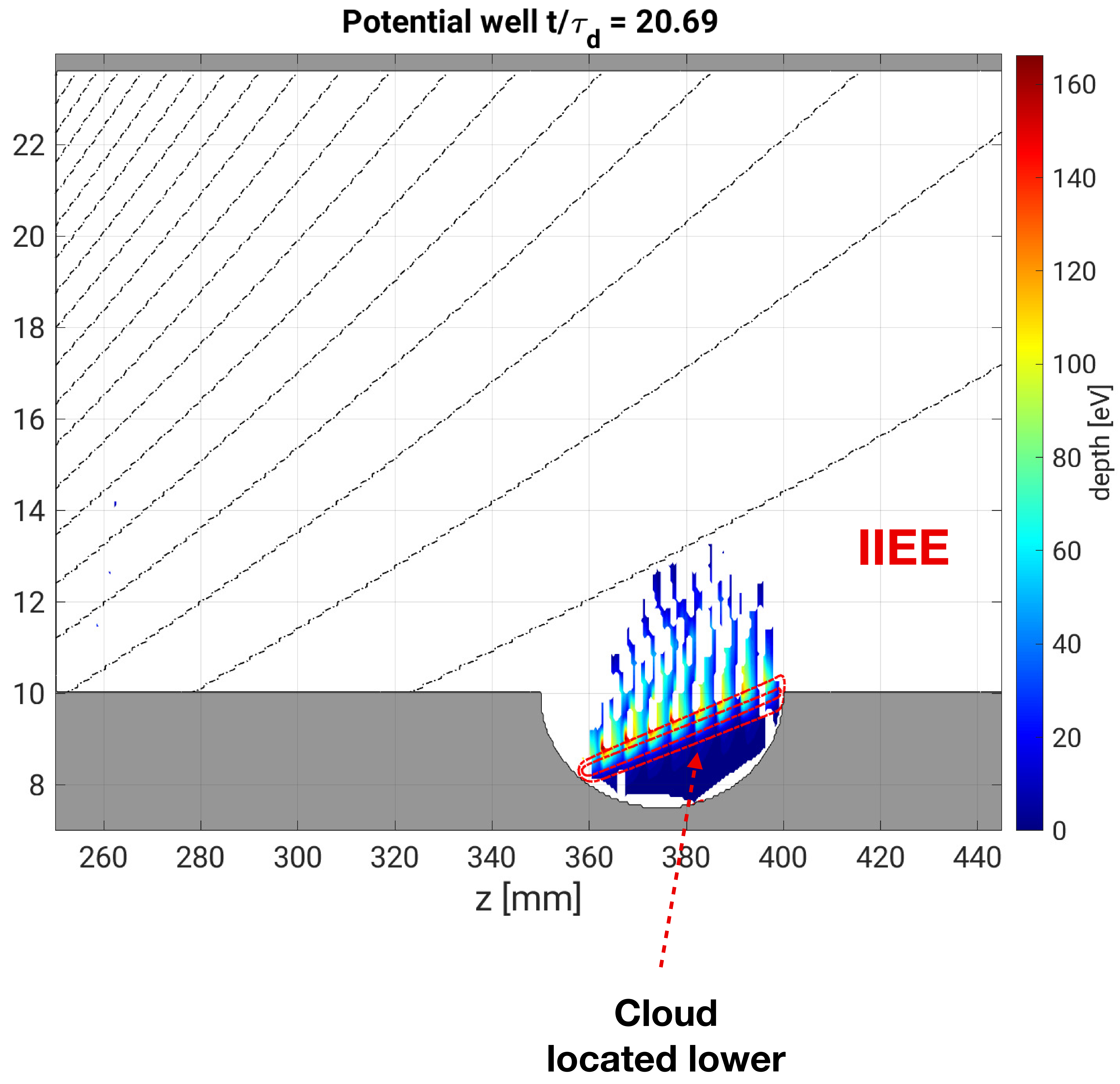
Plasma Center

S. Guinchard

TREX extrude - collected currents

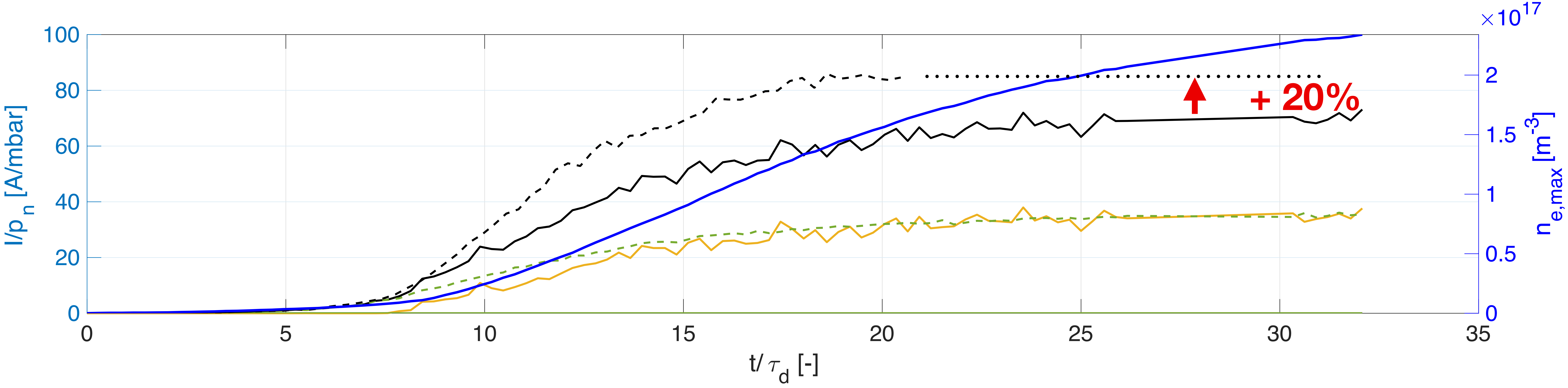
TREX extrude - potential wells and cloud contours





