Theoretical modeling for the thermal stability of solid targets in LEMMA muon collider

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Outline

- Introduction of the LEMMA project
- Features of the Positron beam
- Numerical simulation of the deposited energy onto the target
- Temperature behaviour of the thermal parameters of Beryllium and Carbon
- Temperature field after a single bunch – temperature temporal evolution
- Target steady state temperature
- Thermal stability of the target in case of rotating system
- Conclusions

Introduction of the LEMMA project

Low **EM**ittance **M**uon **A**ccelerator

INFN institutions involved: LNF, Roma1, Pd, Pi, Ts, Fe
Universities: Sapienza, Padova, Insubria
Contributions from: CERN, ESRF, LAL, SLAC

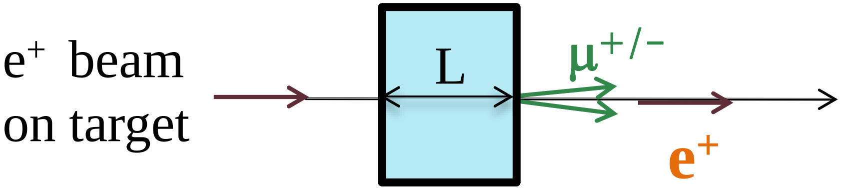
- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 ms (at rest)

Muon source

e^+e^- annihilation - positron beam on target : very low emittance and no cooling needed, baseline for our proposal

e^+ on standard target (including crystals in channeling)
→ Need Positrons of ≈ 45 GeV

Ideally muons will *copy* the positron beam



(finite target length)

Material	Density	Length		eff
	[g/cm^3]	[m]	[X_0]	[$10^{-6}\mu/e^+$]
Be	1.85	0.106	0.3	1.3
C	2.27	0.057	0.3	1.0

