FLASH Radiotherapy with hIgh Dose-rate particle beAms

# UHDR Intertrack effects analysis: a new method

Lorenzo Castelli

Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

UNIVERSITAS STUDIORUM ATHESINA

CNRNANO NEST PISA

# What, why, and How

**(What)** We want to know how close tracks are in UHDR

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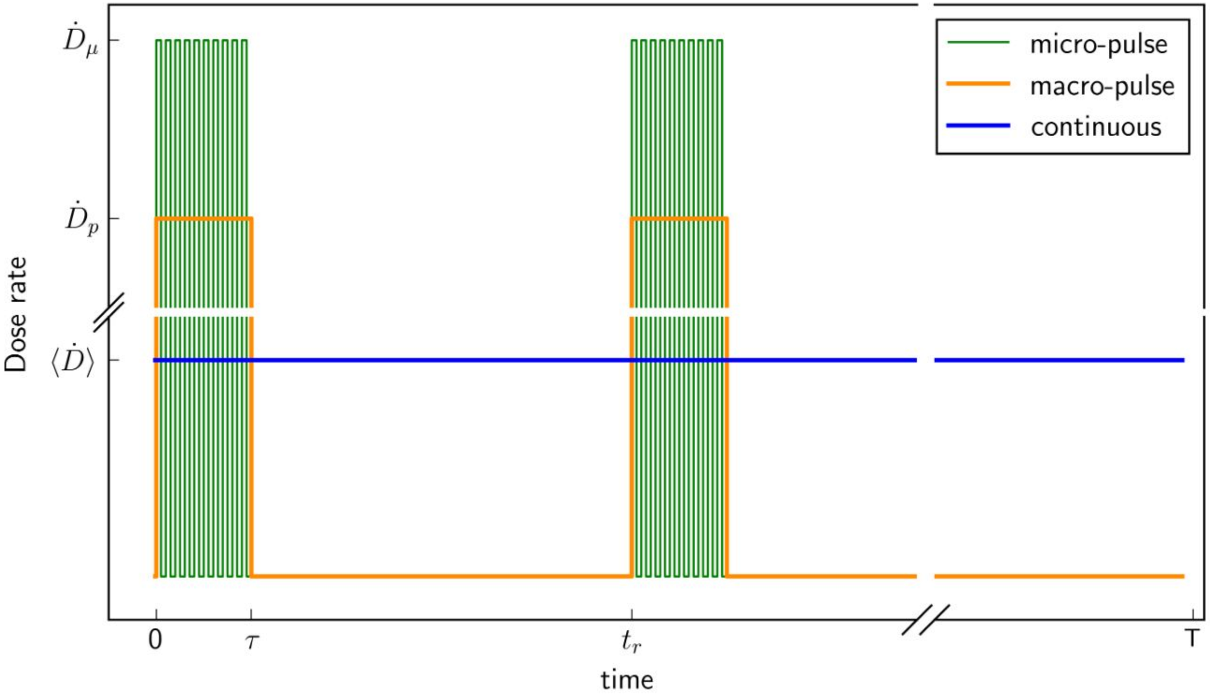
In Practice:
1. Model track arrival as Poisson Random Measure (PRM)
2. Evaluate chemical impact with Monte Carlo (TRAX-CHEM)

# From Beam to PRM: Simplified Beam and conditions

Irradiation condition:

- **Dose:** How many track hit the target
- **Dose Rate:** time distribution

$$D = \frac{N_t \, \mathrm{LET}}{\varrho \, S}$$



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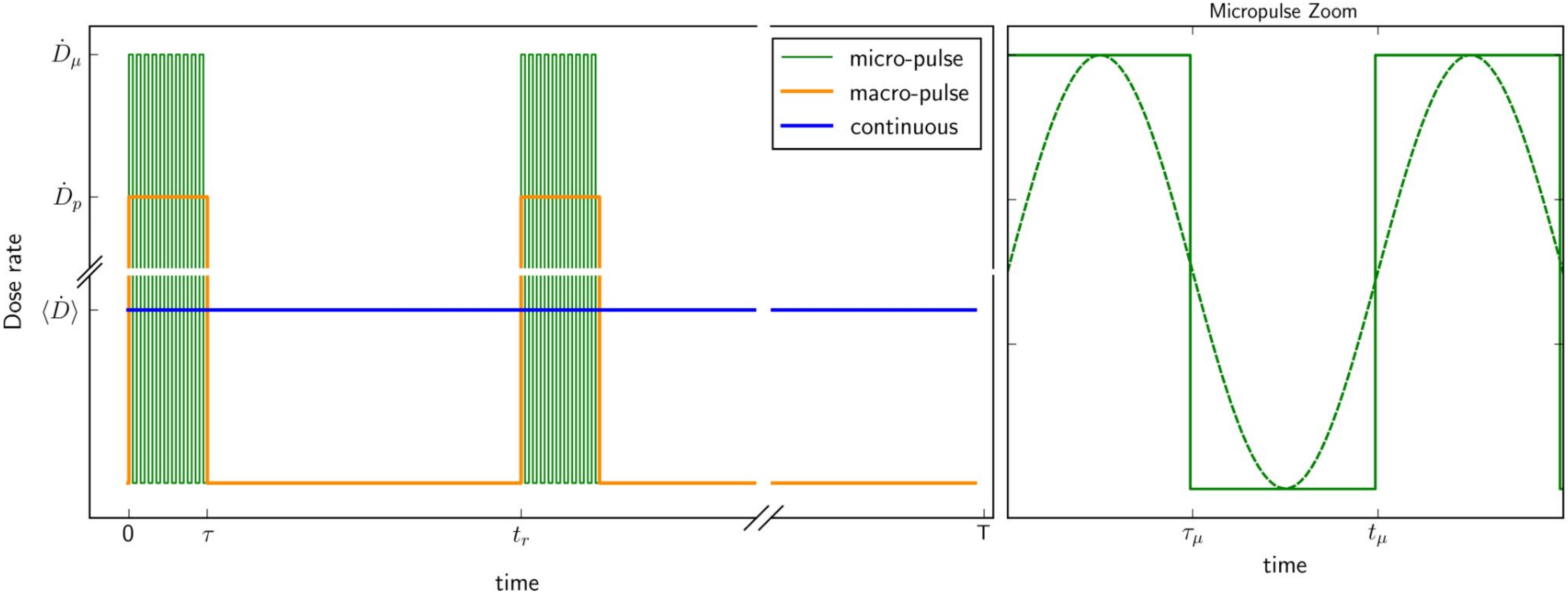

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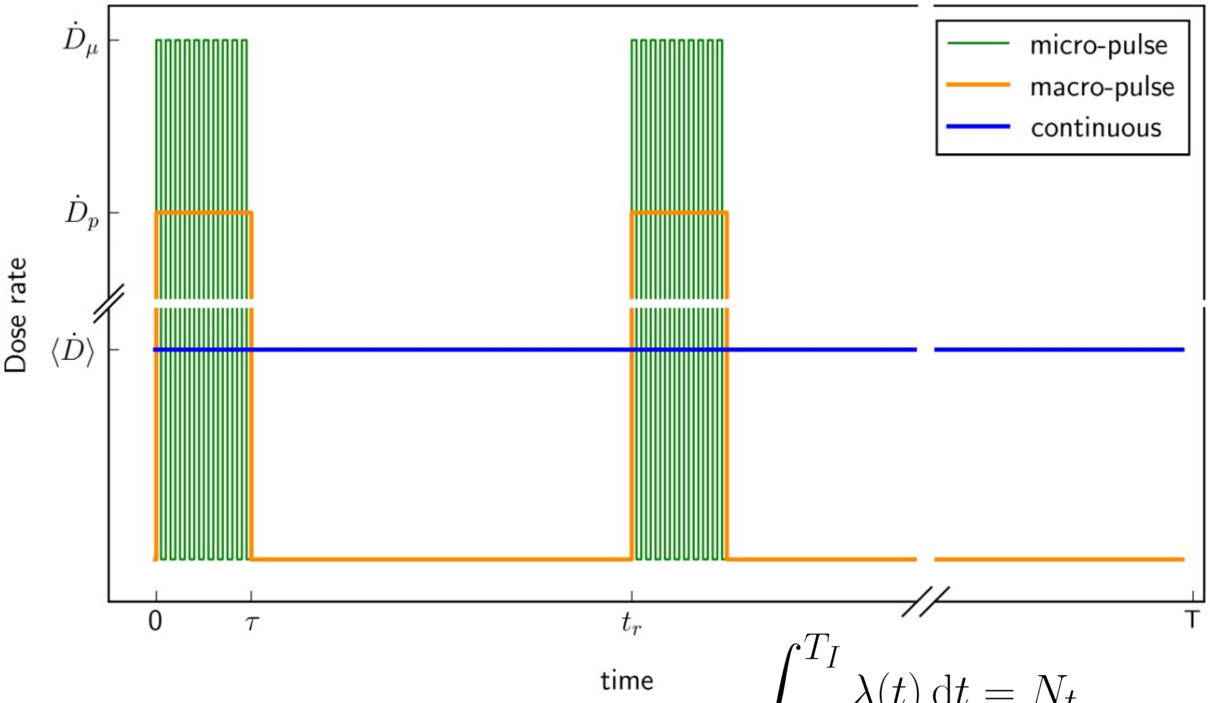


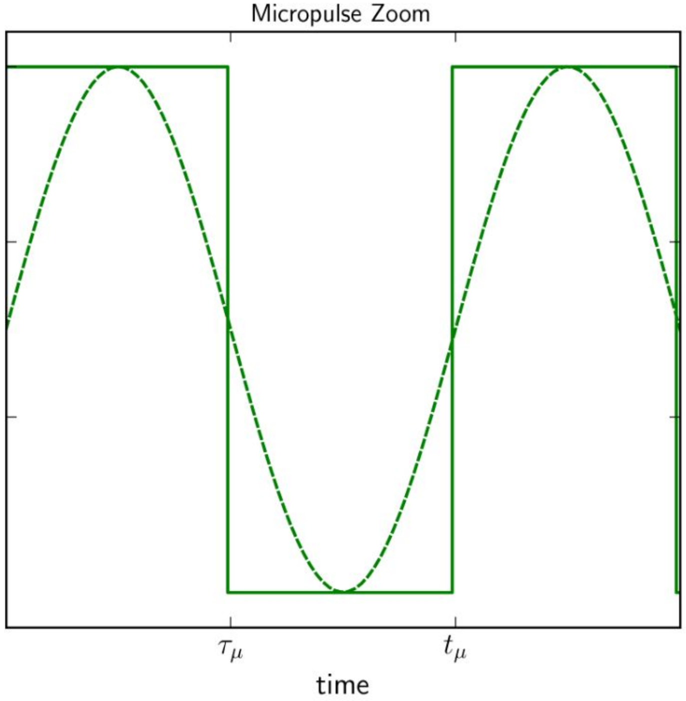


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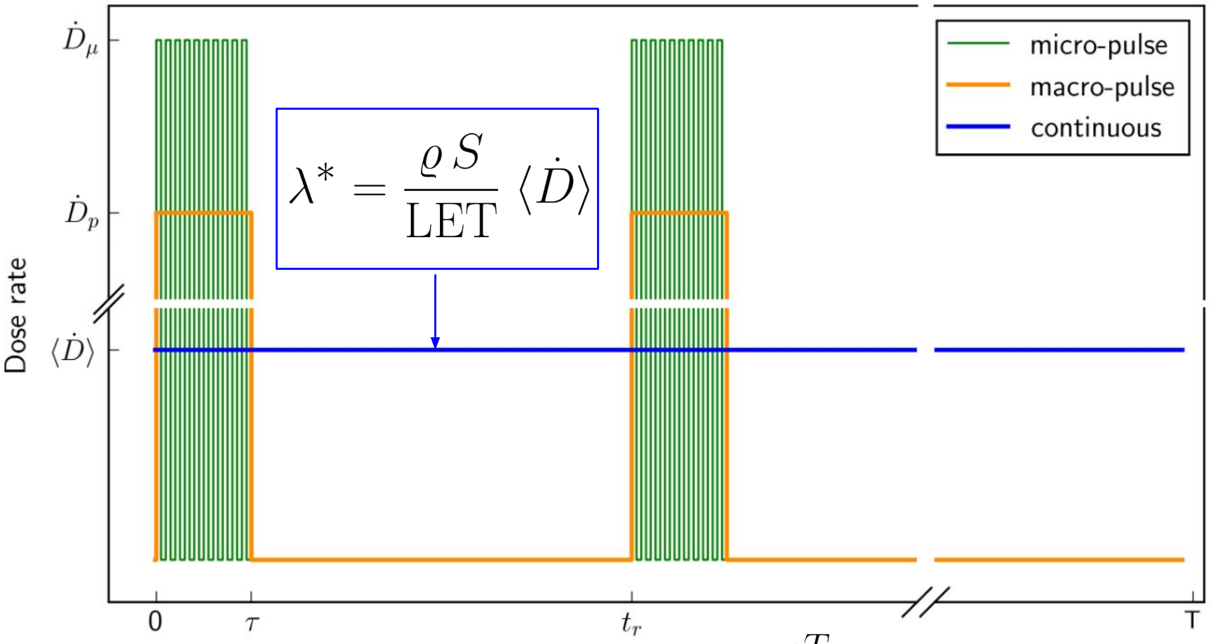


