Light and charge signal amplification in two-phase detectors

Contribution (a chapter) to book in preparation
"Two-phase emission detectors"
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Chapter content

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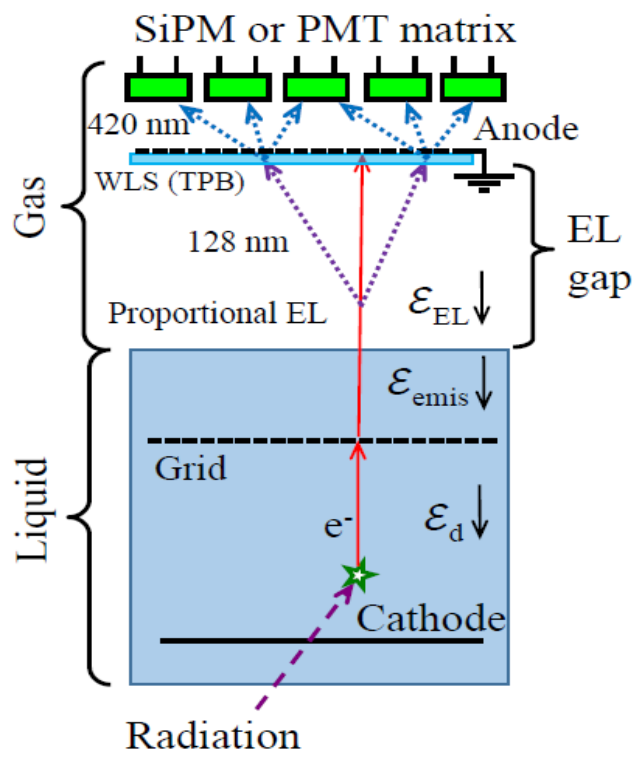
5. Charge and light signal amplification in the liquid phase (skipped in this talk; includes LHM)

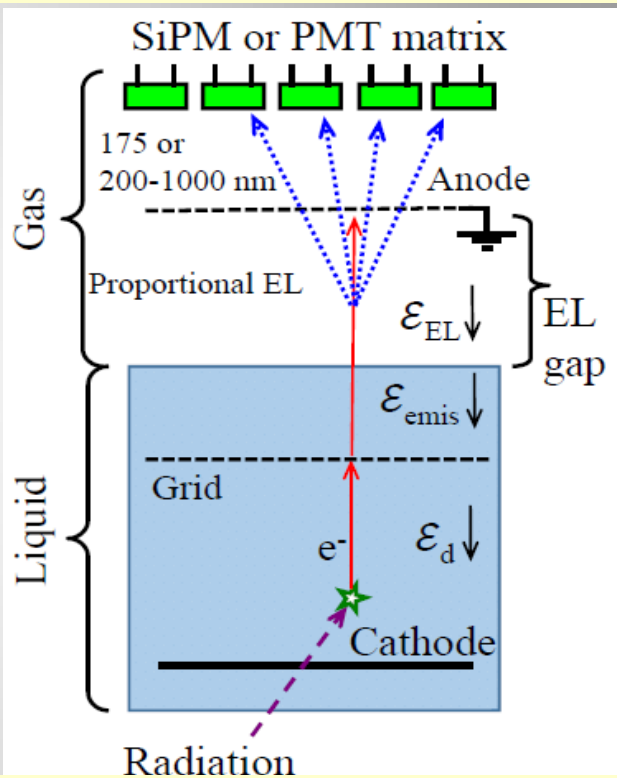
Section 1
Basic concepts of signal amplification in two-phase detectors

In two-phase detectors for dark-matter search and low-energy neutrino detection, the primary ionization and/or scintillation signals have to be amplified. This can be done by amplification of either light or charge signal or else a combination thereof. It has been proposed many ways of light and charge signal amplification in two-phase detectors. Among this variety, two basic concepts can be distinguished, that most other concepts come from.

Basic concept of light signal amplification

Basic concepts of light signal amplification in two-phase detectors is that using proportional electroluminescence (EL) in the EL gap.



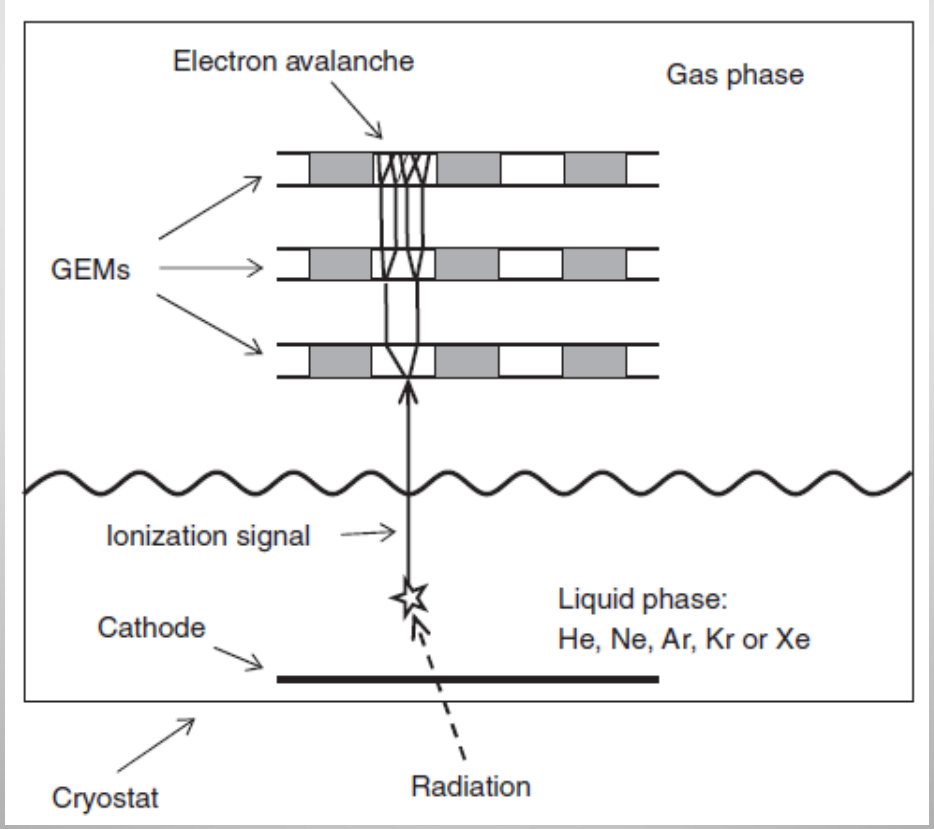


Concept with indirect optical readout via wavelength shifter (WLS), in two-phase Ar using excimer emission in the VUV at 128 nm.

Concept with direct optical readout, either in two-phase Xe using excimer emission in the VUV at 175 nm, or in two-phase Ar using neutral bremsstrahlung (NBrS) emission in the non-VUV range (at 200-1000 nm).

Basic concept of charge signal amplification

Basic concept of charge signal amplification in two-phase detectors is that using a GEM-like structure in the gas phase that provides electron avalanching within GEM holes at cryogenic temperatures.
GEM-like structure = single- or multi-stage GEM or THGEM.



Section 3
Charge signal amplification in the gas phase of two-phase detector, using electron avalanching

3.1Charge signal amplification concepts at cryogenic temperatures

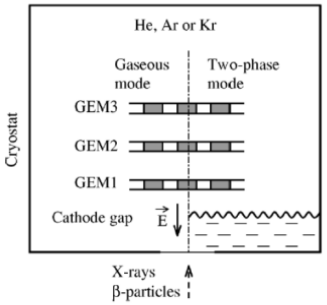
So-called "Cryogenic Avalanche Detectors" (CRADs) (Buzulutskov, 2012) in the wide sense define a class of noble-gas detectors operated at cryogenic temperatures with electron avalanching performed directly in the detection medium, the latter being in a gaseous, liquid or two-phase state. The problem of electron avalanching in cryogenic noble-gas detectors was solved in 2003 (Buzulutskov et al., 2003) after introduction and performance demonstration of cryogenic gaseous and two-phase detectors with Gas Electron Multiplier (GEM) charge readout. Consequently at present, the idea of CRAD in the narrow sense is that of the combination of GEM/THGEM with cryogenic noble-gas detectors, operated in a gaseous, liquid or two-phase mode.

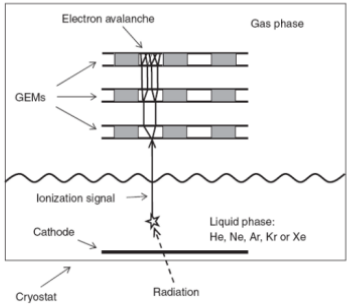
There are more than a dozen of different concepts with charge and light amplification in two-phase and liquid detectors developed by different groups since 2003: their gallery by 2012 is shown in the next slide.

For their detailed description, we refer to review (Buzulutskov, 2012) and appropriate references listed in the figure: (Buzulutskov et al., 2003; Bondar et al., 2006; Periale et al., 2005; Rubbia, 2006; Buzulutskov and Bondar, 2006; Ju et al., 2007; Gai et al., 2007; Bondar et al., 2008; Lightfoot et al., 2009; MvConkey et al., 2010; Akimov et al., 2009; Duval et al., 2009; Bondar et al., 2010; Buzulutskov et al., 2011; Akimov et al., 2011; Duval et al., 2011).

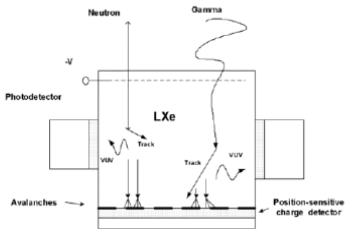
The references to such concepts and their realization after 2012 are as follows: (Bondar et al., 2012; Bondar et al., 2013; Akimov et al., 2013; Breskin, 2013; Arazi et al., 2015; Erdal et al., 2020; Mavrokoridis et al., 2014; Hollywood et al., 2020; Ye et al., 2014).

Gallery of concepts of charge signal amplification in two-phase detectors, using electron avalanching in the gas phase, by 2012

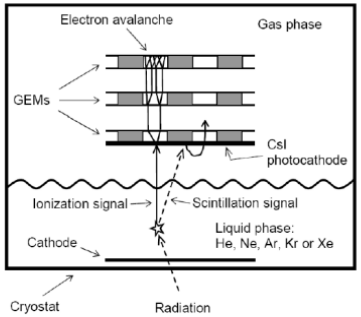




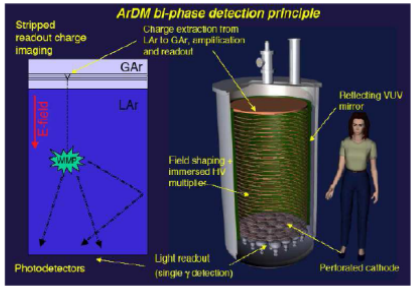
A.Buzulutskov et al, IEEE TNS 50 (2003) 2491;
A.Bondar et al, NIMA 556 (2006) 273



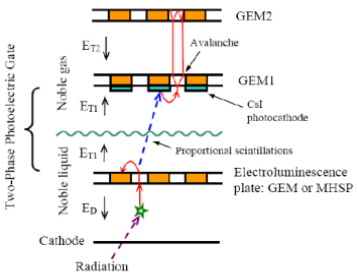
L.Periale et al, IEEE TNS 52 (2005) 927



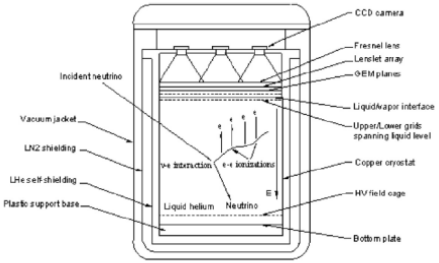
A.Bondar et al, NIMA 556 (2006) 273



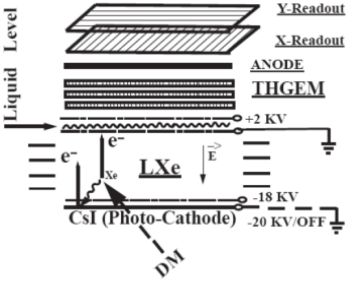
A.Rubbia, J. Phys. Conf. Ser. 39 (2006) 129



