Discussion about the thermical stress of the targets utilized in a muon collider

PHD in «Physics of the Accelerators» **Dir:Prof:Daniele Del Re**

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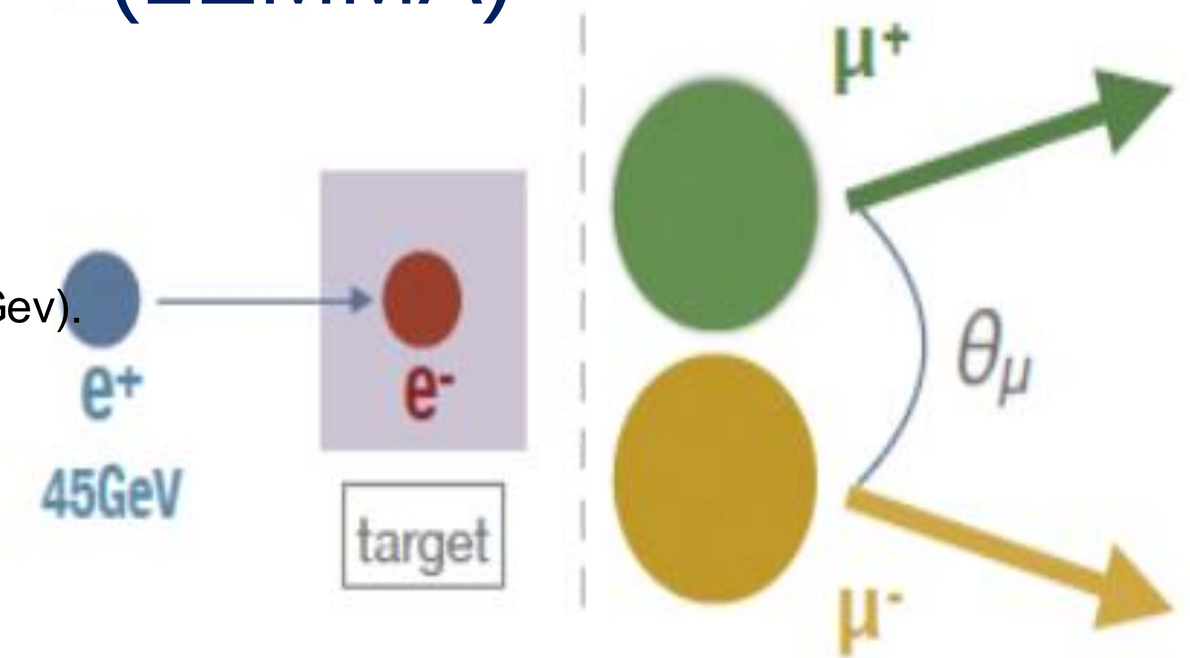
30/09/24

Low EMittance Muon Accelerator (LEMMA)

The LEMMA project:

- Exploit $e^+e^- \rightarrow \mu^+\mu^-$ ($\sqrt{s}$~0.212Gev).
- Positron beam.
- Low Z fixed target (Be, C).
- Goal 10^{11} $\mu^{\pm}$/s.



Muon production in $e^+ e^-$ annihilation

Target options for LEMMA

- ***Goal:***
- Continuos muons production preserving muons and beam quality.

$$N_{\mu^+\mu^-} = \underbrace{N_{e+} \cdot \rho_{e-} \cdot L}_{\text{Maximize the rest}} \cdot \sigma(e^+e^- \to \mu^+\mu^-)$$

Small cross section: O(1 μb)

- ***Heavy & thin:***
- Low emittance.
- High beam loss → low muon efficiency.

Ne+ is the number of positron fighting the target
ρe- is the density of the electron in the target.
L is the depth of the target
σ is the cross section of the reaction
Nμ+μ- is the number of muons produced

- ***Very light & thik:***
- Higher muon efficiency.
- Muon emittance increase.

- ***Not too heavy & thin:***
- Optimization of muon efficiency and emittance → Be, C (ρ^- ~$O(10^{24}e^-/cm^3)$).

Gruppo MuCol

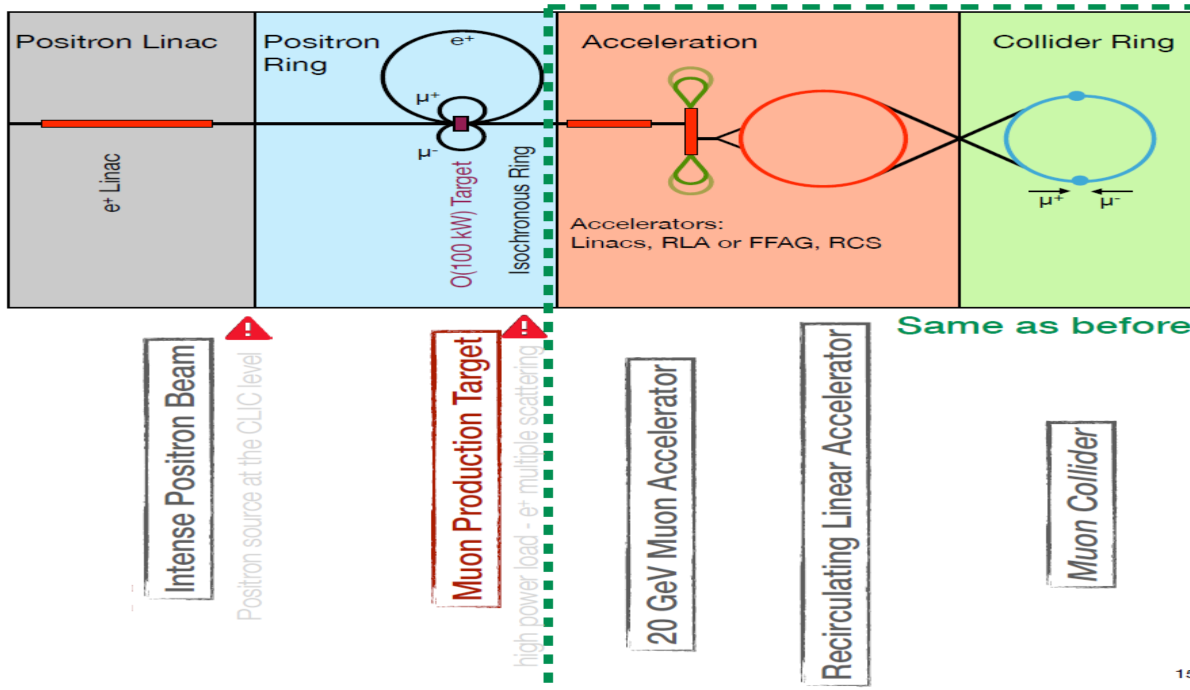
LEMMA
Advantages vs Disadvatages

Advantages:

- High Lorentz boost (γ~214) → laboratory lifetime ~500μs.
- Low emittance → No cooling.

Disadvantages:

- Small cross-section (~1μb at most) → High intensity positron beam.



LEMMA concept

NIM A Reviewer: "A major advantage of this proposal is the lack of cooling of the muons…. the idea presented in this paper may truly revolutionise the design of muon colliders … "
(From R. Raimondi talk at La Thuile 2018).

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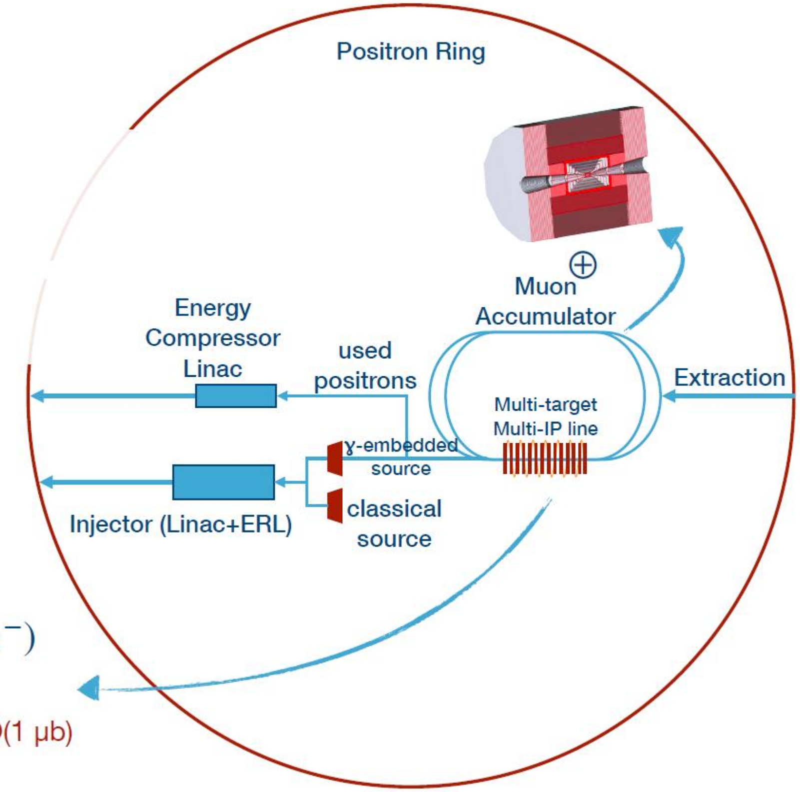
LEMMA proposed scheme

LEMMA scheme:

- Injector.
- Multi-target.
- Muon accumulator.
- Classical source.
- γ-source.
- Positron ring.
- Extraction.
- Energy compressor LINAC.



$$N_{\mu^+\mu^-} = \underbrace{N_{e+} \cdot \rho_{e-} \cdot L}_{\text{Maximize the rest}} \cdot \sigma(e^+e^- \to \mu^+\mu^-)$$

Maximize the rest

Small cross section: O(1 μb)

One of LEMMA scheme

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Proton driven Muon Collider

Classical scheme (proton driven):