Target size and discretization in the FLUKA code

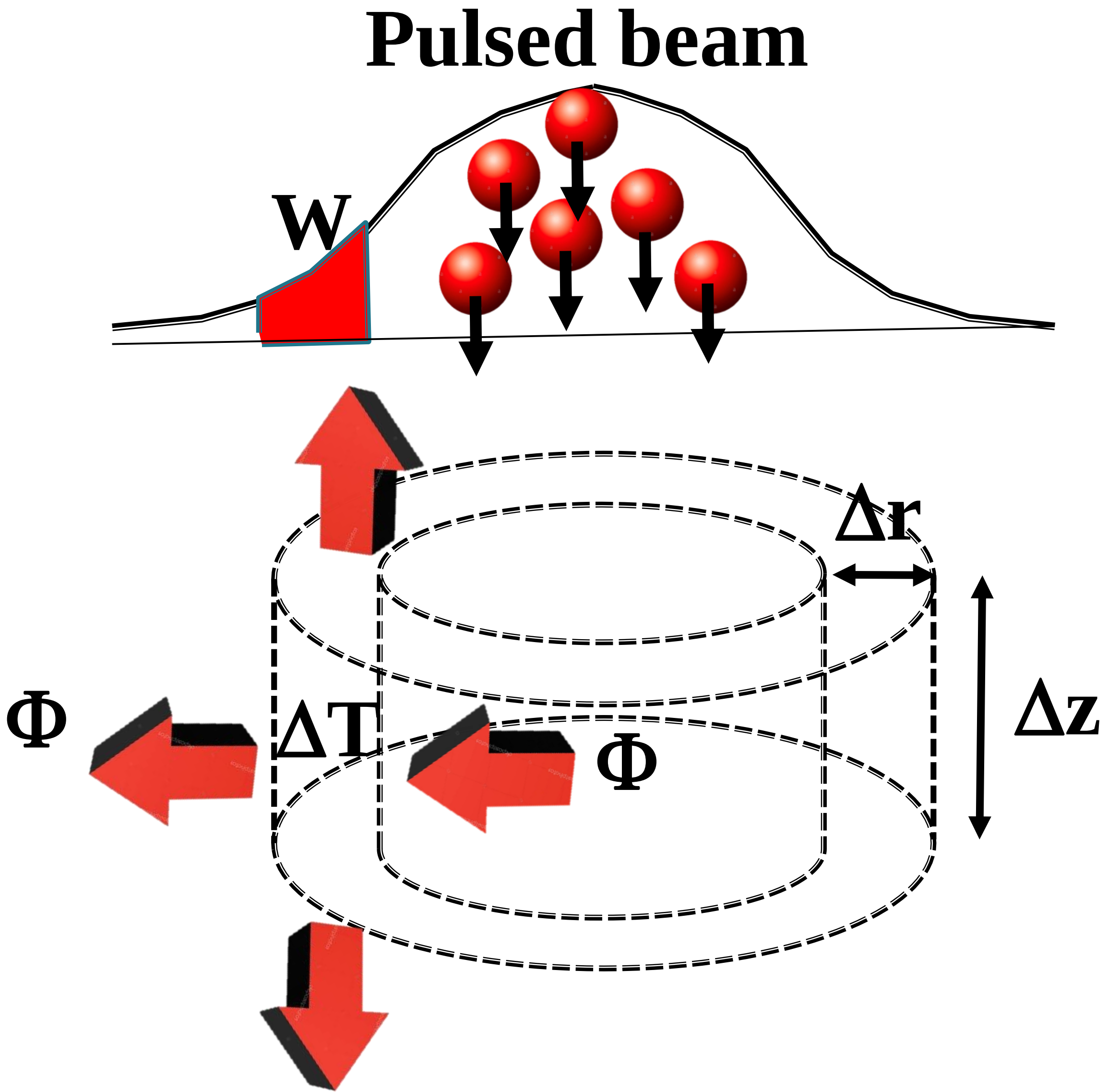
Pulse duration τ : 10 ps

Spot size a : three case studies
(10, 50, 140) μm

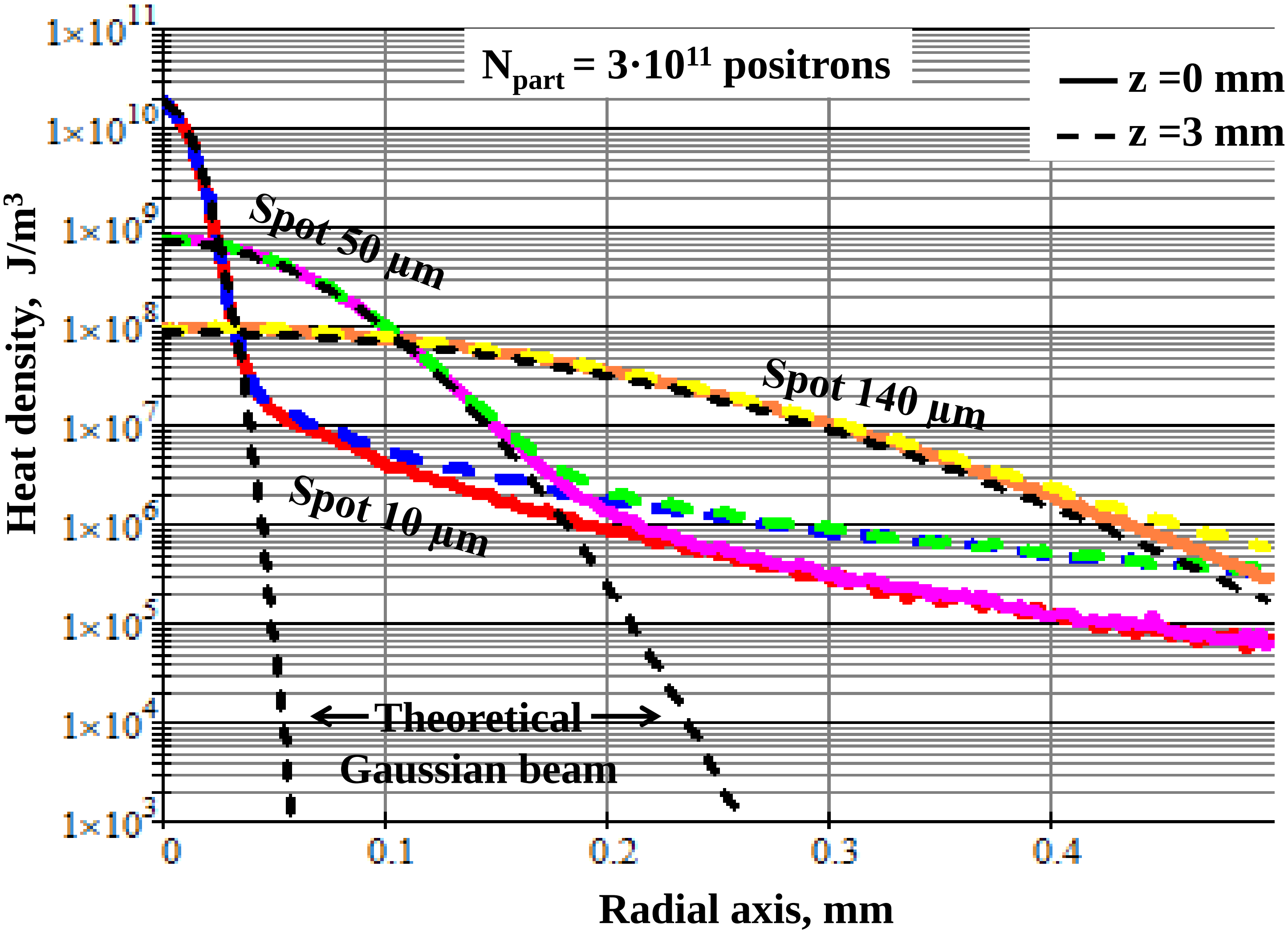
Beryllium thickness: 3 mm

Beryllium radius : 5 cm

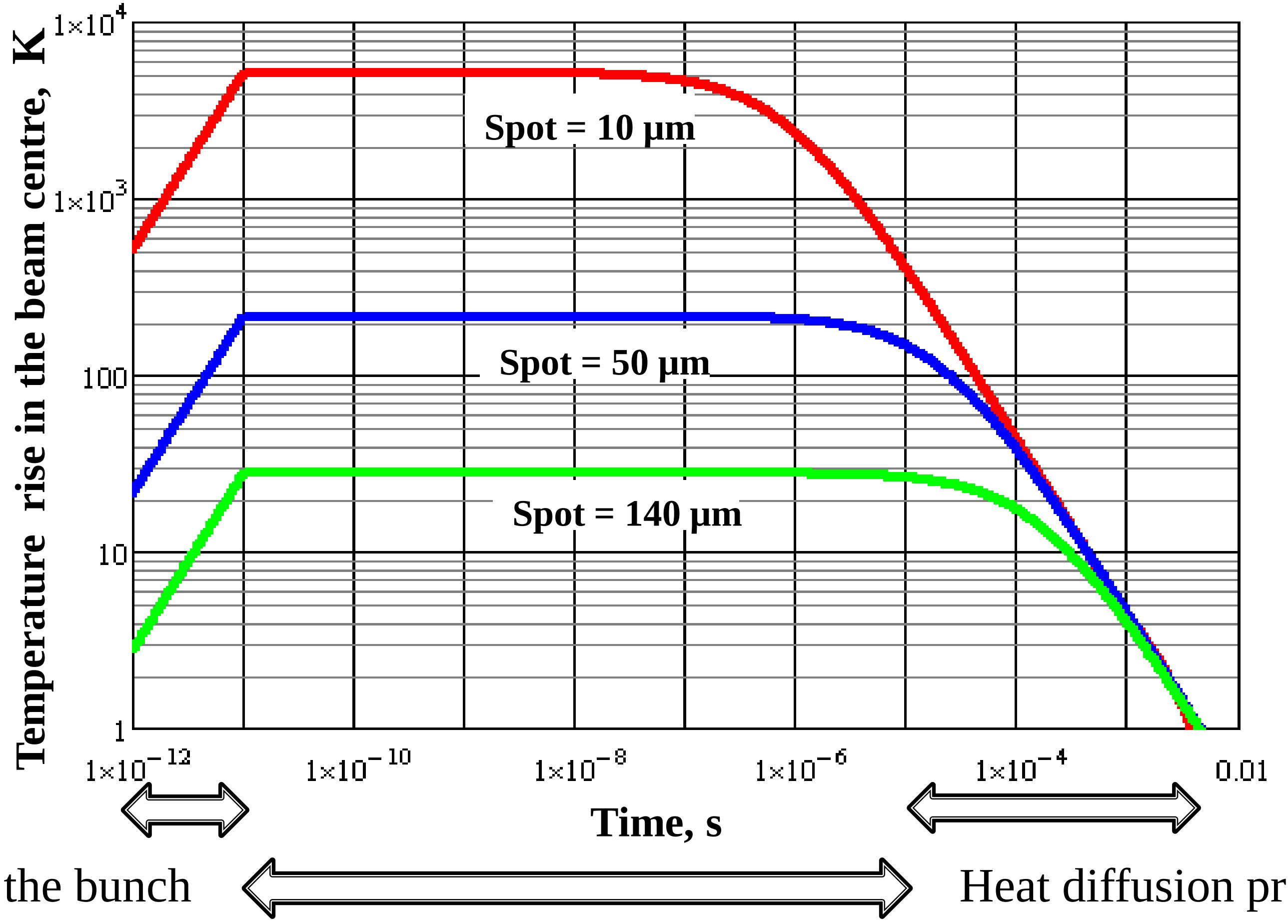
Radial simmetry in the distribution of deposited energy: use of cylindrical coordinates (r, φ=1) and discretization along z.



Energy density deposited for the three case studies



Temperature simulations with constant thermal parameters: linear model – surface temperature rise



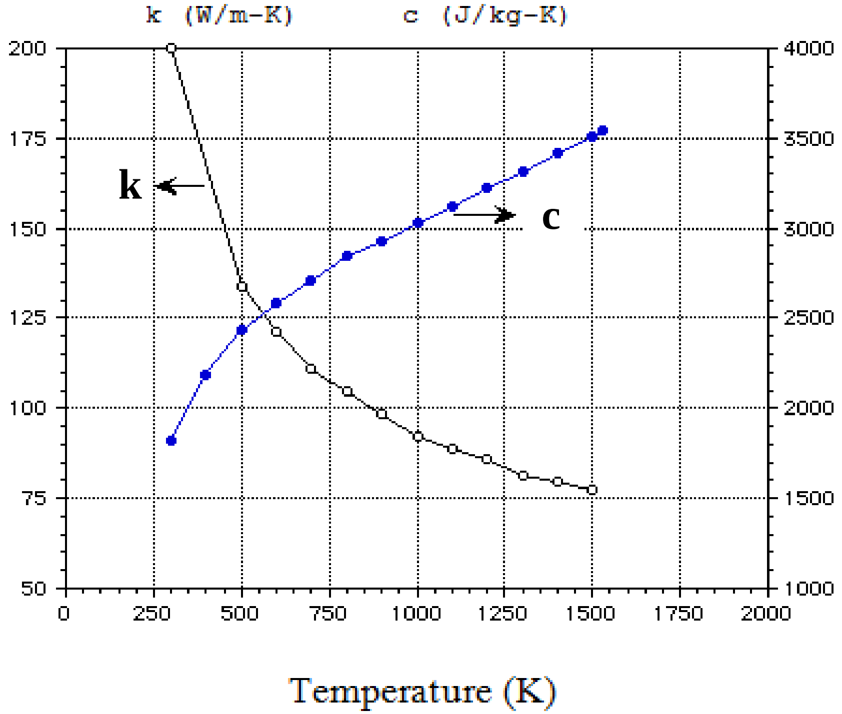
During the bunch

Heat diffusion process

Non-diffusive period

Temperature behaviour of the thermal parameters of Beryllium

Specific heat and **thermal conductivity** of Beryllium are strongly dependent on temperature in the range from room temperature to 1500 K



Beryllium

References

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- J. Phys. Chem. Ref. Data, Vol. 14, Suppl. 1, 1985, pg 354 (JANAF).
- Thermophysical Properties of High Temp. Solid Materials Vol. 1, pt 1, pg 55 - 59.
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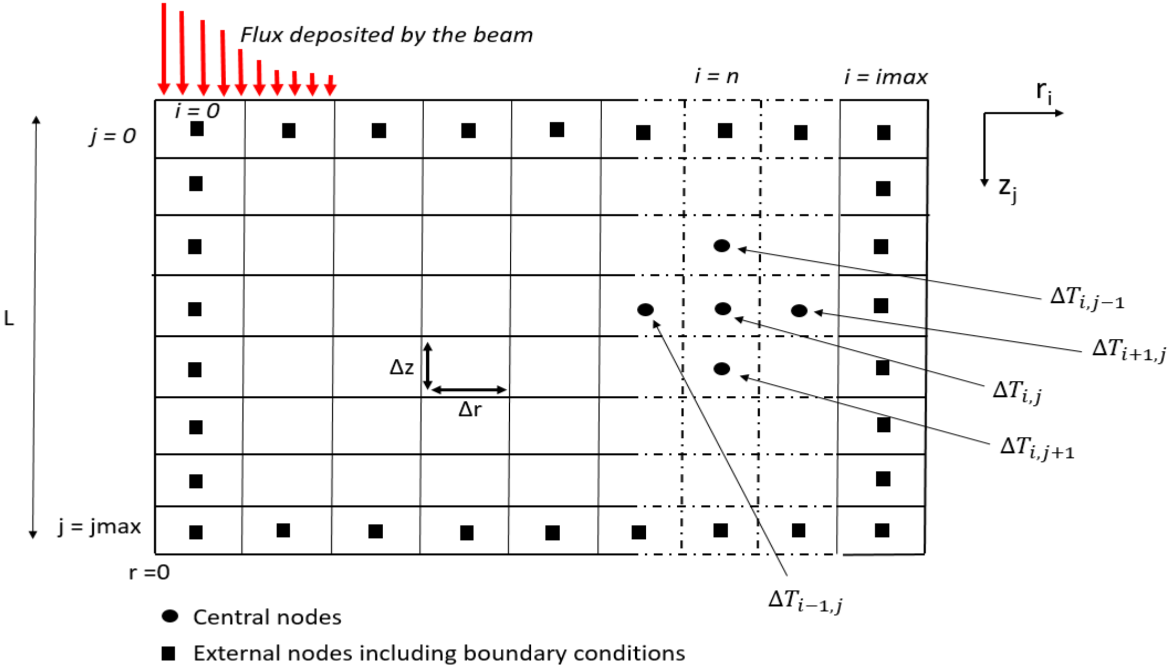
- Eric A. Brandes. Smithells Metals Reference Book, Sixth Edition, Chapter 14, pp 1 - 3.

