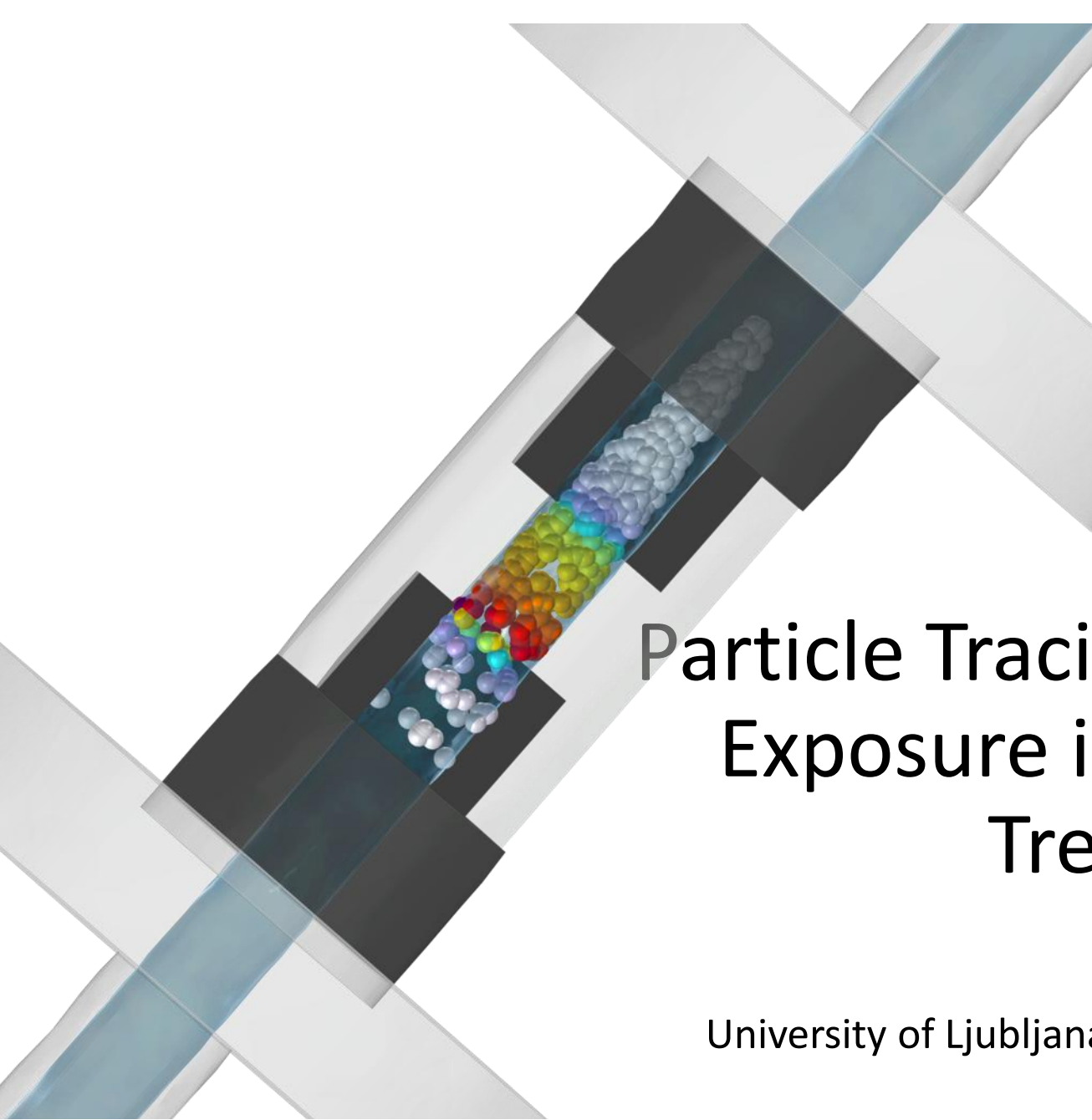




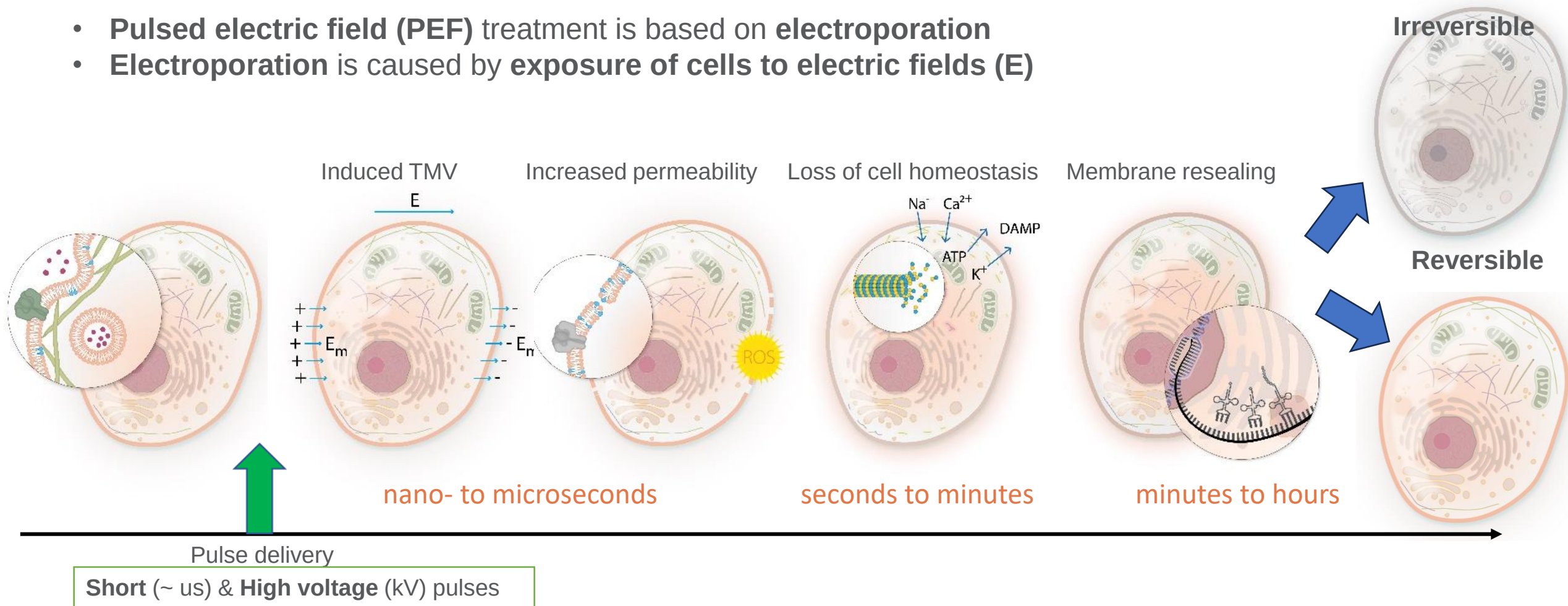
# Particle Tracing for Electric and Thermal Exposure in a Continuous-Flow PEF Treatment Chamber

Peter Lombergar

University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia

# Pulsed Electric Field (PEF) treatment

- Pulsed electric field (PEF) treatment is based on **electroporation**
- Electroporation is caused by **exposure of cells to electric fields (E)**



# Pulsed Electric Field (PEF) treatment

- Pulsed electric field (PEF) treatment is based on **electroporation**
- Electroporation is caused by **exposure of cells to electric fields (E)**
- **Use:** microbial inactivation (juices, milk, wine), extraction of valuable compounds
- **Advantage: non-thermal** mechanism - better preserves sensory, nutritional and functional properties of food



PEF processed juice.