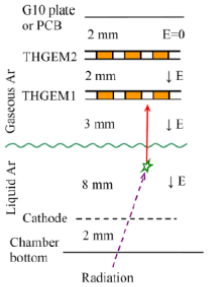
A.Buzulutskov, A.Bondar, JINST 1 (2006) P08006



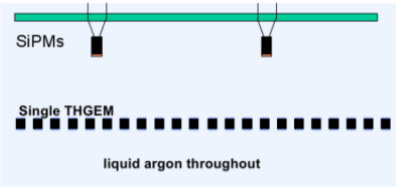
Y.L.Ju et al, Cryogenics 47 (2007) 81



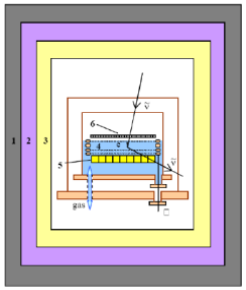
M.Gai et al, Eprint arxiv:0706.1106 (2007)



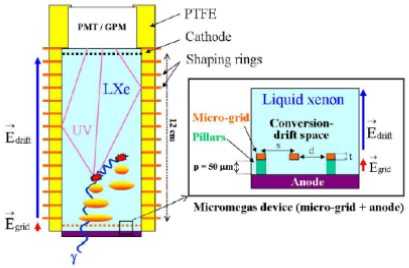
A.Bondar et al, JINST 3 (2008) P07001



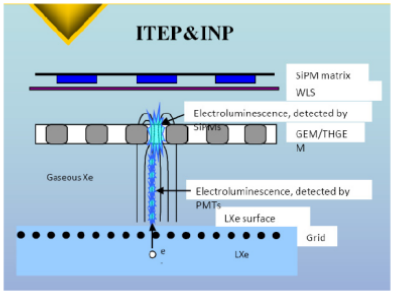
P.K.Lightfoot et al, JINST 4 (2009) P04002
N.McConkey et al, IPRD 2010, Siena, Italy; Nucl. Phys. B Proc. Suppl. 215 (2011) 255



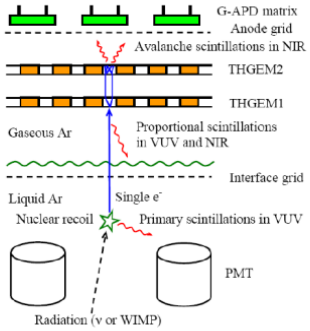
D.Akimov et al, JINST 4 (2009) P06010



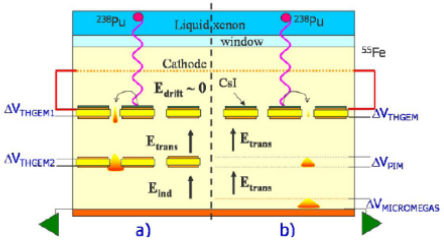
S. Duval et al, JINST 4 (2009) P12008



D.Akimov, NIMA 628 (2011) 50



A. Bondar et al, JINST 5 (2010) P08002
A.Buzulutskov et al, EPL 94 (2011) 52001

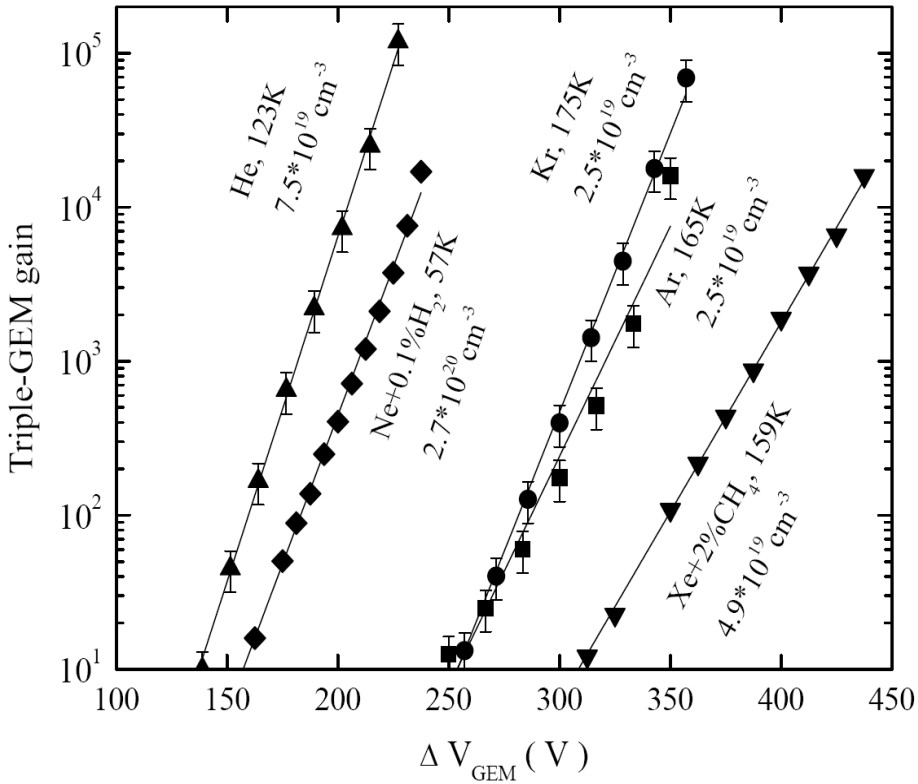


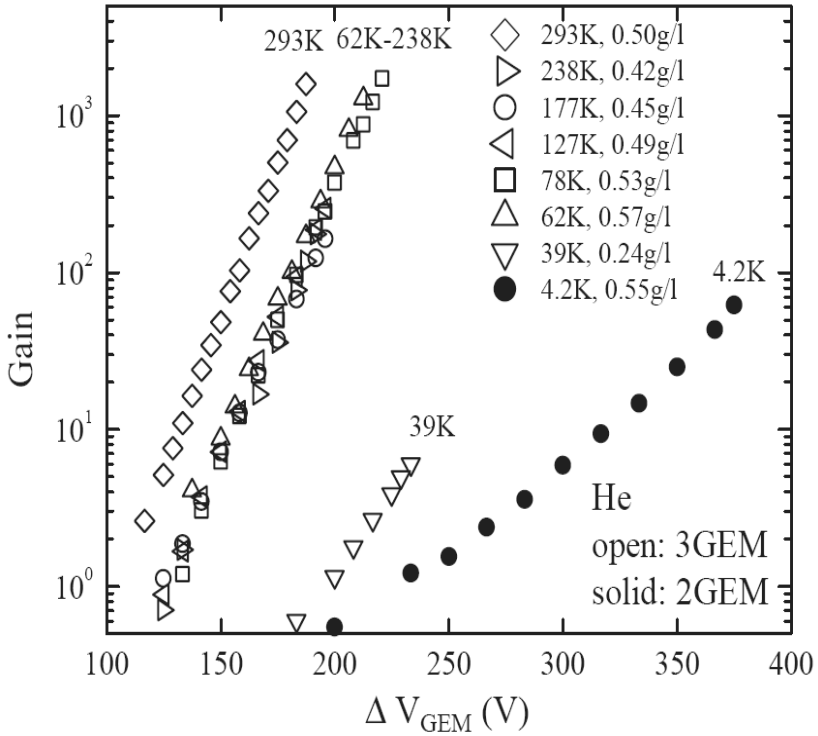
S. Duval et al, JINST 6 (2011) P04007

3.2 GEM operation in pure noble gases at cryogenic temperatures

Stable and high-gain (exceeding 10^4) GEM operation was observed (A. Bondar et al., 2004) in all noble gases and in their mixtures with selected molecular additives that do not freeze (CH4, N2 and H2), at T down to 57 K.

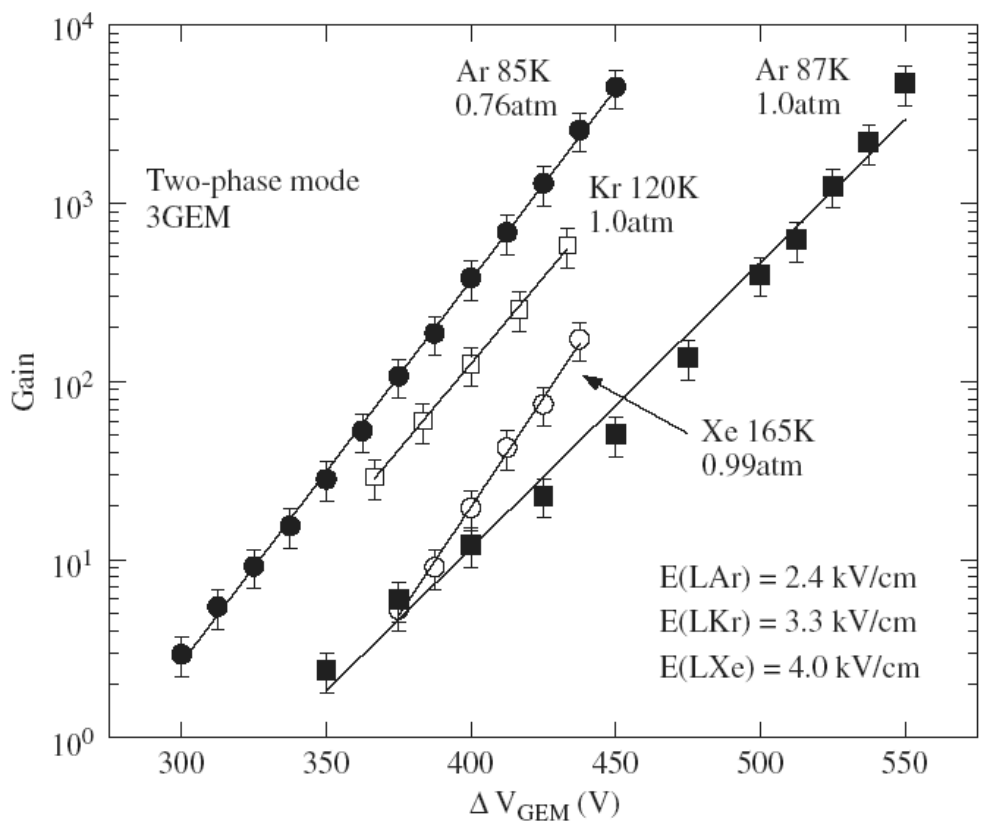
It is amazing that GEMs operate down to 2.6 K in gaseous He (Buzulutskov et al., 2005; Galea et al., 2006). On the other hand, high GEM gains observed in He and Ne above 77 K were due to the Penning effect in uncontrolled ($\geq 10^{-5}$) impurities (i.e. N2) which froze out at lower temperatures, resulting in the considerable gain drop at temperatures below 40 K.





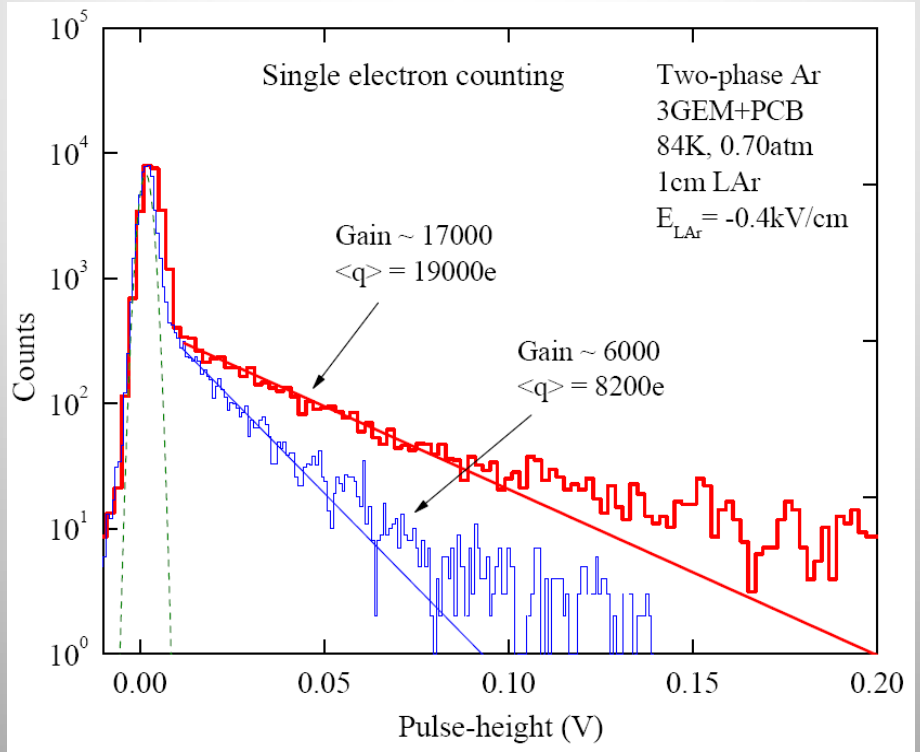
3.3 Two-phase detectors with GEM multipliers

Regarding GEM operation in two-phase detectors, the maximum gain was obtained for two-phase Ar detectors: the stable operation of triple-GEM for tens of hours at charge gain of 5000 was demonstrated (Bondar et al., 2006 and 2009). This maximum gain should be compared to that of 600 and 200 obtained in GEM-based two-phase Kr and Xe detectors respectively.



