Compact multi-layer calorimeter as luminometer for extremely intense environments

(EOI 158)

Anna Ferrari
HZDR

with Maria Molodtsova[1, 2], Tom Cowan[1,2] et al.
and INFN Torino, INFN-LNF

[1]*Helmholtz-Zentrum Dresden-Rossendorf*
[2]*Technische Universität Dresden*

A calorimetry technique for extreme environments

- ✓ Goal: characterize particle spectra in extreme environments
  (in HEP: characterize hot regions, measure luminosity)

- ✓ The concept: we measure the energy deposited
  by multi-photon signals in a multi-scintillator detector
  with a layered structure, increasing density (key point to have suitable response functions for the unfolding!) and
  a read-out based on solid-state photosensor (SiPMs and/or APDs)

- ✓ With respect to a traditional calorimeter for single particle detection:
  we renounce *a priori* to detect single photons emitted "per event"
  (*i.e.* "per laser shot" in high-intensity laser-plasma experiments)

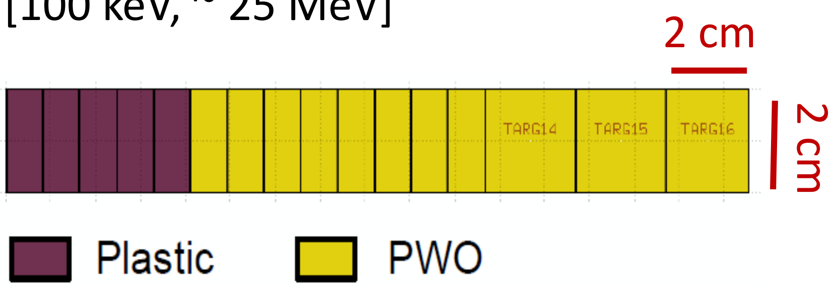
  ⇓

  look at the precise characterization of the longitudinal profile
  of the deposited energy

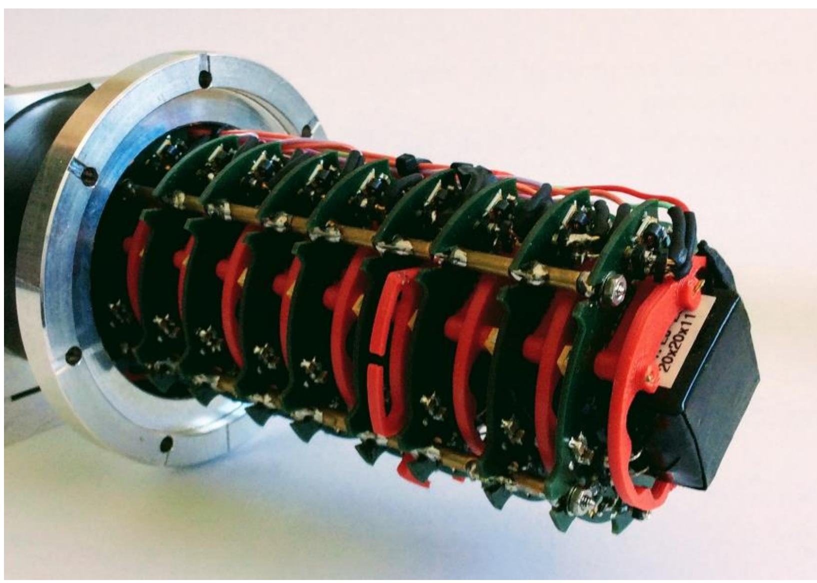
- ✓ we reconstruct the the photon spectrum via an unfolding technique
  using a Monte Carlo based Response Matrix

