Electron multipathing in the presence of an insulator layer

G. Iadarola, M. Taborelli

Many thanks to
L. Giacomel, E. Metral, V. Petit, G. Rumolo

Outlook

- Introduction
- Electric effects
- Surface effects
- Simulation tests
- Two insulator patches

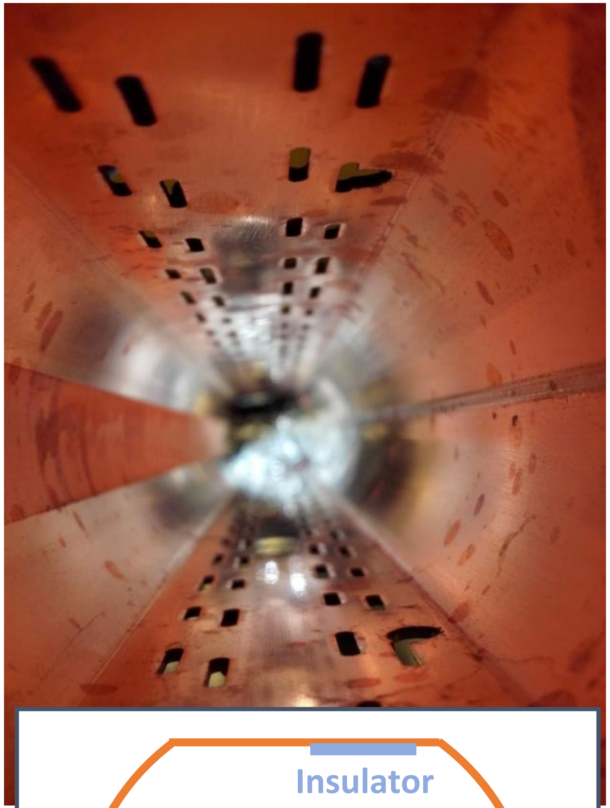
Introduction

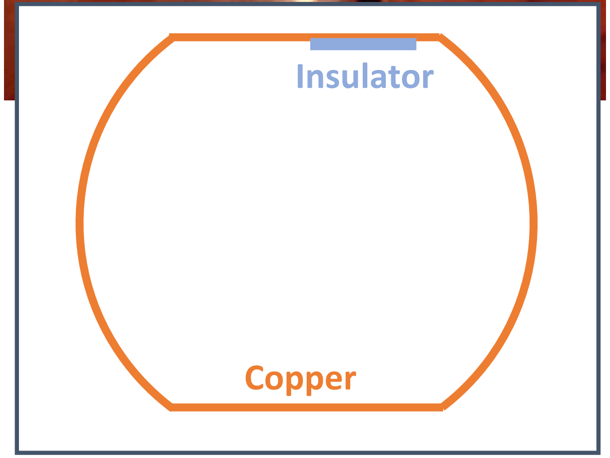
- **Stains** been observed on **spare LHC beam screens**
- When attempting SEY measurements it was found that **some of the stains are charging** → they behave like an **insulating layer**
- Insulators typically **have high SEY**, but their **SEY depends on the charge state**

  → What is the impact on the e-cloud buildup?

- Our test scenario consists in **a copper chamber** with a **single attached insulating patch**

- **Caveat:**
  - As we have no quantitative information on the behavior of these spots, it is not possible to make any quantitative estimate
  - We will instead try to explore possible mechanisms and behaviors.





When secondary emission takes place (emission of more electrons than impacting ones):

- A **conductor** remains neutral (can draw charges from the ground)
- An **insulator** charges positively. This has two consequences:
  - **Electric effect:** charge on the surface can generate a field in the chamber, potentially changing the dynamics of the cloud
  - **Surface effect:** the behavior of the surface, in particular its SEY, change as a function of the charge state[1]

[1] NB: this has nothing to with usual conditioning (which is a "chemical" change), this is a "physical" change, which reverses when the surface discharges

M. Belhaj, "SEY properties of dielectric materials, modelling and measurements", ECLOUD18 workshop

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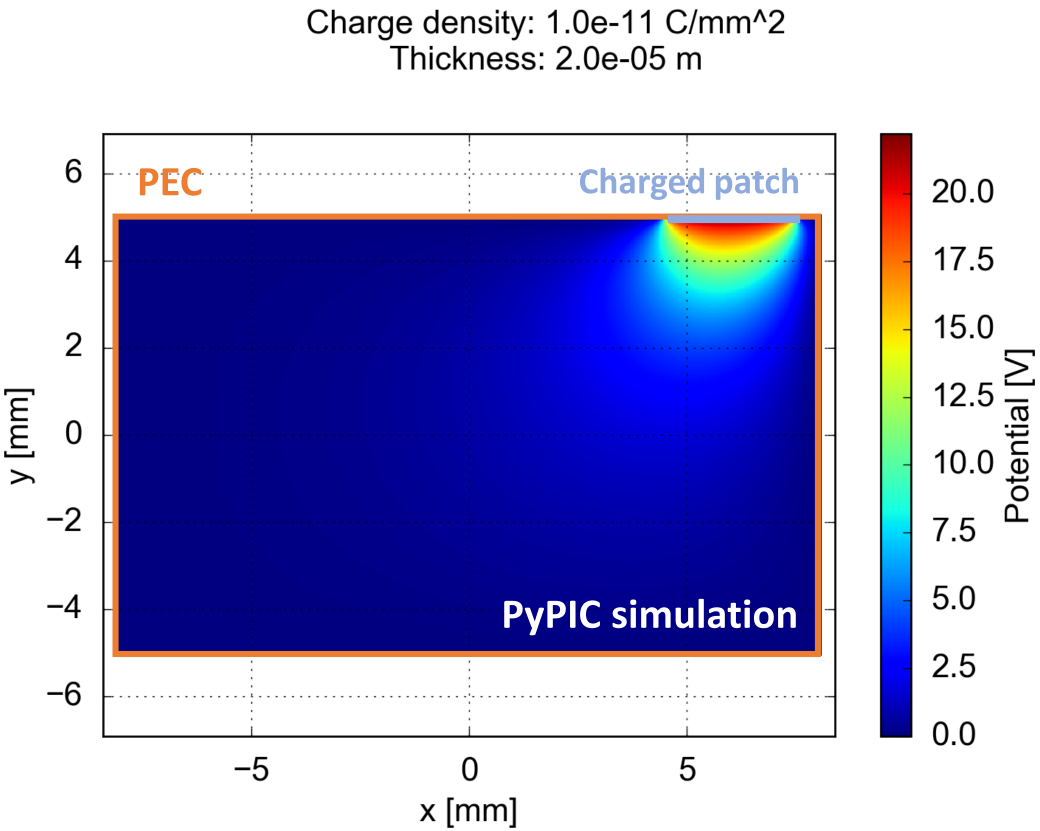
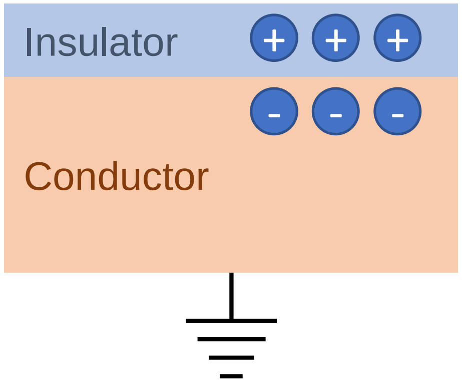
Electric effect

- In general, a charge distribution will generate an **electric field in the beam chamber**



- When the insulator lies on a conducting substrate, **charges are induced in the conductor** which **tend to cancel the field** of the charge in the insulator

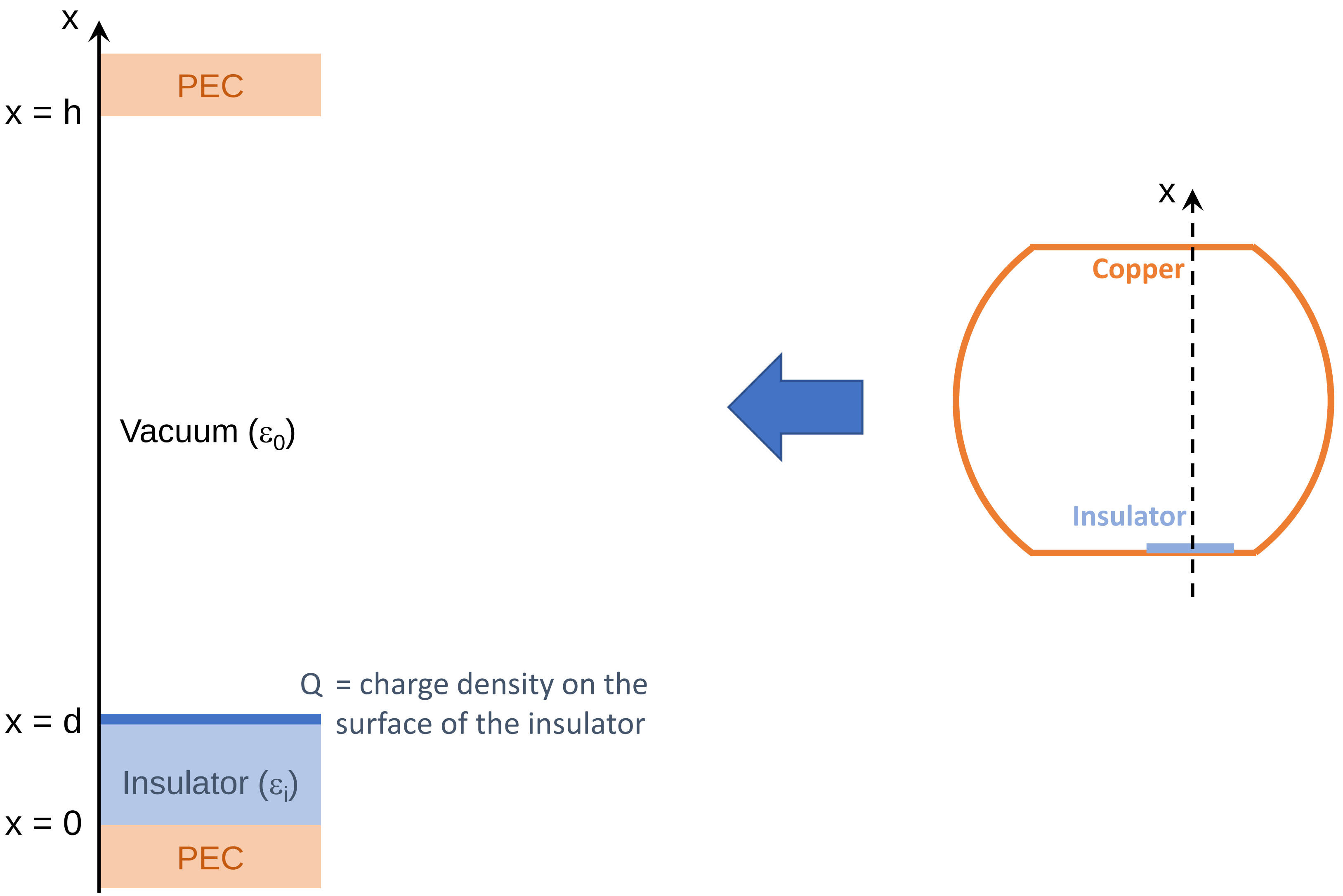


- We expect the field in the chamber to **become smaller when the insulator is thinner**

  → We quantify this using a simple model…

Electric effect: some analytic estimate

We consider a **1D simplification of the problem**:



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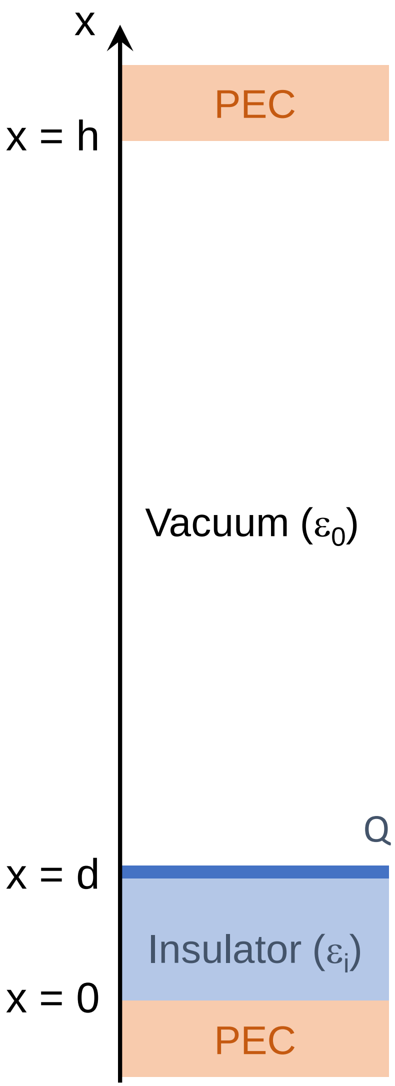

Q = charge density on the surface of the insulator

We introduce the **electrostatic potential**:

$$E = -\nabla\phi \quad \rightarrow \quad E = -\frac{d\phi}{dx} \qquad (1)$$

From **Gauss's law** we can write **Laplace's equation**:

$$\nabla^2\phi = 0 \quad \rightarrow \quad \frac{d^2\phi}{dx^2} = 0 \qquad (2)$$

The **boundary conditions** are simply:

$$\phi(0) = 0 \qquad \phi(h) = 0 \qquad (3)$$

Combining (2) and (3) the **potential must be in the form**:

$$\phi(x) = a_i x \quad \text{in the insulator}$$

$$\phi(x) = a(x-h) \quad \text{in the vacuum}$$

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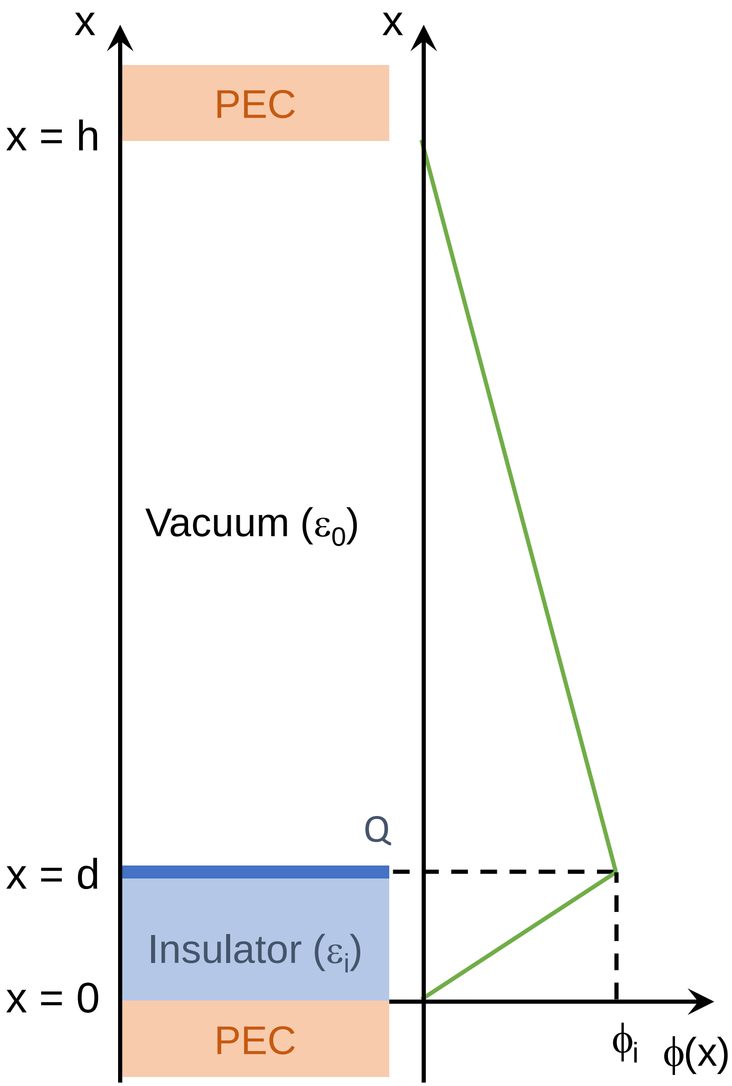