PEF processing is applied for extended shelf-life and the juice is labeled as " fresh "

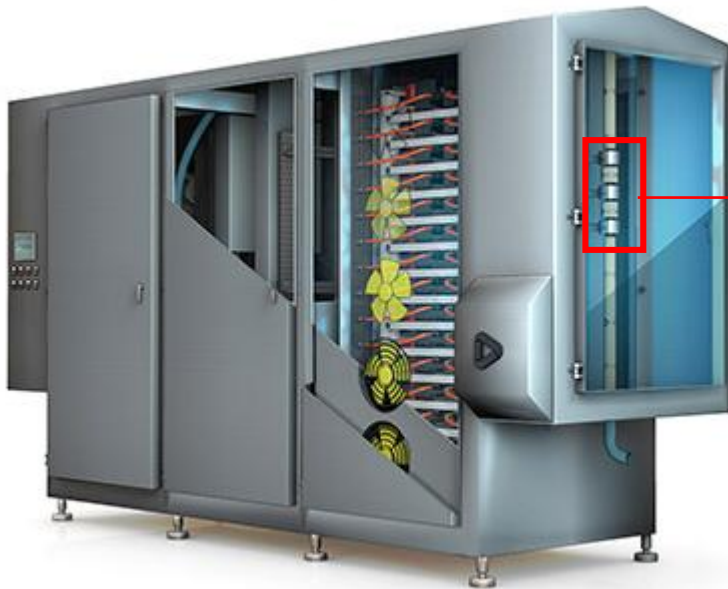
\*Kempkes (2017), Handbook of Electroporation, Springer — Fig. 14

- **Goal:** achieve sufficient exposure to electric field with minimal thermal damage

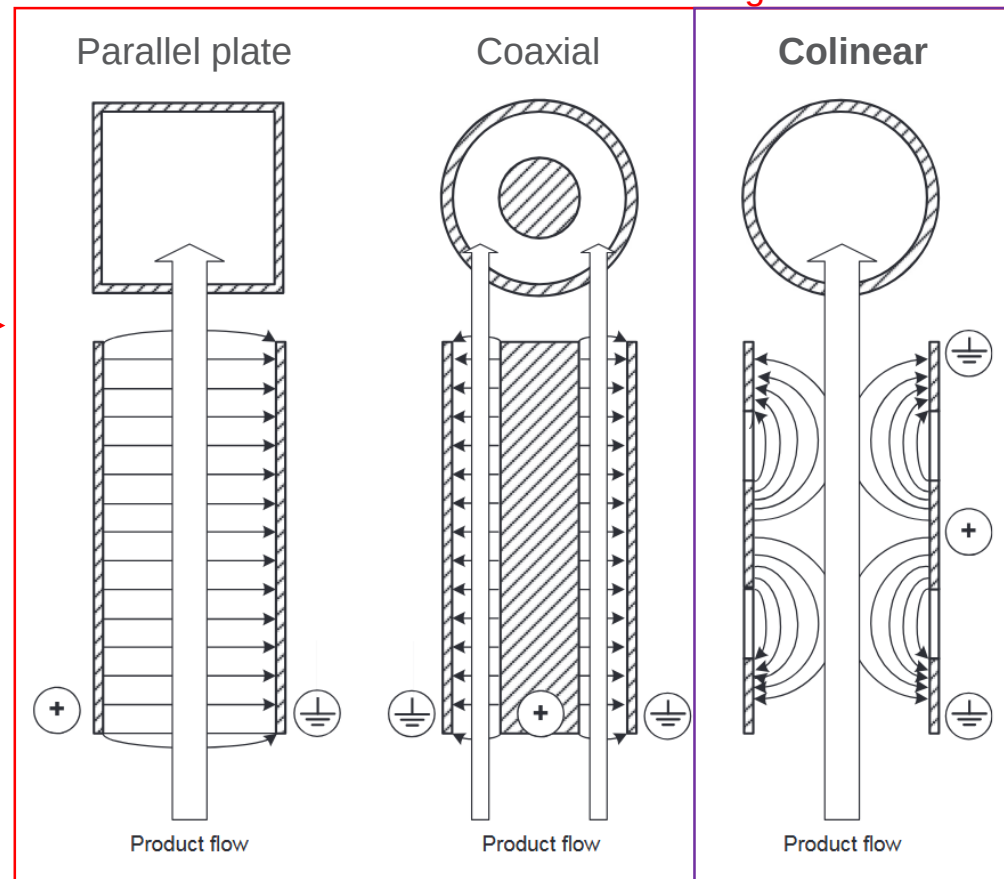
# Continuous-Flow PEF treatment chamber

A key component of the PEF treatment system is the **treatment chamber**, where the product is exposed to electrical pulses

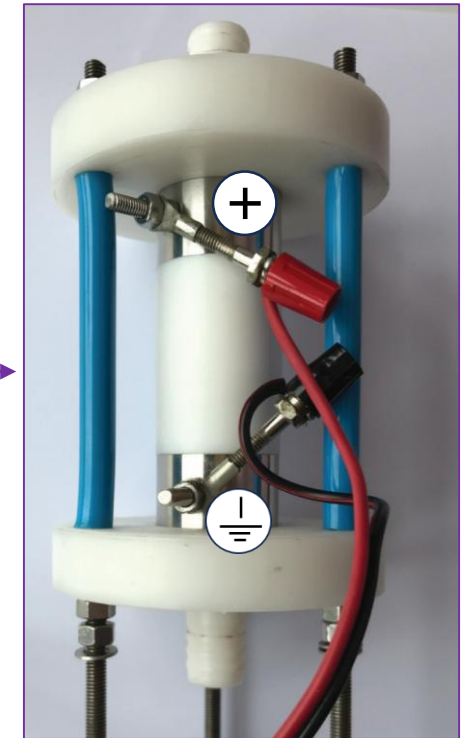
Continuous-Flow PEF system



Different PEF Treatment chamber designs



Colinear treatment chamber



# Continuous-flow PEF treatment parameters

“The electric field strength and the treatment time are the main process parameters that define the PEF treatment intensity.”

