Proposal of a detector for studying high-energy photons generated during laser-plasma interaction

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Outline

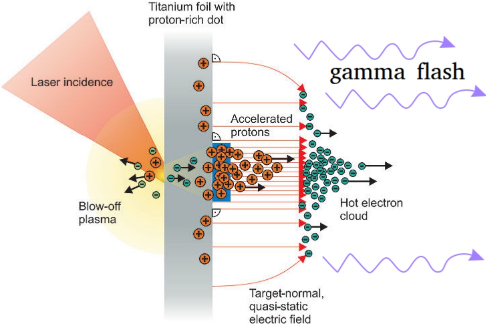
1. Motivation
2. Detector design and simulation setup
3. Signal unfolding algorithm and results
4. Conclusion
5. Next steps

ELI (Extreme Light Infrastructure) Beamlines

- ELIMAIA group (ELI Multidisciplinary Applications of laser-Ion Acceleration): laser-accelerated ion beams

TNSA principle $\longrightarrow$

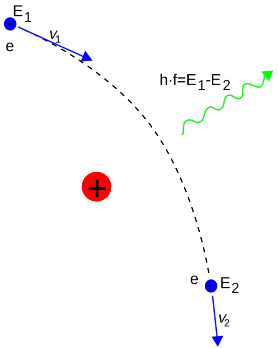
(Target Normal Sheath Acceleration)

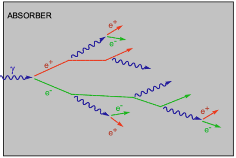


- Energy spectrum of the emitted photons $\Rightarrow$ hot electrons and hence ions T, absorption mechanisms
- BUT emission is short (fs range) and high-energy (up to 50 MeV) $\longrightarrow$ Need of a novel detector: *online, compact*

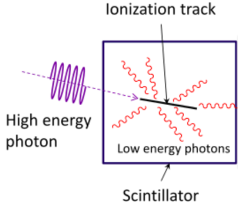
High energy photons($\gtrsim$ 10 MeV):

generation=*bremsstrahlung* absorption=*pair production*





Electromagnetic calorimeter was chosen;
Based on scintillating materials:



WHY: active, compact size, EMP (electromagnetic pulse) resistant; in a calorimeter setup - spectral information.

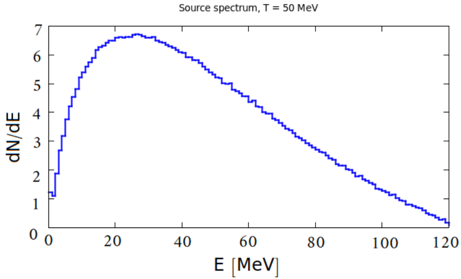
T_{ph} prediction and simulation setup

Beg scaling (hot electron T prediction [1]):

$$T_h(MeV) = 0.215 \left(\frac{I\lambda^2}{10^{18}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2} \right)^{1/3}$$

I is laser intensity, λ is its wavelength

$\Rightarrow$ Photon temperature will not exceed 50 MeV

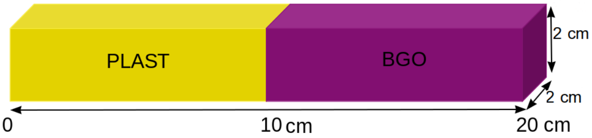


Simulated photon source energy:

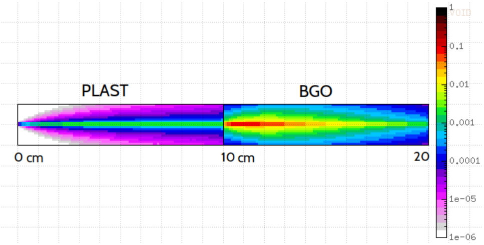
Maxwell-Boltzmann (MB) distribution with T in the range:

100 keV - 1 MeV with 100 keV step; 1 MeV - 50 MeV with 1 MeV step.

Calorimeter *simplified* design for further tests: only 2 layers: plast and BGO



simulations performed using the Monte Carlo FLUKA code [2]



Deposited T = 10 MeV (log. scale), [GeV/cm^3]

Scintillator	Density [g/cm^3]	Light Yield [#/MeV]
PLAST	1.05	10 000
BGO	7.13	8 000

$\Rightarrow$ need of a signal unfolding!

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Basic idea:

- Experiments $\Rightarrow$ usually signal consists of photons of 2 T
- Calorimeter response **D** as a function of 4 variables:

$$\mathbf{D} = A \cdot \mathbf{T}_B + C \cdot \mathbf{T}_D.$$

- We guess parameters *a*, *b*, *c*, *d* and get a guessed response

$$\mathbf{G} = a \cdot \mathbf{t}_b + c \cdot \mathbf{t}_d,$$

where **t** is a detector response for the particular MB temperature simulated beforehand.

