The HARPO (Hermetic ARgon POlarimeter) instrument project

- FRANCE: the detector

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- Japan: the beam.

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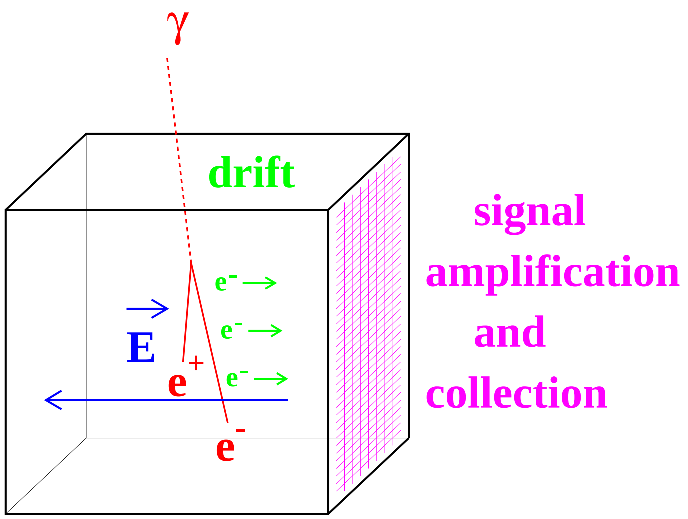
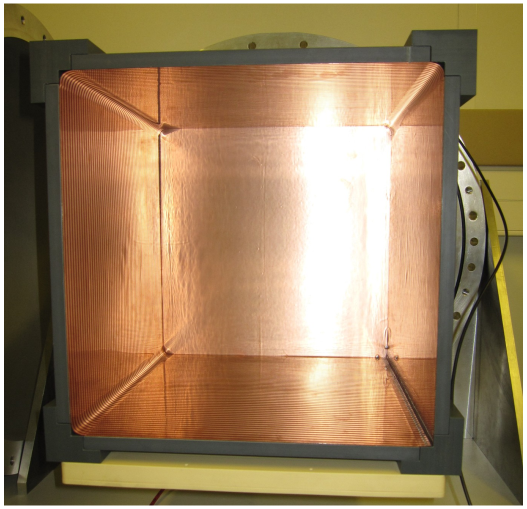
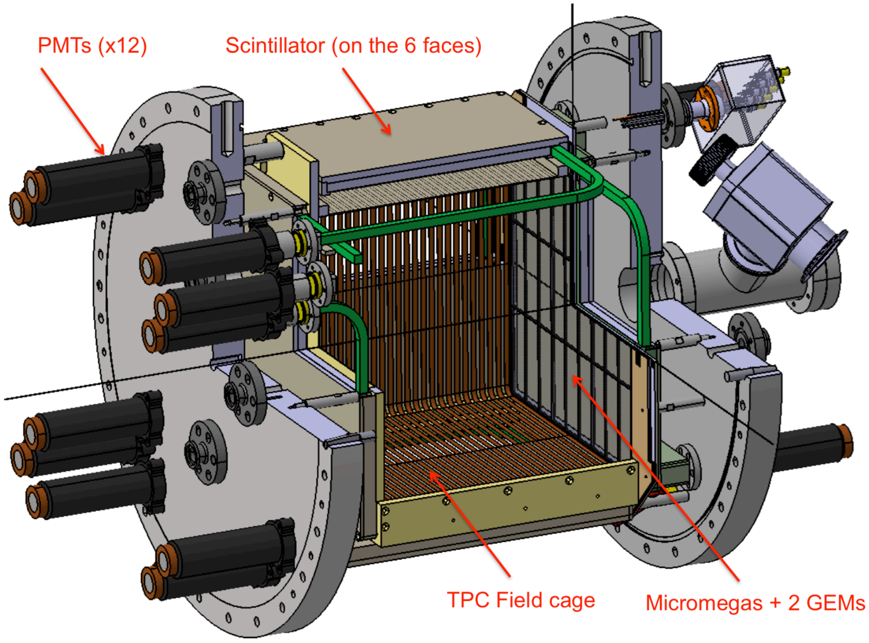
HARPO: the Demonstrator



- Time Projection Chamber (TPC)
- $(30\mathrm{cm})^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on x, y strips, pitch 1 mm.
- AFTER chip digitization, up to 100 MHz.
- Scintillator / WLS / PMT based trigger

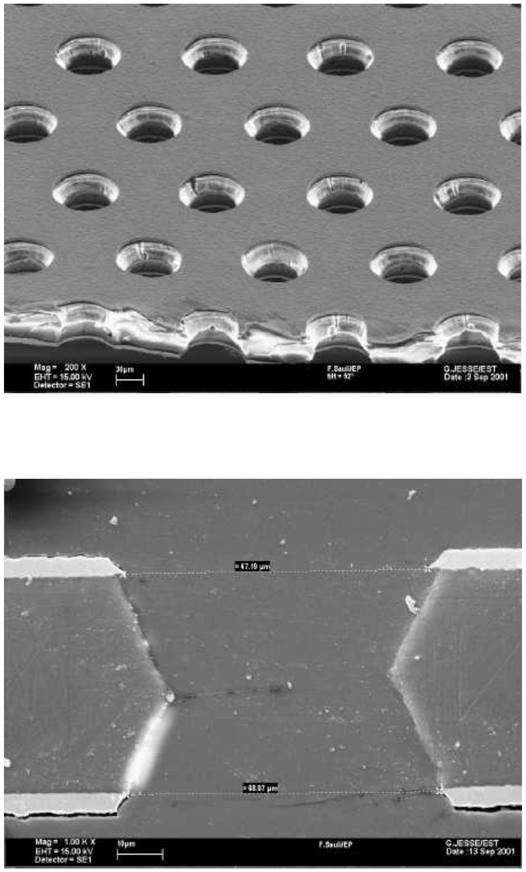




NIM A 695 (2012) 71, NIM A 718 (2013) 395

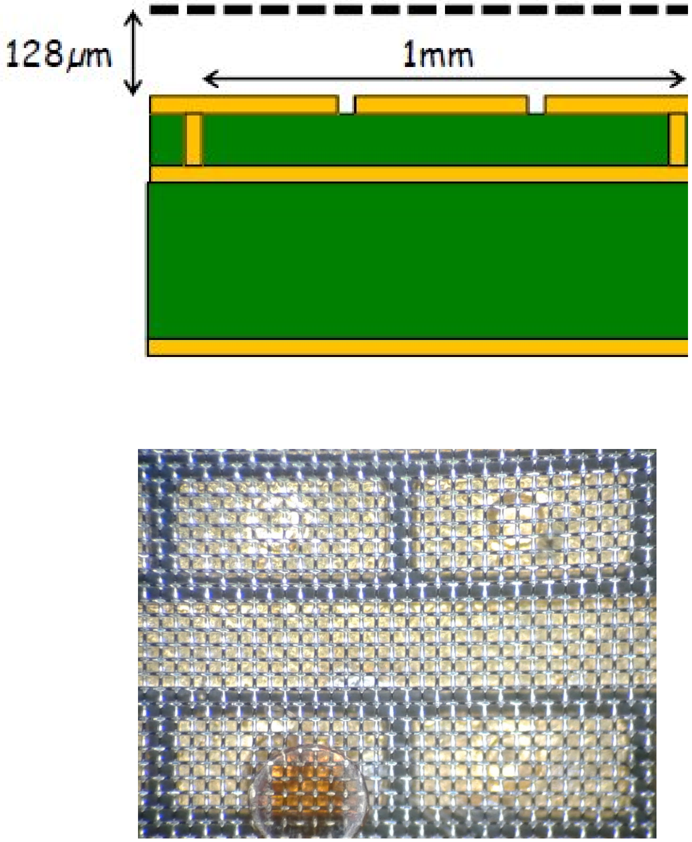
Gas amplification: micromegas + 2 GEM

Gas Electron Multiplier
$50\,\mu\mathrm{m}$ Kapton, copper clad,
pitch $140\,\mu\mathrm{m}$, $\Phi 70\,\mu\mathrm{m}$



F. Sauli, NIM A 386, 531 (1997)

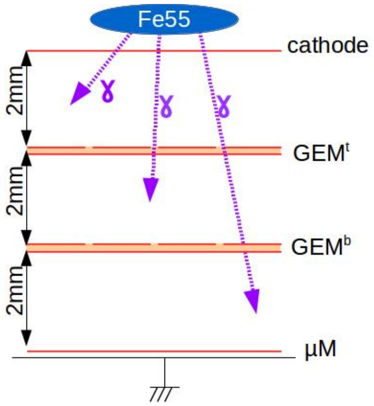
“bulk” micromegas
gap $128\,\mu\mathrm{m}$

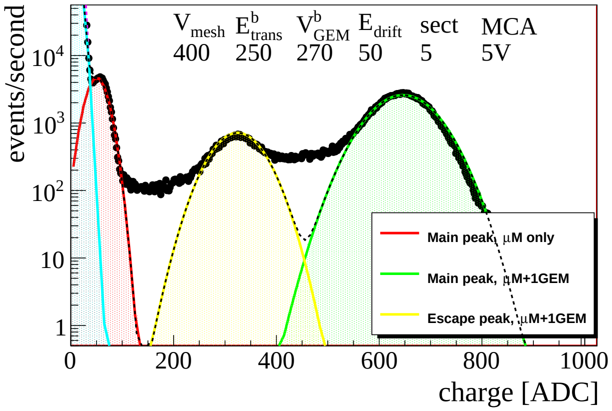


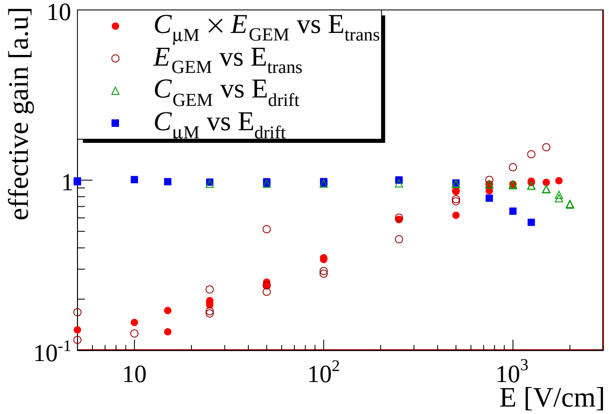
I. Giomataris et al., NIM A 560, 405 (2006)

