Tracking in the Cryogenic Liquids:LHe, LHD, LNeon, LArgon

"There is always room at the bottom"

-R. Feynman, 1962

Bottom: tiny track width, energies, lowest radiation loss, "long" tracks, low backgrounds

Room: big volume, very pure, low background liquid

Collaborators

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+ Visito and Students

Applications: Solar pp fusion neutrinos, 423KeV>E>few KeV

- Most neutrinos come from the pp fusion reaction, with an average energy ten times lower than the threshold of the current real-time experiments in the MeV range; we aim to reach the KeV range detecting the electrons from νe scattering, allowing precision measurements of neutrino disappearance and matter effects from the spectrum of neutrinos observed through the scattering on target electrons, and comparison of neutrinos from different reactions provides unique information on the physics of the Sun
- Very high space resolution and low energy reach allows other applications, such as recoil nucleus measurement, neutrino magnetic moment…

2004 APS Neutrino Matrix Report

- **Third (of 3) Recommendations:**

"We recommend development of an experiment to make precise measurements of the low-energy neutrinos from the Sun."

"A precise measurement of the low-energy neutrino spectrum would test our understanding of how solar neutrinos change flavor, probe the fundamental question of whether the Sun shines only through nuclear fusion, and allow us to predict how bright the Sun will be tens of thousands of years from now."

Detector requirement for very low energy neutrino physics

- **Fine spatial resolution on sub-MeV tracks**
  - **For identification of electrons/nuclei**
  - **For Range measurements**
  - **For Compton rejection**
  - **For track angle measurement**
  - **For z measurement by track width**
- **Good total charge measurement for energy resolution, with high ionization**
- **Energy thresholds down to KeV level**
- **Low background means great purity, self shielding, and "Compton Cluster" rejection**
- **One ton gives ~ 200 solar neutrino events/ year**

The Voxel Challenge

(pixel = 2-D detection element, voxel = 3-D element)

- **We are looking for sub-mm resolution, so a cubic meter has ~10^{12} voxels.**
- **The challenge is to obtain the fundamental resolution, supply a thinkable detector structure and to read it out.**
- **For a homogeneous medium, one dimension must use a drift, so the resolution is limited by diffusion. The Einstein-Nernst law for thermal diffusion**

$$\sigma = \sqrt{\frac{2kTd}{eE}}$$

gives us few handles to get the desired resolution once we have fixed, d, the dimension of the detector: seemingly Temperature and E-field.

- **For pure noble fluids, the electrons heat up in even modest electric fields, T reaches hundreds or thousands of degrees; another handle is "*keeping cool (thermal)*".**
- **A massive charge carrier, like an ion, remains thermal for much higher E.**
- **Diffusion is thermally driven; lowering the temperature T cuts diffusion.**
- **The equilibrium negative charge carrier in low-T helium hydrogen and neon is not a free electron, but a 2nm bubbles containing the electron (or electrons). The positive carrier is a "snowball" with ion^{+} inside, with comparable mobility.**
- **We want to track electron-bubbles in these fluids; they are massive, stay at low temperature and subject to manipulation by their atomic properties.**
- **The origin of the bubble is a strong (Pauli) repulsion between the electron and the helium atoms. For heavy atoms like Argon, this is compensated by the polarization of the atom.**

Thermal Diffusion in Helium and Neon

distance	sigma	V / m	T (K)	velocity	N / mm	"+/-" $error_y(z)$
m	µm			cm/s		µm
Helium						
0.01	60.24	2000	4.21	0.4	780	2.16
0.1	190.50	2000	4.21	0.4	780	6.82
1	602.41	2000	4.21	0.4	780	21.57
10	1905.00	2000	4.21	0.4	780	68.21
100	6024.13	2000	4.21	0.4	780	215.70
0.01	19.05	20000	4.21	4	780	0.68
0.1	60.24	20000	4.21	4	780	2.16
1	190.50	20000	4.21	4	780	6.82
10	602.41	20000	4.21	4	780	21.57
100	1905.00	20000	4.21	4	780	68.21
0.01	6.02	200000	4.21	40	780	0.22
0.1	19.05	200000	4.21	40	780	0.68
1	60.24	200000	4.21	40	780	2.16
10	190.50	200000	4.21	40	780	6.82
100	602.41	200000	4.21	40	780	21.57
Neon						
0.01	152.84	2000	27.1	0.032	7300	1.79
0.1	483.32	2000	27.1	0.032	7300	5.66
1	1528.40	2000	27.1	0.032	7300	17.89
10	4833.24	2000	27.1	0.032	7300	56.57
100	15284.04	2000	27.1	0.032	7300	178.89
0.01	48.33	20000	27.1	0.32	7300	0.57
0.1	152.84	20000	27.1	0.32	7300	1.79
1	483.32	20000	27.1	0.32	7300	5.66
10	1528.40	20000	27.1	0.32	7300	17.89
100	4833.24	20000	27.1	0.32	7300	56.57
0.01	15.28	200000	27.1	3.2	7300	0.18
0.1	48.33	200000	27.1	3.2	7300	0.57
1	152.84	200000	27.1	3.2	7300	1.79
10	483.32	200000	27.1	3.2	7300	5.66
100	1528.40	200000	27.1	3.2	7300	17.89

Compton clusters

- The good energy and spatial resolution and large size give a powerful capability for recognizing "Compton clusters," chains of scatterings initiated by photons entering from outside. Each secondary photon from successive scatters has a lower energy, and a decreased absorption length, leading to events with a number of scattering vertices easily recognized as a Compton cluster.
- Our calculations indicate large rejection factors by Compton cluster recognition (on the order of hundreds, depending on the source).