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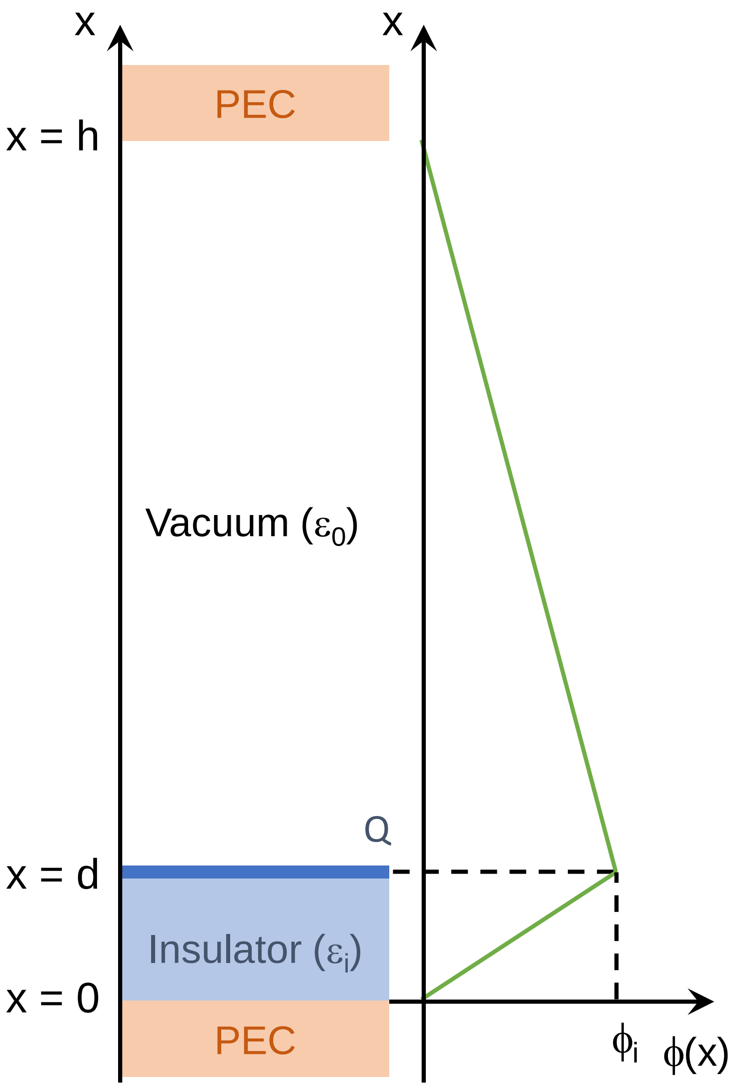

The **potential** must be in the form:

$$\phi(x) = a_i x \qquad \text{in the insulator}$$

$$\phi(x) = a\left(x - h\right) \qquad \text{in the vacuum}$$

We impose the **continuity of the potential**:

$$\phi(d^+) = \phi(d^-) \quad \rightarrow \quad a_i = a\frac{d-h}{d}$$

We are **left with one unknown** (i.e. *a*).

Applying **Gauss's law at the charged surface**:

$$\varepsilon_0 E\left(d^+\right) - \varepsilon_i E\left(d^-\right) = Q$$

$$\downarrow$$

$$\varepsilon_0 \left.\frac{d\phi}{dx}\right|_{x=d^+} - \varepsilon_i \left.\frac{d\phi}{dx}\right|_{x=d^-} = -Q$$

which gives:

$$a = \frac{Q}{\varepsilon_i\left(\frac{d-h}{d}\right) - \varepsilon_0}$$

Electric effect: some analytic estimate

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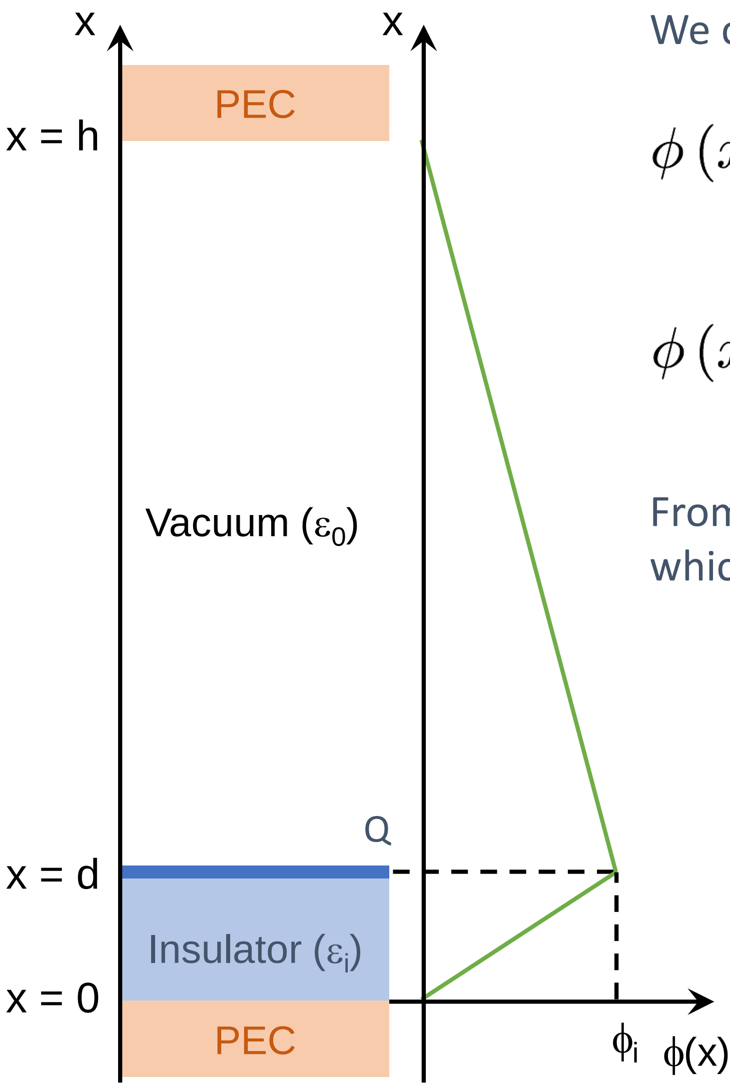

We can write the **potential** explicitly:

$$\phi\left(x\right) = \frac{Q}{\varepsilon_i\left(\frac{d-h}{d}\right) - \varepsilon_0}\left(\frac{d-h}{d}\right)x \quad \text{in the insulator}$$

$$\phi\left(x\right) = \frac{Q}{\varepsilon_i\left(\frac{d-h}{d}\right) - \varepsilon_0}\left(x-h\right) \quad \text{in the vacuum}$$

From any of the two we can get the **maximum potential**, which occurs **at the interface**:

$$\phi\left(d\right) = \frac{Q}{\varepsilon_i}\frac{d\left(h-d\right)}{h-d\left(1-\frac{\varepsilon_0}{\varepsilon_i}\right)}$$

As expected it becomes zero when d or Q tend to zaro.

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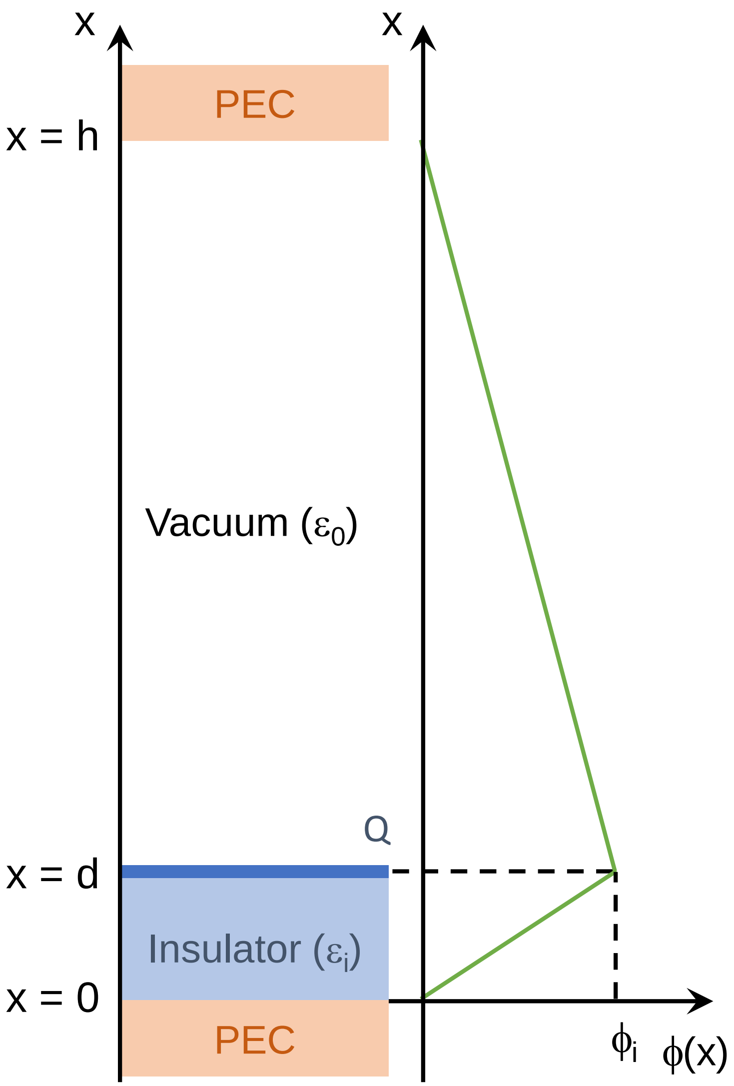


Potential at the interface:

$$\phi\left(d\right) = \frac{Q}{\varepsilon_i} \frac{d\left(h-d\right)}{h-d\left(1-\frac{\varepsilon_0}{\varepsilon_i}\right)}$$

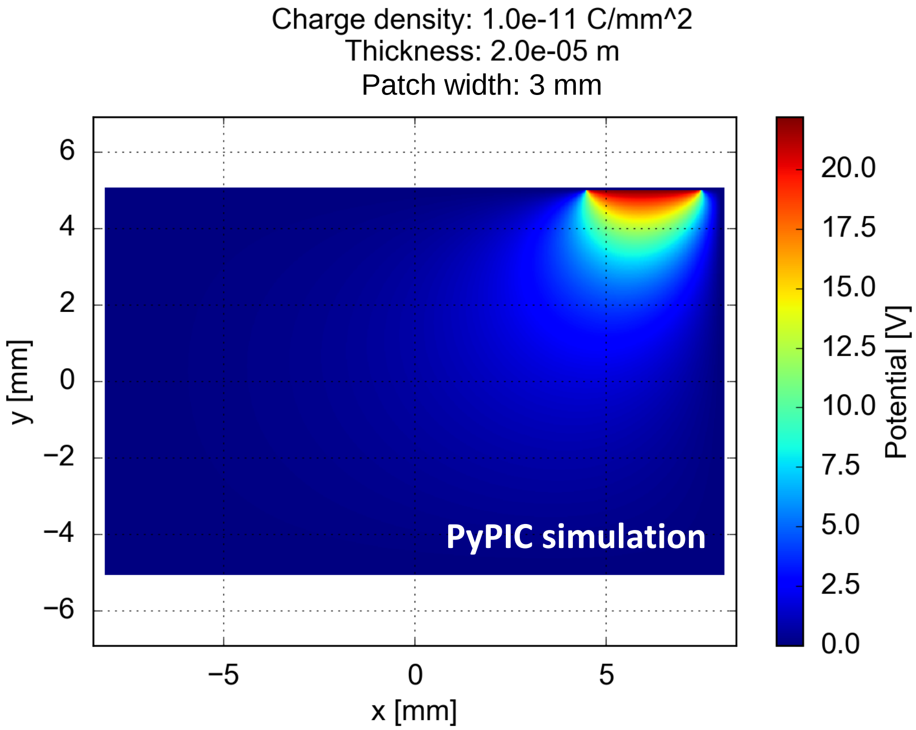
For d << h, we simply get:

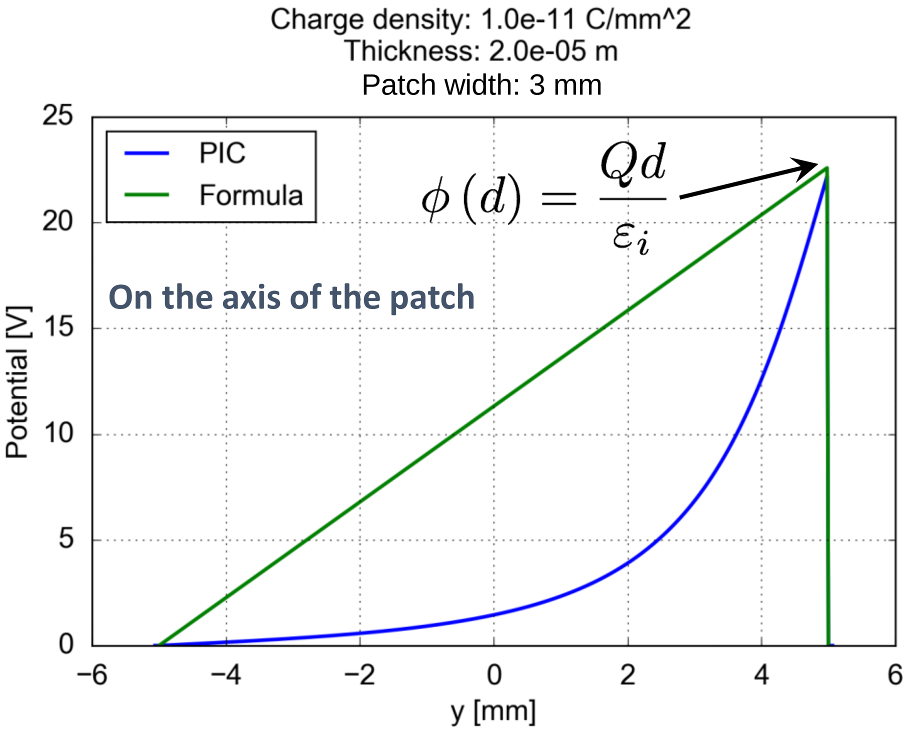
$$\phi\left(d\right) = \frac{Qd}{\varepsilon_i}$$