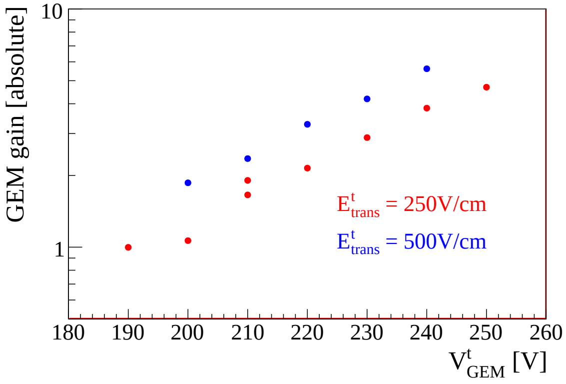
Micromegas + 2 GEM assemblies: characterization

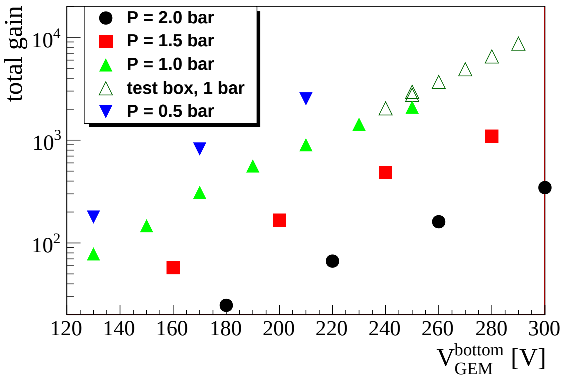
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







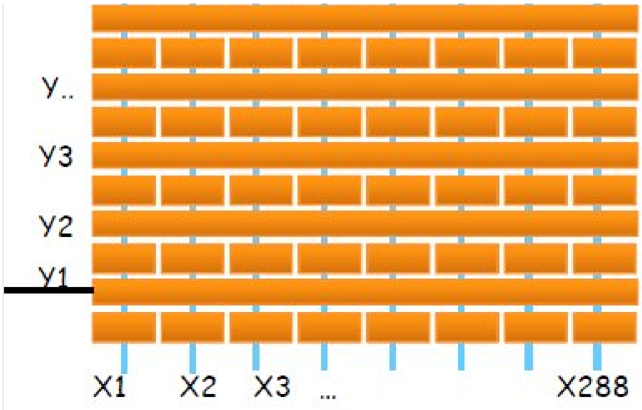


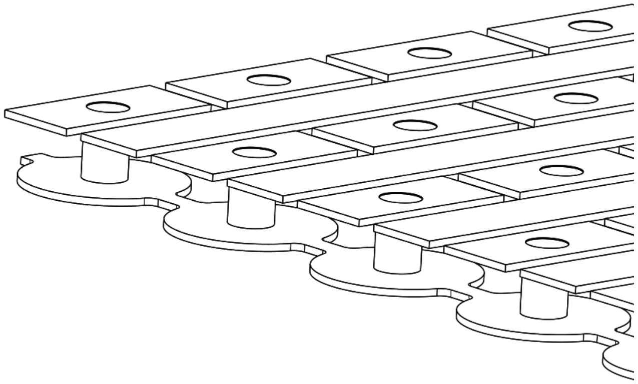


Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Anode segmentation

- Avalanche electrons collected on a segmented anode.

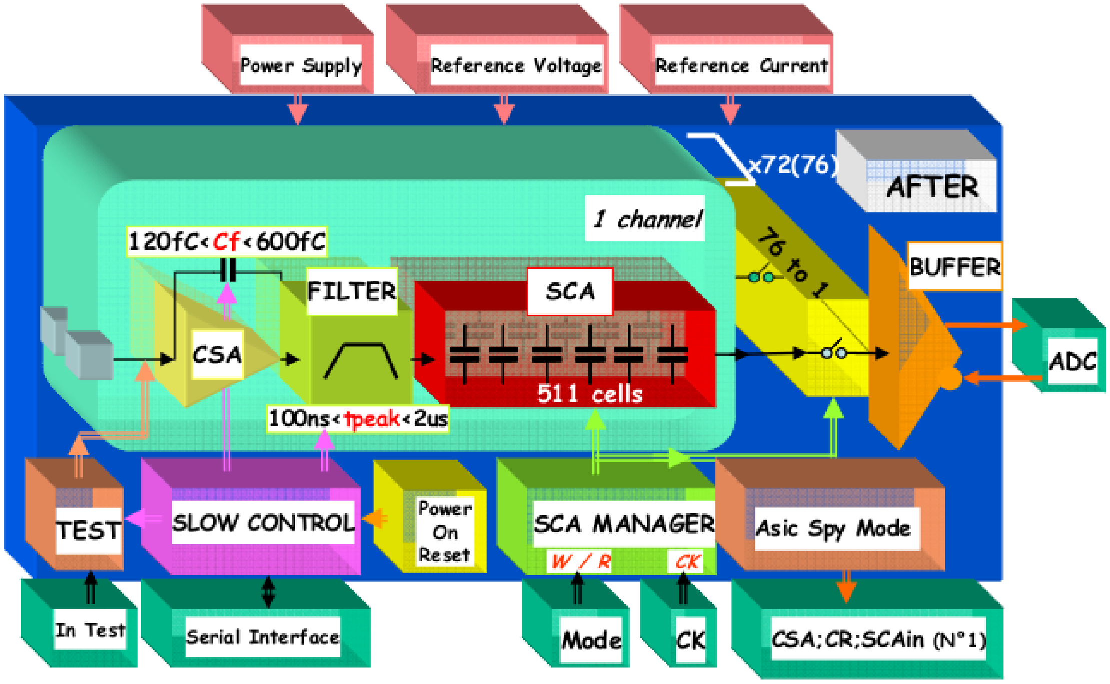




- Cu-clad PCB, strip pitch 1 mm, strip width $\approx 400\,\mu\mathrm{m}$

Signal digitization

- 2 directions x, y, 288 strips (channels) / direction
- 72 channels /chip
- 4 chips / direction
- 511 time bins, “circular” SCA (Switched Capacitor Array)
- Input: 120 fC to 600 fC
- Up to 100 MHz sampling
- Shaping time 100 ns to 2 µs
- 12 bit ADC.