Raso, J. et al. *Innovative Food Science & Emerging Technologies* **37**, 312–321 (2016)

Set parameters:

- |                                |                   |
|--------------------------------|-------------------|
| • Amplitude of electric pulses | $U_0$ (~ kV)      |
| • Pulse width/duration         | $t_p$ (~ $\mu$ s) |
| • Pulse repetition frequency   | $f$ (~ Hz)        |
| • Flow rate                    | $F$ (~ l/h)       |

Calculated/reported parameters:

- Electric field strength as VDR
- Number of pulses received by the product:
- Treatment time:
- Total specific energy input:

$$E \approx VDR = \frac{U_0}{d_{el}}$$

Assumes a uniform field

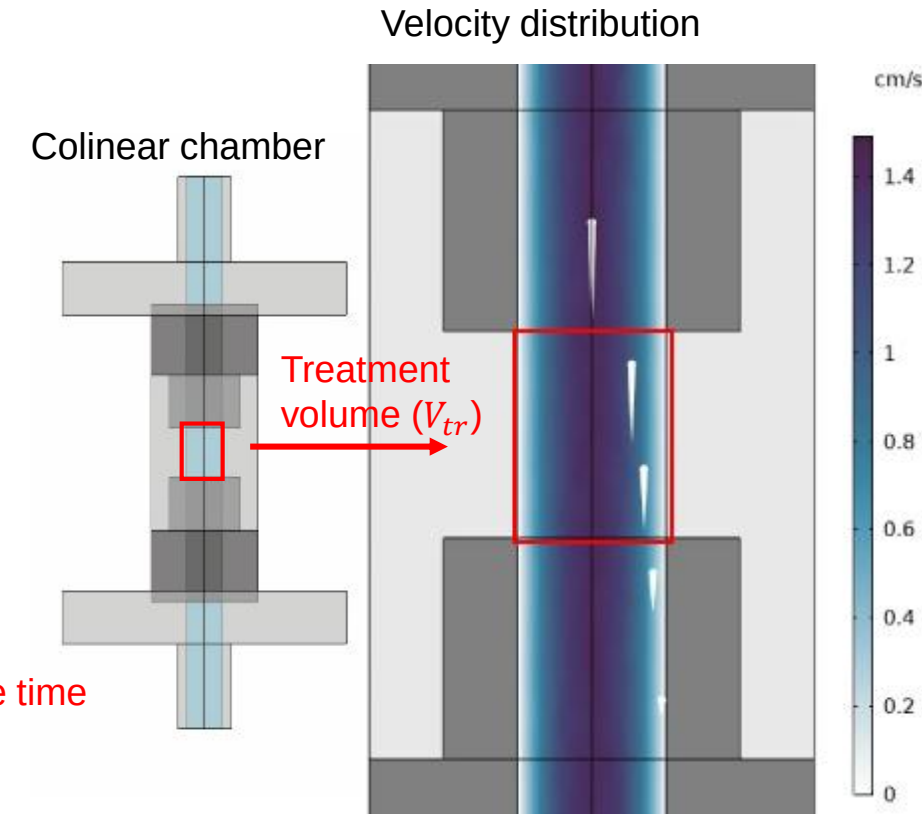
$$n = f \cdot t_r$$

$$t_r = \frac{V_{tr}}{F}$$

Avg. Residence time

$$t_{tr} = n \cdot t_p$$

$$W_T = n \cdot W_{pulse}$$

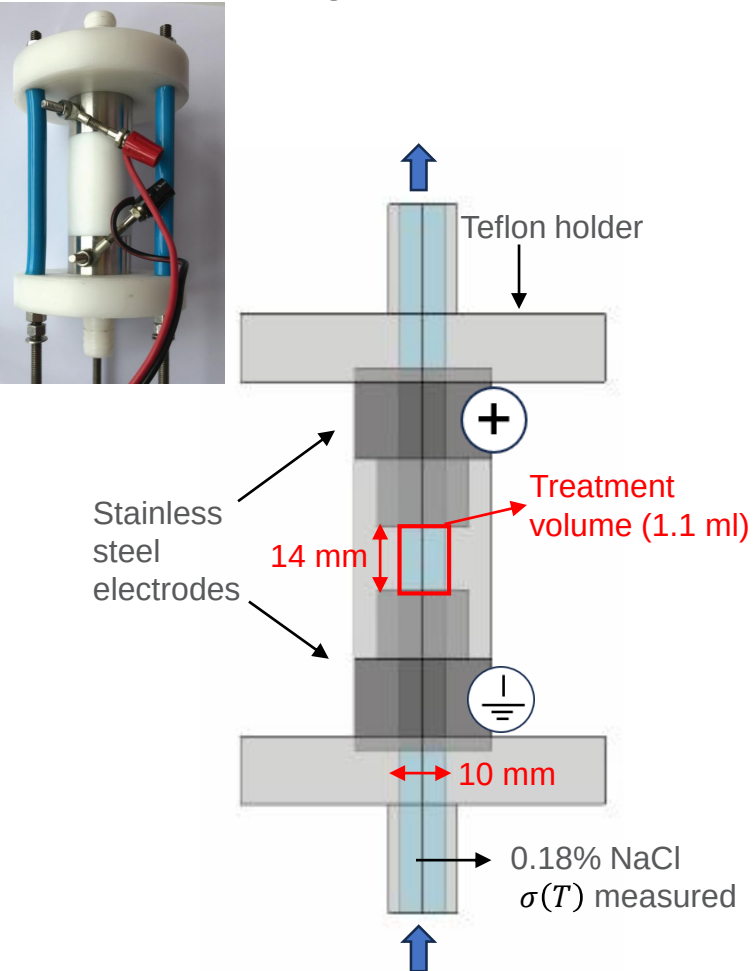


Average values received by the product - can vary substantially depending on the trajectory of specific cells or particles within the treatment chamber

**Idea:** Evaluate E and T exposure for individual cells as they flow through the chamber

# Methods: Coupled Electro–thermal-flow model

## Geometry & Materials



## Coupled Electro–thermal-flow model

Stationary study

Laminar Flow (spf)

Time Dependent study

$u(x,y,z)$

Heat Transfer in Solids and Fluids (ht)

$\sigma(T)$

$Q(t)$

Electric Currents (ec)

Events (ev)

Two different approaches:

- “Pulse resolved” method:

$$U=U(t) \text{ \& } Q(t) = \sigma(T)E(t)^2$$

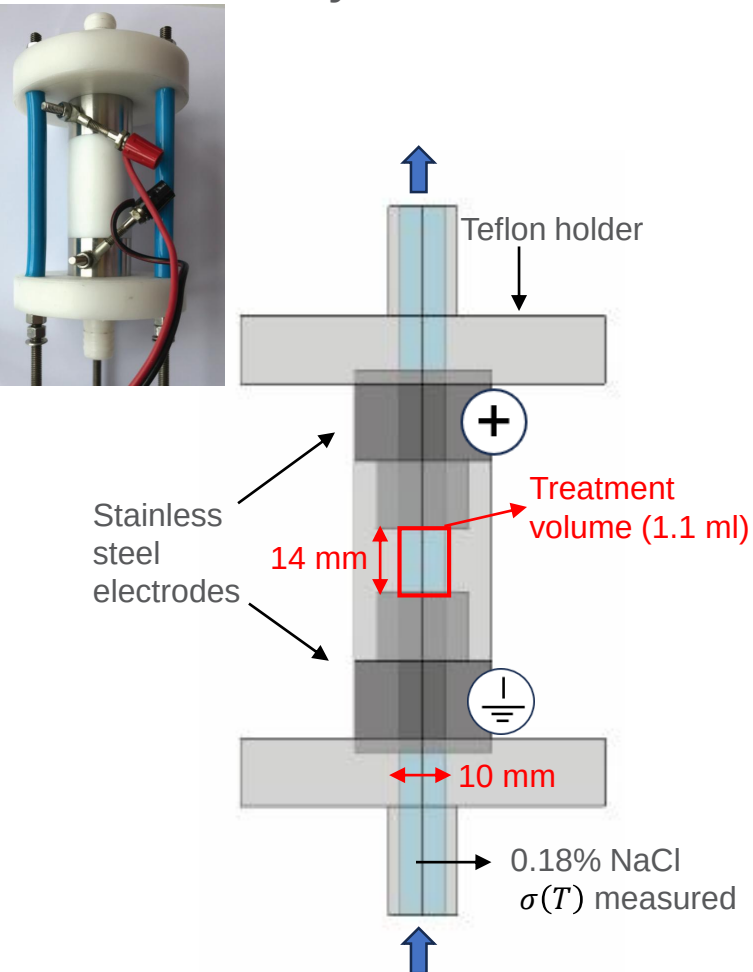
- “Duty cycle” method:

$$U= U_0 \text{ \& } Q = \text{duty} \cdot \sigma E^2; \text{ duty} = f t_{\text{pulse}}$$

\*run to thermal periodic steady state

# Methods: Particle tracing

## Geometry & Materials



## Coupled Electro-thermal-flow model

### Stationary study

Laminar Flow (spf)

### Time Dependent study

Heat Transfer in Solids and Fluids (ht)

$\sigma(T)$

$Q(t)$

Electric Currents (ec)

Events (ev)

### Two different approaches:

- “Pulse resolved” method:

$$U=U(t) \quad \& \quad Q(t) = \sigma(T)E(t)^2$$

- “Duty cycle” method:

$$U=U_0 \quad \& \quad Q = \text{duty} \cdot \sigma E^2; \quad \text{duty} = f \cdot t_{\text{pulse}}$$

\*run to thermal periodic steady state

## Cell-level exposure to E & T

### Time Dependent study

Particle Tracing for Fluid Flow (fpt)

Massless particles ( $St \ll 1$ )  
follow the streamlines exactly

### Two release strategies:

- **5 representative particles**  
volumetric flow percentiles: 0% (centerline), 50%, 75%, 90%, 99% (hugging the wall)
- **10,000 particles**  
**representative sample of the treated product**  
Release density  $\propto$  velocity magnitude  
10 × 1,000 staggered across one pulse period

\*run until the slowest particle exits

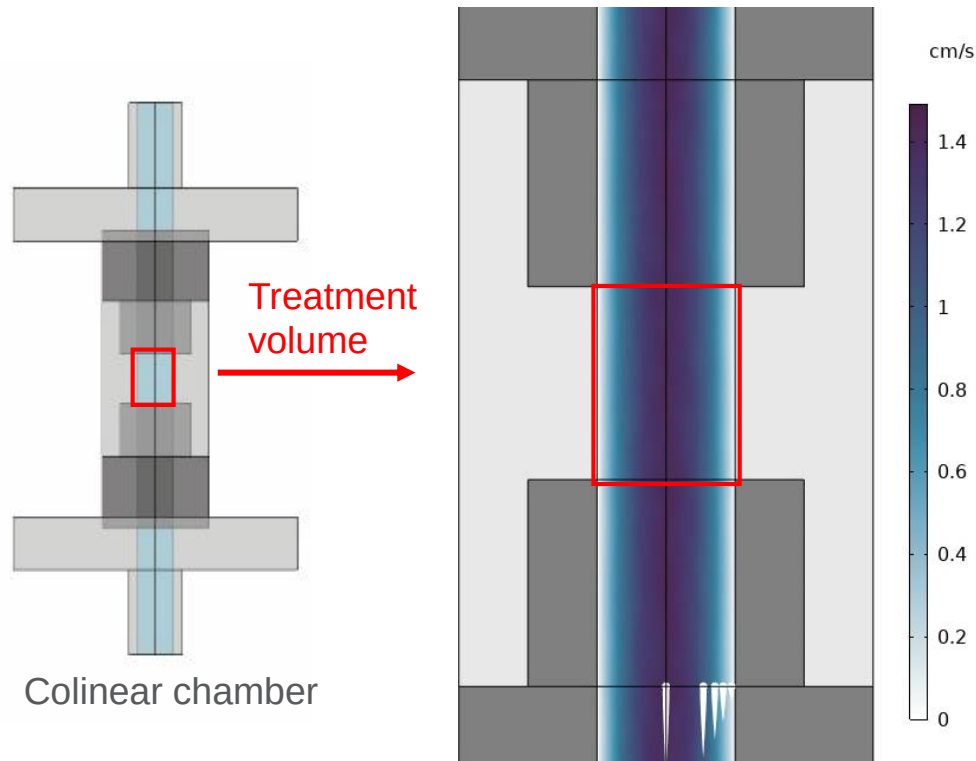
LiveLink™ for MATLAB®

$E(t)$  and  $T(t)$  extracted along every trajectory for post-processing

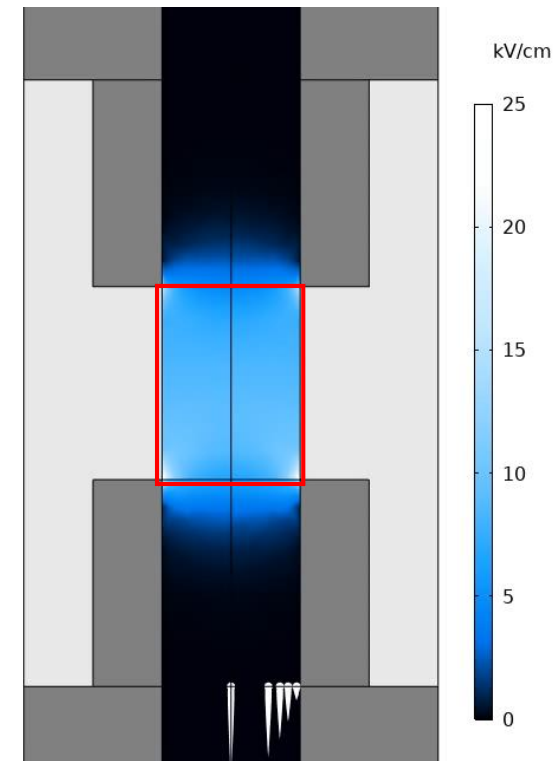
# Exposure of particles to E & T

**Continuous-flow PEF protocol:**  $U_0 = 14$  kV,  $F = 2$  l/h,  $t_p = 100$   $\mu$ s,  $f = 1$  Hz  $\rightarrow$   **$n = 2$  pulses received by the product**

