Advances in GEM-based cryogenic avalanche detectors

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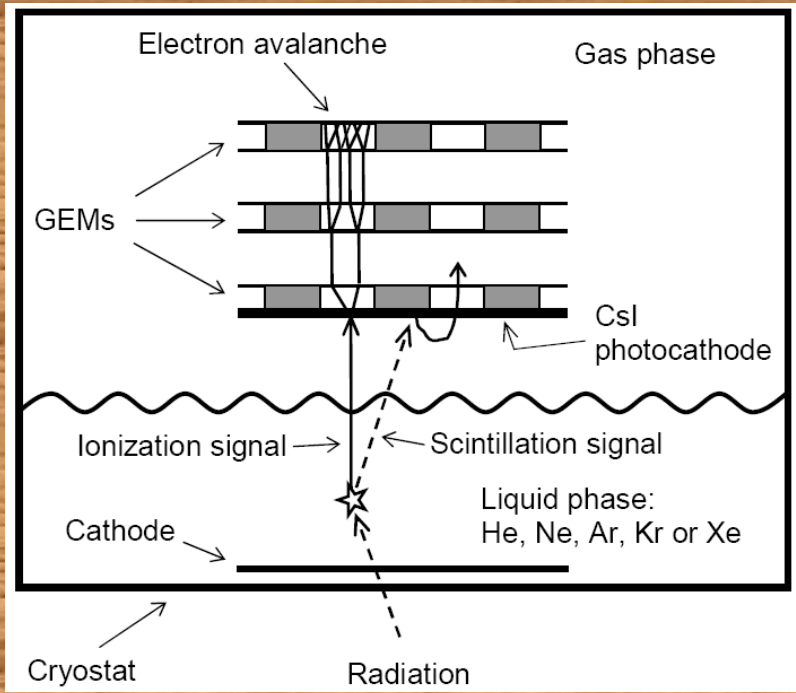
Outline

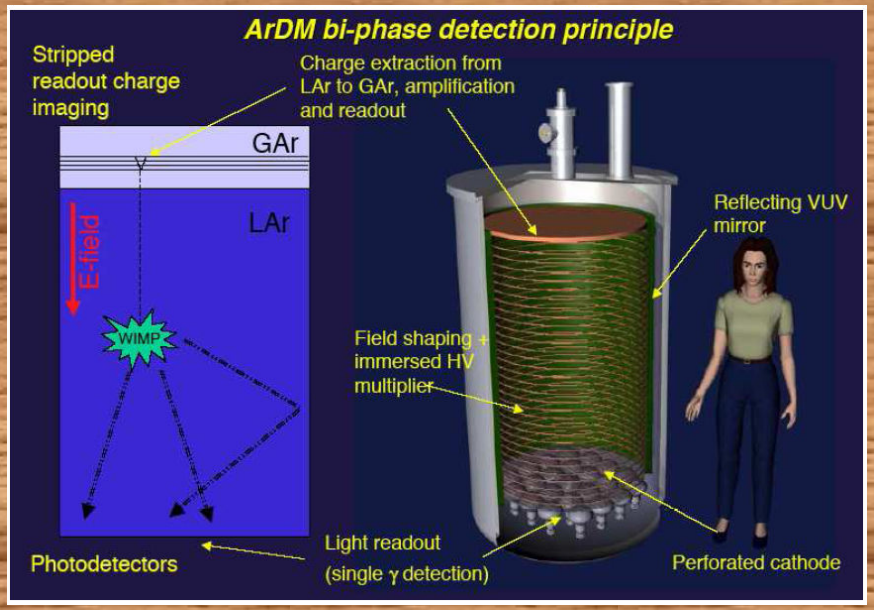
- Conception and motivation
- Review of recent results
- SiPM performance at cryogenic T
- THGEM+SiPM based two-phase Ar detector
- THGEM performance in gaseous Xe at cryogenic T
- Summary

Cryogenic two-phase avalanche detectors: the concept



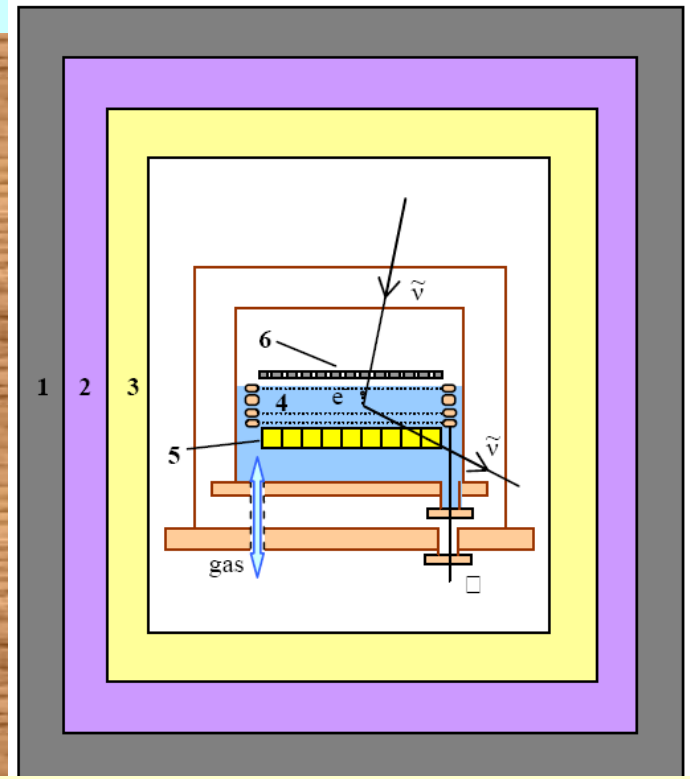
The concept was introduced and realized in 2003 *[Buzulutskov et al. IEEE Trans. Nucl. Sci. 50(2003)2491]* **: traditional two-phase emission detector + electron avalanching in the gas phase using GEM multiplier**

Motivation: dark matter search and coherent neutrino-nucleus scattering experiments



ArDM: Two-phase Ar detector using THGEM for dark matter search *[A.Rubbia et al., J. Phys. Conf. Ser. 39(2006)129]*

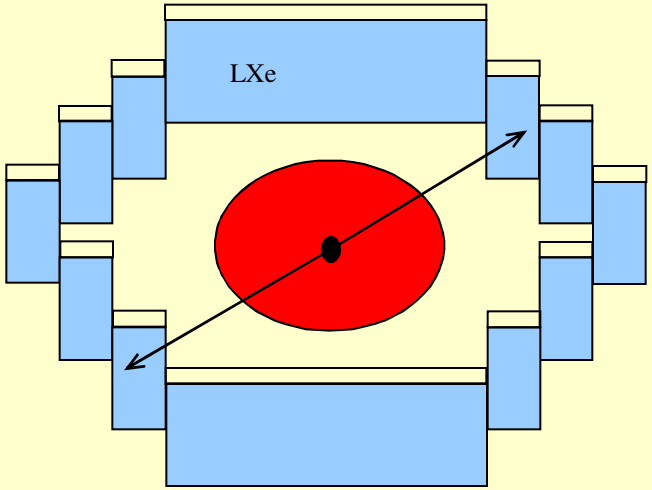
Need for detector recording both ionization and scintillation signals with a threshold of ≤ 10 keV (200 electrons)



Two-phase Ar and Xe detectors using GEM/THGEM for coherent neutrino-nucleus scattering *[ITEP & Budker INP: Akimov et al. JINST 4 (2009) P06010]*

Need for noiseless (<0.1 event/hour/kg) detector with a threshold of 1 e (single-electron counting)

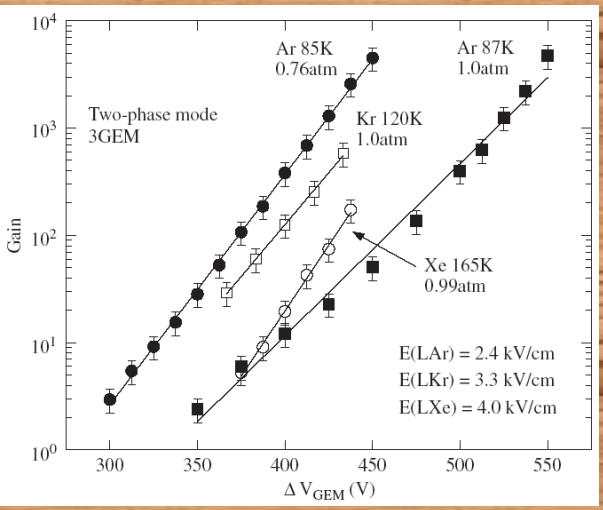
Motivation: PET applications



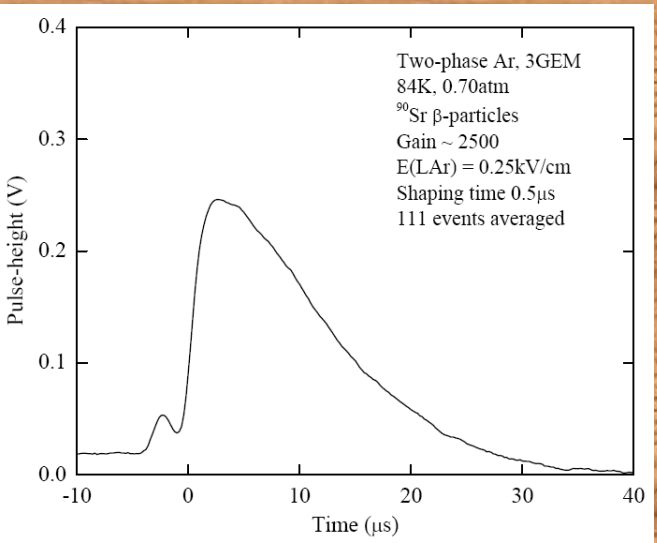
GEM-based two-phase Xe avalanche detector for PET: 3D liquid TPC recording 511 keV γ-rays, using GEM/THGEM. This will help to solve parallax problem
and obtain superior (~1mm) spatial resolution.
[Budker INP: CRDF grant RP1-2550 (2003)]

Need for Xe detector with 3D readout recording both ionization and scintillation signals with a threshold of > 100 keV (2000 electrons)

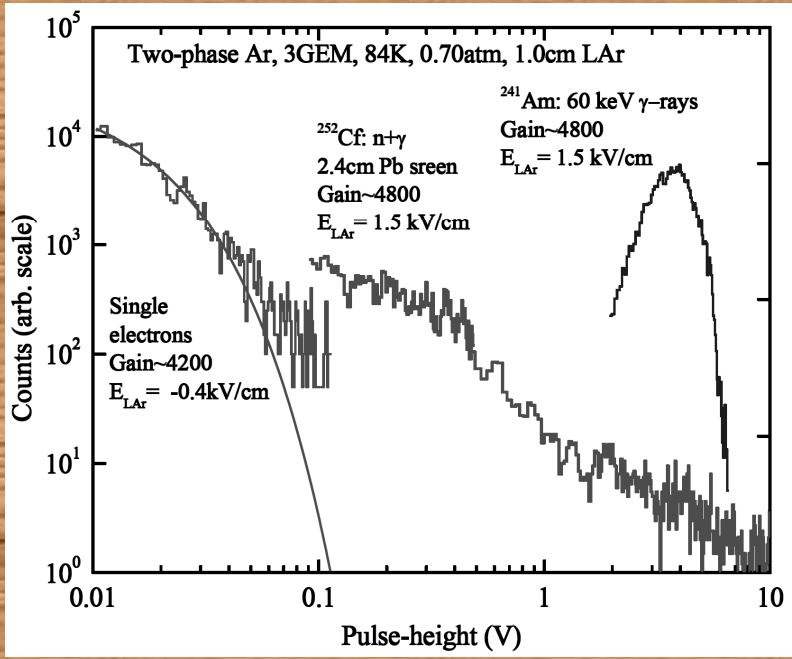
GEM-based two-phase avalanche detectors: summary of previous results



Stable operation in two-phase Ar with gains reaching 10^4 and in two-phase Kr and Xe with gains reaching 10^3 and 200 respectively.