Numerical model for temperature variation inside the material



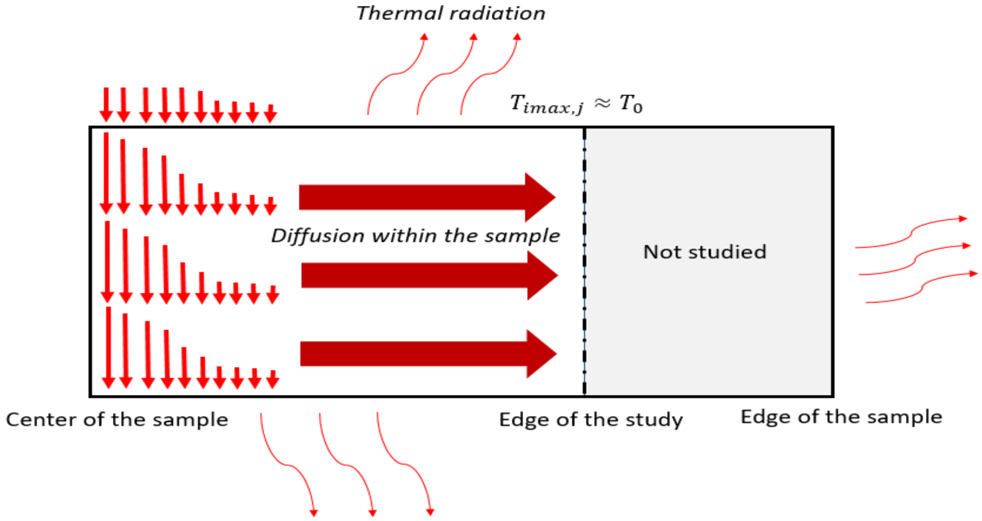
Basic model equation

$$\Delta T'_{i,j} = \Delta T_{i,j} + \left(\frac{W_{i,j} + \Phi_{net}}{V_{i,j}}\right)\frac{\Delta t}{\rho c_p}$$

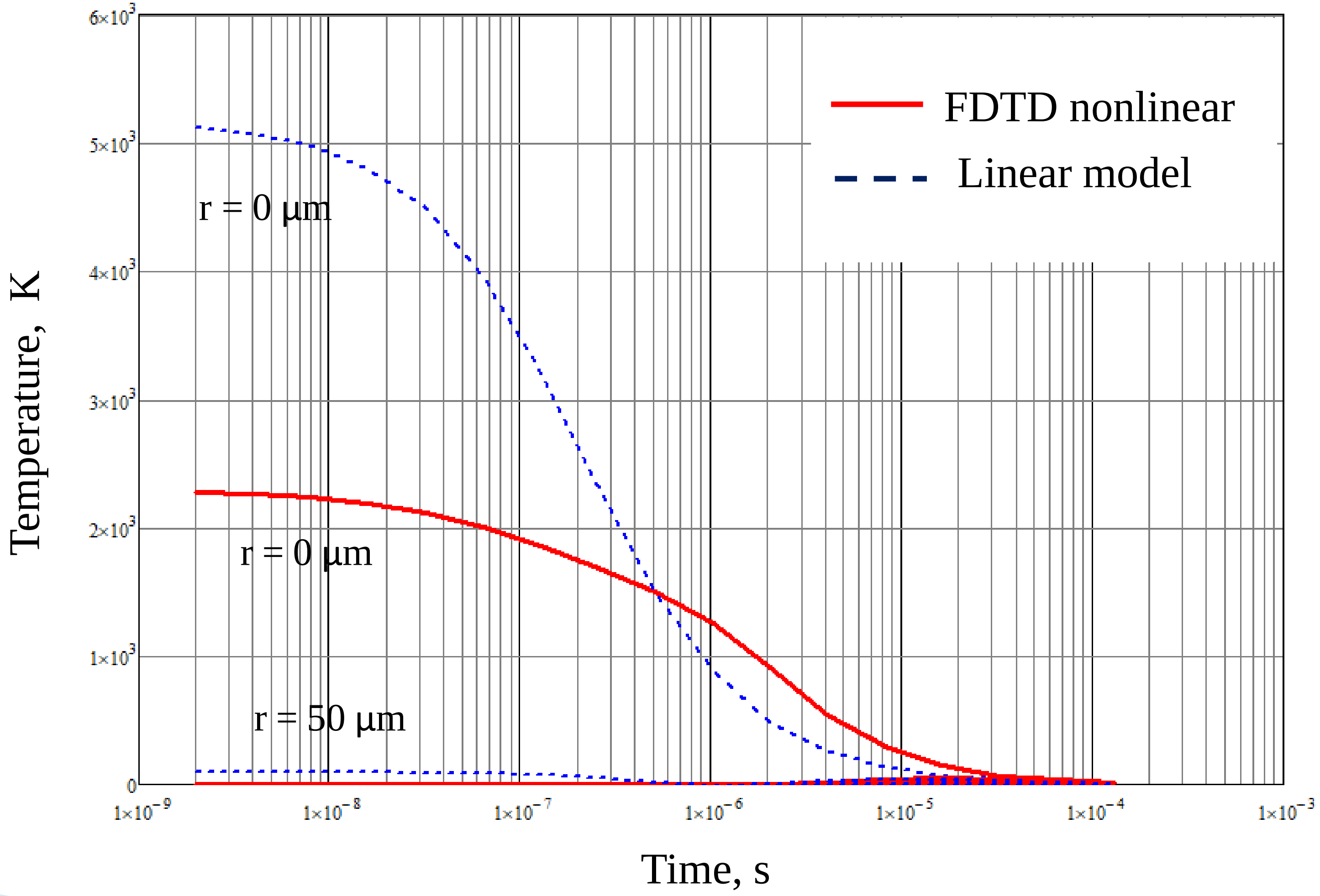
Convergence condition
(Fourier number F**0** = Dt/L^2 ≤ ½): $\Delta t < \frac{min(\Delta r^2, \Delta z^2)}{4D_{max}}$