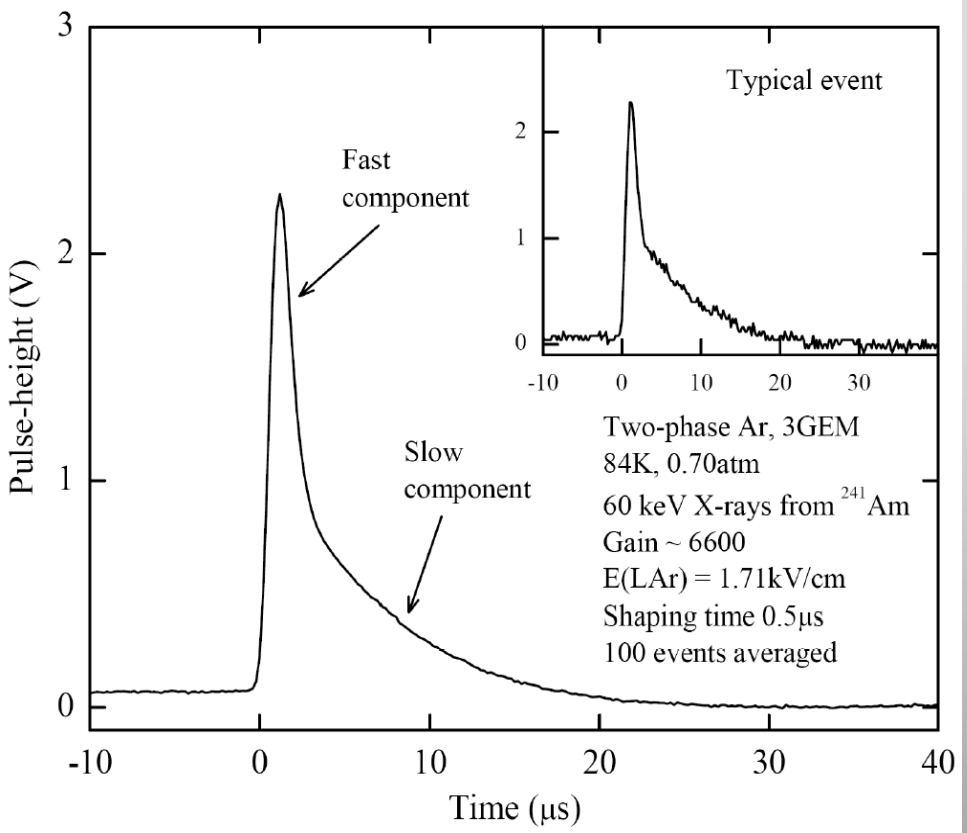
Operation in single-electron counting mode

High triple-GEM gain provided operation of two-phase detector in single-electron counting mode (Bondar et al., 2007). Though single-electron spectra are well separated from electronic noise at gains exceeding 5000, they are described by an exponential function. Therefore, single- and double-electron events can hardly be distinguished in two-phase Ar detectors with GEM (or THGEM) charge readout. For that, a combination with PMT- or SiPM-based optical readout should be used.



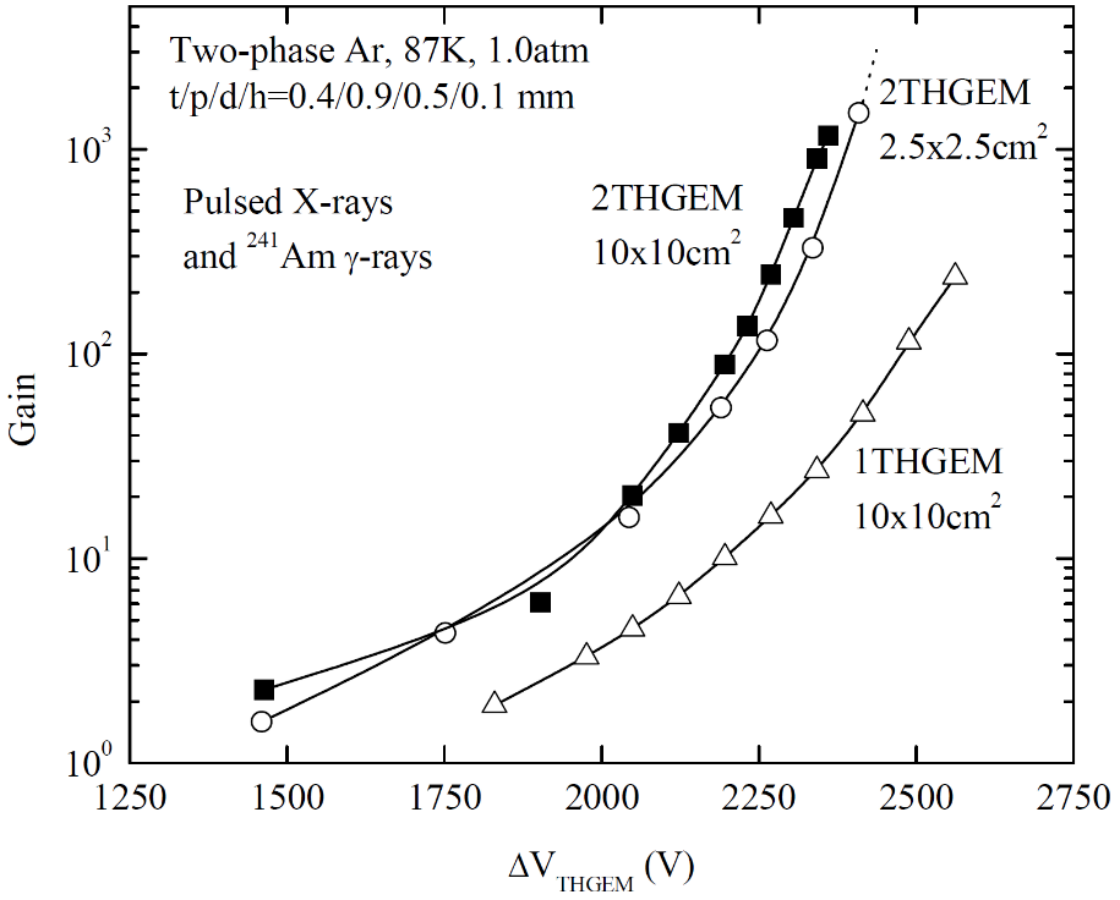
Direct observation of fast and slow component of electron emission at liquid-gas interface, in charge signal

Due to high gain and fast response, the two-phase Ar detector with GEM charge readout has unique ability to observe directly and simultaneously the fast and slow components of electron emission through the liquid-gas interface (Bondar et al., 2009a). Note that the two-phase Ar detector with EL gap optical readout cannot provide such an ability, due interference with the slow component of excimer (VUV) photon emission.



3.4 Two-phase detectors with THGEM multipliers

In two-phase detectors with THGEM charge readout, the maximum gains are comparable to those with GEM readout: gains as high as 3000 (Bondar et al., 2008) and 600 (Bondar et al., 2011) were obtained in two-phase detectors in Ar and Xe respectively, with double-THGEM multipliers with 2.5x2.5 cm2 active area.

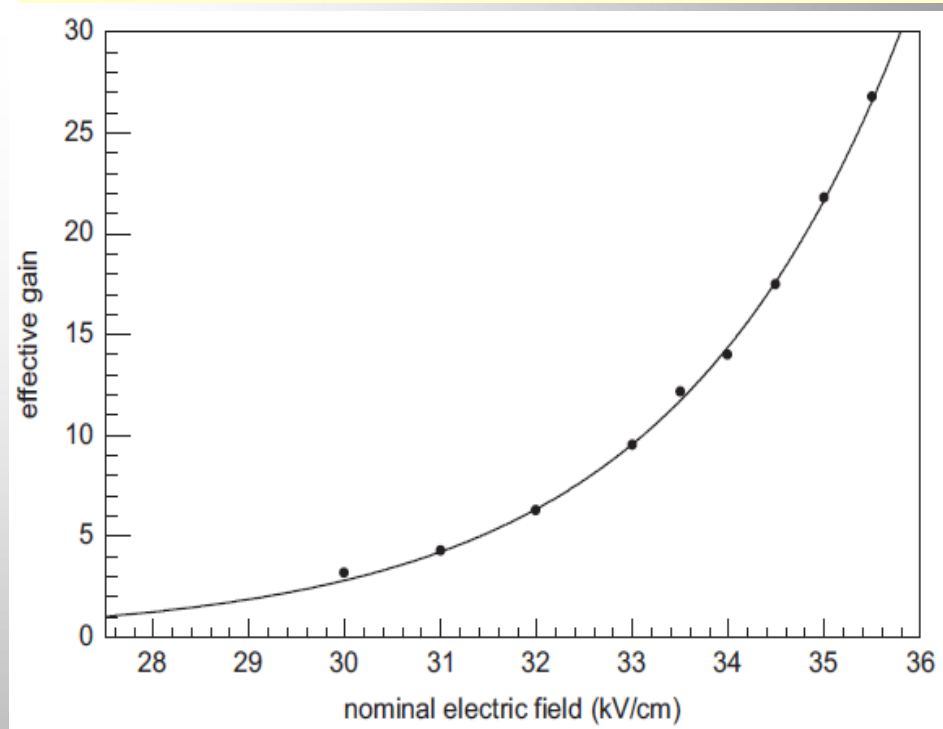


Maximum gain drop for larger THGEM area

However for larger active area, of 10x10 cm2, the maximum gain in two-phase Ar detector decreased three-fold: down to about 1000 for double-THGEM multiplier (Bondar et al., 2013a) and 100-200 for single-THGEM multiplier (Badertscher et al., 2011; Bondar et al., 2013a). This could result from the larger number of holes, implying a larger discharge probability on defects.

(Badertscher et al, 2011). "effective gain" should be multiplied by a factor of 3, to be normalized to the gain definition of the present review.