Simultaneous detection of primary scintillation and ionization signals using CsI PC on top of 1st GEM



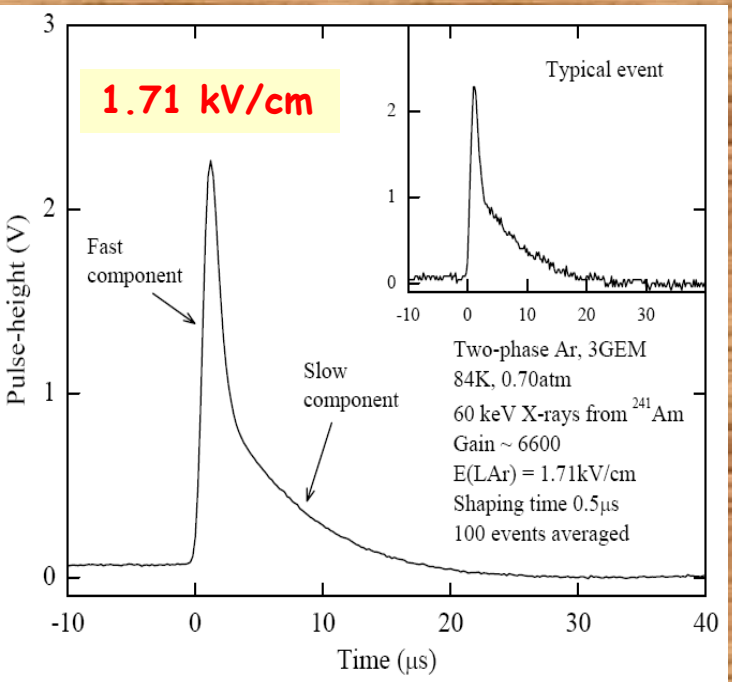
Wide dynamical range and reasonable energy resolution: from single electrons to ~100 keV.

Bondar et al NIM A 556(2006)273, 574(2007)493, 581(2007)241, 598(2009)121

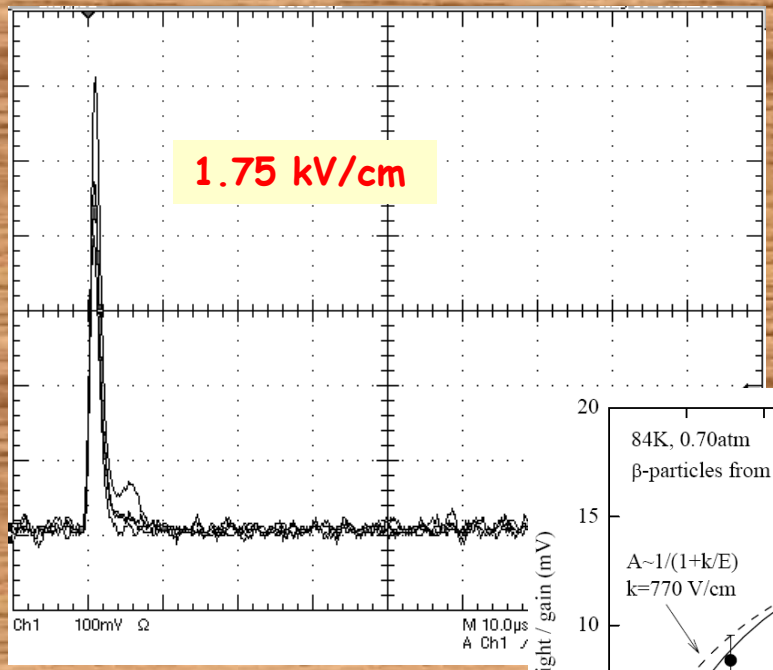
Recent results: Electron emission properties in two-phase systems

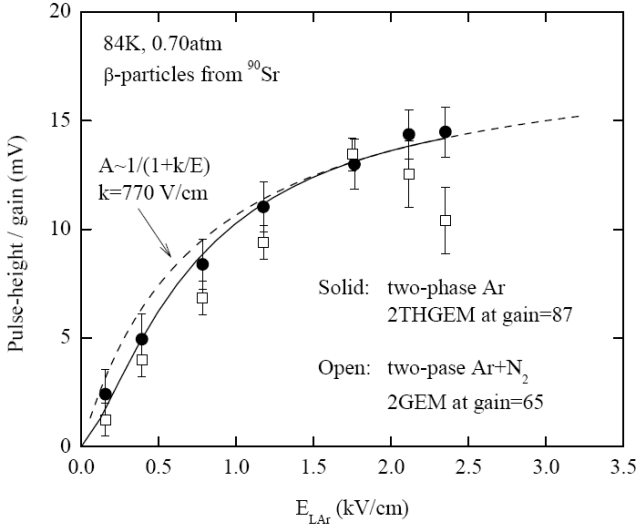
- Direct observation of both fast and slow electron emission components in Ar using fast GEM multiplier.
- Disappearance of slow component in Ar+N_2 and its conversion to fast component.

Two-phase Ar at gain 6600



Two-phase Ar+N_2 (0.5% in liquid and 1.5% in gas) at gain 200

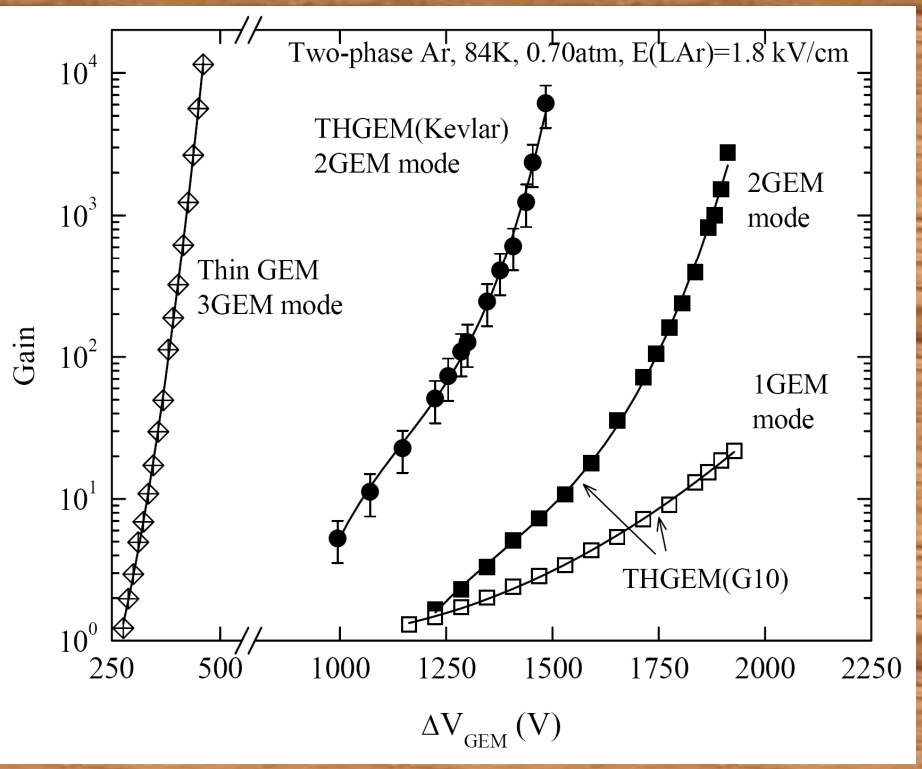


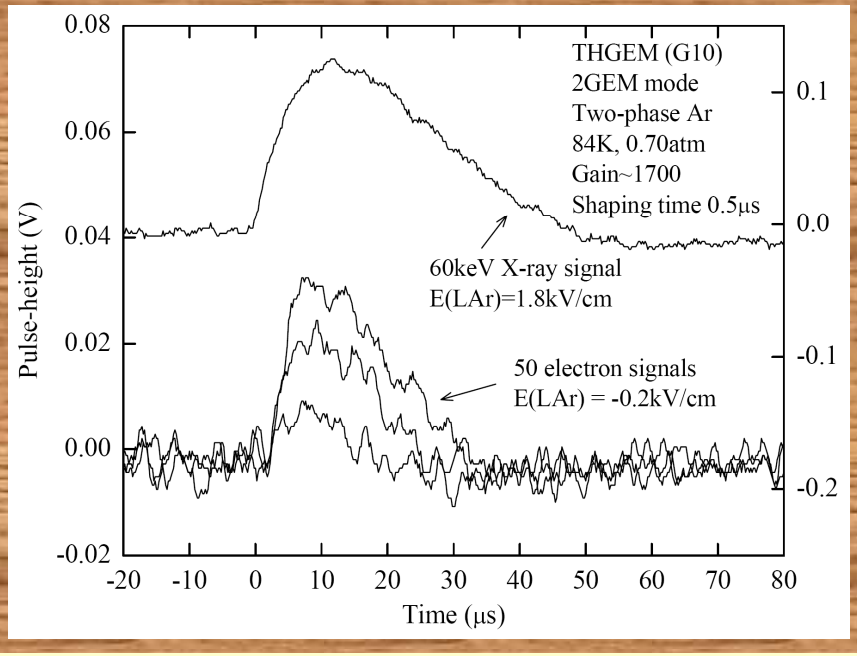


Electron emission efficiency in two-phase Ar+N_2 is close to that of Ar

Bondar et al JINST 4 (2009) P09013

Recent results: thick-GEM (THGEM)-based two-phase Ar avalanche detector





Stable operation of double-THGEM in two-phase Ar at gains reaching 3×10^3

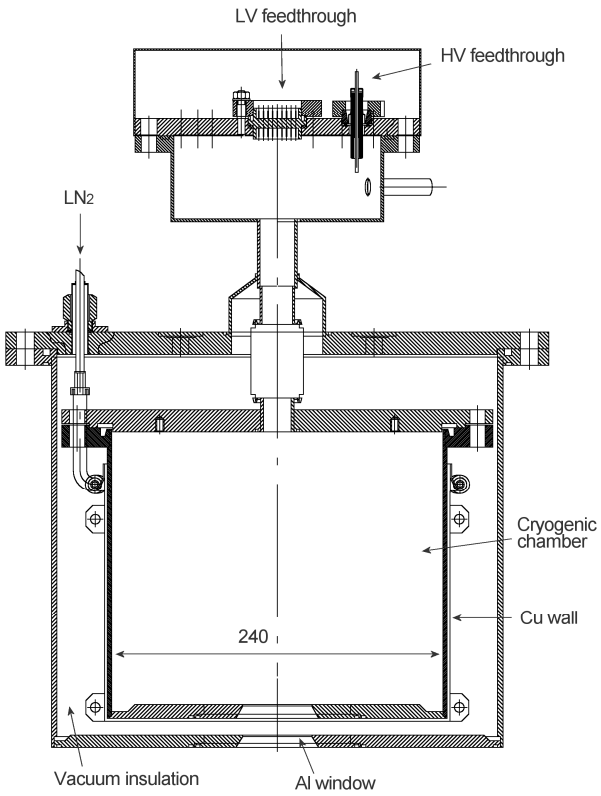
Typical signals of double-THGEM in two-phase Ar:

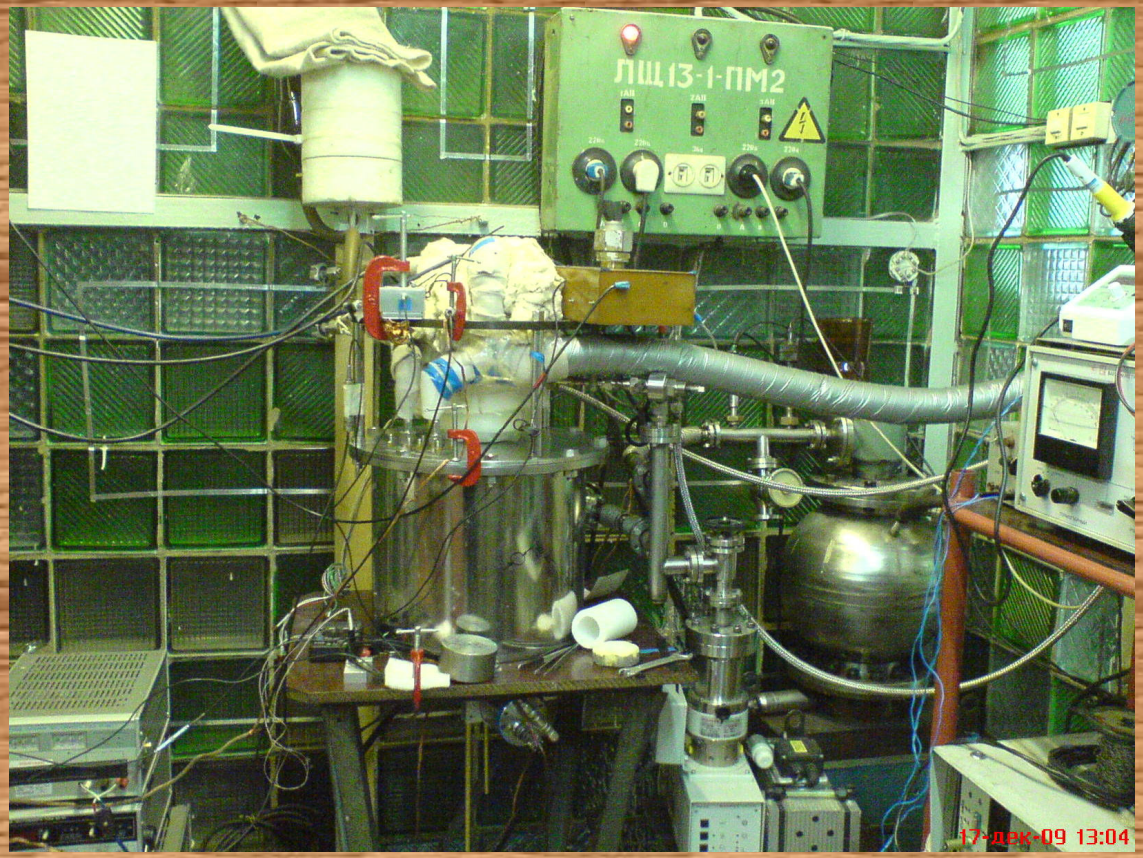
- induced by 1000 initial e (prior to multiplication) in emission mode
- induced by 50 initial e in non-emission mode

Bondar et al JINST 3 (2008) P07001

Experimental setup: 2nd generation

9 l cryogenic chamber
0.5 l of liquid Ar or Xe; 1 cm thick liquid layer





We present the following results performed with this setup:
1. SiPM performance at cryogenic T
2. Two-phase Ar avalanche detector using THGEM+SiPM
3. Cryogenic gaseous Xe avalanche detector using THGEM

Two-phase avalanche detector using Silicon PhotoMultiplier (SiPM) optical readout from THGEM multiplier: motivation

- Need for noiseless self-triggered cryogenic two-phase detectors having single-electron sensitivity, in particular for coherent neutrino-nucleus scattering experiments.