Prototype 1: an optimized design for low-energy range, very high rates

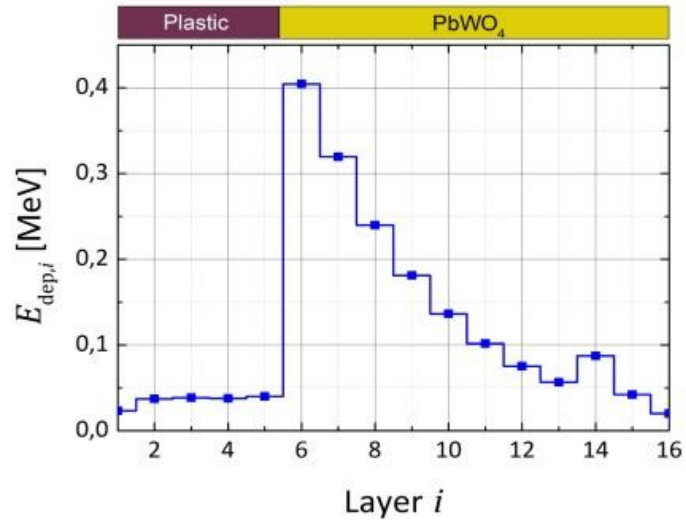
Target energy range (single particle):
[100 keV, ~ 25 MeV]



EJ200 and $PbWO_4$ serve both as detectors and absorbers, with SIPM readout

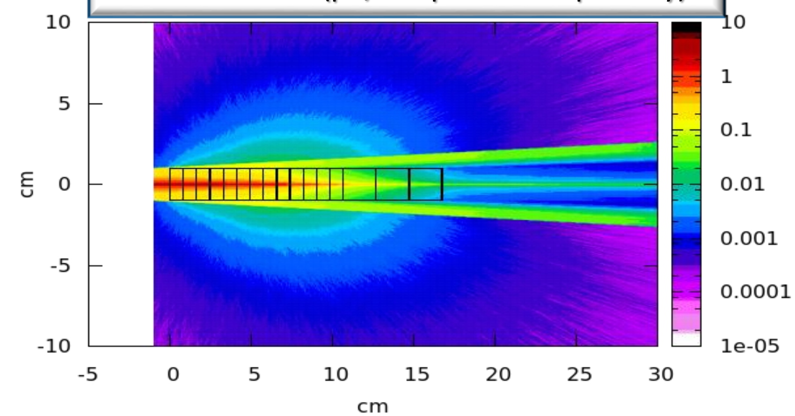


Deposited Energy from a Maxwell-Boltzmann photon distribution with T = 2 MeV



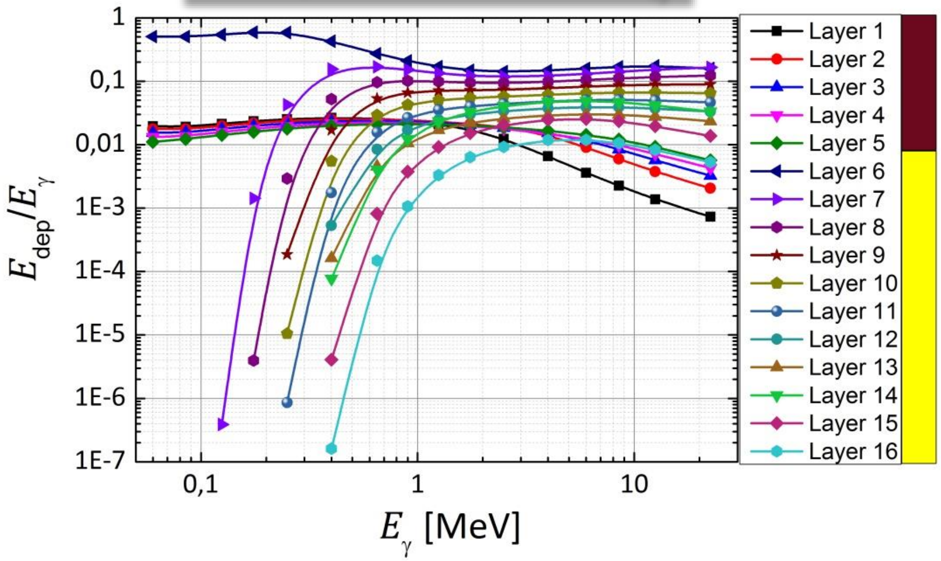
FLUKA simulations

Photon fluence (ph/cm² per source primary)