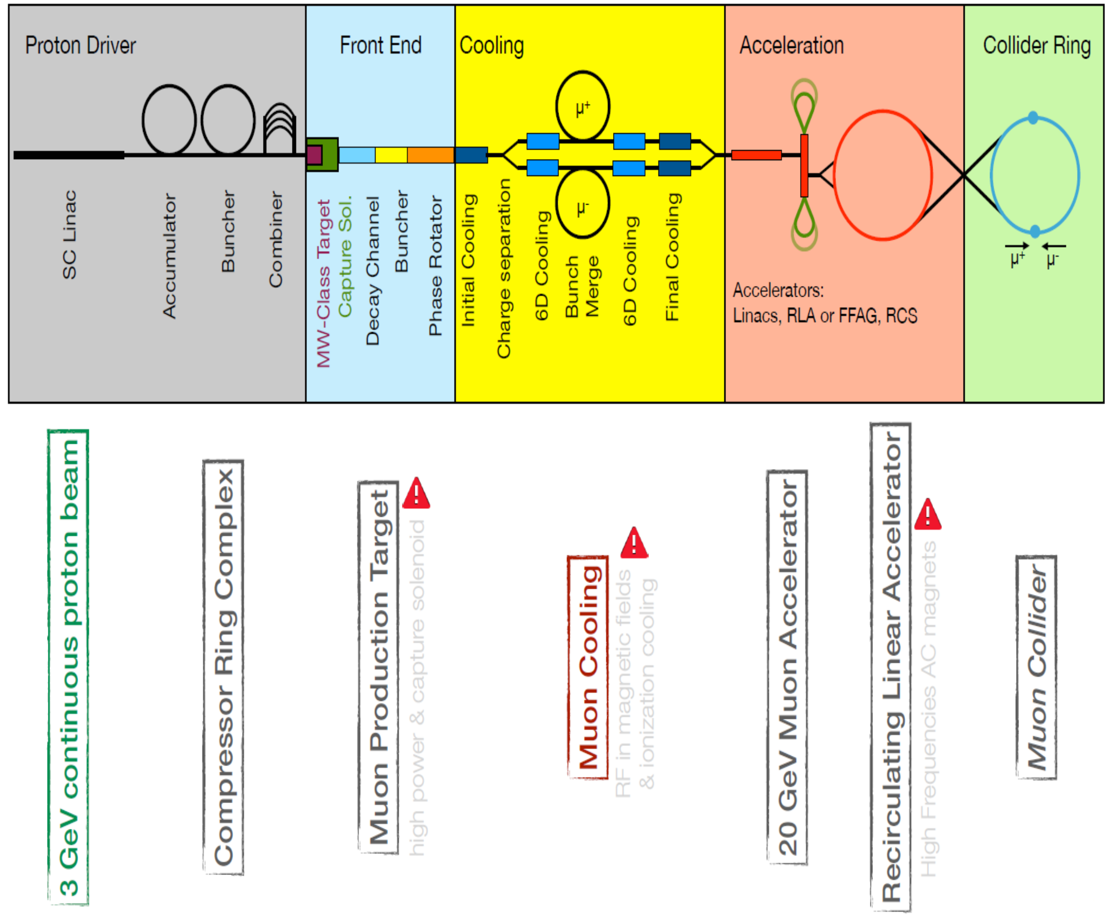
- Few GeV protons on target.
- Muons produced as tertiary particles (p_μ~100MeV).

Advantages:

- Cross-section (~1mb at most) → High muon rate (10^{13}-10^{14}μ/s).

Disadvantages:

- High emittance → Cooling system.



Proton driven muon collider scheme

Reason of discussion:

In this study we want to know , in the context of LEMMA scheme, if the **targets utilized are able to bear the power of the beam** this is the reason for which I study the thermomechanical properties of some materials. In primis :graphite and berillium that are the principal materials candidates to be used as targets.

Reason of discussion:

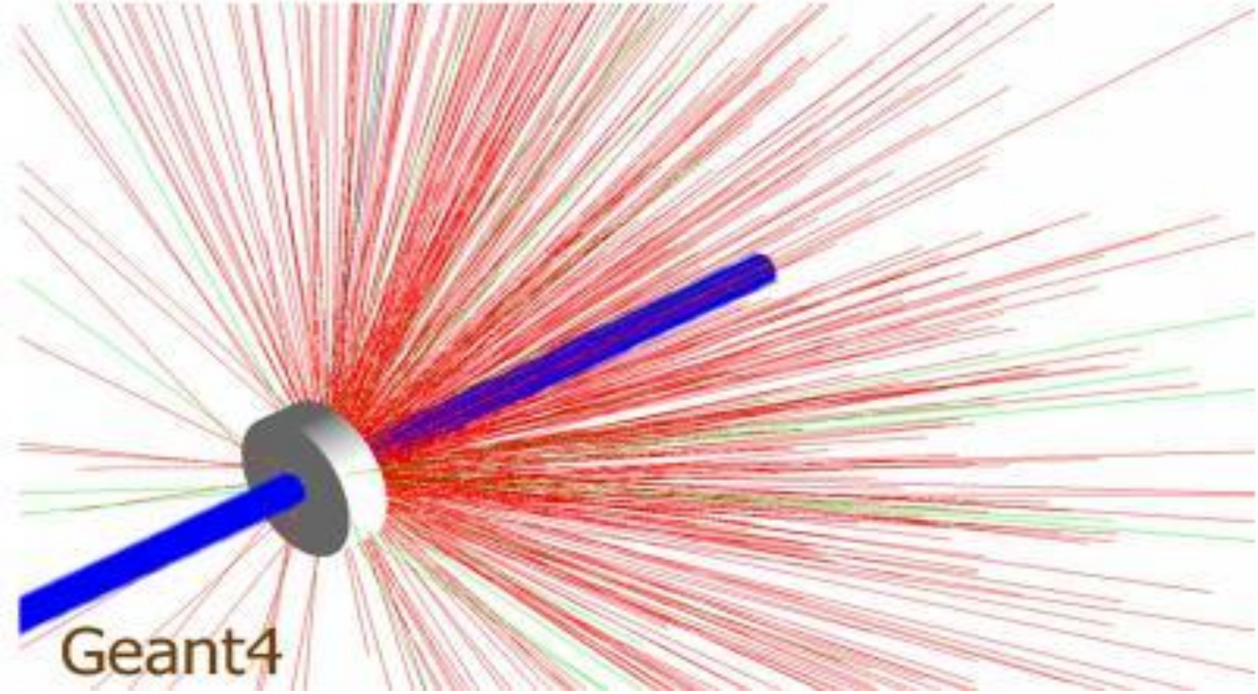
At the end of this presentation we show the thermal properties of some materials that will be utilized in the future for parts of the muon collider called the **thin windows**, in the phase of **cooling**.

This materials are: **LiH** , **SiC** , **Si3N4** .

LiH is specifically used in a **wedge**.

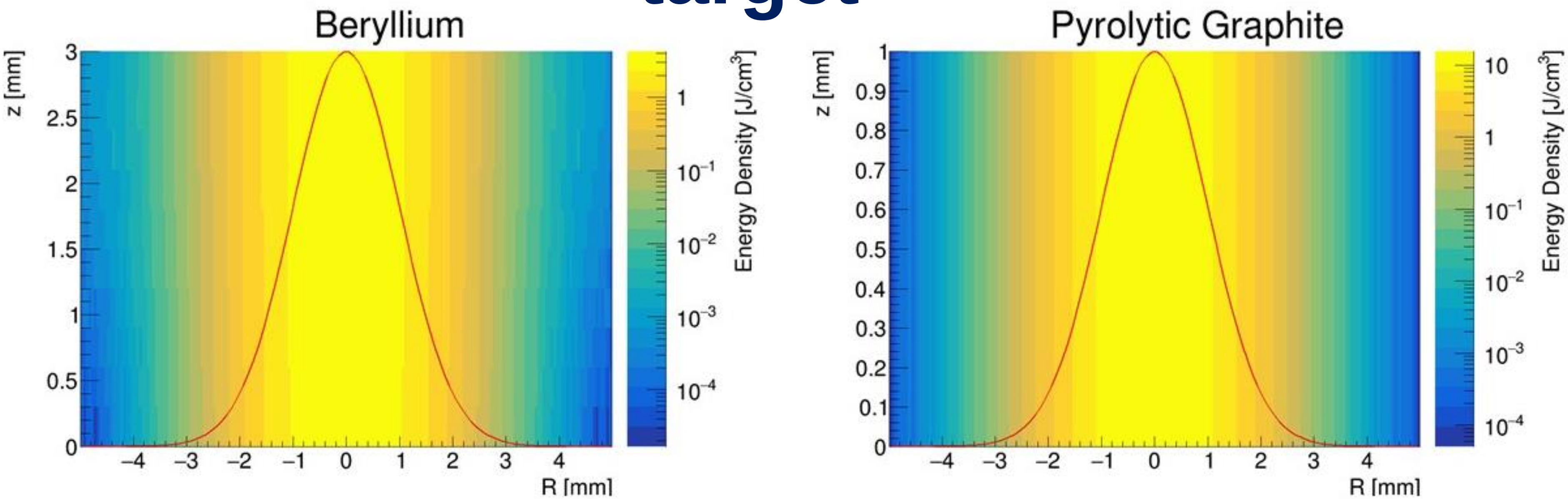
Then in my thesis I have spoken of some **metals** utitized to build pars of the muon collider.

Simulations - Geant 4



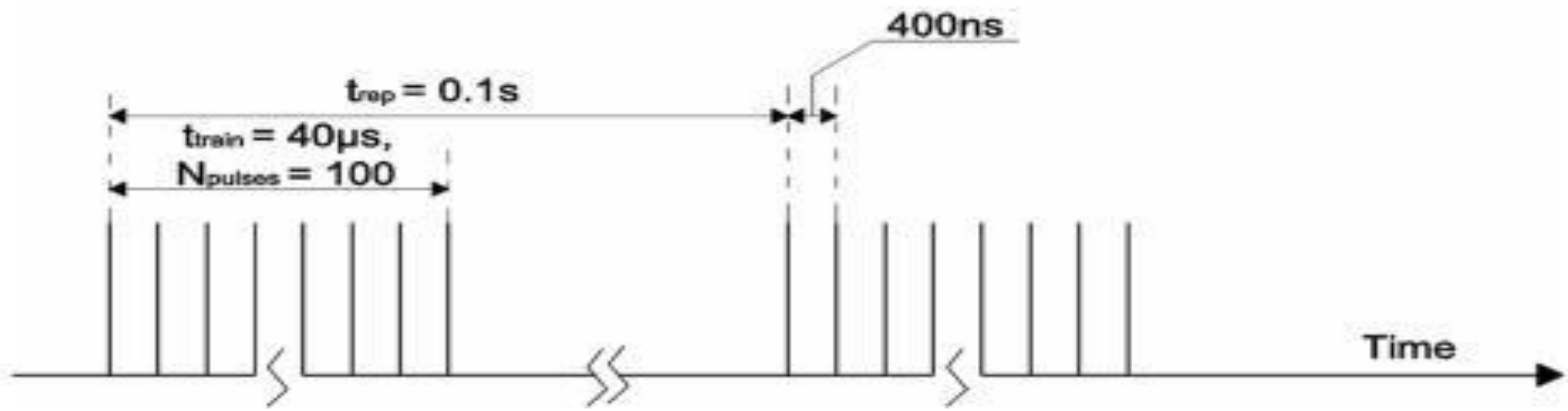
Visualization, obtained by Geant4, of a primary 45 GeV positron beam (blue, coming from the left) hitting a 3mm beryllium target and producing secondary particles (red and green lines)

Thermic energy released in the target



Deposited energy density, obtained by Geant4, from a **single bunch** of 3 × 10 ^11 positrons and a beam spot size of 1000μm on (left) a 3mm thick Beryllium target and (right) a 1mm thick Graphite target; the Gaussian function (red line) has been drawn to underline the energy density profile (colour figure online):1J/cm3 vuol dire che il bersaglio è riscaldato quasi al massimo.