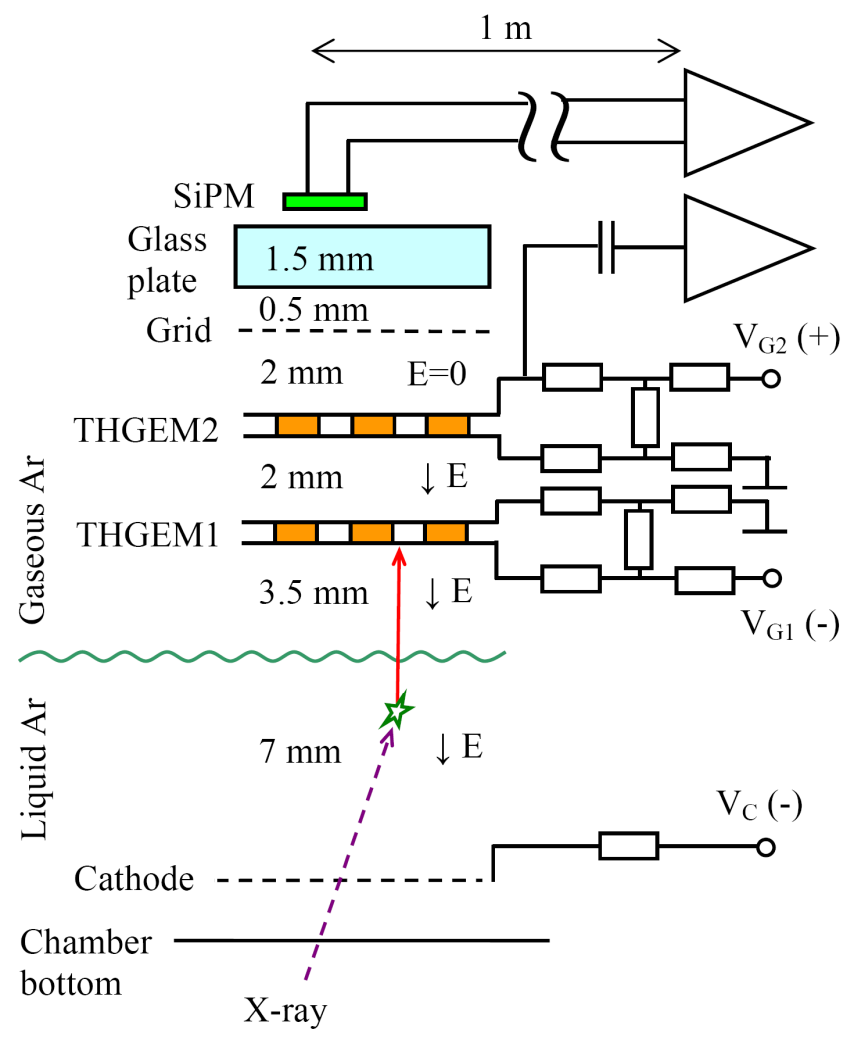
- Gains reached in GEM/THGEM-based two-phase avalanche detectors, $<10^4$, might not be enough for operation in single electron counting mode at self-triggering. Accordingly, high SiPM gain would substantially increase the overall gain providing effective single-electron counting, at reduced THGEM gain and correspondingly at reduced noises.

- Multi-channel optical readout is preferable in terms of noise suppression, compared to charge readout, since it would enable to obtain coincidences between channels.

- SiPM performance at cryogenic T is superior to that of room T.

Earlier studies in Sheffield *[Lightfoot et al. JINST 4 (2009) P04002]*:
SiPM readout from THGEM in two-phase Ar using TPB wavelength shifter provided 200 pe from SiPM at THGEM gain=100 for 6 keV X-rays.

Experimental setup: THGEM+SiPM based two-phase Ar detector

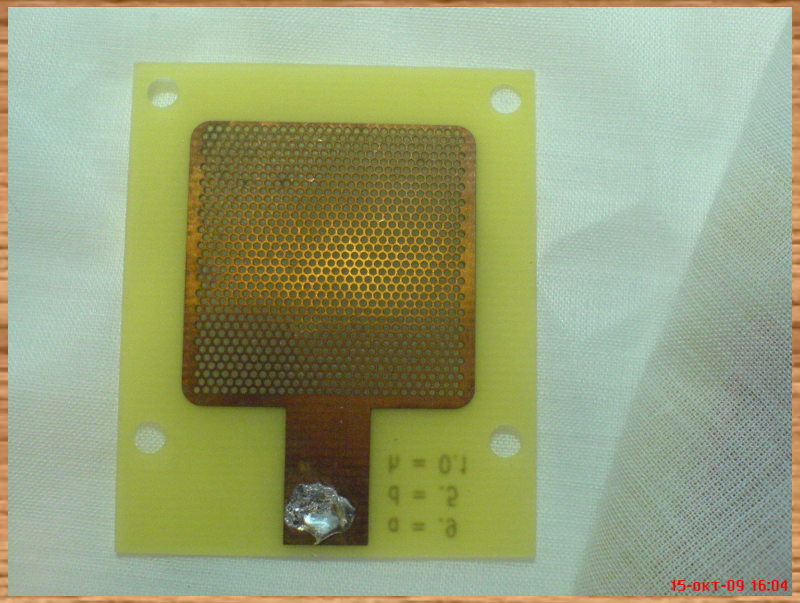


THGEM readout: charge-sensitive preamplifier + shaping amplifier at shaping time 0.5 or 10 μs with overall sensitivity 10 V/pC.

SiPM readout: fast amplifier CPTA with 3 ns pulse rise (300 MHz bandwidth) and amplification factor 30.

Both amplifiers were placed outside the chamber and connected via 1 m long wires: a challenge to minimize electronic noise (pick-ups and self-generation).

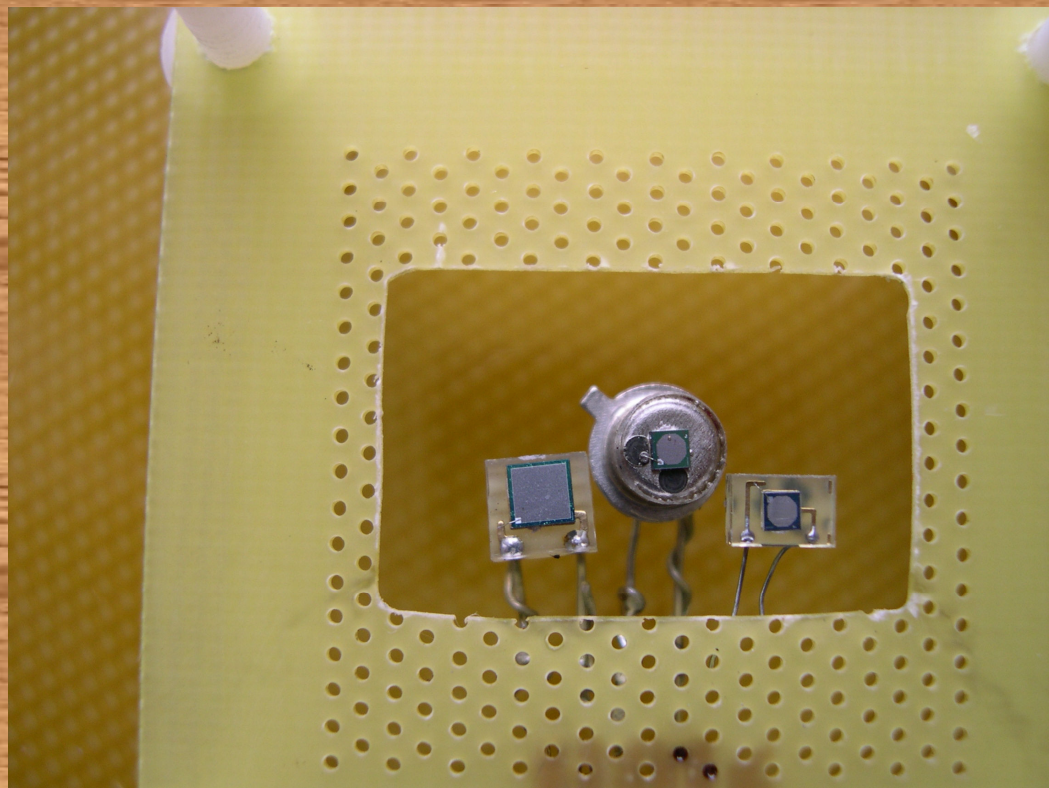
Experimental setup: THGEM+SiPM in two-phase Ar



SiPMs optimized for green-red spectrum range.
From left to right:
- CPTA 149-35, 4.41 mm^2, 1764 pixels (4 mm out of frame center);
- CPTA 143-22, 0.95 mm^2, 556 pixels;
- Pulsar, 1 mm^2.

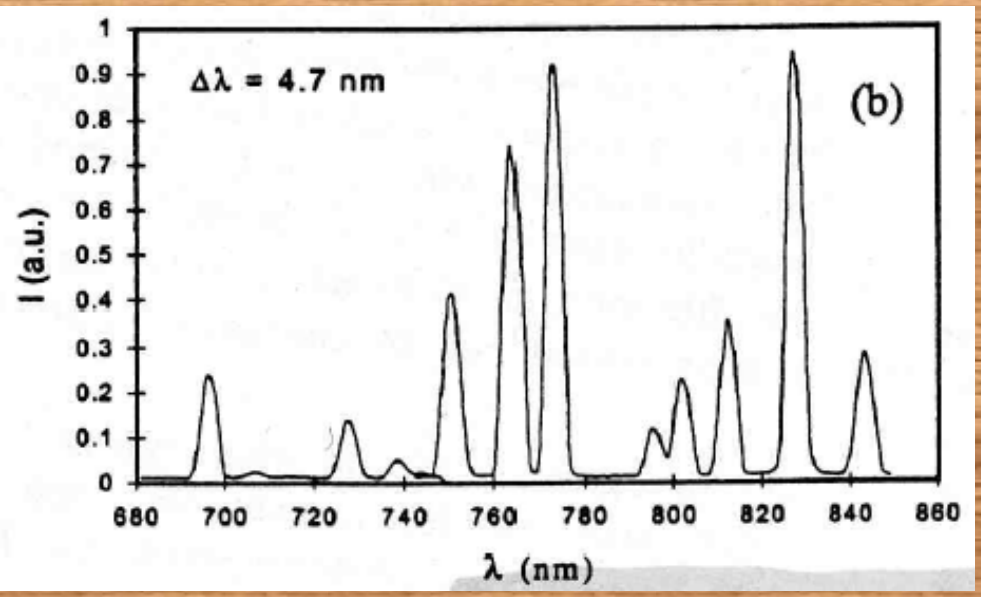
SiPMs were not coated with WLS.

THGEM (from Weizmann Inst.):
G10 plate
thickness 0.4 mm
hole pitch 0.9 mm
hole diameter 0.5 mm
hole rim 0.1 mm
25*25 mm^2 active area

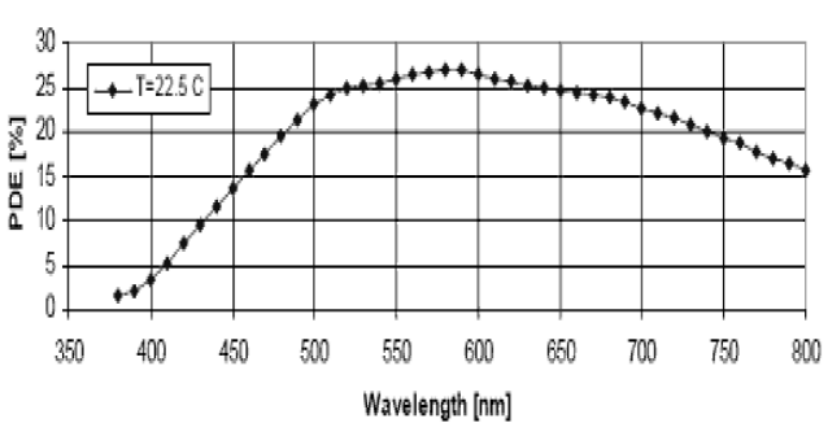


Gas Ar emission spectrum and SiPM QE in near infrared

It was believed that Ar scintillations take place mostly in the VUV region, peaked at 127 nm. This results in necessity to use wavelength shifter (WLS) coatings. On the other hand, in 2000 it was shown by Coimbra group *[Fraga et al.]* that Ar has effective avalanche scintillations in NIR region, at 750-850 nm. In this region SiPM can have rather high quantum efficiency, reaching 20%, providing direct and effective detection of scintillations without using WLS.