i scan on r, **j** scan on z

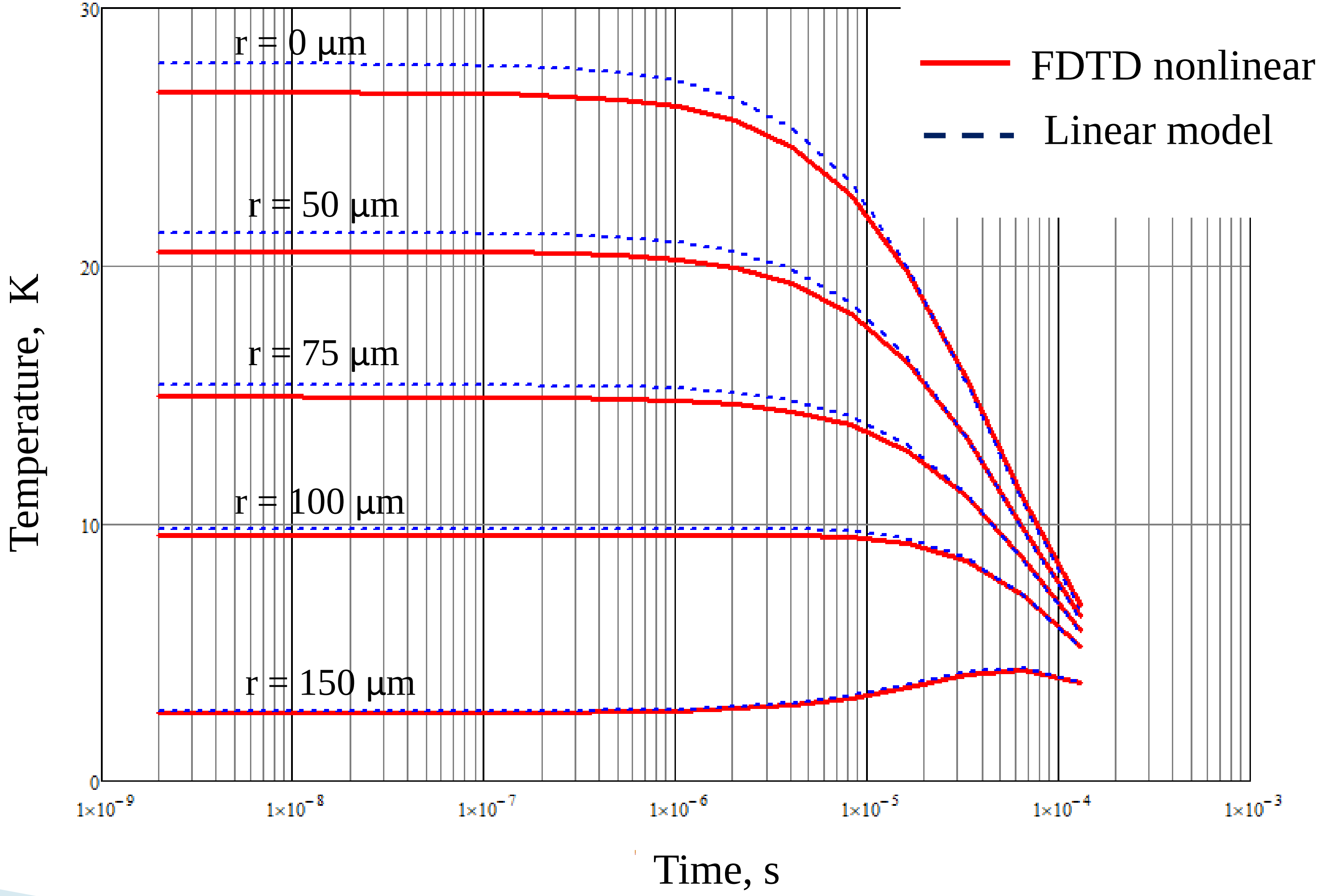
$\mathbf{\Delta T_{i,j}}$’	temperature at time t’, $\mathbf{\Delta T_{i,j}}$ at time t
$\mathbf{W_{i,j}}$	power deposited in element i,j
$\mathbf{\Phi_{net}}$	heat flow exchanged by the element i,j in the time unit
Δt	time lapse
V	element volume i,j
ρ	density
$\mathbf{C_p}$	specific heat
D	thermal diffusivity



Comparison between linear model and numerical model with thermal parameters as a function of temperature (Gaussian beam spot 10 μm)

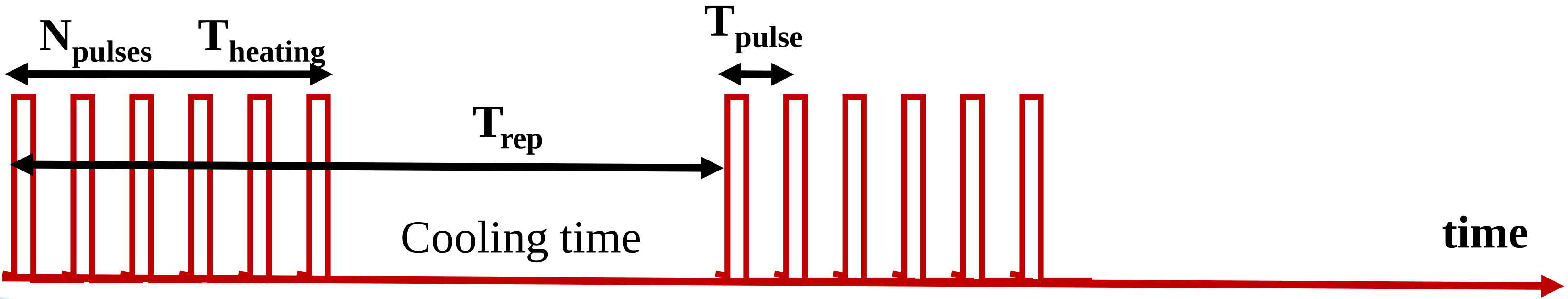


Comparison between linear model and numerical model with thermal parameters as a function of temperature (Gaussian beam spot 140 μm)



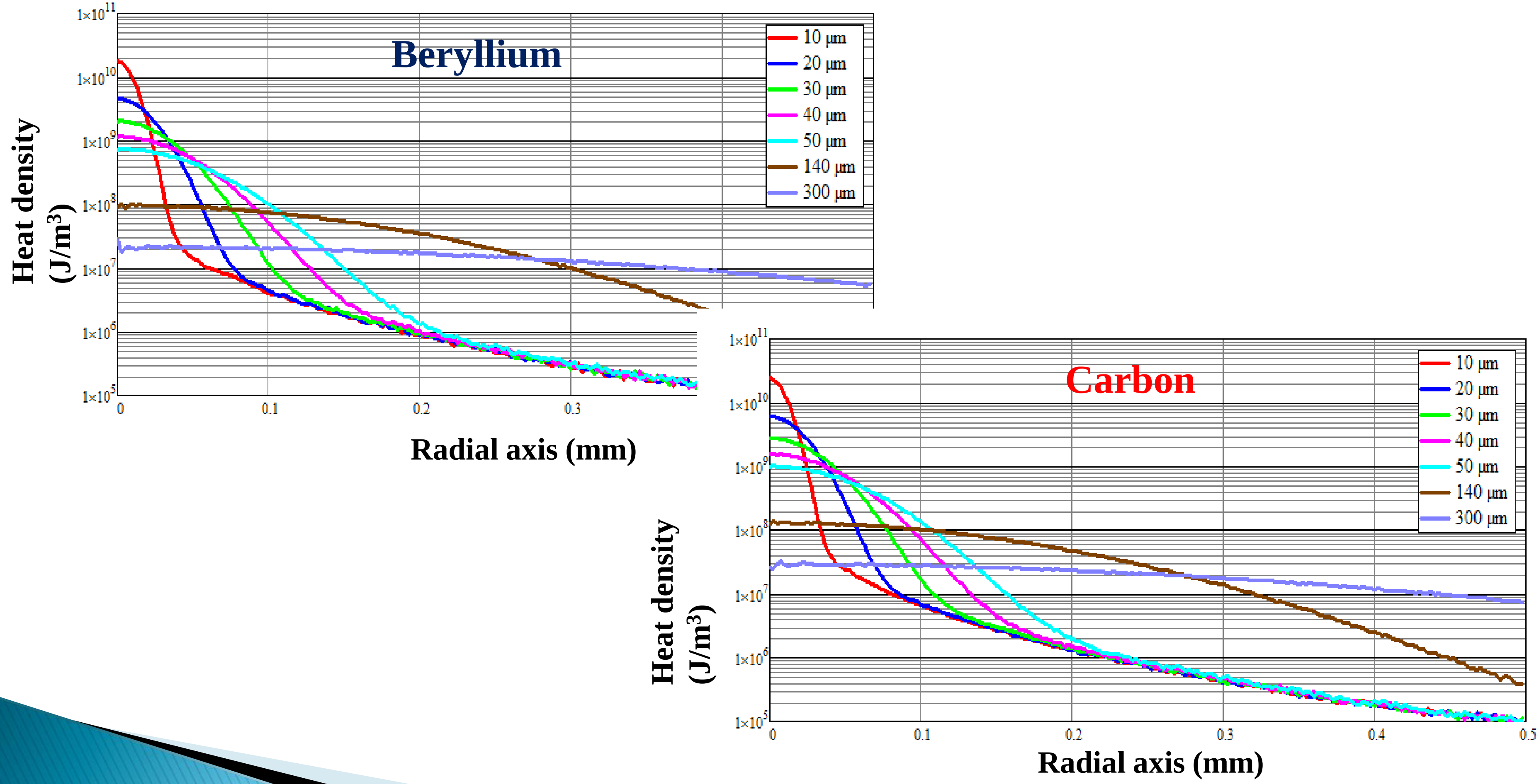
Features of the benchmark positron beam

Symbol	Description	Reference Value
a	Gaussian beam spot size	300 µm
τ	bunch duration	10 ps
N_{part}	positron number	$3 \cdot 10^{11}$
N_{pulses}	number of consecutive bunches	100
T_{pulse}	time between two bunches	400 ns
$T_{heating}$	total time of N_{pulses}	40 µs
T_{rep}	repetition time of the N_{pulses} sequence	0.1 s