- The potential on the surface **only depends on on the insulator thickness and material**
- It does not depend on the on the geometry of the "chamber" (h)
- It is **linearly proportional to the insulator thickness** → It vanishes for infinitely thin layer (as guessed by image charges considerations)
- In reduces if the insulator has a high permittivity

Electric effect: comparison against 2D Poisson solver

- Even in the 2D geometry, the formula gives a **very good approximation of the potential at the surface** (potential in the rest of the chamber is instead overestimated)





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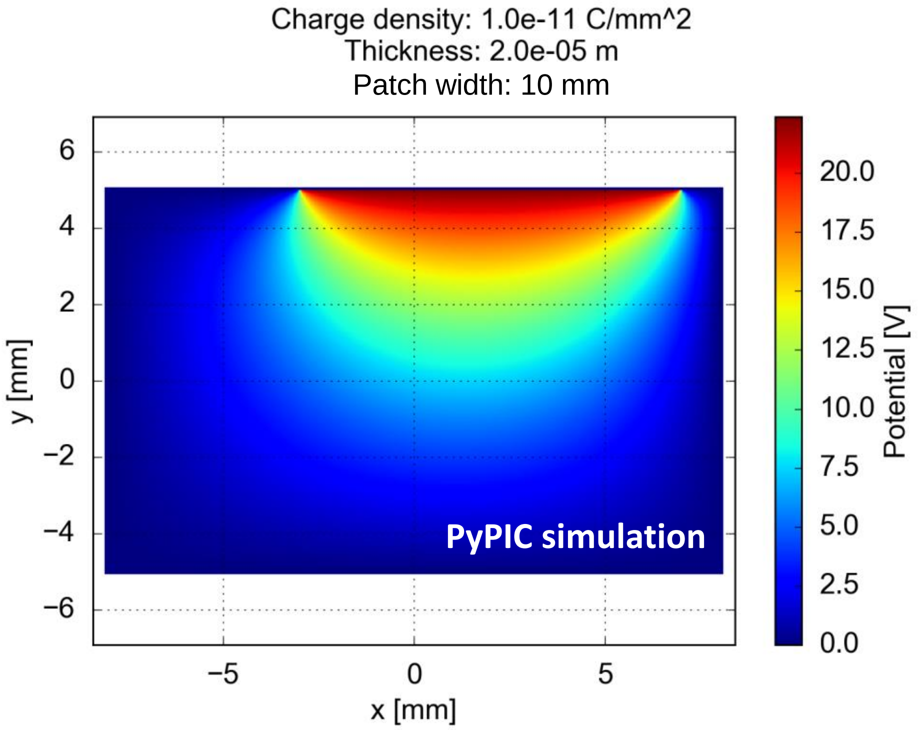
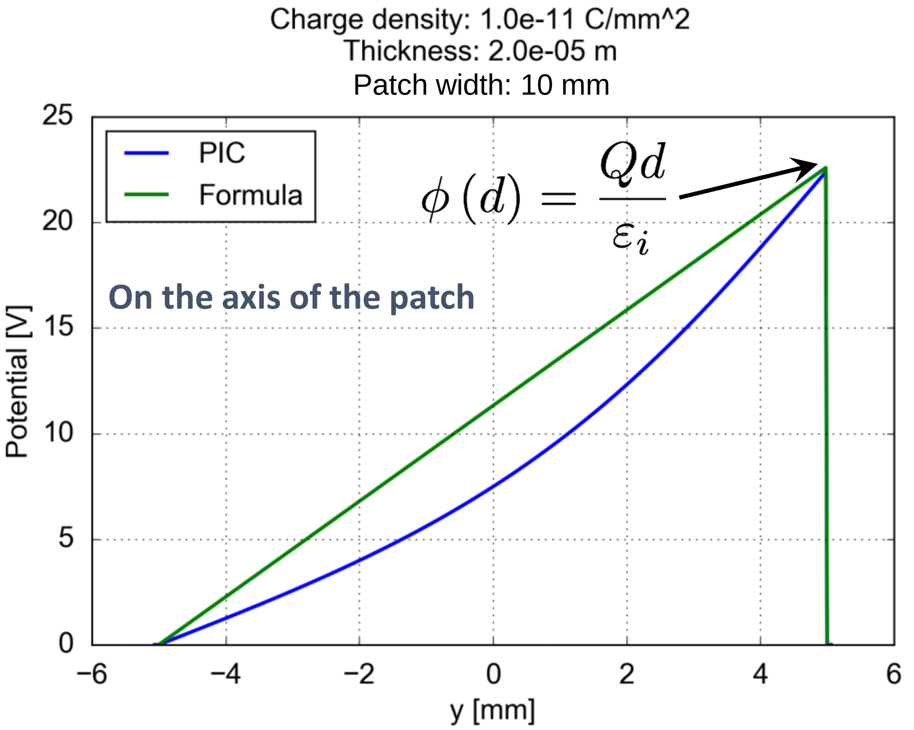
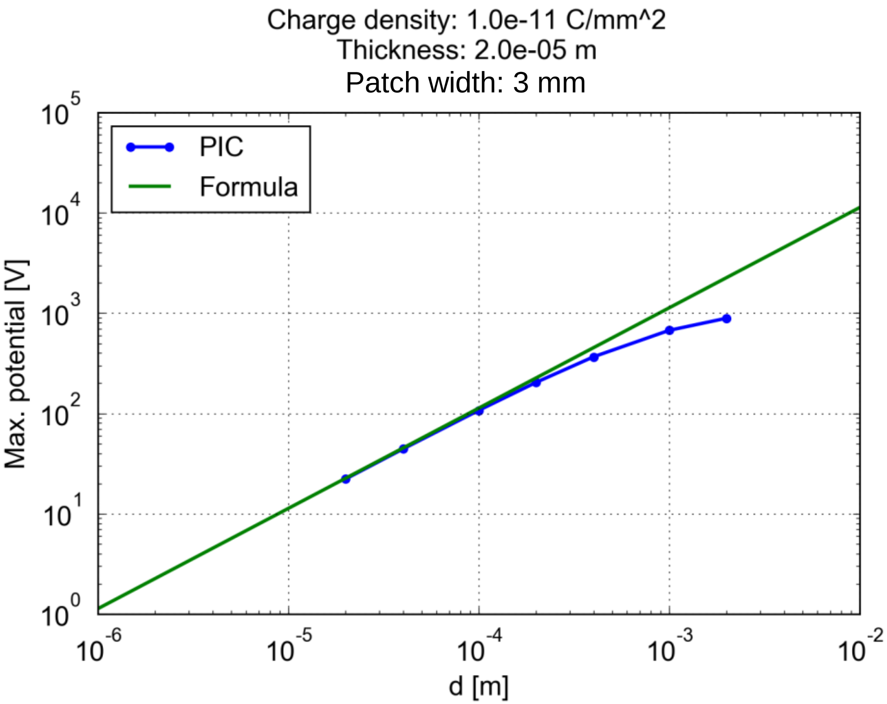


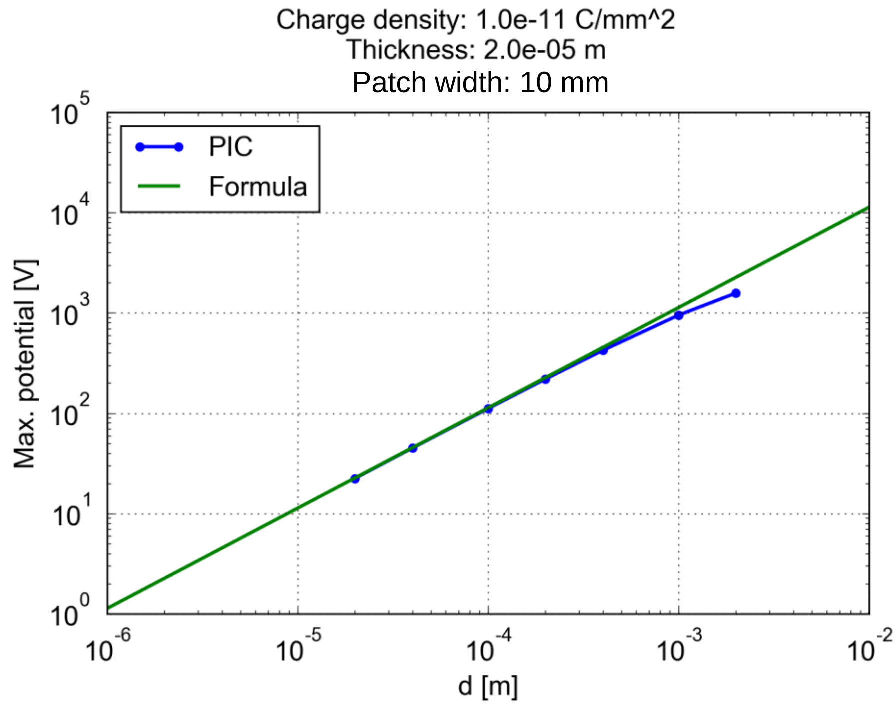


- As expected, the approximation in the rest of the chamber gets betted for a wider patch

Electric effect: comparison against 2D Poisson solver

- Even in the 2D geometry, the formula gives a **very good approximation of the potential at the surface**
- **Agreement** becomes better for **smaller thickness of the insulator**
- For **realistic values of the insulator thickness**, the potential is relatively small → in first approximation **we will neglect the electrostatic effect** of the charge on the patch





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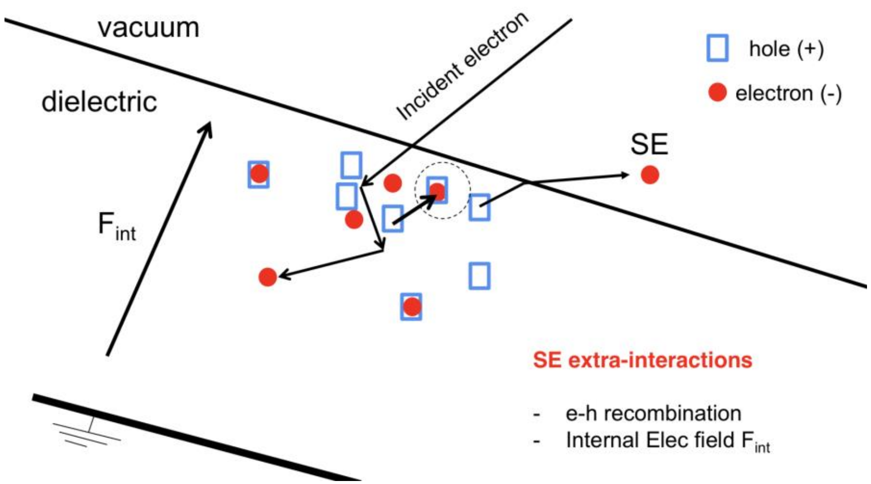
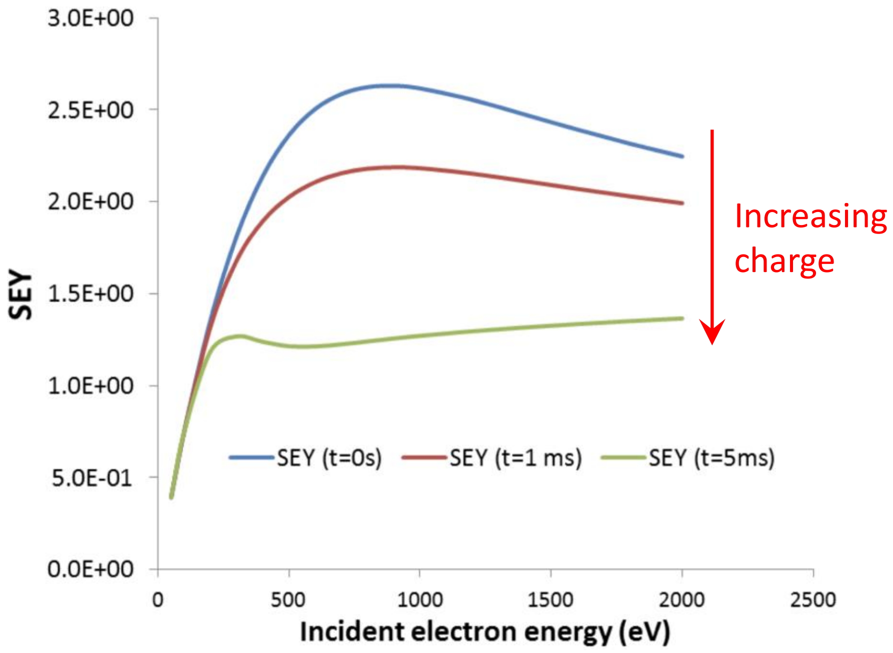
- When an insulator emits electrons its valence band starts being depopulated → **formation of holes**
- This **affects the Secondary Electron Yield**:
  - When the surface charges, the **Secondary Electron Yield tends to 1.0** over a wide range of energies
  - This is a **reversible process**, the SEY recovers its initial value when the surface discharges





M. Belhaj, "SEY properties of dielectric materials, modelling and measurements", ECLOUD18 workshop

An **insulator module has been included in PyECLOUD**: the code keeps track of the accumulated charge and adapts the SEY curve accordingly:

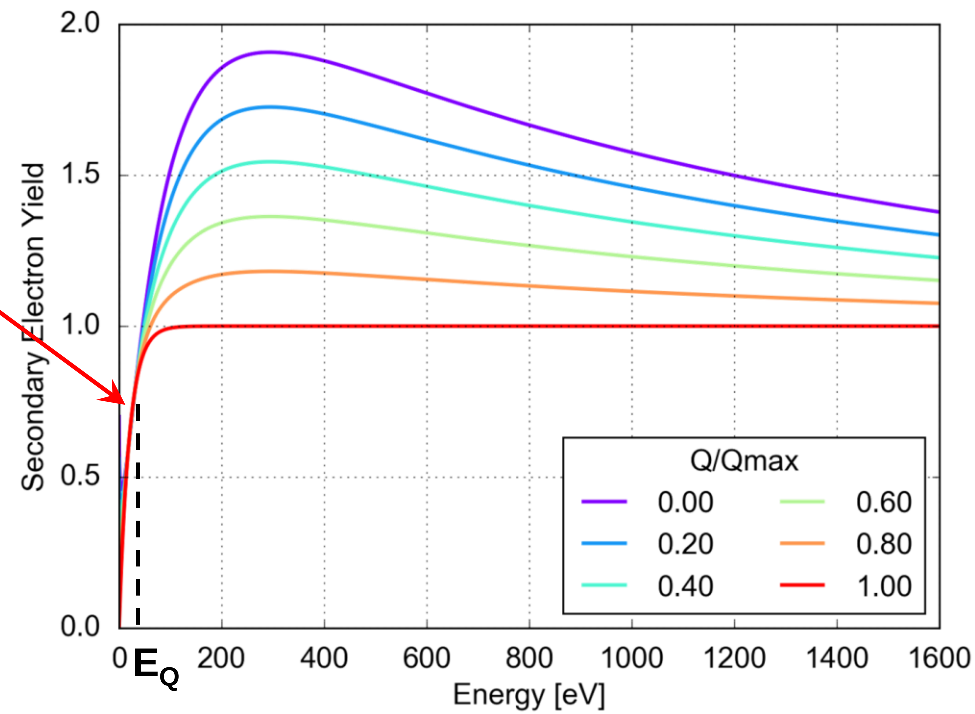
- The **"starting curve" (Q=0)** uses the usual SEY models (custom SEY_{max})
- The **"arrival curve" ($Q >= Q_{max}$)** the SEY has the form (Q_{max} and E_Q are defined by the user):

$$\delta_{\text{charged}}\left(E\right) = 1 - e^{-\frac{E}{E_Q}}$$

- For **$0<Q< Q_{max}$** a linear weighting between the two is used

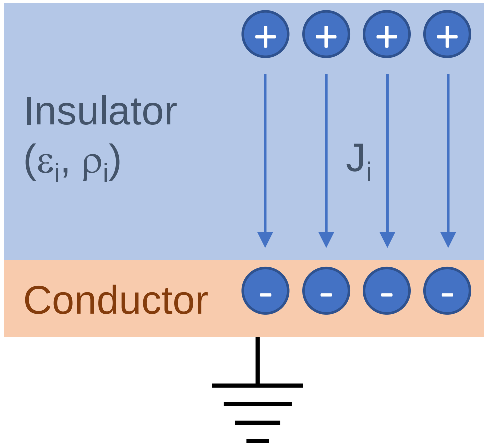
$$\delta\left(Q,E\right) = \left(\frac{Q}{Q_{\text{max}}}\right)\delta_{\text{charged}}\left(E\right) + \left(1-\frac{Q}{Q_{\text{max}}}\right)\delta_{\text{uncharged}}\left(E\right)$$