Example of temporal repetition of positron bunches



A schematic representation of the bunch structure considered in this study. The beam is composed of bunches (pulses) 10ps long, separated from each other by 400ns and gathered in trains of 100 bunches.
Each train is therefore 40µs long and separated from the following one by 0.1s

Thermal model
Fourier equation based

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Thermal evolution in the target: $$\nabla \cdot (k \cdot \nabla T) + w = \rho c_p \frac{\partial T}{\partial t}$$

where ρ=M/V is the volumetric density , Cp=(Q/mΔT)p : is the specific heat at constant pressure, kij= -q ○ (gradT)^-1 is the thermal conductivity ,q is the termal current density ,w is the heat volumetric power density w=(dQ/dt)/V=w, T is the temperature:

$$E = \varepsilon\, \sigma T_s^{\,4}$$

Here is showed the Stephan-Boltzmann Law, here we can see for the first time the emissivity ε and б which is the S.B. constant. Ts is the temperature. E is the power radiated for unit of surface.

Definition of emissivity:

the emissivity **ε** is the defined as the ratio between energy radiated by the material and the energy radiated by a black body at the same temperature, so it's a dimensionless number and is comprised between 0 if there is not radiation and 1 if the body behaves as a perfect black body with maximal radiation, it depends not only from the material but even on temperature , emission angle, wavelenght and from his geometrical features and finiture .Generally the metals have a low emissivity growing with temperature, while non metals and metal ossides have a higher emissivity and descending if temperature grows. In this work with emissivity we want to study the thermomechanical characterization of the targets.

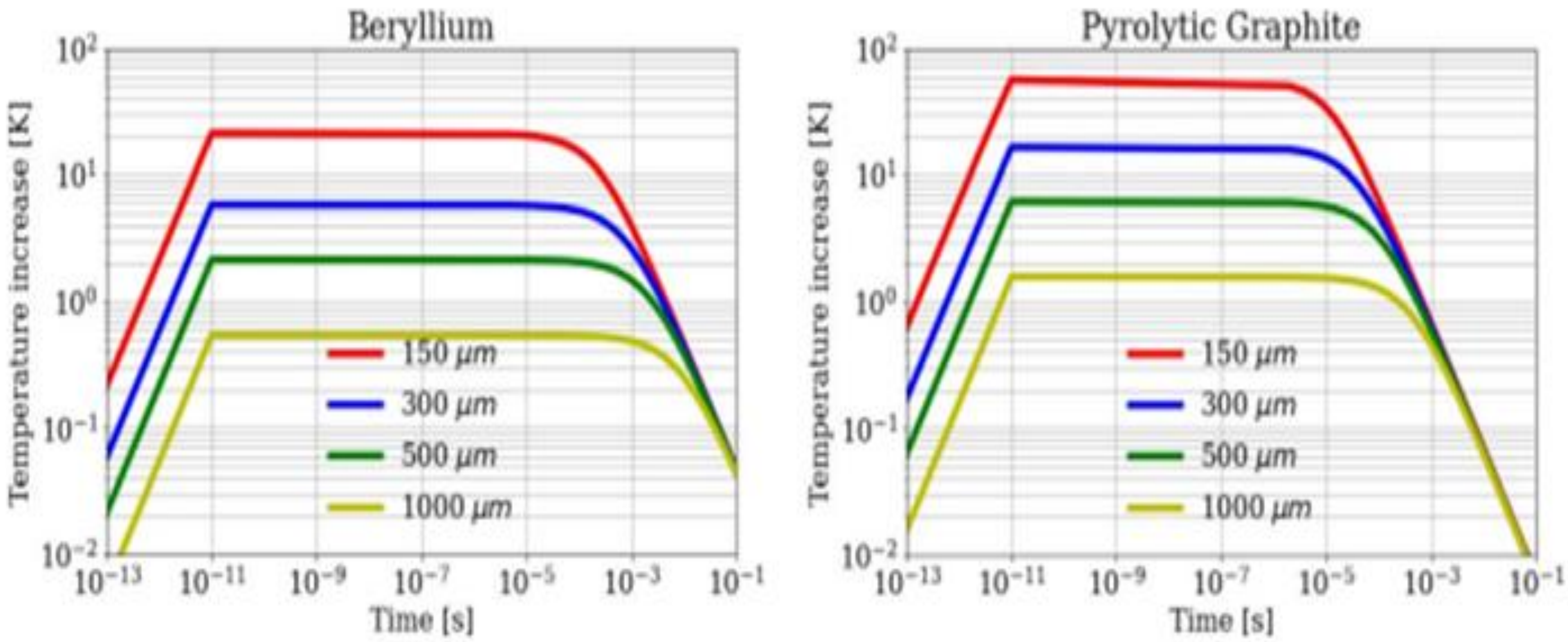


Fig. 8 Temperature rise in the position corresponding to the beam center ($r=0$), as a function of time, for a single bunch of 3×10^{11} positrons impinging on the (left) Beryllium and (right) Carbon target for different beam spot sizes

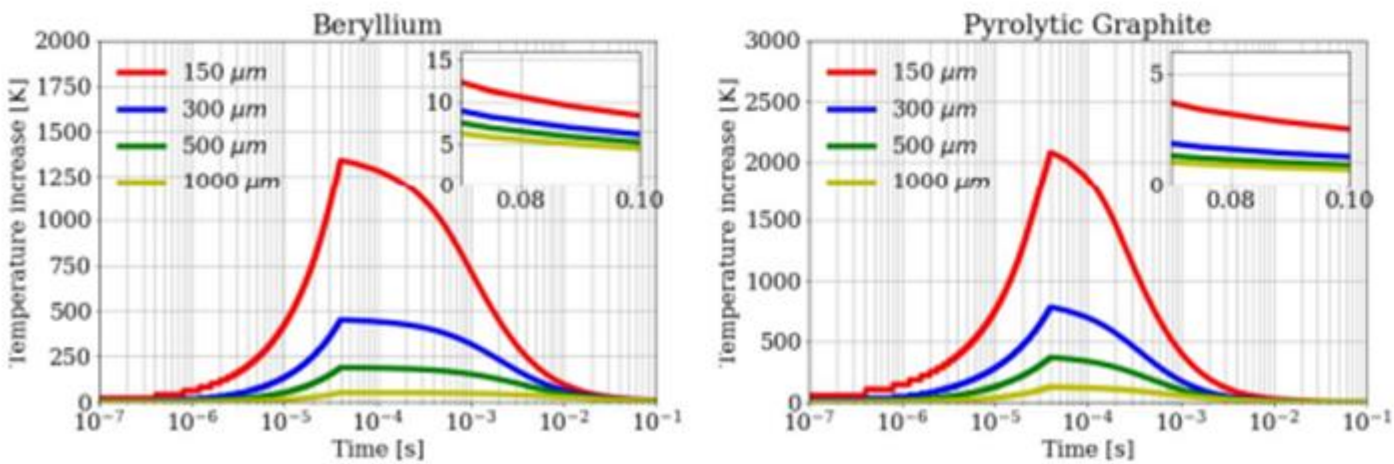


Fig. 10 Temperature rise in the position corresponding to the beam center ($r=0$), as a function of time, for a train of 100 bunches of 3×10^{11} positrons each impinging on the (left) Beryllium and (right) Carbon target for different beam spot sizes. The zoomed inserts highlight the *residual* temperature increase after 0.1 s from the start of the bunch train, which corresponds to the arrival of the subsequent train of bunches

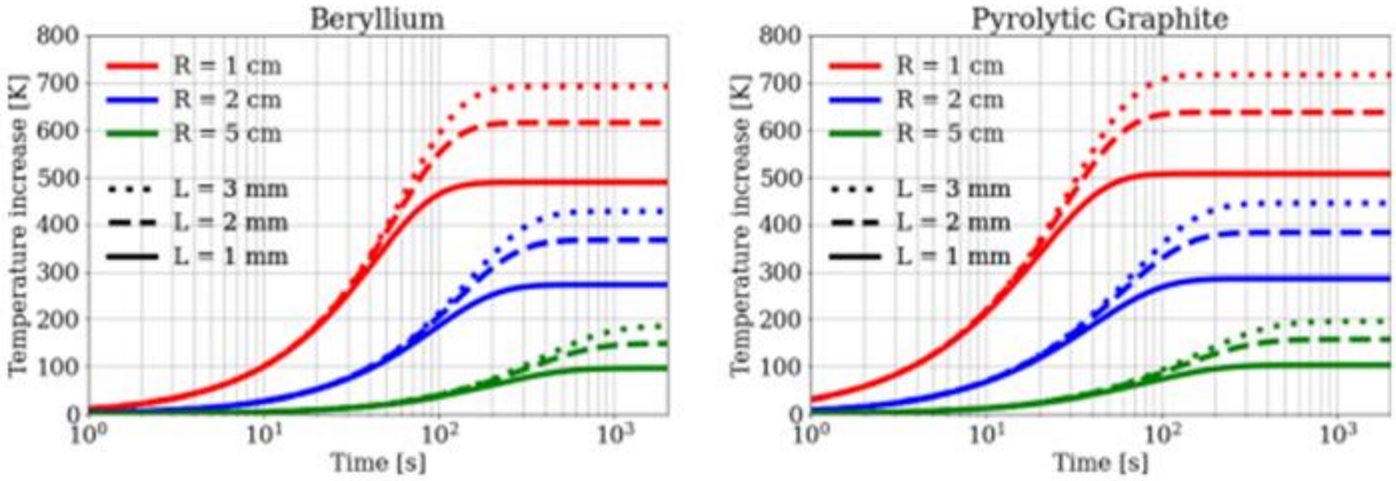


Fig. 12 Temporal variation of residual temperatures and steady state temperatures, obtained with the simplified model, for (left) Beryllium and (right) Carbon