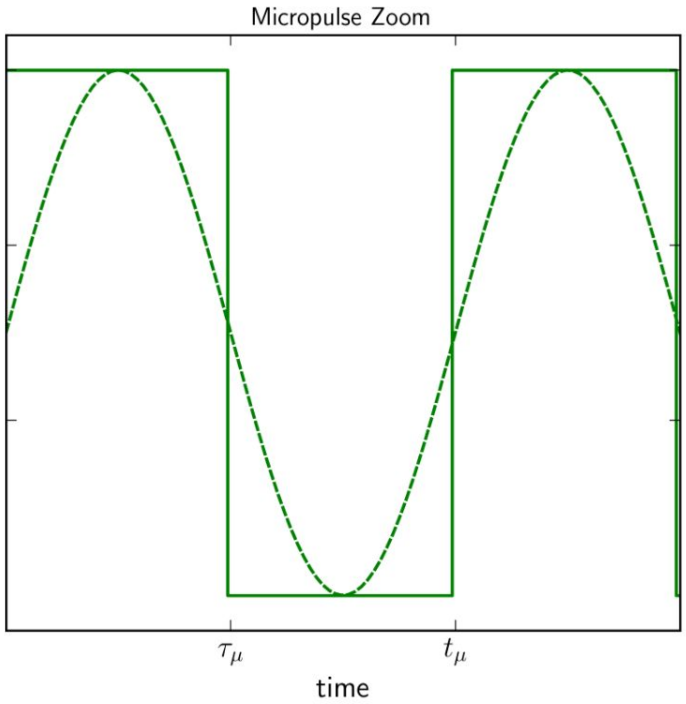


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**Assumptions** :

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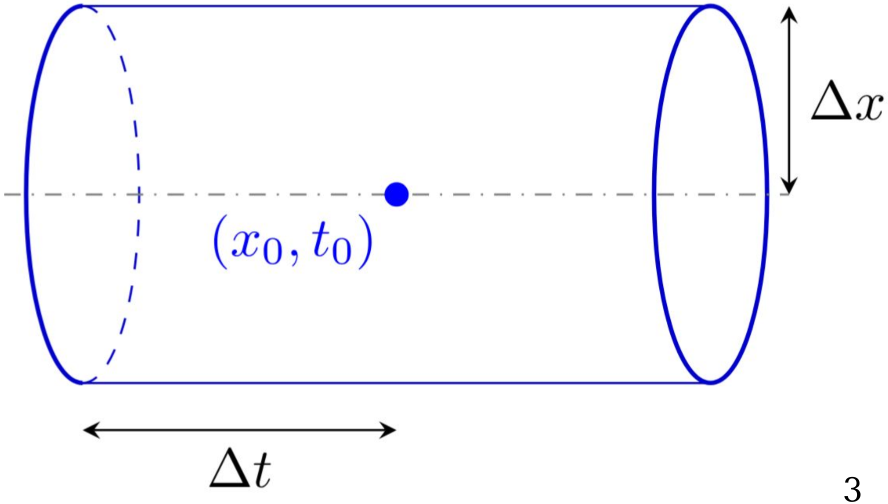

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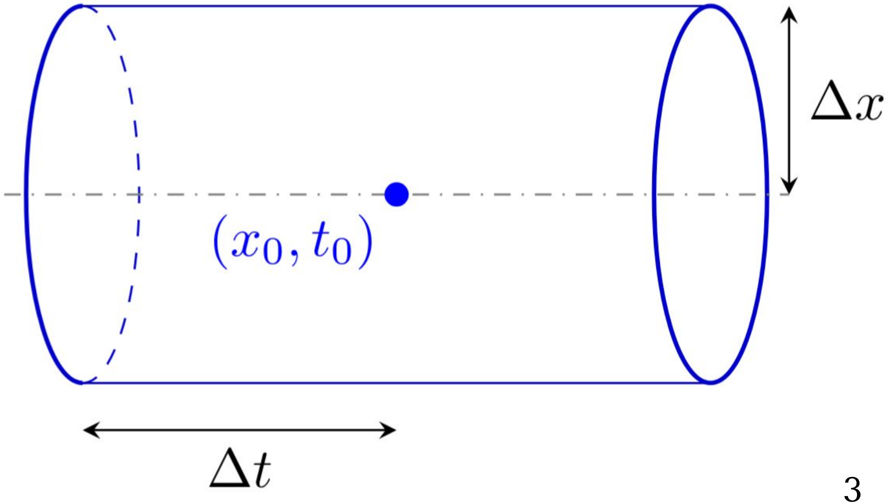

# From Beam to PRM: final

**Issues**:

- Account for <u>different beam structures</u>
- Compute the quantities <u>averages</u>

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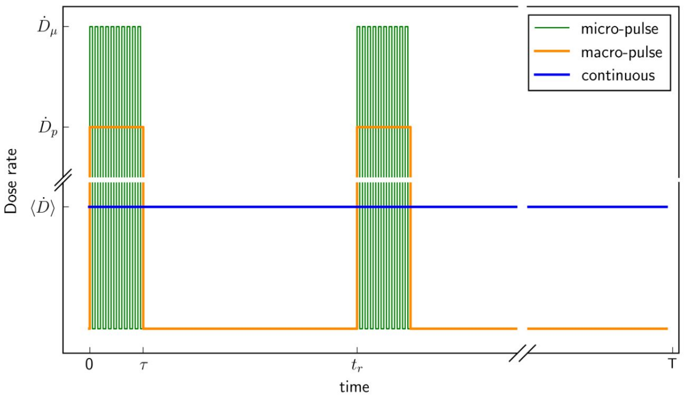

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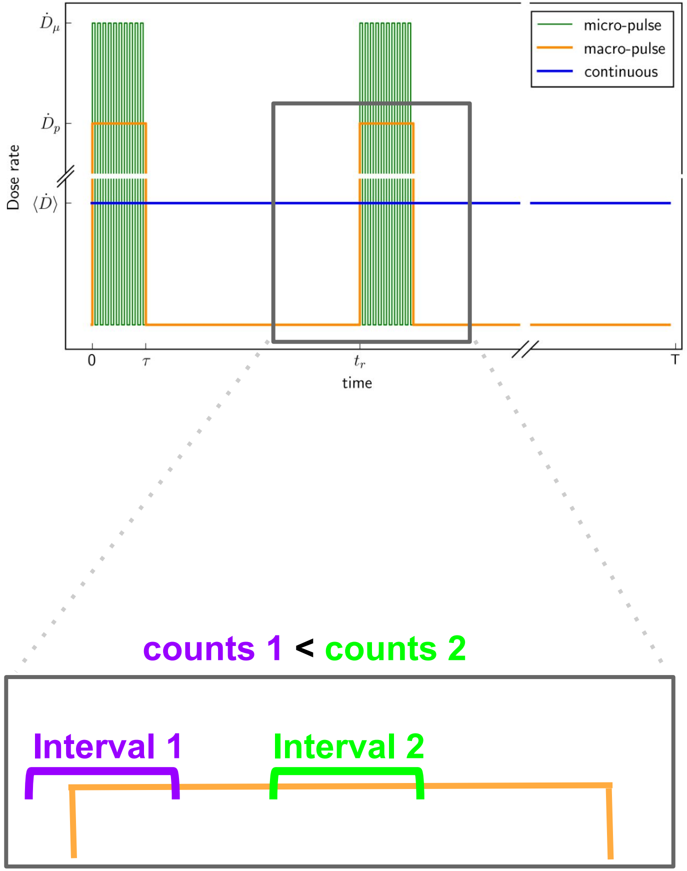

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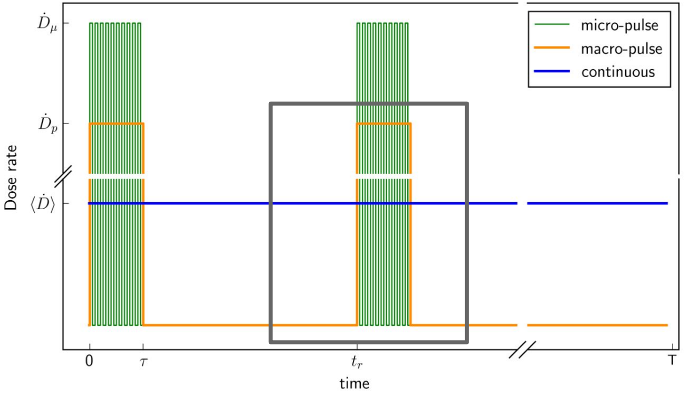


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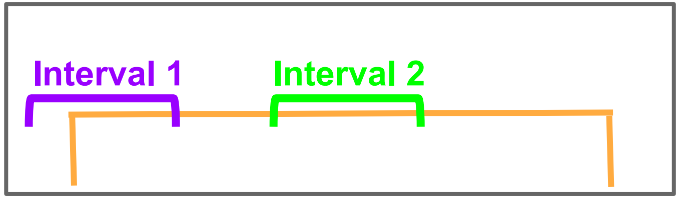
counts 1 < counts 2



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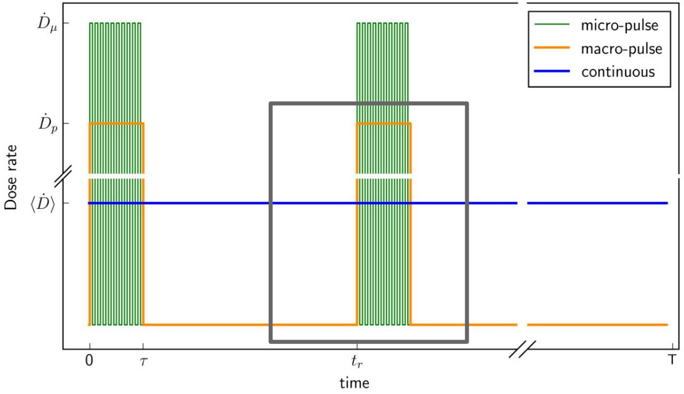