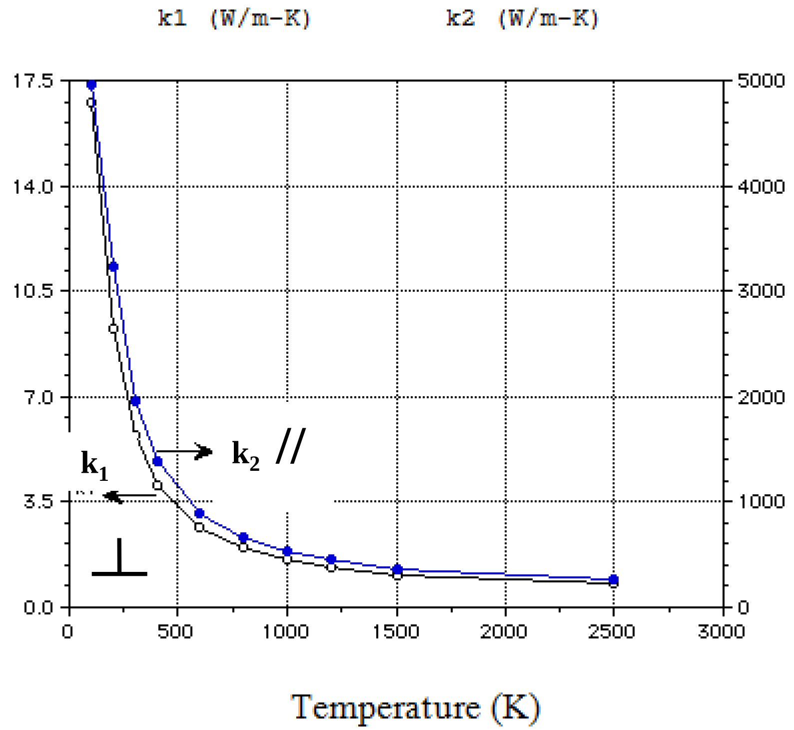


Numerical simulation of the deposited energy onto the target

For this purpose Monte Carlo simulations have been performed with FLUKA both for Beryllium and Carbon (Low-Z materials). The figures show the heat deposited by a single bunch of $3 \cdot 10^{11}$ e^+ as a function of the radial distance from the center.

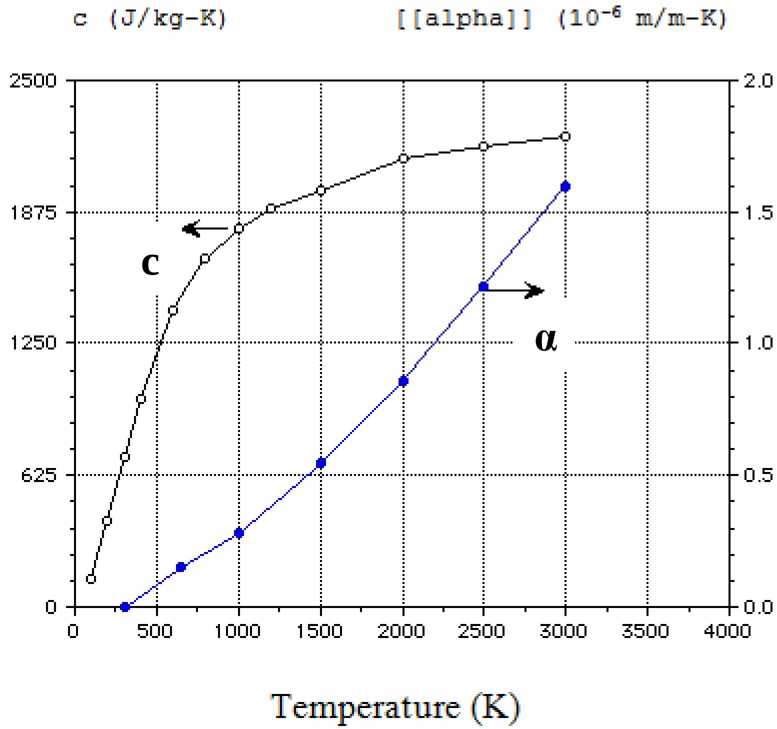


Temperature behaviour of the thermal parameters of Beryllium and Carbon



Thermal conductivity of pyrolytic graphite both parallel and perpendicular to the layers.

Carbon



Specific heat and coefficient of thermal expansion of pyrolytic graphite.

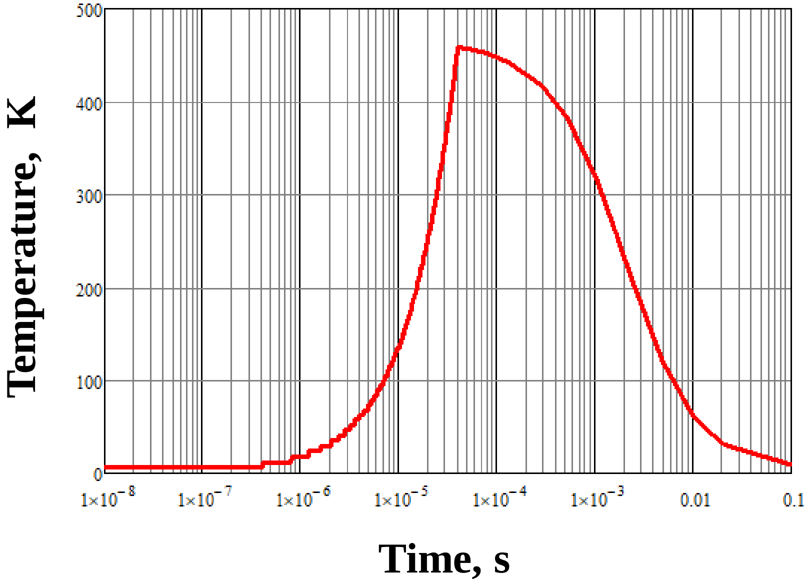
References

Goodfellow. Metals, Alloys, Compounds, Ceramics, Polymers, Composites. Catalogues 1993/94.

Frank P. Incropera, David P. Dewitt, Fundamentals of Heat Mass Transfer, Second Edition pg 759.

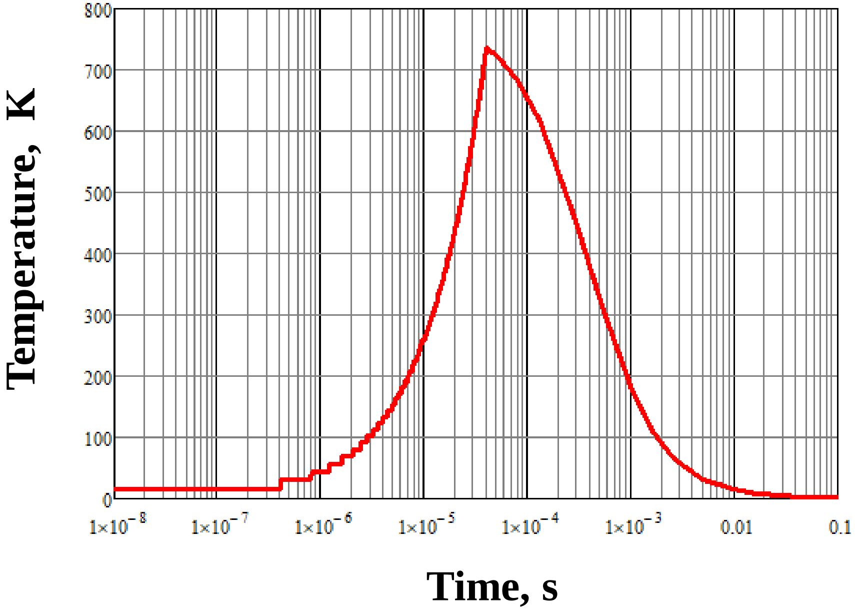
Temperature temporal evolution in the beam spot center after a sequence of bunches