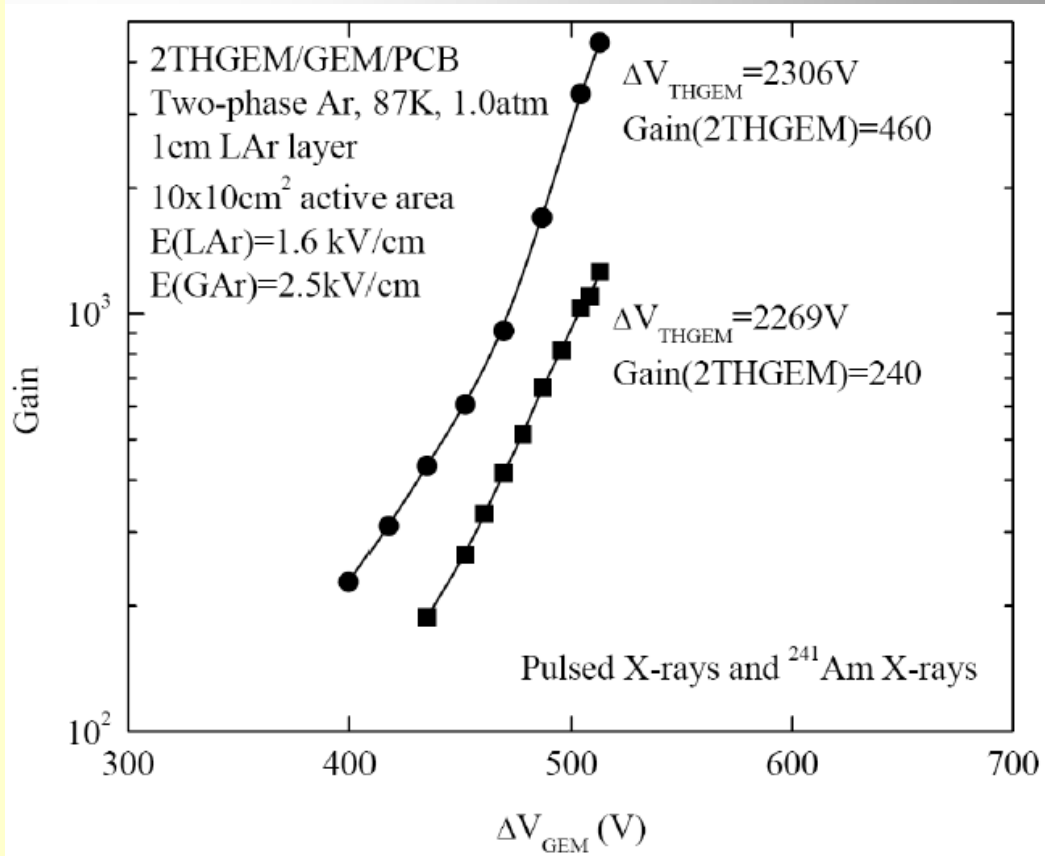
Further reduction of maximum THGEM gain in two-phase Ar detector when increasing the active area up to 40x40 and 50x50 cm2, was reported in (Badertscher et al., 2013) and (Aimard et al., 2018) respectively. For the latter, the THGEM multiplier could not operate at nominal electric fields higher than 28 kV/cm, i.e. at charge gain higher than 3 according to the figure. This is the real problem; it is discussed below.



Hybrid 3-stage 2THGEM/GEM multiplier in two-phase Ar detector

Interesting way to increase the maximum gain in two-phase Ar detector (Bondar et al., 2013a): the idea is that the avalanche charge from a THGEM hole is distributed between several GEM holes; this might reduce the overall avalanche charge density and thus increase the discharge voltage.

In hybrid 3-stage 2THGEM/GEM multiplier, the maximum gain of 5000 was attained for 10x10 cm2 active area (compare to 1000 of 2THGEM), in practical readout configuration with Printed Circuit Board (PCB) anode. This is almost enough for stable operation in single-electron counting mode with 2D readout, for which charge gains of 10^4 are needed. The idea of hybrid multiplier can be realized without "fragile" GEMs: by cascading more robust THGEMs of different geometry, with sequential increasing hole densities and decreasing thicknesses.



3.5 Gain limit, gain stability and discharge-resistance problems in two-phase detectors with GEM and THGEM multipliers

Several problems of the performance of two-phase Ar detectors with GEM and THGEM charge readout remain unsolved.

Problem of gain limit due to discharges

The first problem is that of the gain limit due to discharges. The obvious way to increase the gain would be adding an additional multiplication stage, i.e. up to overall 4 stages in the case of GEMs and 3 stages in the case of THGEMs.

Also, it looks attractive to combine GEMs and THGEMs in a hybrid multiplier like that discussed above.

Another way is an optical readout from THGEMs. Indeed, the THGEM charge gain of the order of 100 is still significant if combined with optical readout using SiPM matrices (Bondar et al., 2013) or CCD cameras (Mavrokoridis et al., 2014), and might be sufficient for track imaging and even for single-electron counting mode.

Problem of resistance to electrical discharges

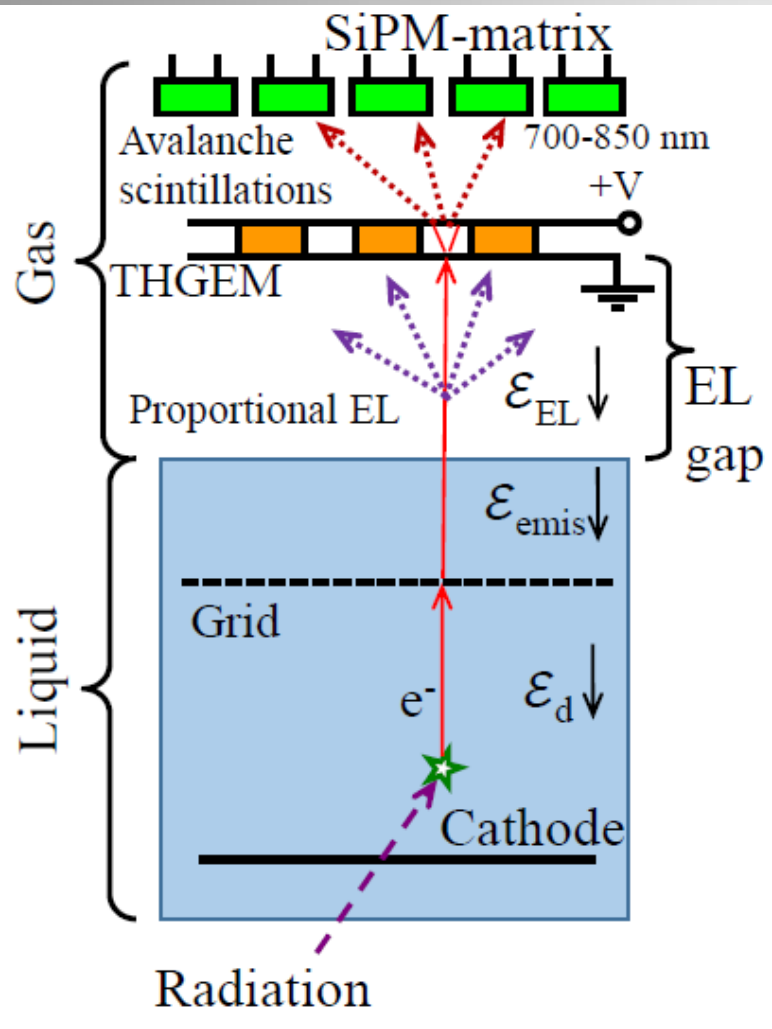
The second problem is that of the resistance to electrical discharges of "standard" (thin Kapton) GEMs. It was observed (Buzulutskov, 2020) that when operating two-phase Ar detectors with triple-GEM multiplier at maximum gains (approaching 10^4), the triple-GEM was not able to withstand electrical discharges on a long term: after several series of measurements, the maximum reachable gain decreased by several times. Obviously, this is due the low resistance of thin GEMs to discharges because of metal evaporation from the electrodes and its deposition on the insulator in the GEM holes. The solution of the problem might be switching to thicker THGEMs that were found to behave in more reliable way under discharges, or else combining THGEM and GEM multipliers or THGEM multipliers with increasing hole density, as discussed above.

Problem of understanding of MPGD performance in two-phase mode

The performance of MPGD multipliers in two-phase Ar and Xe is not fully understood: not all multiplier types were able to operate with electron multiplication in saturated vapour. In two-phase Ar, while G10-based THGEM multipliers successfully operated for tens of hours with gains reaching a few thousands, others, namely RETHGEM and Kapton THGEMs, did not show stable multiplication in the two-phase mode (Buzulutskov, 2012; Bondar et al., 2013a): they either did not multiply at all (with gain below 1) or showed unstable operation due to large gain variations. The most rational explanation of these instabilities is the effect of vapour condensation within the THGEM holes that prevents electron multiplication. The criteria for such a condensation are not yet clear.

Section 4
Combined charge/light signal amplification in the gas phase of two-phase detector, using avalanche scintillations

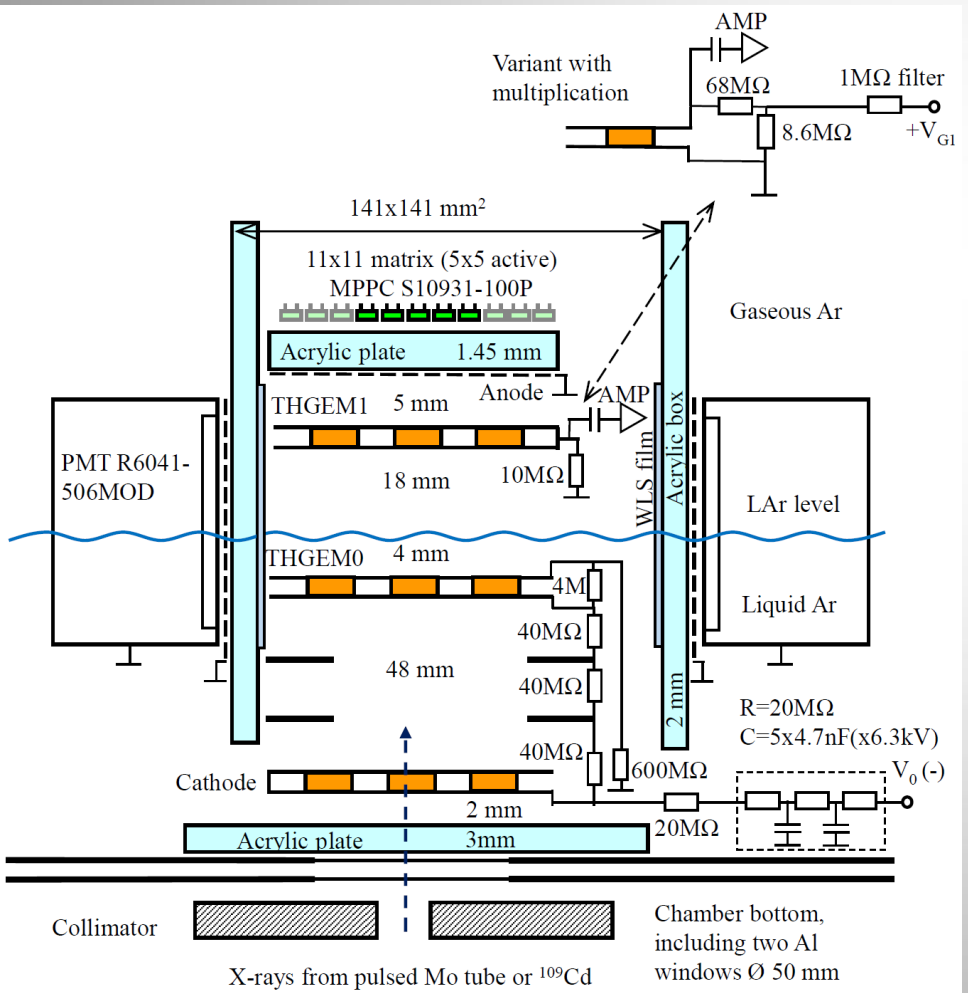
4.1Two-phase Ar detector with combined THGEM/SiPM-matrix multiplier