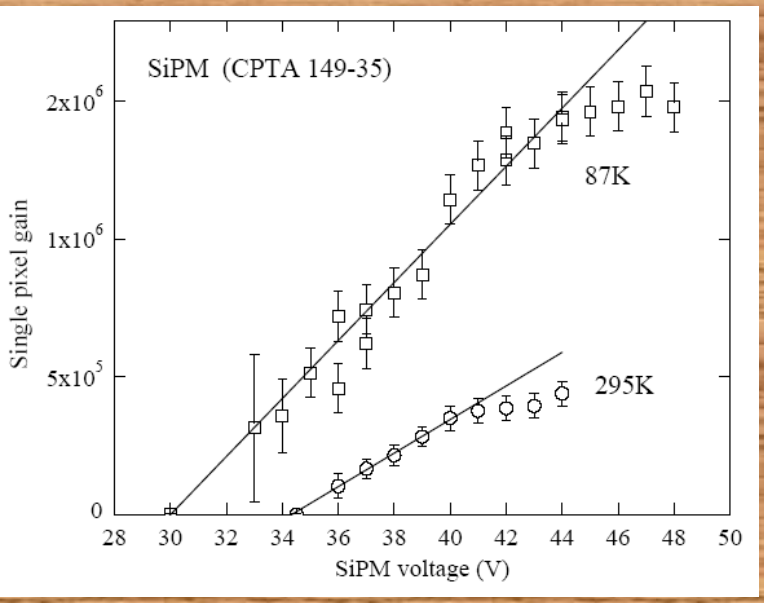


NIR emission spectrum of pure Ar (due to Ar I atomic lines) from avalanche scintillations at 750 Torr, gain~30, yield~1ph/e.
[M.M.Fraga et al. IEEE Trans.Nucl.Sci. 47(2000)933]

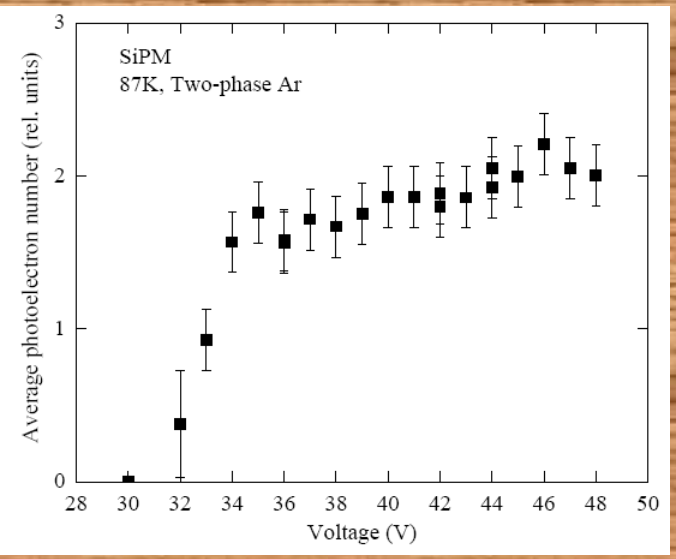


Quantum efficiency spectrum of 4.4 mm^2 SiPM (CPTA 149-35)
[http://www.photonique.ch/]

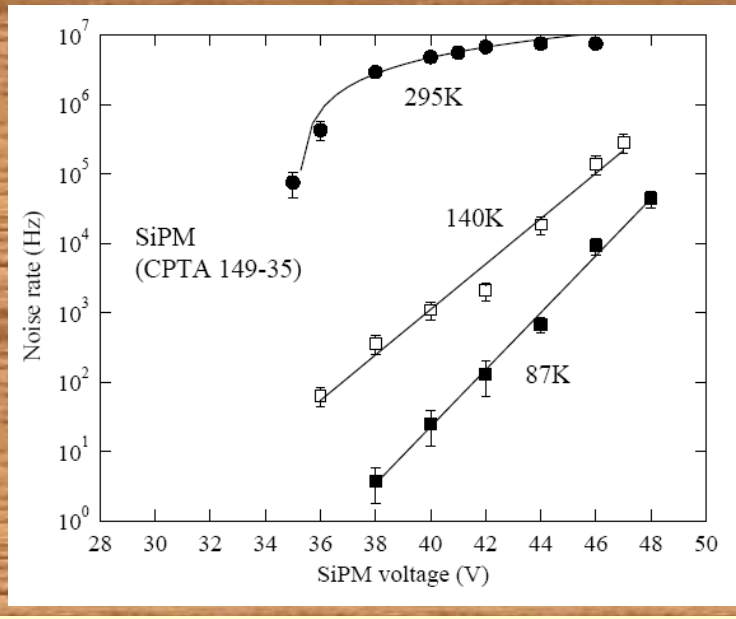
SiPM (4.4 mm^2) performance at cryogenic temperatures



Gain characteristics:
- At 87K breakdown voltage is 2.5V lower compared to 295K.
- Gain saturates at overvoltage of 14V at 87K and 6.5V at room T.
- The maximum gain at 87K approaches $2*10^6$, which is 4 times larger compared to room T.

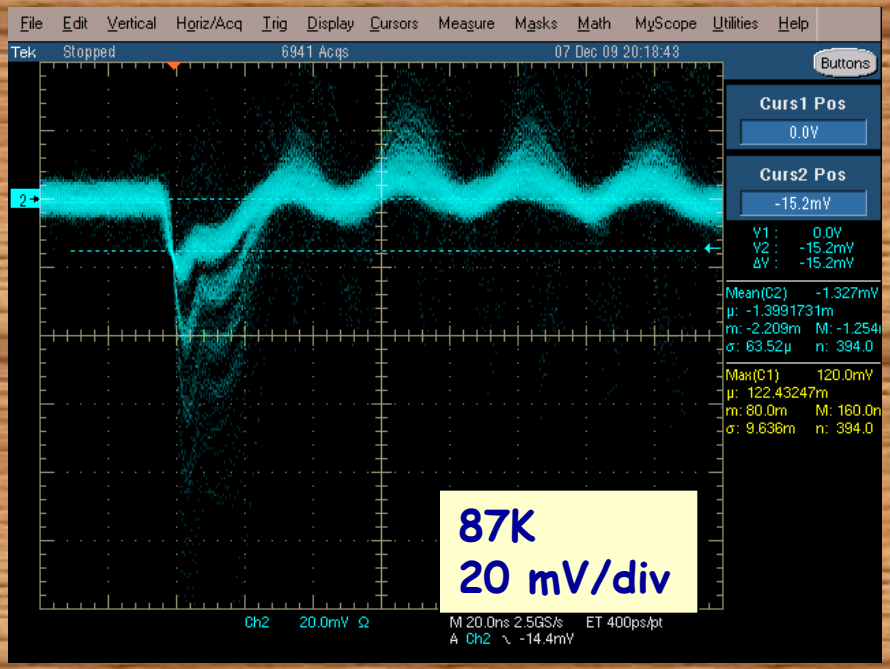


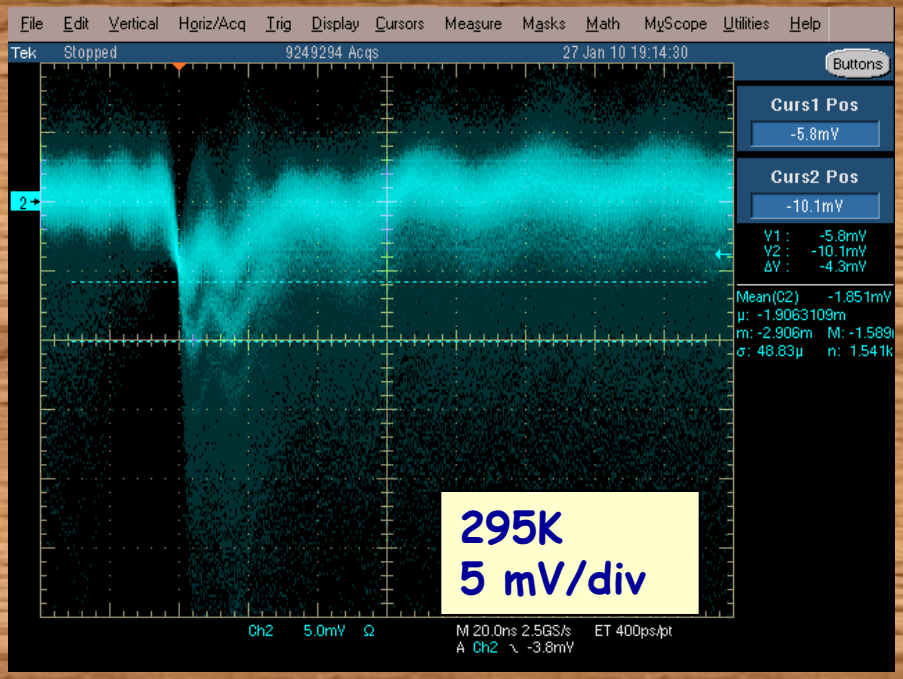
Photon detection efficiency at 87K goes onto plateau at overvoltage of 4V.



Noise rate:
- at cryogenic T is low (<1kHz) and increases exponentially with voltage;
- at room T is high (>1MHz) and increases linearly with voltage.

SiPM (4.4 mm^2) performance at cryogenic temperatures: cryogenic T vs. room T



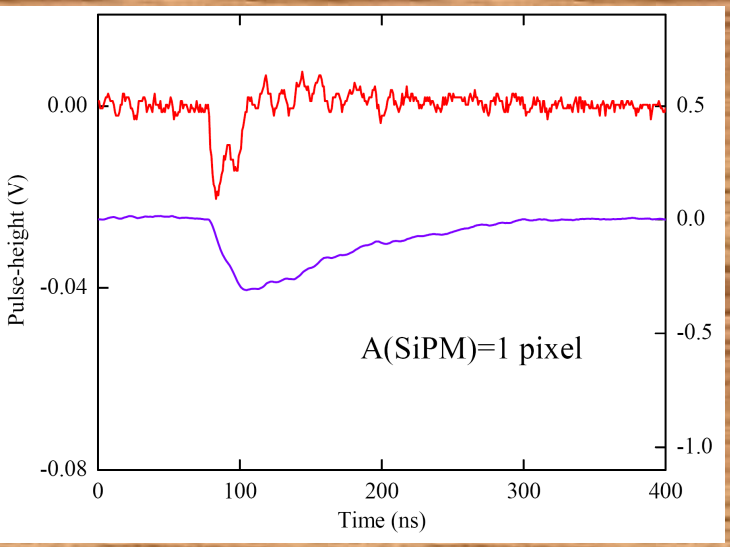


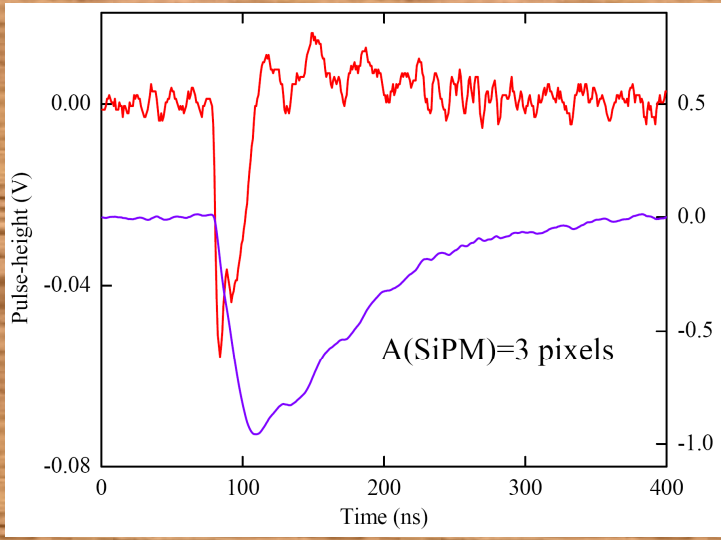
Noise signals: at 87K and room T, both in gain saturation mode, at 46 and 41 V respectively. Single pixel amplitude at 87K is ~4 times larger compared to room T.