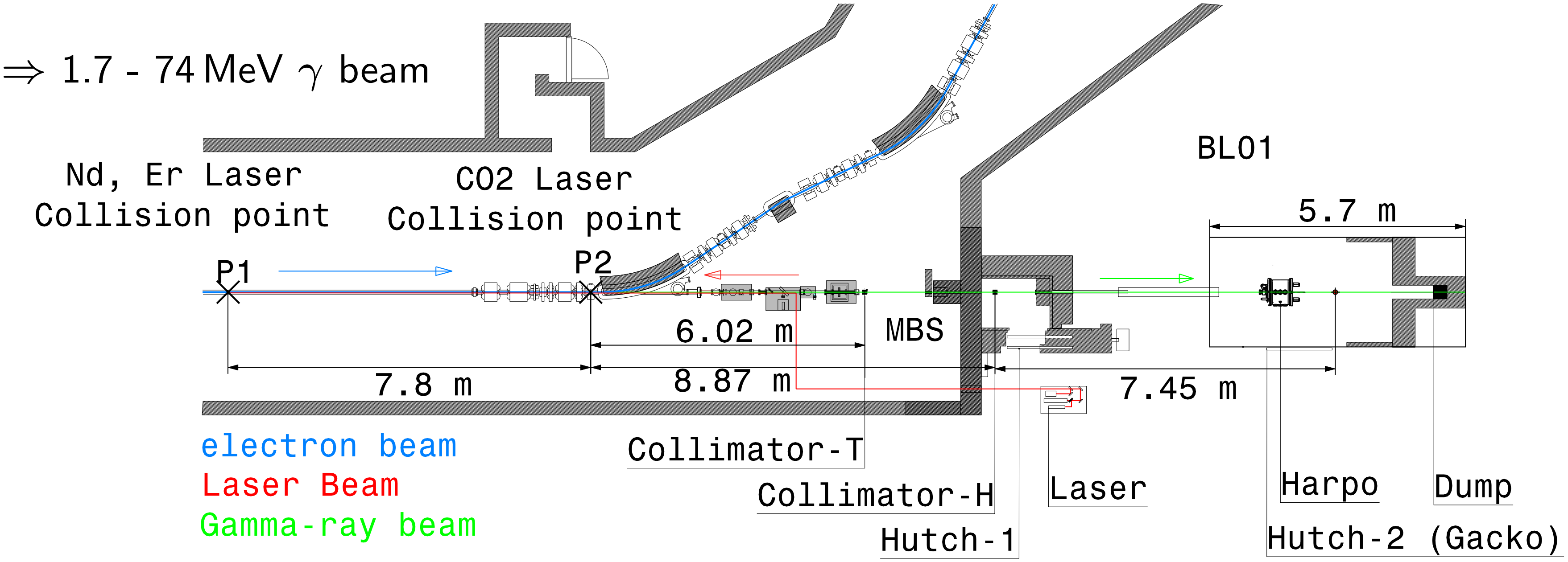


Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

P. Baron et al., IEEE Trans. Nucl. Sci. 55, 1744 (2008).

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

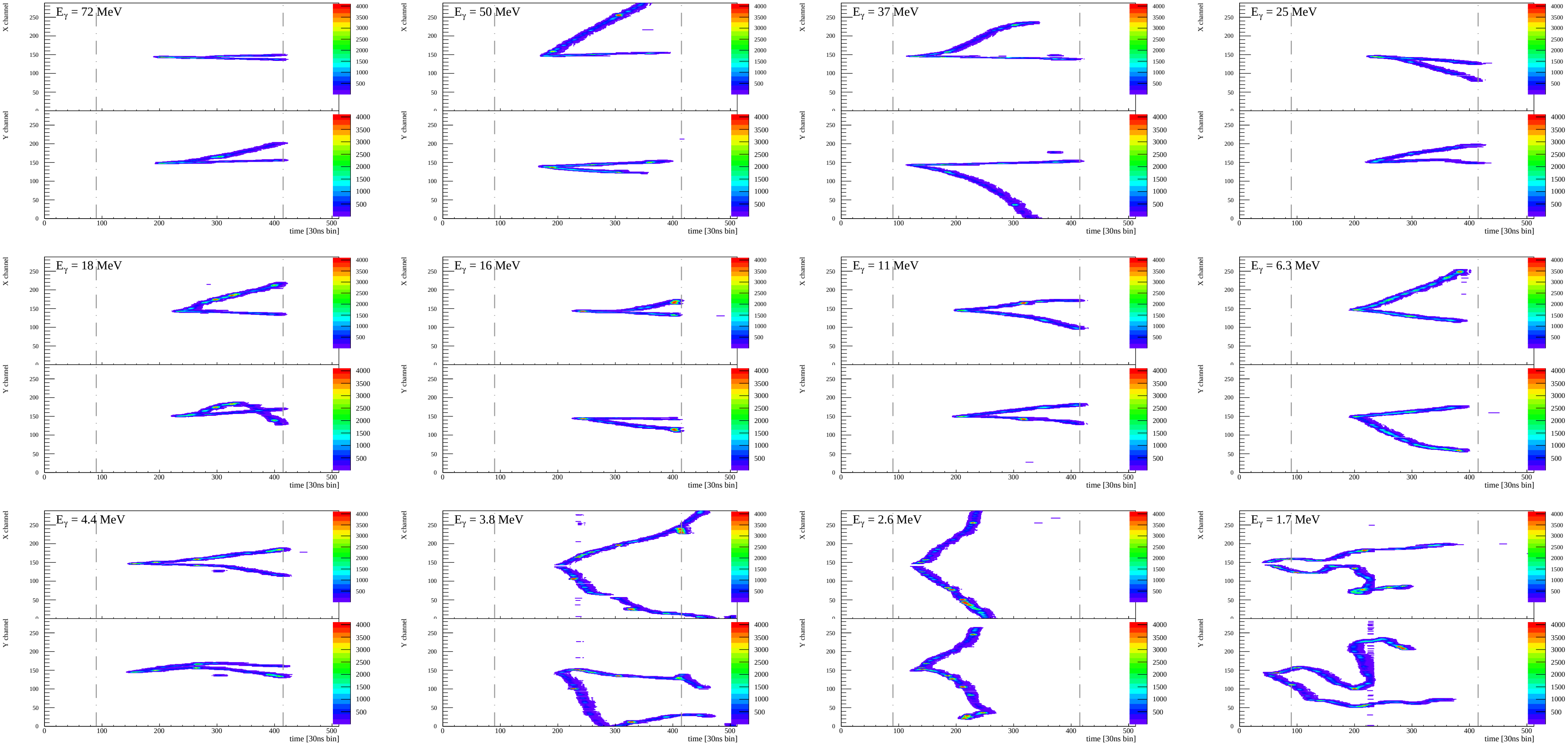
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu\mathrm{m}$ and $1.064\,\mu\mathrm{m}$ $20\,\mathrm{kHz}$ pulsed Nd:YVO$_4$ (2ω and 1ω),
  $1.540\,\mu\mathrm{m}$ $200\,\mathrm{kHz}$ pulsed Er (fibre) and
  $10.55\,\mu\mathrm{m}$ CW CO$_2$ lasers
- $\Rightarrow$ 1.7 - 74 MeV γ beam



- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams ($P = 0$, $P = 1$)
- 2.1 bar Ar:isoC$_4$H$_{10}$ 95:5 (+ a 1-4 bar scan).

A. Delbart et al., ICRC2015, The Hague, 2015

Japan beam Data: gallery

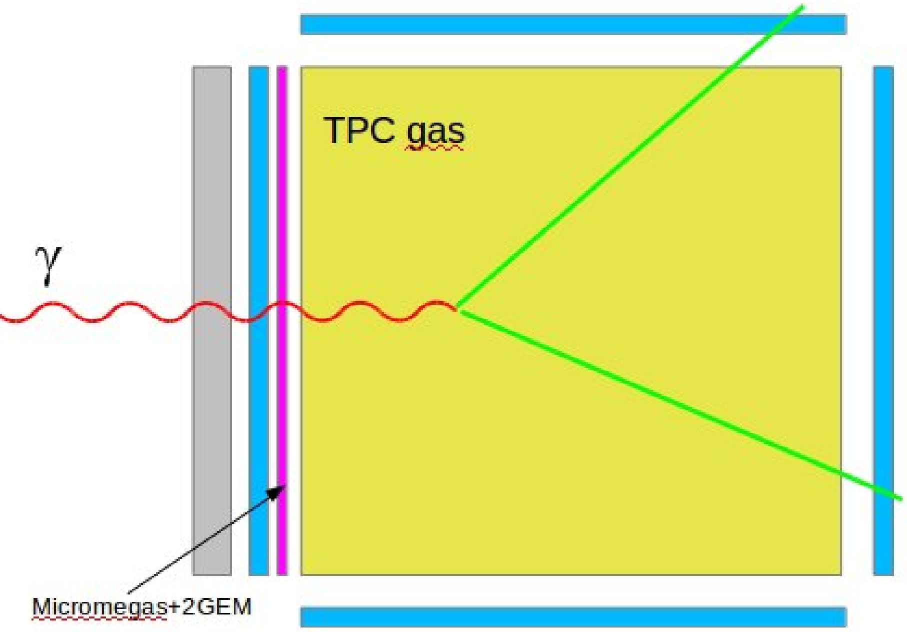


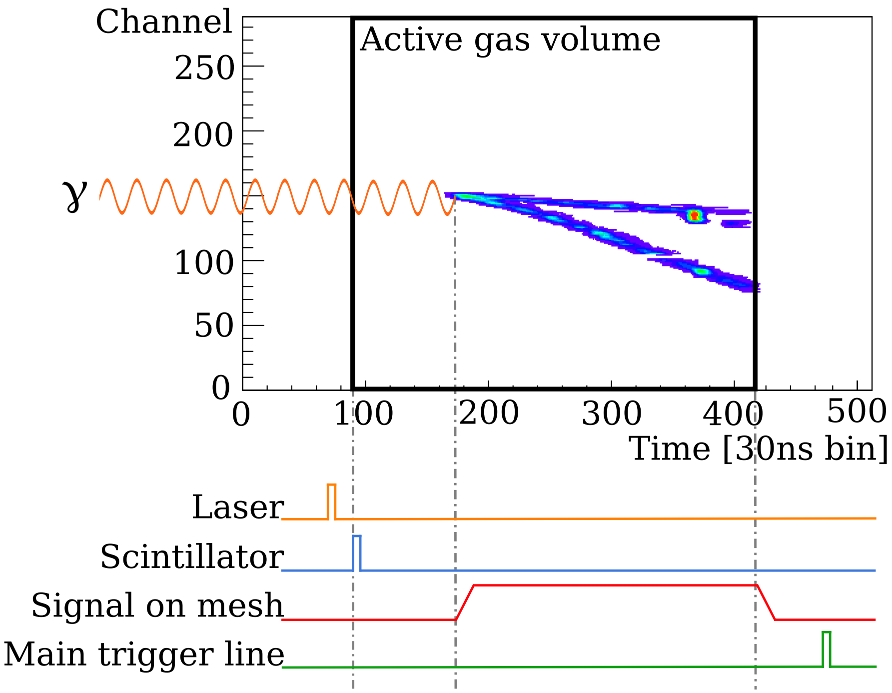
Sample of γ-rays from 74 to 1.7 MeV converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5

detected by the HARPO TPC

(pre-beam-calibration γ-ray energy on plots)

"Beam" trigger system





- S_{up} upstream scintillator
- O one of the 5 other scintillators
- M_{slow}: a delayed ($> 1\mu s$) signal on the micromegas mesh
- L laser trigger pulse

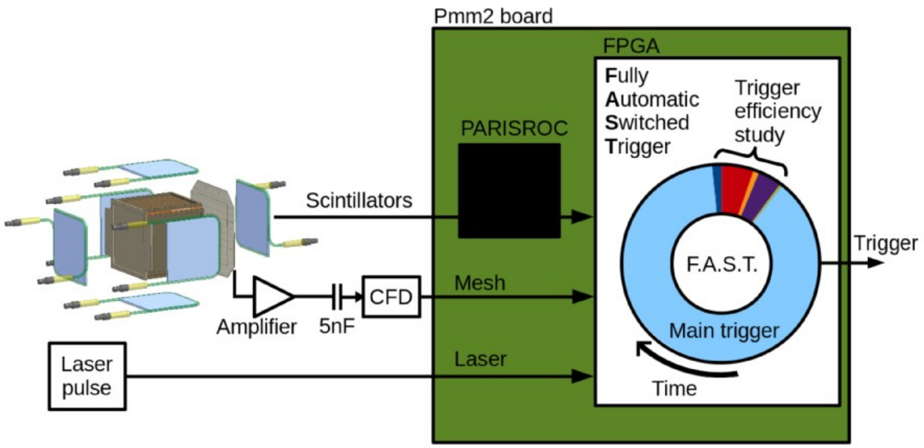
"Main line": $T_{\gamma,laser} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