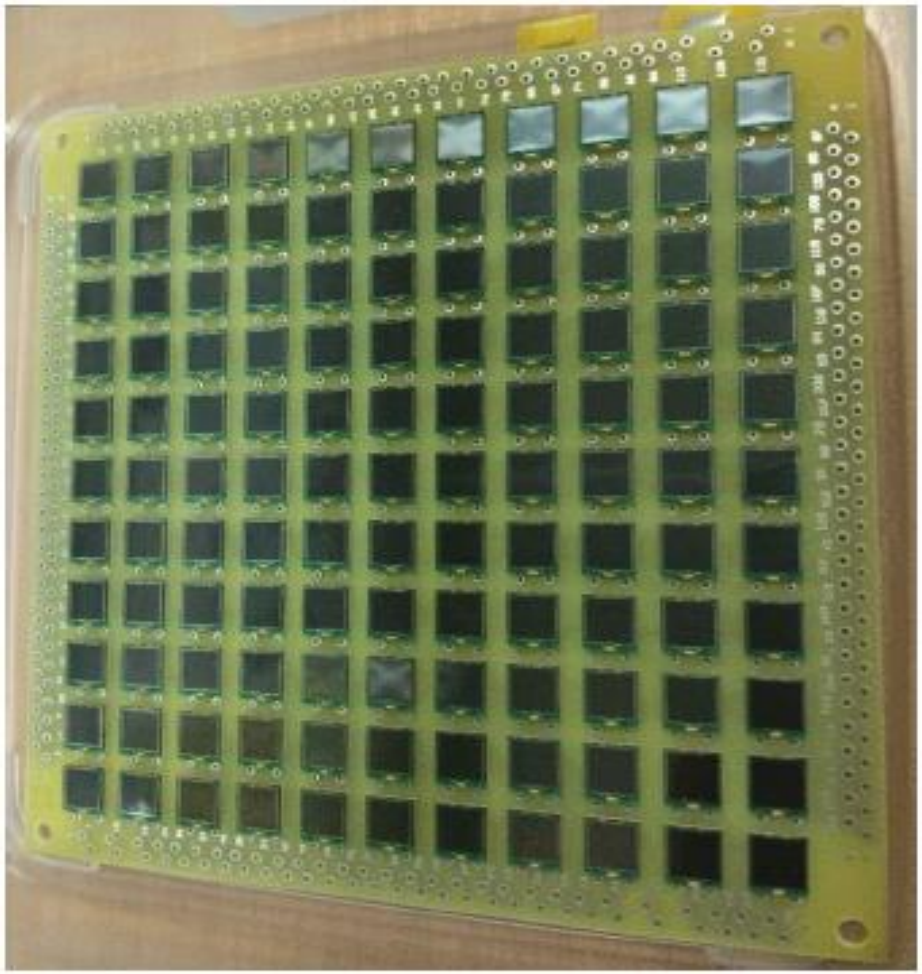


Concept of combined charge/light signal amplification in two-phase detector with EL gap, using avalanche scintillations and combined THGEM/SiPM-matrix multiplier (Aalseth et al., 2020). Here THGEM/SiPM-matrix multiplier is coupled to the EL gap: the THGEM provides the charge signal amplification by operating in electron avalanching mode, while the SiPM matrix optically records avalanche scintillations produced in the THGEM holes thus providing the light signal amplification with position resolution. Avalanche scintillations can be recorded in two ways: either directly, using avalanche scintillations due to atomic transitions in the NIR, or indirectly via WLS film in front of SiPM matrix, using excimer avalanche scintillations in the VUV.

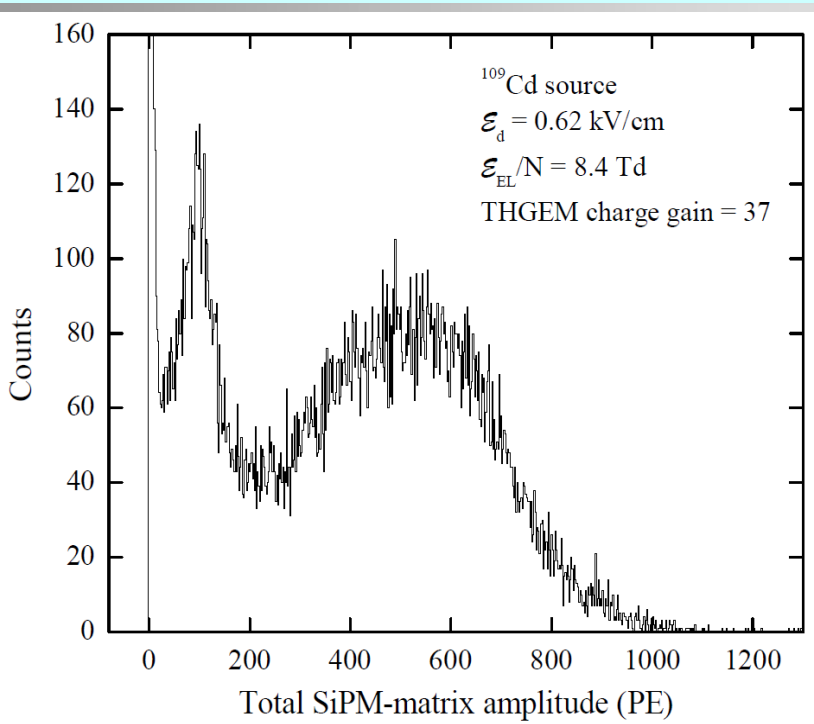
Realization of the concept

The concept was realized in two-phase Ar detector with combined THGEM/SiPM-matrix multiplier of 10x10 cm2 active area in (Aalseth et al., 2020), using a 11x11 SiPM matrix having 1 cm pitch of SiPM elements (6x6 mm2 area each).

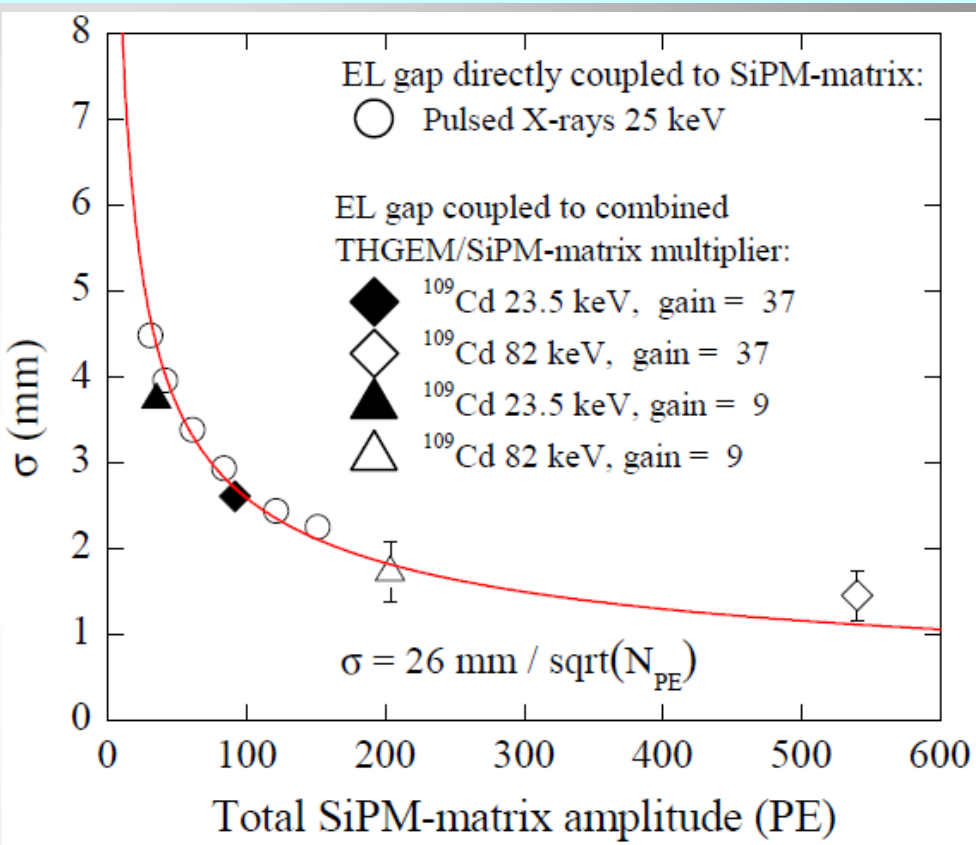




Amplitude and position resolution properties of two-phase Ar detector with THGEM/SiPM-matrix readout

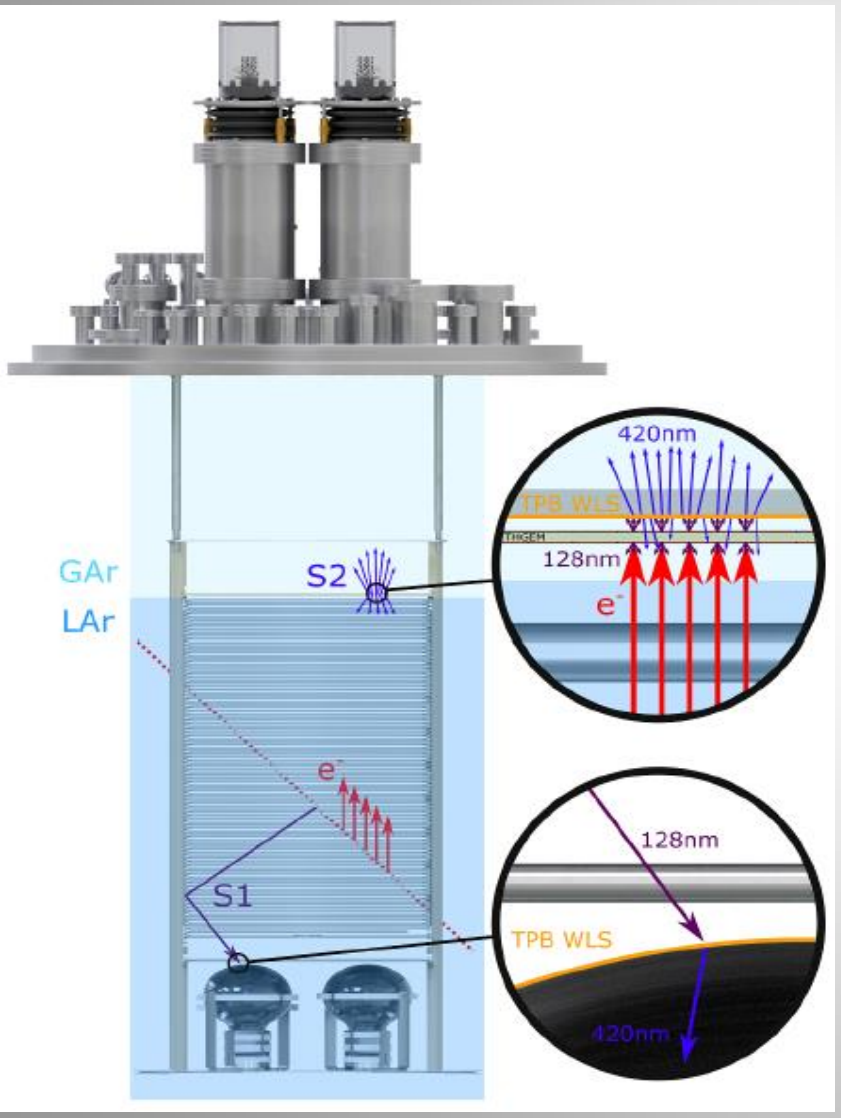


Amplitude spectrum of the total SiPM-matrix signal obtained with ^{109}Cd source, at THGEM charge gain of 37



Summary of position resolution results obtained for direct SiPM-matrix and THGEM/SiPM-matrix readout. Shown is the position resolution as a function of the total number of photoelectrons at SiPM matrix

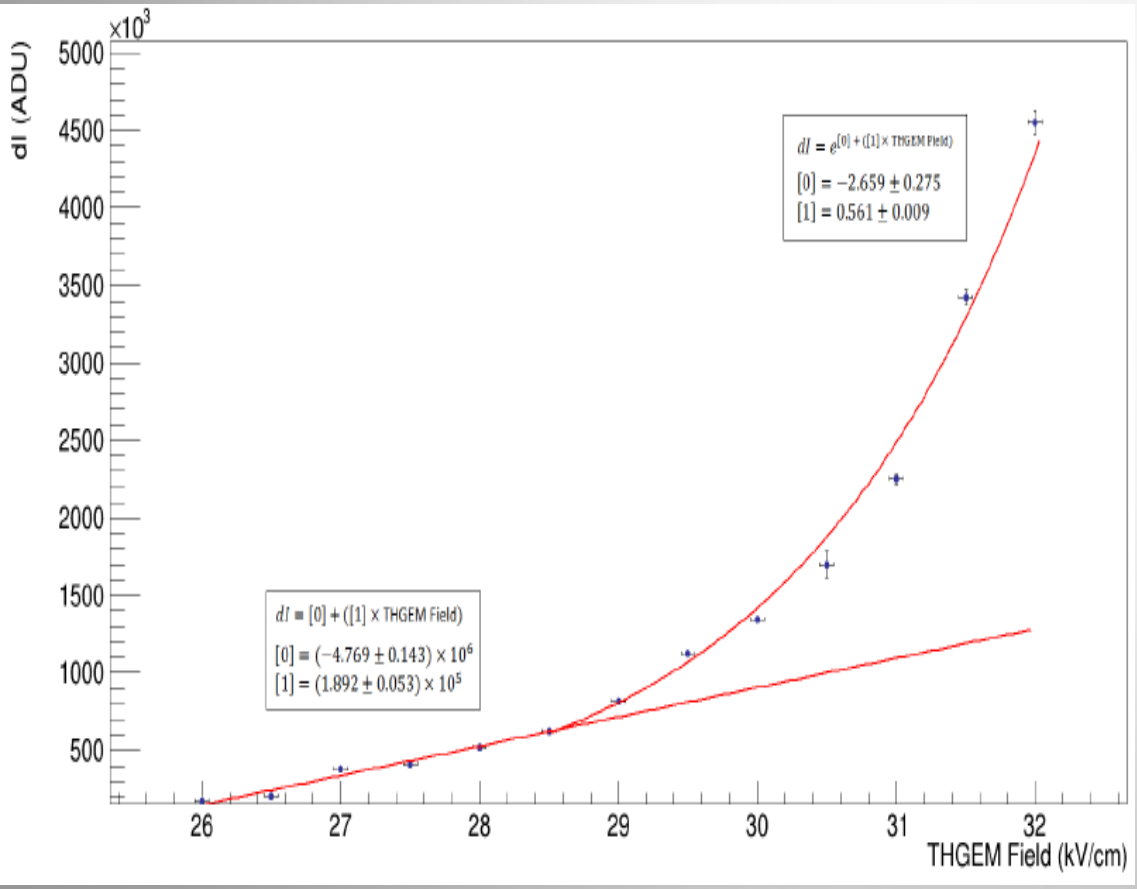
4.2 Two-phase Ar detector with combined THGEM/SiPM-matrix multiplier