- Let us define a function which says how **D** and **G** differ

$$\chi(a, b, c, d) = \sum_i (G_i - R_i)^2,$$

- If $\chi = 0$, then $a,b,c,d = A,B,C,D$ and the problem is solved
$\Rightarrow$ need to find minimum of χ

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$\Rightarrow$ how to find minimum of $\chi(a,b,c,d) = \sum_i (G_i - R_i)^2$?

we found two ways

1. Check all the possible combinations:

2. Use gradients:
   Gradient tells which way the function rise the most.

$$\chi(a,b,c,d) = \left(\frac{\partial\chi}{\partial a}, \frac{\partial\chi}{\partial b}, \frac{\partial\chi}{\partial c}, \frac{\partial\chi}{\partial d}\right) =: \mathrm{grad}$$

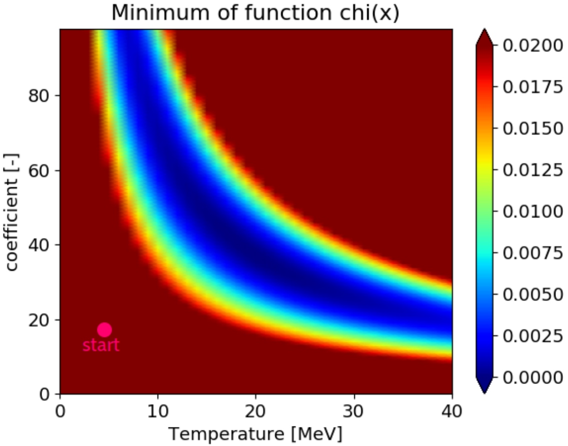
- Start at a random point *start* and keep minimizing χ:
  start(k+1) = start(k) - α(k)·grad(k), k is iteration step
- α(k) is calculated so that to move *in the minimum direction as far as possible*

Signal unfolding

1. Check all the possible combinations:
   + Very simple and reliable, - but not precise enough, not noise resistant, time consuming and not able to guess decimal T values.
2. Use gradients:
   + fast and precise, - but depends on the starting point: possible to stop at local minimum, not global.
3. Solution: Combination of 2 algorithms:
   the 1st one: approximation→*save to start*;
   start→ as a starting point in the 2nd algorithm

   Code written in Python

2D response: $\mathbf{D} = 40 \cdot \mathbf{T}_{20}$



$\text{chi(x)} := \chi(a, b)$

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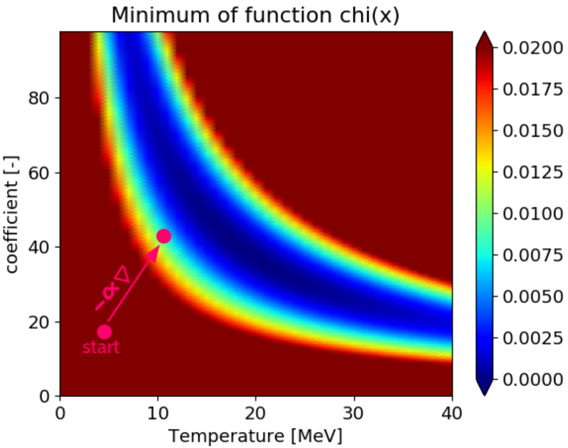

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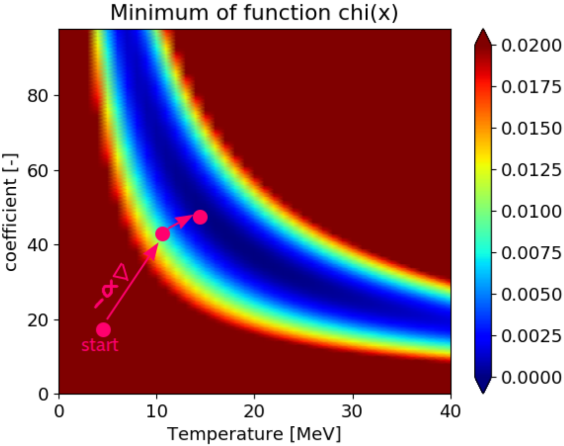

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Intuitive explanation

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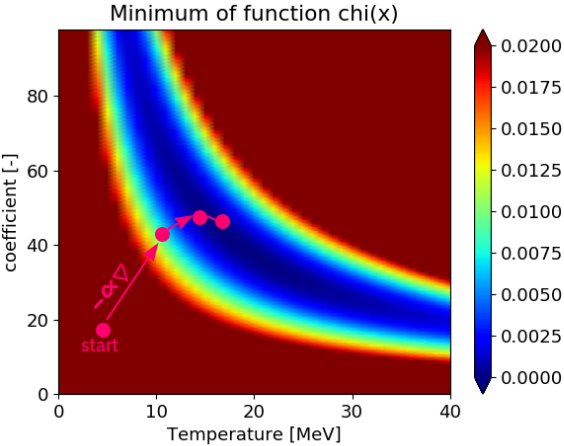