When charged the surface absorbs only low-energy electrons



Surface effects: relaxation constant

If the **resistivity of the insulator** is **not infinite** there will be a small current to ground



Ohm's law: $$J = \frac{dQ}{dt} = \frac{1}{\rho_i} E_i$$

From our previous calculation: $$E_i = \frac{Q}{\varepsilon_i}$$

Combining the two: $$\frac{dQ}{dt} = \frac{Q(t)}{\rho_i \varepsilon_i}$$

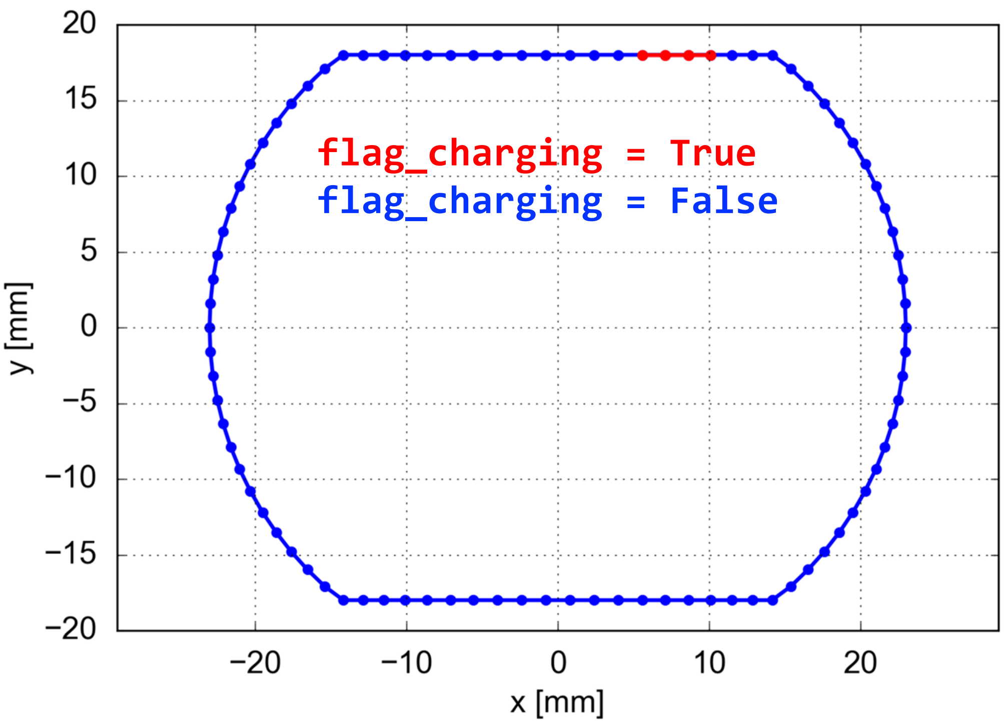
which gives: $Q(t) = Q_0 e^{-\frac{t}{\tau_i}}$ with: $\tau_i = \rho_i \varepsilon_i$

Even for relatively high resistivity the **discharge can be quite fast**:

- Ex. $\rho_i = 10^7\ \Omega$ m → $\tau_i = 100\ \mu$s

Surface effects: implemented model

- The charging module **is built on top of the existing non-uniform SEY module**
- Can be activated by selecting `switch_model = 'ECLOUD_nunif_charging'`
- Surface properties can be **defined independently for each segment** of the chamber (via the chamber mat files)



Attributes are defined for all segments:

- **flag_charging** → decides which segments behave like insulators
- **Q_max_segments** → defines the charge density for which δ_{max} is 1
- **EQ_segments** → defines the shape of the SEY curve of the charged surface
- **tau_segments** → defines the charge relaxation time

Available in [PyECLOUD 7.7.0]()

full example at: https://github.com/PyCOMPLETE/PyECLOUD/tree/master/other/charging_effects/

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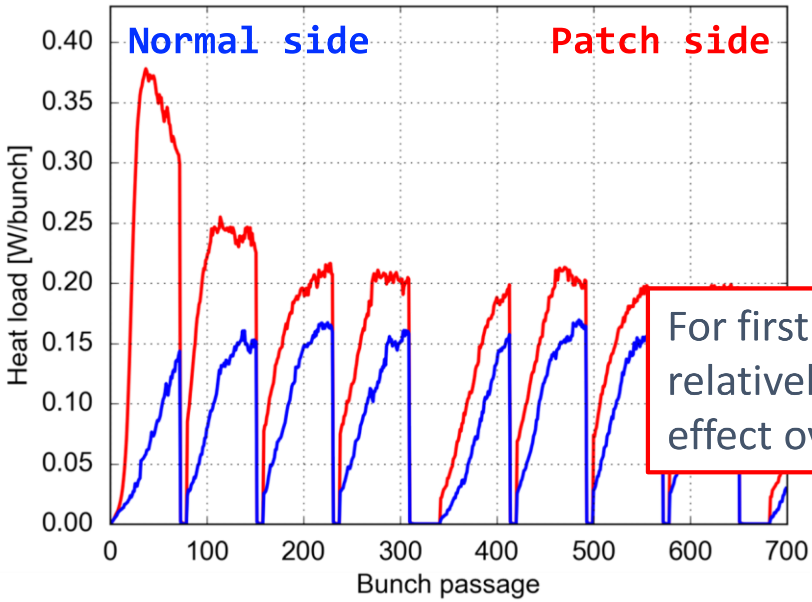
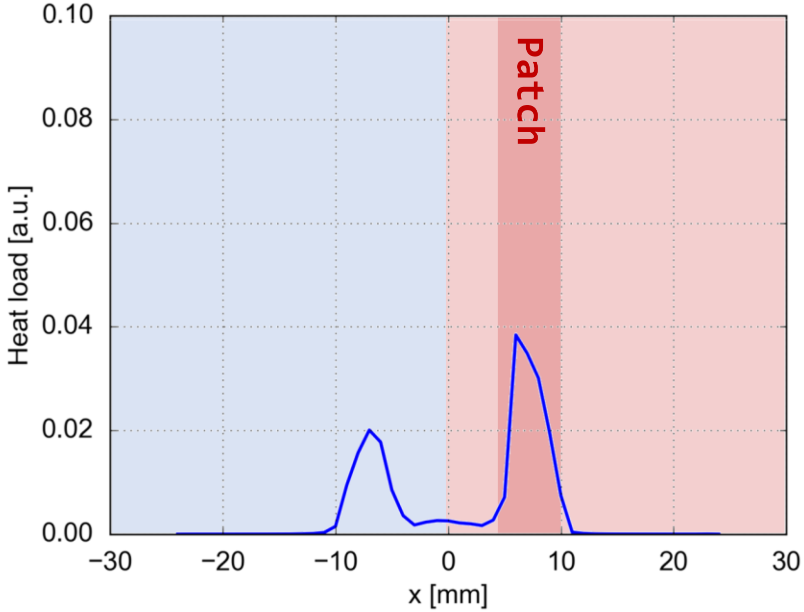
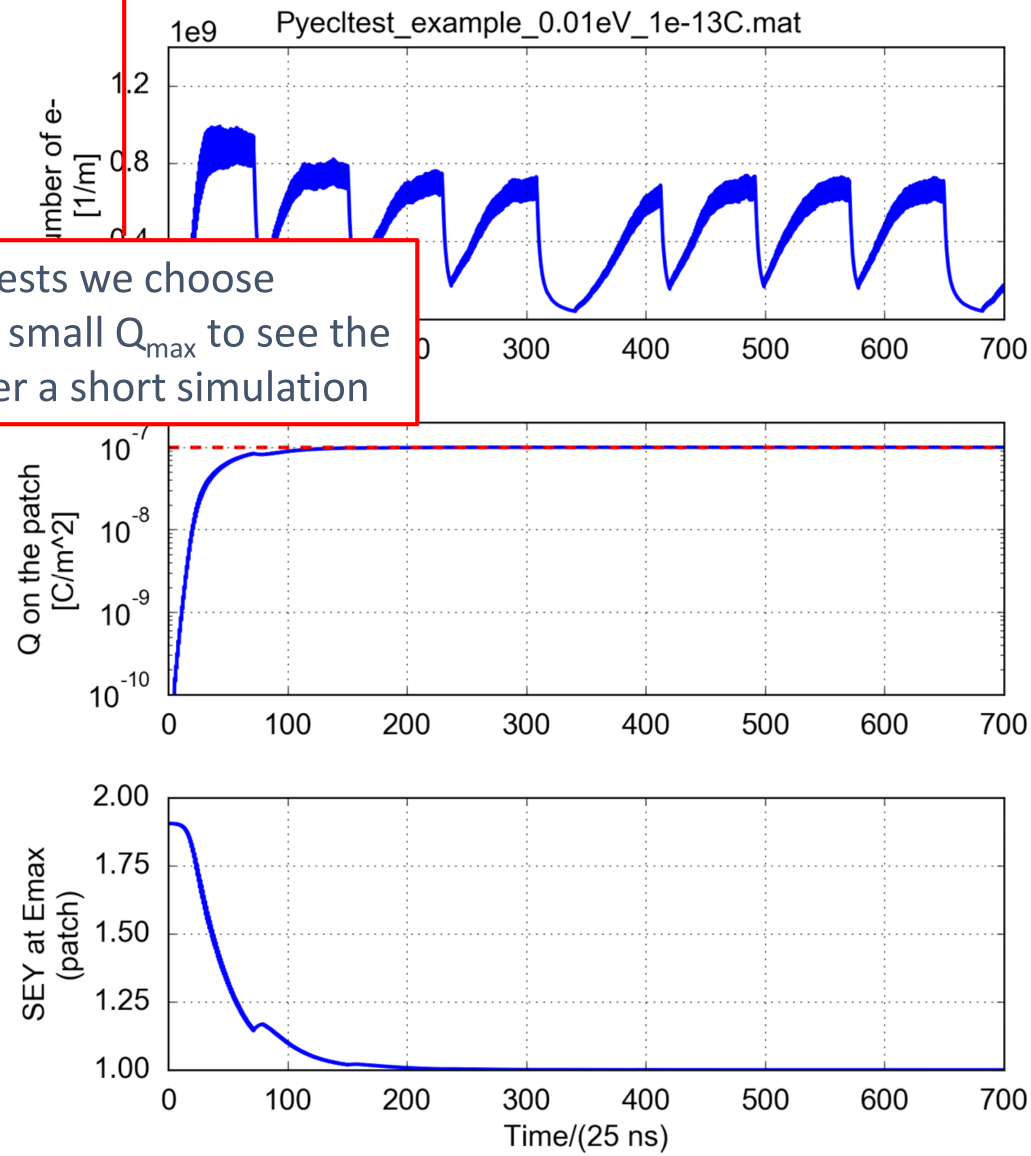
Simulation tests: no discharging, low E_Q

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm² E_Q: 0.01 eV τ_i: Inf us





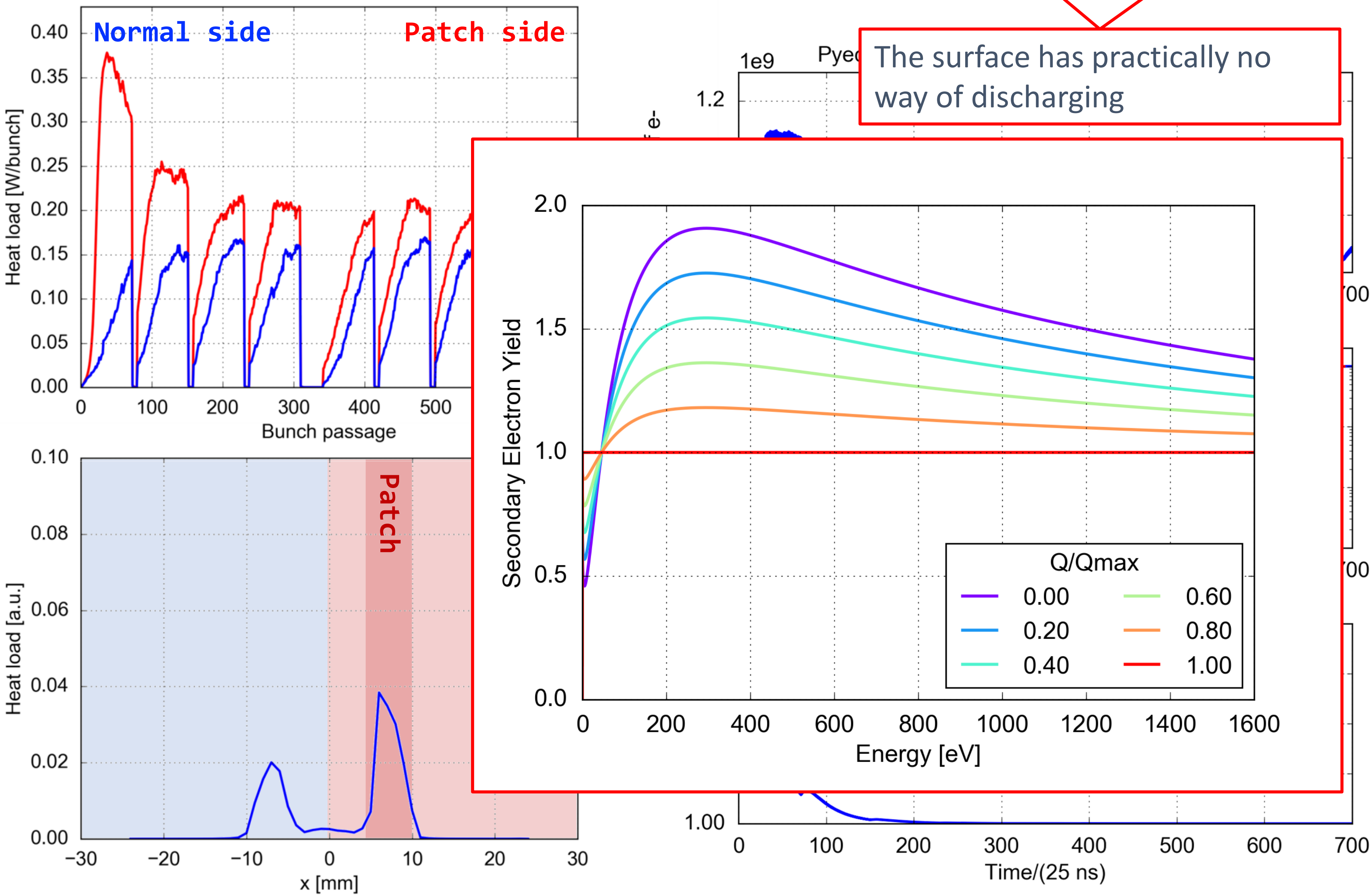


For first tests we choose relatively small Q_{max} to see the effect over a short simulation