Concept of combined charge/light signal amplification in two-phase Ar detector, using avalanche scintillations in combined THGEM/CCD-camera multiplier (Mavrokoridis et al., 2014). It is similar to that considered above, with the difference that SiPM matrix is replaced by CCD cameras. Avalanche scintillations were recorded indirectly via WLS film behind THGEM plate. The concept was realized in (Hollywood et al., 2020) in two-phase Ar detector with 54x54 cm2 active area and overall LAr mass of 1 t.

Light signal amplitude on CCD-cameras as a function of the nominal electric field in THGEM holes.

Two operation modes were observed: that of proportional EL (linear part) and that of electron avalanching (exponential rise part). The maximum charge gain of the latter is estimated to be about 8 (for 54x54 cm2 THGEM active area).



Optical readout allows to measure THGEM charge gain ad hoc: using light signal intensity dependence on the electric field. At the maximum field of 32 kV/cm, avalanche light gain, defined as measured light intensity normalized to that of linear extrapolation from lower electric fields, is close to 4. This avalanche light gain corresponds to larger charge gain value, because secondary (avalanche) electrons produce less EL light per drifting electron compared to initial electron. If to approximate the THGEM hole by a parallel-plate gap, it can be shown that the light yield of 4 corresponds to the charge gain of 8.

Conclusions

THGEM multipliers of moderate active area (10x10 cm2) can effectively operate in two-phase Ar detectors with charge gains reaching 1000 for double-THGEM and 100-200 for single-THGEM.

However, the maximum gain of single-THGEM multipliers of larger area (50x50 cm2) is significantly reduced, down to values of 3-8.

The solution of the problem might be the hybrid multiplier, combining THGEM and GEM multipliers or cascaded THGEM multipliers with sequentially increasing hole density.

Another way to solve the problem is optical readout from THGEMs using SiPM matrices or CCD cameras. In addition, optical readout allows to directly measure THGEM charge gain using light signal dependence on the electric field.

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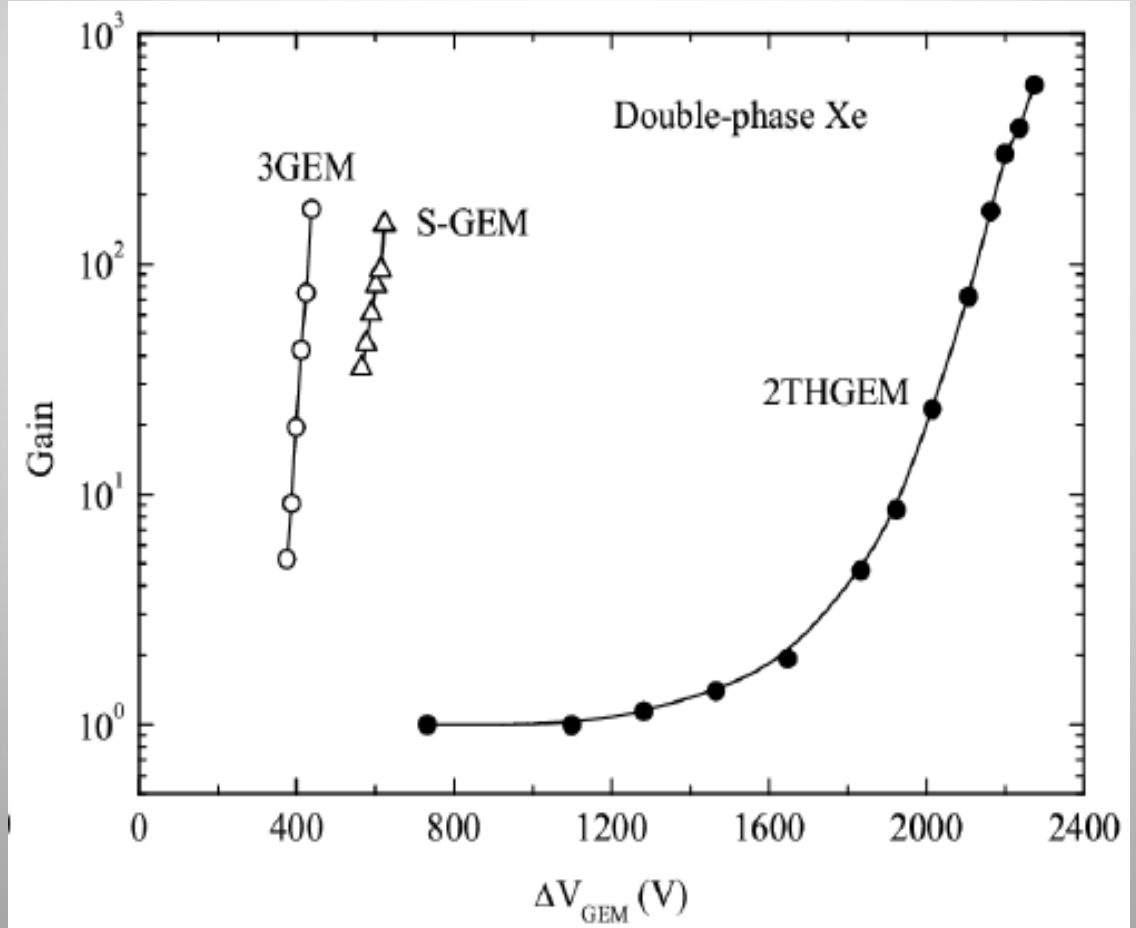
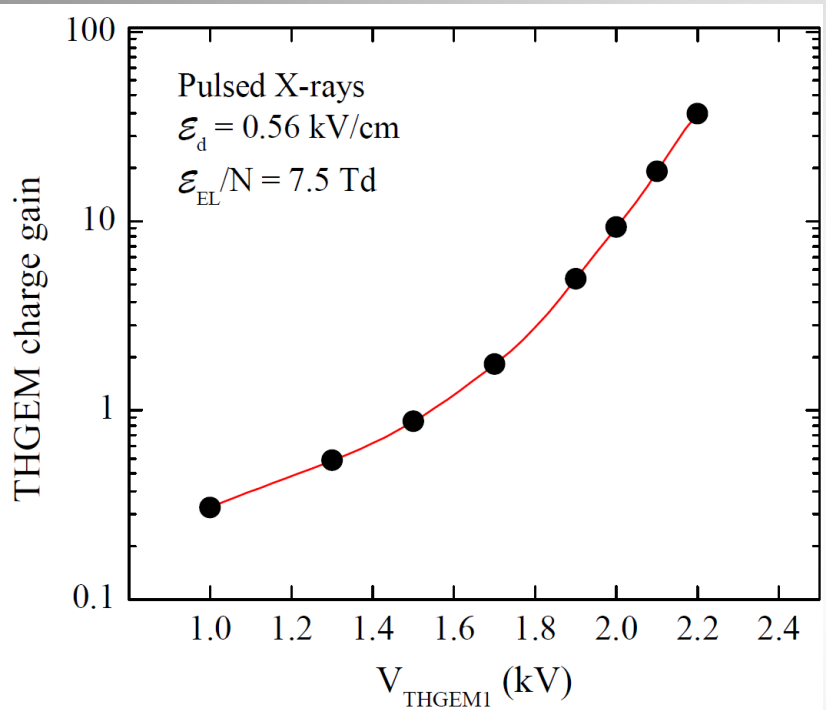
Backup slides

THGEM vs GEM in two-phase Xe detector

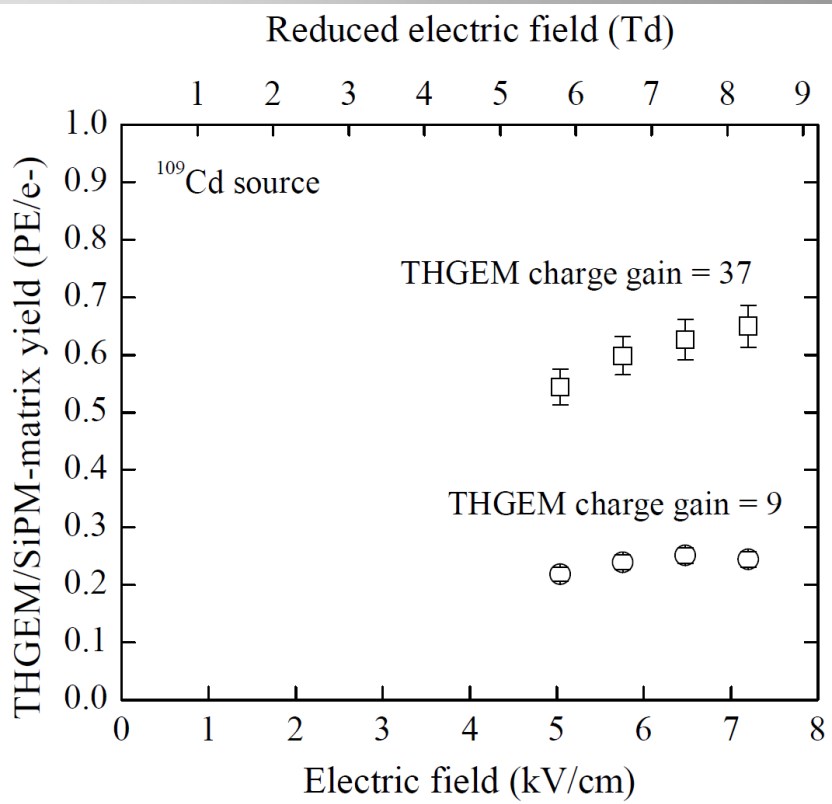
Gain characteristics of double-THGEM multipliers in two-phase Xe detector for THGEM active area of 2.5x2.5 cm2 (Bondar et al., 2011). Gain characteristics of triple-GEM (Bondar et al., 2006) and single-GEM (Balau et al., 2009) multipliers (of similar active area) are shown for comparison. Here the maximum gains were limited by discharges.



