INVESTIGATION OF THERMAL DAMAGE OF THE EXIT WINDOW DURING THE PASSAGE OF ELECTRON BUNCHES

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- **Heat transfer mechanisms and on axis temperature for various exit window materials**
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INTRODUCTION

Motivation:

- **The beam diagnostics used for high repetition rate and high brightness electron bunches can be overheated or destroyed by radiation caused by the interaction of electrons with the matter. Therefore, it is important to study the thermal stability of the material depending on the parameters of the electron beam.**

Objective

- **The goal of this work is to find the optimal material and thickness of the exit window for particular electron beam parameters.**

Simulation setup used in FLUKA

Material

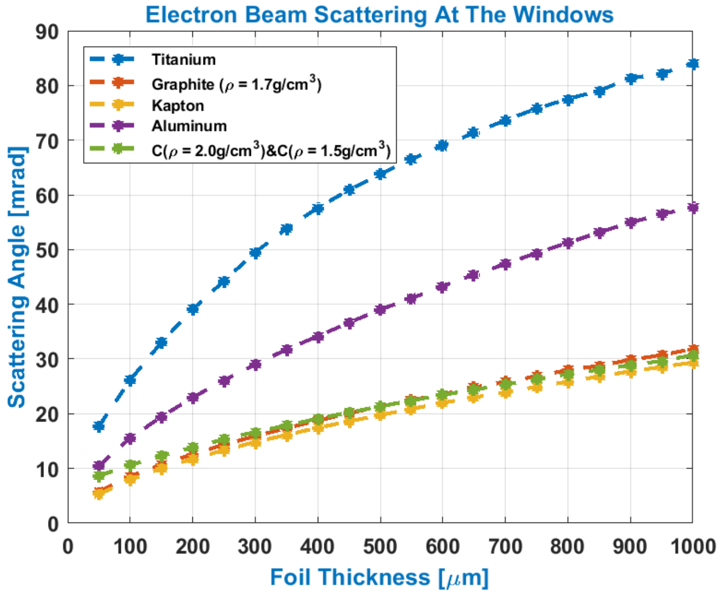
- ***Titanium* *foil with a thickness of* $50 - 1000\mu m$**
- **Graphite *foil with a thickness of* $50 - 1000\mu m$ and density is $\rho = 1.7\ g/cm^3$**
- ***Kapton* *foil with a thickness of* $50 - 1000\mu m$**
- ***Aluminum* *foil with a thickness of* $50 - 1000\mu m$**
- **Pyrolytic graphite of two layers**
  - **First layer density is $\rho = 2.0\ g/cm^3$ and thickness is $50\mu m$ and second layer density is $\rho = 1.5\ g/cm^3$ and thickness of 50-$500\mu m$.**