Simulation tests: no discharging, low E_Q

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm^2 E_Q: 0.01 eV τ_i: Inf us

The surface has practically no way of discharging



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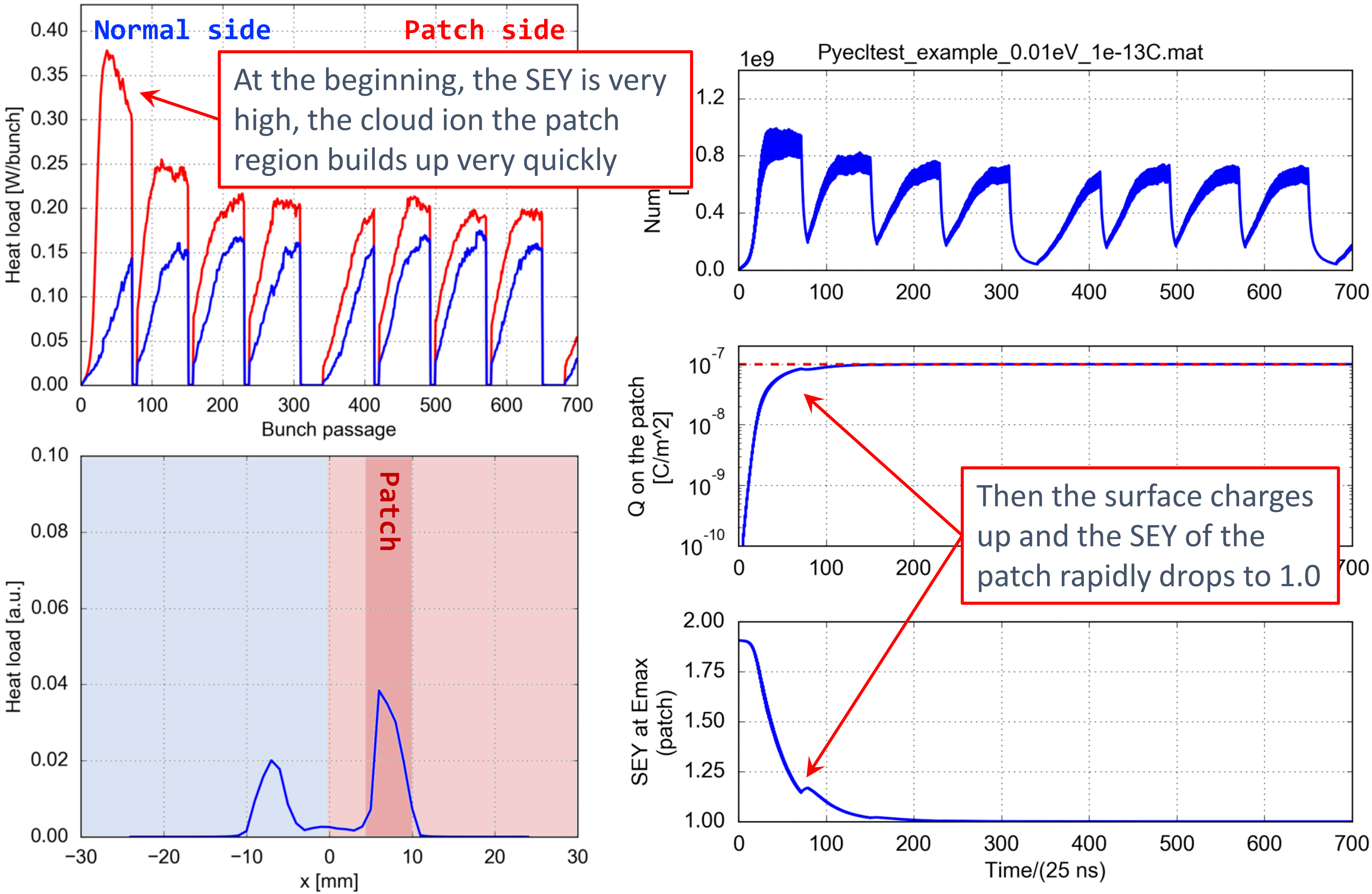
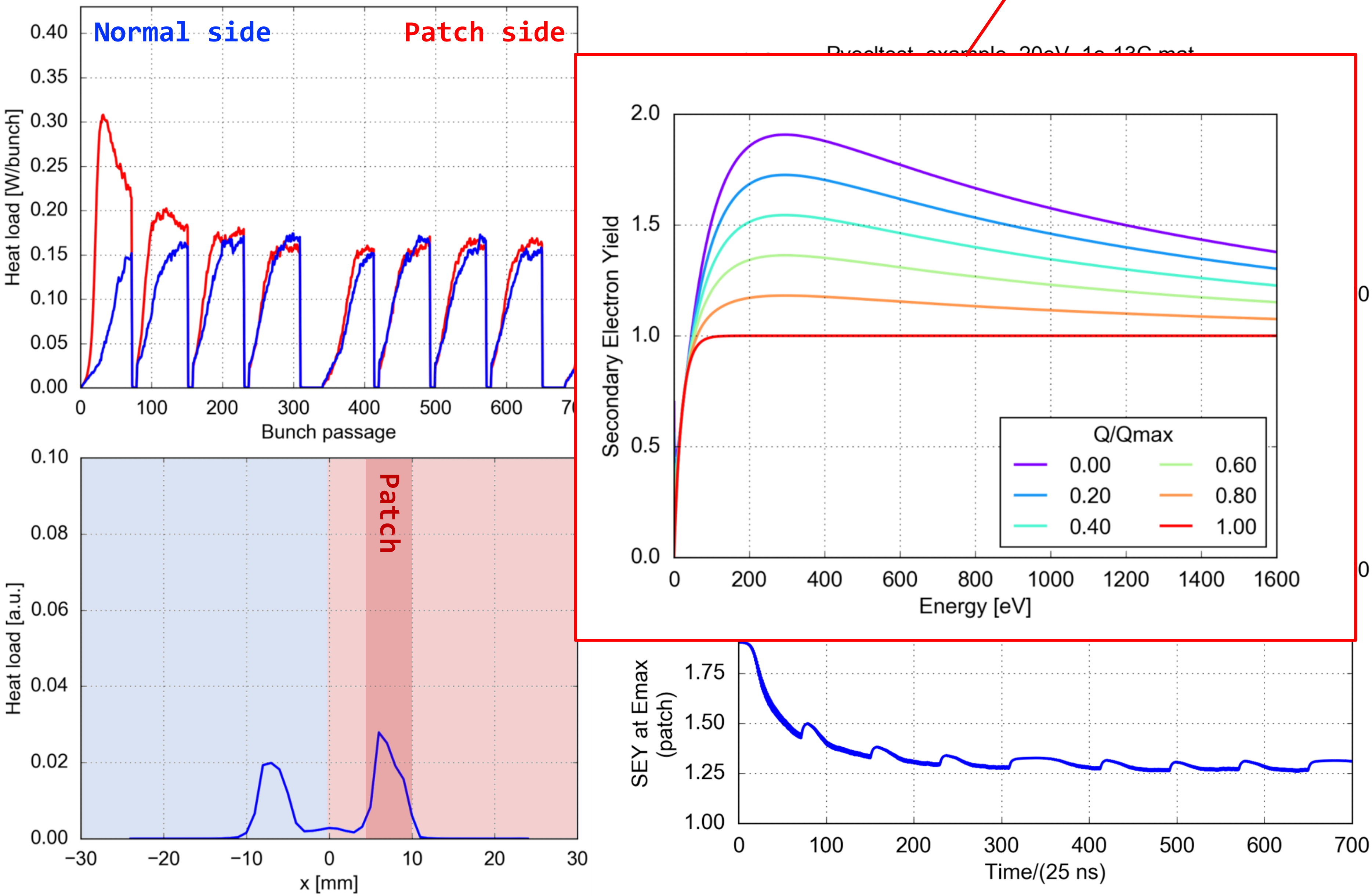


Simulation tests: no discharging, higher E_Q

δ_{Cu}: `1.3` $\delta_i(Q=0)$: `1.9` Q_{max}: `1.0e-13 C/mm²` E_Q: `20.0 eV` τ_i: `Inf us`



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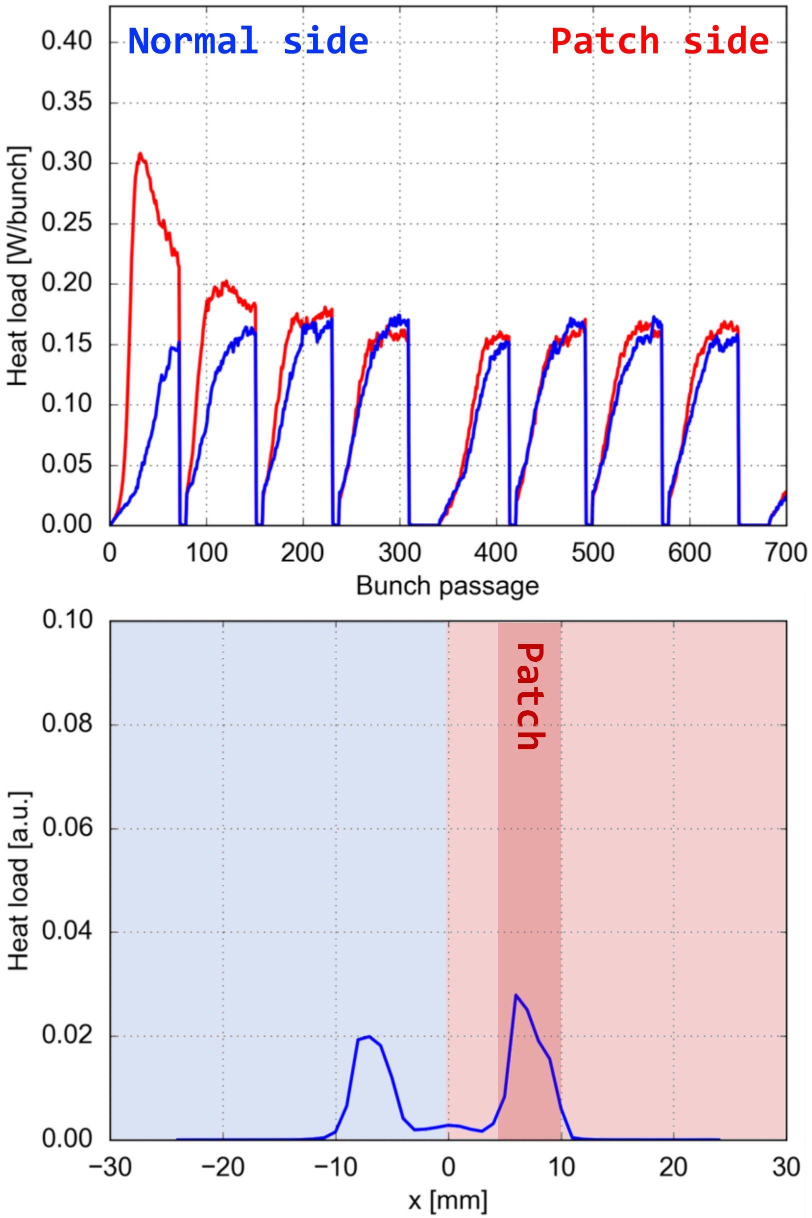
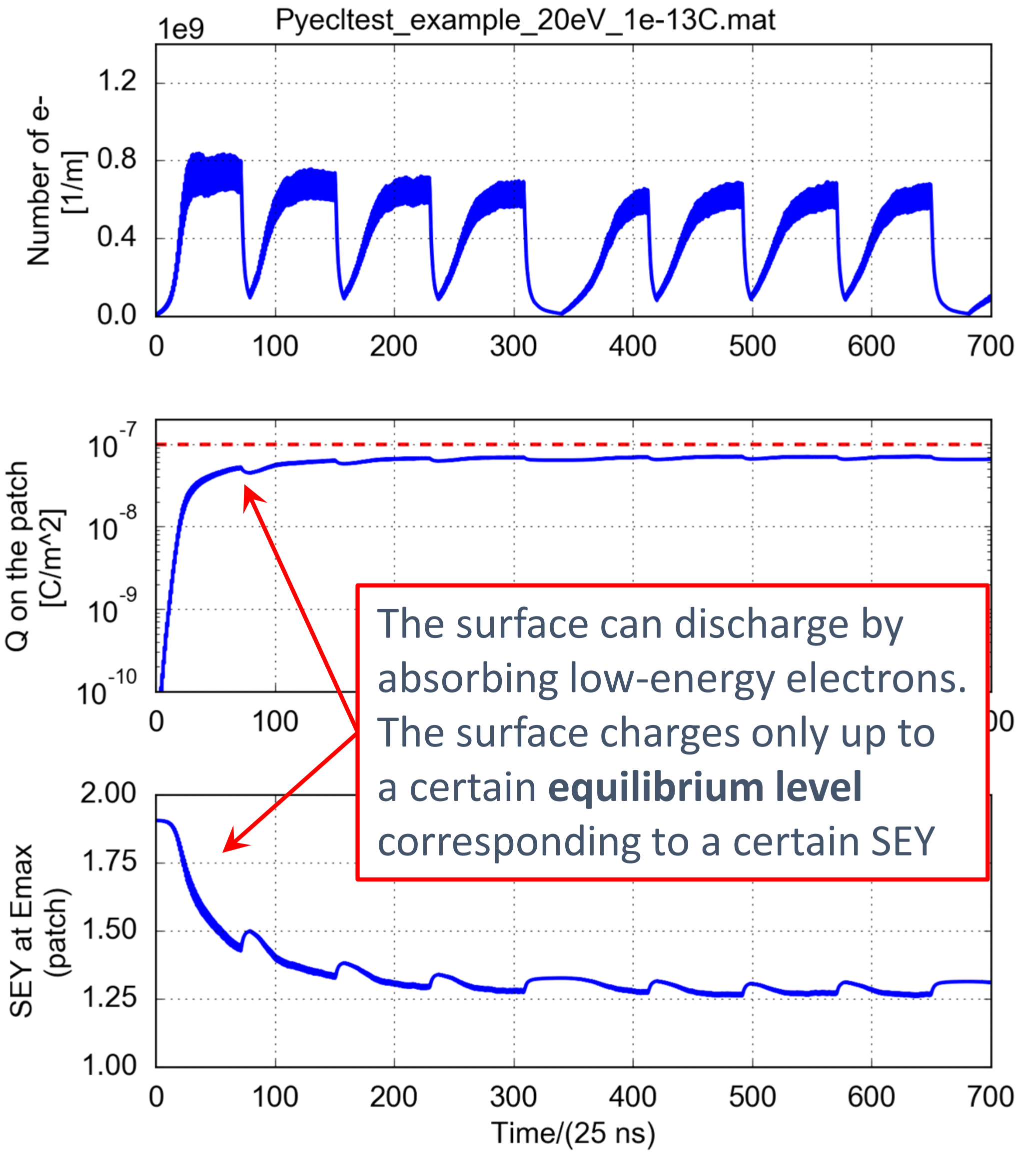