Wang et al., TPC2014, Paris, J. Phys. Conf. Ser. 650 (2015) 012016, arXiv:1503.03772 [astro-ph.IM]

“Beam” trigger system: additional lines

- Additional trigger lines:

7	$T_{\gamma,laser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap L$
8	$T_{noMesh,laser}$	$\overline{S}_{up} \cap O \cap L$
9	$T_{invMesh,laser}$	$\overline{S}_{up} \cap O \cap M_{quick} \cap L$
10	$T_{noUp,laser}$	$O \cap M_{slow} \cap L$
11	$T_{noPM,laser}$	$\overline{S}_{up} \cap M_{slow} \cap L$
12	$T_{noLaser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap \overline{L}$

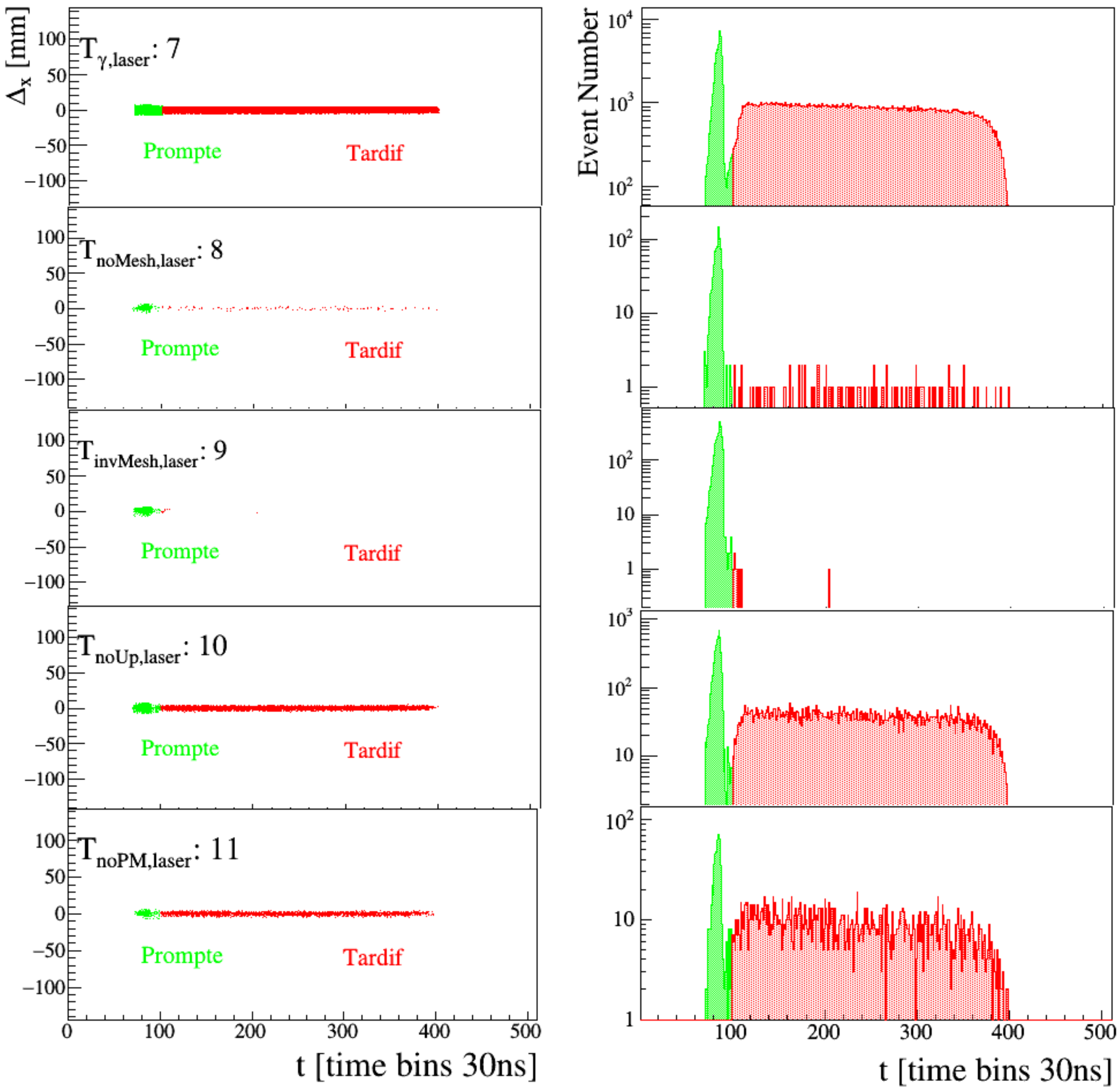


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

Y. Geerebaert, P. Gros, et al., Vienna Conference on Instrumentation 2016

"Beam" trigger system: conversion point distributions

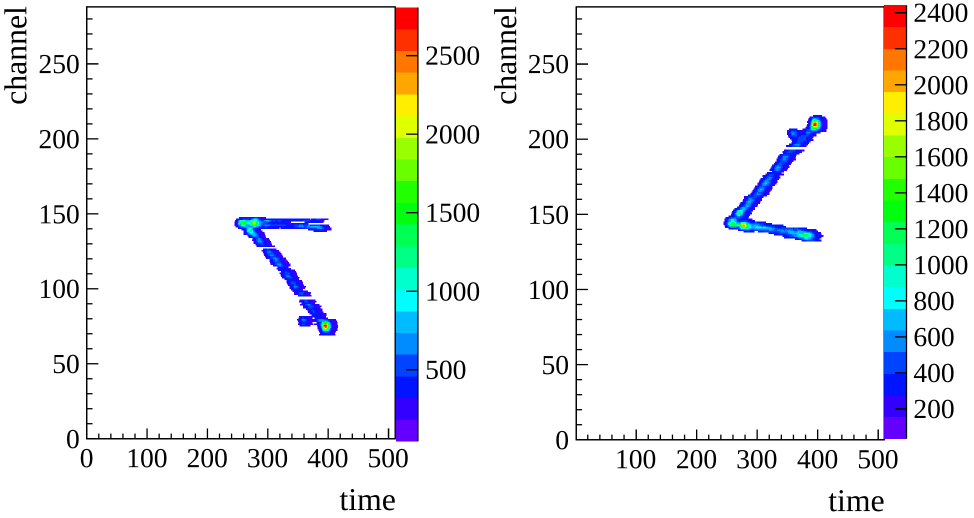
- signal efficiency 51 %
- background rejection 99.3 %
- incident rate 2 kHz
- signal on disk 50 Hz



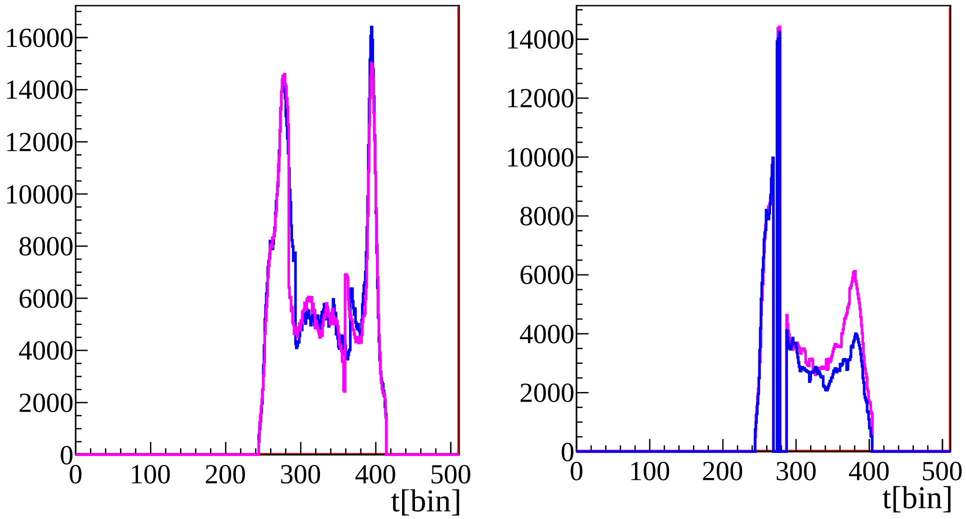
S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015, in French

A 16.7 MeV γ-ray converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5

raw “maps”