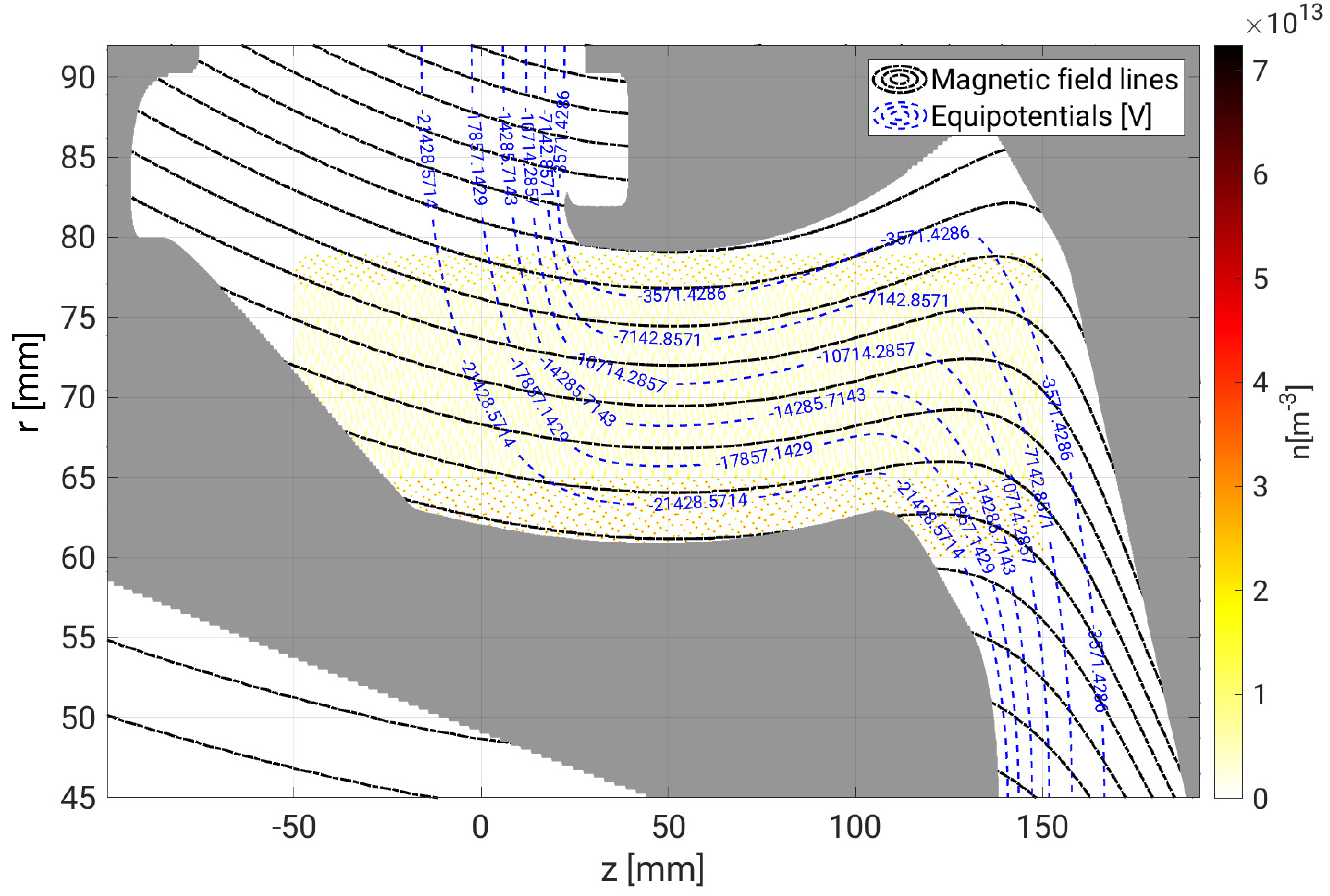
TREX extrude - SUMMARY

- Density increased by IIEE of 20%
- Cloud forming about 3 times faster
- Current increased by ∼ **20%**
- Cloud radially lower: well fills by bottom (IIE)