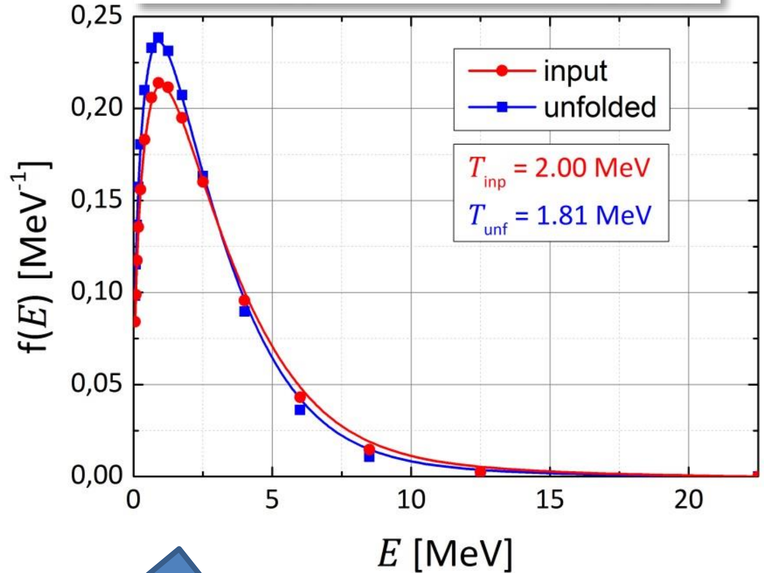


Response matrix and unfolding

Response matrix R_{ij}



Energy distribution $f(E)$



For every layer:

$$E_{\mathrm{dep},i} = \sum_{j=1}^{16} R_{i,j} \cdot f(E_j) \cdot E_j \cdot \Delta E_j$$

Unfolding of $f(E_j)$
with response matrix $R_{i,j}$

Residual minimization
to find the best f(E) that reproduces $E_{\mathrm{dep,i}}$

[Proceedings of *SATIF 13*, OECD Publishing, Paris, NEA/NSC/R(2018)2, 2018, p.430]

A closer look at the unfolding procedure

Prior f_E

↓

INVERSE PROBLEM

$$D_i = \sum_E R_{i,E} \cdot f_E \cdot E \cdot \Delta E$$

↓

CHI²-MAP

$$\chi^2 = \sum_i \frac{(D_i - D_{meas})^2}{\Delta D_{meas,i}{}^2}$$

↓

Chi² Minimum?

↓

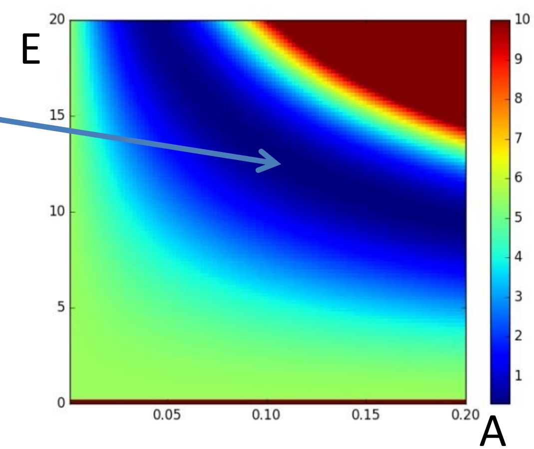
FINISH
(A, E known)

f_E is the prior input spectrum (e.g. Maxwellian, Bremsstrahlung) with parameters E (energy), A (amplitude)

$R_{i,E}$ is the calculated response matrix

E is the mean energy of the energy bin
ΔE is the width of the energy bin

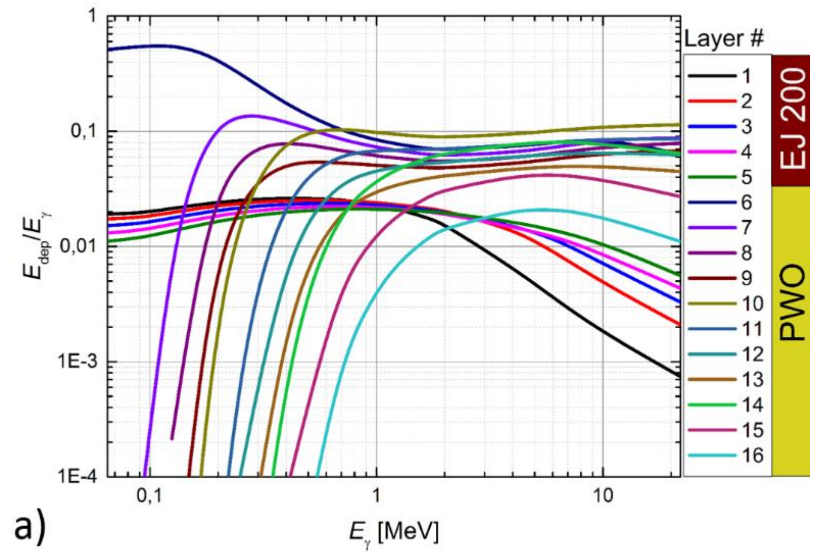
D_i is the calculated dose in layer i
$D_{meas,i}$ is the measured dose in layer i