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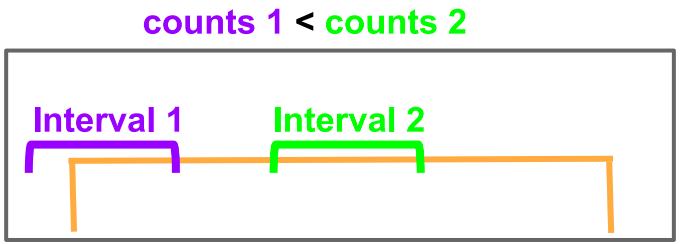
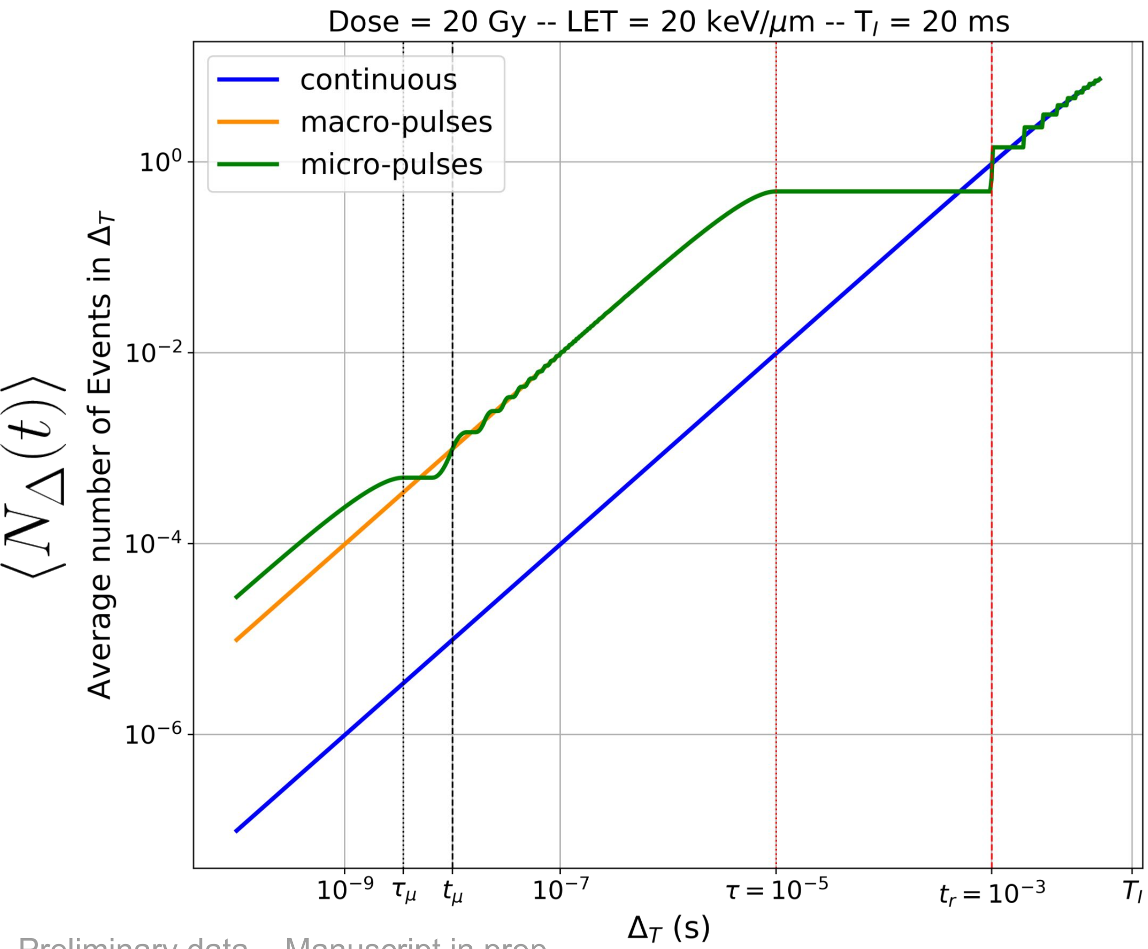


# Results: Beam parameters impact on <N>




**Differences:**

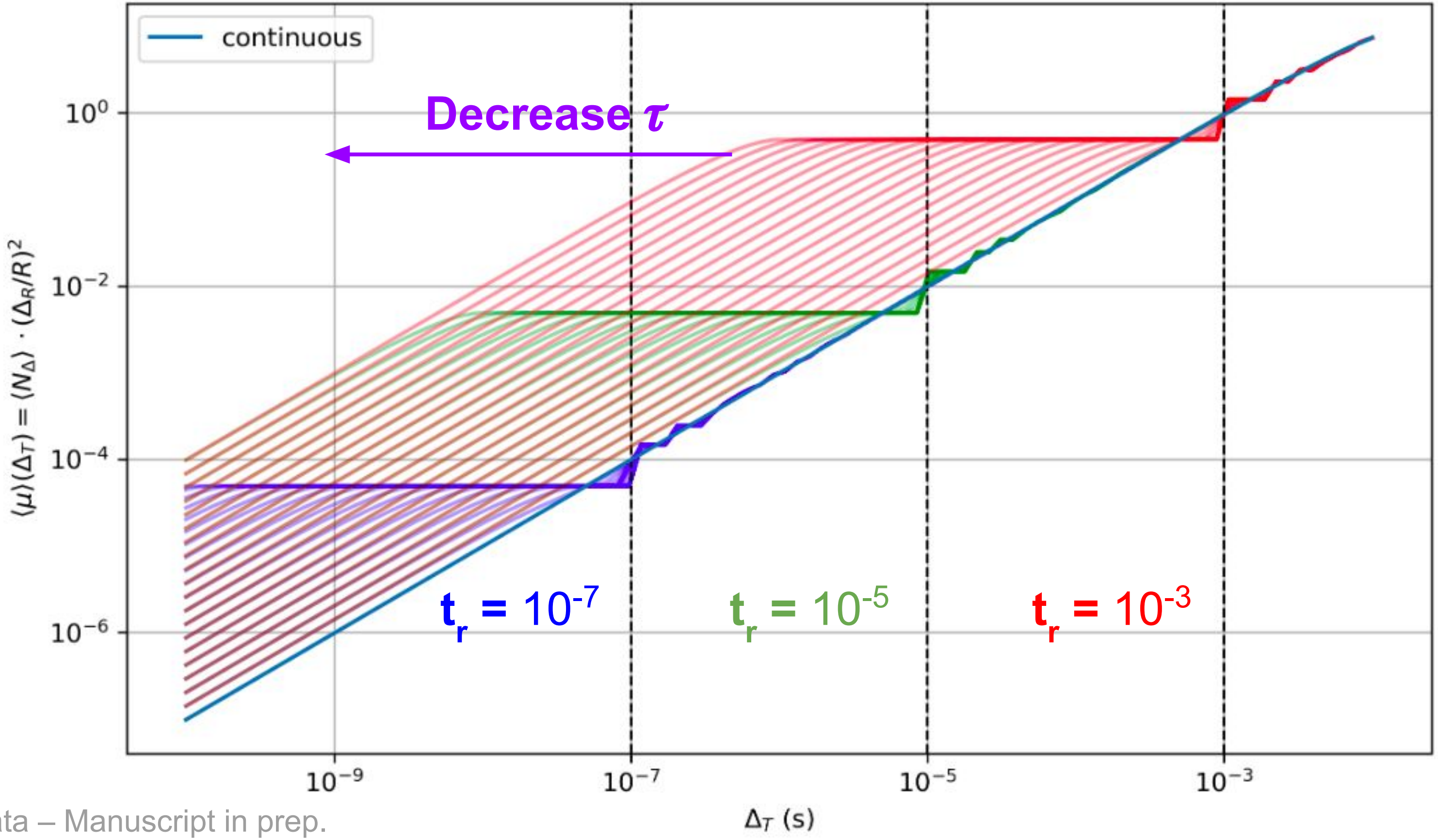
- **Micropulse** structure "collapse" to **macropulse** after surpassing the repetition time ($t_\mu$)
- **Macropulse** does the same with **continuous** version after $t_r$
- Counting saturate and then rise with same slope as the continuous case

Preliminary data – Manuscript in prep.

# Results: Macropulse with different $t_r$ and $\tau$

- Same D, LET and T as before

$t_r$ = ($10^{-7}$,$10^{-5}$,$10^{-3}$ )s
$\tau$ = ($10^{-3}$ ·$t_r$,..., $t_r$) s

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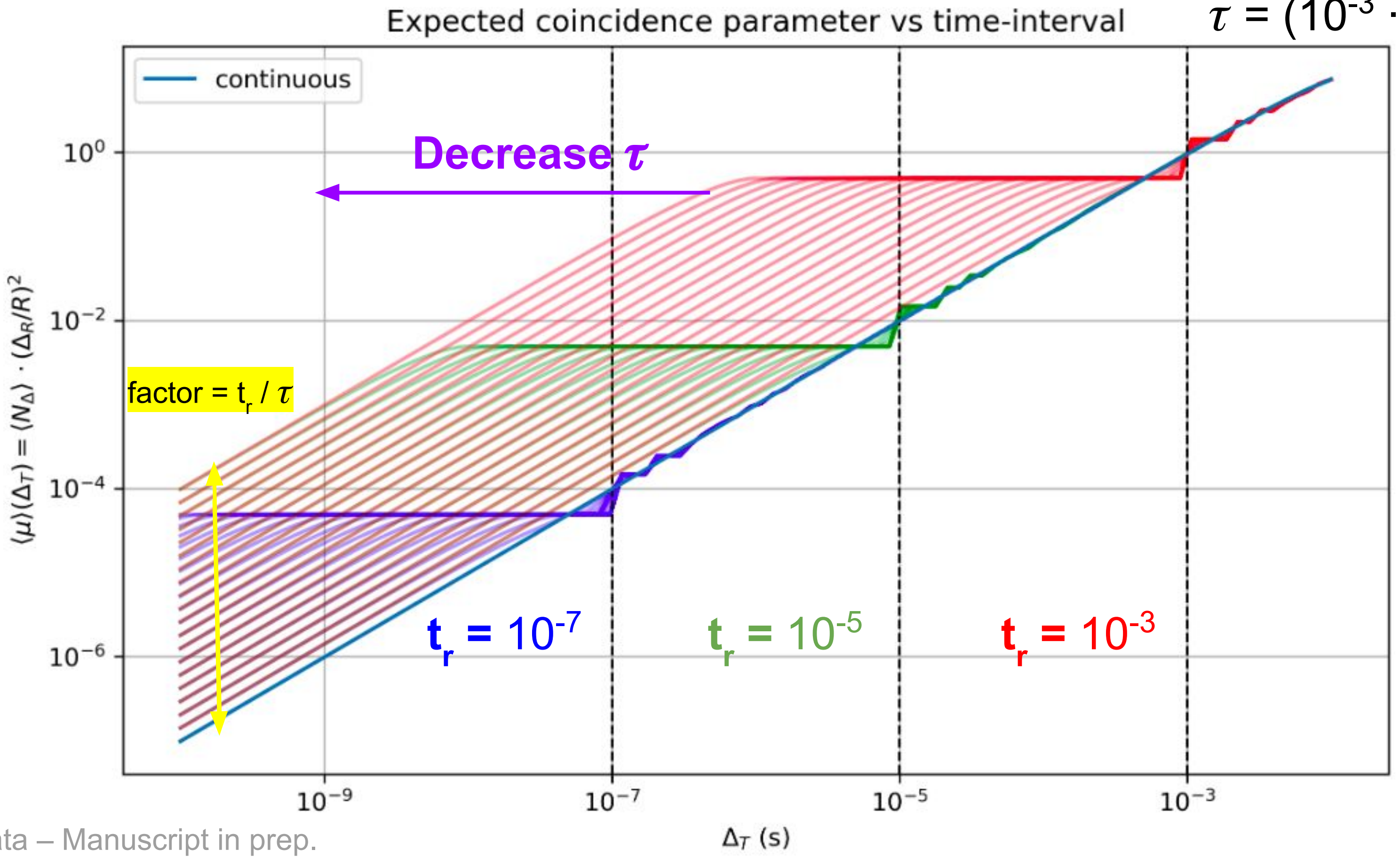
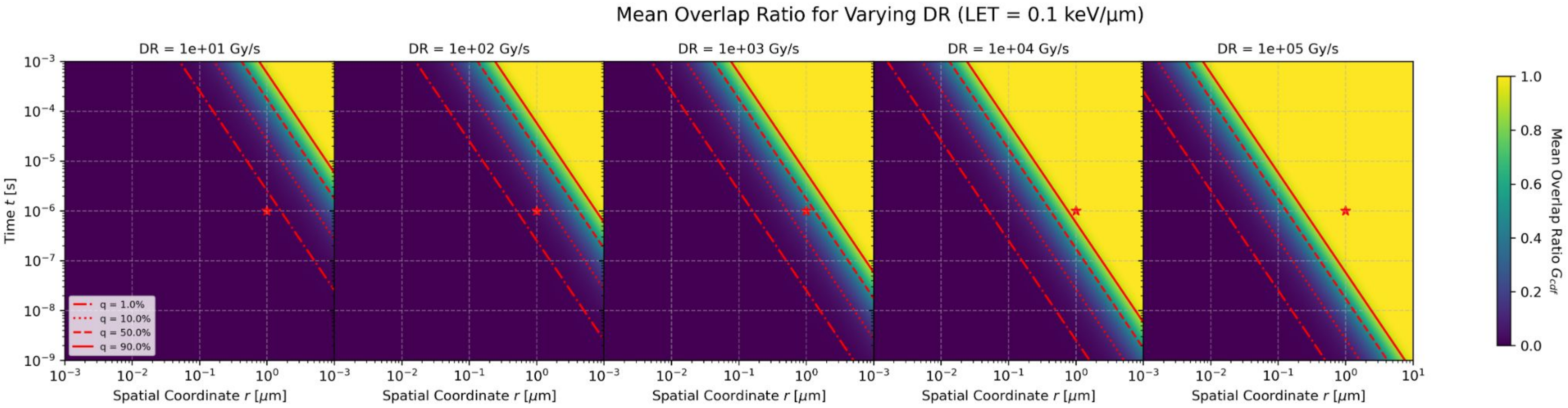