Beryllium



After 100 bunches

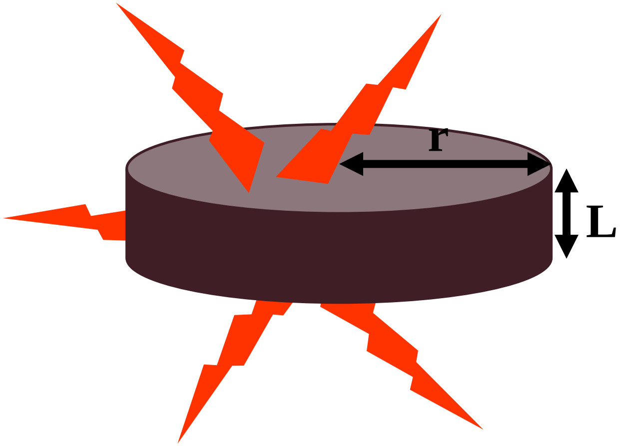
Carbon



Asymptotic temperature increase: Steady State Temperature

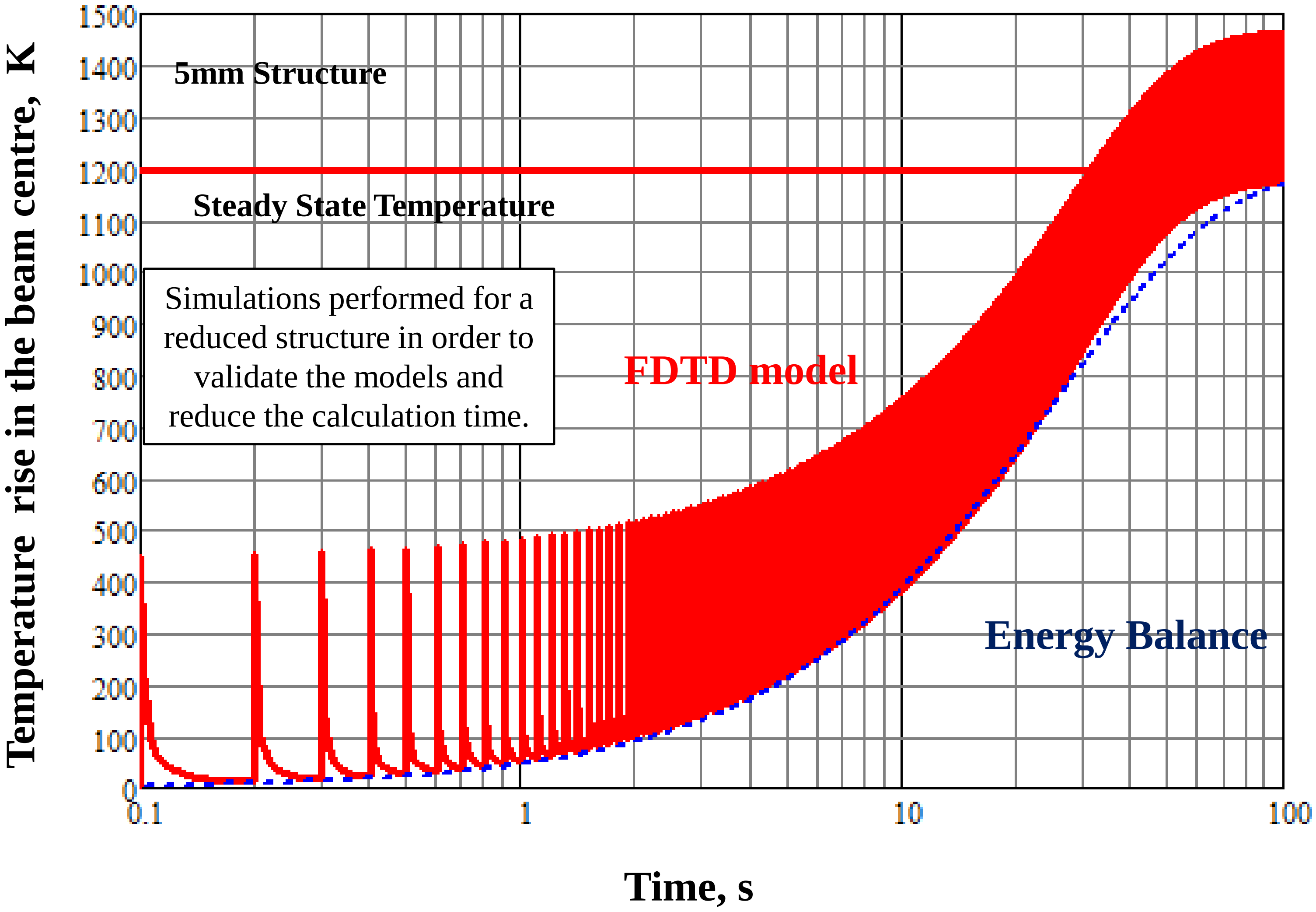
Obtained from the energy balance between the deposited energy and the dissipation by ***thermal radiation***

$$\Delta T = \sqrt[4]{T_{amb}^{4} + \left(\frac{a^{2} \cdot L}{r^{2} + r \cdot L} \right) \frac{C_{\max,a} \cdot N_{part} \cdot N_{pulses}}{\varepsilon \cdot \sigma_{B} \cdot T_{rep}}} - T_{amb}$$



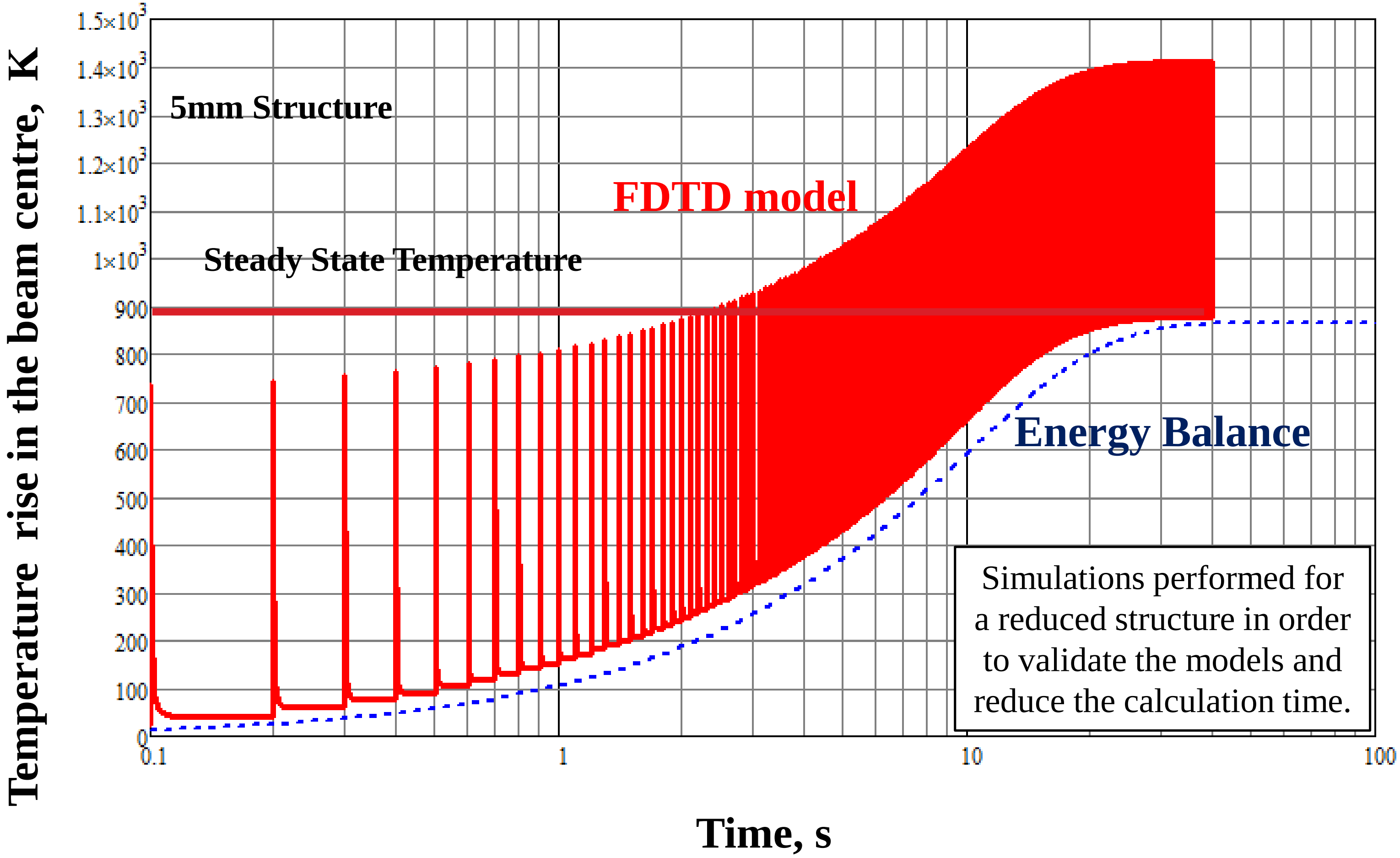
ε emissivity, **σ_B** Stefan-Boltzmann constant, **T_{rep}** pulse train repetition period, **$C_{max,a}$** deposited energy density peak by the Fluka data

Comparison between the numerical model and the model based on the energy balance for the Beryllium target