Key points

✓ To guarantee an effective unfolding, response functions corresponding to different layers must exhibit different derivatives
-> the design of the scintillating elements (thickness, choice of material with special attention to the density) proceeds via a systematic Monte Carlo study

✓ Response matrix must be tailored for every **experimental situation** (ex: description of the housing). The simulated set of monoenergetic gamma beams must be as much as possible geometrically close as the one in the experiment (**lateral dimensions, profile, divergence)**

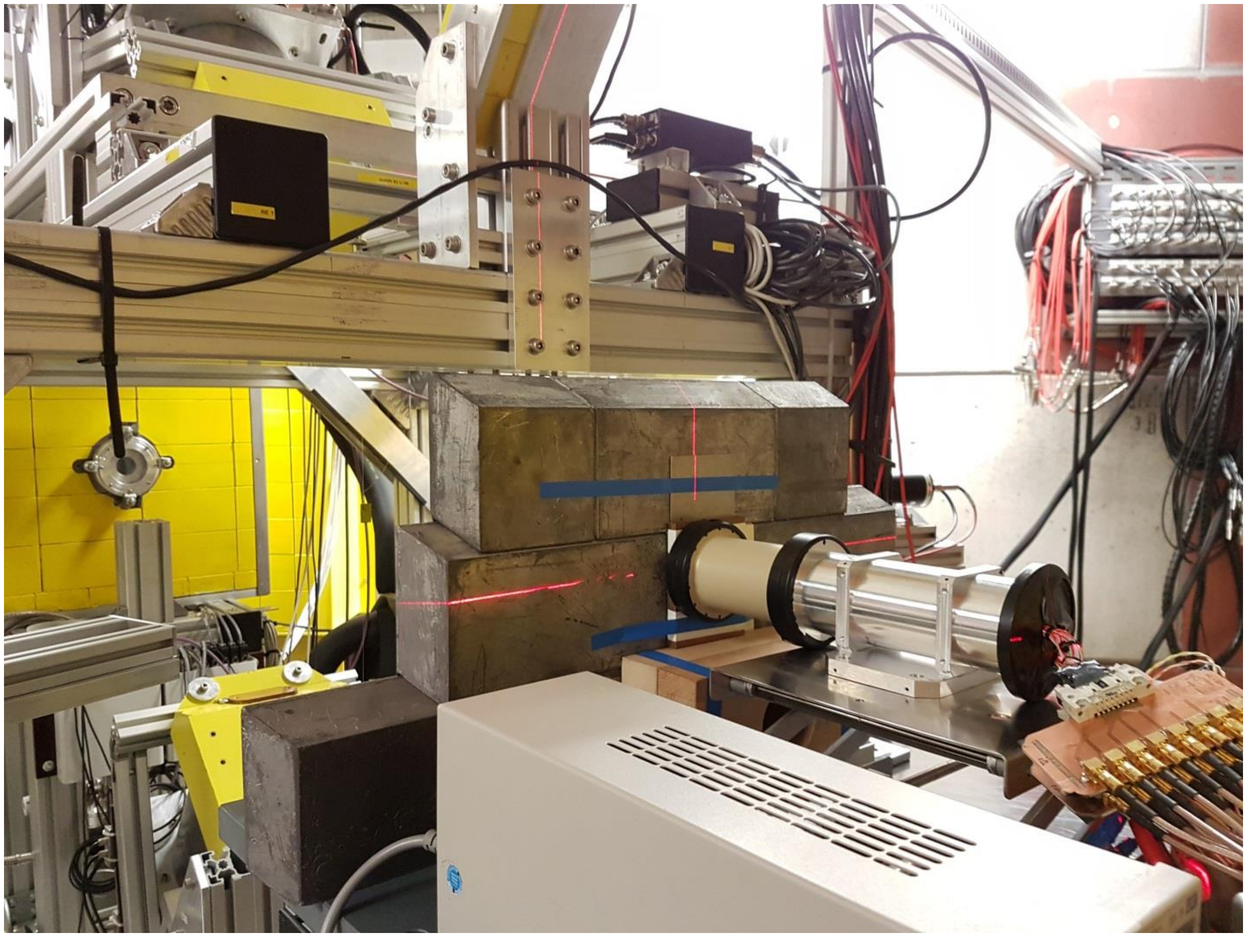


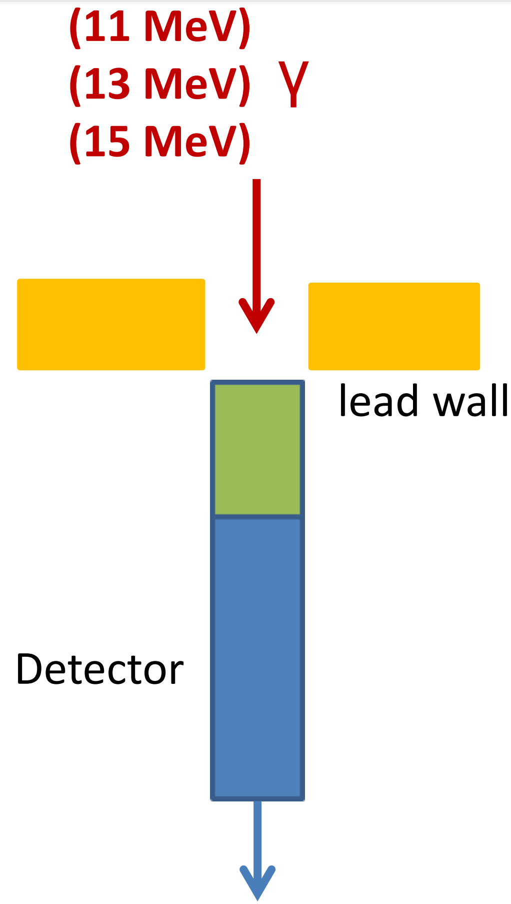
Response functions of Prototype 1 simulated with FLUKA

Challenges in the electronic read-out

- High instantaneous gamma fluxes → saturation must be avoided
- Only in high-power laser environments: electronics suffer and/or break from high EMP => we already tested the robustness of the SiPMs in a such environment!