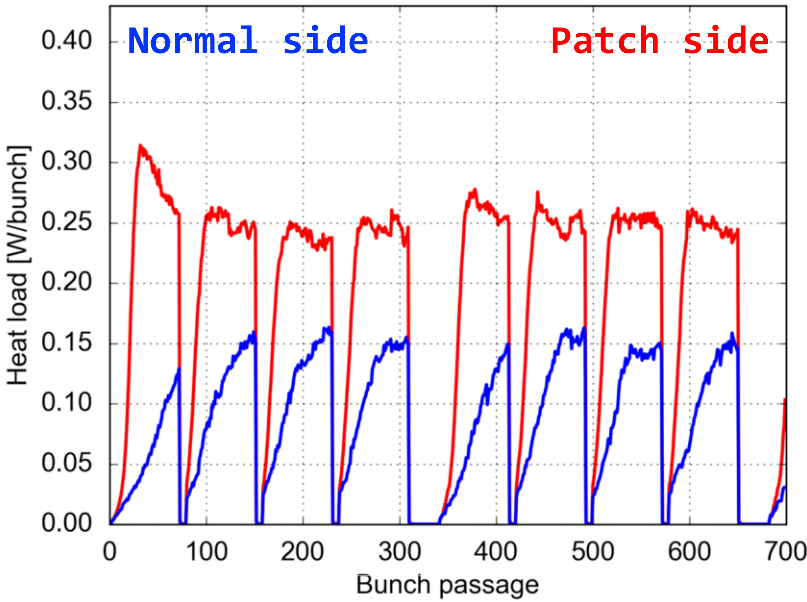


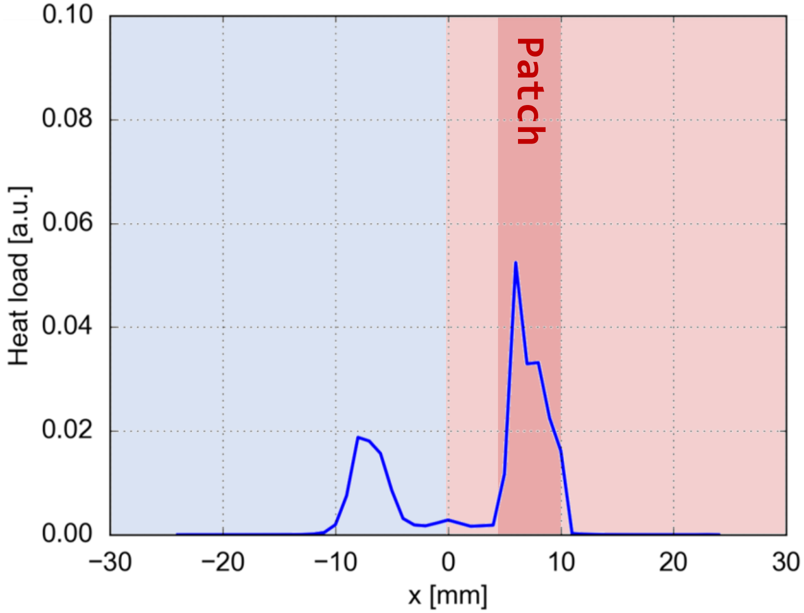
The surface can discharge by absorbing low-energy electrons. The surface charges only up to a certain **equilibrium level** corresponding to a certain SEY

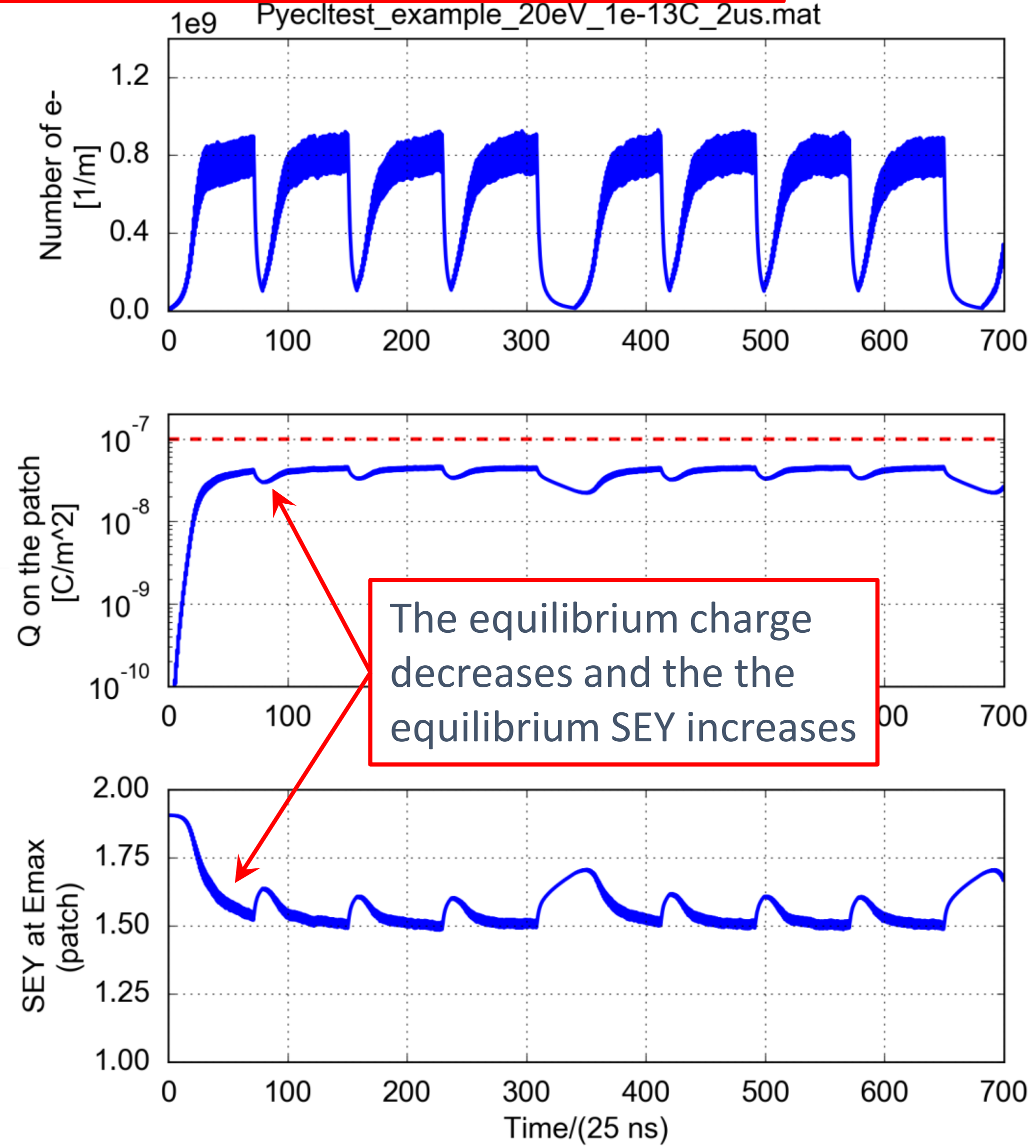
Simulation tests: discharging

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm^2 E_Q: 20.0 eV τ_i: 2.0 us

We introduce a discharging time-constant





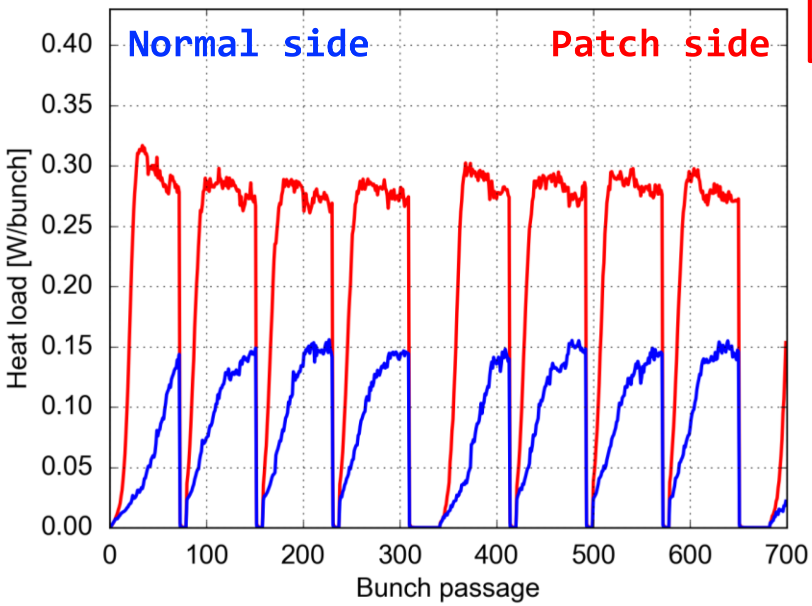


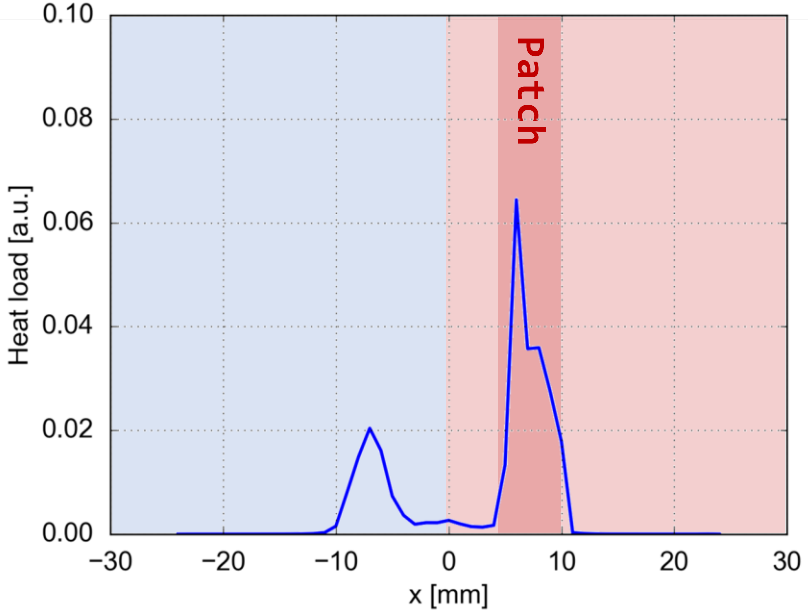
The equilibrium charge decreases and the the equilibrium SEY increases

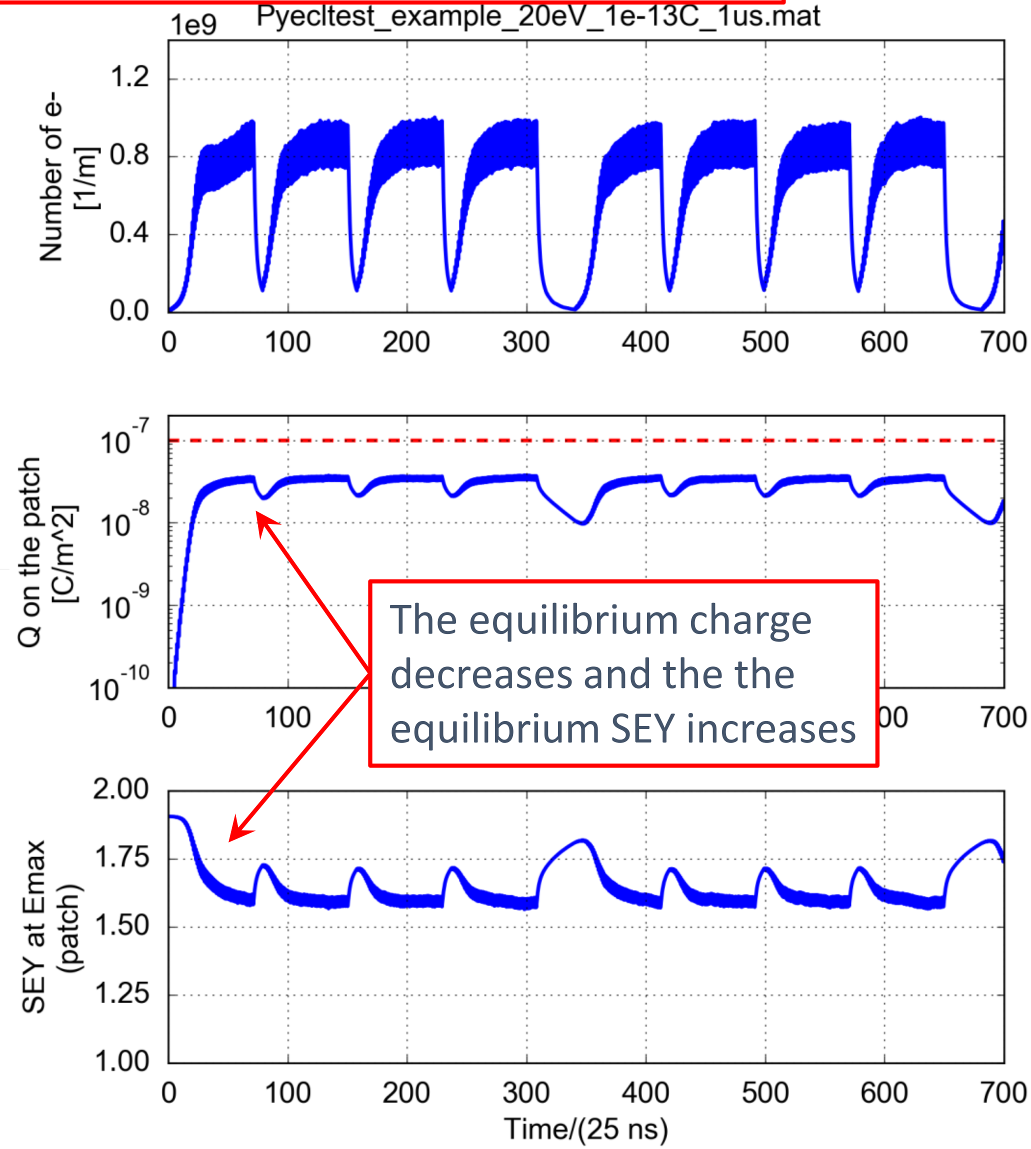
Simulation tests: discharging

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm^2 E_Q: 20.0 eV τ_i: 1.0 us