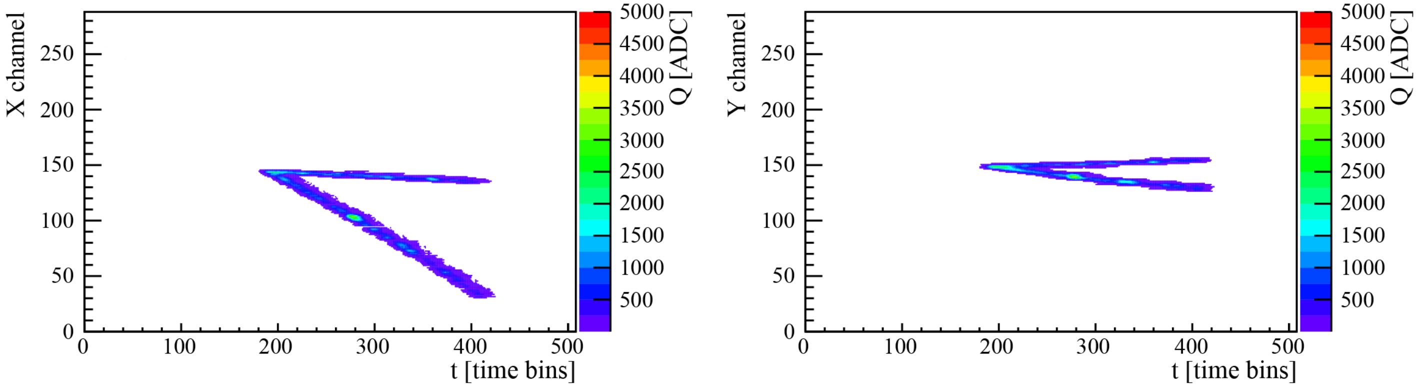
track time spectra



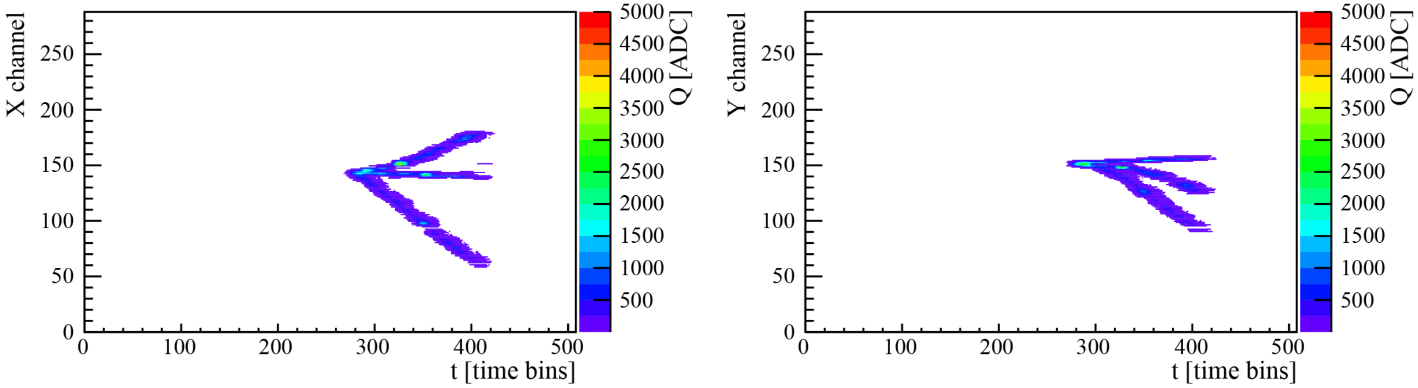
- x, y two-track ambiguity solved by track time spectra matching
- 1 channel $= 1\,\mathrm{mm}$.
- 1 time bin $= 30\,\mathrm{ns}$, $v_{\text{drift}} \approx 3.3\,\mathrm{cm}/\mu\mathrm{s}$ $\Rightarrow$ 1 time bin $\propto 1\,\mathrm{mm}$

End of "ground" prototype validation section

$$\gamma Z \rightarrow e^+ e^- Z$$



$$\gamma e^- \rightarrow e^+ e^- e^-$$



74 MeV γ-rays from NewSUBARU conversions in 2.1 bar Ar:Isobutane 95:5

Towards a space detector: some elements

- Gas composition
- Gas pressure
- Temperature range
- Gas purity on the long term
- . . .

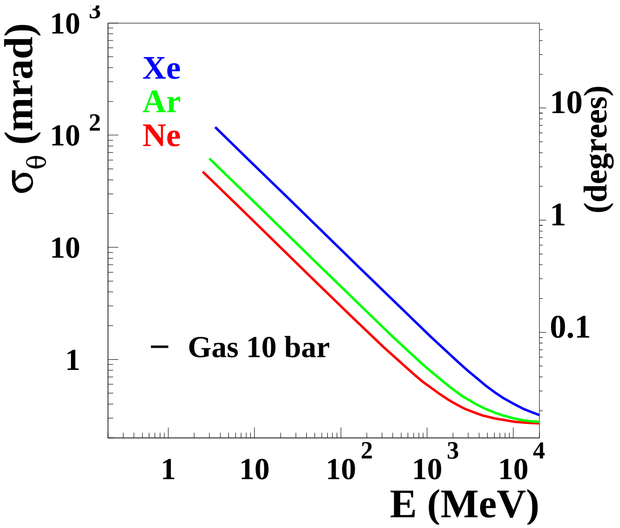
Towards a space detector: Gas composition: drifting species ?

- TPC's to some extent imune to pile-up
- $2 \times 1D$ orthogonal strips given the (small) available electronic powering (i.e., not pads)
- proton flux $20\text{kHz}/\text{m}^2$ at Fermi/LAT orbit.
- need "fast gas":

drifting species	example	v_{drift}	t_{drift}	pile-up fraction	
electron	Ar:isoC_4H_{10}	$3.3\,\text{cm}/\mu\text{s}$	$10\mu\text{s}$	0.2 proton$/\text{m}^2$	manageable
negative ion	Ar:CS_2	$3.3\,\text{cm}/\text{ms}$	10ms	200 proton$/\text{m}^2$	nope

Gas composition: light / heavy Z ? Gas pressure ?

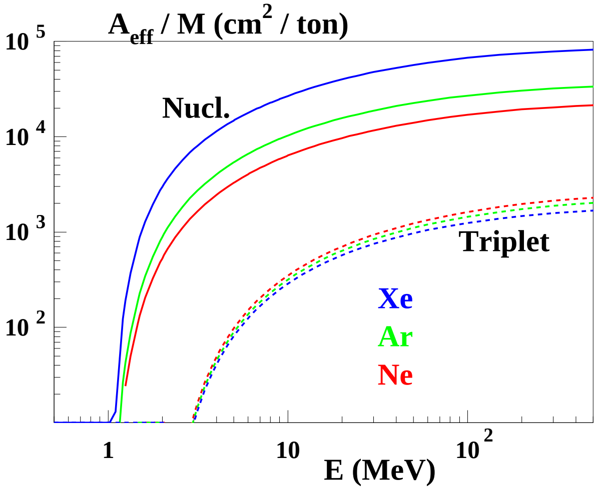
- $\rho \times X_0 = \frac{A}{Z^2} b, \quad \rho = aAP, \quad M = V\rho = VaAP, \quad X_0 = \frac{b}{aZ^2P} \quad a, b$ constants.



angular resolution degrades with Z

$\sigma_\theta \propto X_0^{-3/8} \propto Z^{3/4} P^{3/8}$

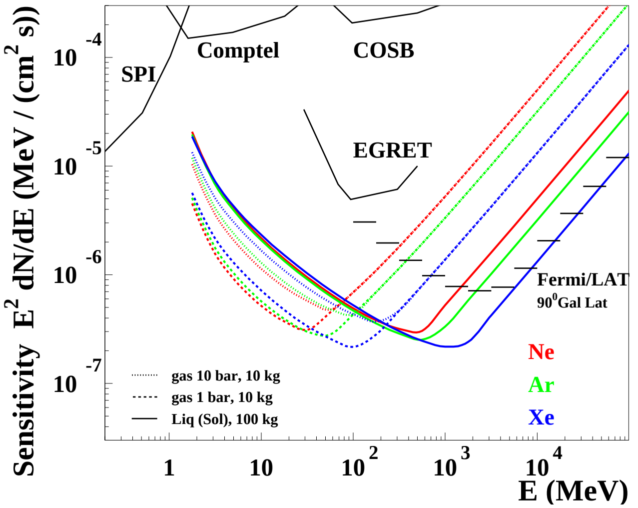
(multiple scattering)



effective area improves with Z

$A_{\text{eff}} \propto \frac{V}{X_0} \propto VPZ^2$

(asymptotically)



sensitivity mildly affected

$s \propto \frac{\sigma_\theta}{\sqrt{A_{\text{eff}}}} \propto \frac{X_0^{1/8}}{\sqrt{V}} \propto \frac{1}{V^{1/2} Z^{1/4} P^{1/8}}$

(asymptotically)

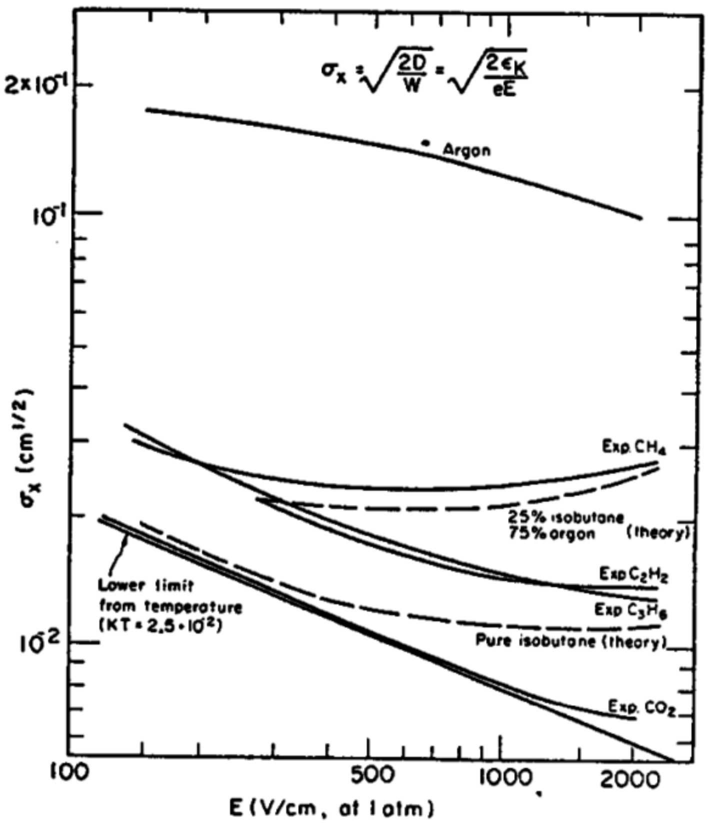
(assuming gaussian stats.)