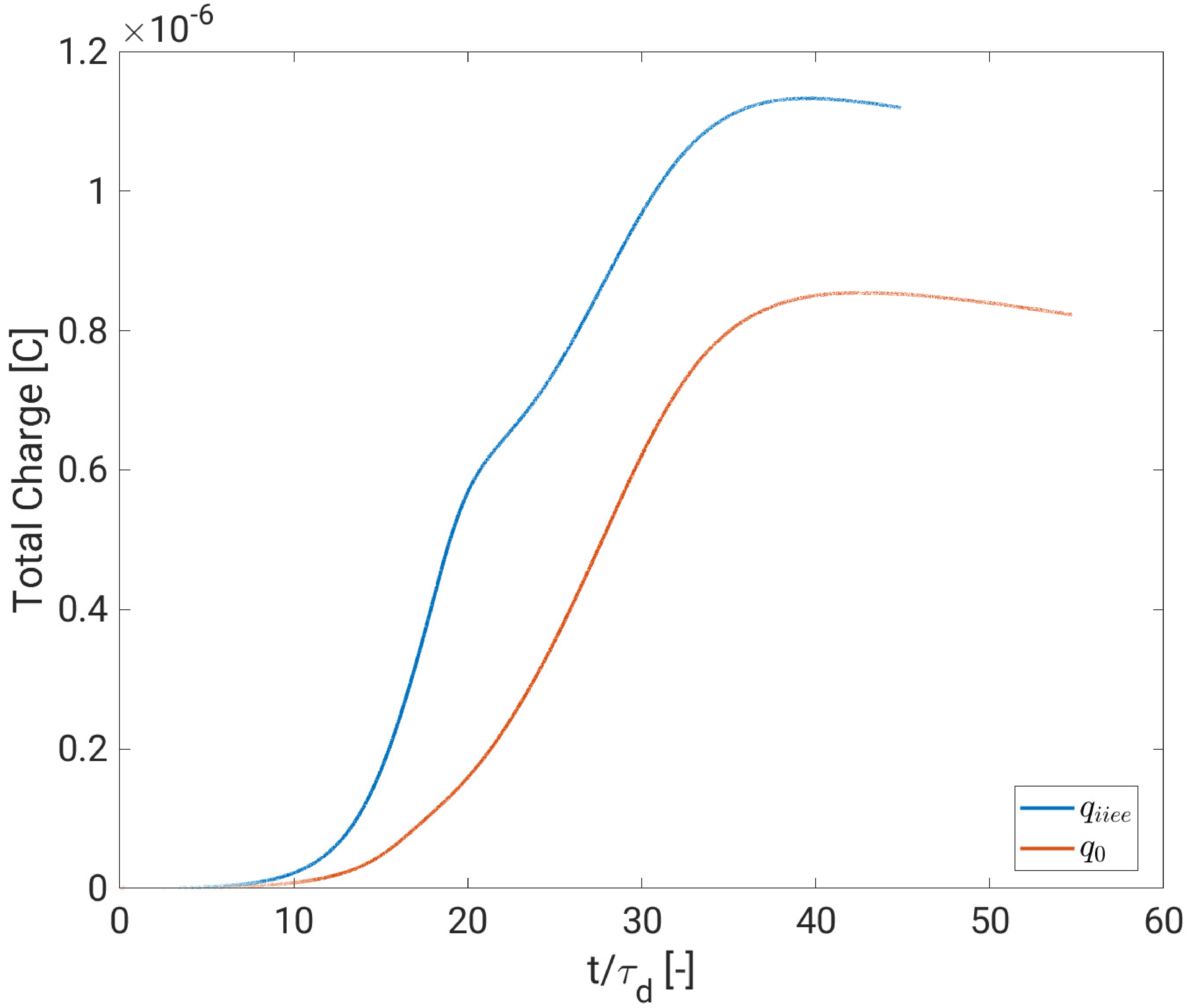


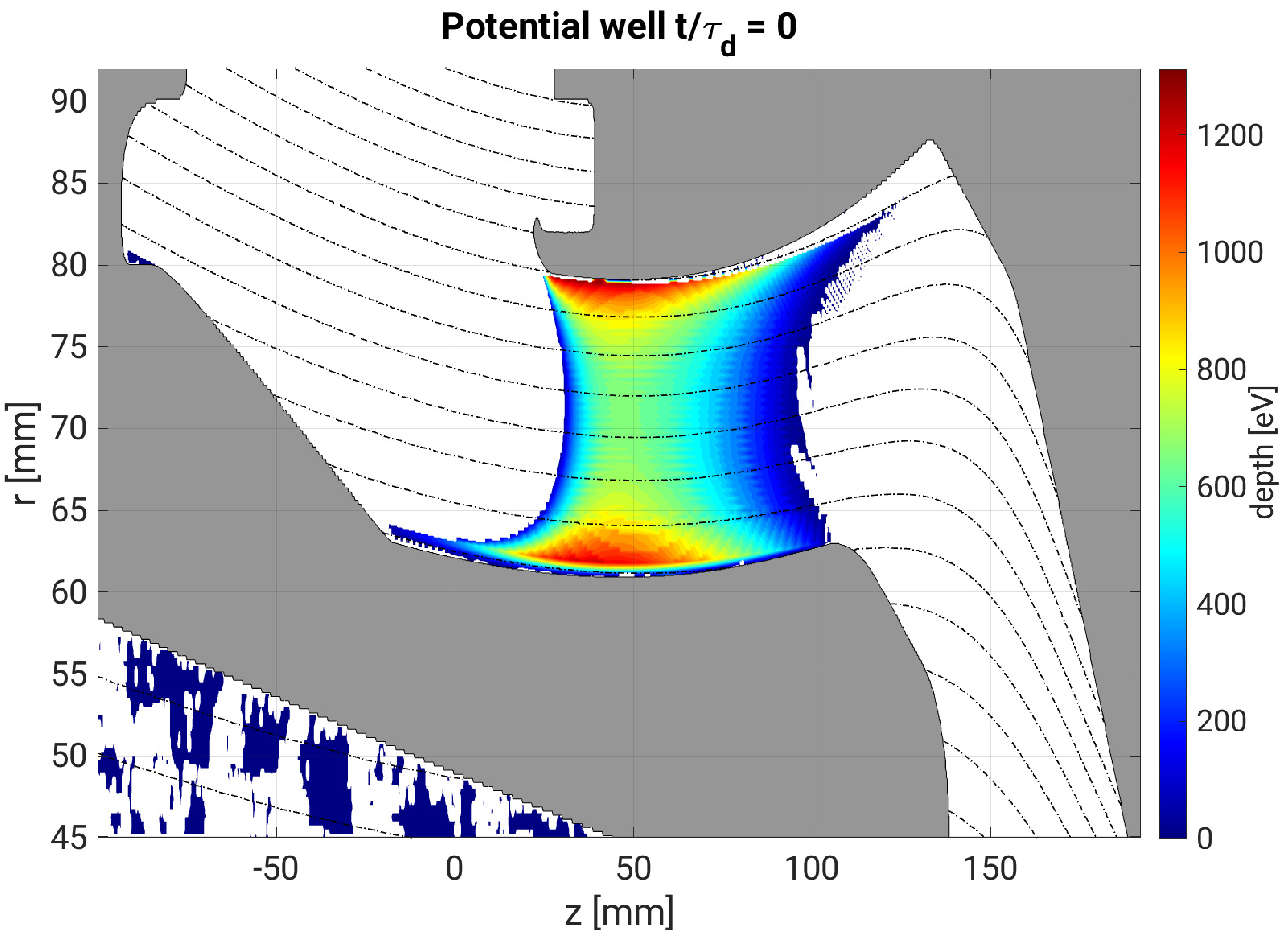
Gt-170 refurbished MIG

- **Physical parameters**
  - $\Delta\Phi = 25$ kV
  - Neutral pressure $P_n \sim 2 \cdot 10^{-2}$ mbar
  - 2 potential wells formed by equipotentials and magnetic field lines