# Results: Continuous Beam LET a impact

□ = (Δx = µm ; Δt = µs)

$$\langle e^{-\mu} \rangle = \frac{(T - 2\Delta_T)e^{-2C\Delta_T}}{T} + \frac{2}{TC} e^{-2C\Delta_T}(1 - e^{-2C\Delta_T})$$

$$C = \lambda^* \frac{\Delta x^2}{R^2}$$

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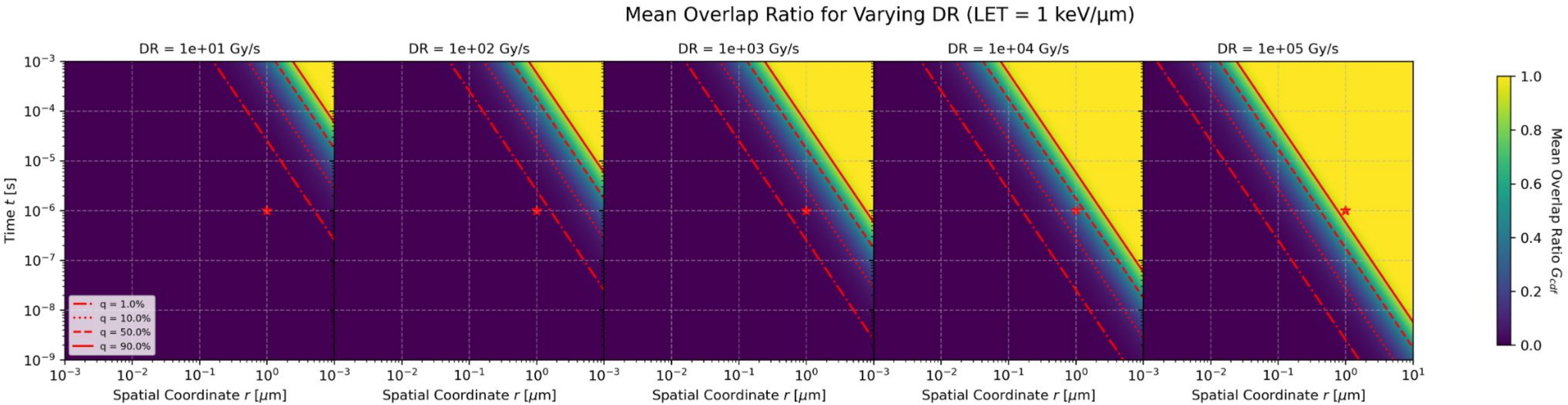

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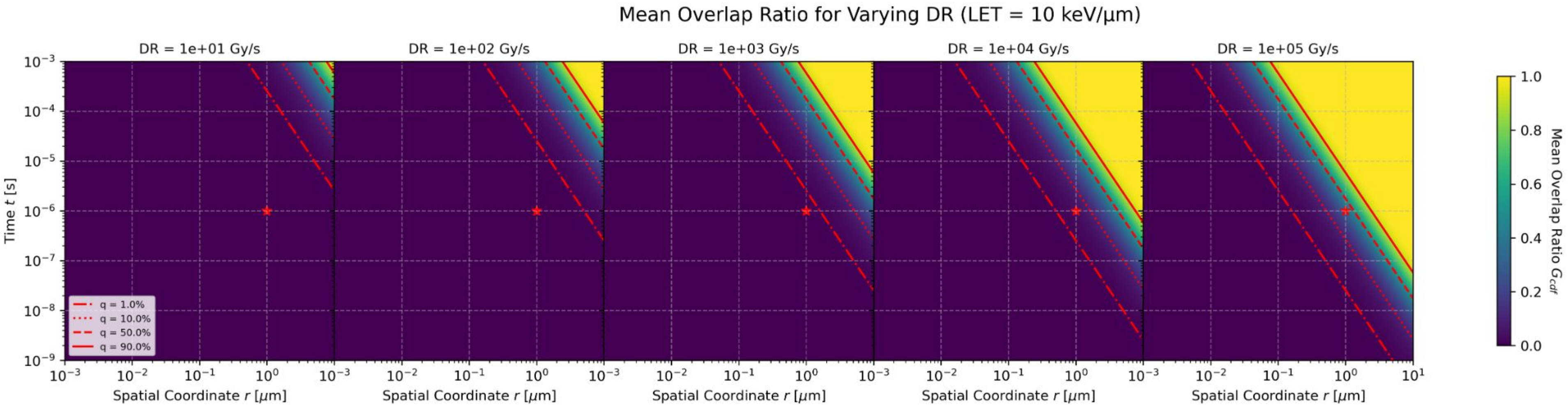

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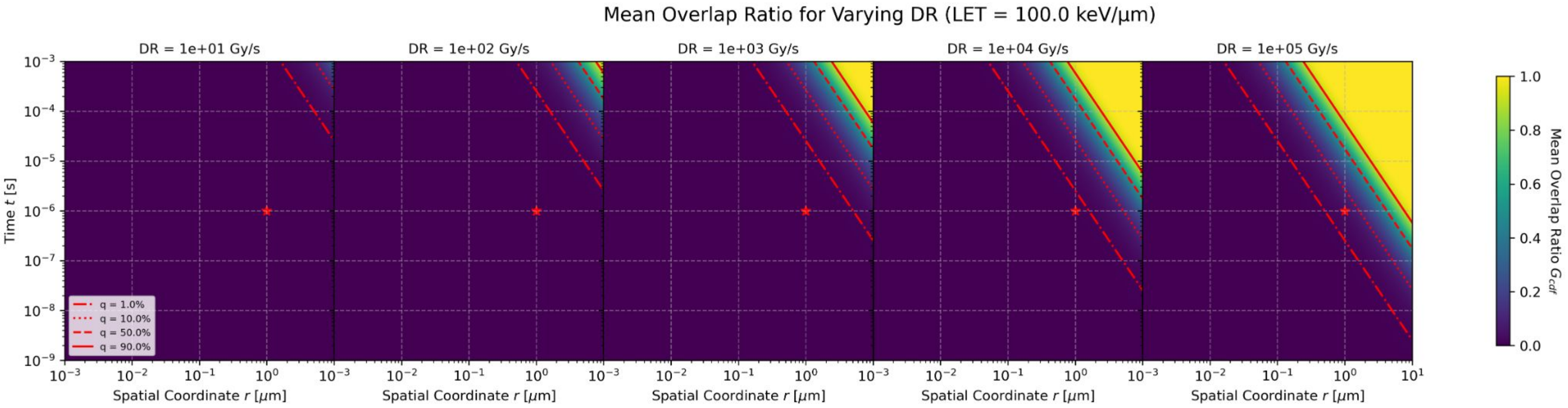


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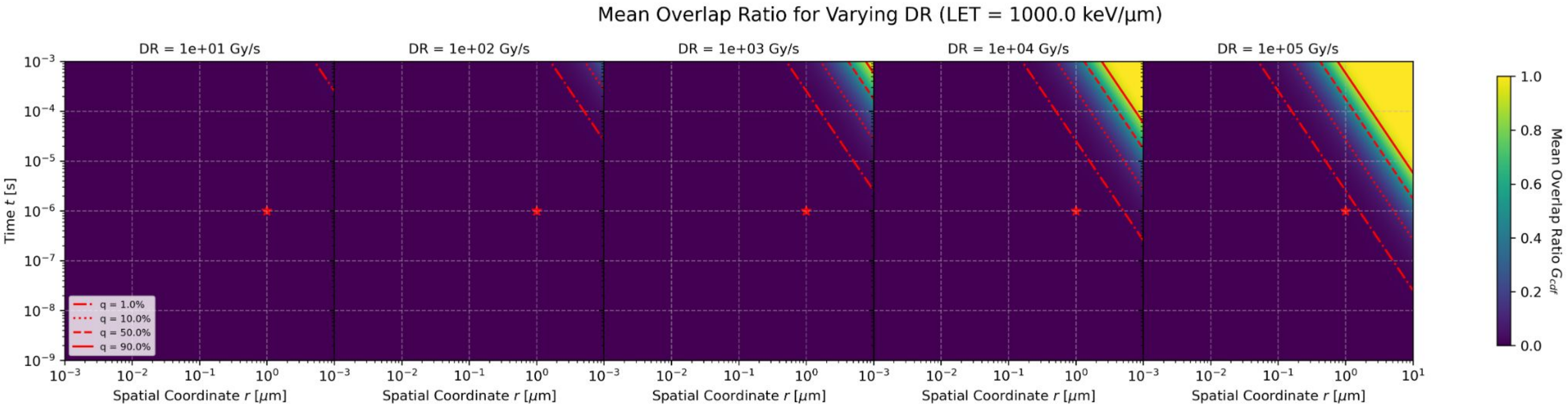
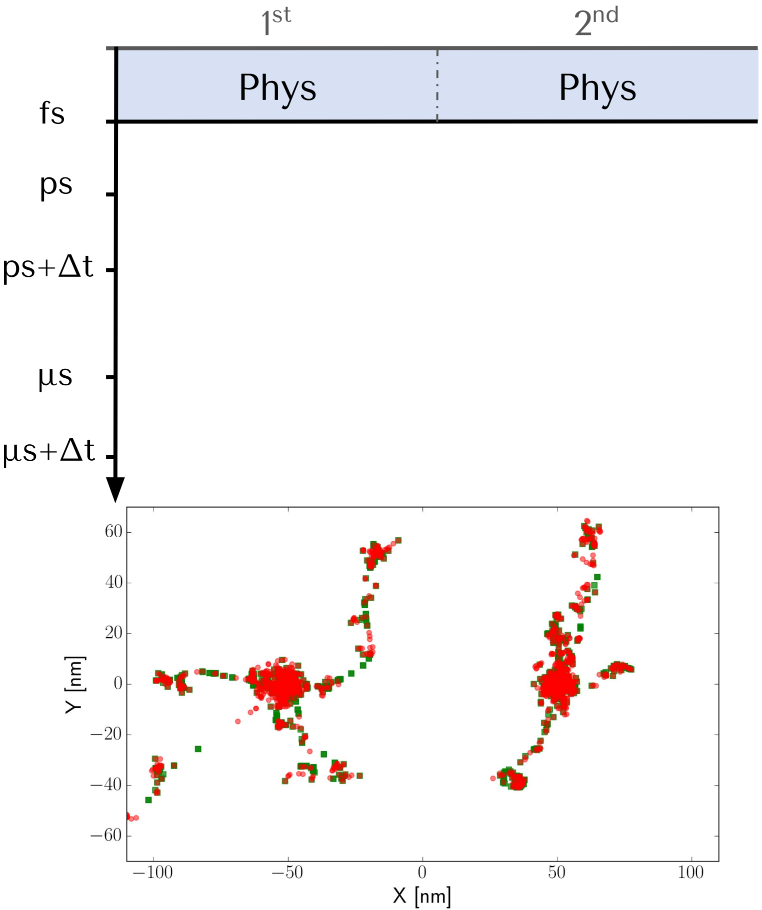



- Increase LET → decrease probability of intertrack
- Increase Dose rate → increase probability of intertrack

# Monte Carlo Track Structure: Intertrack at Heterogeneous stage

**INTERTRACK** : 2 Proj. $\Delta x = 100$ nm ; $\Delta t = 1$ ns



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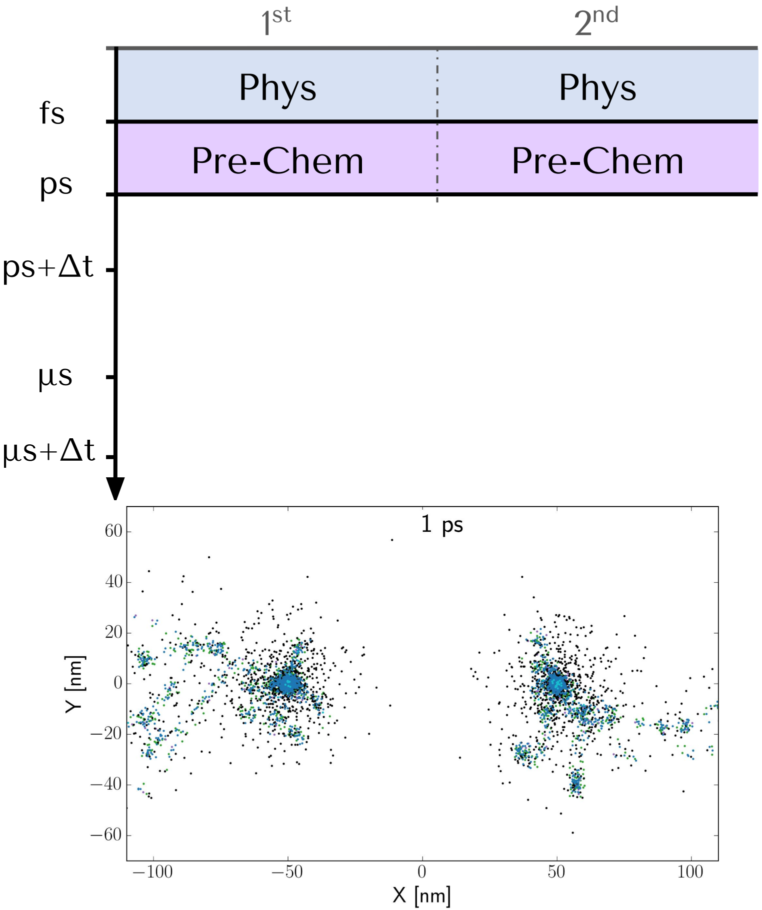