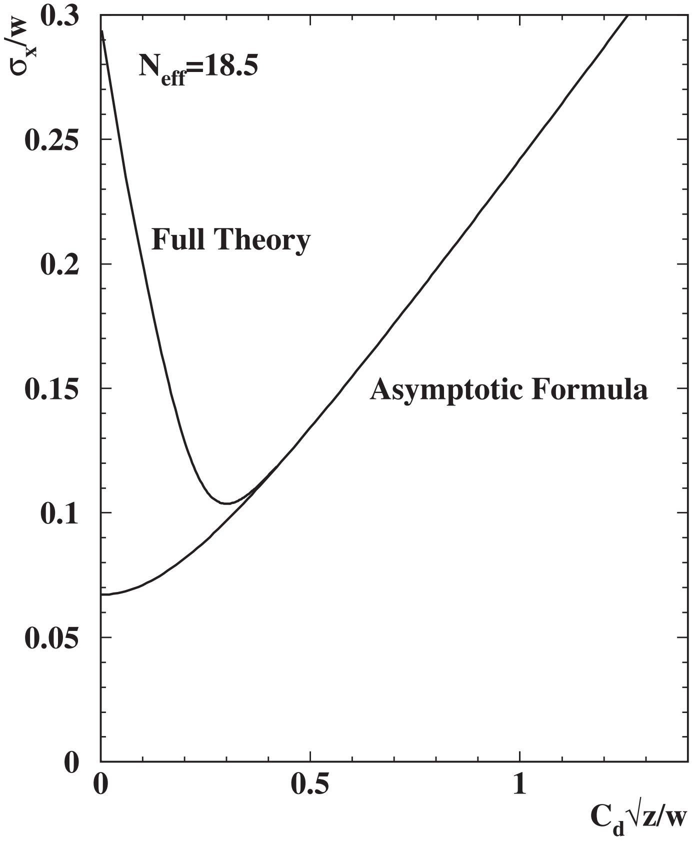
- Note that $M_{\text{vessel}} \propto P$ and $M_{\text{gas}} \propto P$ so $M_{\text{vessel}} \propto M_{\text{gas}}$

  $M_{\text{vessel}}/M_{\text{gas}} \approx 0.36$ for Ti alloy sphere at elastic limit / Argon.

NIM A 701 (2013) 225

Gas composition, quencher





F. Sauli CERN-EP-83-103, 1983

D. C. Arogancia et al., NIM A 602, 403 (2009)

- Gas detectors need limitation of breakdown from UV photoelectric effect on the cathode: add poly($n > 2$)molecular "quencher" gas (alcanes, CO$_2$ ..)
- Mitigates diffusion $\sigma = \sigma_x/\sqrt{z}$, $\sigma_x = 200\,\mu\mathrm{m}/\sqrt{\mathrm{cm}}$, ($\sigma \approx 0.6\,\mathrm{mm}$ after $z = 9\,\mathrm{cm}$ drift)
- Diffusion is needed to minimize the TPC spatial resolution ! $C_D \equiv \sigma_x$, w strip pitch.

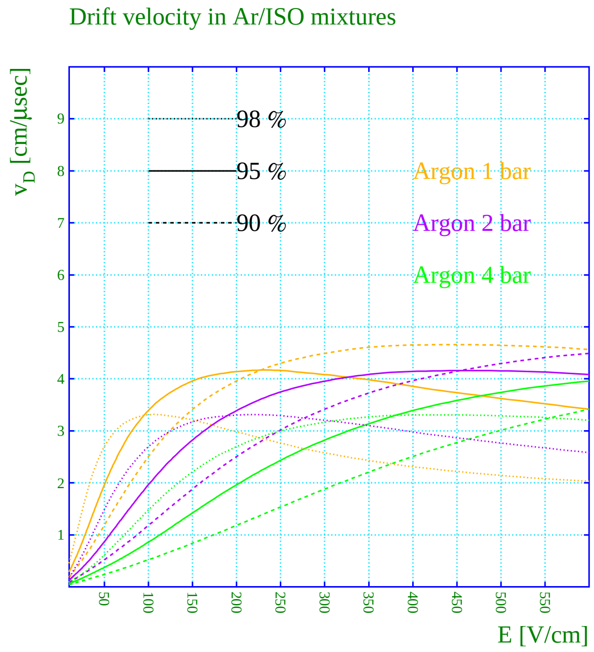
Pressure, Quencher fraction, e^- transport properties

- Argon-iso-butane mixture with $(2, 5, 10)\%$ iso-butane and pressure $1, 2, 4\,\text{bar}$

Drift velocity

v_{drift}

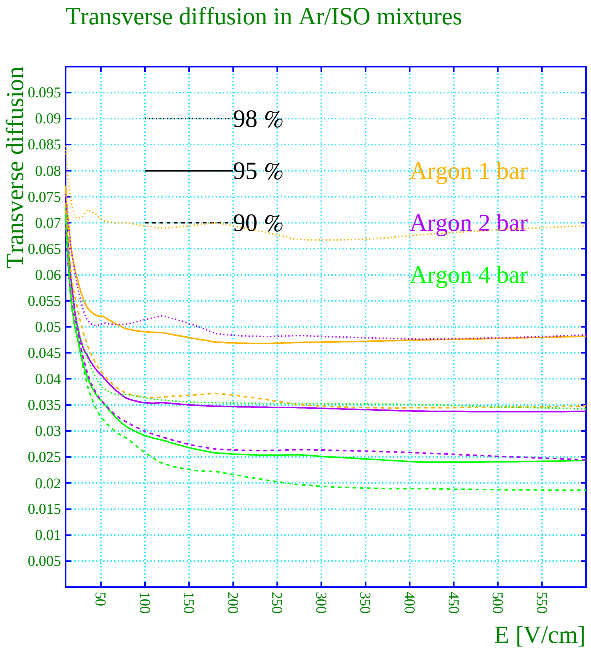
$\text{cm}/\mu\text{s}$



Transverse diffusion coefficient

$C_{D,T}$

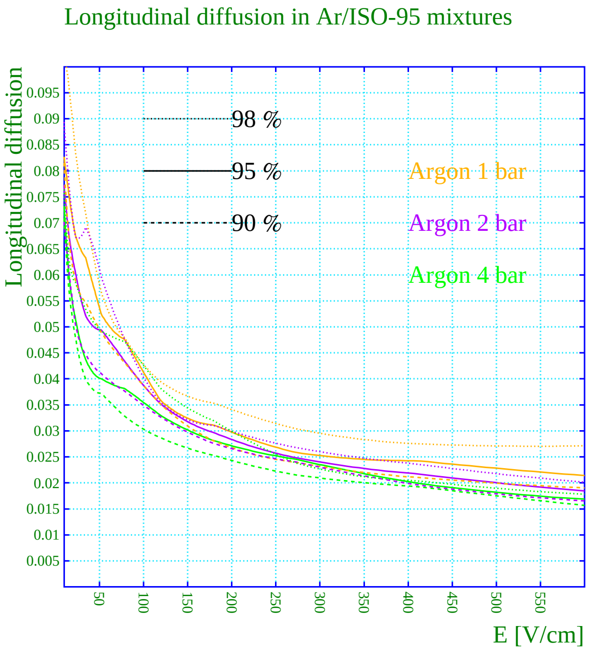
$\text{cm}/\sqrt{\text{cm}}$



Longitudinal diffusion coefficient

$C_{D,L}$

$\text{cm}/\sqrt{\text{cm}}$



- v_{drift} max value does not depend on P; E value for v_{drift} maximum is $\propto P_{\text{C4H10}}$.
- $C_{D,T} \propto 1/\sqrt{P_{\text{C4H10}}}$, Transverse diffusion coefficient determined by quencher partial pressure
- $C_{D,L}$ fn of E, Longitudinal diffusion coefficient determined by drift field

garfield.web.cern.ch/

Temperature variation, Temperature range

- TPC parameters depend on gas density ρ, not on (pressure P, temperature T)
- Thermal vessel volume variations corrected by small (drift, amplification) voltages.

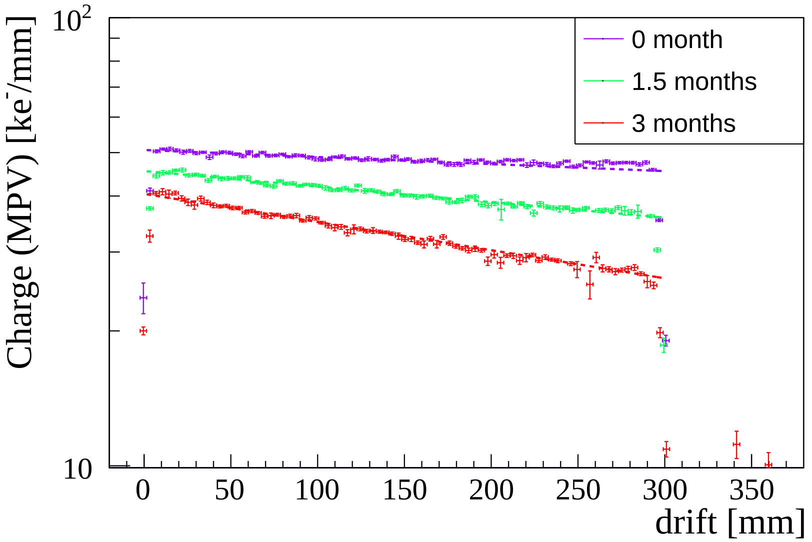
  (We operated the same set-up in the range 1-4 bar by simple voltage ajustments)
- Maximal temperature ?
  - check your electronics !
  - plastic scintillator dome will soften at $\approx 80^\circ$
- Minimal temperature ?
  - avoid quencher partial liquefaction

gas	Ar	Xe	CH_4	C_2H_6	iso C_4H_{10}
boiling point at 1.013 bar ($^\circ$C)	-185.8	-108.1	-161.5	-89	-11.7

  - alcanes have similar quencher properties.