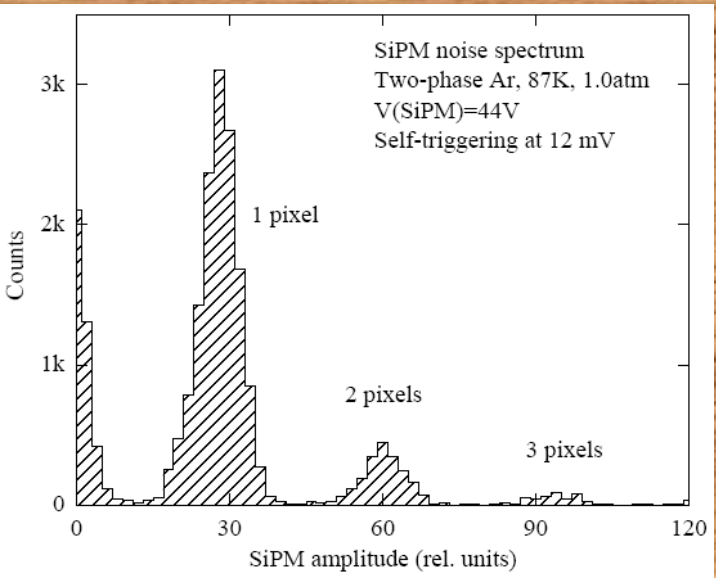
Conclusion:
SiPM performance at cryogenic T is superior to that of room T in terms of the maximum gain, noise rate and amplitude resolution.

SiPM (4.4 mm^2) performance at cryogenic temperatures: single-pixel characteristics at 87K

Examples of SiPM signals having 1-pixel and 3-pixel amplitude



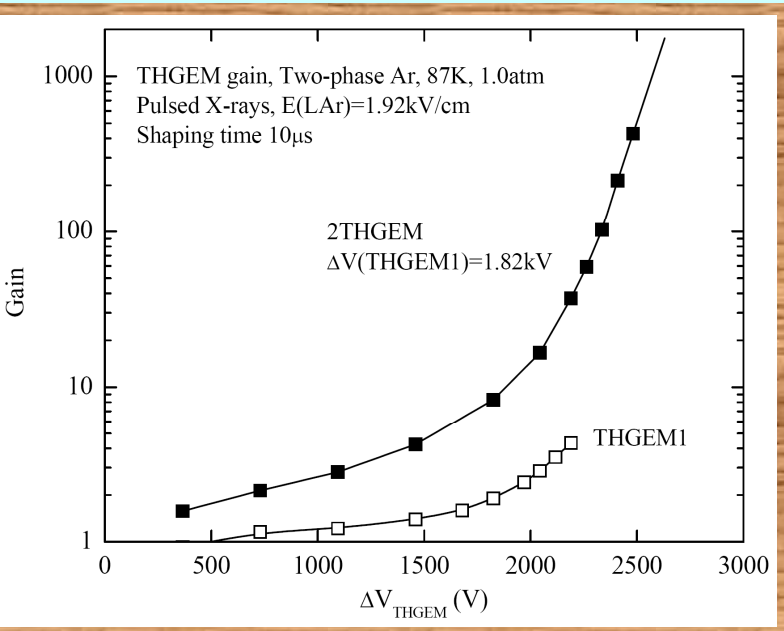


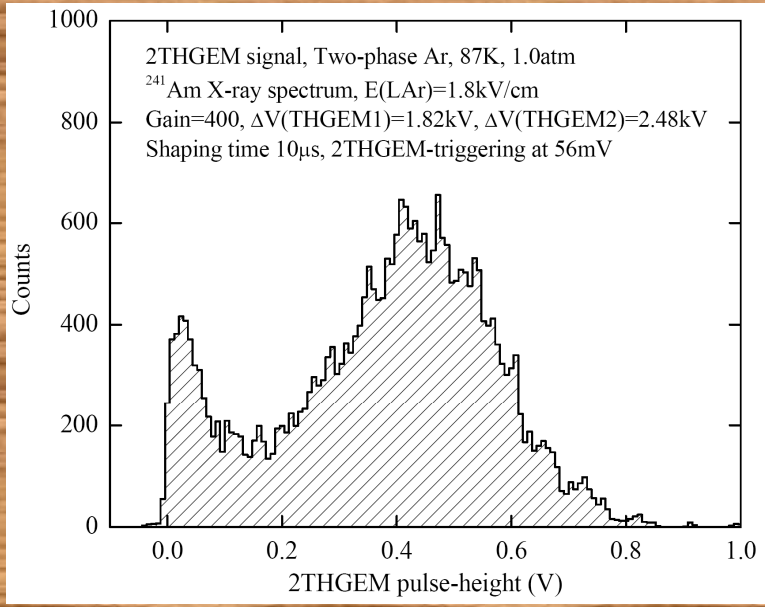


In conditions optimized to have the highest amplitude from SiPM at fast amplifier output, the signal is bipolar. This fast signal was transformed into unipolar signal (with a shaping time of ~100 ns); the area of the latter provided the integral amplitude of the SiPM signal. This technique permitted to calculate the total amplitude of long signals consisting of multiple short pulses separated in time.

SiPM noise amplitude spectrum at 87K. 1-pixel and 2-pixel amplitude signals are well separated from each other.

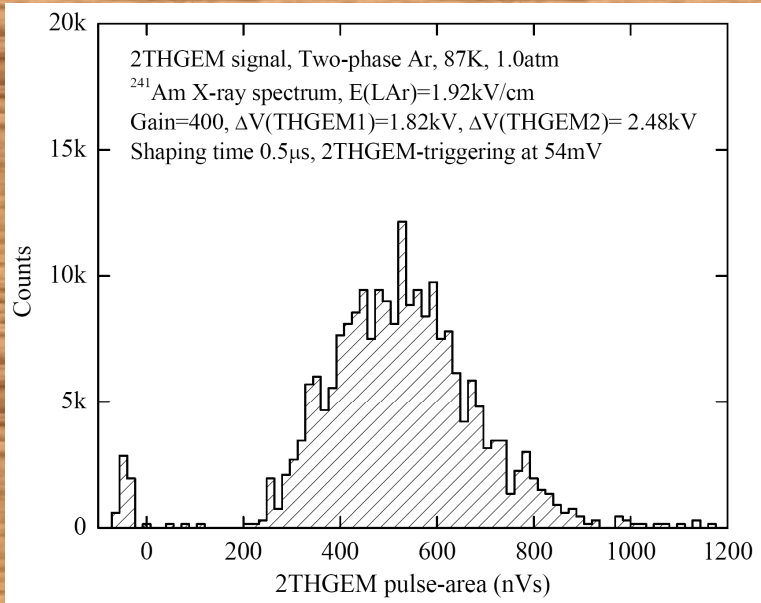
THGEM performance in two-phase Ar





High THGEM gains, reaching 1500, were obtained in two-phase Ar.

Asymmetrical mode of operation of double-THGEM multiplier was chosen, with fixed first THGEM voltage corresponding to gain of 2, the second THGEM gain being varied. This provides the effective collection of the ionization into the first THGEM holes, at the same time providing the SiPM to be sensitive to avalanche scintillations essentially from the second THGEM. The latter facilitates interpretation of the results.

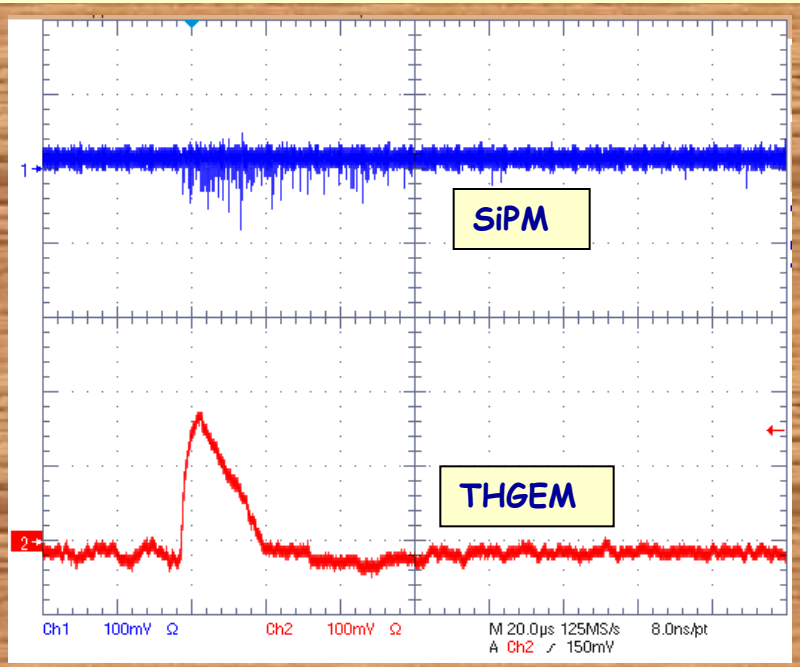


For X-rays from ^{241}Am, the energy deposited in the liquid typically corresponded to 60 keV peak, provided by high enough trigger threshold.

Avalanche-induced scintillations using THGEM+SiPM readout

We have observed avalanche-induced scintillations in Ar both in two-phase mode and at room T, using THGEMs and SiPMs, the latter not coated with WLS i.e. insensitive in VUV and UV.

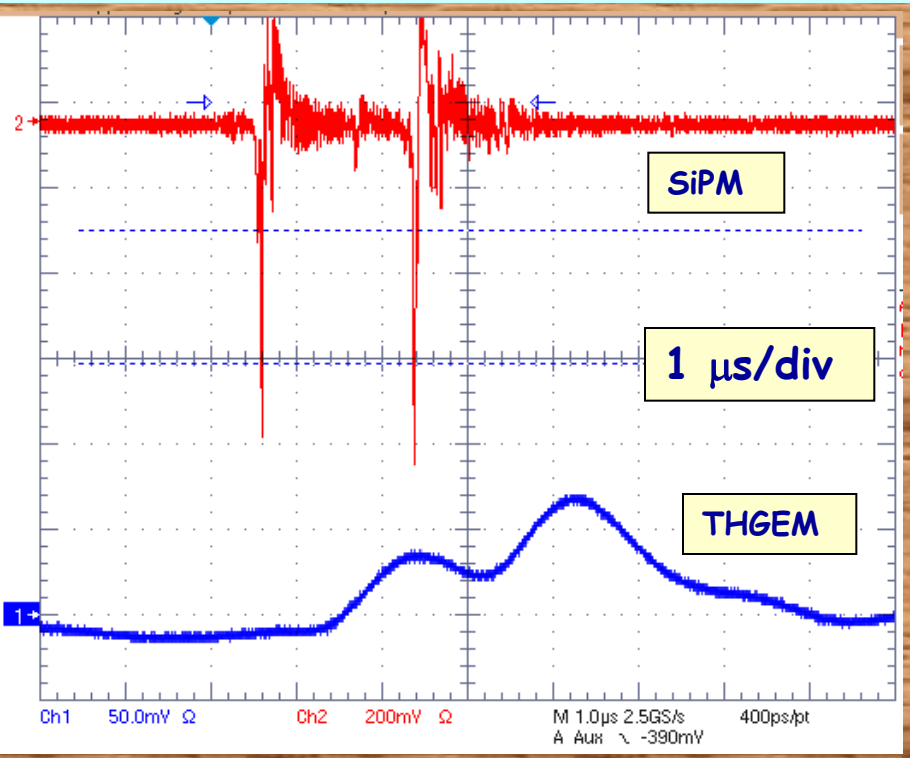
Accordingly, the scintillations recorded most probably take place in NIR.

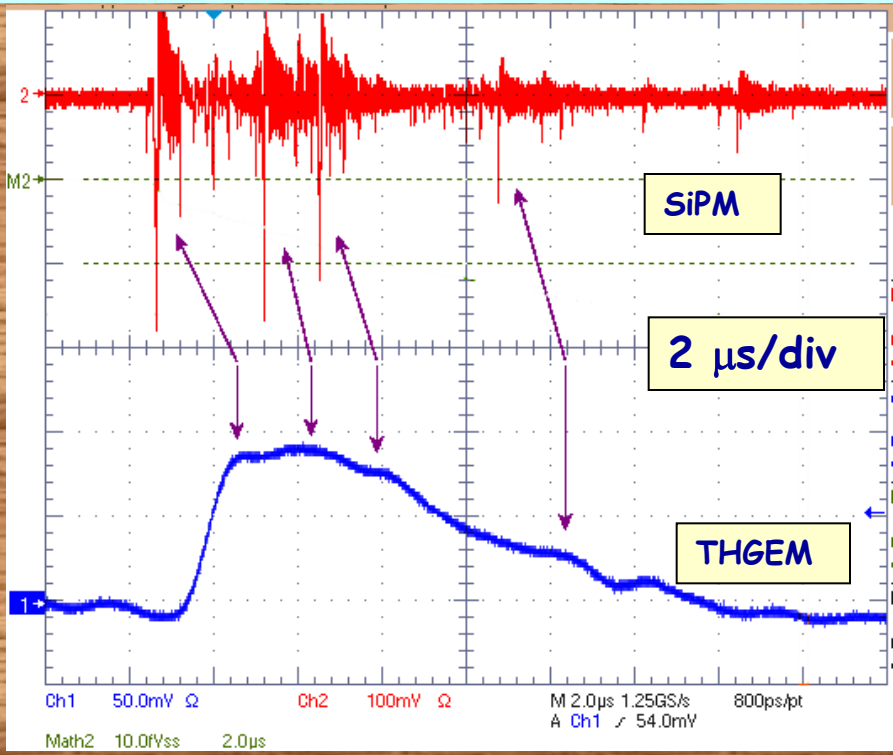


An example of 60 keV X-ray-induced signals in two-phase Ar at 2THGEM gain~1000, obtained using 1mm^2 SiPM (Pulsar).