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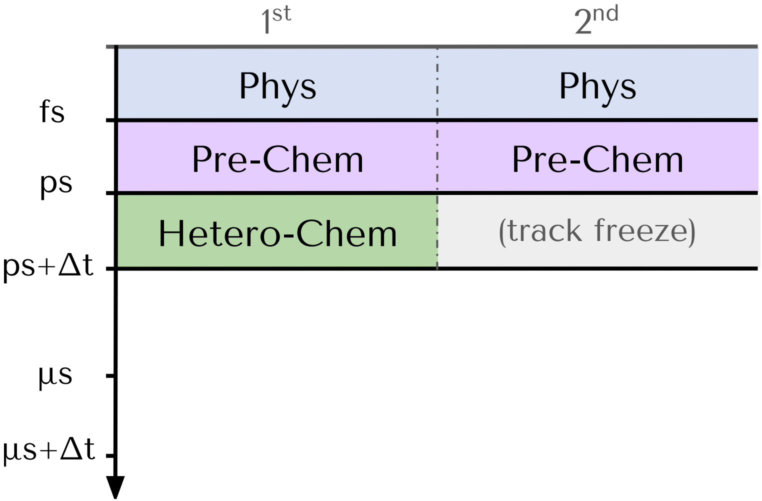


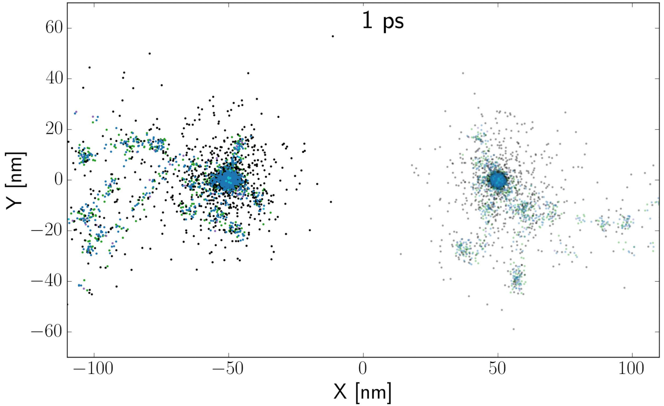

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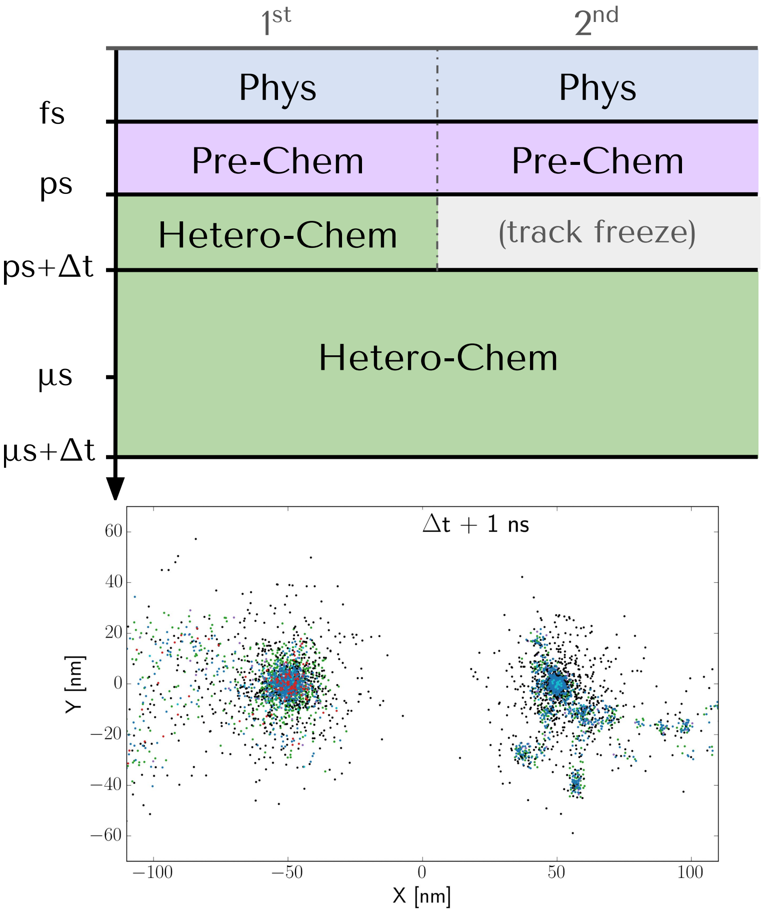

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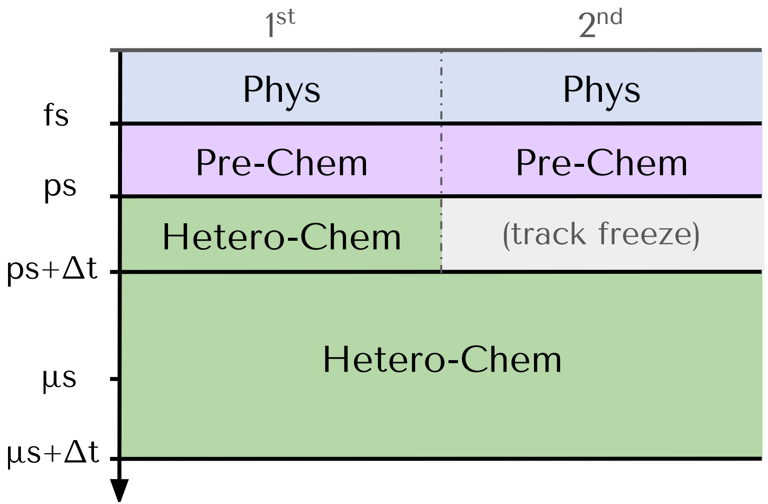


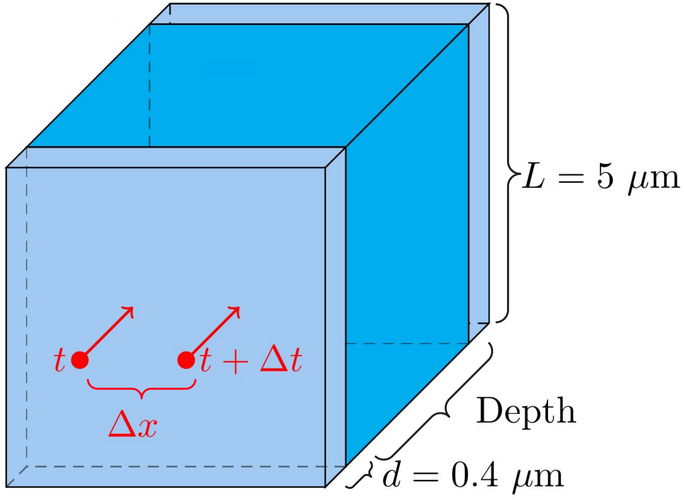


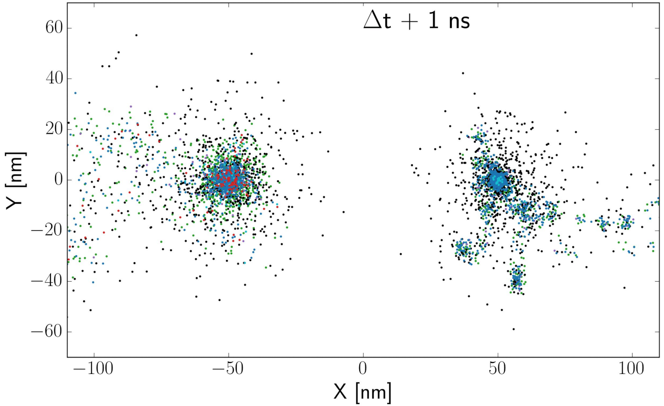


**Projectile:**

- Proton 20 MeV
- Helium 5 MeV/u
- Carbon 10 MeV/u
- **Δt** = (ps, ns, μs)
- **Δx** from 1 nm to 1 μm

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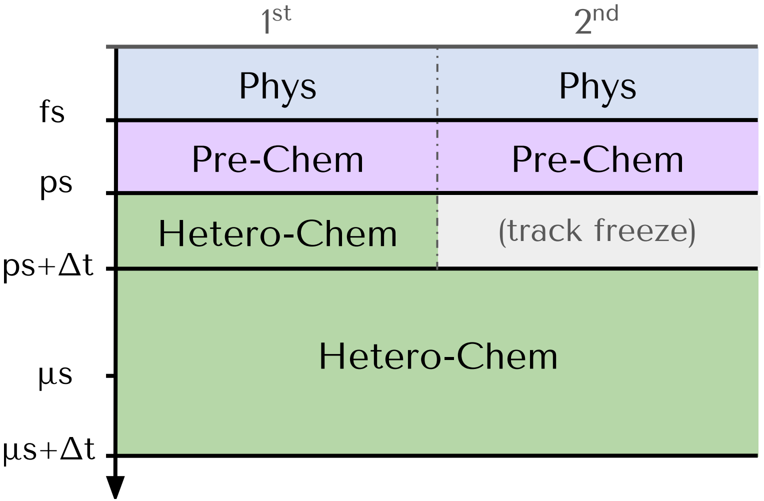


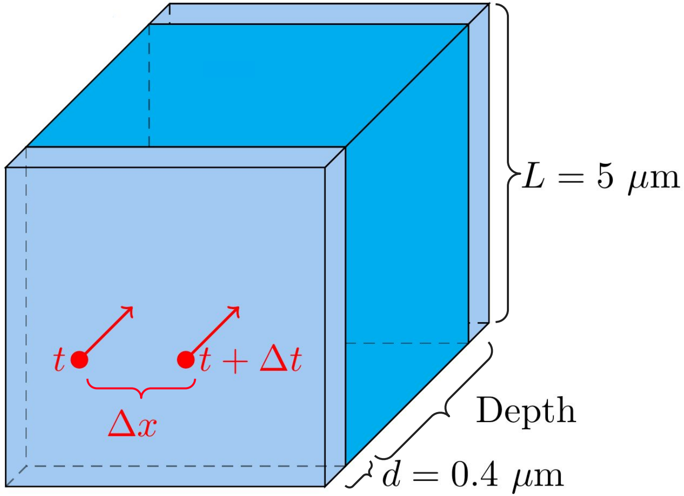


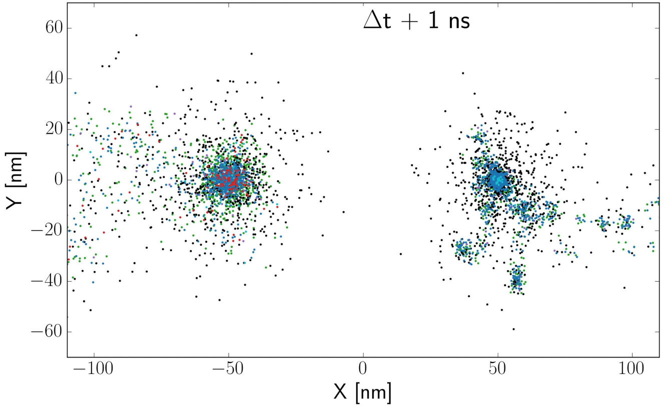


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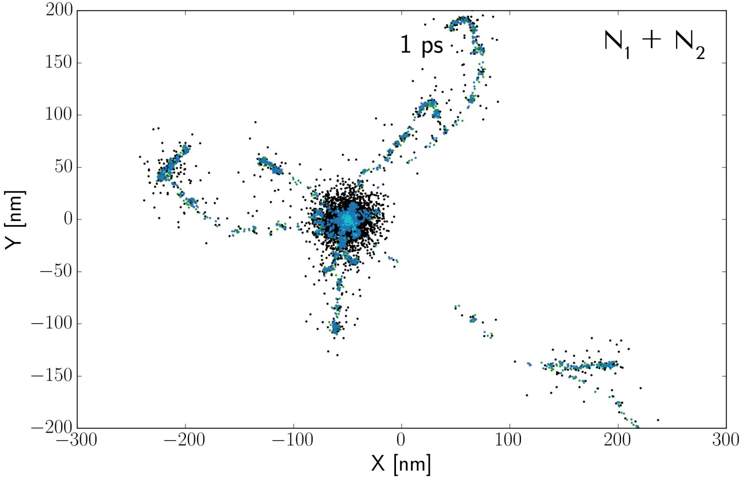
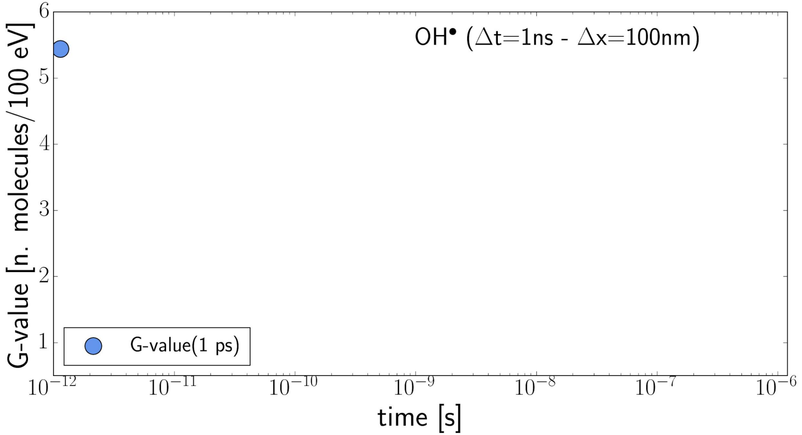
**$pO_2$ :**