Beam parameters

Beam energy 22MeV

Beam spot size 0.1mm

BEAM SCATTERING

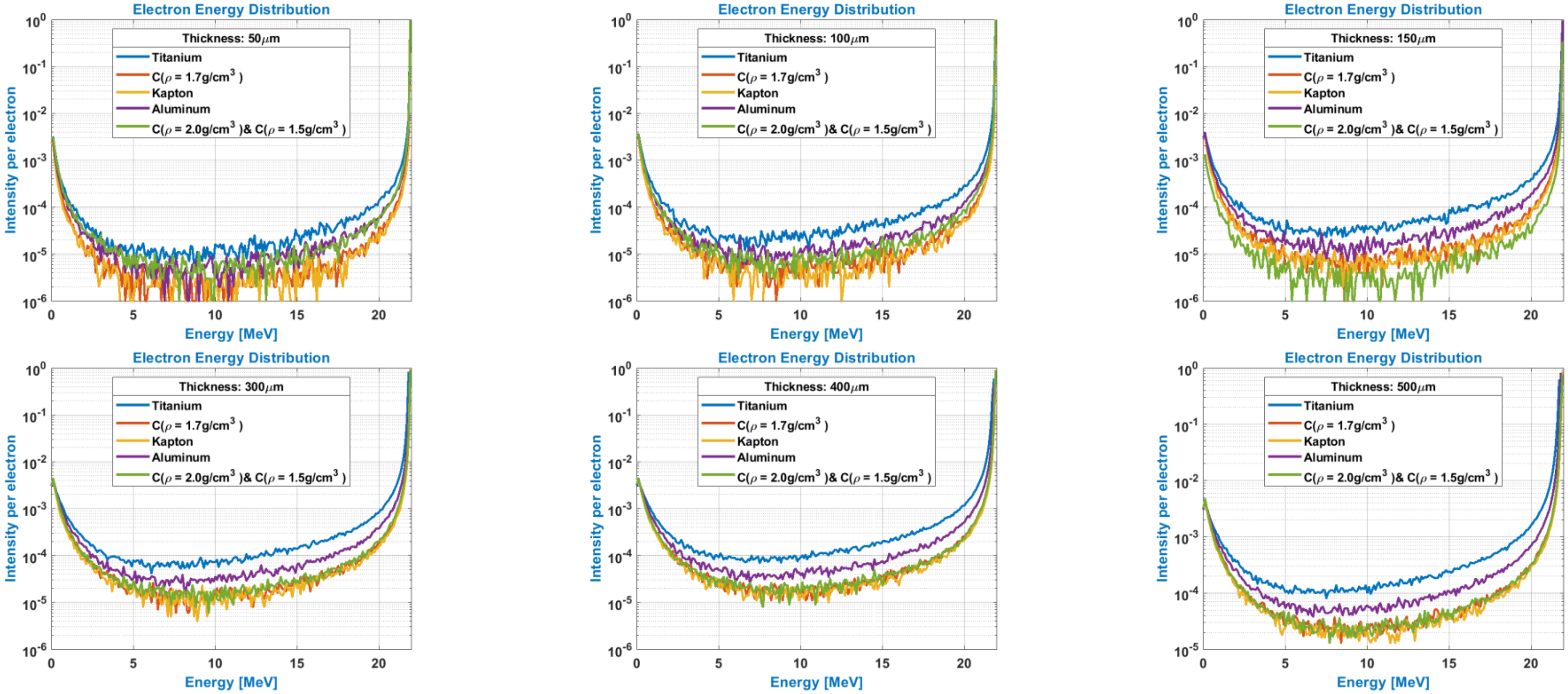


Exit Window	Scattering Angle [mrad]
$Titanium\ \ 50\mu m$	17.73
$Titanium\ \ 127\mu m$	30.19
$Titanium\ \ 100\mu m$ $Graphite\ 800\mu m$	41.01
$Kapton\ 412\mu m$	18.11
$Graphite(\rho = 2.0\ g/cm^3)\ 50\mu m$ $Graphite(\rho = 1.5\ g/cm^3)\ 500\mu m$	21.34

The dependence of the electron beam **scattering angle** on the thickness of the exit windows.
Line colors correspond to different materials of the **exit windows**.

Thickness of the **titanium** foil of $50\ - 1000\mu m$, corresponds to the scattering angle of $17.73\ - 84.04mrad$.
Thickness of the **graphite(**$2.0\ g/cm^3$**)&graphite(**$1.5\ g/cm^3$) foil of $50 - 1000\mu m$, corresponds to the scattering angle of $8.65\ - 30.73mrad$.

ENERGY DISTRIBUTION



Energy distribution of electrons after passage through the exit windows of various thicknesses and material types.

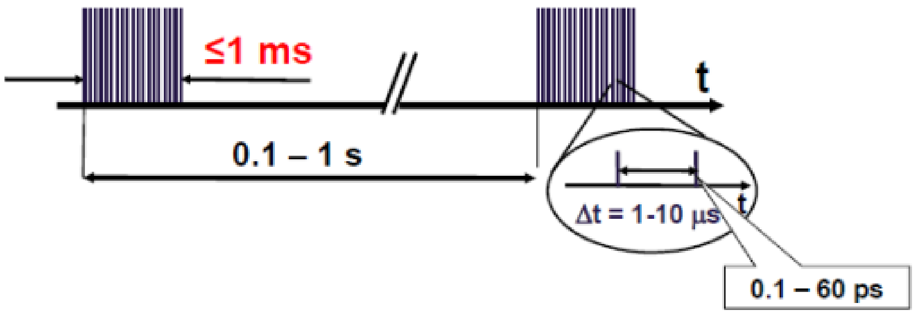
The same behavior of **energy spectra** of **graphite(red)**, **Kapton(yellow)**, **pyrolytic graphite(green)** for $\mathbf{50 - 1000\mu m}$ thicknesses.