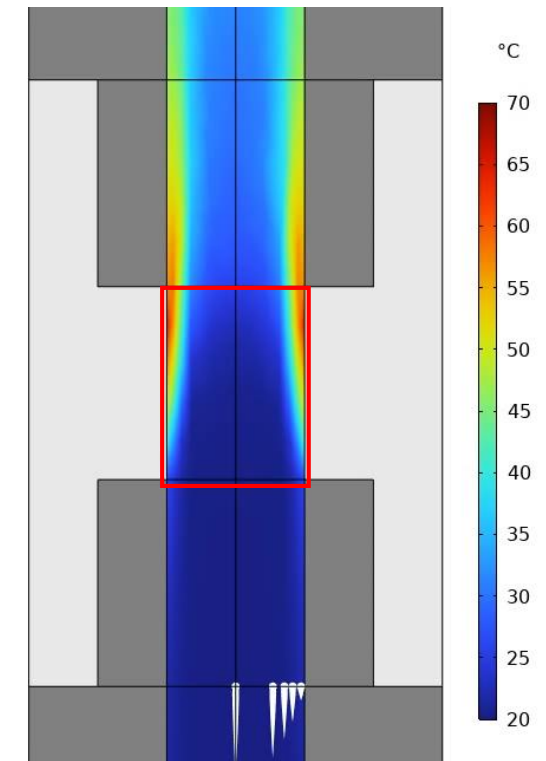
Velocity distribution



Electric field distribution

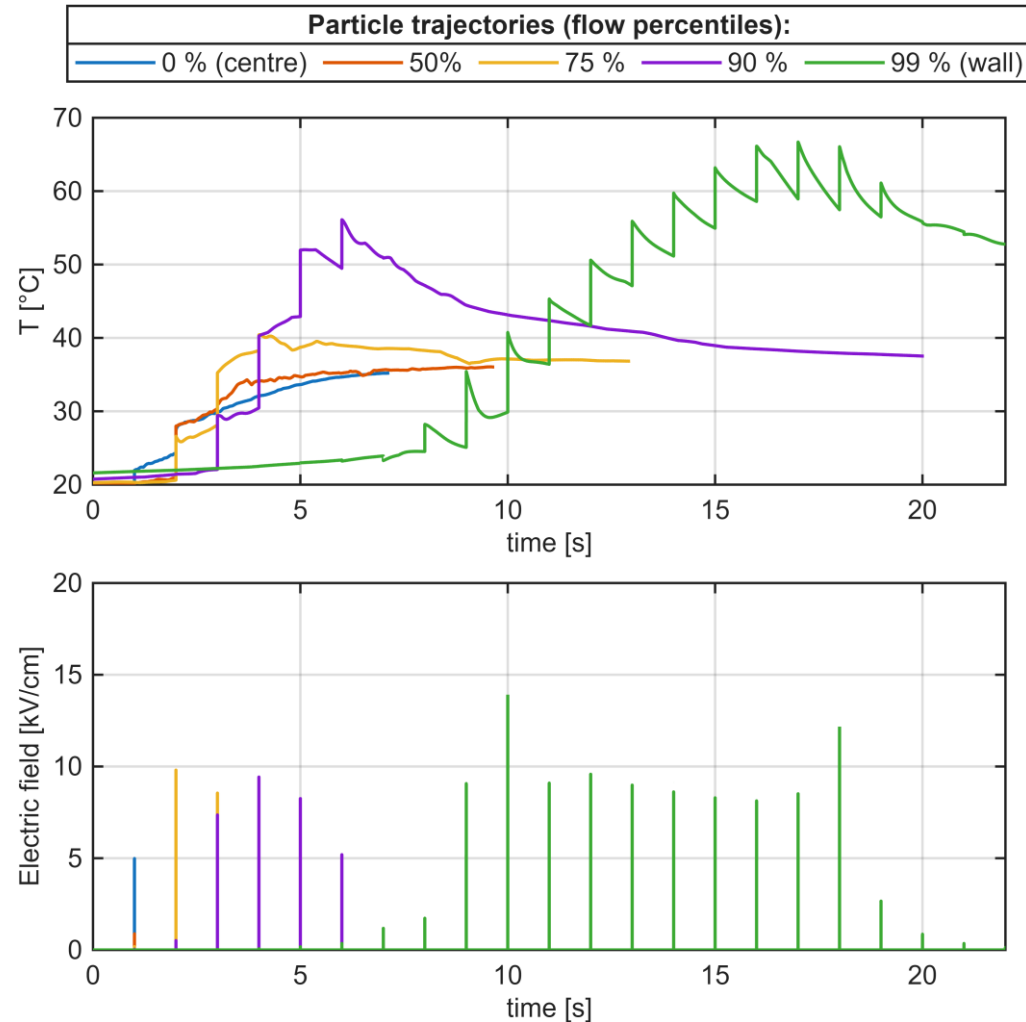


Temperature distribution

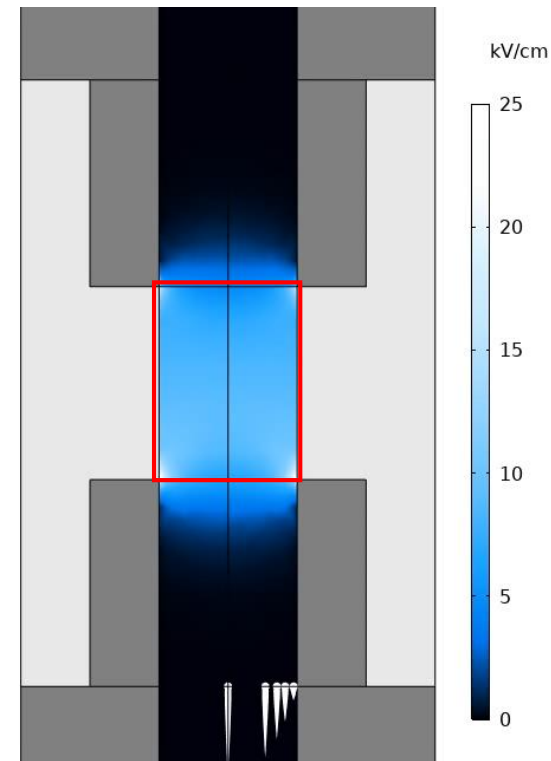


# Exposure of particles to E & T

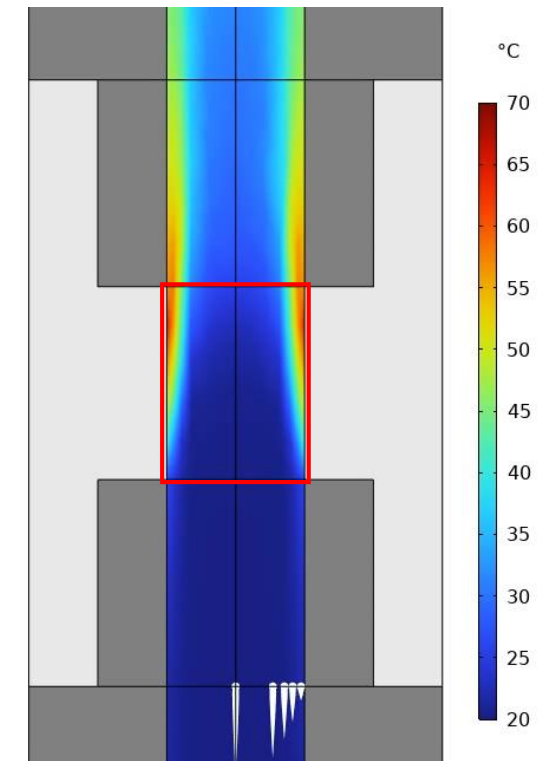
**Continuous-flow PEF protocol:**  $U_0 = 14 \text{ kV}$ ,  $F = 2 \text{ l/h}$ ,  $t_p = 100 \text{ } \mu\text{s}$ ,  $f = 1 \text{ Hz}$  →  **$n = 2$  pulses received by the product**