In the following the data obtained using <u>4.4 mm^2 SiPM (CPTA 149-35)</u> will only be considered.

Scintillation-ionization (SiPM vs. THGEM) signal <u>time correlation</u> : selected signals



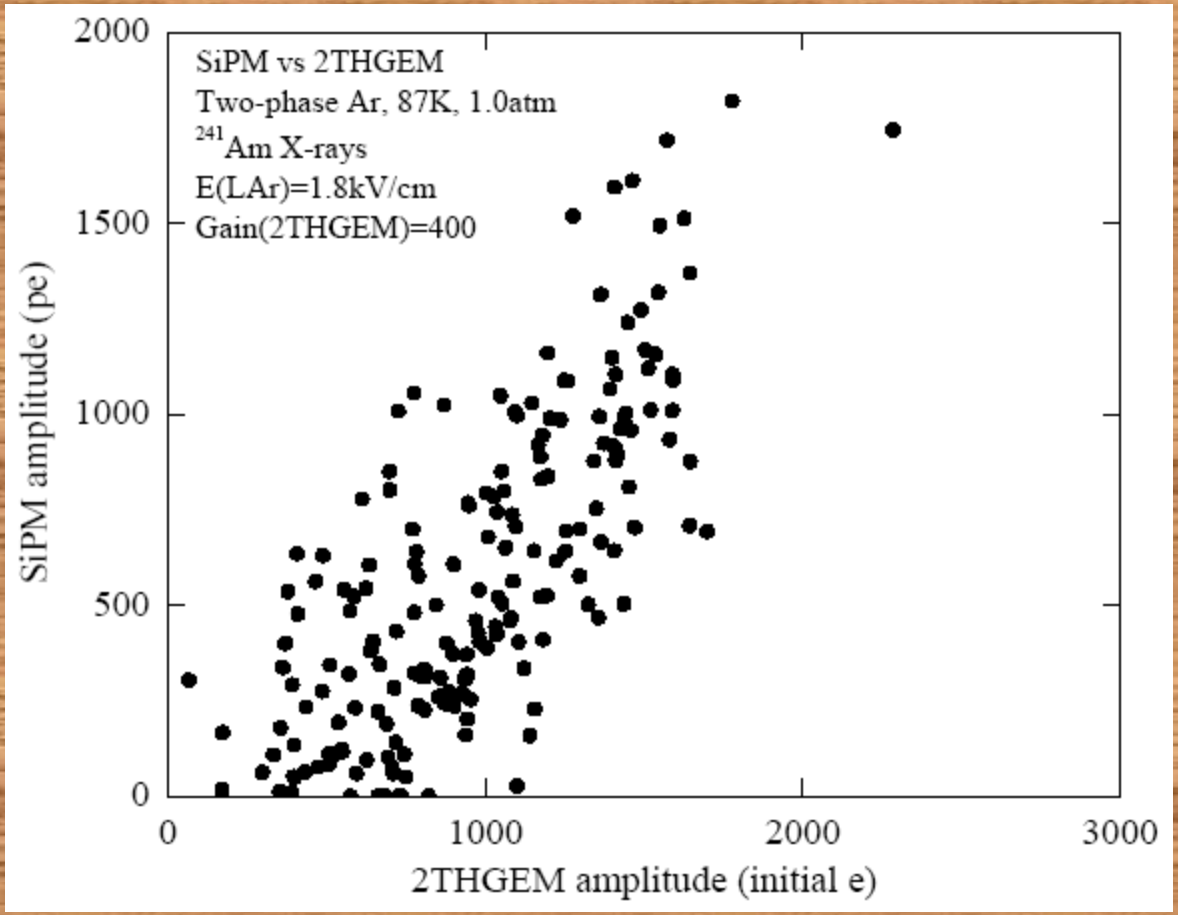


Gaseous Ar, room T, 1atm. Pulsed X-rays. 2THGEM gain=18. Selected to have primary ionization clusters separated in time. THGEM signal at room T is relatively fast compared to two-phase Ar. Time correlation between ionization (THGEM) and scintillation (SiPM) signals is distinctly seen.

Two-phase Ar, 87K, 1atm. 60 keV X-rays. 2THGEM gain=400. Selected to have spikes. Time correlation between ionization (THGEM) and scintillation (SiPM) spikes is seen.

Scintillation-ionization (SiPM vs. THGEM) signal amplitude correlation in two-phase Ar

60 keV X-ray-induced signals at 2THGEM gain=400. The correlation between SiPM and THGEM total signal amplitudes is seen.



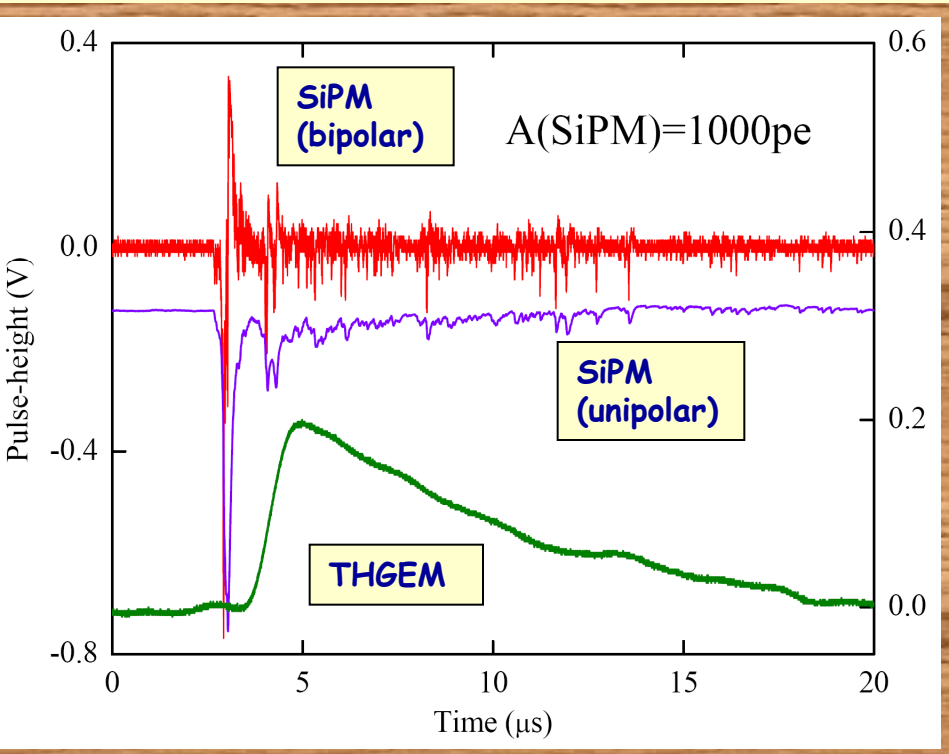
SiPM amplitude is expressed in photoelectrons: the total SiPM amplitude was integrated over ~20 μs and then normalized to SiPM single pixel amplitude.

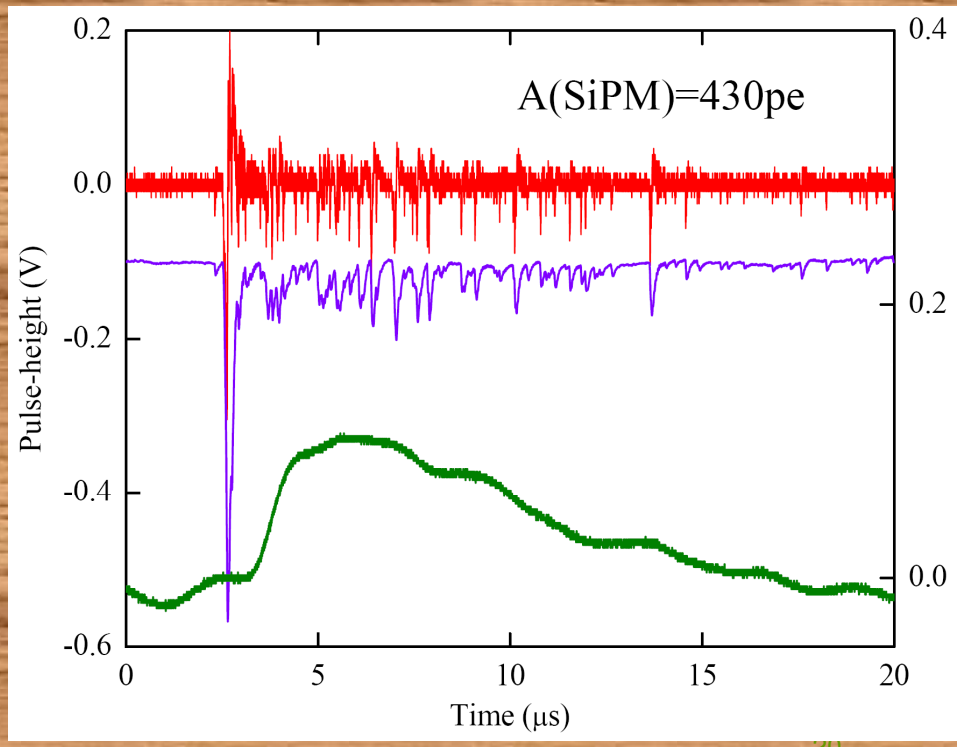
THGEM amplitude is expressed in initial (prior to multiplication) electrons.

Pulse-shape analysis in two-phase Ar: typical signals

Fast SiPM signal provides an effective means to study electron emission and avalanche mechanism by analyzing avalanche time structure.

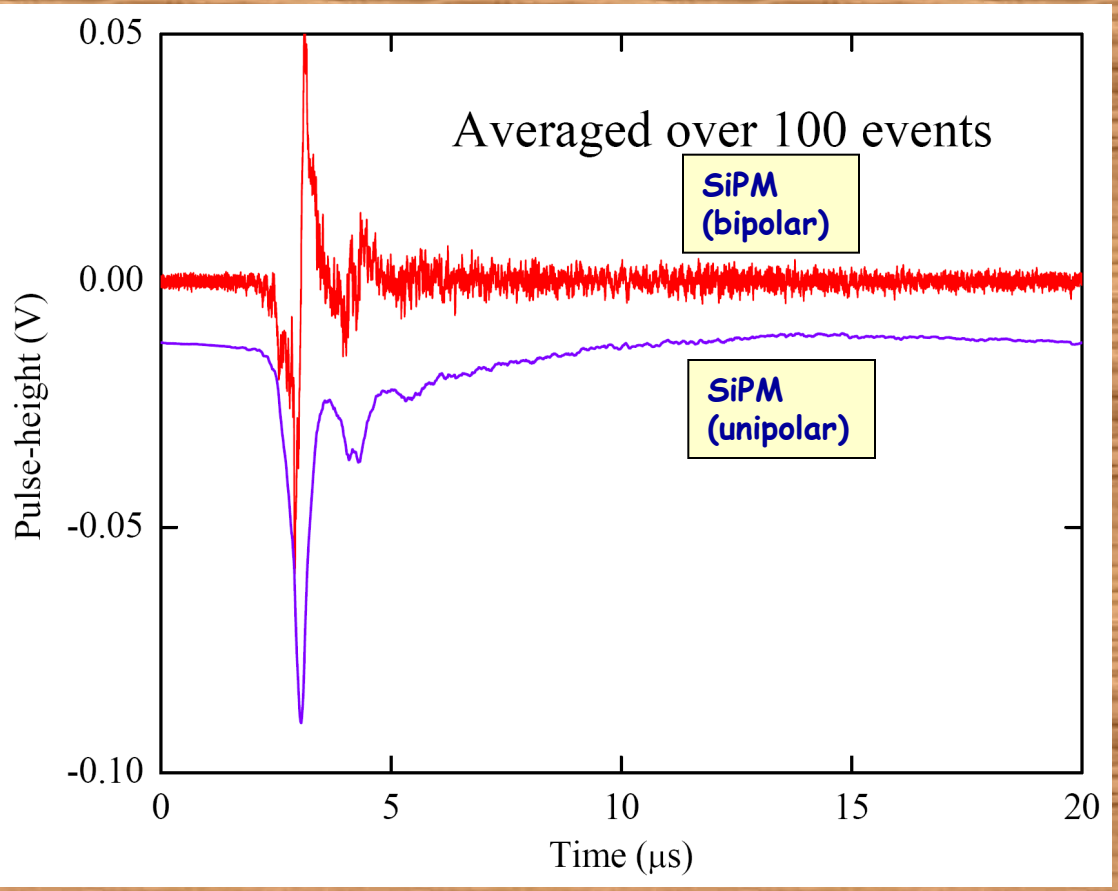
60 keV X-ray-induced signals at 2THGEM gain=400 and electric field in liquid Ar of 1.8 kV/cm. Typical SiPM signal has a pulse spike at the beginning, induced by fast electron emission component, and a tail due to slow emission component, sometimes modulated by ion feedback-induced secondary avalanches.