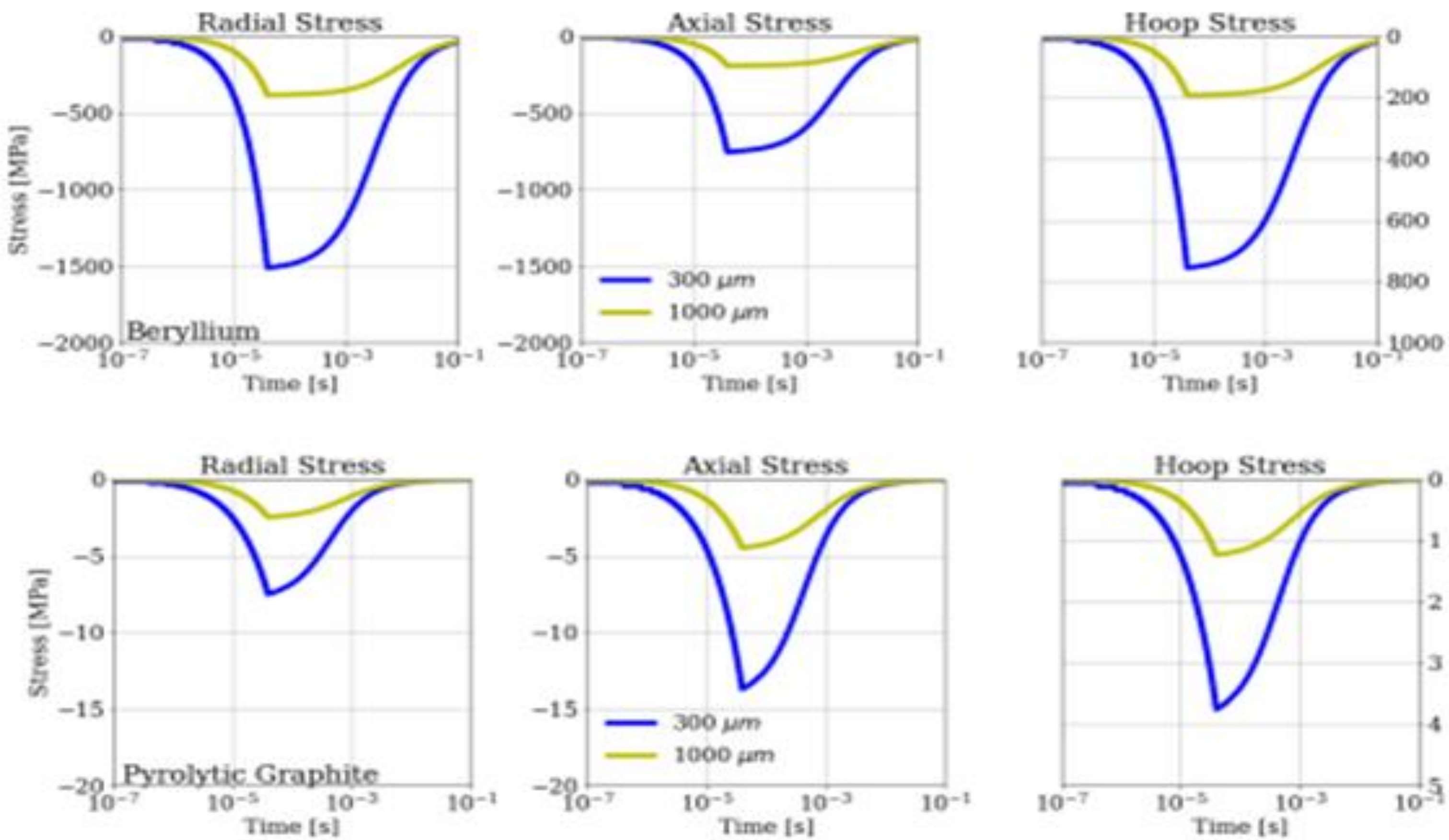


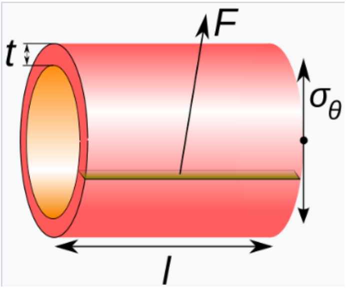
Fig. 13 Radial, hoop and axial stresses for (top row) Beryllium and (bottom row) Pyrolytic Graphite targets, for different beam spot sizes

Wikipedia

Stress σ :hoop stress, axial stress and radial stress

$$\sigma_\theta = \frac{F}{tl}$$

F forza torsionale, t spessore del vaso nel nostro caso uguale ad r ,L lunghezza del cilindro



$$\sigma_a = \frac{F_a}{A}$$

Fa is the axial force , while A is the cross sectional area

$$\sigma_r(r) = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2 (p_o - p_i)}{r^2 (r_o^2 - r_i^2)}$$

where r_i is the inner radius, r_o is the outer radius, p_i is the inner absolute pressure and p_o is the outer absolute pressure.[1] Maximum radial stress occurs when $r = r_i$ (at the inside surface) and is equal to gauge pressure, or $p_i - p_o$.[2]

muon collider targets

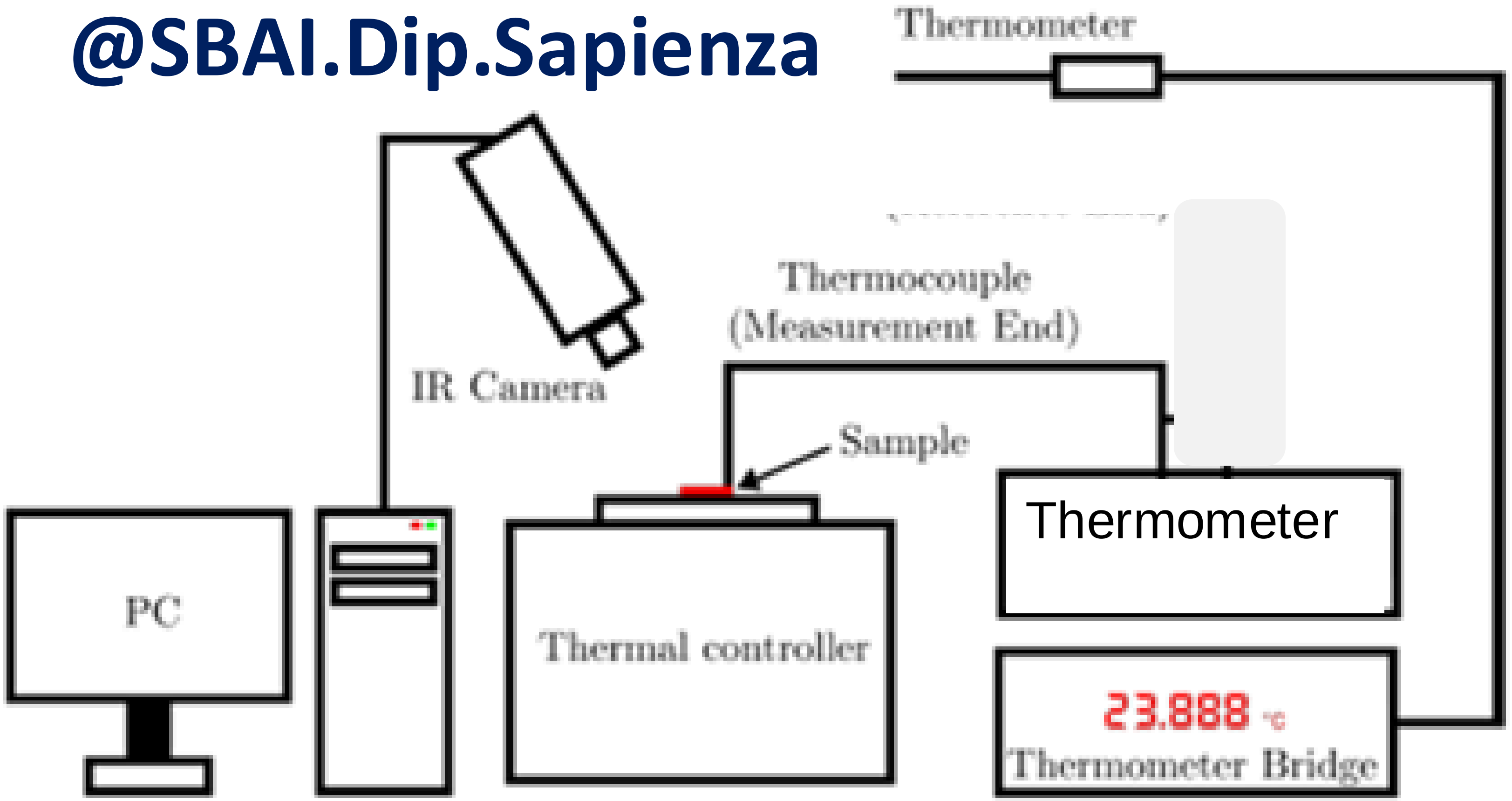
- 1)Laser heats the target

- 2)Heater heats the target to measure after the emissivity from the formula of Stephan B. in function of Tapp, Troom,Treal,εref

- Emissivity measured front e back to investigate The imperfections of the disk subjected previously a stress test.

- While laser causes superficial effects , positron beam heats in a more isotropic way inside the target.

Experimental SET UP @SBAI.Dip.Sapienza



SET UP sperimentale @SBAI Dip. Sapienza

IR camera: CX320 COX Co., wavelength band LWIR 8–14 μm

Heater con thermal controller: PTC-100 MJ Research inc

Reading Software : it permits to measure the T apparent

Targets : 2 cylindrical grafite targets d=1mm; r=1.5/2cm;

Environment Thermometer: measurement of T_{room}

Thermocouple: measures T_{real} on the surface of the sample

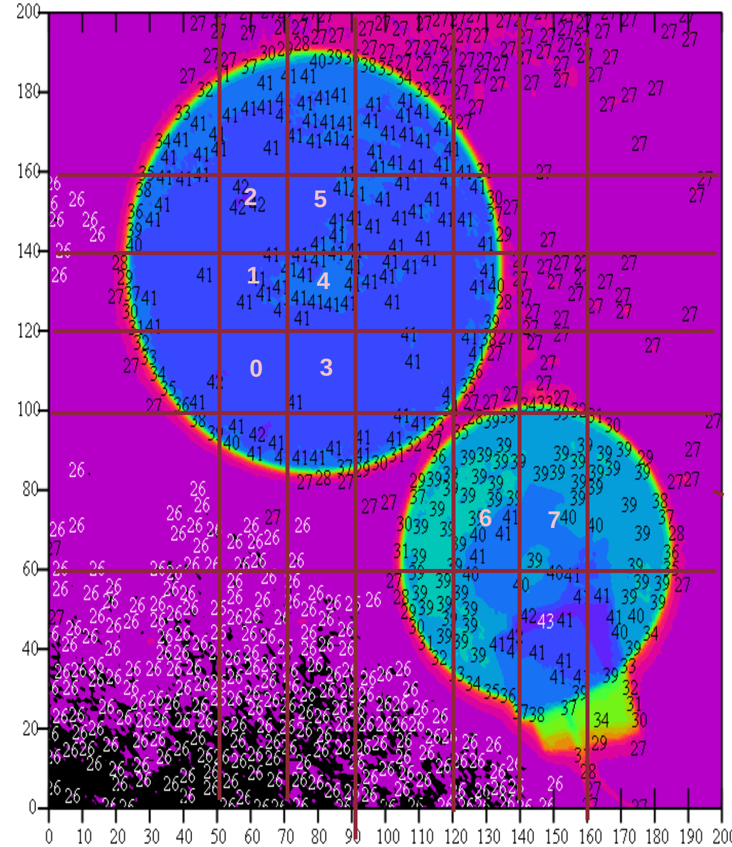
Cardboard screen: riduces noise and IR reflections

Computer and home made programs: measure of emissivity with MATCAD

Eperimental SETUP@SBAI.DiP. Sapienza

Here the fake colors indicate the Tapparent where a little λ indicates a stronger value of T app, you can verify this reading the numbers written above.