- 0 and 5

# Intertrack: Quantities and their time evolution




$$\text{G-value} = \frac{N_1 + N_2}{E_1 + E_2}$$



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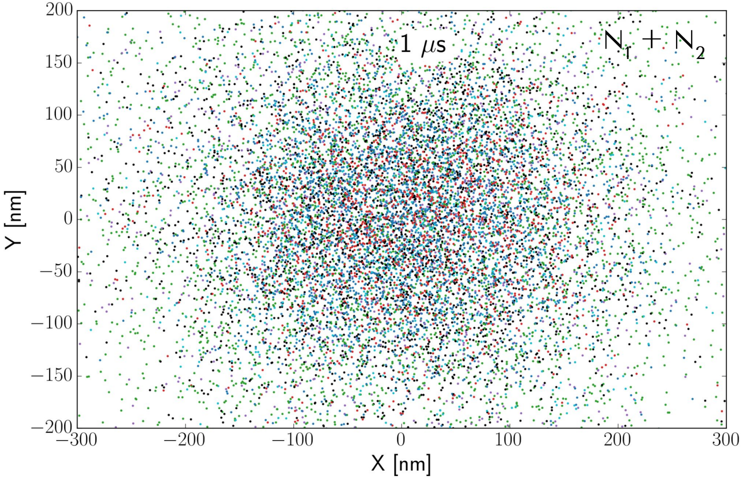


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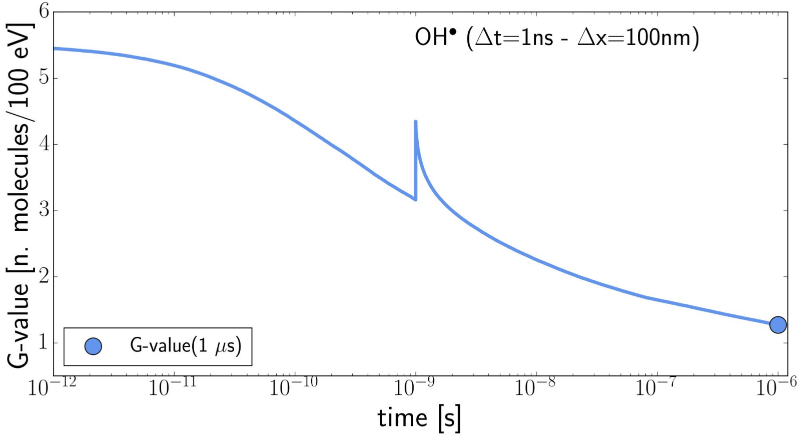

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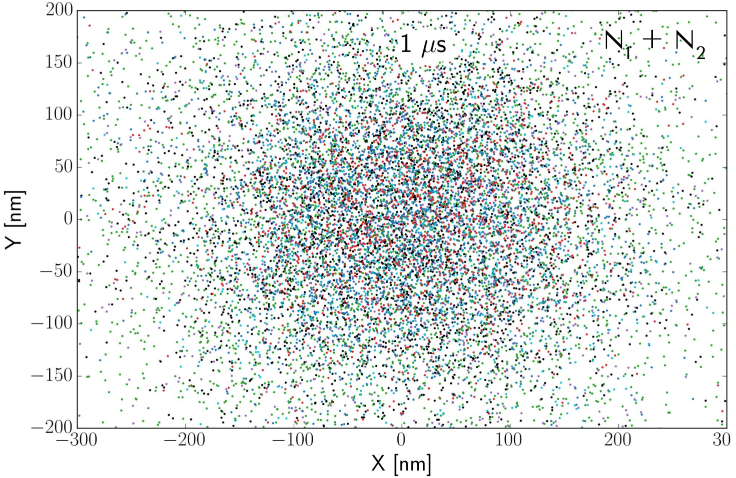


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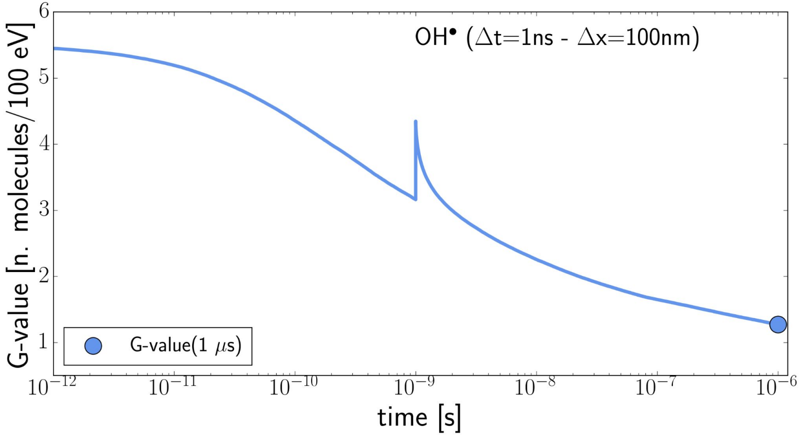
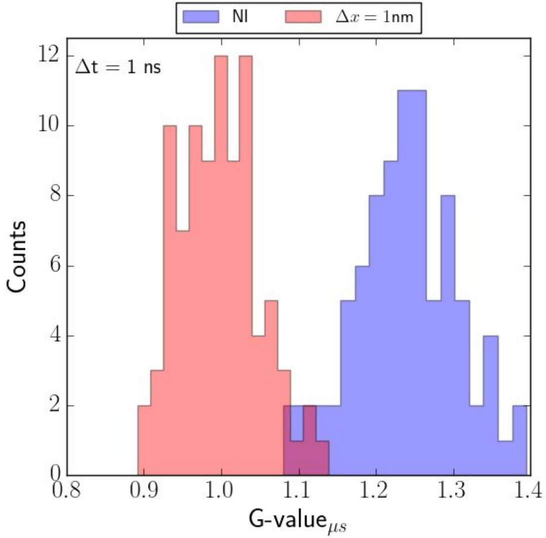



$$\text{G-value}(\mu s) = \text{G-value}_{\mu s}$$



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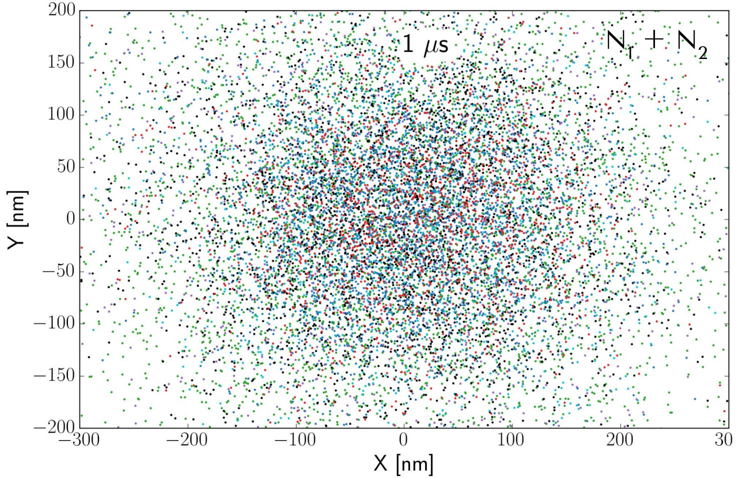


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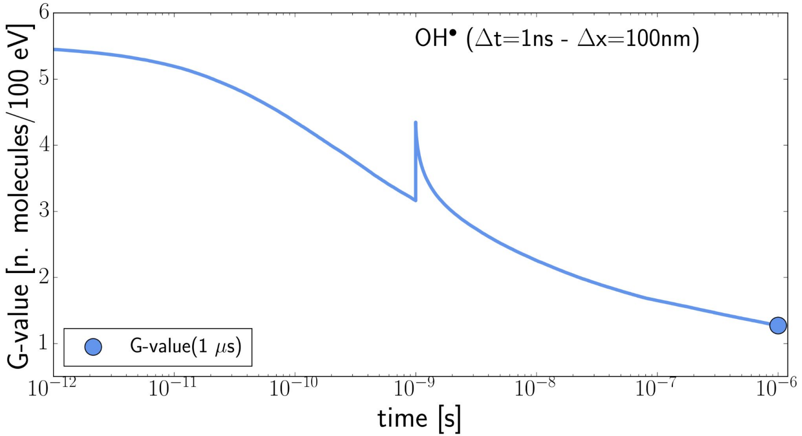
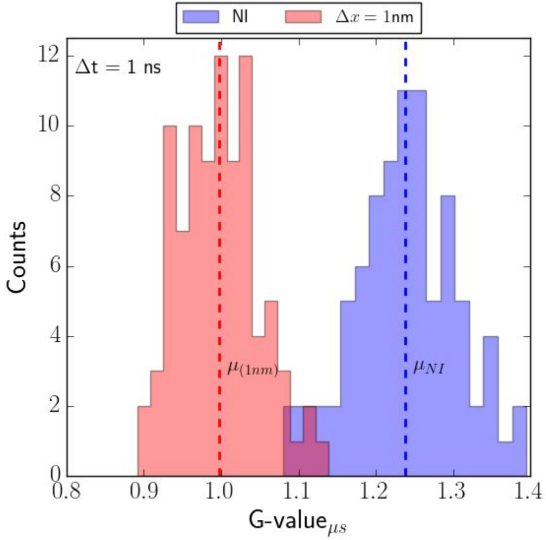
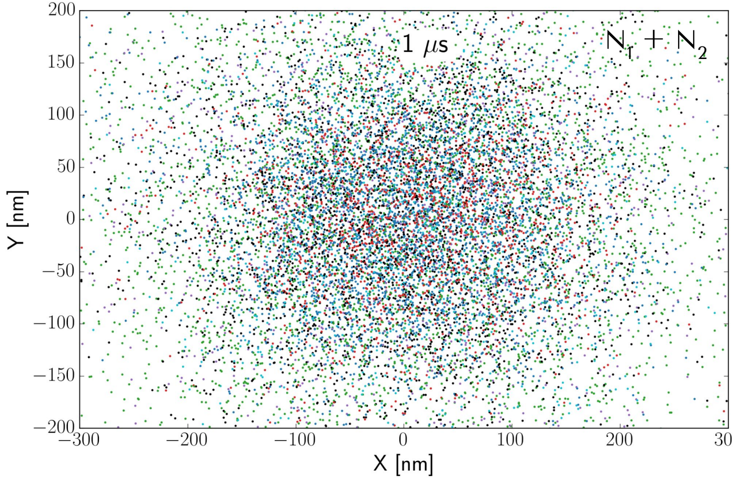



$$\text{G-value}(\mu s) = \text{G-value}_{\mu s}$$

$$\delta = \mu_{Inter} - \mu_{NI}$$



# Intertrack: Quantities and their time evolution

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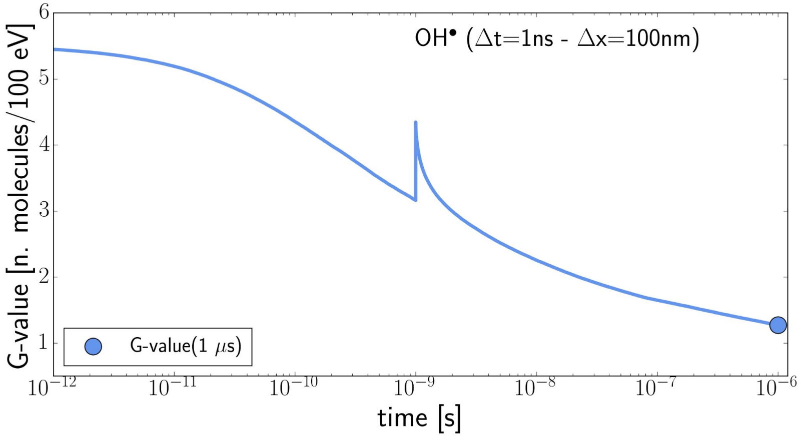