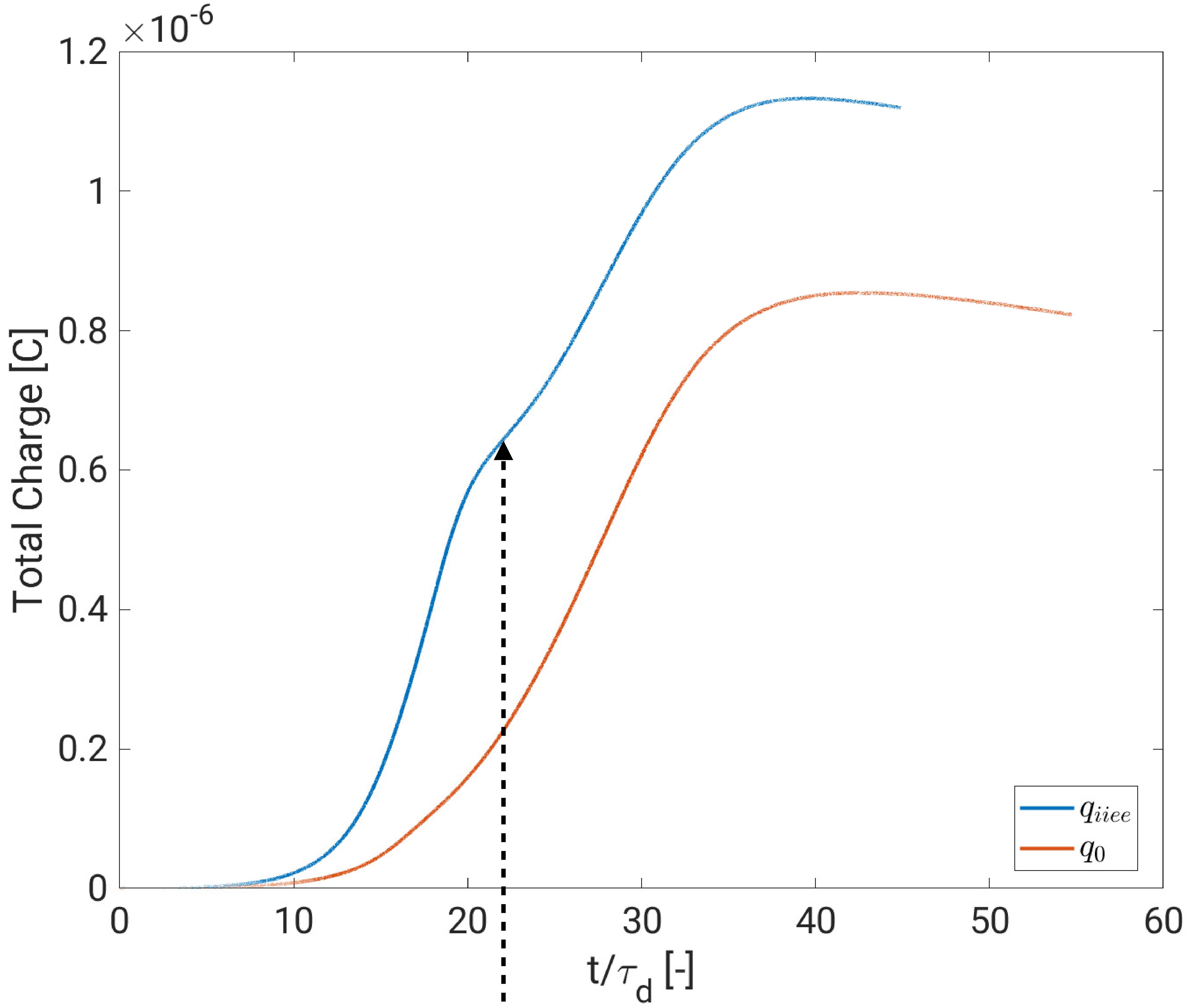


Gt-170: Total charge and vacuum potential well

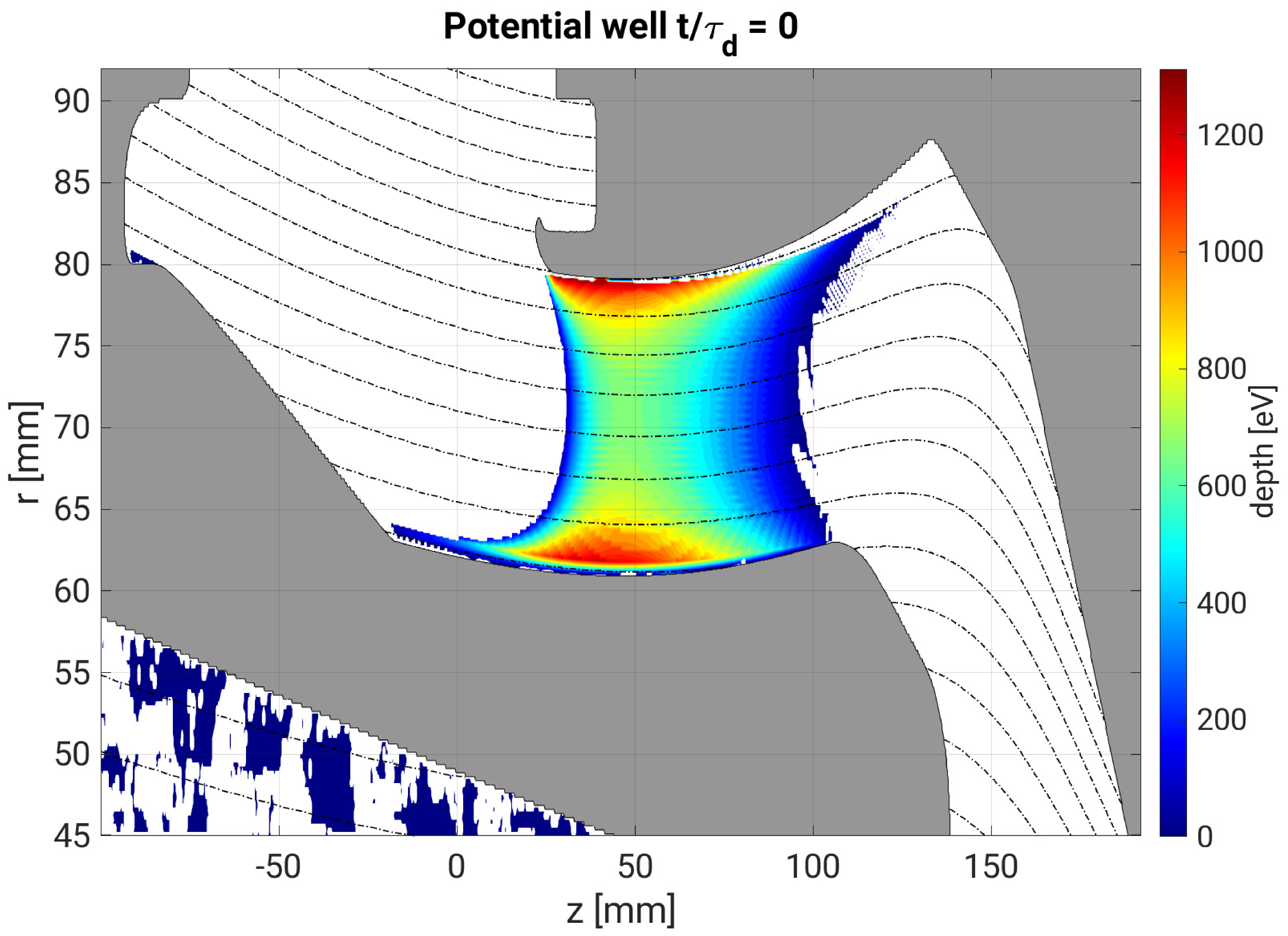