Gas purity on the long term

- HARPO pressure vessel extremely dirty: scintillator, WLS, PVC box, PCB, epoxy, O-rings ..
- We have observed the evolution of the gaz quality in sealed mode [Fev. - Jun.] 2015 (2.1 bar).

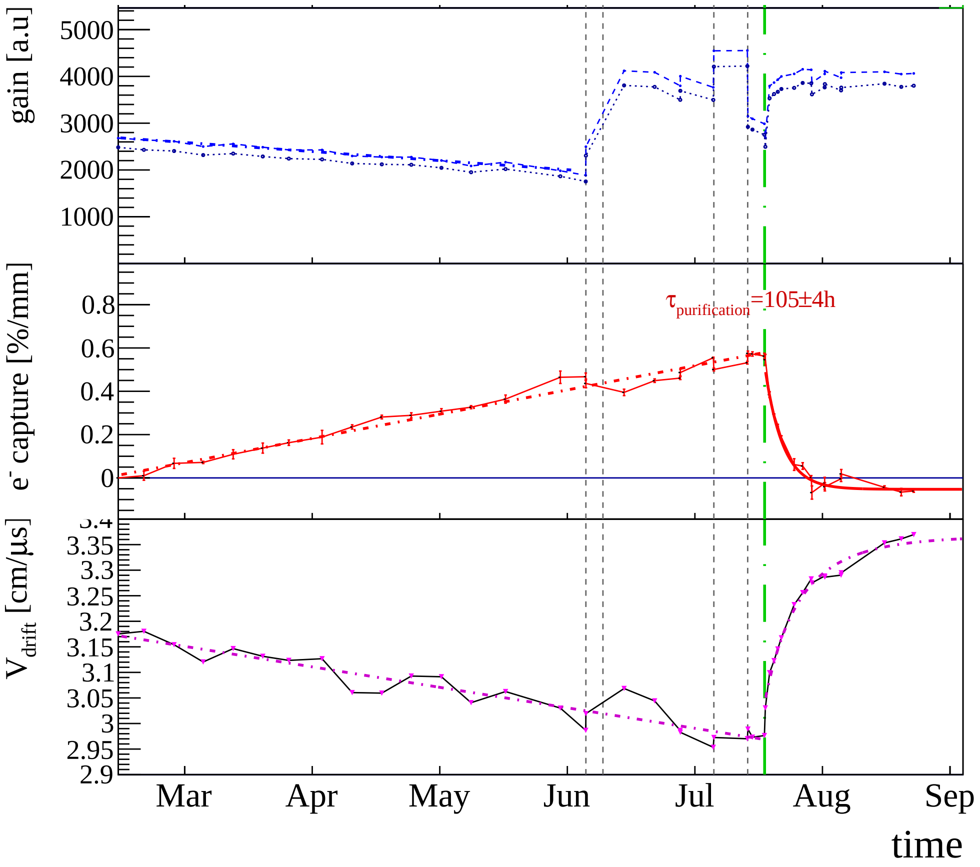


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- O_2 fraction peaked at 180 ppm on Jul. 08. $O_2/(O_2 + N_2) = 0.225$, compatible with air.
- Then we switched an oxisorb recirculation to operation. O_2 fraction disappeared (< 20 ppm)

M. Frotin et al., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences

Gas purity on the long term: results



vertical lines: amplification voltage ajustments.

Time evolution of the amplification gain, of the electron capture and of the drift velocity as measured with cosmic-rays through [Fev. - Sept.] 2015.

- Interpreted as air leak or air outgassing, with complete gas cleaning upon purification
- Good prospects to run a TPC for years with a simple oxisorb cleaning

M. Frotin et al., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences

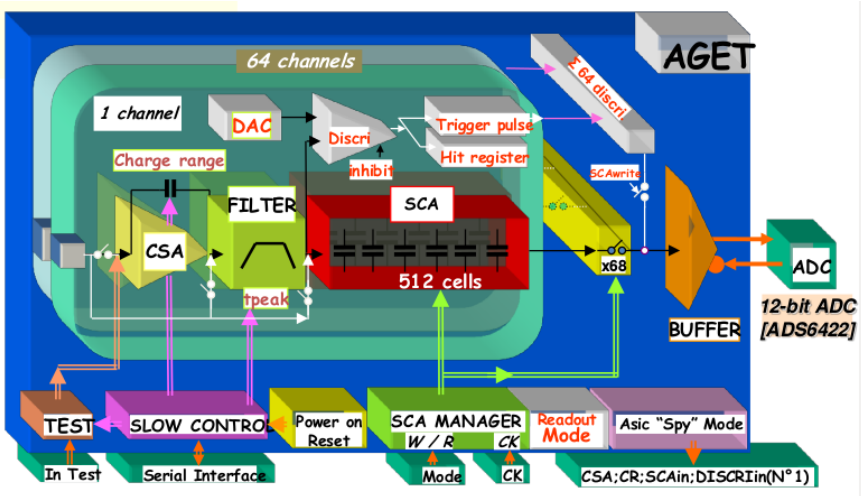
ST3G: Self Triggered TPC as Gamma-ray Telescope

- proton flux $20\,\mathrm{kHz/m^2}$
- drift duration $10\,\mu\mathrm{s}$
- digitization duration $1.6\,\mathrm{ms}$
- must use information as it arrives after drift in real time !

  $\Rightarrow$ change digitizing chip AFTER → AGET

- ST3G trigger mechanism.
  - goal is to decipher one single through track (proton) from a pair that originates inside the gas volume ($\gamma \rightarrow e^+e^-$)
  - remember that entering tracks look like exiting tracks very much !

AGET: ASIC for Generic Electronics for TPC



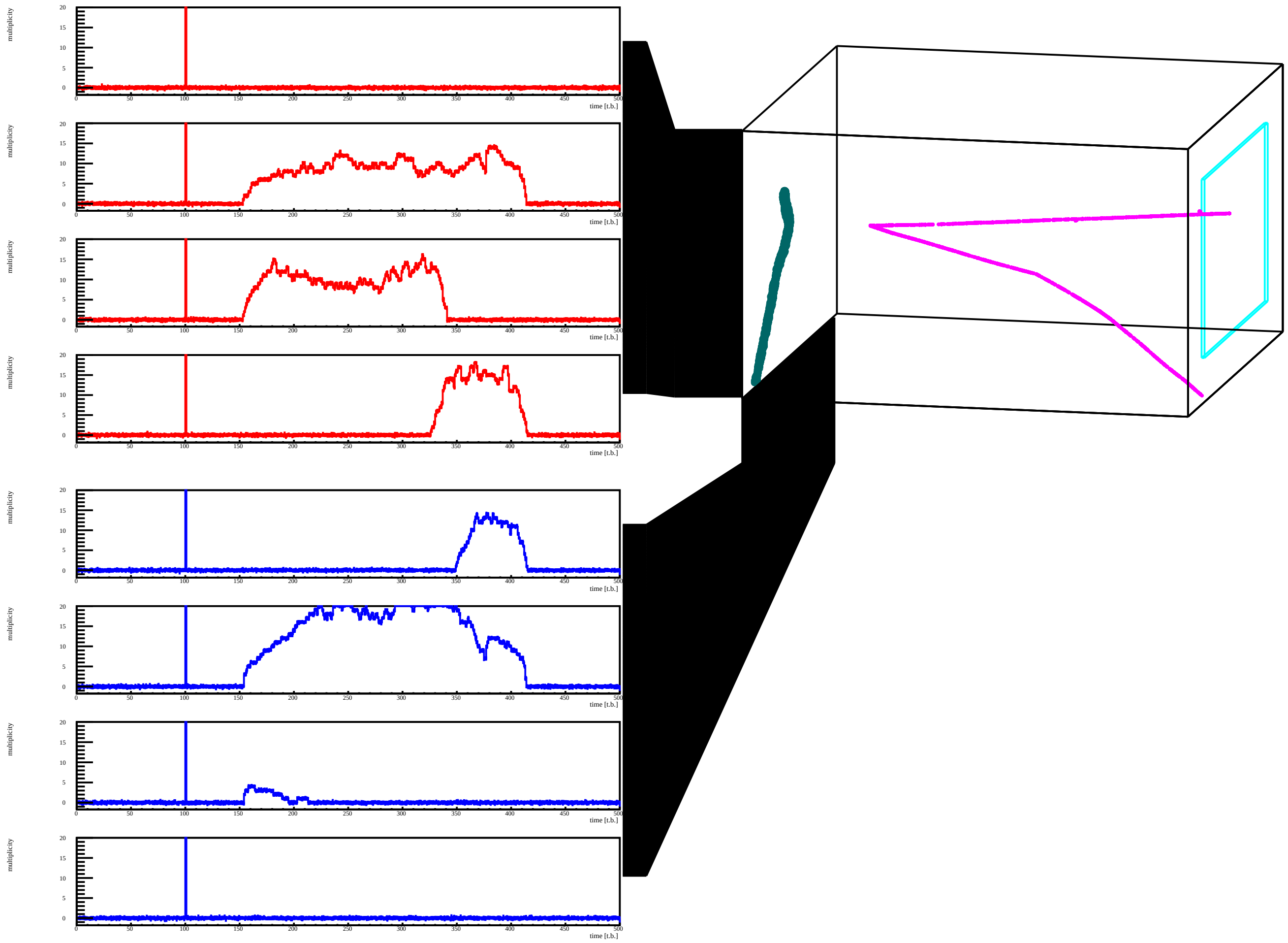
- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to 1 μs
- 512 analog memory cells / channel
- Fsampling: 1 MHz to 100 MHz; Fread: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discri Outputs
- Readout:
  - Address of the hit channel(s)
  - 3 readout modes: All, hit or specific channels
  - Predefined number of analog cells / trigger (1 to 512)

S. Anvar *et al.*, NSS/MIC, 2011 IEEE 745 - 749.

- AGET → radhard ASTRE: "Asic with SCA & Trigger for detector Readout Electronics":

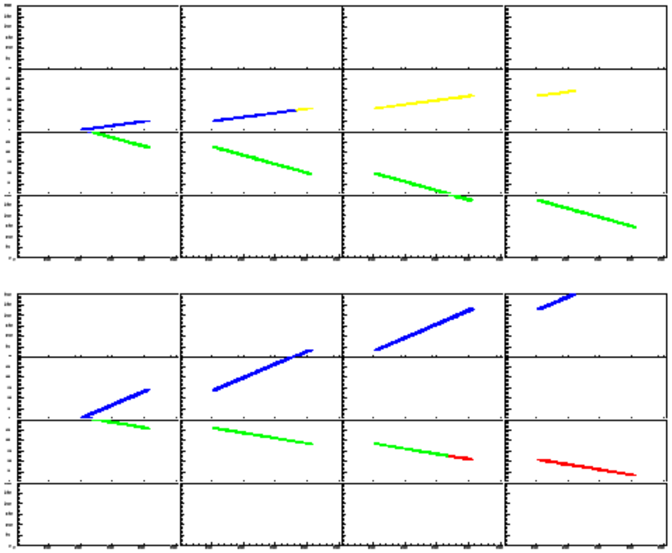
  presently being designed; submission to foundry hopefully end 2016.