BEAM PARAMETERS

Interaction of high brightness bunches with an exit window leads to fast and significant local heating as a result of which the exit window could be overheated because the train typically consists of few thousand bunches. Hence one should be sure that the local temperature in the interaction area does not exceed the critical temperature.

Electron Beam parameters

- **Bunches**: up to $\mathbf{4500}$ bunches in $\mathbf{1}\boldsymbol{ms}$
- **Bunch charge:** up to $\mathbf{5}\boldsymbol{nC}$
- **Bunch length:** $\mathbf{0.1-60}\boldsymbol{ps}$
- **Beam energy:** $\mathbf{22}\boldsymbol{MeV}$, **future option** $\mathbf{250}\boldsymbol{MeV}$



HEAT TRANSFER MECHANISMS

Heat is classified into various mechanisms, such as

- **Thermal conduction:**

  The transfer of energy between objects that are in physical contact. Thermal conductivity is the property of a material to conduct heat and evaluated primarily in terms of Fourier's Law for heat conduction.

$$\frac{\partial Q}{\partial t} = -k \oiint \nabla T \cdot dS \Rightarrow \frac{Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

- **Thermal convection:**

  The transfer of energy between an object and its environment, due to fluid motion. The average temperature is a reference for evaluating properties related to convective heat transfer.

$$\frac{\partial Q}{\partial t} = -hA\Delta T$$

- **Thermal radiation:**

  The transfer of energy by the emission of electromagnetic radiation.

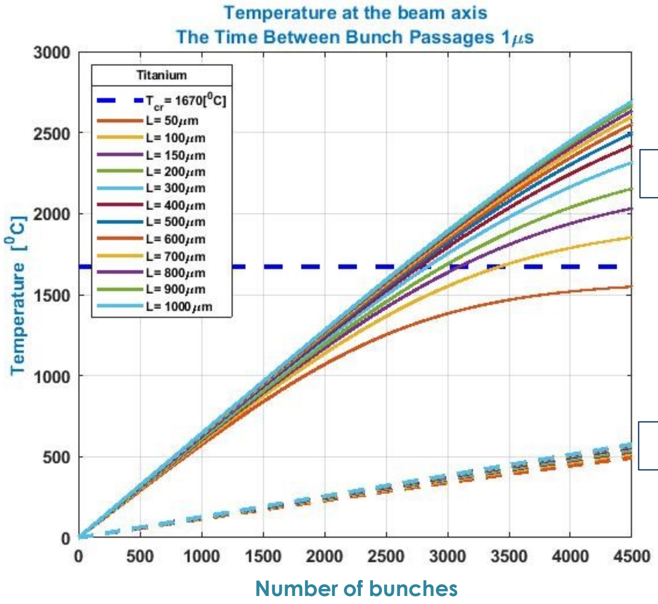
$$\frac{\partial Q}{\partial t} = \varepsilon\sigma A\left(T^4 - T_a^4\right)$$

Conductive heat transport was calculated to be several orders of magnitude smaller in the case of $\mu m - thick$ foils than radiative heat transport.

where:
Δt - time Interval
A - cross-sectional surface area
ΔT - temperature difference between the ends
Δx - distance between the ends.
k- thermal conductivity
h- heat transfer coefficient
ε – surface emissivity
σ –Stefan-Boltzmann constant
T_a- ambient temperature