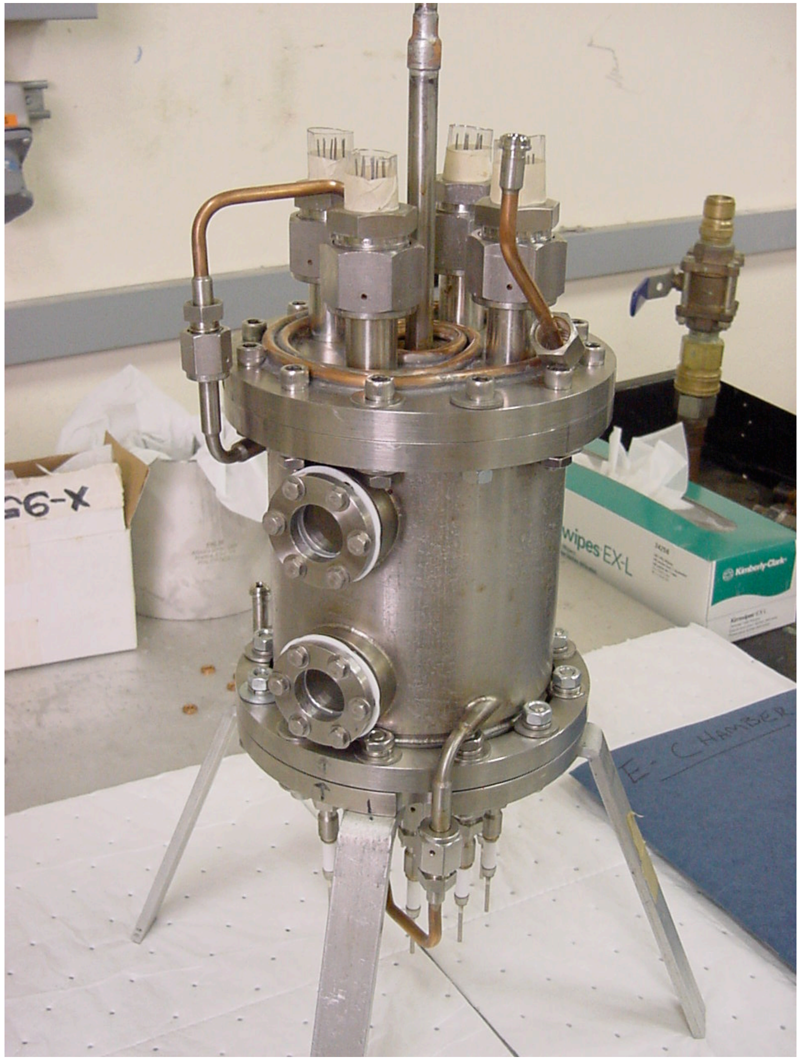
Environment background photon flux

- **We (A. Levine) calculated the equilibrium distribution of photons emitted by U and Th and all decay products. After filtering with water and nitrogen shielding, 95% of the photons reaching the detector are from the 2.614 MeV line from Thorium daughter Tl^{208}, at a few per day (reduced from 40 million). The Compton Cluster cut and angle cuts can bring backgrounds below the signal: the background rates go down with energy in the region below ~100KeV. Self shielding takes over, if the detector medium is really pure.**

We needed key physical measurements to move forward, as well as practical experience: a Test Chamber has been constructed on the 10 cm scale:

- **Five windows transmitting from infra-red to UV**
- **Lots of HV feedthroughs**
- **Lots of Signal feedthroughs**
- **Temperature and pressure over a wide range, ~1K-300K and up to ten atmospheres, above the critical pressure in He,**
- **A field cage for uniform drift field**
- **A photoelectric source for accurately timed current pulses from a Xe flash lamp**
- **Alpha and spontaneous fission source from ^{254}Cf**
- **A tungsten needle with 200 nm tip for field emission into the liquids**