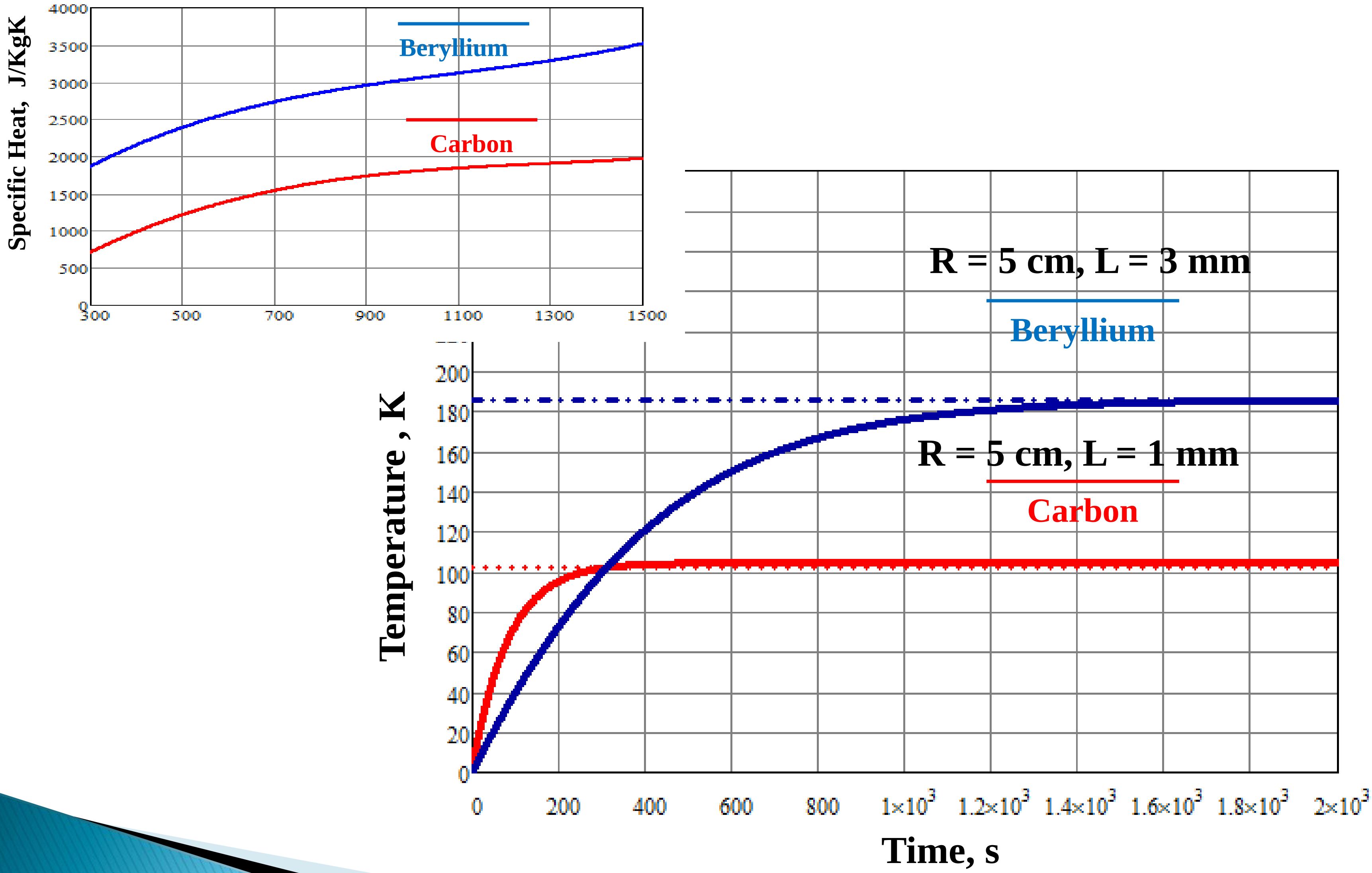
Simulations performed for a reduced structure in order to validate the models and reduce the calculation time.

Comparison between the numerical model and the model based on the energy balance for the Carbon target



Simulations performed for a reduced structure in order to validate the models and reduce the calculation time.

Energy Balance Model and Steady State Temperature



Steady State Temperature

Beryllium target
radius r = 5 cm, thickness L = 3 mm;
Beam spot size: a = 300 µm;
Number of positrons: $N = 3 \cdot 10^{11}$
Cooling time: $T_{Rep} = 0.1$ s.

Steady state temperature increase: $\mathbf{\Delta T_{SS} = 185.5\ K}$
Melting point: 1551 K

Carbon target
radius r = 5 cm, thickness L = 1 mm;
Beam spot size: a = 300 µm;
Number of positrons: $N = 3 \cdot 10^{11}$
Cooling time: $T_{Rep} = 0.1$ s.

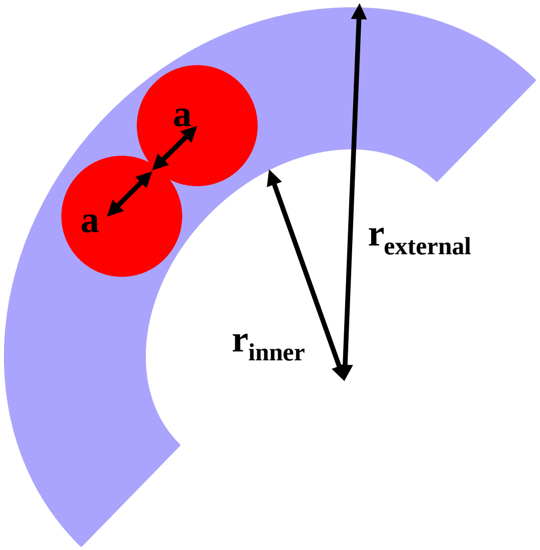
Steady state temperature increase: $\mathbf{\Delta T_{SS} = 102.5\ K}$
Melting point: 3923 K

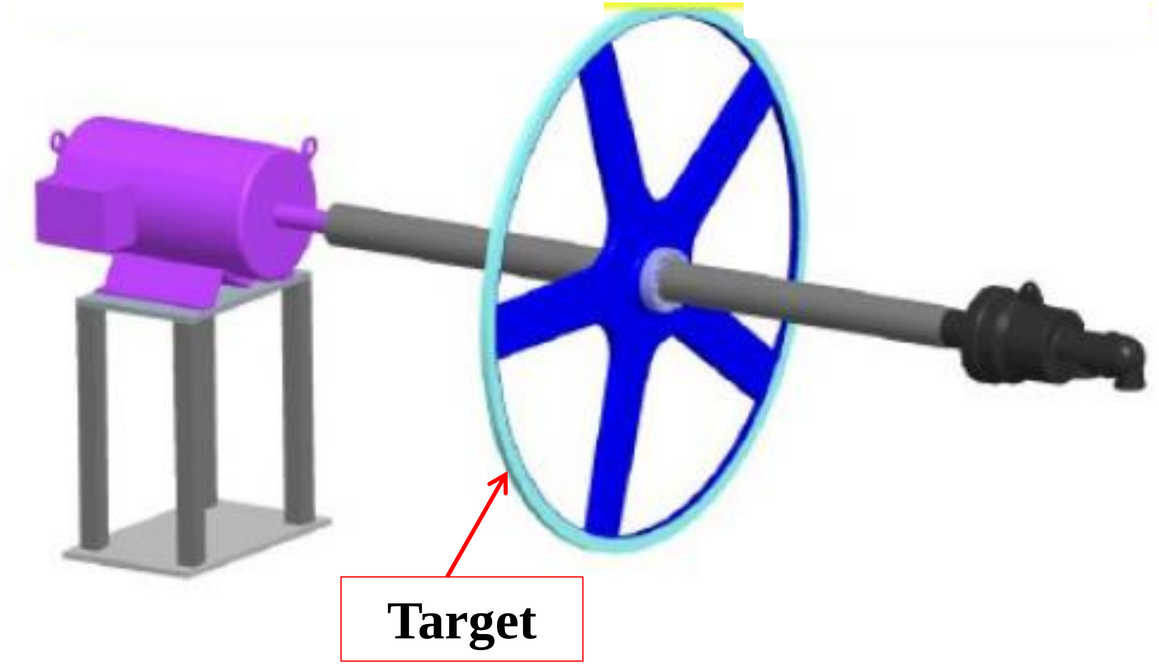
Thermal stability of the target in case of rotating system