Test-beam at the gELBE Facility





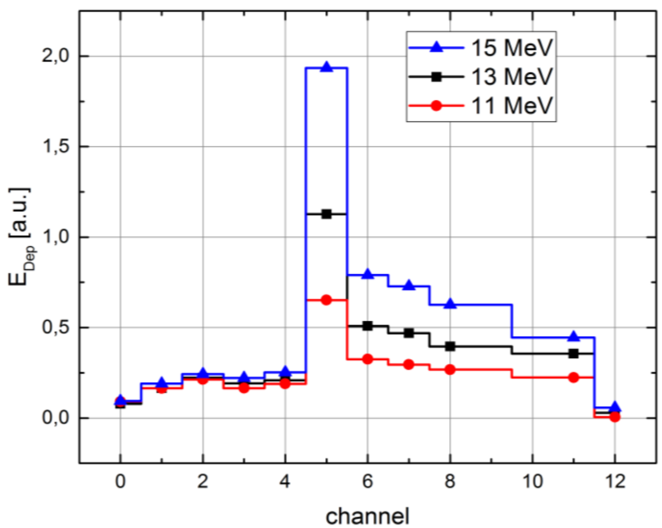
Signal recorded with waveform digitizer

Each scintillator layer was equipped with a SensL 30020 Silicon photomultiplier

Reconstruction of the gELBE Bremsstrahlung spectra

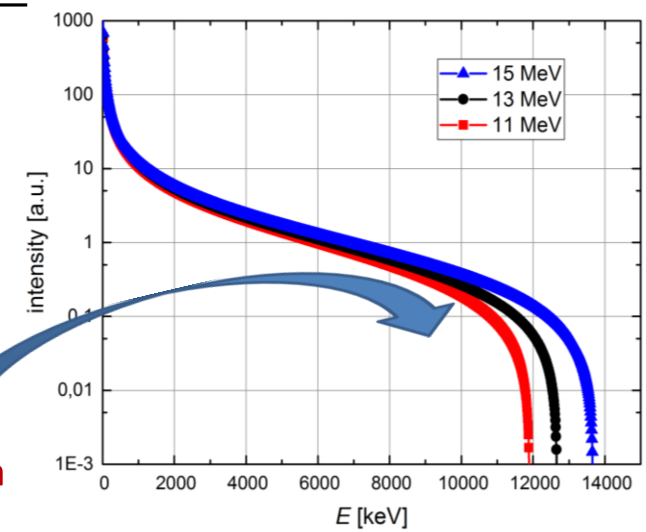
HZDR
HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

A) gELBE Bremsstrahlung spectra with 11, 13, 15 MeV Endpoint



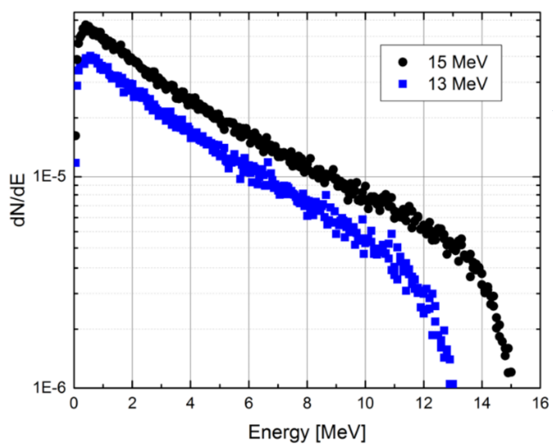
Measured depth-energy profiles with 3 different endpoint energies

Endpoint Unfolding of the gELBE Bremsrahlung spectra



B) gELBE Bremsstrahlung spectra with Al attenuator (hardener)

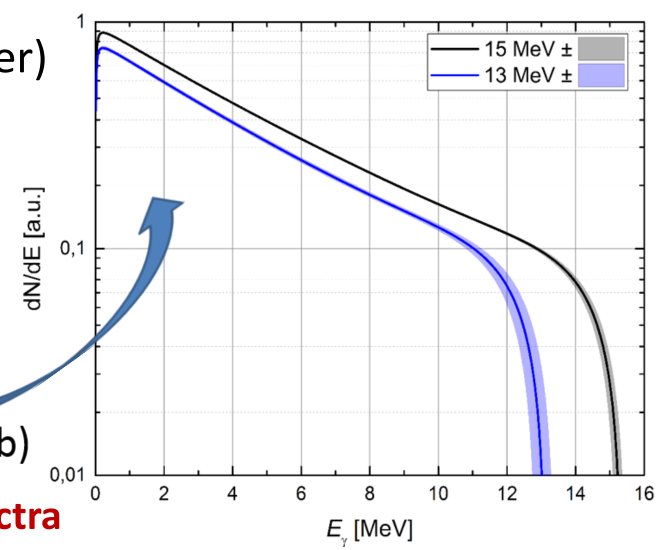
a)



FLUKA simulation

Unfolding of the gELBE Bremsrahlung spectra

b)



Important remarks

✓ We realized very soon that the very high particle yield considered (up to 10^8 photons/cm^2) translate in an energy deposition in each calorimeter element up to the multi-TeV range.
This has 2 consequences:
- **advantage**: the energy resolution is dramatically improved, already in the low energy range
- **challenge**: an innovative, robust electronics read-out must be developed (→ cooperation with the groups – 2 INFN groups in the proposals, Torino and Frascati- that experienced the need of an extended dynamic range)

✓ **The extension of the idea to the higher energy range – goal in AIDA++ – is straightforward**: we add layers increasing the length of the calorimeter depending on the number of radiation lengths that we require