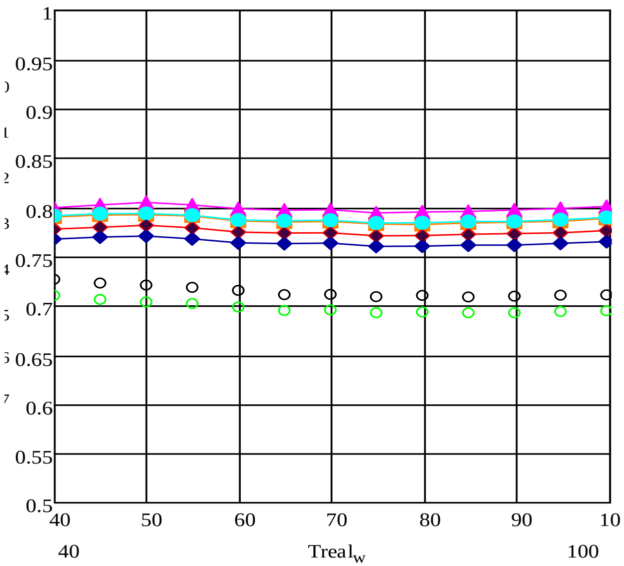
1) Targets grafite (Legnaro) with termocouple
2) Example of 8 zones on target elaboration out from termocouple 200x200 pixel

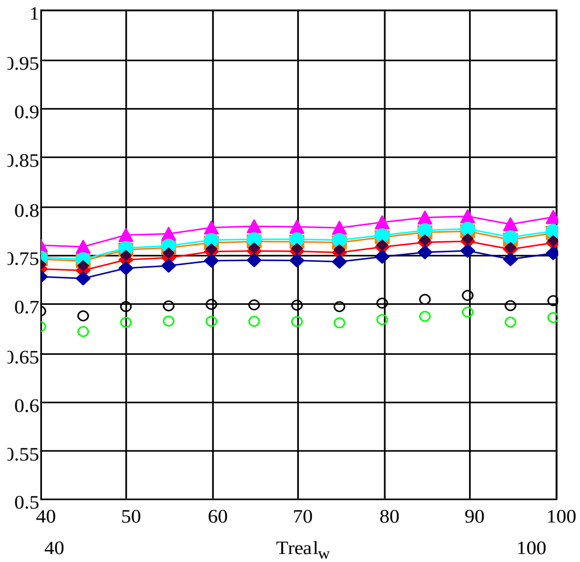


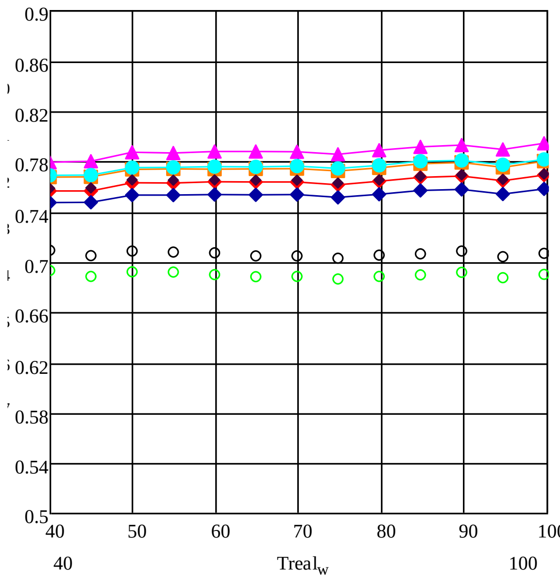
A1(3,imin,imax,jmin,jmax)

Graphite front side – experiment 22.03

ε





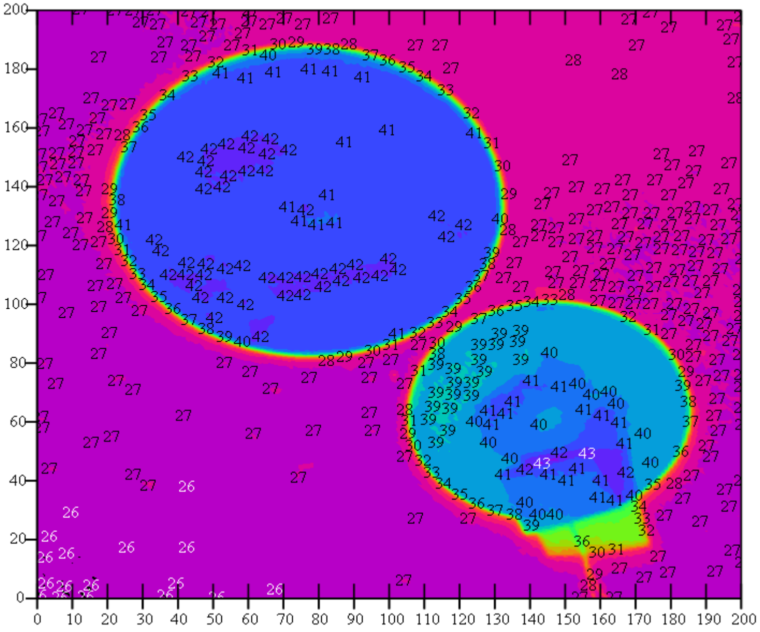


Treal Treal Treal

Emissivity(dimensionless)vs real temperature in 8 zones of the target measured far from termocouple for the phase of heating and cooling and average for temperature comprised between 40-100° C.

Here the untrue colors indicate the Tapparent where a little λ indicates a stronger value of T app, you can verify this reading the numbers written above.

Graphite front side – experiment 22.03

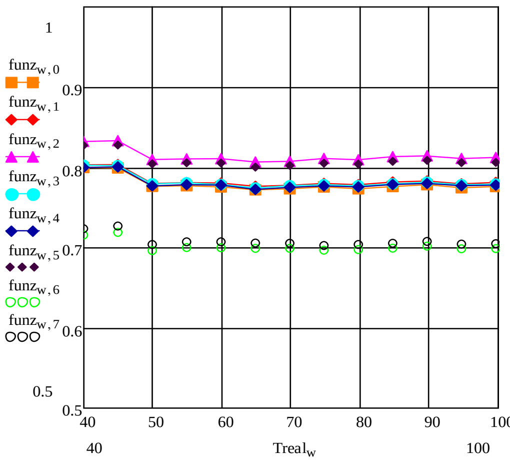


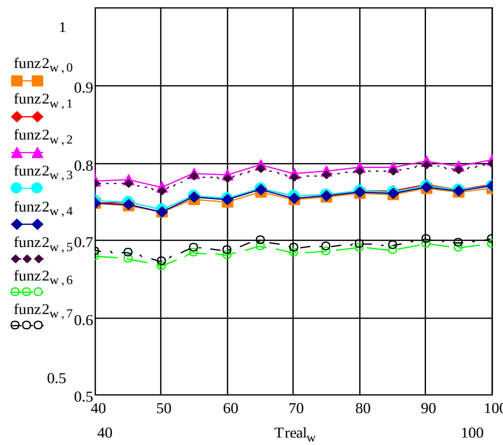
A1(3, imin, imax, jmin, jmax)

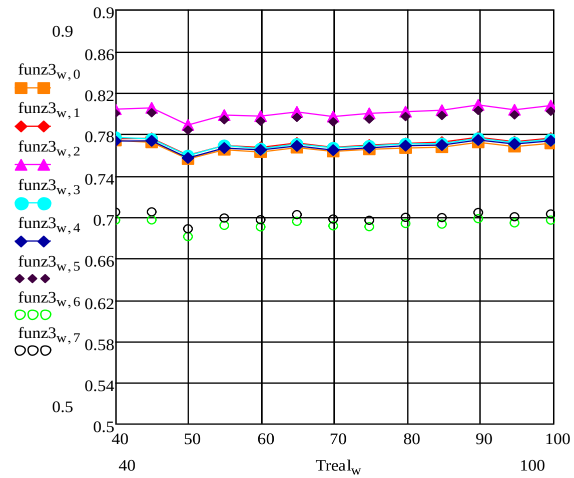
1)Graphite targets with thermocouple above 2)Tapparent image measured with untrue colors with the thermocamera from which we obtain the map of emissivity from the stephan Bolzmann low, image 200x200 pixel.

Graphite reverse side 30.03

ε





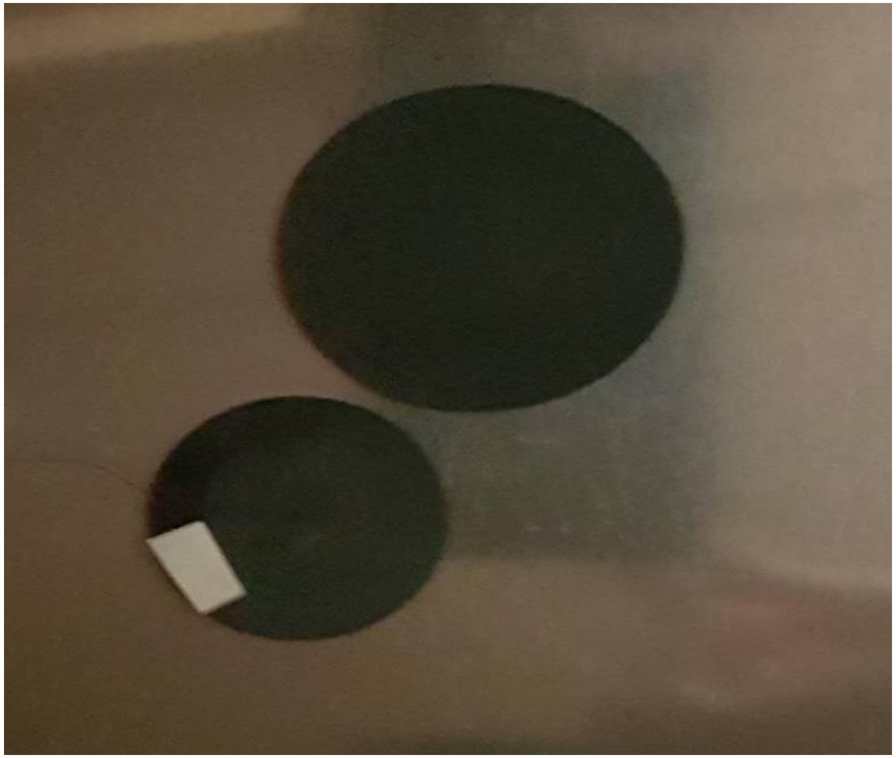


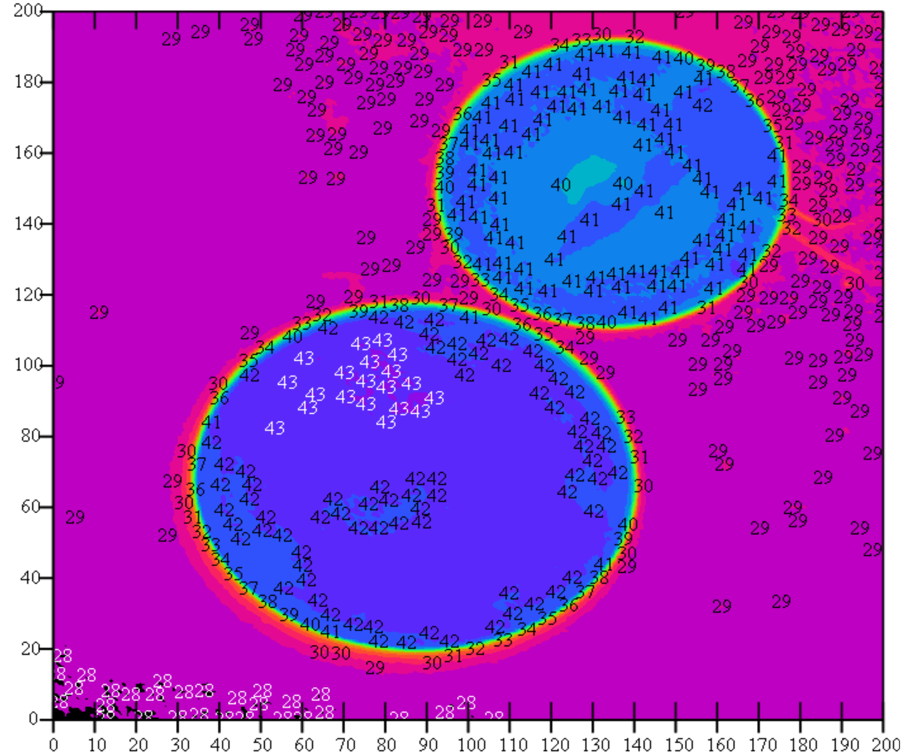
Treal Treal Treal

Emissivity (dimensionless)vs real temperature in 8 zones of the target measured far from termocouple for the phase of heating, cooling and average with temperature comprised between 40-100° C.