Wheel rim speed 100 m/s

Wheel diameter ~ 1 m

→ **We can discriminate single bunches**

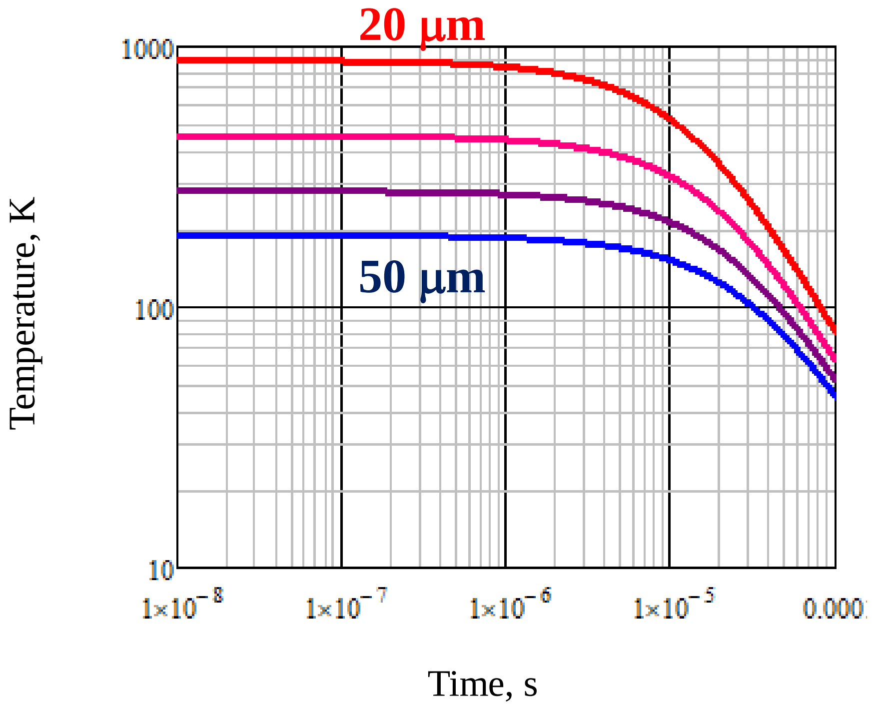


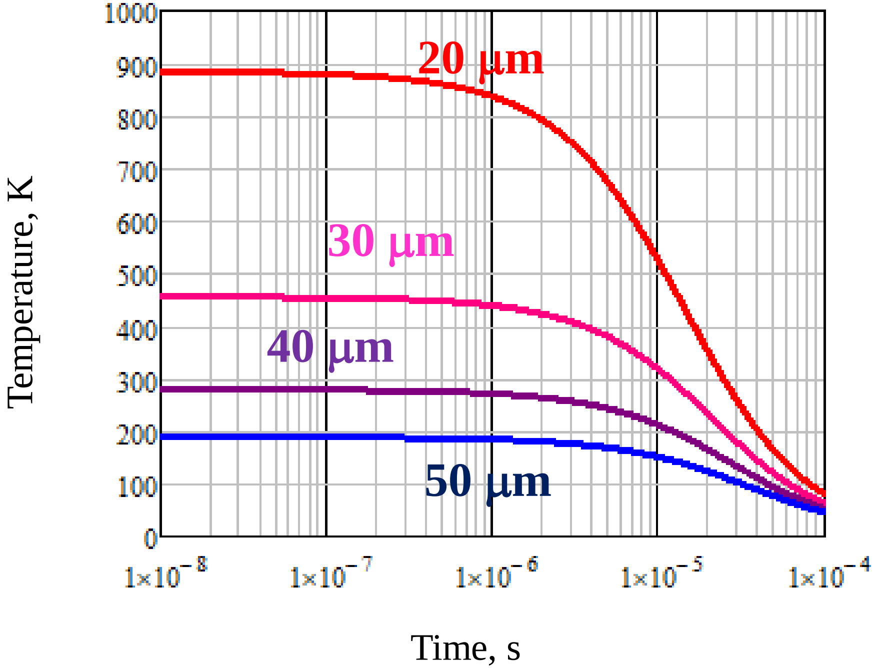


Temperature field after a single bunch – temperature temporal evolution (1)

The spatial and temporal distribution of the thermal field has been calculated using the Fourier heat transfer from the heat density deposited taking into account the dependence on temperature of the thermal parameters of the material. A Finite difference time domain method (**FDTD**) code has been developed for the evaluation of the temperature gradient on the target and the timing of heat diffusion on the latter.

Beryllium



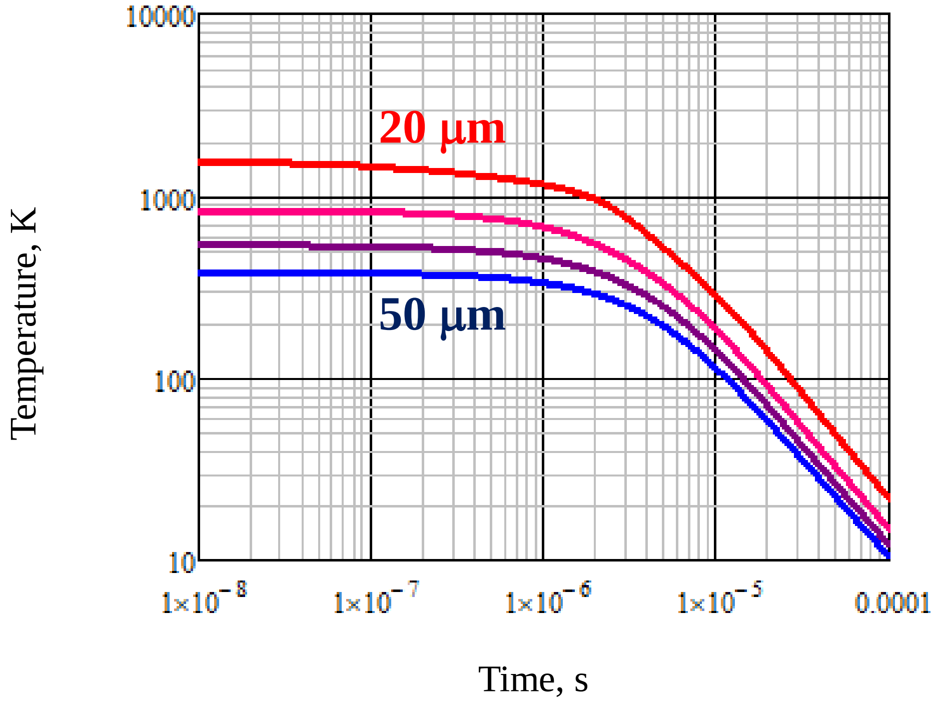


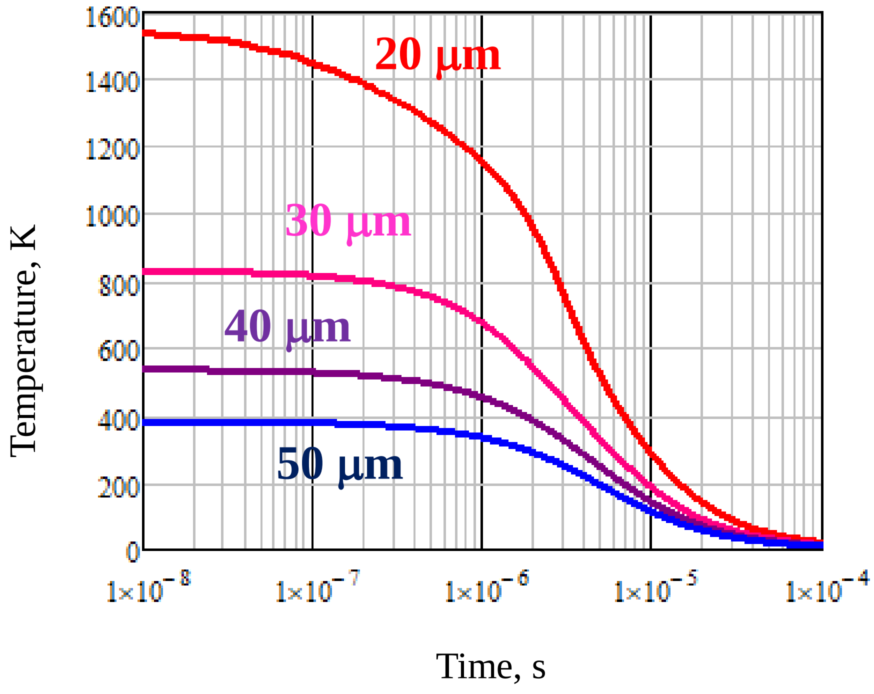
Melting point 1551,15 K

Temperature field after a single bunch – temperature temporal evolution (2)

Here we have chosen smaller spot sizes in order to evaluate the increase in temperature in the incidence area as the spot size decreases. For both materials considered as targets, cylindrical symmetry was used for the analysis of heat diffusion, starting from the symmetry of the Gaussian beam.

Carbon





Melting point 3773 K

Work in progress..

Conclusions

We can use a two-way approach:

❑ use the numerical model (FDTD) in order to evaluate the spatial and temporal gradients of temperature due to a single bunch or to sequence of bunches that can cause thermomechanical stresses and therefore damage or fractures of the target;

❑ use the model based on the energy balance to obtain the steady state temperature and evaluate its sustainability both for a static configuration of the target and for an application on a rotating support.

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