Optimization of the layer number (the number of measurements for the unfolding) will be also done (we adapt the sampling frequency)

Deliverables and plan of work

- ✓ **Deliverable 1**: Prototypes design for intermediate and high-energy range: optimization, response functions and unfolding

- ✓ **Deliverable 2**: SiPM/APD read-out system electronics
  - APD electronics read-out system (with INFN-TO)
  - SiPM electronics read-out system (with INFN-LNF)

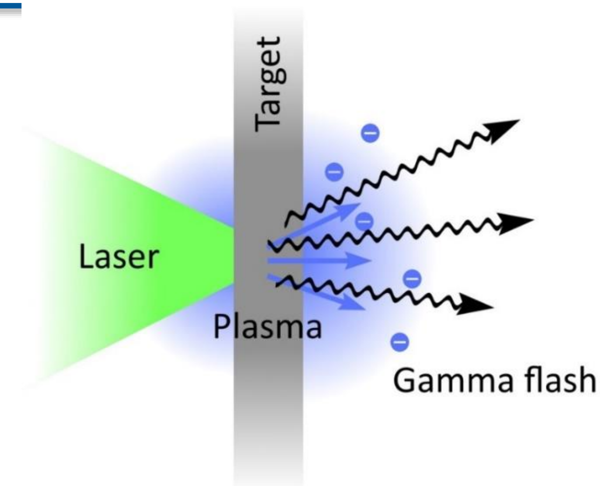
- ✓ **Deliverable 3**: Test of the prototypes with SiPM/APD read-out with intense gamma beams (HZDR) and possibly muon beams (CERN)
  - Test beam preparation and results

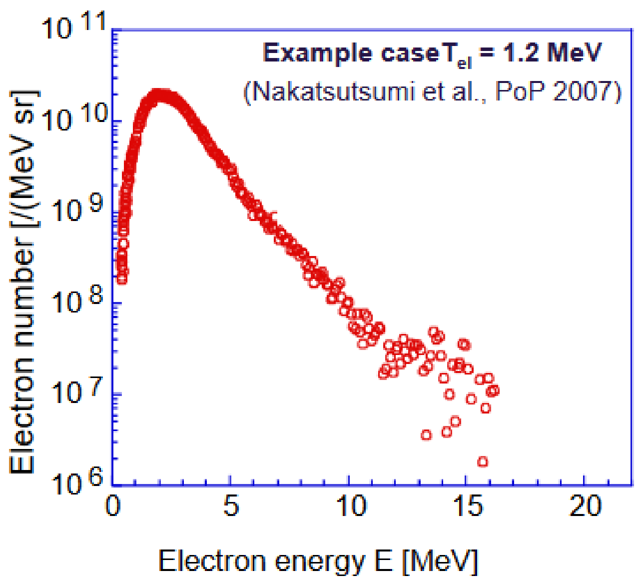
The Front End Electronics can be adapted from the one used in the Mu2e calorimeter prototype (developed at LNF) or the one used in the CMS ECAL (developed in Torino). Both choices provide an integrated LV supply, a distribution of HV configurable for each individual channel, and a multi-level gain to maintain low noise at the full dynamic range of the photosensor output. The INFN-TO will contribute with an ASIC optimised for the readout of the said APD/SiPM photosensors, while a versatile 32-channel chip for SiPM readout is currently being designed.

Spares

Original motivation: characterize Bremsstrahlung spectra in high-intensity, high-power laser-plasma experiments

- ✓ high intensity (up to 10^{22} W/cm²) lasers hit targets and create plasma
- ✓ Hot electrons and accelerated particles are produced
- ✓ Hot electrons emit Bremsstrahlung pulses → „gamma flash“: up **to ~10^{12} photons/sr per laser shot**





- ✓ Electrons follow a Maxwellian energy distribution:

$$f(E) = E^{1/2} e^{-E/T} / T^{3/2}$$

- ✓ Photon energy spectrum N_γ depends on electron temperature (average kin. energy) T_e:

$$N_\gamma(E_\gamma, T_e) = C \frac{1}{E_\gamma} e^{-\left(\frac{E_\gamma}{T_e}\right)} \Rightarrow T_e$$