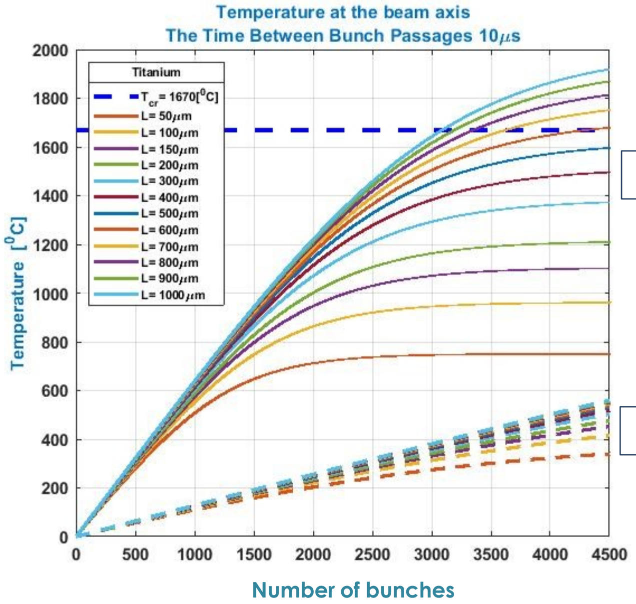
TEMPERATURE AT THE BEAM AXIS

Titanium



$q_0 = 5nC$

$q_0 = 1nC$



$q_0 = 5nC$

$q_0 = 1nC$

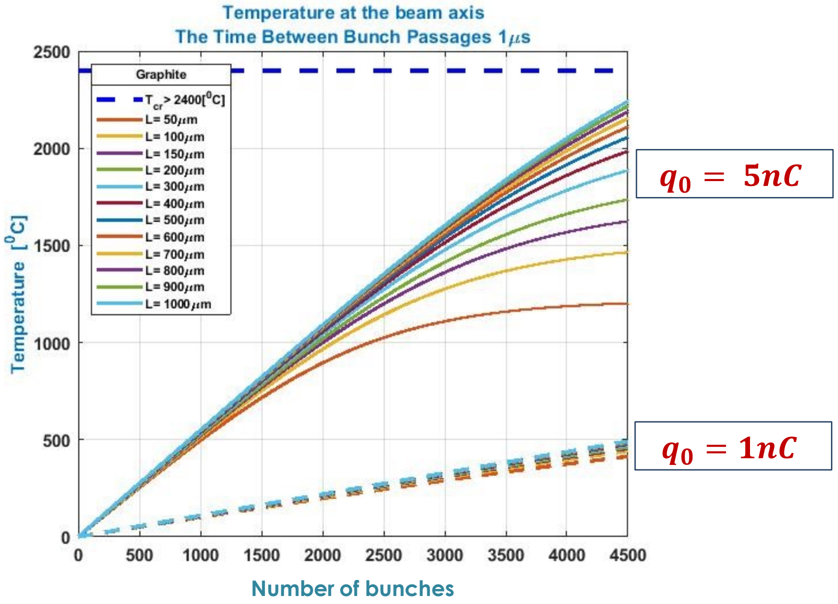
On axis temperature as function of number of bunches. Dash line corresponds to titanium melt temperature.

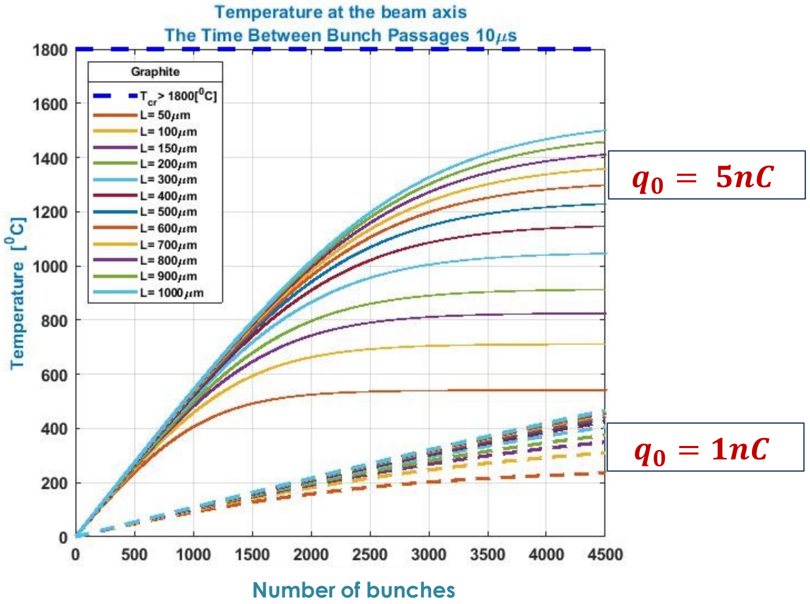
Highest **bunch charge** $5nC$ and repetition rate $\mathbf{1\mu s}$ the acceptable thickness of titanium foil is $\mathbf{50\mu m}$.