Electric field distribution



Temperature distribution



Same PEF protocol, five very different treatments

# Duty cycle vs Pulse resolved approach

$$t_p = 100 \mu\text{s}, f = 1 \text{ Hz} \rightarrow n=2$$

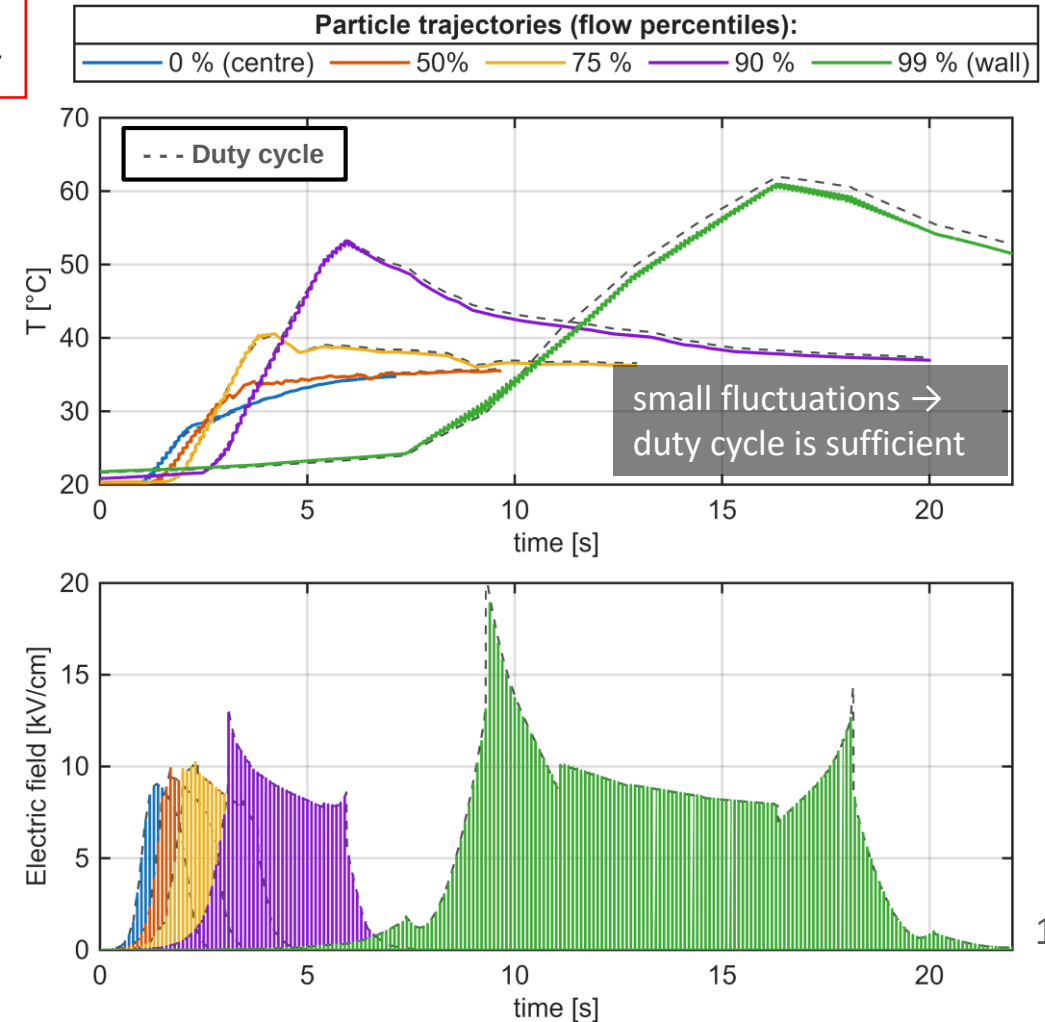
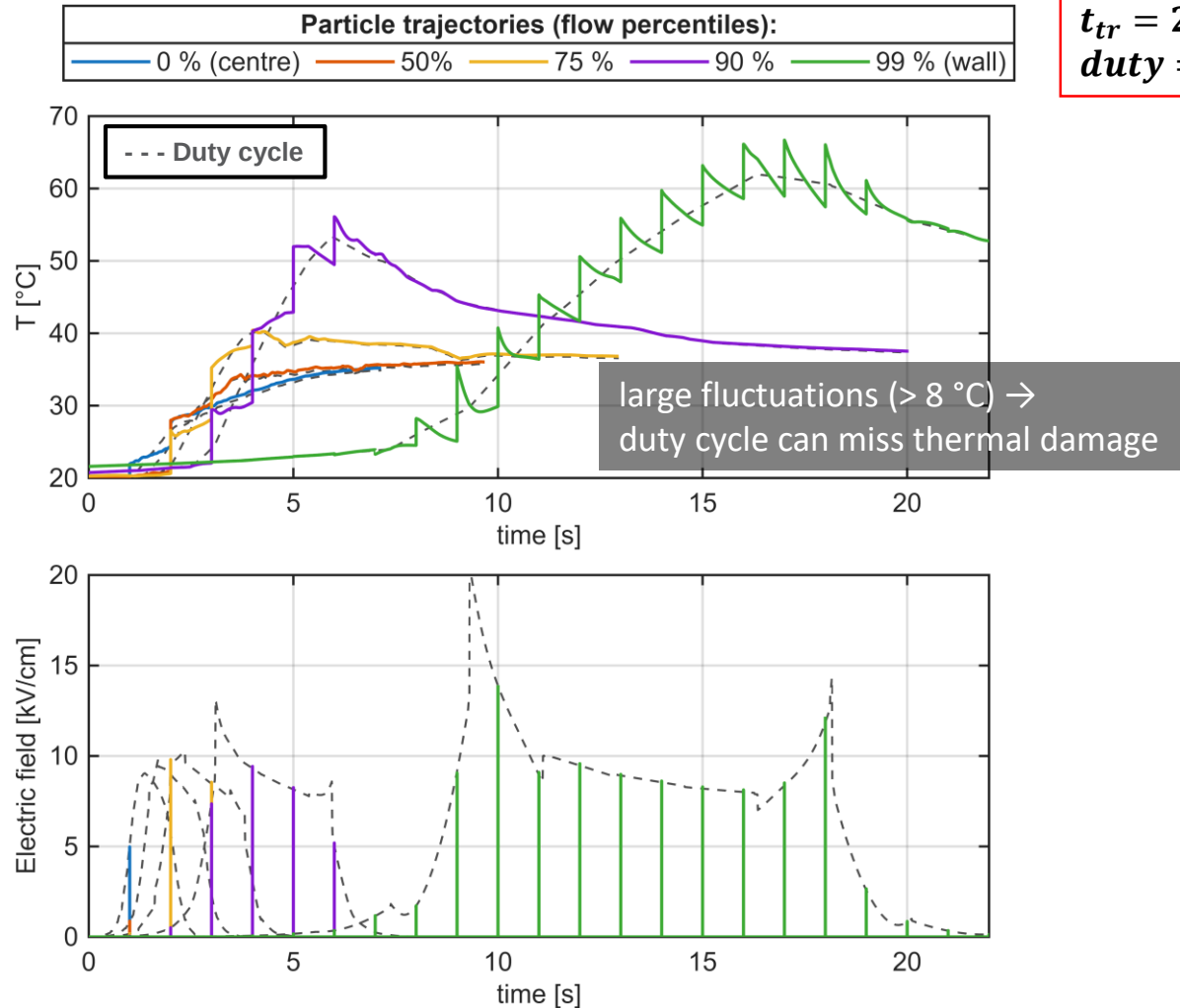
$$U_0 = 14 \text{ kV},$$