We introduce a discharging time-constant



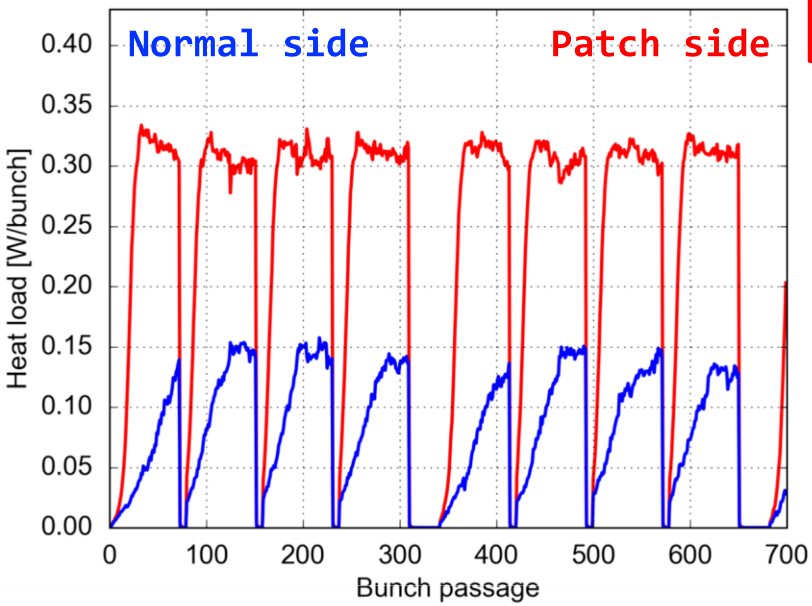


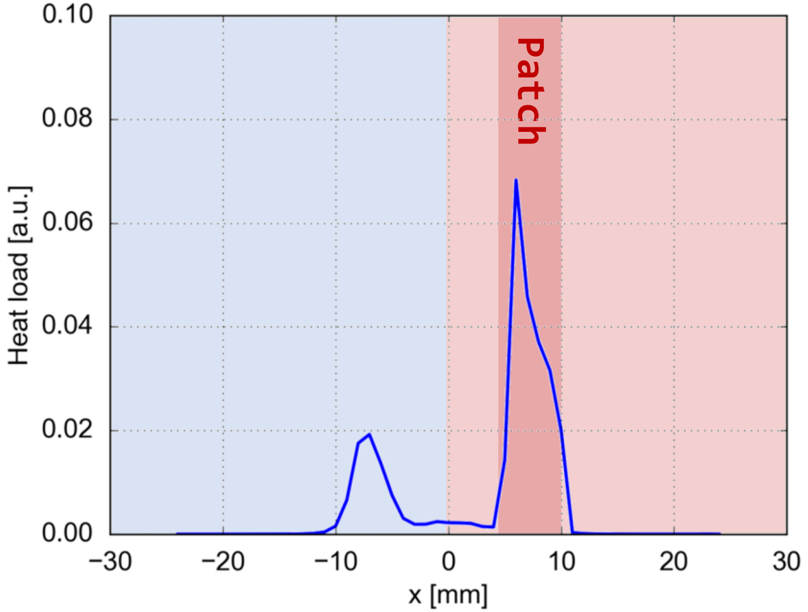


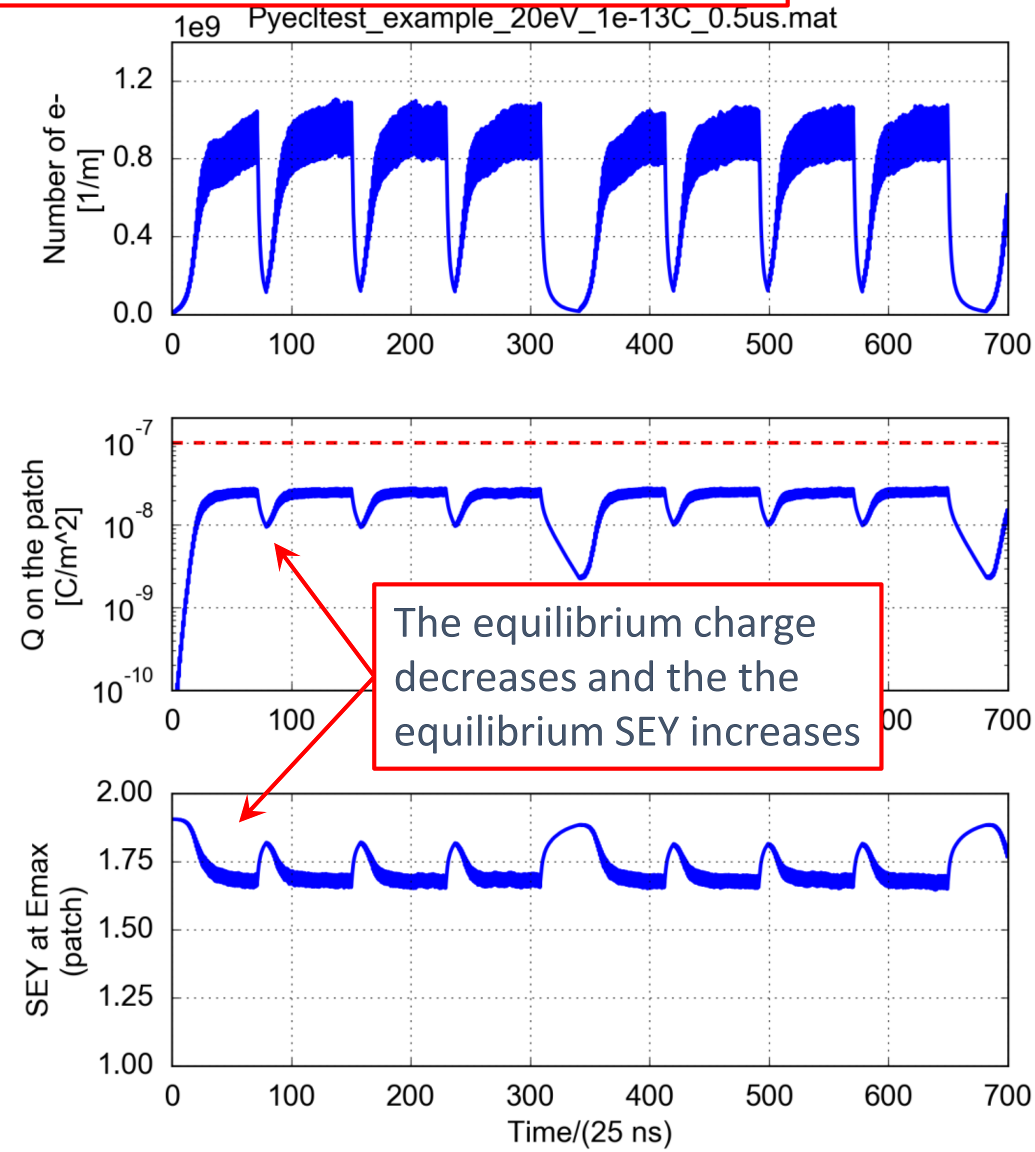
Simulation tests: discharging

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm² E_Q: 20.0 eV τ_i: 0.5 us

We introduce a discharging time-constant



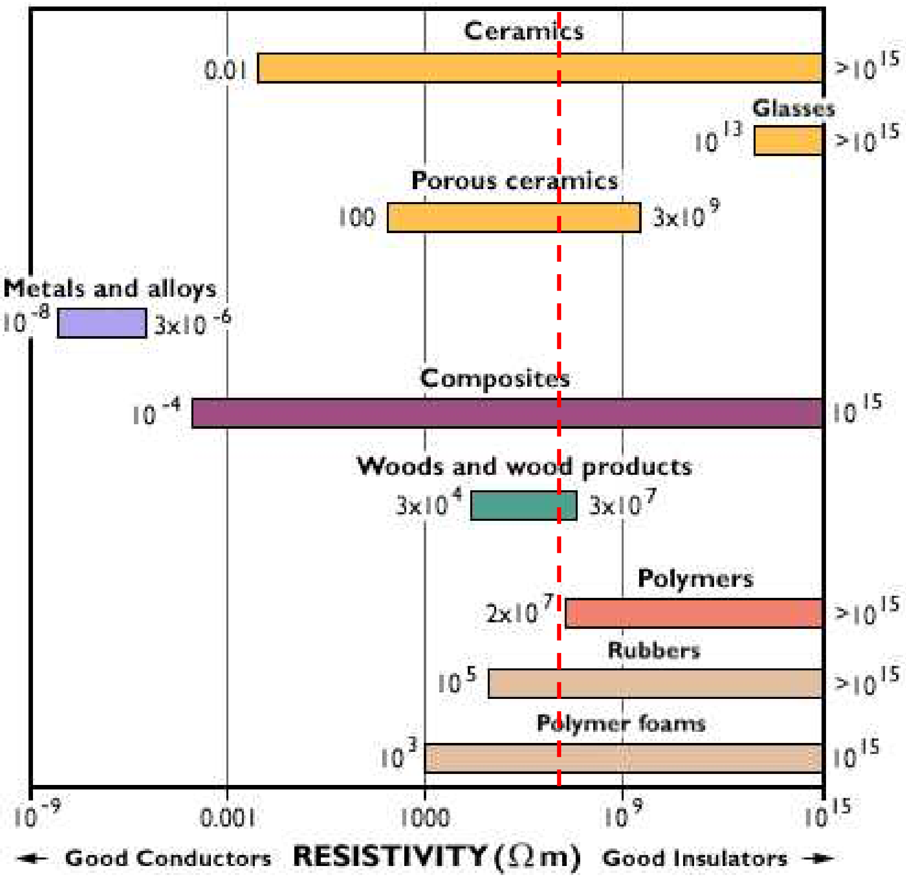




The equilibrium charge decreases and the the equilibrium SEY increases

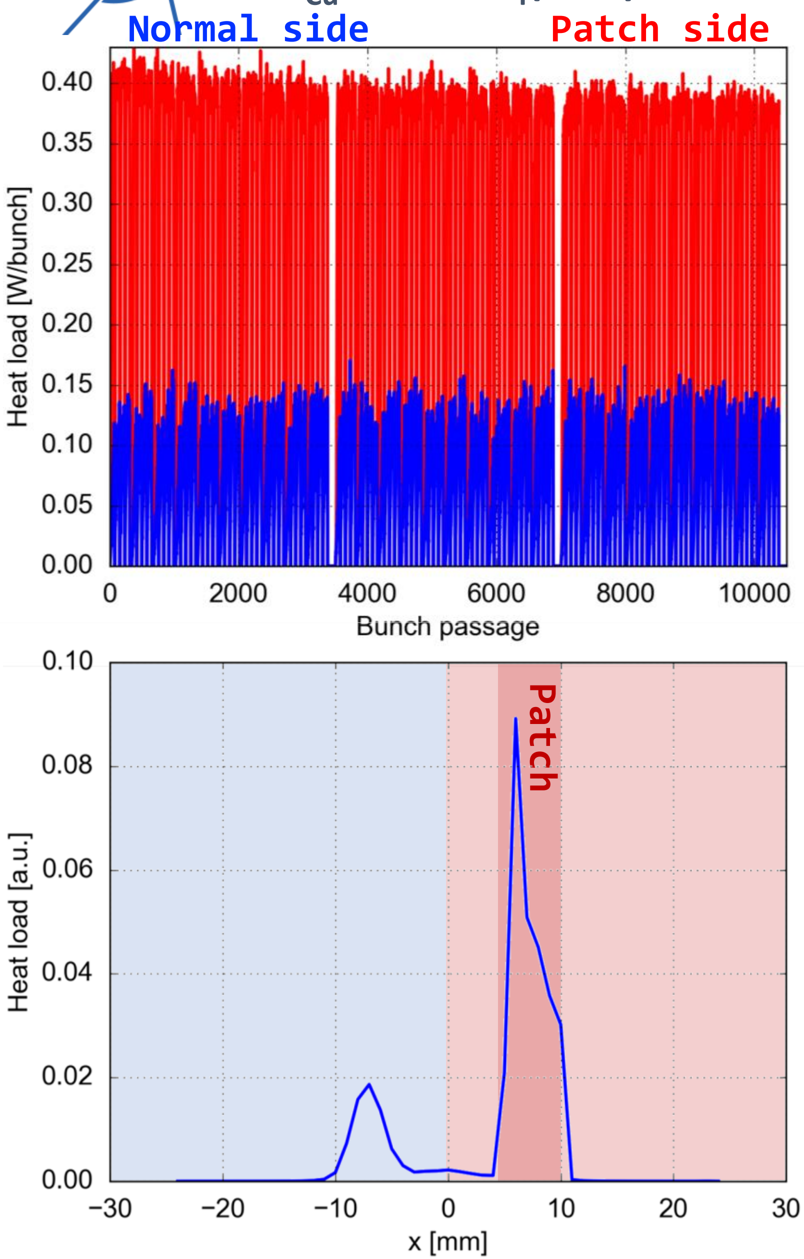
A “realistic” simulation

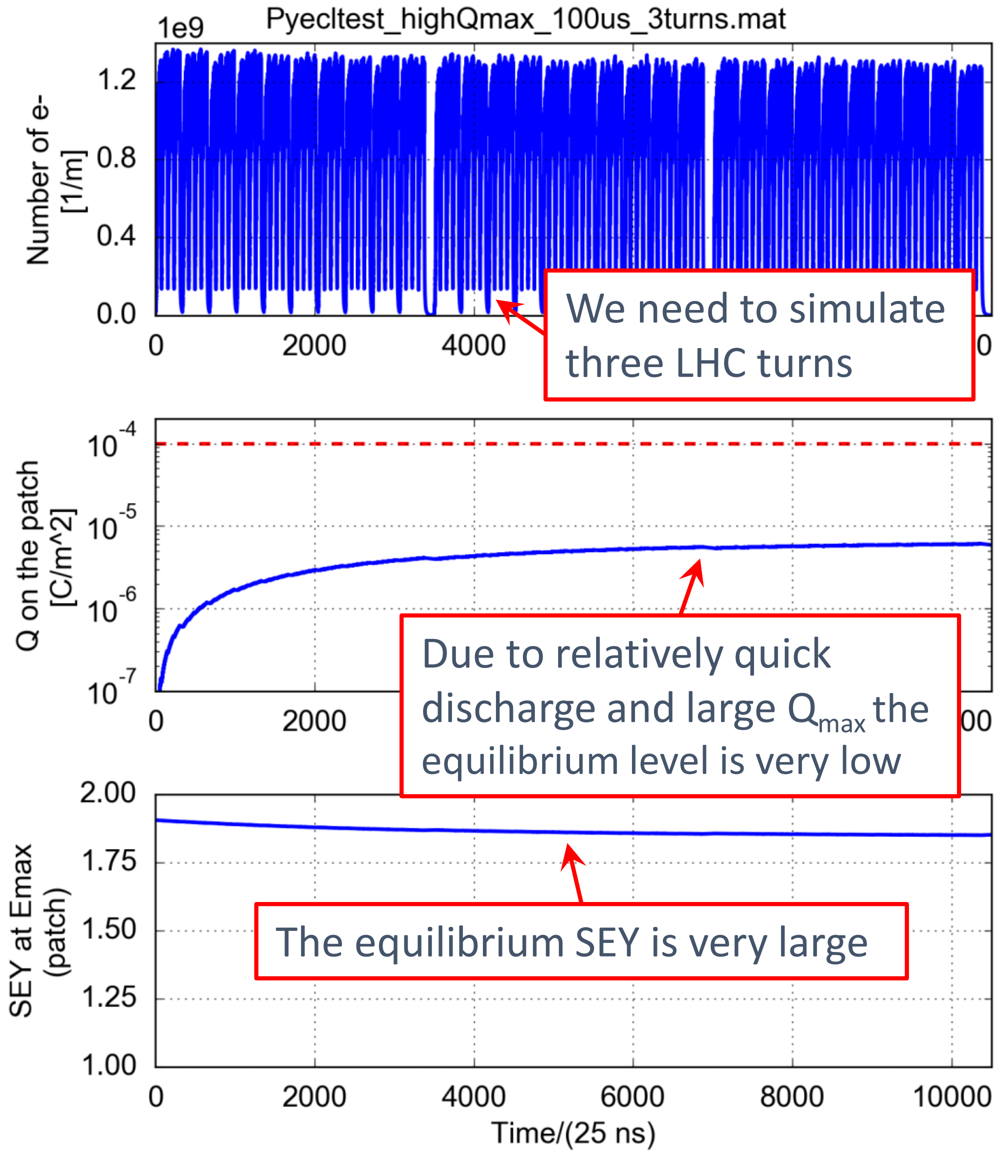
- From lab measurements on insulators we know **that Q_{max} = ~10^{-10} C/mm^2**
- $\rho_i = 10^7\ \Omega$ m → τ_i = 100 μs
- E_Q = 20 eV