Highest **bunch charge** $5nC$ and repetition rate $\mathbf{10\mu s}$ the optimum thickness of titanium foil is $\mathbf{500\mu m}$.

TEMPERATURE AT THE BEAM AXIS

Graphite $(\rho = 1.7\ g/cm^3)$



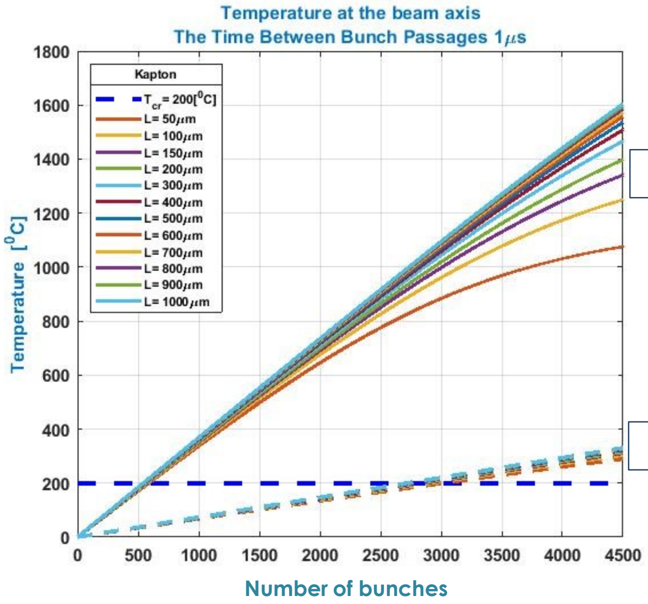


On axis temperature as function of number of bunches. Dash line corresponds to titanium melt temperature.

Highest **bunch charge** $5nC$ and repetition rate $1-10\mu s$ the acceptable thickness of titanium foil is $1000\mu m$.