$$F = 2 \text{ l/h}$$

$$t_{tr} = 200 \mu\text{s}$$

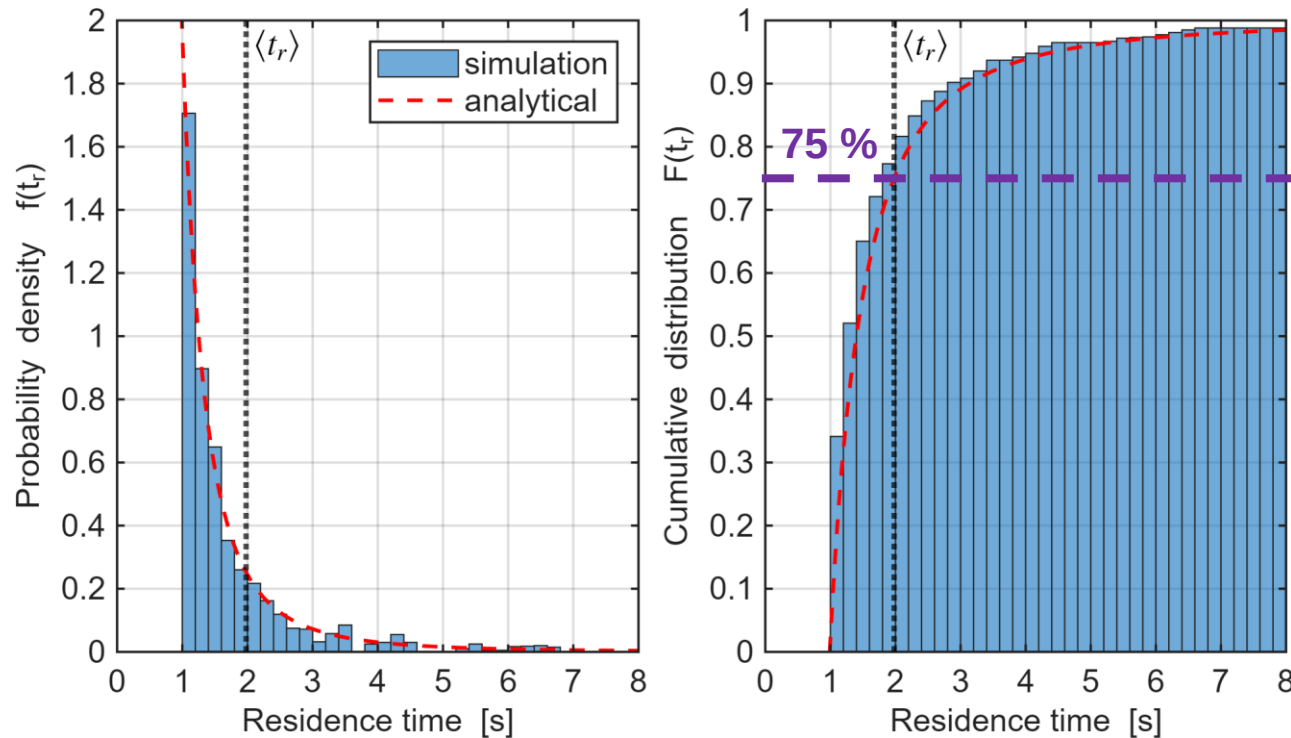
$$\text{duty} = 1e^{-4}$$

$$t_p = 10 \mu\text{s}, f = 10 \text{ Hz} \rightarrow n=20$$



# Residence time distribution of treated product

fully developed laminar pipe flow has a closed-form solution - so the tracked particles can be checked against theory.