Prototype eBubble Detector

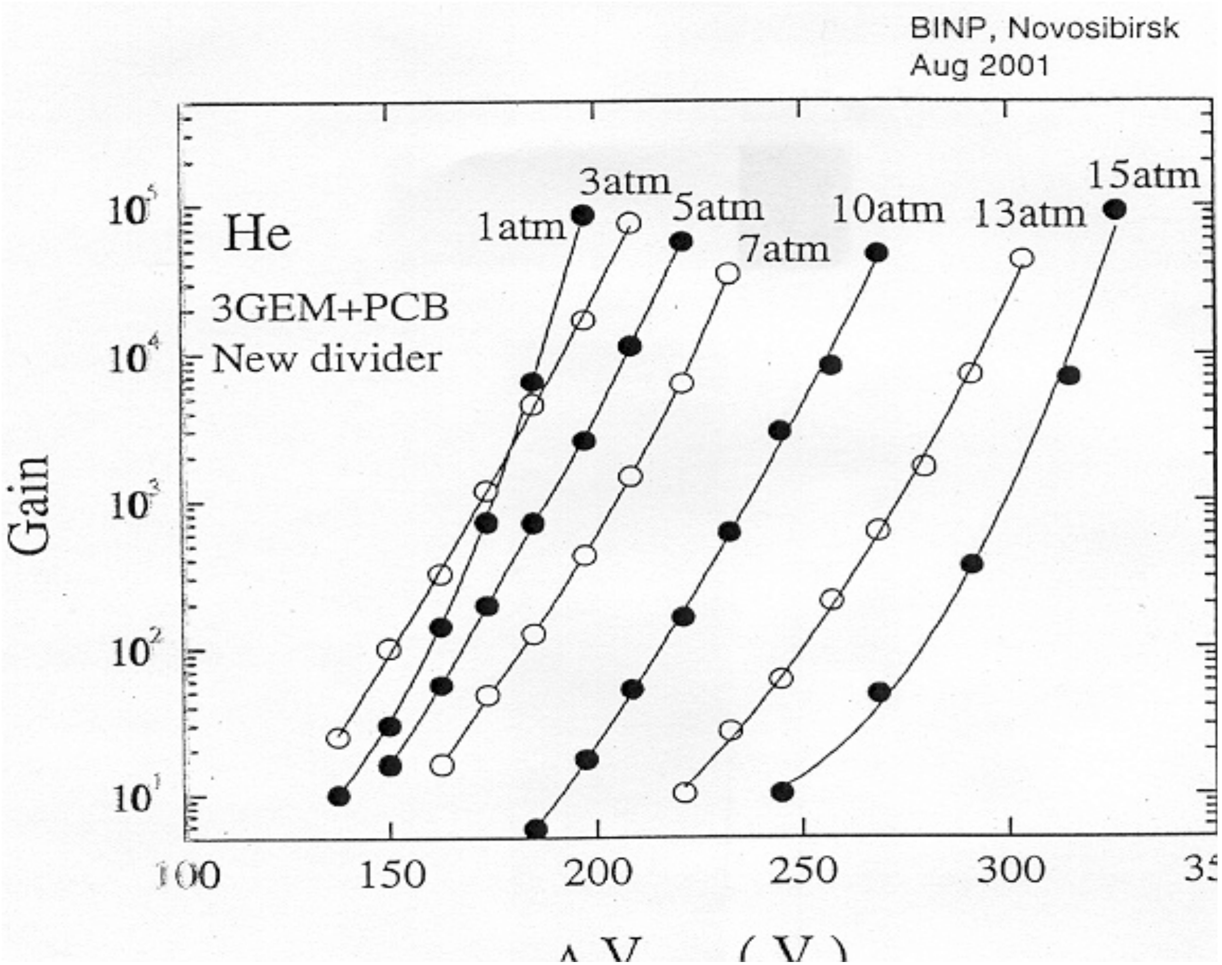


Readout!

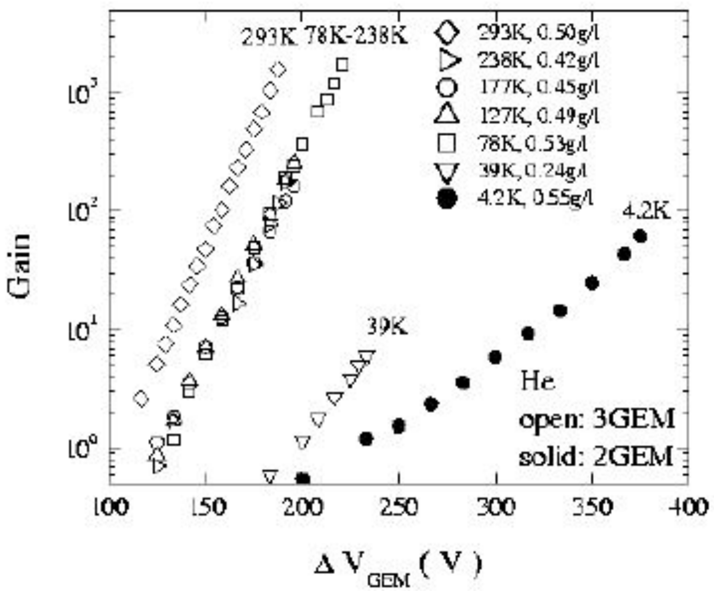
- Consider $2m^3$ with 2m drift in a Solar Neutrino Detector: there are 0.6×10^{12} voxels to read for $(0.15mm)^3$ voxel.
- Drift at 10 cm/s through 2m in 20 seconds (yes, we have simulated convection).
- We see the slow drift time is very useful! Our signals are stored in the detector volume and we deal with them one plane at a time, every millisecond.
- Zero suppression reduces this to < a few kHz.
- We have extracted electrons through the liquid surface, but we also work in vapor, where the electrons are still localized and thermal.
- We obtain gain by amplifying them in a three-stage GEM.
- We use an optical readout, described below, observing light from a GEM avalanche detector giving gain > 1000
- The readout plane must then sample 25×10^6 pixels,m^2, with 7 commercial available cameras at 3M pixels/camera. We have a DOE ADR grant to buy such a camera.