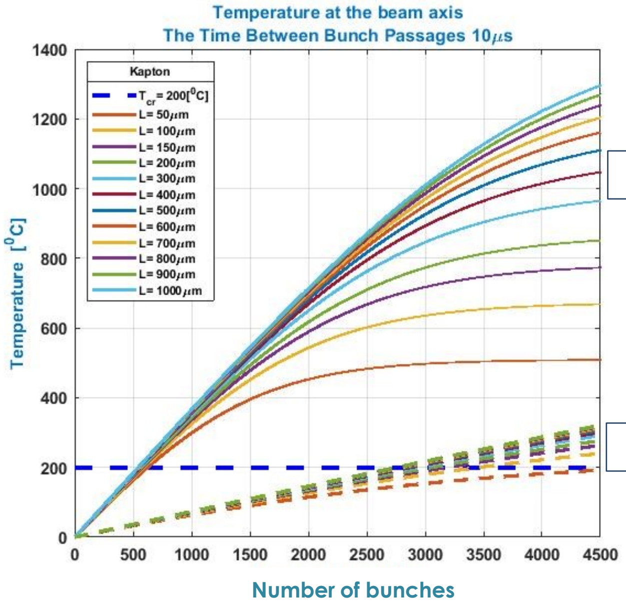
TEMPERATURE AT THE BEAM AXIS

Kapton



$q_0 = 5nC$

$q_0 = 1nC$



$q_0 = 5nC$

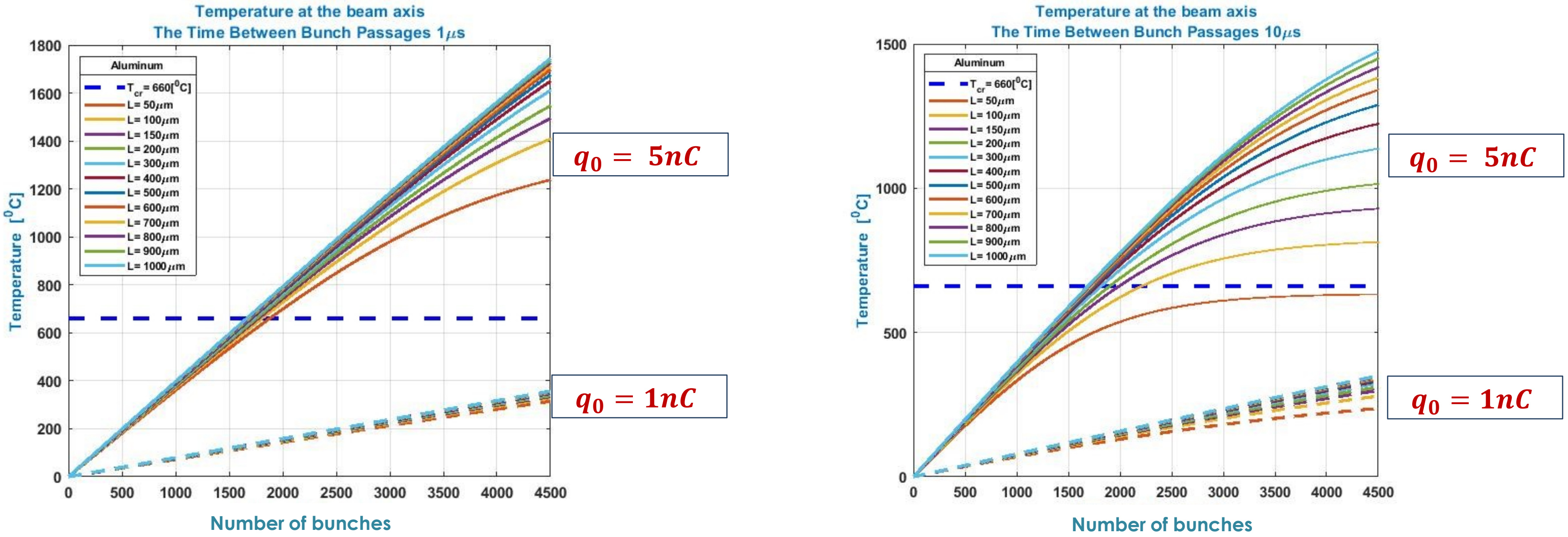
$q_0 = 1nC$

On axis temperature as function of number of bunches. Dash line corresponds to titanium melt temperature.

Bunch charge $1nC$ and repetition rate $\mathbf{10\mu s}$ the optimum thickness of titanium foil is $\mathbf{50\mu m}$.