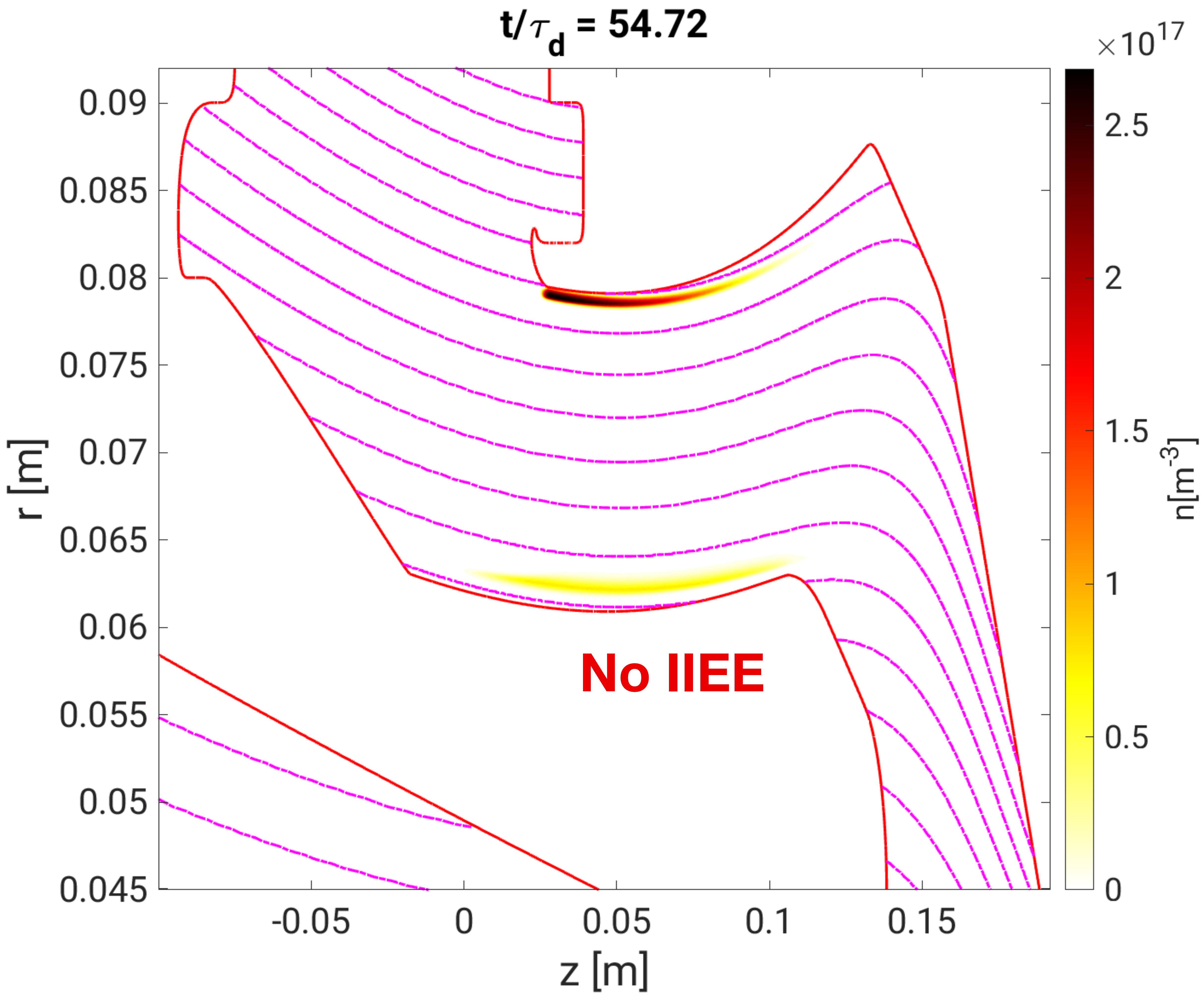
Gt-170: Total charge and vacuum potential well