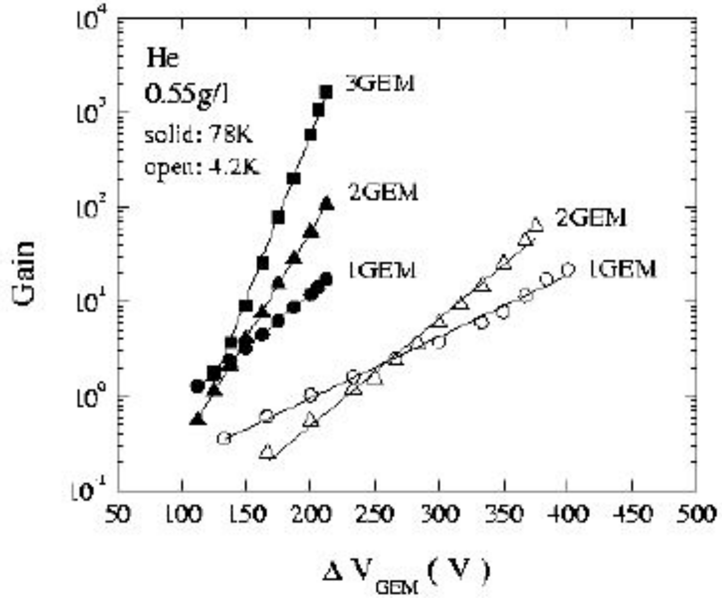
With extraction into vapor, we are set for gain:

Our collaborator A. Buzulutzkov first investigated GEM in high pressure He, to simulate the high density at low temperature. Alexei found good operation in all noble gases *with no quencher (?!).* In He, unlike common gases, the performance holds up at high pressure:

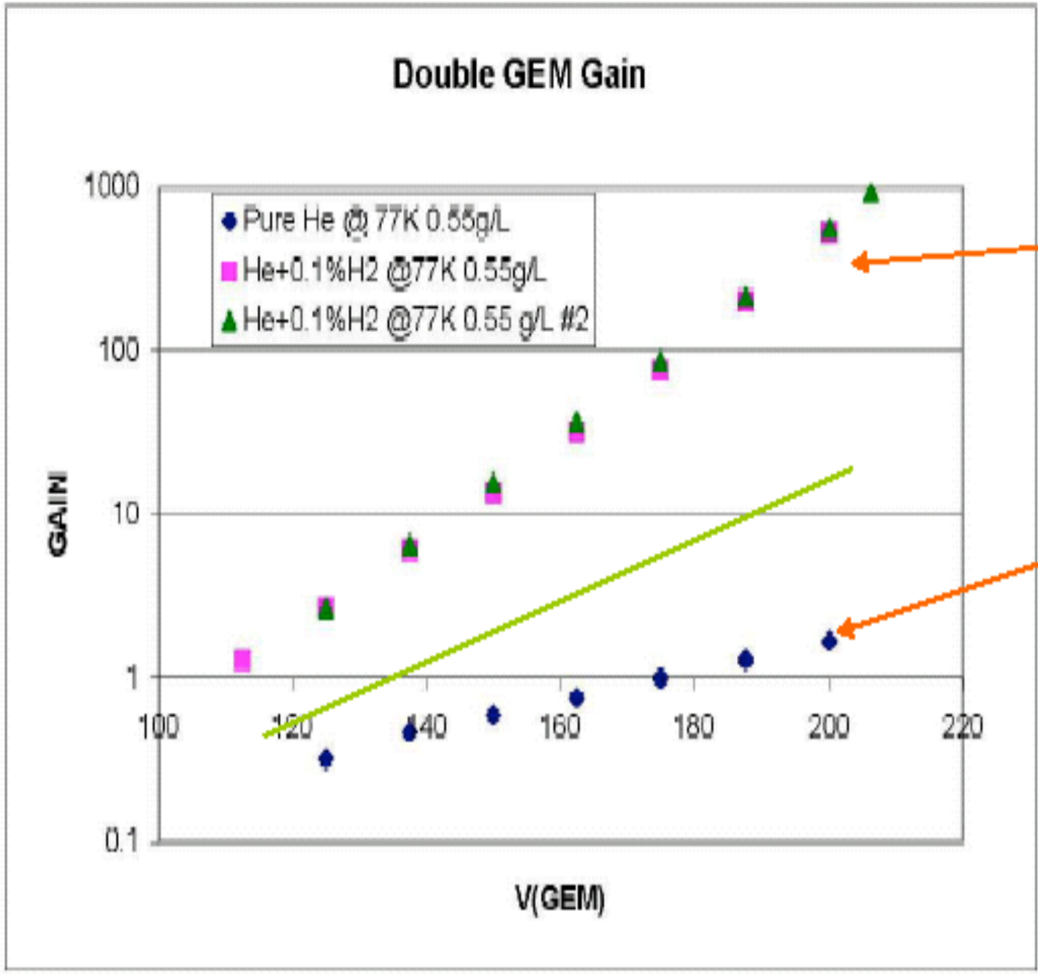


Helium gain results, with very pure gas, with getter purifier, with ordinary "ultra pure:" there was a temperature dependence