Simulation tests: a realistic simulation

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-10 C/mm² E_Q: 20.0 eV τ_i: 100 us





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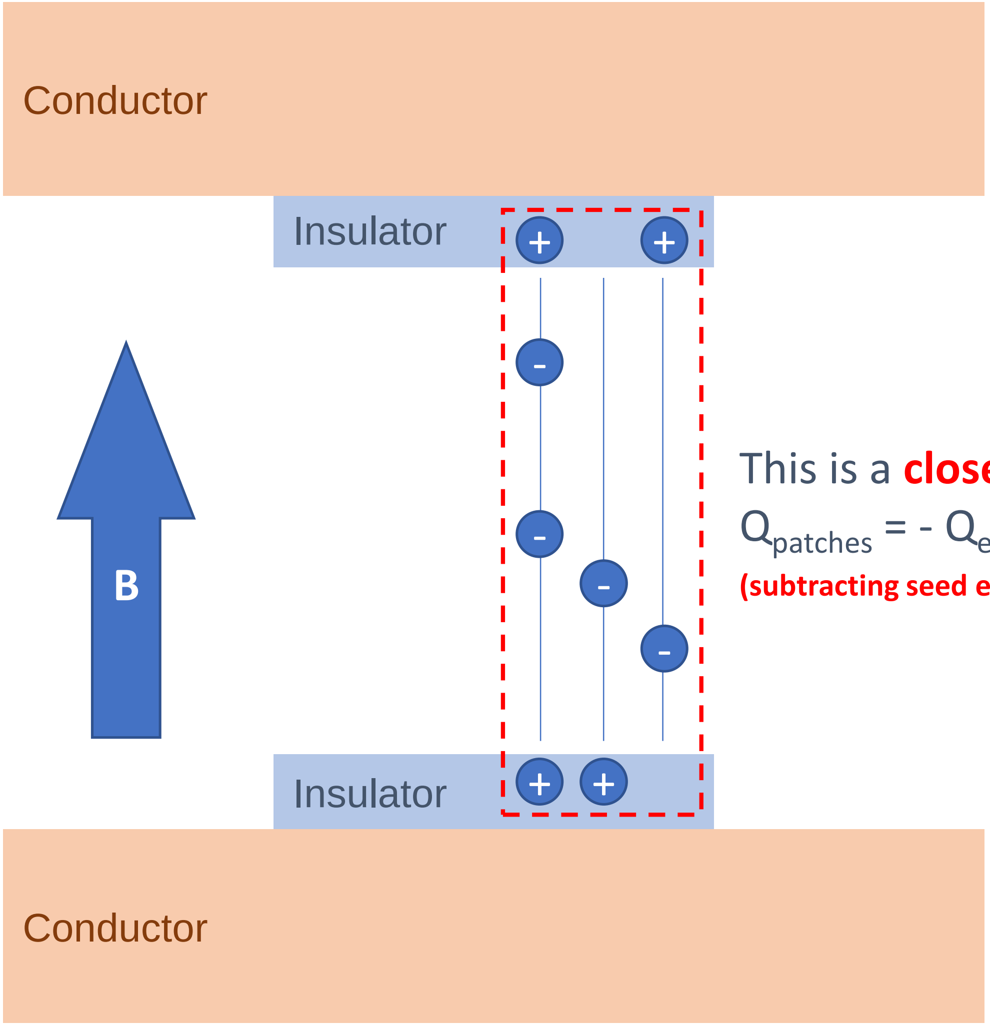
A crosscheck: two patches facing each other

- At some point **the electrons in the column will be limited by their space charge**
- This will **limit** also the charge on the patches and therefore **the decrease in SEY**



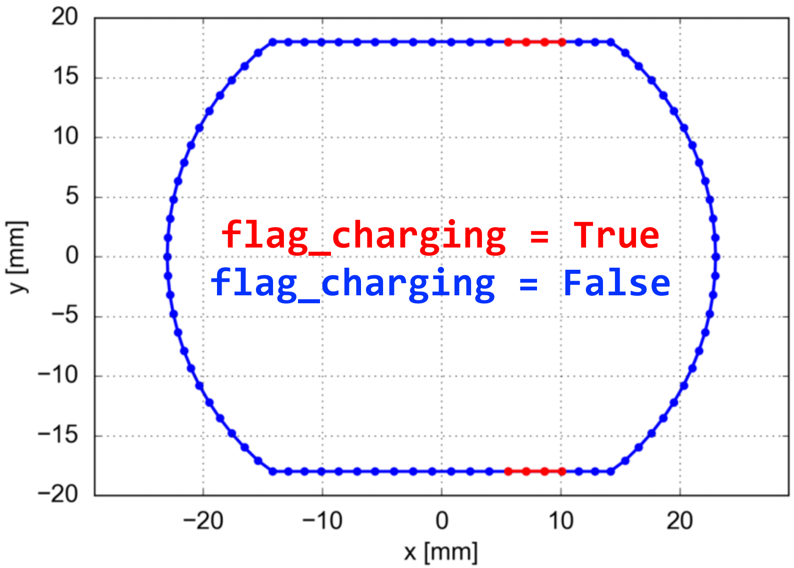
This is a **closed system**:

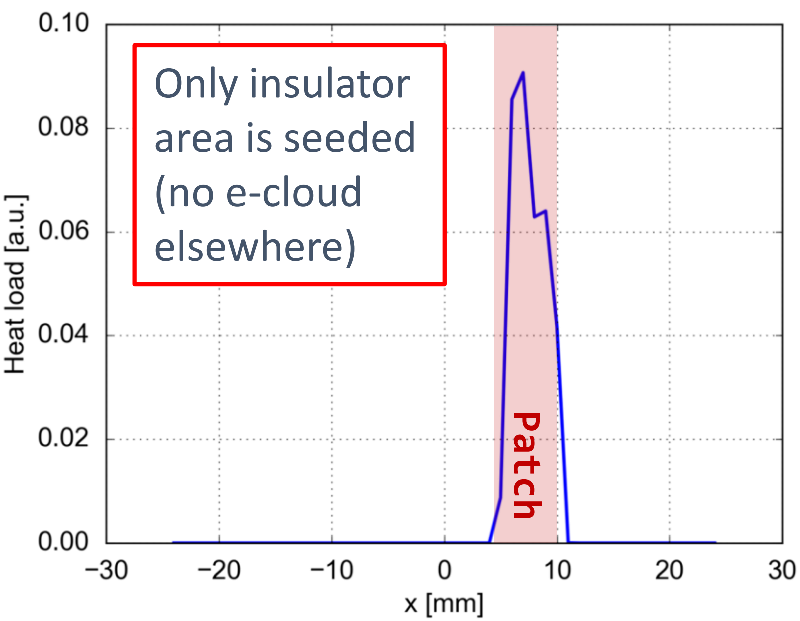
$Q_{patches} = - Q_{ele}$

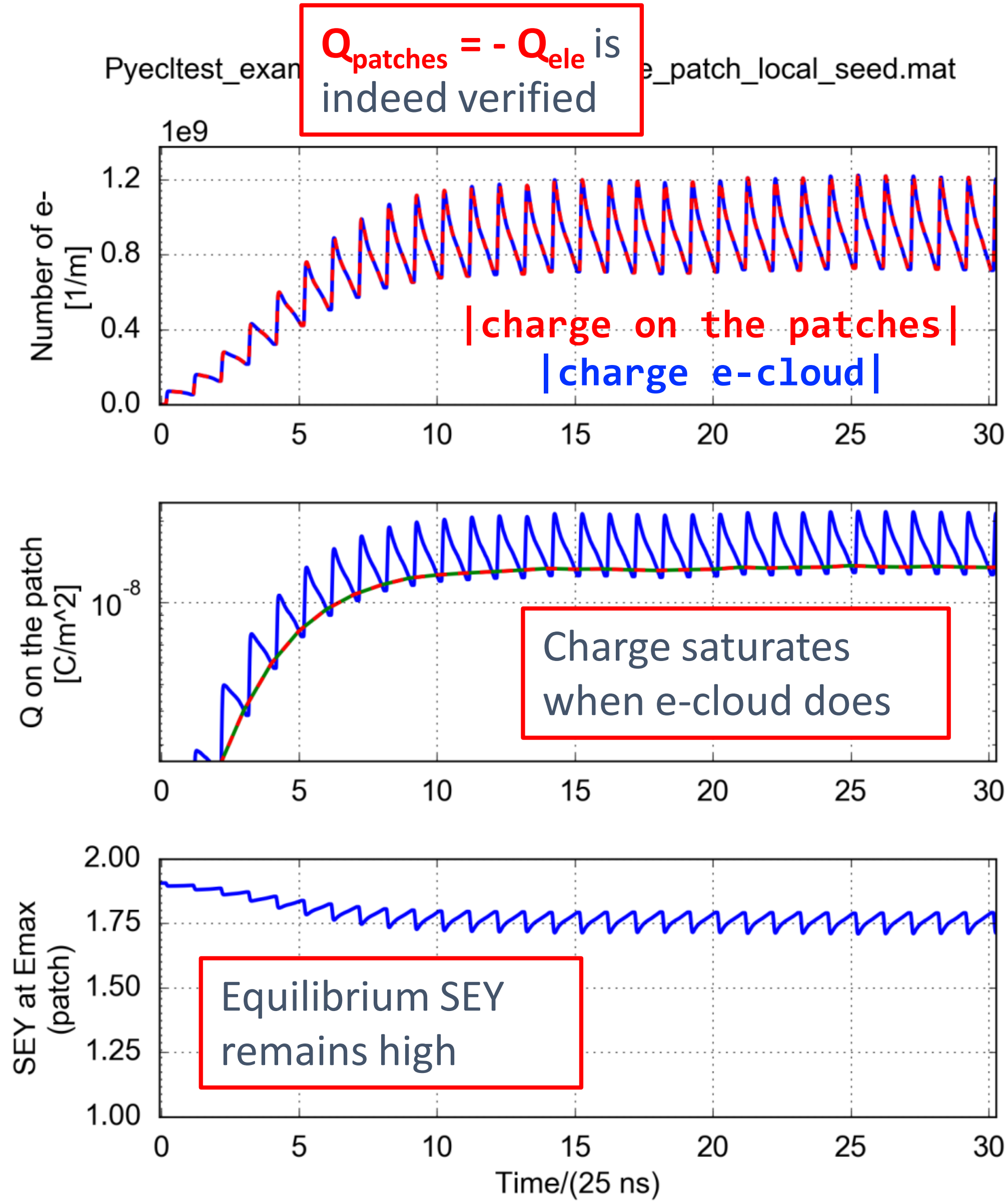
(subtracting seed electrons)

Simulation tests: two patches facing each other

δ_{Cu}: 1.3 $\delta_i(Q=0)$: 1.9 Q_{max}: 1.0e-13 C/mm² E_Q: 20 eV τ_i: Inf us







A byproduct of this study: custom output in PyECLOUD

Introduced possibility to save complex custom output during the simulations:

```
from PyECLOUD.buildup_simulation import BuildupSimulation

# Define a function that extracts a quantity of interest
def sey_at_emax_patch(sim):
    ec = sim.cloud_list[0]
    flag_patch = ec.impact_man.sey_mod.flag_charging
    i_patch = np.where(flag_patch)[0]
    Emax_patch = ec.impact_man.sey_mod.Emax_segments[flag_patch]

    nel_probe = 0.0001
    nel_out, _, _ = ec.impact_man.sey_mod.SEY_process(
        nel_impact=0*Emax_patch+nel_probe,
        E_impact_eV=Emax_patch,
        costheta_impact=0*Emax_patch+1.,
        i_impact = i_patch)
    del_emax = np.mean(nel_out)/nel_probe

    return del_emax

# Define dictionaries with custom observables, e.g. {“name”: function}
step_by_step_custom_observables = {
    'sey_at_emax_patch': sey_at_emax_patch,
    }
pass_by_pass_custom_observables = {
    'Q_segments' : lambda sim: sim.cloud_list[0].impact_man.sey_mod.Q_segments.copy()
    }
save_once_custom_observables = {
    'L_edg': lambda sim: sim.cloud_list[0].impact_man.chamb.L_edg,
    'flag_charging': lambda sim: sim.cloud_list[0].impact_man.sey_mod.flag_charging,
    }

# Build simulation object (provide custom observable)
sim = BuildupSimulation(
    step_by_step_custom_observables=step_by_step_custom_observables,
    pass_by_pass_custom_observables=pass_by_pass_custom_observables,
    save_once_custom_observables=save_once_custom_observables,
    )

# Run simulation (custom observables will be saved in the output file)
sim.run(t_end_sim = None)
```

Full example at: https://github.com/PyCOMPLETE/PyECLOUD/tree/master/other/scriptable_simulation

Summary

- In the presence of an **insulating layer** on a beam pipe, **charge can accumulate** on the surface
- If the layer is **sufficiently thin**, there is **no significant field induced in the pipe** (charge induced in the conductor behind)
- Experiments show that the **accumulation of charge affects also the Secondary Electron Yield**, in particular it pushes it towards 1.0
- The surface can **discharge** due to different mechanisms. Two effects were considered here
  - **Absorption of low-energy electrons** (SEY < 1.0 at at very low energies)
  - **Conductivity is poor** but not zero
- **PyECLOUD** has been **extended** to include these mechanisms and investigate the dynamics
- Simulations show that an **equilibrium charge is found** as a result of a balance between charging and discharging mechanisms

  → this results in an **equilibrium SEY** on the patch surface
- For some **plausible numbers (δ_i = 1.9, Q_{max}=1.0e-10 C/mm^2, τ_i: 100 us)**, due to a relatively fast discharging, the **SEY can remain quite high** with a visible effect on the heat loads
- For quantitative estimates a **lab characterization** of the insulator is **needed**… stay tuned…