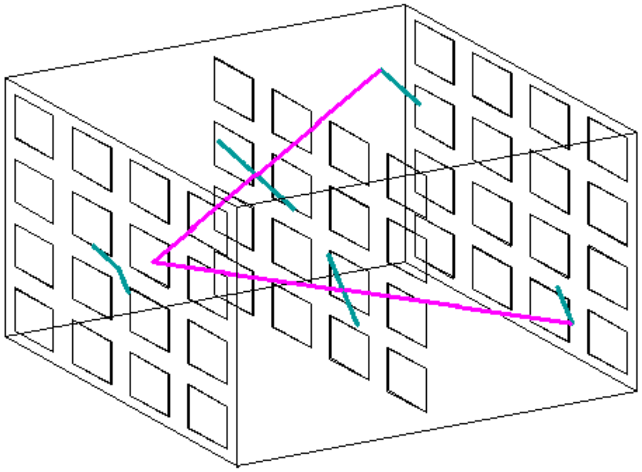
ST3G trigger mechanism: signal from a single bloc



Simulation of the multiplicity signal for a γ-ray conversion in the present HARPO-prototype.

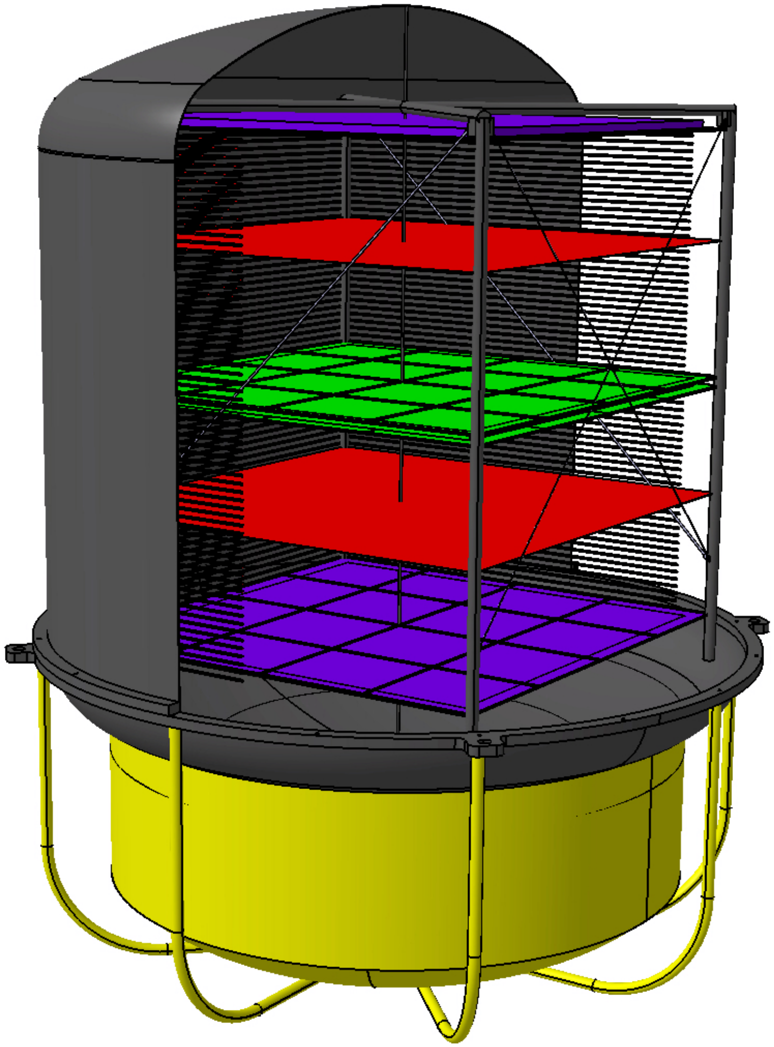
ST3G trigger: multi-bloc scheme





- $4 \times 4 \times 4 = 64$, $(30\text{cm})^3$, modules
- Sensitive volume $(1.2\text{m})^3$
- L0 trigger: coincidence of several modules (≥ 2) that see signal at the same time.
- Complete trigger mechanism to be designed and optimized
- geant4 simulation well advanced.

ST3G scheme validation : prototype for a balloon test



Conclusion

- Gas TPC is THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ astronomy and polarimetry
- Robust detector used in HEP since the 1980's from sub-cm^3 to multi-m^3
- From the lowest (eg. T2K) to the highest (eg. ALICE) rate, radiation, track multiplicity
- Use of a "Fast" gas ($v_{\text{drift}} \gg 1\,\mathrm{cm}/\mu\mathrm{s}$) mitigates background pile-up
- 4π acceptance, $\approx$ isotropic performances (x, y, z), $< 30\,\mathrm{ns}$ event time resolution
- Low number of electronics modules by use of projections – strips.
    - induced track matching issue easily solved.
- Ability to cope with intense GRB – dedicated buffer needed
- Key issue is self-triggering: ST3G scheme under study
    - radhard and upgraded version of digitizing chip under design.
    - balloon flight prototype under study.
- Data taken:
    - with a $(30\mathrm{cm})^3$ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
    - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam

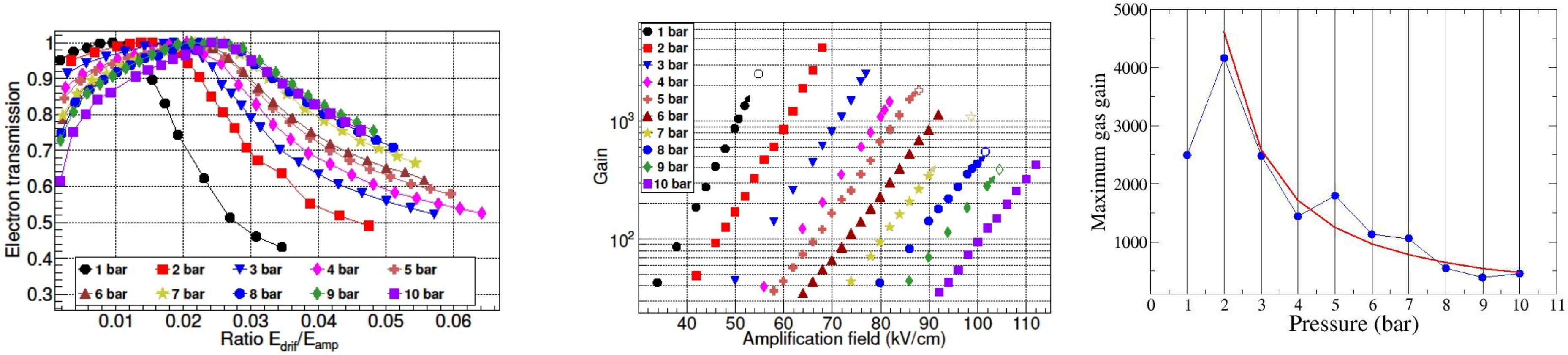
: analysis in progres.

Je vous remercie de votre attention distinguée !

Back-up Slides

Which Pressure ?

- **Science**. Rising the pressure:
    - degrades the angular resolution and (mildly) point like source sensitivity
    - Increases the effective area improves the precision on the polarization
- Maximum **micropattern gas amplification gain** (micromegas, GEM) known to decrease with pressure .. but $\mathrm{d}E/\mathrm{d}x$ increases ..



D. C. Herrera, *et al.*, "Micromegas-TPC operation at high pressure in Xenon-trimethylamine mixtures," J. Phys. Conf. Ser. 460, 012012 (2013).

micropattern gas amplification above 10 bar a concern, unless very small gap devices can be produced.

- **Vessel Mass** $\propto$ gas mass to 1rst order.
    - For a given mission: which limit will we touch first (volume, mass) ?

In this talks, examples given at 1, 5, 10 bar. Data taken mostly at 2.1 bar, + a 1-4 bar scan.

Search for Axions

- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2 γ through triangle anomaly.
- γ propagation through $B \Rightarrow$ Dichroism $\Rightarrow$ E dependant rotation of linear polarization $\Rightarrow$ linear polarization dilution.

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B\sqrt{\Delta\omega L_{GRB}}}$$

- Saturation over $L = 2\pi\omega/m_a^2 > L_{GRB}$ for

$$m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$$

and the limit $g_{a\gamma\gamma}$ reaches a ω-independent constant.

A. Rubbia and A. S. Sakharov, Astropart. Phys. 29, 20 (2008)