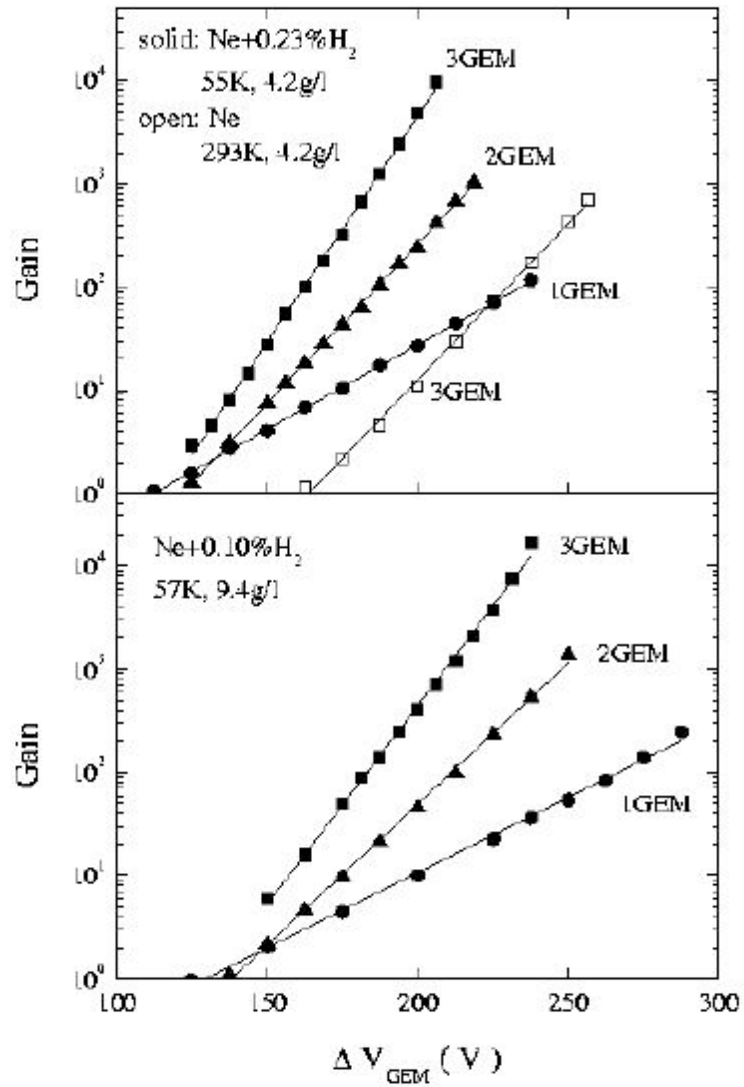


Very pure Helium (getter)



- He+H2 mixtures show higher gain than Pure He.
- Pure He lower gain than Alexei's measurements

Neon results, with and without H2



Summary of GEM Studies:

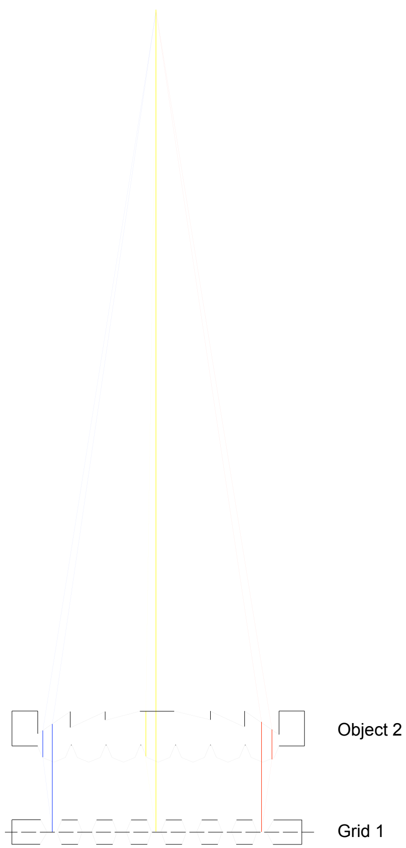
- There is little true temperature effect in very pure gas, with Nitrogen eliminated by a getter, for example
- Both Ne and Neon with hydrogen doping give more than 10,000 gain in 3 GEM configuration
- Helium must be at ~10, i.e. supercritical, 5 bar to add enough Hydrogen to quench
- Neon can be at 1bar