Here the untrue colors indicate the Tapparent where a little λ indicates a stronger value of T app, you can verify this reading the numbers written above.

Graphite reverse side 30.03

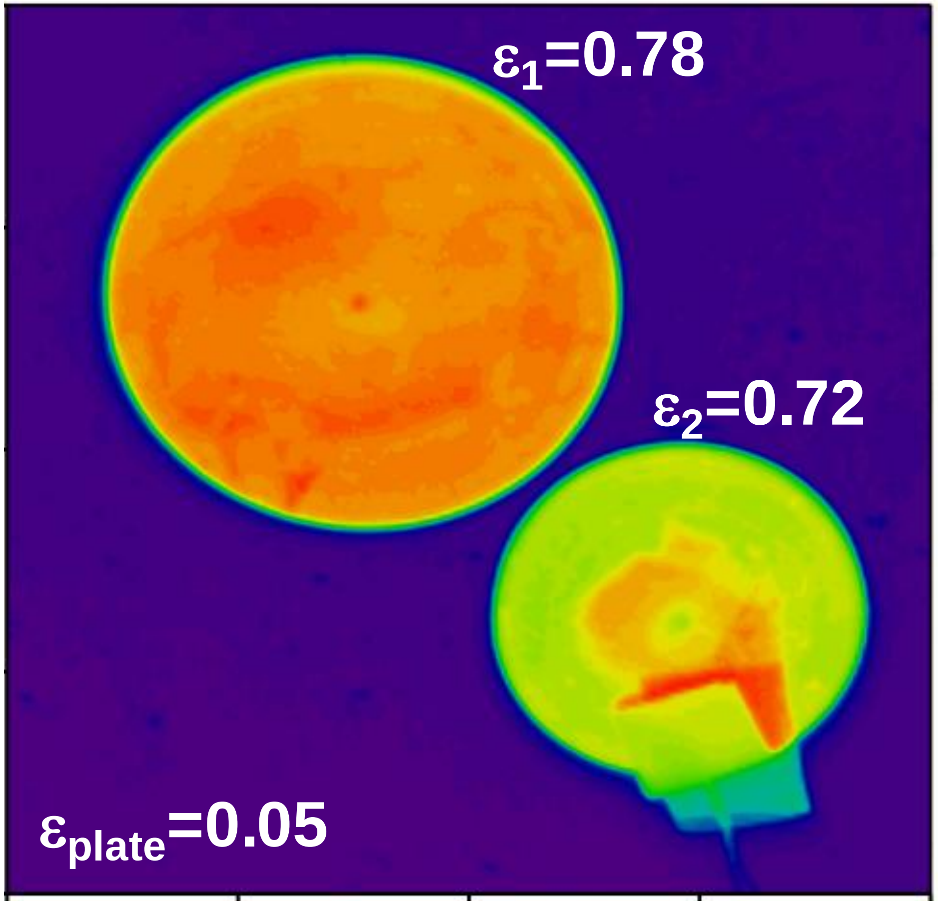




A1(3, imin, imax, jmin, jmax)

1)Targets of graphite wiuth termocouple above 2)image of Tapparent measured with untrue colors with the thermocamera from which you can obtain the map of emissivity using theStephan –Bolzmann low. Image 200x200 pixel.

Optical Image vs Infrared Image

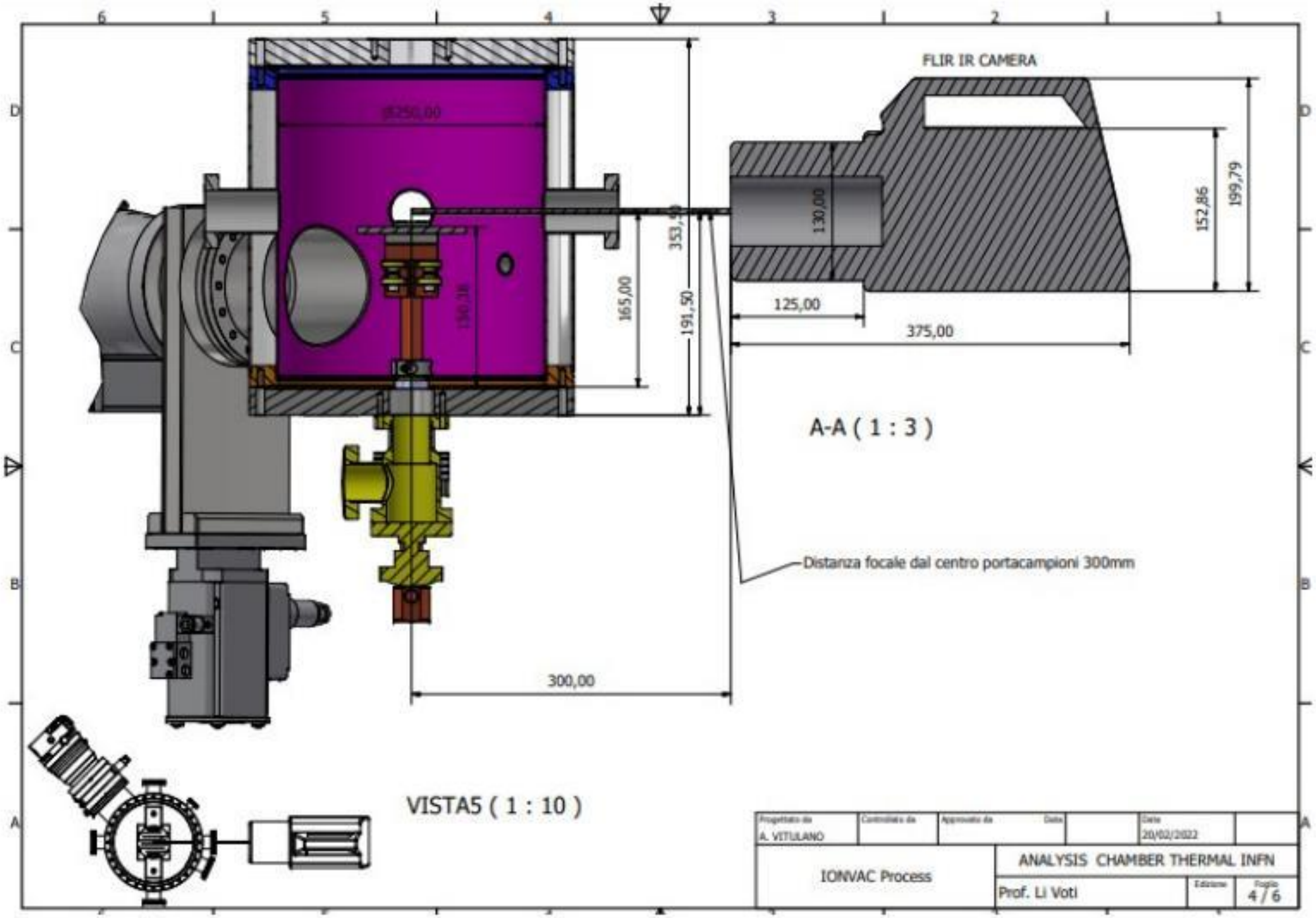


R&D

1) feature characterization of the targets at high temperature in a vacuum chamber

(emissivity, diffusivity depending onT)

2) Use with new IR camera at high spatial and temporal resolution(thermical imaging for the relevation of surface and inward fractures)


FLIR IR CAMERA
353,50
130,00
152,86
199,79
165,00
191,50
125,00
375,00
A-A (1 : 3)
Distanza focale dal centro portacampioni 300mm
300,00
VISTA5 (1 : 10)
A. VITULANO
20/02/2022
IONVAC Process
ANALYSIS CHAMBER THERMAL INFN
Prof. Li Voti
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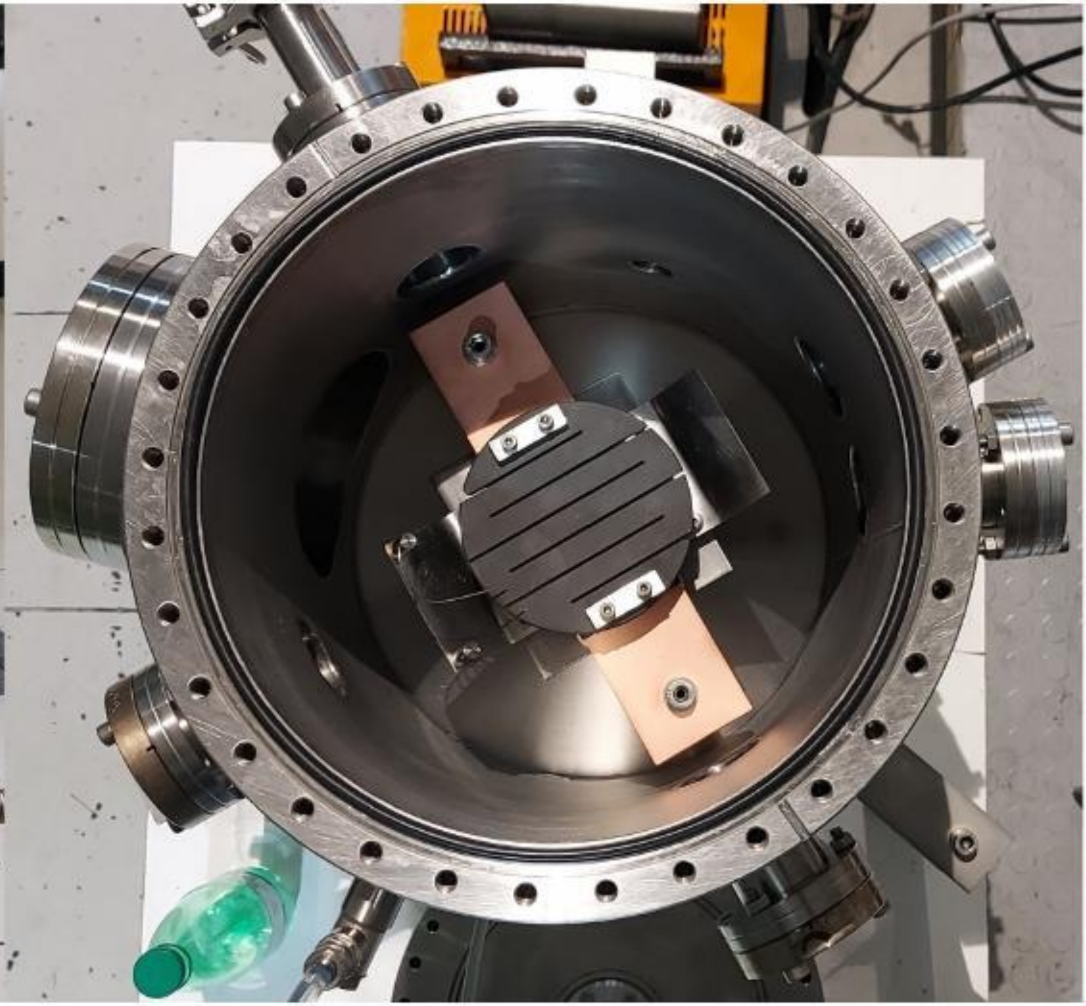