TEMPERATURE AT THE BEAM AXIS

Aluminium

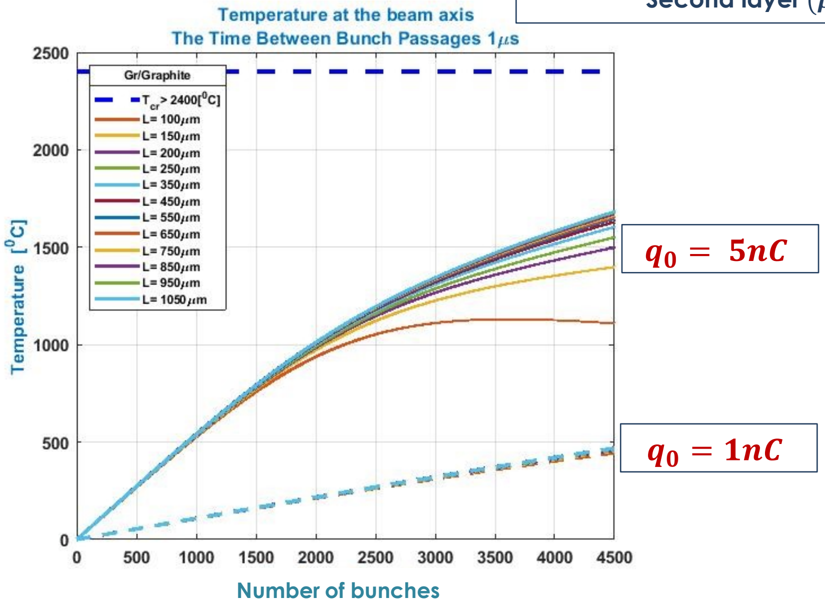


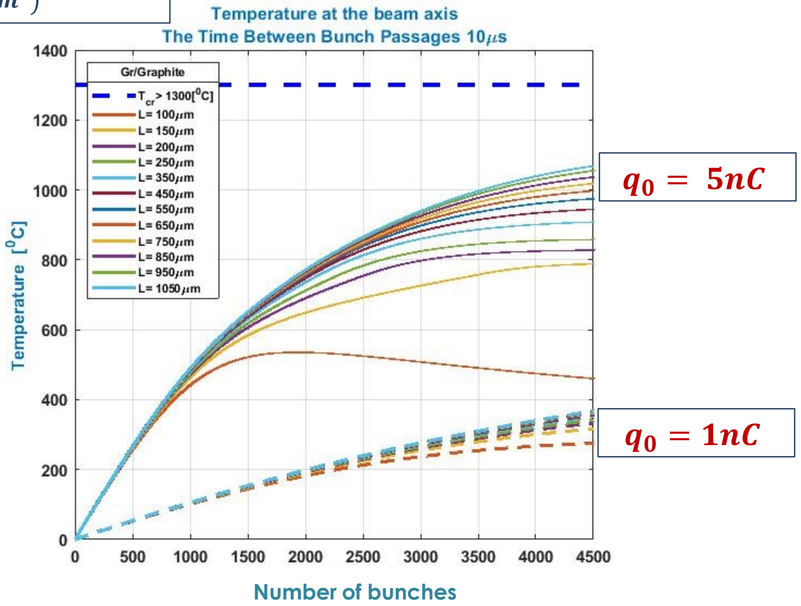
On axis temperature as function of number of bunches. Dash line corresponds to titanium melt temperature.

Highest **bunch charge** $\mathbf{5}\boldsymbol{nC}$ and repetition rate $\mathbf{10}\boldsymbol{\mu s}$ the optimum thickness of titanium foil is $\mathbf{50}\boldsymbol{\mu m}$.

TEMPERATURE AT THE BEAM AXIS

Graphite
First layer $(\rho = 2.0\, g/cm^3\,; 50\mu m)$
Second layer $(\rho = 1.5\, g/cm^3)$