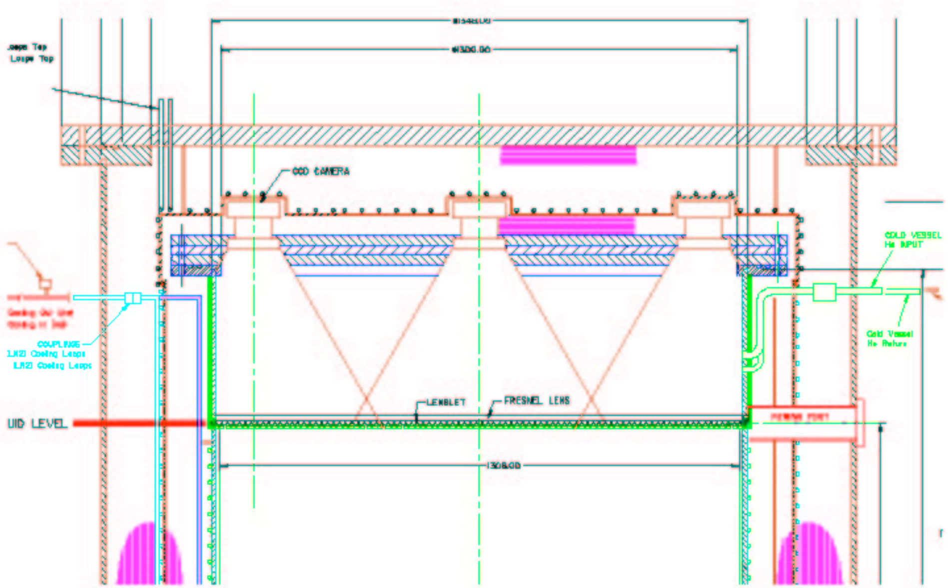
- We now move on to studying the LIGHT output of the GEM
- This light comes from a 20 micron core of the GEM aperture, i.e. a rather bright source: we need to match it to a detector

Matching light from GEM to camera

- We image each GEM hole to a CCD camera, to get granularity of ~150micron in the detector plane
- We want to collect much more light that a bare system would give, with say 2cm lens at .5m
- The tiny source (20 microns) allows this if we have a field lens covering each GEM hole, nearby with f/4
- We do have such a device, a “lenslet,” on the same 0.15mm pitch and f/7, available on large plastic sheets at low cost, rendering the light “parallel” with a waist at 0.5m

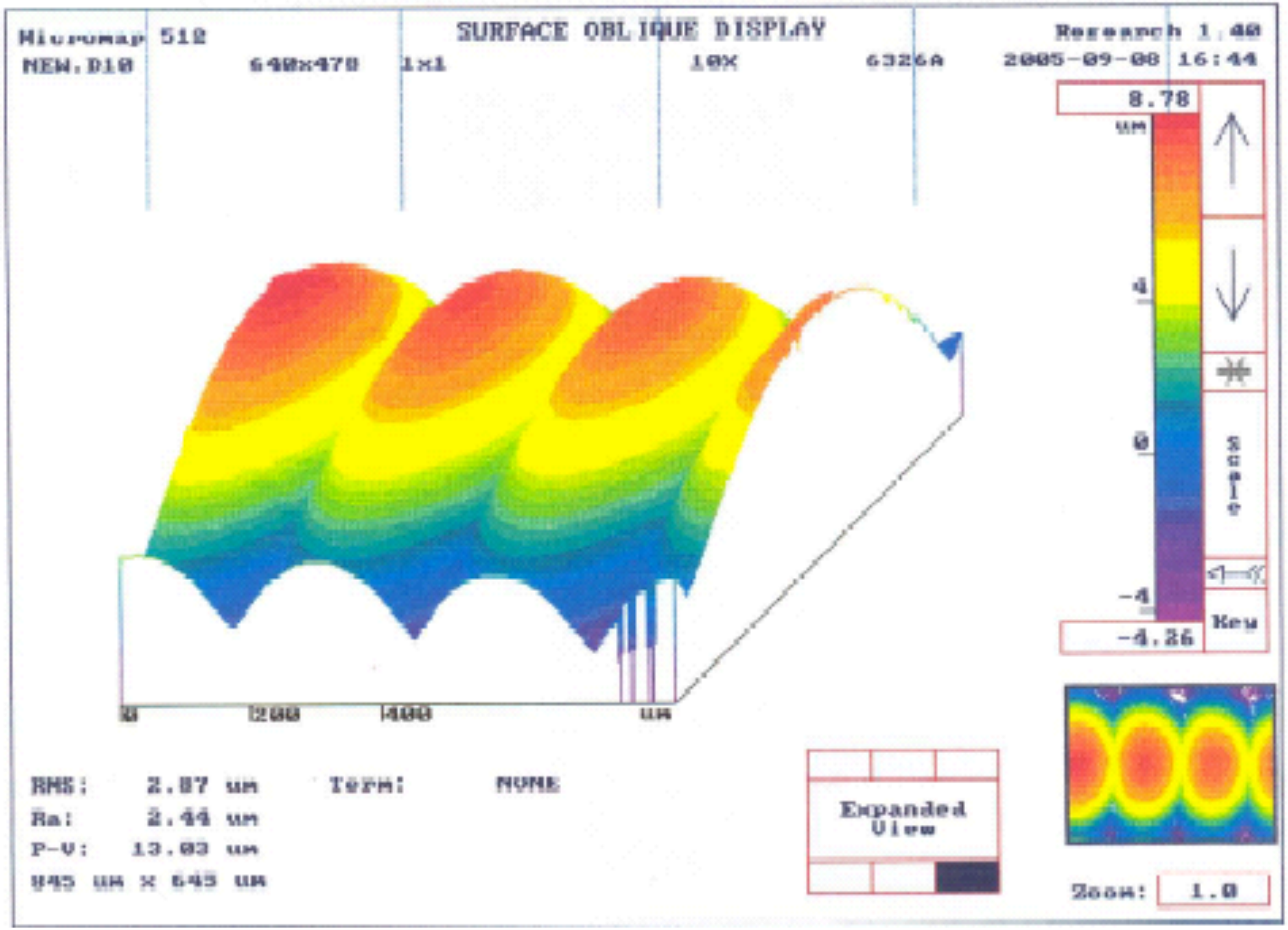
Lenslet optics for GEM readout





Lenslet array, plus Fresnel lens, to focus light from GEM holes onto camera plane