THGEM charge gain and THGEM/SiPM-matrix yield in two-phase Ar detector



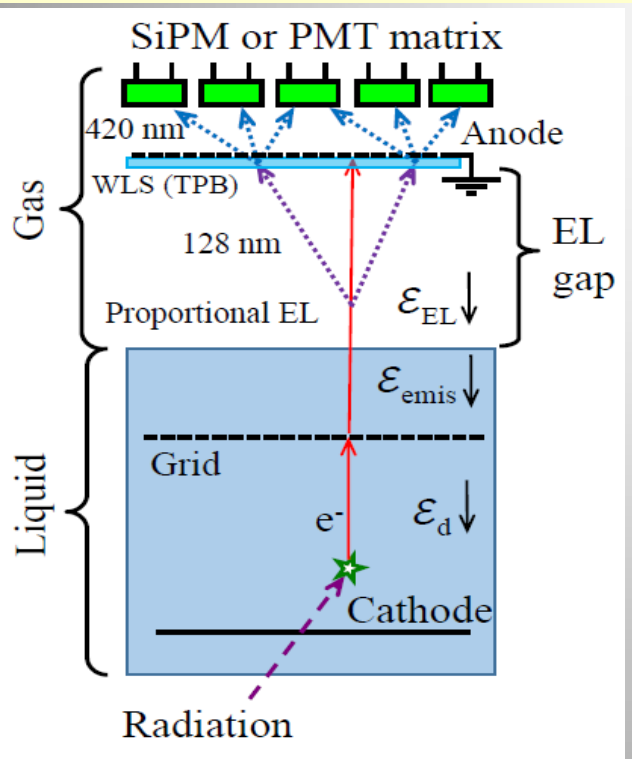
Charge gain of THGEM as a function of the THGEM voltage, at fixed electric fields in the drift and EL regions



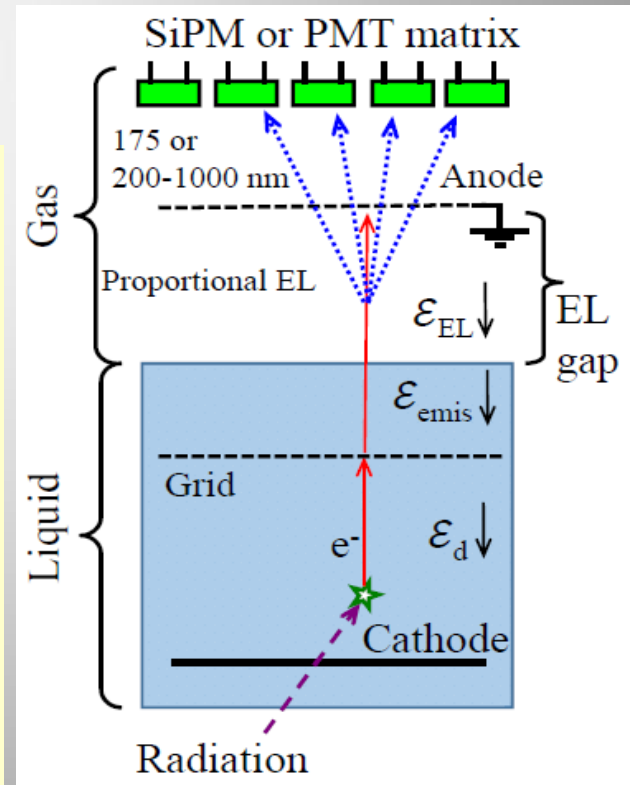
THGEM/SiPM-matrix yield as a function of the (reduced) electric field in the EL gap at the average energy of 82 keV, deposited by gamma-rays from ^{109}Cd source in liquid argon, measured at two THGEM charge gains

Section 2
Light signal amplification in the gas phase of two-phase detector, using proportional electroluminescence

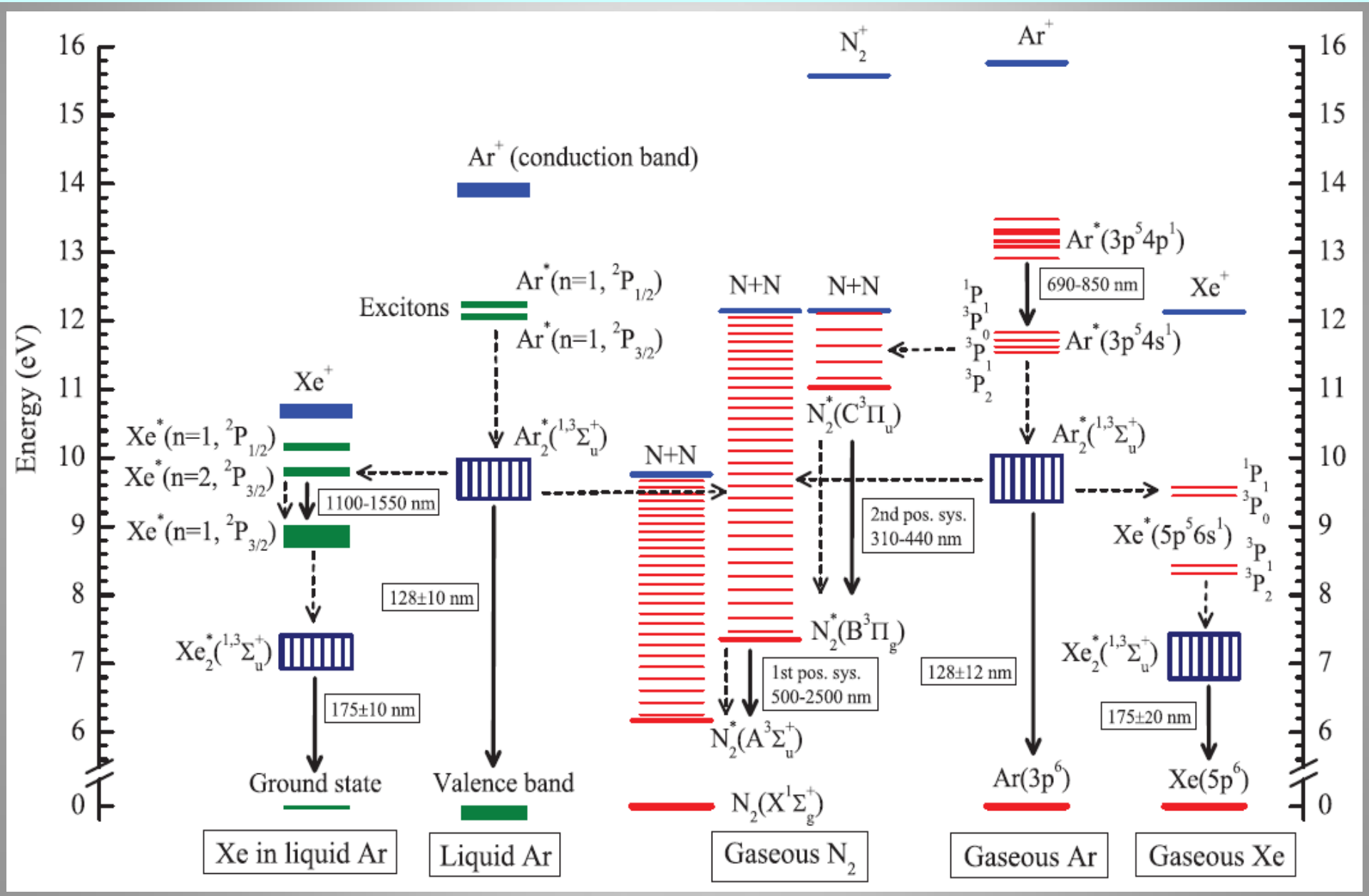
Concept with indirect optical readout via wavelength shifter (WLS), in two-phase Ar using excimer emission in the VUV at 128 nm.



Concept with direct optical readout, either in two-phase Xe using excimer emission in the VUV at 175 nm, or in two-phase Ar using neutral bremsstrahlung (NBrS) emission in the non-VUV range (at 200-1000 nm).

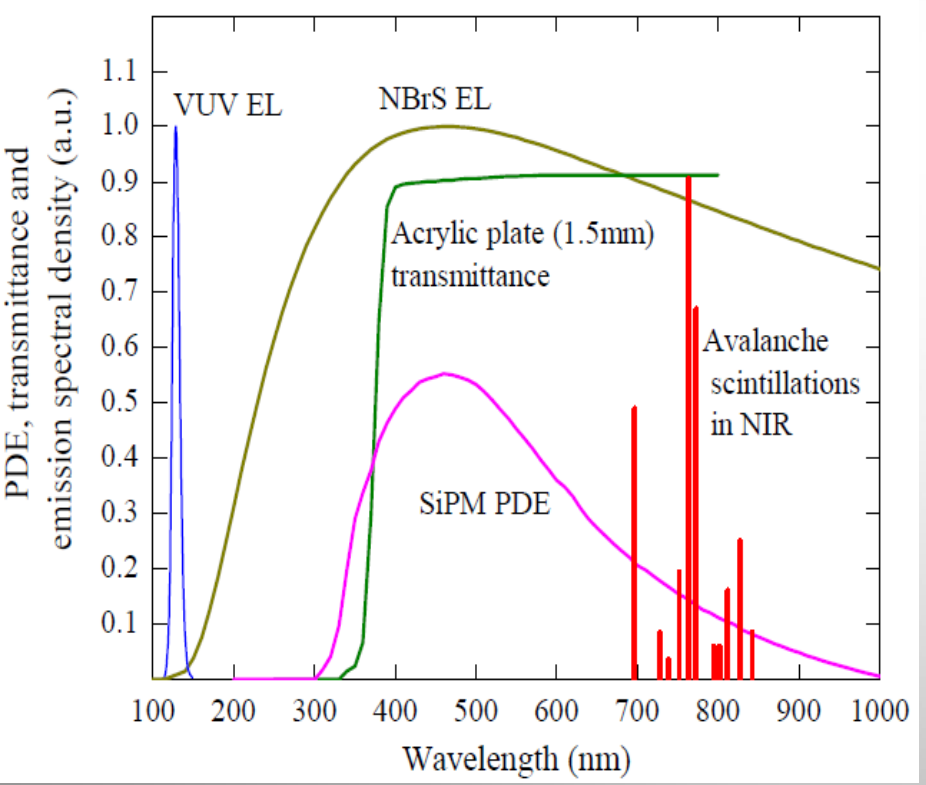


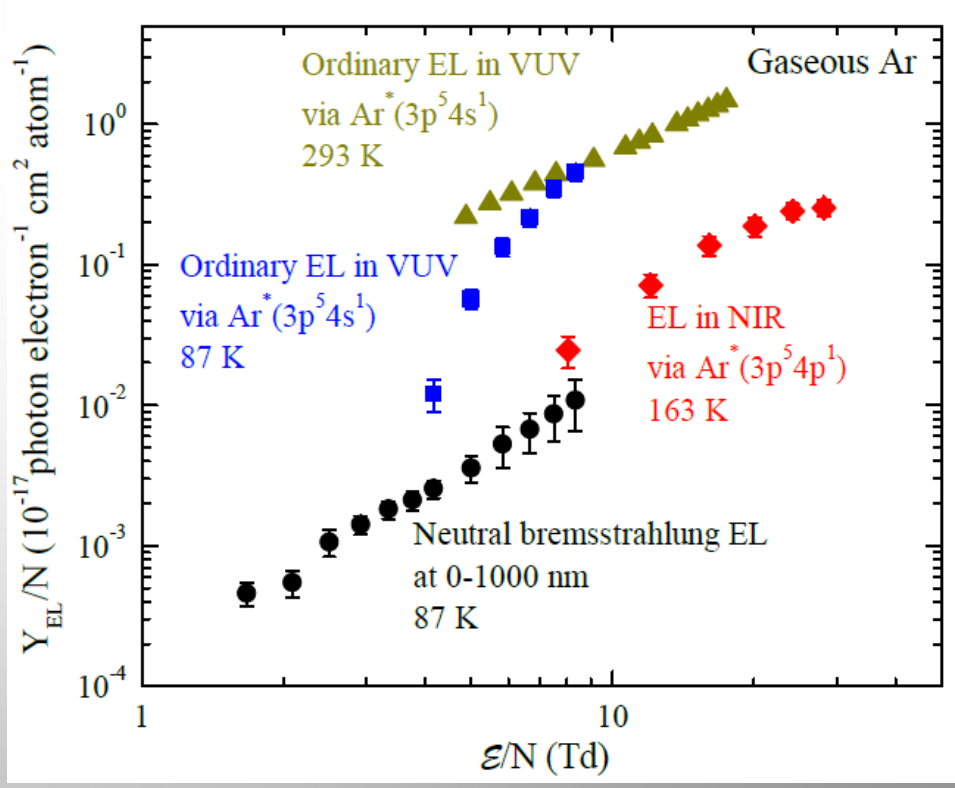
Energy levels of the lower excited and ionized states relevant to the ternary mixture of Ar doped with Xe and N2 in the two-phase mode (Buzulutskov, 2017).