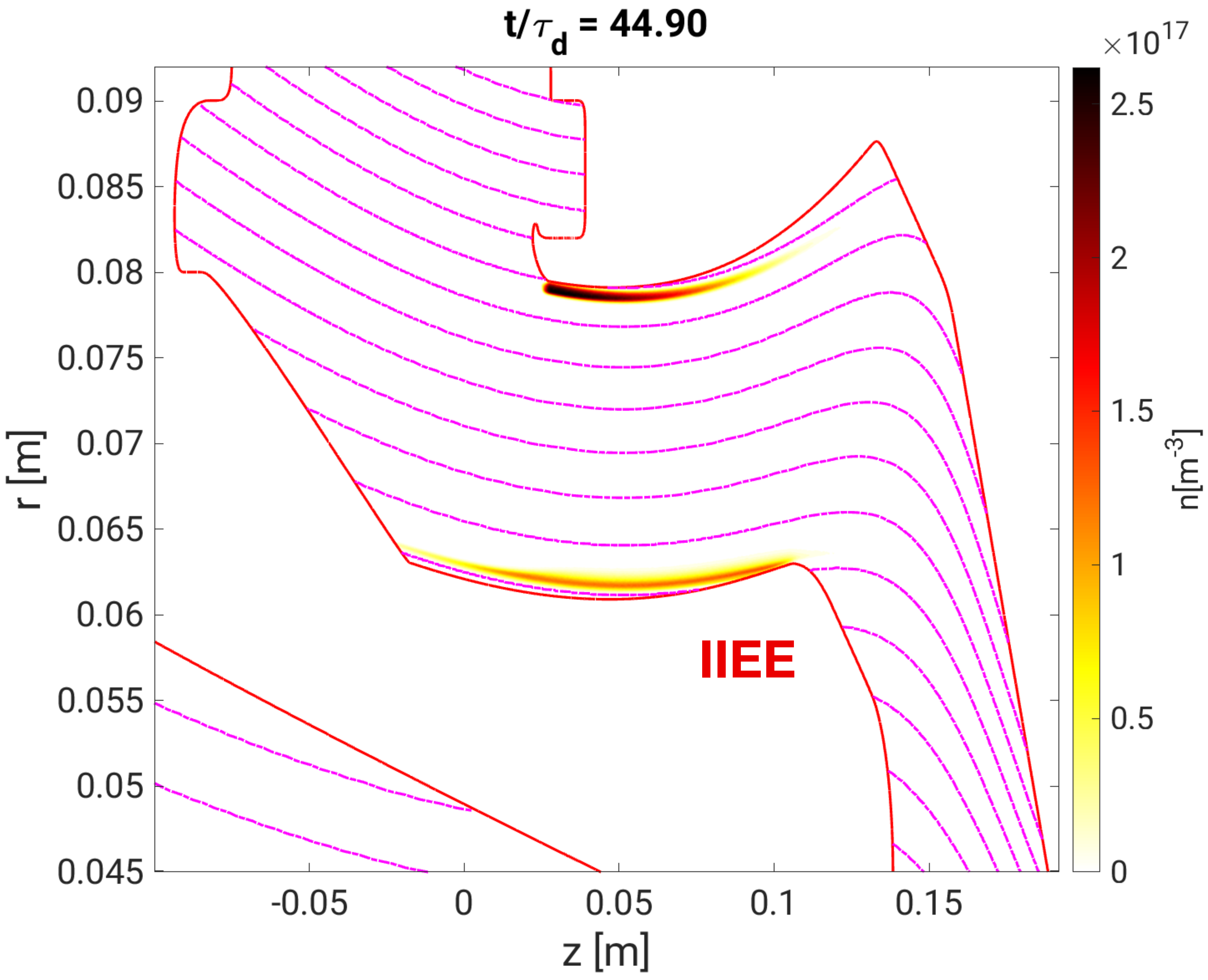


Bottom cloud filled first by IIE



Gt-170: Final densities (both)