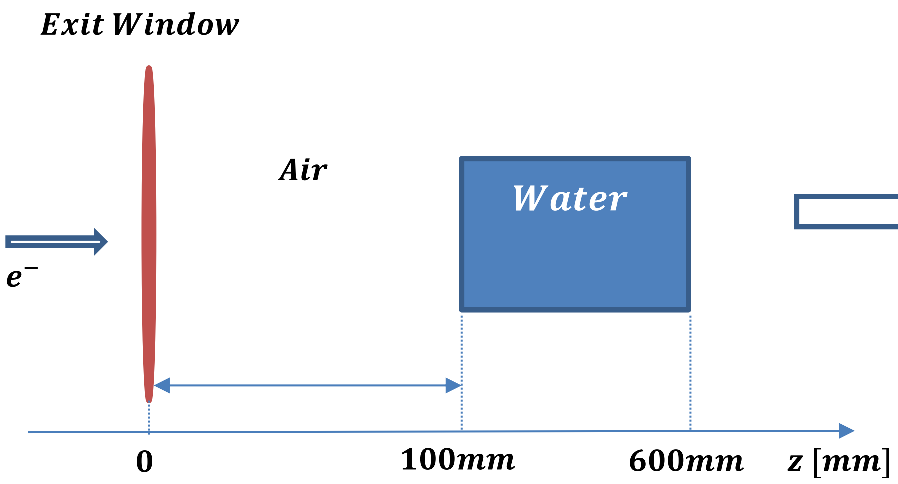


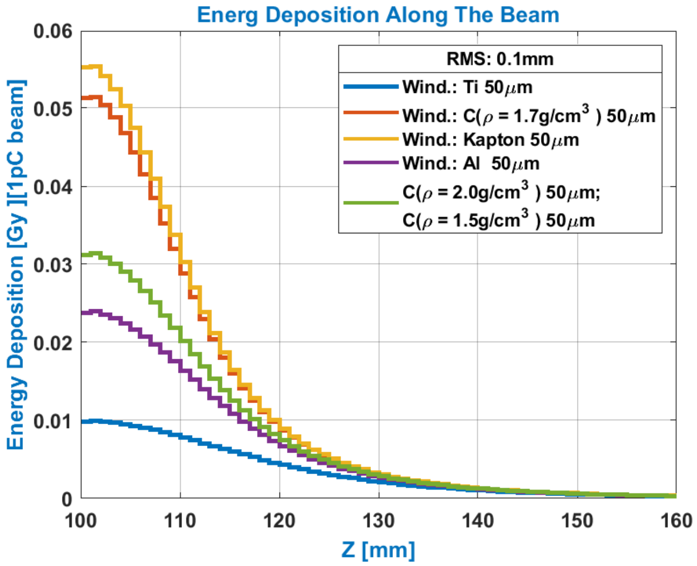


On axis temperature as function of number of bunches. Dash line corresponds to titanium melt temperature.

Highest **bunch charge** $\mathbf{5nC}$ and repetition rate $\mathbf{1-10\mu s}$ the acceptable thickness of titanium foil is $\mathbf{1000\mu m}$.

ENERGY DEPOSITION ALONG BEAM





Energy deposition along the beam path where two transverse dimensions are integrated for central $1 \times 1mm^2$ space.

The incident beam **RMS is 0.1mm.**

CONCLUSION

Titanium:

- scattering angle of $\mathbf{17.73-84.04}\boldsymbol{mrad}$ for thickness of $\mathbf{50-1000}\boldsymbol{\mu m}$.
- Higher energy loss for entire thickness range.
- Acceptable thickness less than $\mathbf{50}\boldsymbol{\mu m}$for $\mathbf{5}\boldsymbol{nC}$ and $\mathbf{1}\boldsymbol{\mu s}$ repetition rate
- Acceptable thickness less than $\mathbf{500}\boldsymbol{\mu m}$ for $\mathbf{5}\boldsymbol{nC}$ and $\mathbf{10}\boldsymbol{\mu s}$ repetition rate

Graphite ($\boldsymbol{\rho}=\mathbf{1.7}\ \boldsymbol{g/cm^3}$):

- scattering angle of $\mathbf{5.72-31.83}\boldsymbol{mrad}$ for thickness of $\mathbf{50-1000}\boldsymbol{\mu m}$.
- Lower energy loss for entire thickness range.
- Acceptable thickness less than $\mathbf{1000}\boldsymbol{\mu m}$for $\mathbf{5}\boldsymbol{nC}$ and $\mathbf{1}\boldsymbol{\mu s}$ repetition rate

Kapton:

- scattering angle of $\mathbf{5.26-29.37}\boldsymbol{mrad}$ for thickness of $\mathbf{50-1000}\boldsymbol{\mu m}$.
- Lower energy loss for entire thickness range.
- Acceptable thickness less than $\mathbf{50}\boldsymbol{\mu m}$for $\mathbf{1}\boldsymbol{nC}$ and $\mathbf{10}\boldsymbol{\mu s}$ repetition rate

Aluminum:

- scattering angle of $\mathbf{10.49-57.67}\boldsymbol{mrad}$ for thickness of $\mathbf{50-1000}\boldsymbol{\mu m}$.
- Lower energy loss for entire thickness range.
- Acceptable thickness less than $\mathbf{50}\boldsymbol{\mu m}$for $\mathbf{5}\boldsymbol{nC}$ and $\mathbf{10}\boldsymbol{\mu s}$ repetition rate

Pyrolytic graphite ($\boldsymbol{\rho}=\mathbf{2.0}\boldsymbol{g/cm^3}$; $\mathbf{50}\boldsymbol{\mu m}$) and graphite ($\boldsymbol{\rho}=\mathbf{1.5}\boldsymbol{g/cm^3}$):

- scattering angle of $\mathbf{8.65-30.73}\boldsymbol{mrad}$ for thickness of $\mathbf{50-1000}\boldsymbol{\mu m}$.
- Lower energy loss for entire thickness range.
- Acceptable thickness less than $\mathbf{1000}\boldsymbol{\mu m}$for $\mathbf{5}\boldsymbol{nC}$ and $\mathbf{1}\boldsymbol{\mu s}$ repetition rate

Thank you for your attention