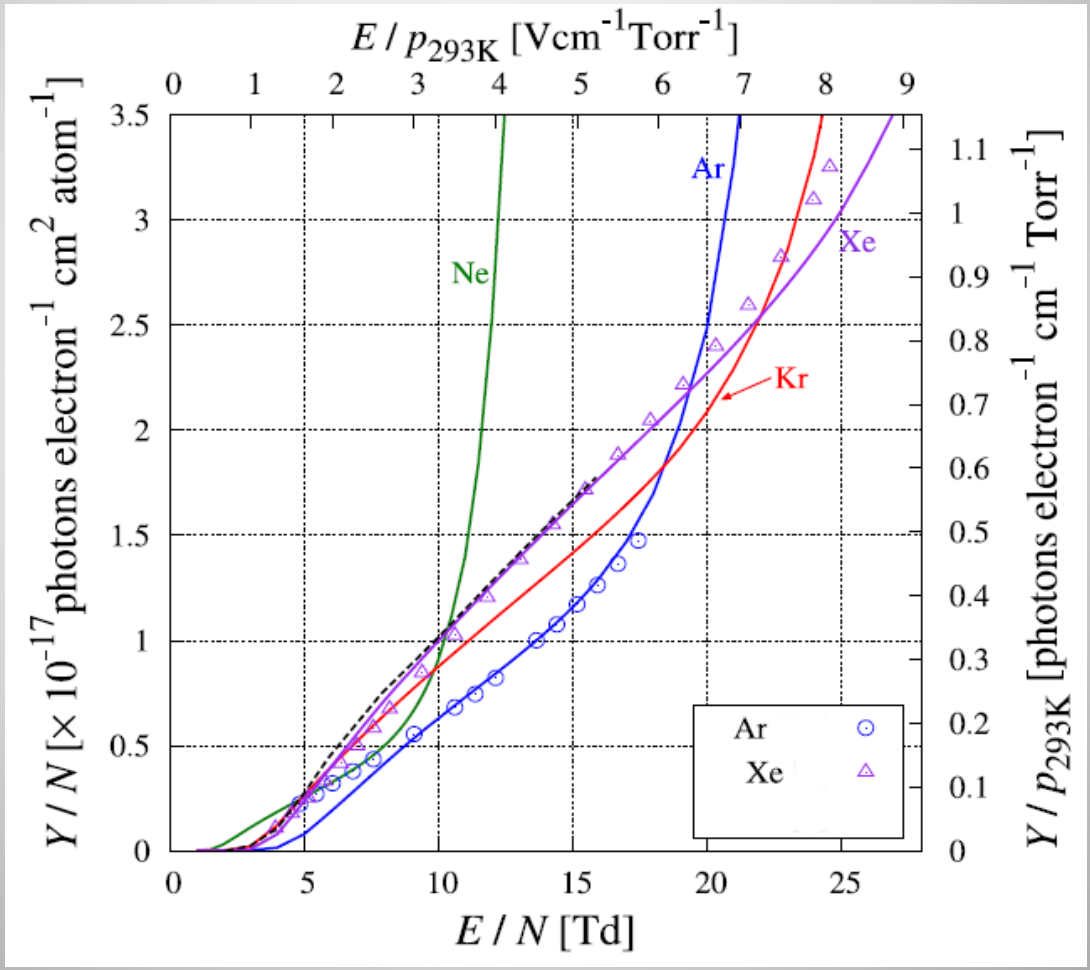
1. Photon emission spectra in gaseous Ar due to ordinary scintillations in VUV, neutral bresmsstrahlung (NBrS) electroluminescence (EL) at 8.3 Td and avalanche scintillations in NIR (Aalseth et al., 2020)

2. Summary of experimental data on reduced EL yield in gaseous Ar for all known electroluminescence (EL) mechanisms: for NBrS EL below 1000 nm, ordinary EL due to excimer emission in VUV and EL in NIR (Bondar et al., 2020)

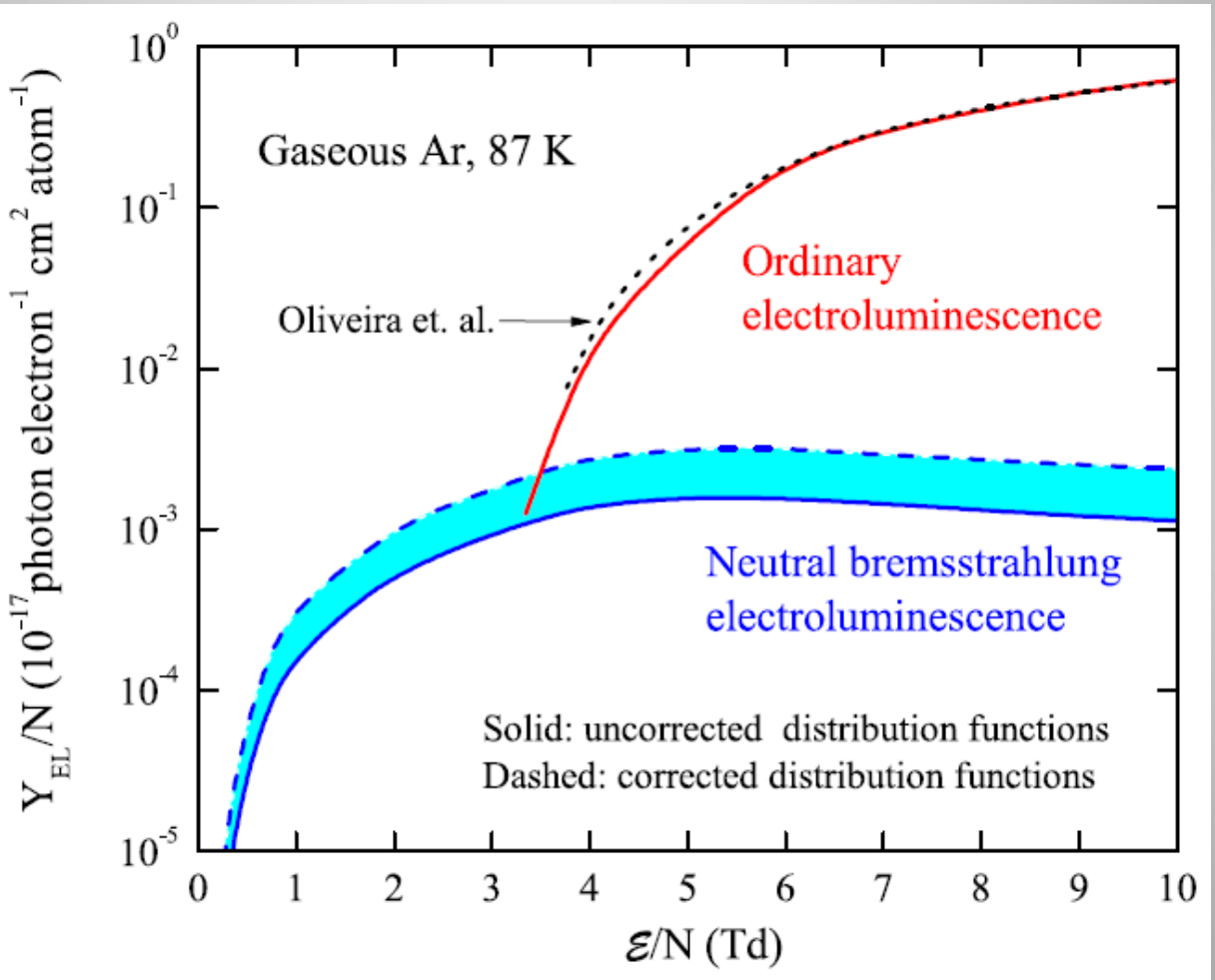




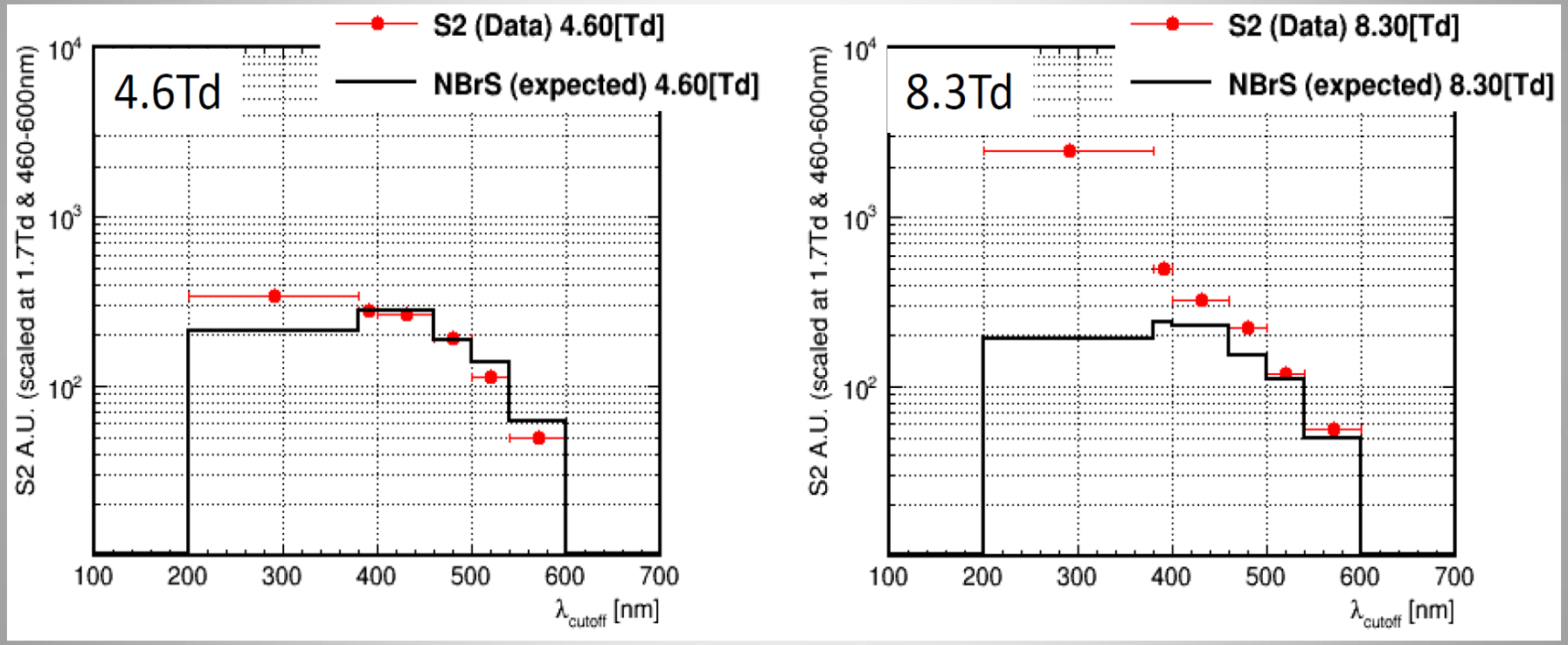
Measured reduced EL yield for ordinary (excimer) EL at room temperature (data points), as a function of the reduced electric field, compared with Monte Carlo simulation data (curves), for Ne, Ar, Kr and Xe (Oliveira et al., 2011).



Reduced EL yield in gaseous Ar as a function of the reduced electric field, for neutral bremsstrahlung EL (below 1000 nm) calculated theoretically in (Buzulutskov et al., 2018), compared to ordinary (excimer) EL calculated in (Oliveira et al., 2011).



Photon emission spectra of proportional EL in Ar in UV and visible range measured at room temperature in (Tanaka et al., 2020) (data points) in comparison with those of NBrS EL theory (Buzulutskov et al., 2018) (lines), at reduced electric field of 4.6 and 8.3 Td.



Reduced EL yield in gaseous Ar as a function of the reduced electric field, for atomic EL in NIR due to atomic transitions going via Ar*(3p54p1) excited states measured in (Buzulutskov et al., 2011) at 163 K (data points) and theoretically calculated in (Oliveira et al., 2013) (hatched area between two curves). For comparison, that for ordinary EL in VUV going via Ar*(3p54s1), theoretically calculated in (Oliveira et al., 2013) (solid curve), is shown.