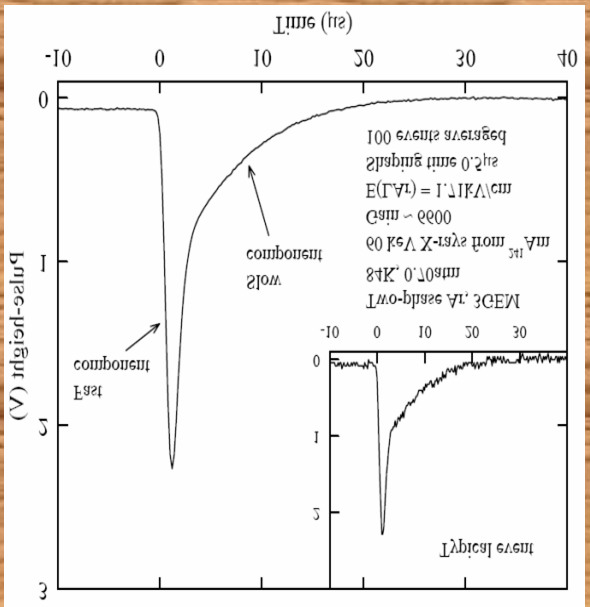


Pulse-shape analysis in two-phase Ar: SiPM averaged signal

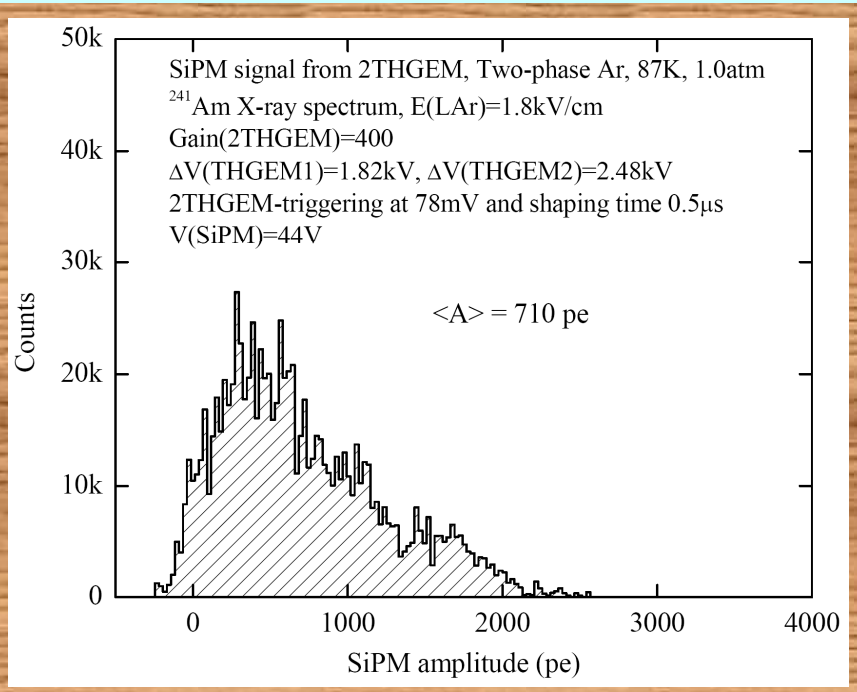
60 keV X-ray-induced signals at 2THGEM gain=400. Averaged SiPM signal has a pulse spike at the beginning, induced by fast electron emission component, and a tail due to slow emission component (with τ~5 μs), modulated by two cycles of ion feedback. The ion feedback cycle is 1.2 μs, corresponding to ion drift time though THGEM hole.



Averaged SiPM signal resembles that obtained earlier in two-phase Ar using fast GEM multiplier at similar emission field (1.8 kV/cm).



Scintillation signal amplitude distribution in two-phase Ar. THGEM+SiPM multiplier yield.



<SiPM amplitude> at gain=400 is 710 pe for 60 keV X-ray deposited in the liquid, producing about 900 initial electrons, i.e. prior multiplication in the gas phase.

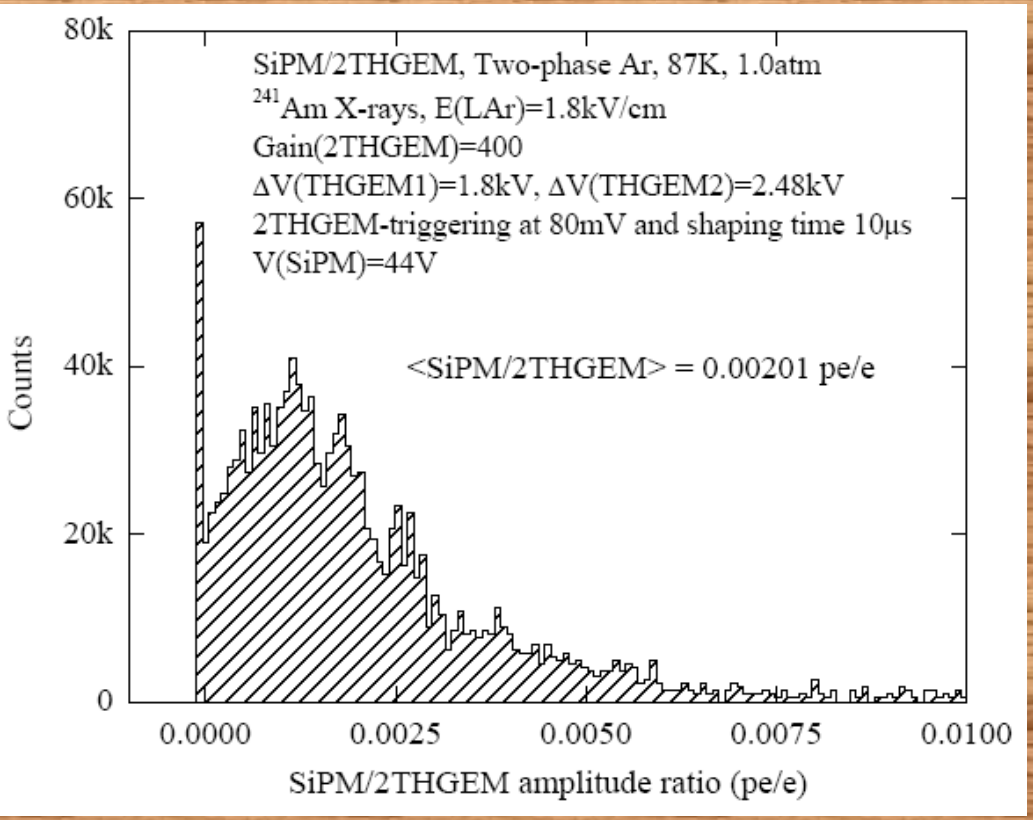
At this particular gain (400) and geometry (4mm^2 SiPM at 4mm distance from THGEM2)
→ THGEM+SiPM multiplier yield:

$$Y_{2THGEM+SiPM} = 0.80 \text{ pe/initial e}$$

$\langle \Delta\Omega_{SiPM}/4\pi \rangle$ (with respect to THGEM2) = $2.5*10^{-3}$
→ Yield in 4π per unit THGEM gain:

$$Y_{SiPM} = 12 \text{ pe/keV}$$

Scintillation/ionization signal ratio distribution in two-phase Ar. Light yield.



SiPM/THGEM distribution reflects that of the solid angle of SiPM with respect to THGEM2

At gain=400:

<SiPM/2THGEM> = $2.0*10^{-3}$ pe/e . → Light yield from an avalanche:

Photoelectron yield per avalanche electron in 4π for this particular SiPM :

Y_{pe} = 0.84 pe/e .

NIR photon yield per avalanche electron in 4π (taking QE=15%) :

Y_{ph} = 5.4 ph/e .

THGEM+SiPM vs. THGEM+WLS+SiPM

In two-phase Ar using THGEM+SiPM, we have the following yield in 4π per unit THGEM gain:

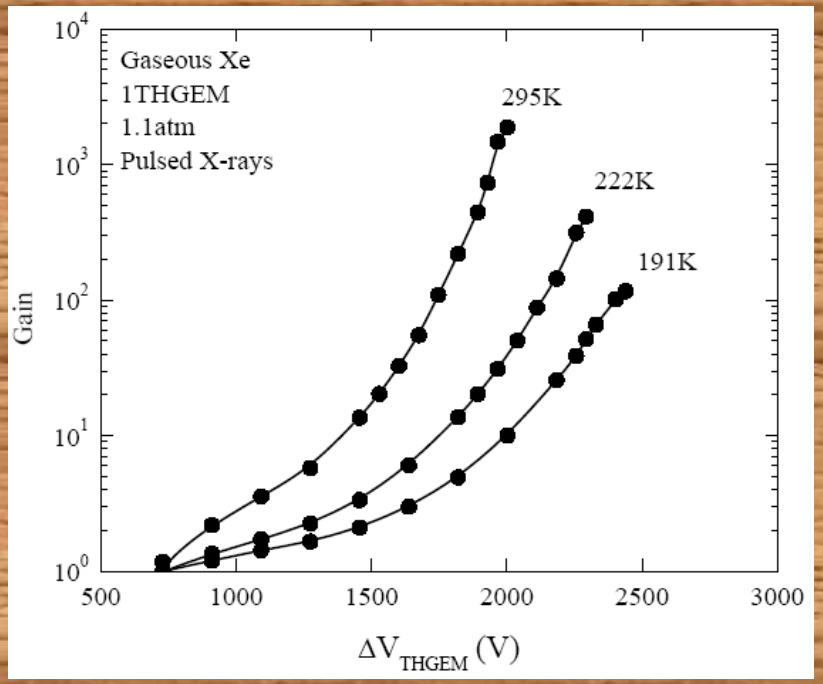
$$Y_{SiPM} = 12 \text{ pe/keV}$$

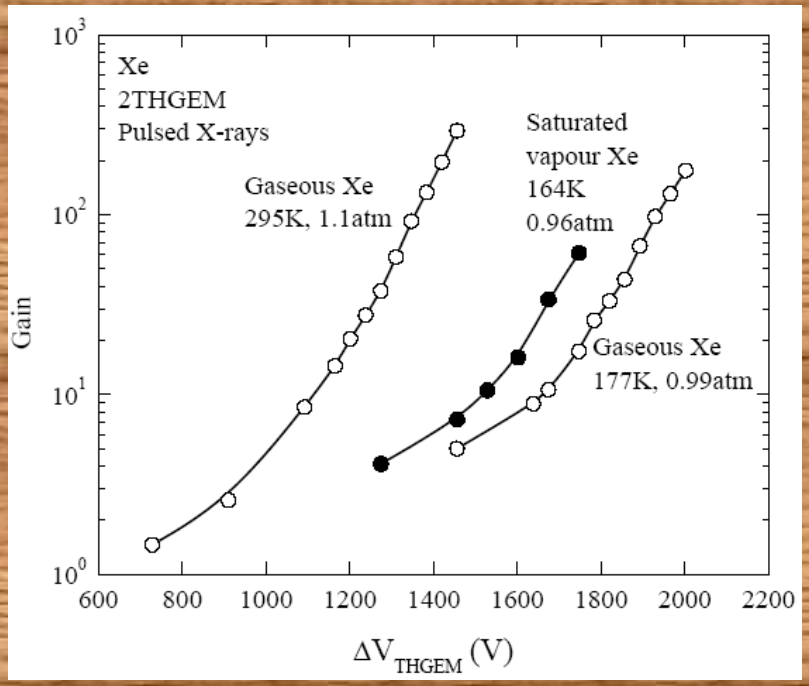
In two-phase Ar using THGEM+WLS+SiPM, Sheffield had *[Lightfoot et al. JINST 4 (2009) P04002]* :

$$Y_{SiPM} = 6.5 \text{ pe/keV}$$

Accordingly, in two-phase Ar avalanche detectors, NIR-sensitive SiPMs (not coated with WLS) provide at least the same yield as that of VUV-sensitive SiPMs (coated with WLS).