Profile measurement of lenslet



Light collection efficiency

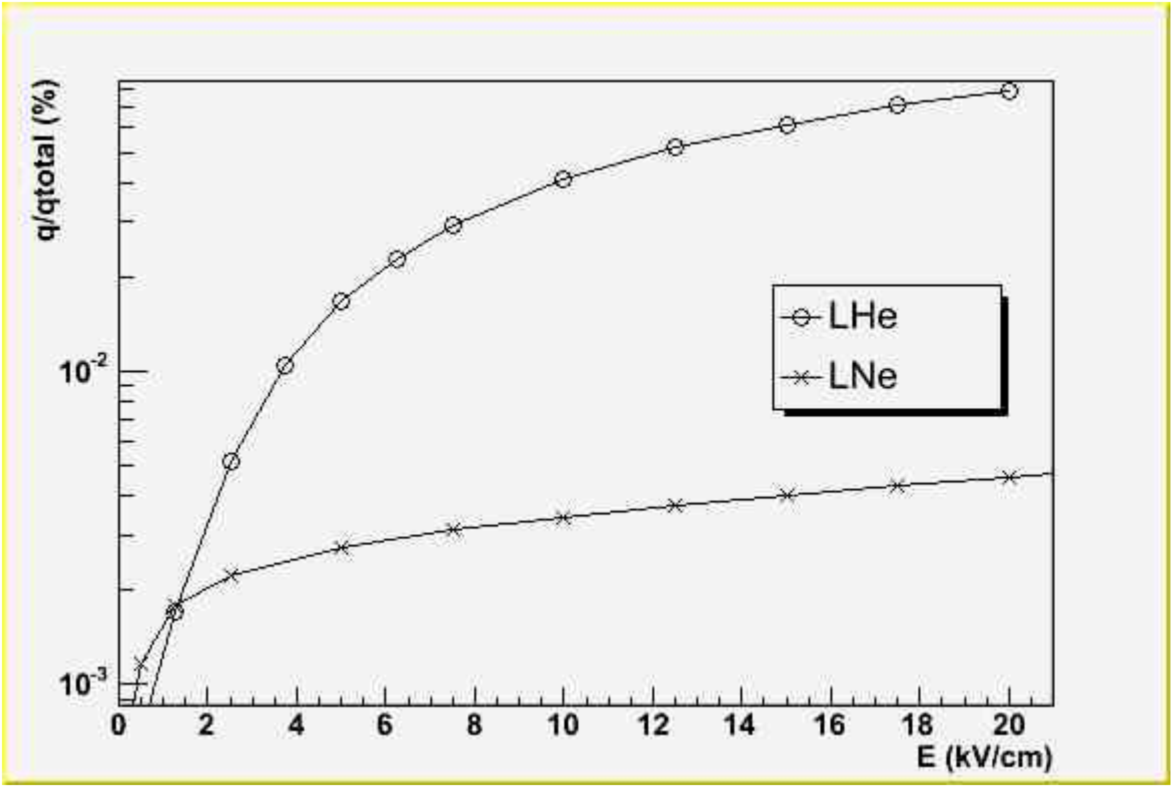
- P.Takacs (BNL Instrumentation) has measured the quality of the lenslet
- He has run a detailed transport of the light collection, finds we can get about 5%
- A simple camera would have about a thousand times worse light collection

- Next we will measure the light output of the GEM, crude look shows a lot of light:
  - Note that the GEM is essential: the primary light in noble gases is in the VUV, it is the transfer of the excitation to the triplet states in the avalanche that gives visible light
  - Commercial CCD cameras will serve the readout

Control of Fluid Density

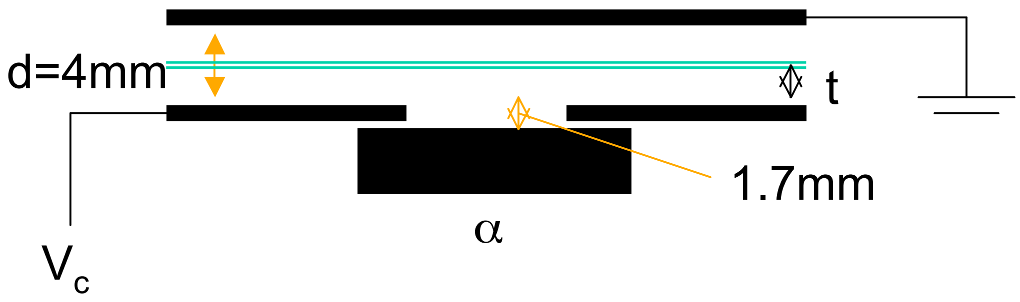
- Our push to lower the energy threshold for track measurement has been confirmed by understanding that the interest in measuring the form of the spectrum for solar pp neutrinos is at the low energy end; note that the electron energy spectrum is a convolution of the neutron spectrum with the scattering energy partition.
- A search for other processes (thermal neutrino production for example) is centered on low energies, those below 50KeV, where the electron is not a minimum ionizing particle.
- The recombination of electrons and ions on tracks is highly dependent on fluid density; we have found that the density of the liquid state (particularly for Neon) is probably too high to allow good measurement of densely ionizing tracks.
- This has led us to investigations of GEM performance in the vapor at pressures up to 10 atmospheres and we are considering going to 30 atmospheres.
- This also opens up the possibility of measuring the recoil nucleus, in WIMP scattering, enhanced by the high spatial resolution allowed by the diffusion limit in our system.