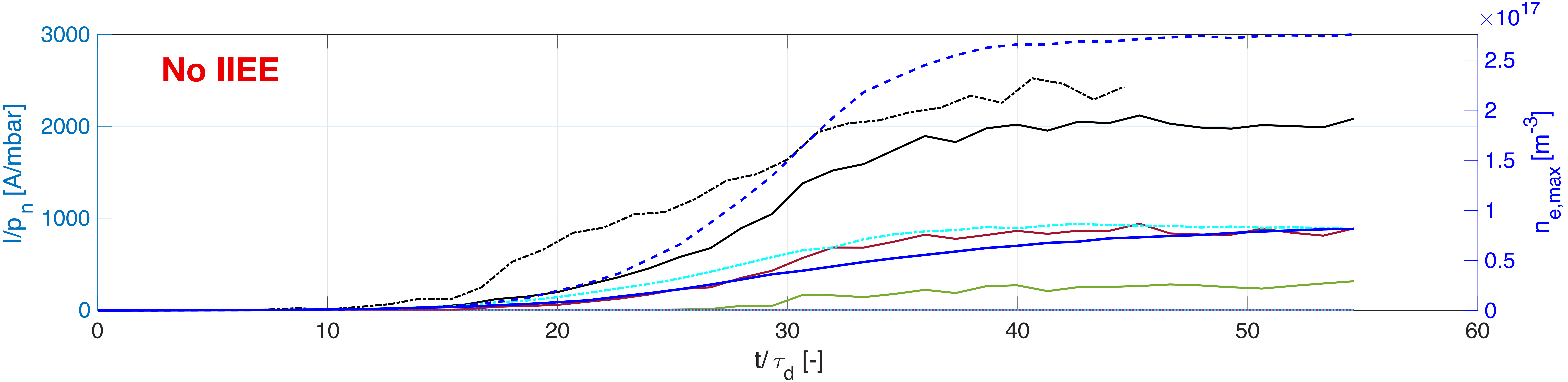
EPFL

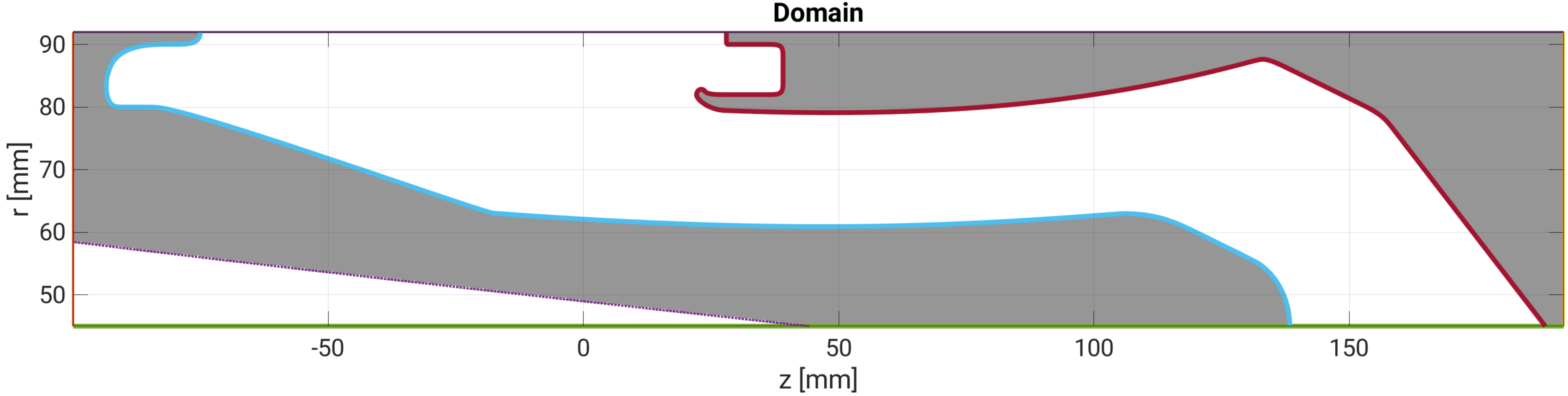
Gt-170: potential well and cloud contours

Bottom cloud located higher (See TREX extrude)

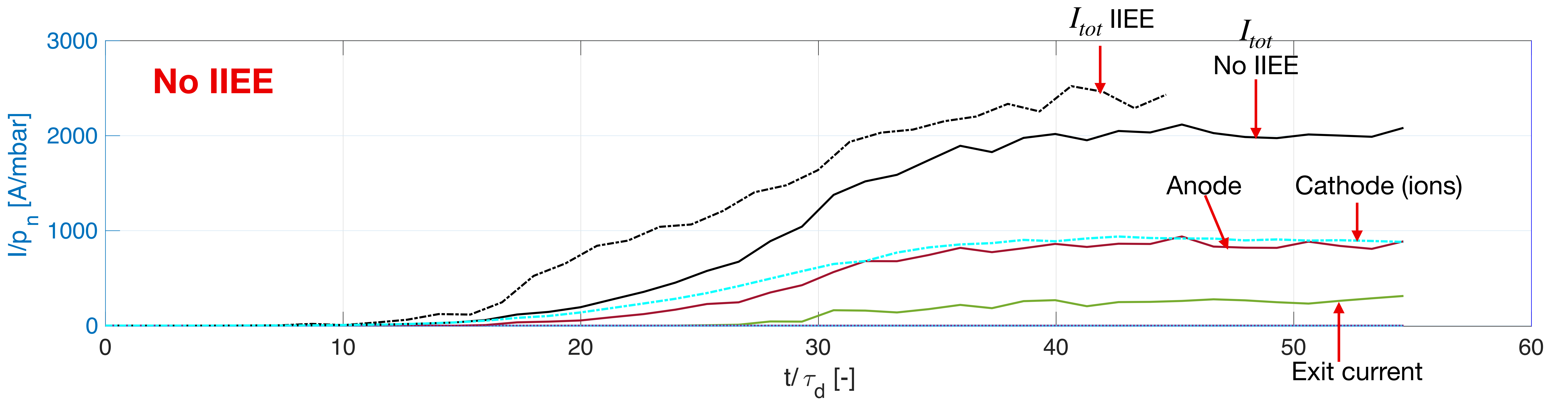
Bottom cloud located lower (See TREX extrude)

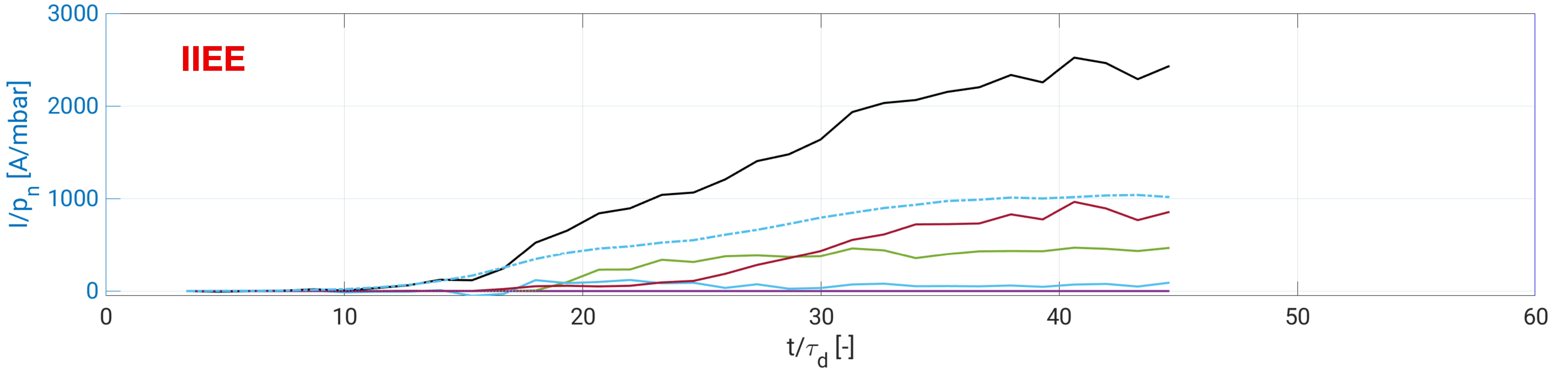
Gt-170: collected currents (No IIEE)