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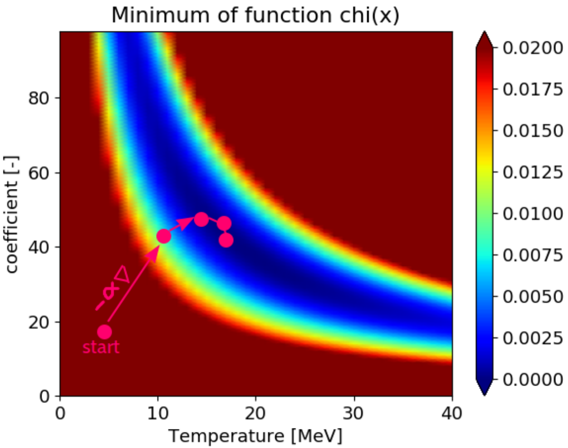

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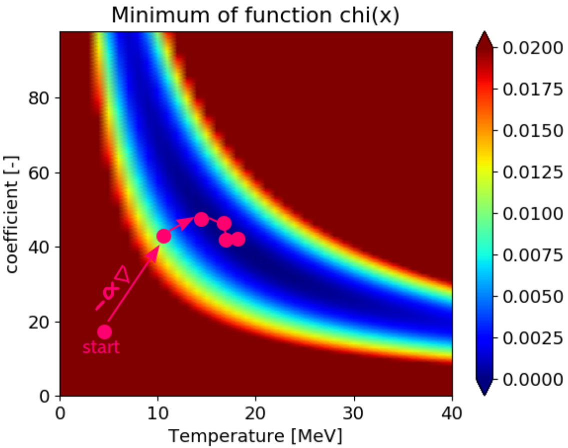

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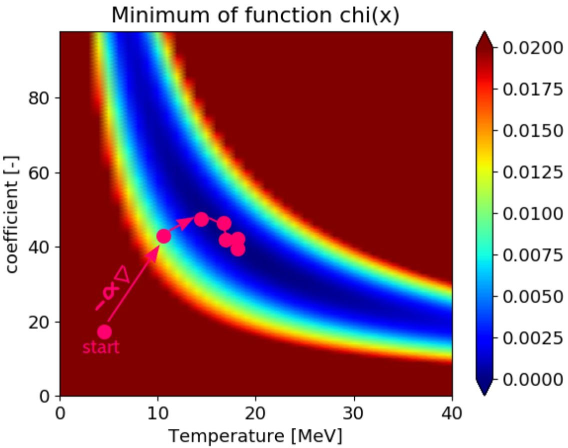
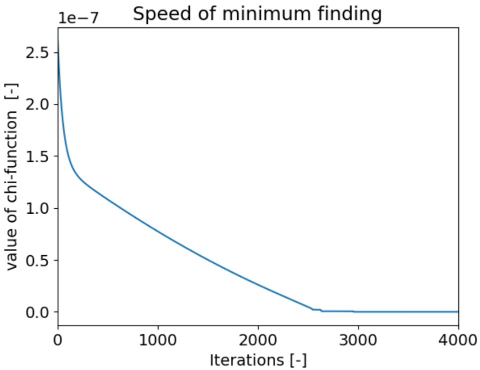


$\text{chi(x)} := \chi(a, b)$

- Detector response: $\mathbf{D} = 5.50{\cdot}\mathbf{T}_{4.10} + 1.20{\cdot}\mathbf{T}_{39.90}$
- Unfolded response: $\mathbf{D} = 5.49..{\cdot}\mathbf{T}_{4.10..} + 1.19..{\cdot}\mathbf{T}_{39.90..}$
- execution time: $\sim$ 180 seconds



<1% precision

Conclusion

- An electromagnetic calorimeter: *plastic and BGO scintillators* with length not exceeding *20 cm*: suitable for high-energy photons *(<50 MeV)* detection.
- To test the design, T_{ph} was estimated, calorimeter geometry was built and multiple simulations were performed via the FLUKA code.
- Success in the unfolding algorithm development:
  - fast (3 mins)
  - noise resistant
  - able to work not only with integer temperatures (as simulated), but also with decimal.
- Ready to move on with design improvements and detector manufacturing.

Next steps

- More realistic design (number of layers, layer thickness..)
- Simulations using realistic photon beam shape (covering the whole detector facing surface instead of pencil-beam) and creation of new response matrix
- Manufacturing of the detector (contact a manufacturer)
- Experimental tests and calibration

References

1. Beg, F. N et al., Physics of plasmas, 4(2): 447 (1997).
2. A. Ferrari, et al. No. INFN-TC-05-11 (2005).
3. D. Margarone, *et al.*, Quantum Beam Science, 2(2):8 (2018).
4. ELI Beamlines official website: `https://www.eli-beams.eu/`
5. H. Schwoerer, *et al.*, Nature 439(7075): 445 (2006).
6. G. F. Knoll, Radiation Detection and Measurement. 4th edition, John Wiley & Sons (2010).