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  $H_0 : \delta = 0$ ;
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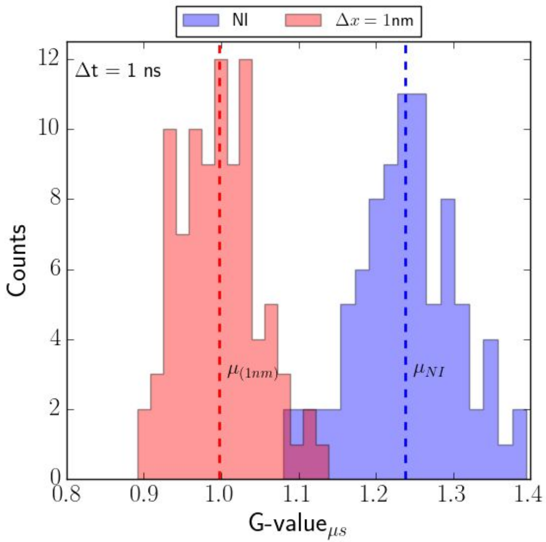


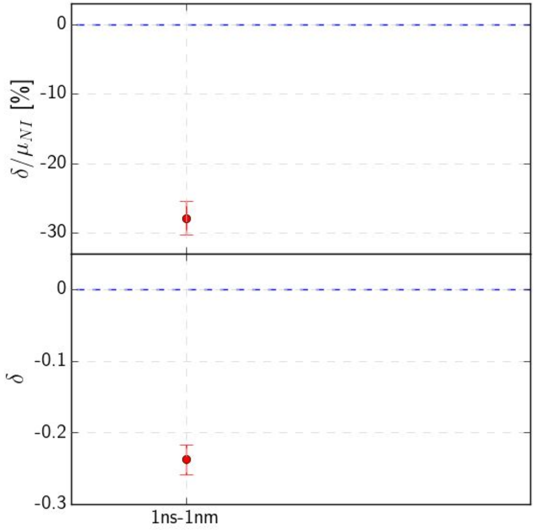

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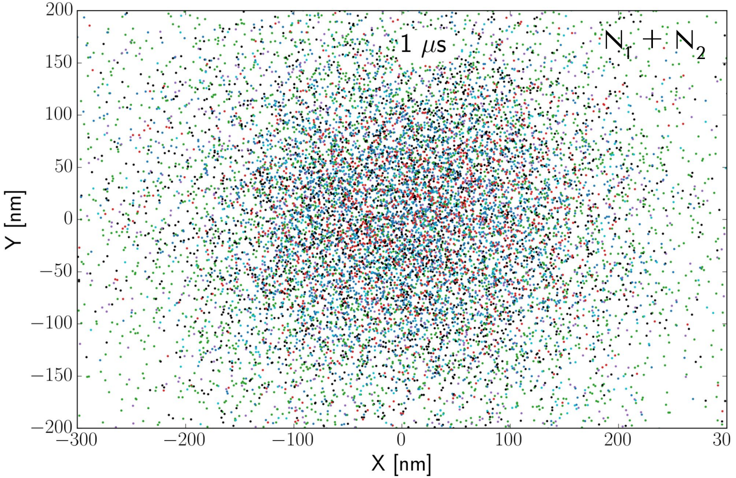


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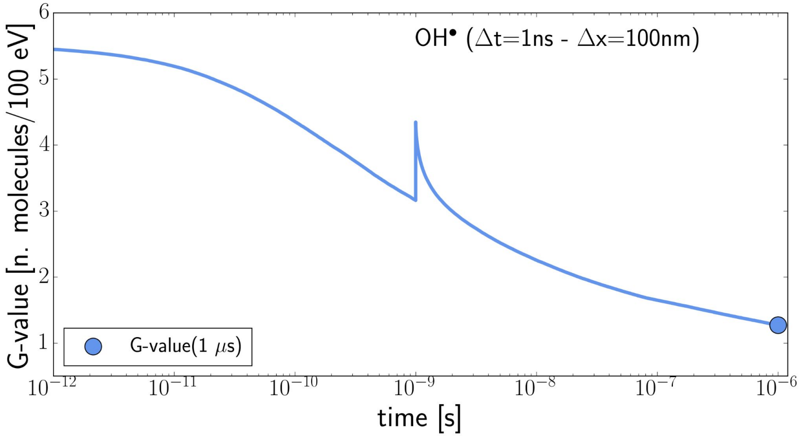


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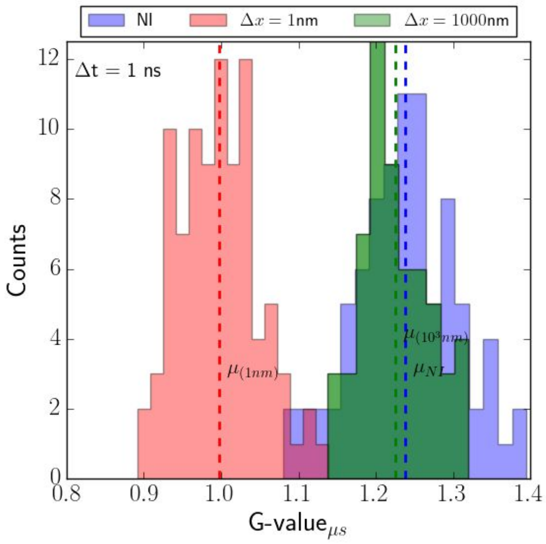
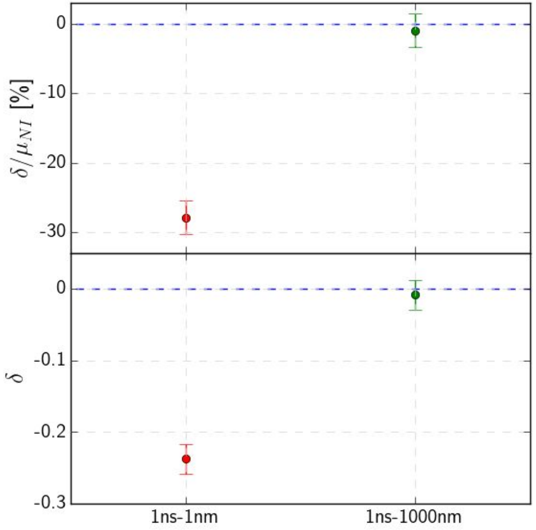


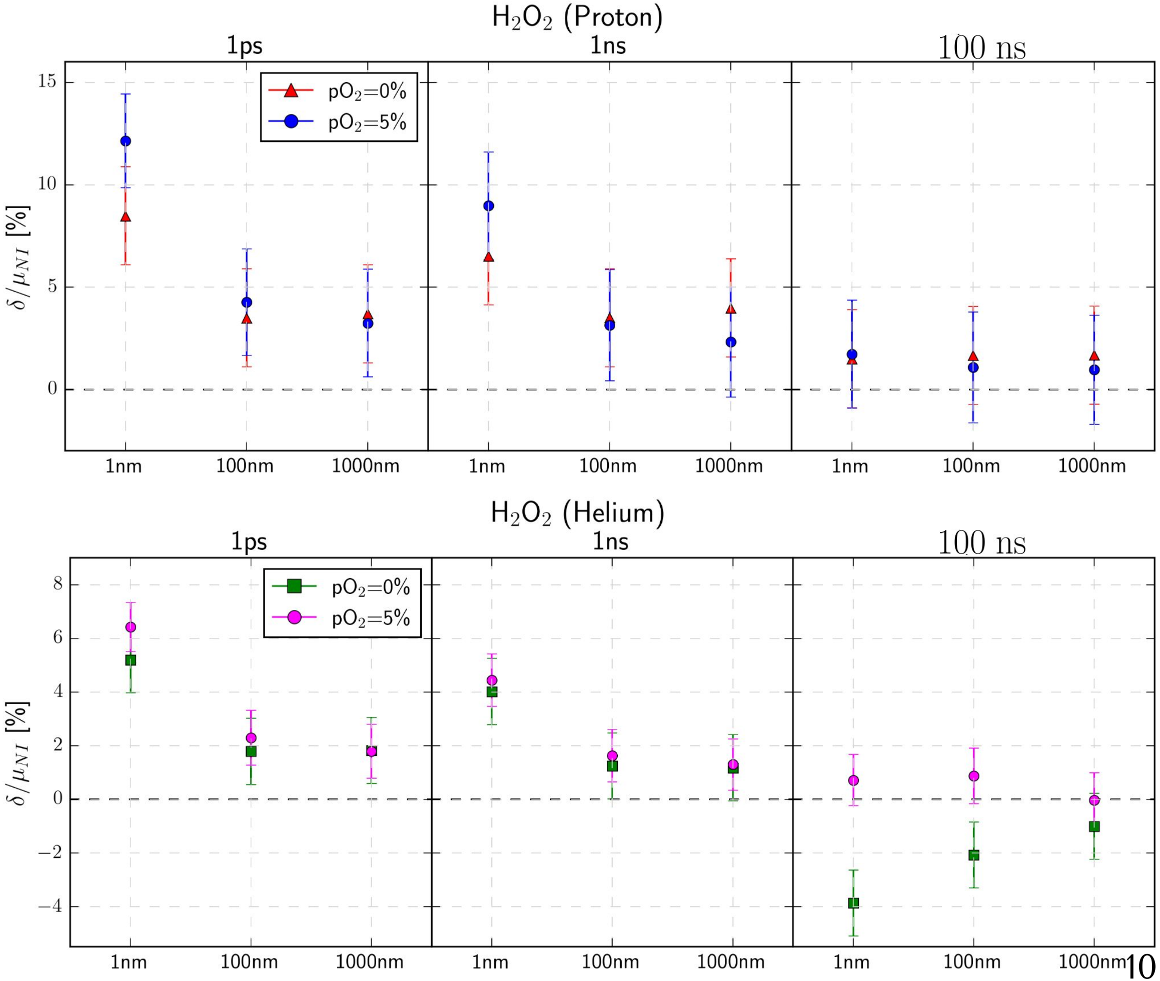
# Results: Monte Carlo impact on chemical endpoint

## INTERTRACK:

- **Δx - Δt** track overlap and number of available species
- **Intra-track** influence intertrack

## OXYGENATION:

- Production of $HO_2^{\bullet}$ and $O_2^{\bullet -}$ by consuming $e^{-}$ and $H^{\bullet}$
- Effects only after 1 ns




To be submitted to Radiat.Res.