Gt-170: collected currents (Both)



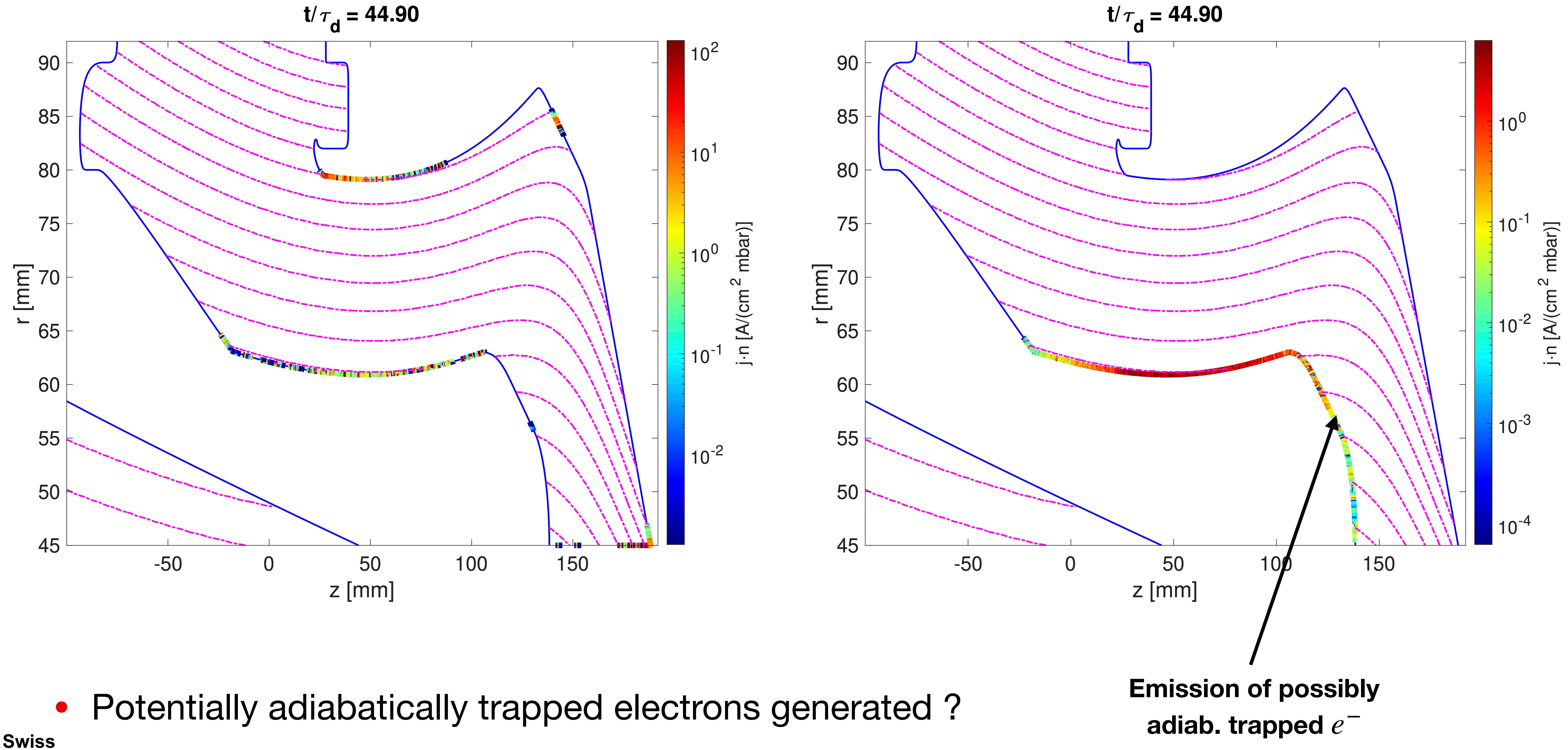


Gt-170: Collected currents steady state (IIEE + no IIEE)

No IIEE

- Total current increased by about 20-25% (current from bottom well weaker).
- Bottom cloud density 2 twice as high as without IIEE.

Gt-170: surface current-densities (IIEE)



- Potentially adiabatically trapped electrons generated ?

Gt-170: Summary

- Density doubled in lower well.
- Bottom cloud lower (radially) - See TREX results.
- Same behavior for upper cloud.
- TREX design is appropriate to describe this type of MIG.
- Overall current increased by ~ **20%**.

Conclusion

- TREX slanted and extrude geometry succeeded at predicting results in more general MIG geometries (see GT-170).
- Overall, the total current measured was affected by IIEE, increasing (on average) by 20%.
- However, still same order of magnitude.
- Bottom cloud density (only) affected.
- Potentially some non-desired effects induced: generation of adiabatically trapped electrons ?

References

[DS]: Davidson. *Physics of Non Neutral Plasmas.*

[LB22]: Guillaume Le Bars. *Models, manual and validations for FENNECS code*, 2022.

[Kis73]: L. M. Kishinevsky. *Estimation of electron potential emission yield on metal and ion parameters*.

[DH]: D. Hasselkamp. *Particle Induced Electron Emissions II.* Springer Berlin. Heidelberg

[PPZ+16]: I. Gr. Pagonakis et al. *Electron trapping mechanisms in Magnetron Injection Guns*. Physics of Plasmas, 2016.

[Cern]: *A remedy against electron clouds inside particle colliders*, home.cern (online)

Thank you !