R&D:

So far we have studied the heating process till few hundreds of Celsius degrees: in the external heater we have studied the range 40-100° C. After we have used the vacuum chamber and we have measured higher temperatures compatibly with the heating system used that has been optimized many times, the goal is to measure more than 1000 degrees with vacuum chamber.

in SBAI will be object of study the thermical effects on other targets that will be used in a muon collider, the so called thin windows utilized in the different stages of muon cooling

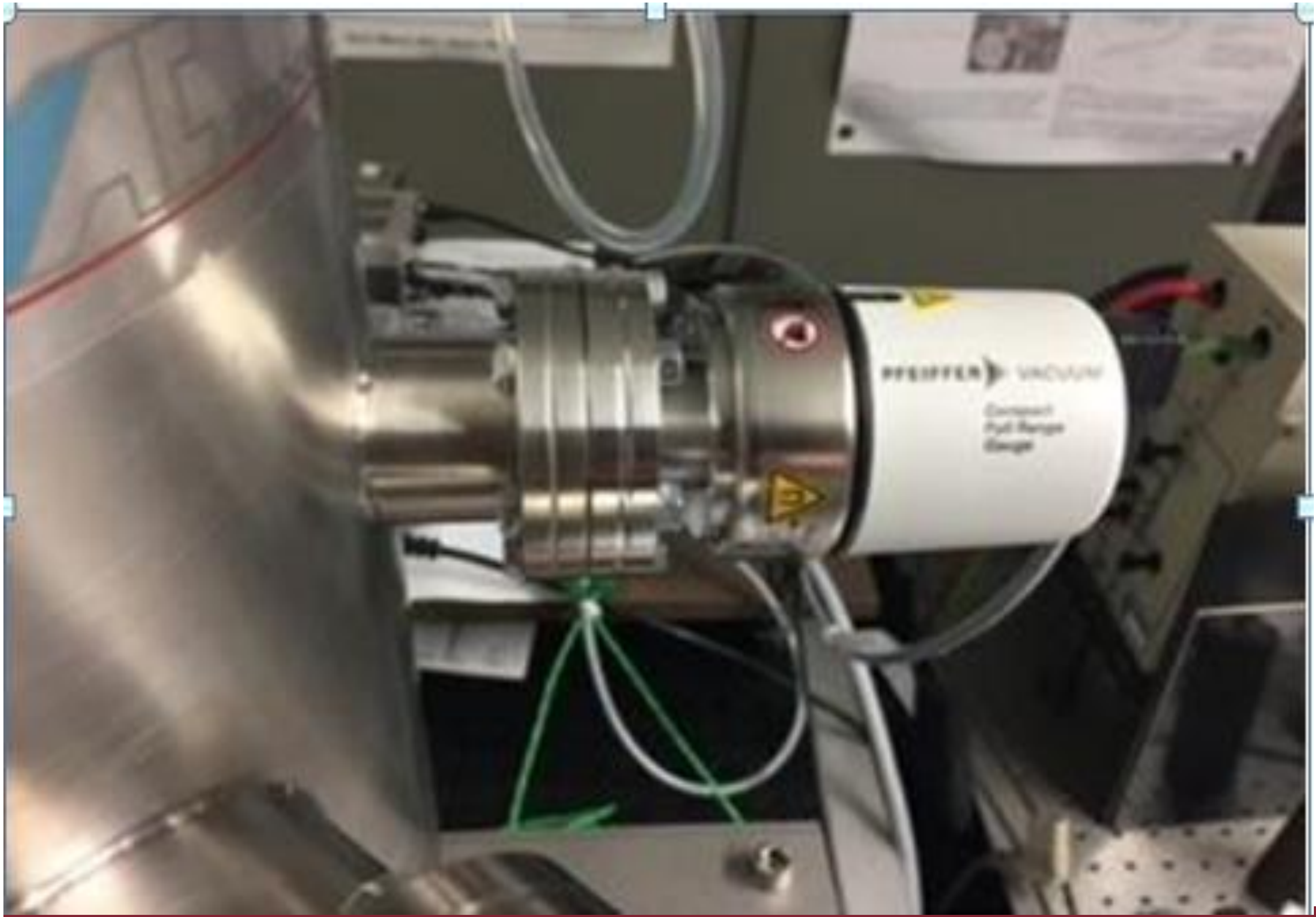
LiH (lithium hydride) Wedge Adsorber

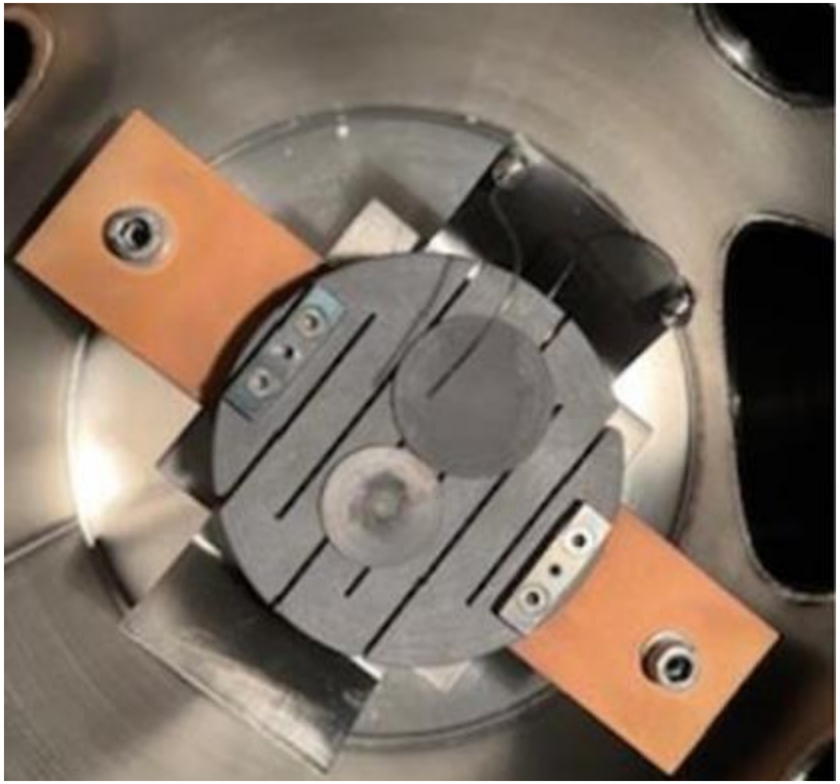
Si3N4 (silicon nidride)

SiC (silicon carbide)

Vacuum Chamber

After the measures with the traditional heater, have been designed and built the vacuum chamber to make new measures. This work has been proposed to **improve** the situation utilizing **higher temperatures** and to exploit the vacuum.The chamber has been disassembled and we have put the two thermocouples inside, it has been assembled the turbomolecular pump, it has been opened the valves and conducted the pression to minimal levels. It has been changed many time the external heating device that was not optimized. In the image we can see the ruler and the blue coil device utilized to replace it.


PFEIFFER VACUUM



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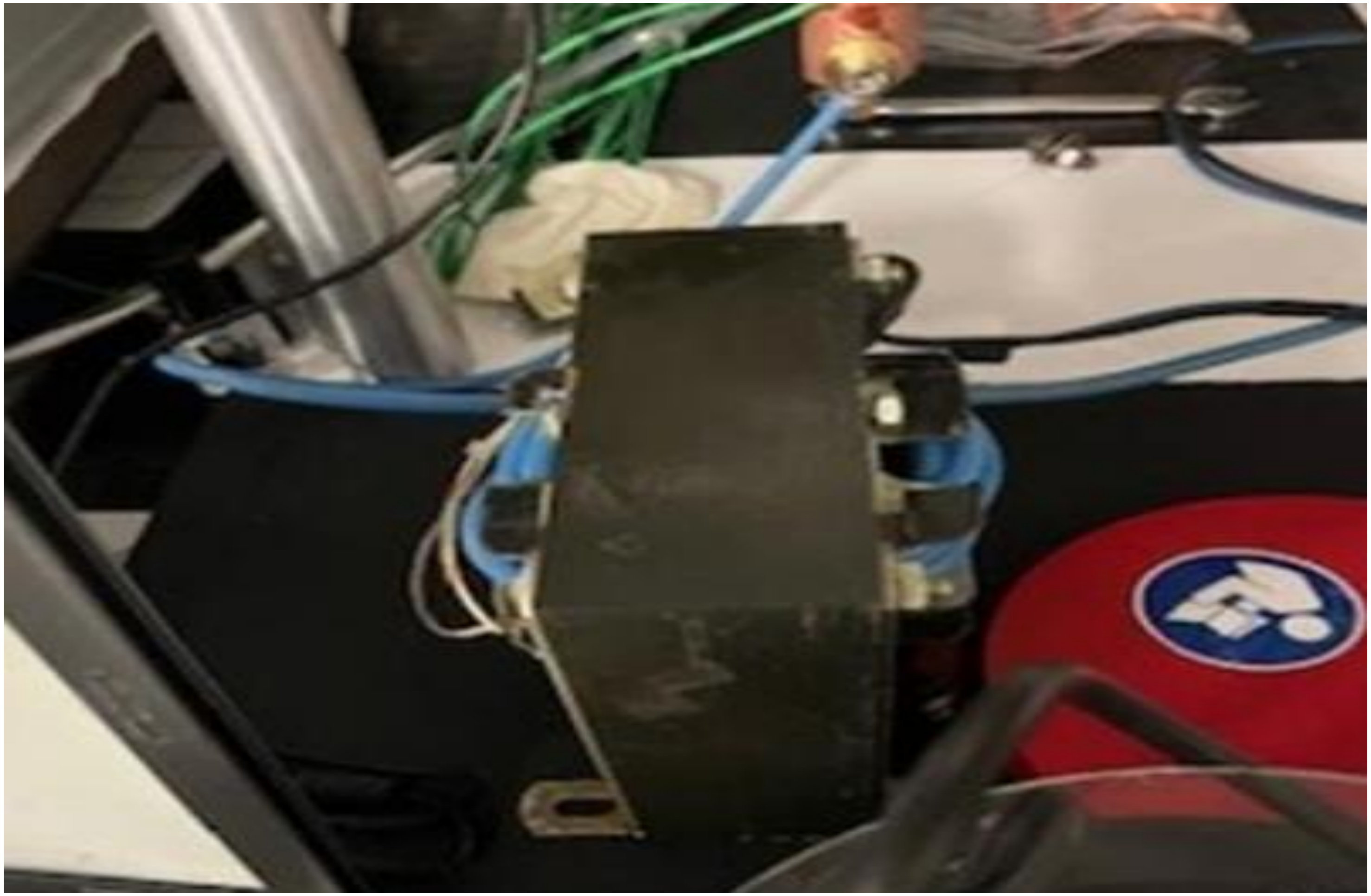