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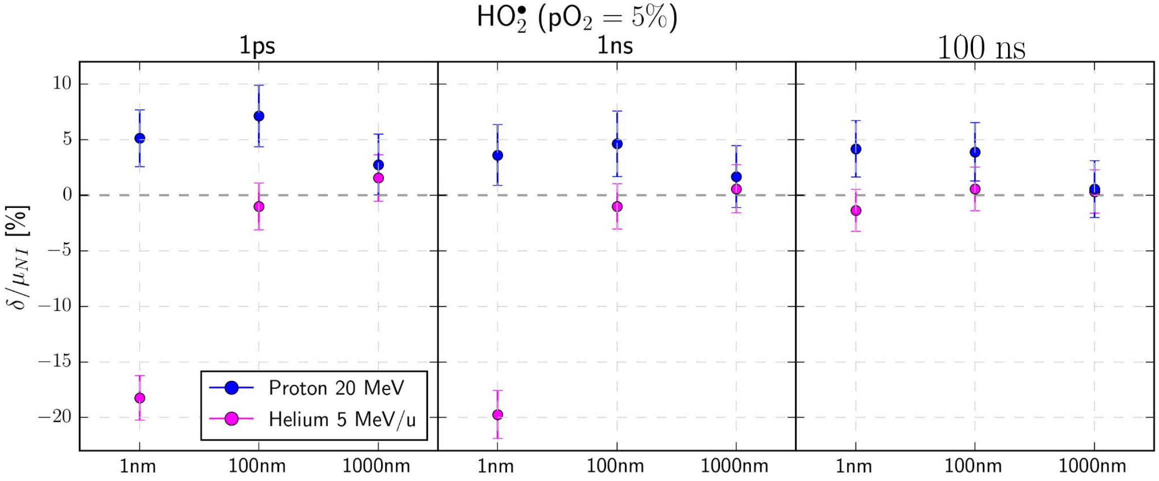
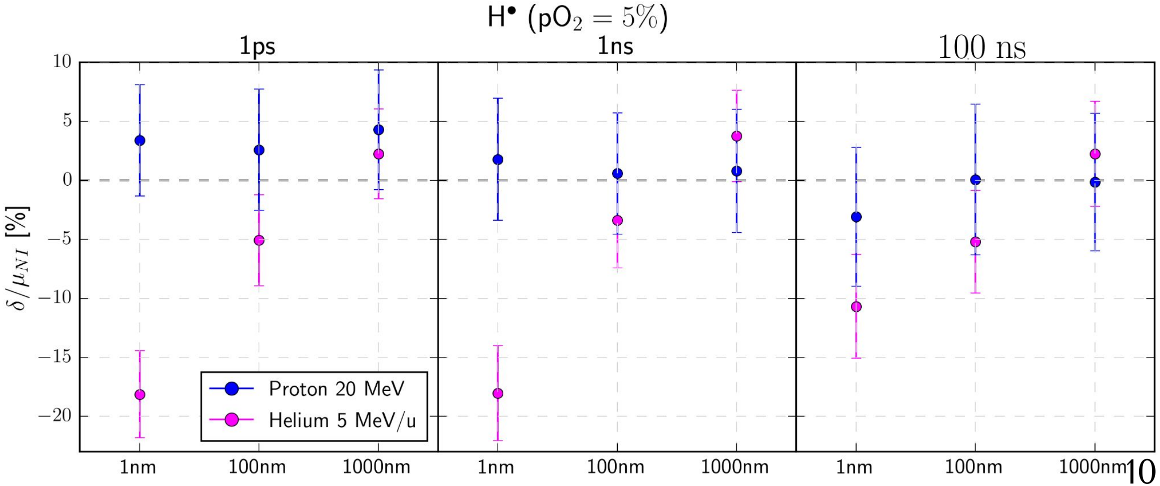
## OXYG + INTER

- Difference from 0% only at **Δt**>1ns
- $e^-$ consumption cause depletion of $O_2^{\bullet -}$
- $H^{\bullet}$ consumption at high LET cause depletion of $HO_2^{\bullet}$

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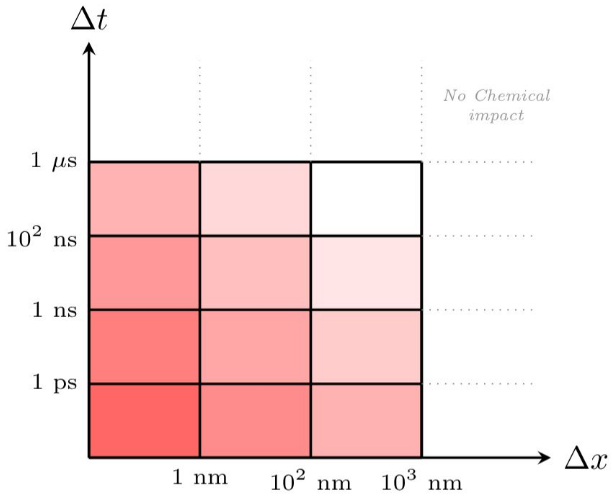
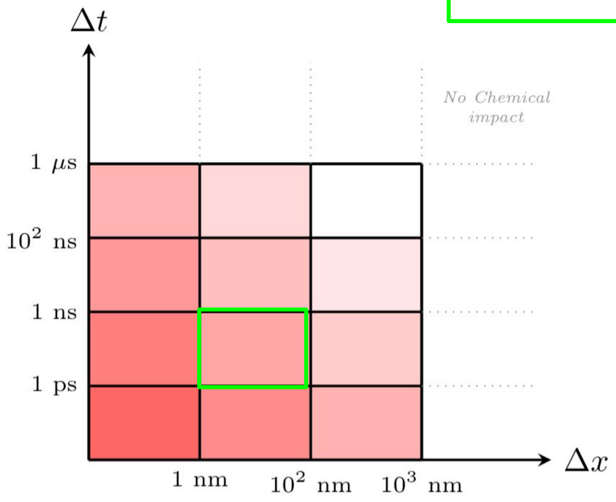
# Chemical Impact estimation



# Chemical Impact estimation

$$\frac{\delta(\Delta x_i, \Delta t_j)}{\mu_{\text{ref}}}$$



# Chemical Impact estimation

$$\Pr(\Delta x_i, \Delta t_j) = P(\Delta x_i, \Delta t_j) - P(\Delta x_{i-1}, \Delta t_j) - P(\Delta x_i, \Delta t_{j-1}) + P(\Delta x_{i-1}, \Delta t_{j-1}).$$

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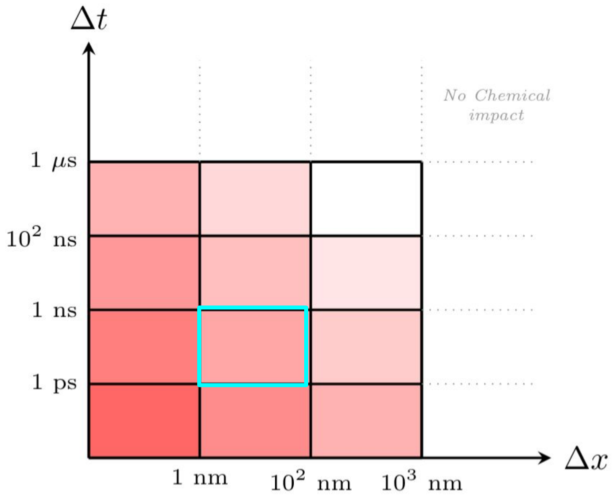

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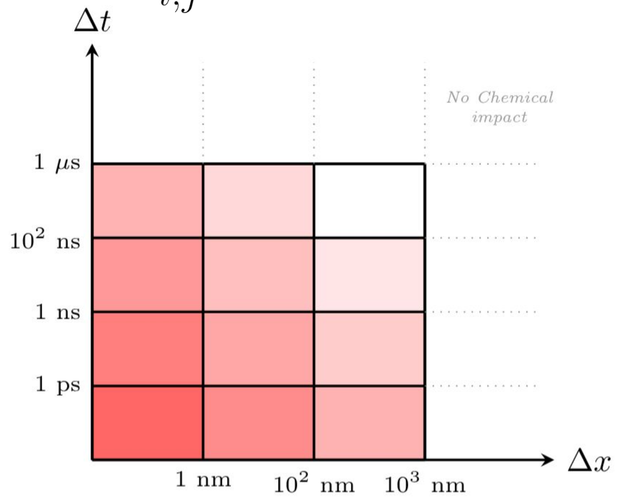

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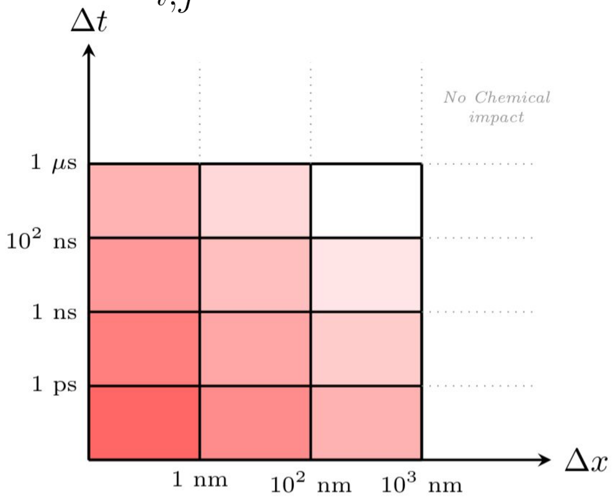


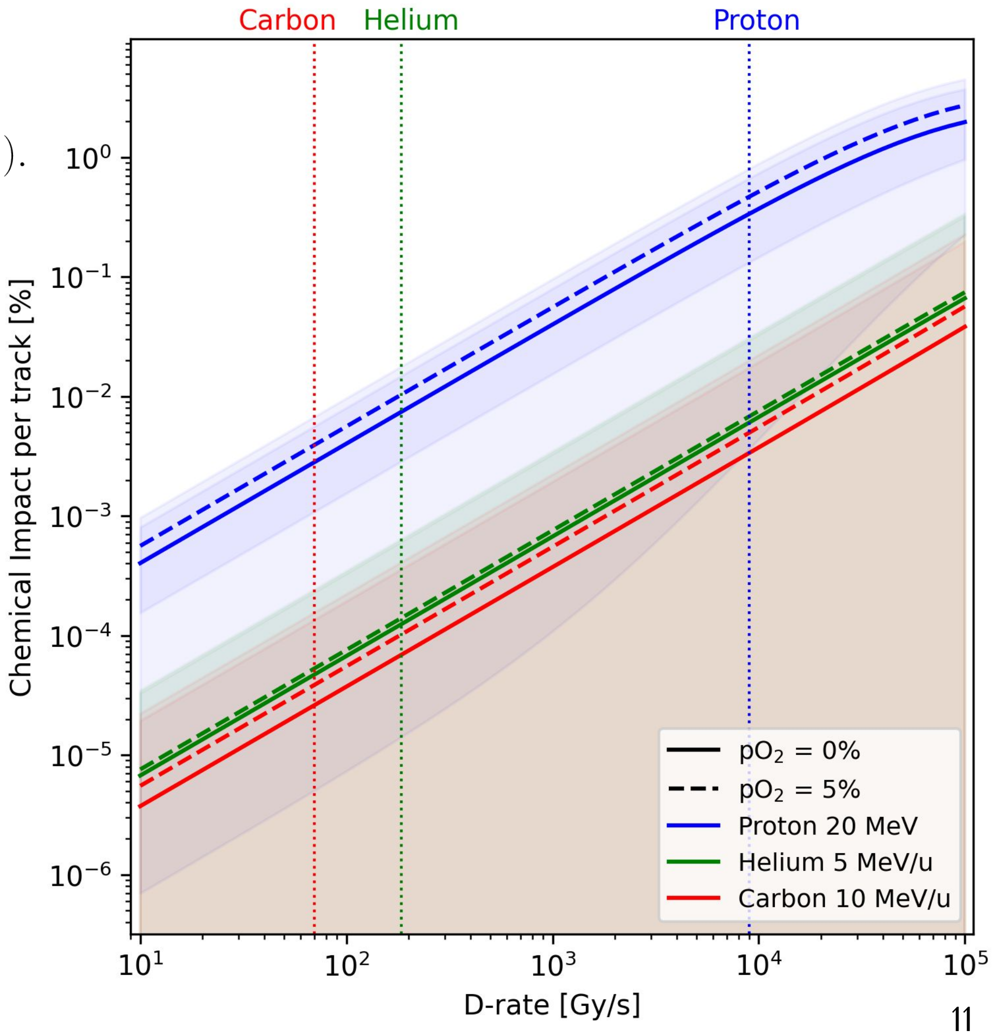


- Proton 20 MeV **small effect**
- Helium 5 MeV/u **no effect**
- Carbon 10 MeV/u **no effect**

# Conclusions

### MCTS (TRAX-CHEM)

- New implementation of TRAX-CHEM with intertrack and oxygen
- Small **Δx-Δt** □ high effect
- Big **Δx-Δt** □ small effect (nothing after 2μm)
- **Intratrack** effect impact on **intertrack**
- $O_2$ can reduce and change intertrack effect for high **Δt** (rad. dependent)
- $O_2$ species undergo strong intertrack effect

### PRM Model

- Develop PRM model for track proximity quantification
- **Micro-** structure "collapse" to **macro-** after surpassing the repetition time ($t_\mu$)
- **Macro-** does the same with **continuous** version after $t_r$
- Factor = $t_r$ / $\tau$ between continuous and macropulse
- Increase LET → decrease probability of intertrack
- Increase Dose rate → increase probability of intertrack

- **No potential impact in heterogeneous chemistry of intertrack** (e-