mean residence time:  
1.89 s **simulated**  
1.98 s **analytical**

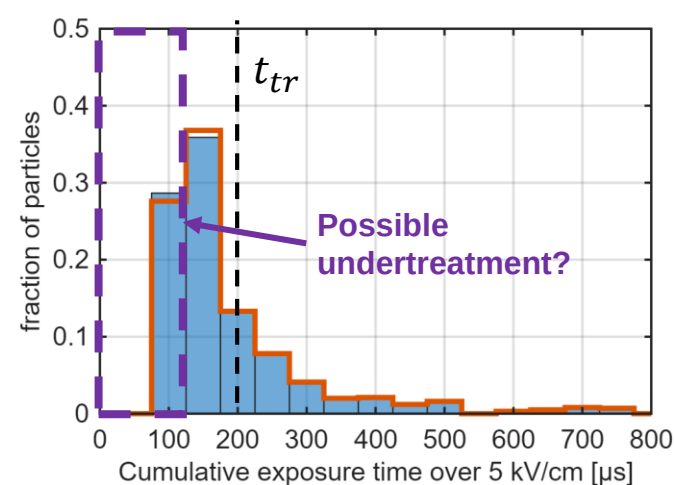
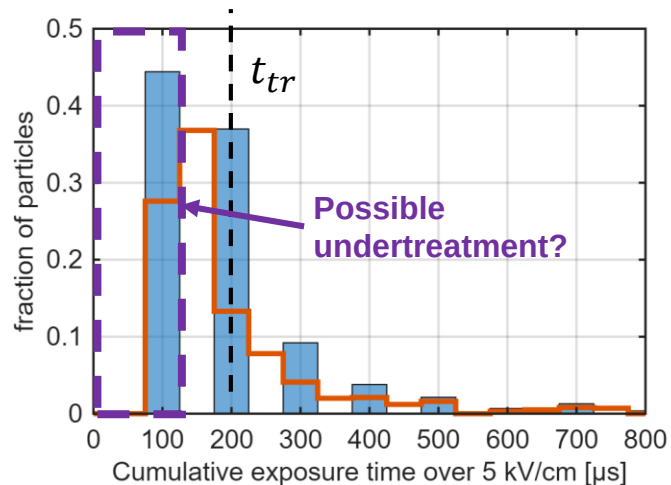
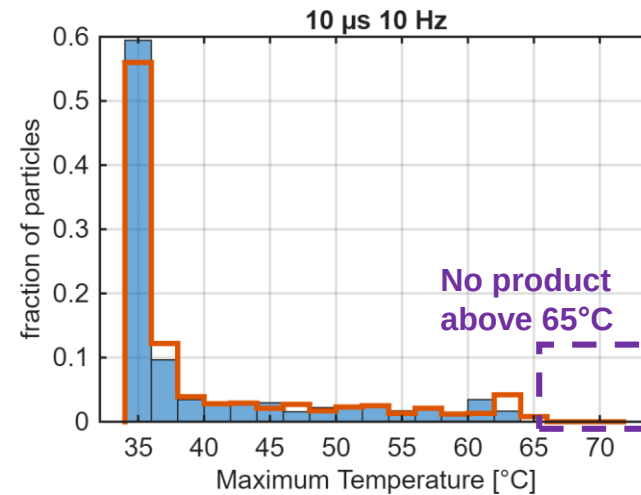
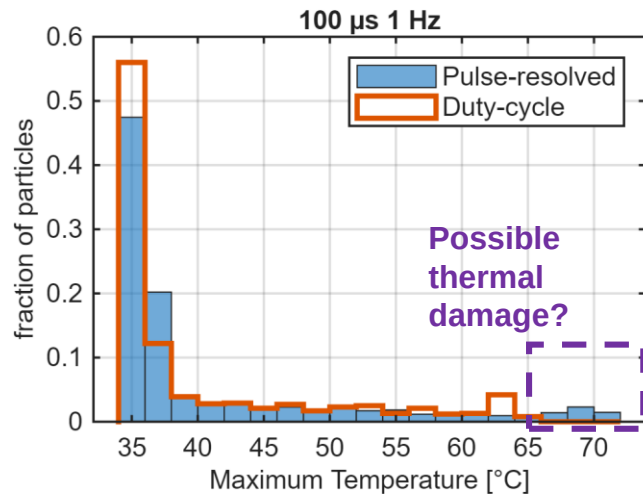
**75%**  
of the product is below  
mean residence time

$$F(t_r) = 1 - \frac{\langle t_r \rangle^2}{4t_r^2}$$

$$F(\langle t_r \rangle) = 1 - \frac{1}{4} = 0.75$$

exact for any laminar pipe flow

# Exposure of the treated product to E and T



## Two “identical” protocols:

- $t_{tr} = 200 \mu$ s
- VDR = 10 kV/cm
- $W_t = 71$  kJ/kg

## Maximum temperature:

100  $\mu$ s, 1 Hz - a few % of product above 65 °C  
 10  $\mu$ s, 10 Hz - none of product above 65 °C

## A large fraction receives half the reported field for half the reported time:

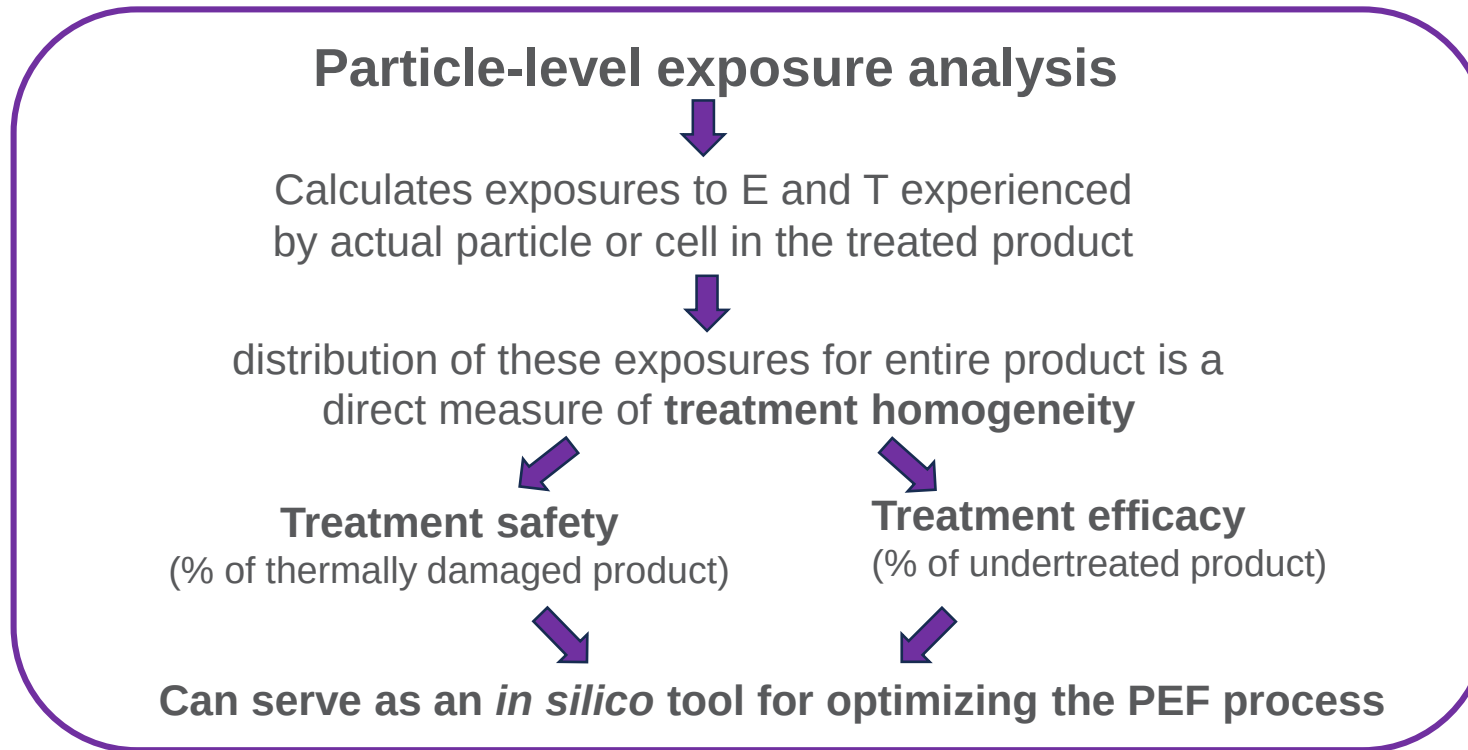
- 100  $\mu$ s, 1 Hz ~ 44%
- 10  $\mu$ s, 10 Hz ~ 28%

\*Cumulative exposure time over kV/cm <125  $\mu$ s

## Duty-cycle approximation:

- 10  $\mu$ s, 10 Hz - matches the pulse-resolved result
- 100  $\mu$ s, 1 Hz - misses the hot tail and the discrete steps

# Key findings



## Pulse-resolved vs duty-cycle approach:

- Short, frequent pulses (large n): Duty cycle approach is sufficient
- Few, long pulses (small n): Pulse-resolved approach is needed