LiH

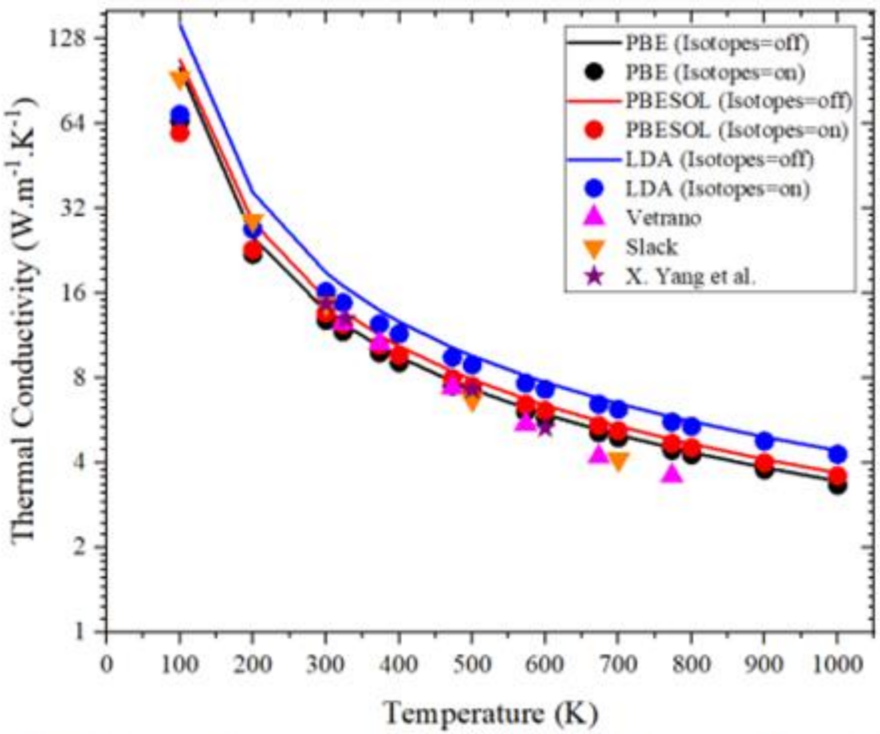
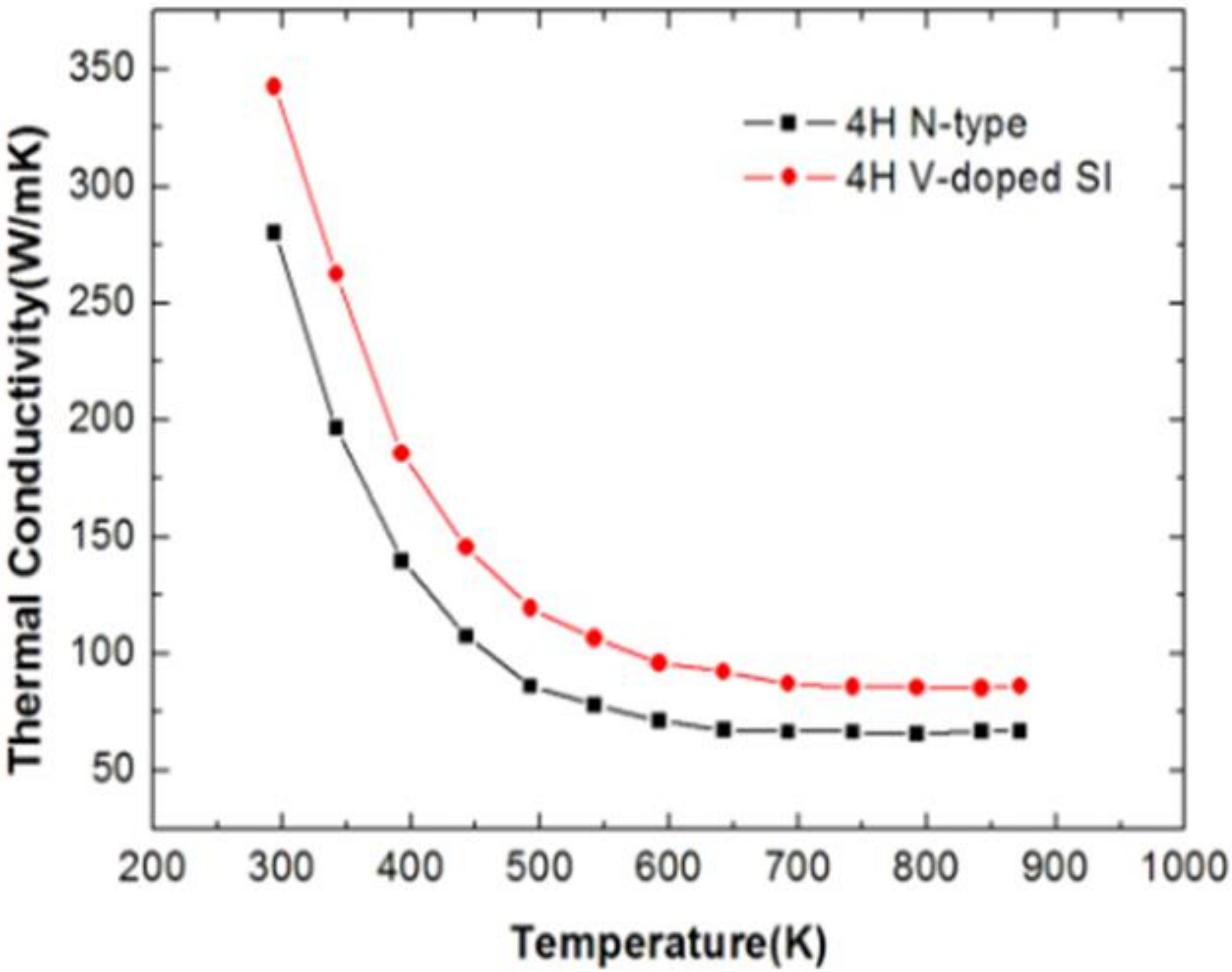


FIG. 9. Calculated lattice thermal conductivity for LiH. Calculations were done with PBE (black solid line), PBESOL (red solid line), and LDA (blue solid line). Calculations show the effect of the isotopes on the thermal conductivity: PBE (black circles), PBESOL (red circles), and LDA (blue circles). Experimental data: Ref. [96] (pink up triangles), Ref. [97] (orange down triangles). Theoretical data: Ref. [76] (purple stars).

SiC



Art. Wei/Song

SiC

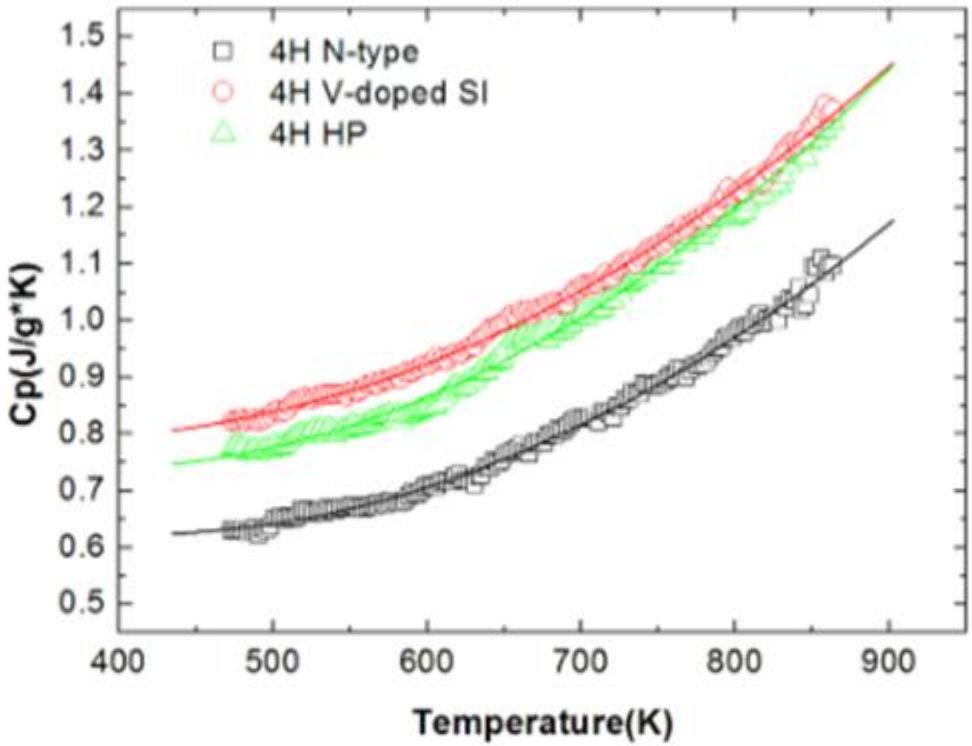


FIG. 2. Temperature dependent specific heat capacity of 4H-SiC single crystals. The specific heat capacity increases monotonically with the increase of temperature. The specific heat capacities of V-doped SI sample are approach to those of high purity sample and larger than those of N-type.

Approximate values of the thermodinamical parameters for this materials:

LiH(400K):Cs=1.92 J/(Kg.K)a.u.,ther.conductivity=10W/(mK)

SiC(400K): Cs=750J/(KgK), thermal conductivity=120W/(mK)

Si3N4(400K) Cs=673J/(KgK)thermal conductivity=10W(mK)

Conclusions:

The target can reach temperature very high for this reason is necessary a vacuum chamber .It can reach even a difference of temperature(DDT) of 1500K .

We have measured with the external heater in a range (30-120)° C and little more hundreds in the early measures of vacumm chamber.

It has been proposed even heating with laser even if heating was less isotropic on the target. The future is all here to test the emissivity for higher temperatures with vacuum chamber and more powerful thermocameras and make new measures of stress as those already done.

As we have seen in the image of the emissivity of the two targets the emissivity is strongly infuenced by the treatment of material and we must decide if the stress is bearable.

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Prof. Maria Innocenza Montesanti, Dr.Gianpaolo Bei

Theoretical Modeling for the Thermal Stability of Solid

Target in a positron-driven Muon collider

Dr.Gianmario Cesarini

Referee:Prof.Nadia Pastrone, Prof.Alessandro Belardini

Thanks

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