Recombination:

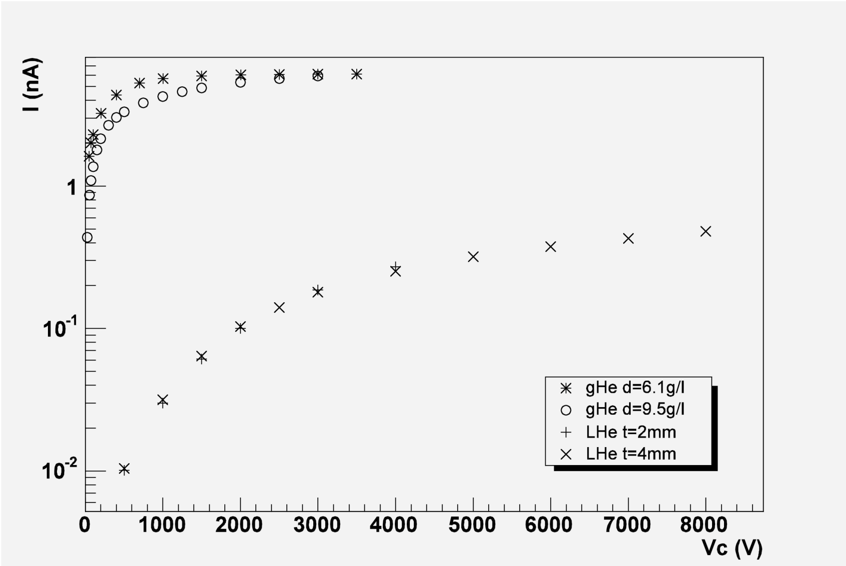


*Internal conversion sources not advertised (isotopes?)

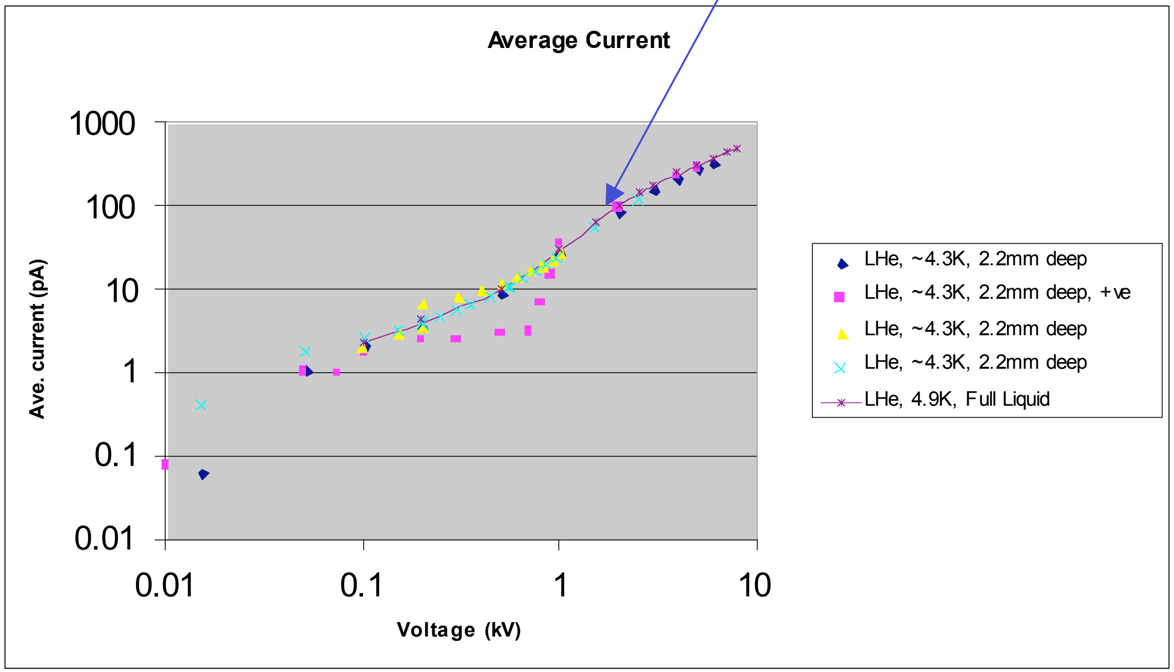
LNe surface measurements



LHe



No surface pulsing observed in -ve case



Summary

- Fluid Helium seems to have the right properties, including recombination at about 10K
- Liquid Neon has long trapping time with the fields and temperatures we have used so far
- Probably the density of the LNe is too high for recombination as well, we will investigate lower density in the near future
- We have some more R&D to do, then we will look at a one ton detector