Cryogenic gaseous Xe avalanche detector using THGEM





Stable operation of single-THGEM in gaseous Xe at cryogenic temperatures

Double-THGEM performance in saturated Xe vapour. Maximum gains might not be reached: were limited due to HV feedthrough problem

Conclusions

1. GEM- and THGEM-based two-phase avalanche detectors show good performance in Ar.

2. SiPM performance at cryogenic T is superior to that of room T.

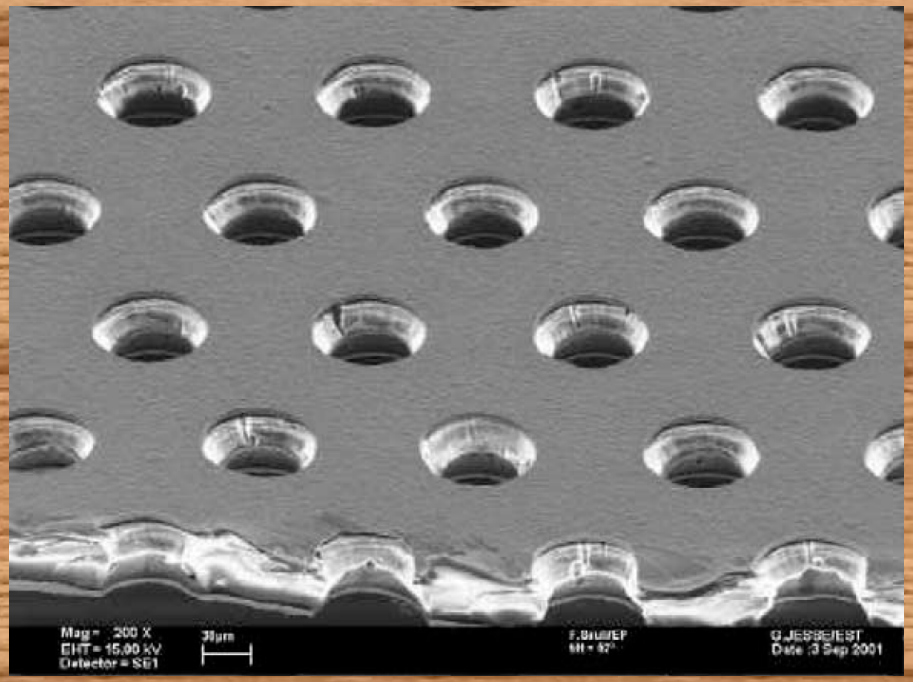
3. Two-phase avalanche detectors with THGEM+SiPM readout (SiPM being not coated with WLS) show excellent performance.

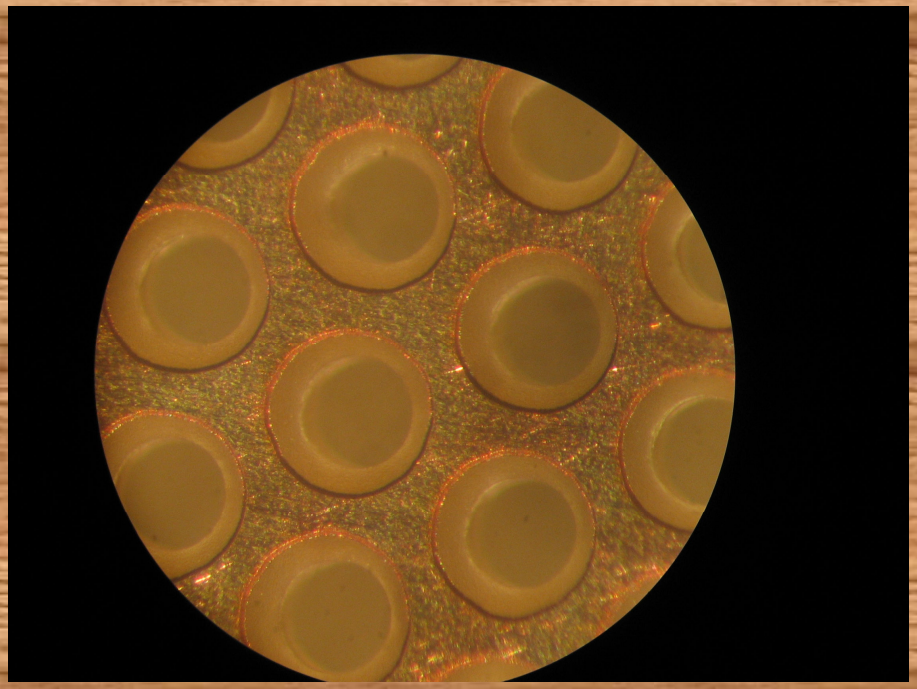
4. THGEM multiplier is capable to operate in gaseous Xe at cryogenic T.

5. Such detectors may find applications in the field of rare-event experiments and PET.

Spare slides

Gas electron multiplier (GEM): "standard" GEM and thick GEM (THGEM)

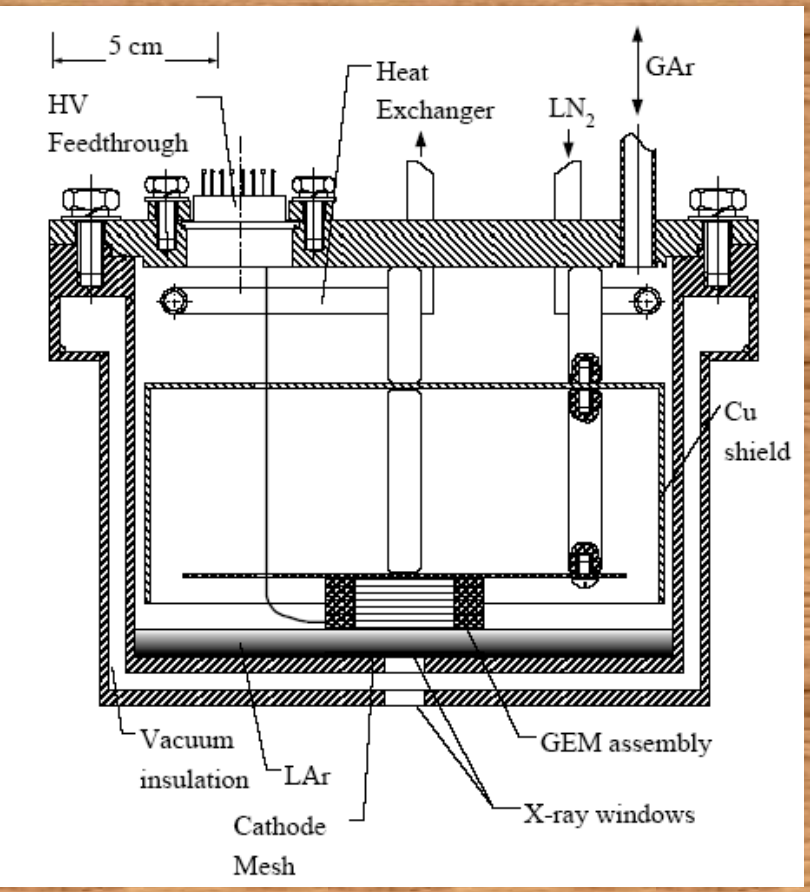


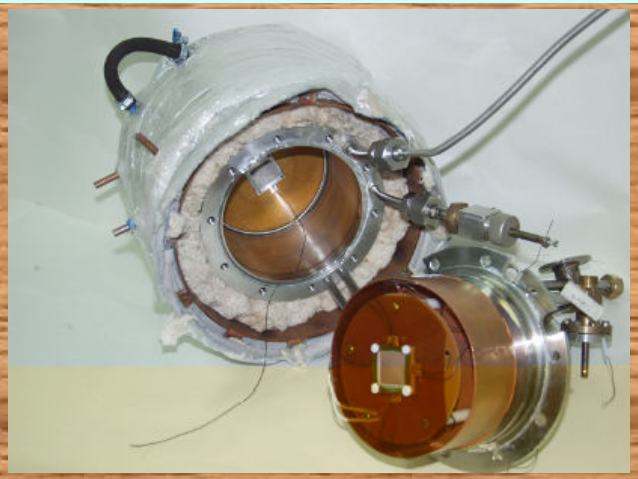


Typical <u>standard GEM</u>: dielectric (kapton) thickness 50 μm, hole pitch 140 μm, hole diameter 55 μm in dielectric and 70 μm in metal

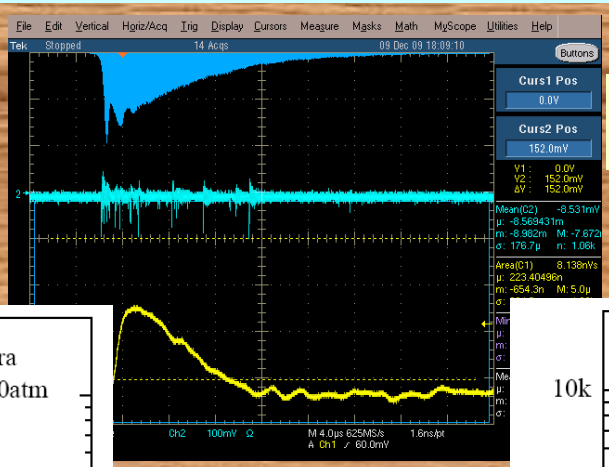
Typical <u>thick GEM</u>: dielectric (G10) thickness 0.40 mm, hole pitch 0.9 mm, hole diameter 0.5 mm in dielectric and 0.7 mm in metal

Experimental setups with 2.5 l cryogenic chamber (2003-2008)

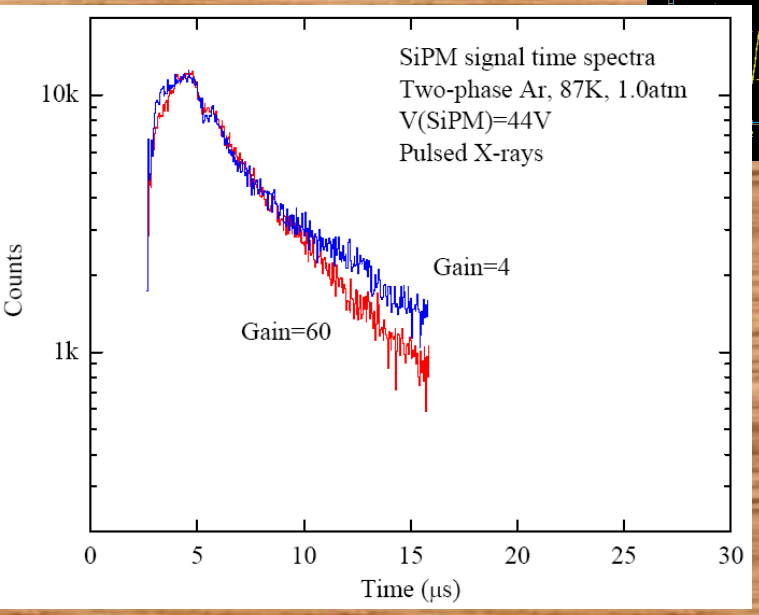


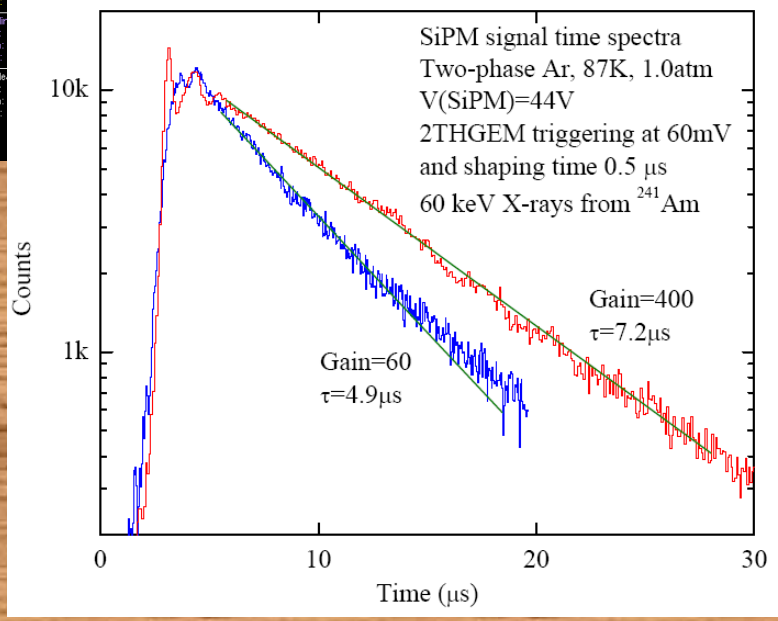


Pulse-shape analysis in two-phase Ar: SiPM signal time histogram



← Only negative part of SiPM bipolar signal is recorded in time histogram.





No difference in SiPM signal time distribution between gain 4 and 60. Signal tail is defined by slow electron emission component in two-phase Ar with decay time τ~5 µs (at electric field in liquid Ar of 1.8 kV/cm).

At higher gains (400) the signal becomes wider extending to that with τ~7 µs, partially due to ion feedback-induced avalanches.