An eBubble TPC for Low Energy Neutrino Detection

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Coherent Neutrino Workshop

December 6, 2012

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1932 - 2012

Continuing my long-standing interest in using the electron transport in noble liquids to develop new particle detectors, I have started to work with liquid helium and neon, where the charged state is unusual, an electron in a cavity, an "electron bubble." The use of this state for tracking offers unusual opportunities for applications to studies of neutrinos, due to the high spatial resolution and low backgrounds available in large volumes. There are outstanding questions in the physics of the electron bubbles that we wish to study for the tracking applications we are pursuing and well as for their own interest.

From Bill's Faculty Bio page at the Columbia University Physics Department web site

The eBubble Detector

The electron-Bubble (eBubble) Project was motivated as a low-energy solar (pp fusion) neutrino detector looking at elastic scattering on atomic electrons

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

with good energy resolution and directional track determination for neutrinos below 300 keV.

In helium and neon, thermalized ionization electrons produced by neutrino scattering recoils are trapped in a vacuum bubble states (ebubbles) along the original trajectory.

The ebubble states are thermal carriers, ensuring minimum diffusion, and therefore highest spatial resolution.

BUT, we need gain to approach lowest neutrino energies, AND we want optical readout to use commercial CCD readout.

Baseline is critical density Ne at 0.48 kg/l (~26atm@ 44K)

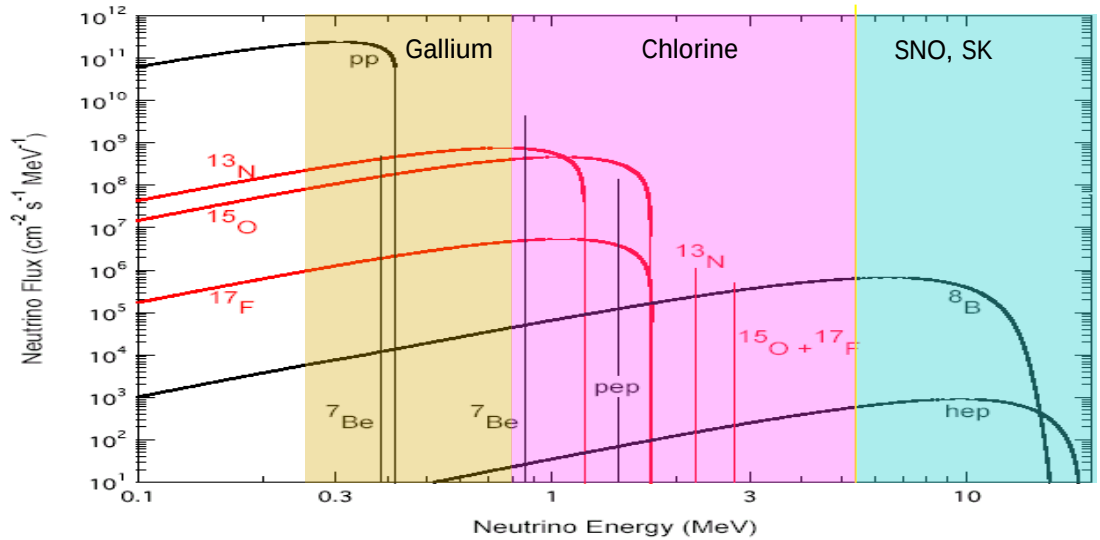
Our Signal: Recoil Energies

The electron-bubble (eBubble) Project was originally proposed as a low-energy solar (pp fusion) neutrino detector looking at elastic scattering on atomic electrons

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

with good energy resolution and directional track determination for neutrinos below 500 keV.

Enu	Ee
2.	0.0155
5.	0.096
10.	0.377
20.	1.45
50.	8.18
100.	28.1
200.	87.8
500.	331.
1000.	796.



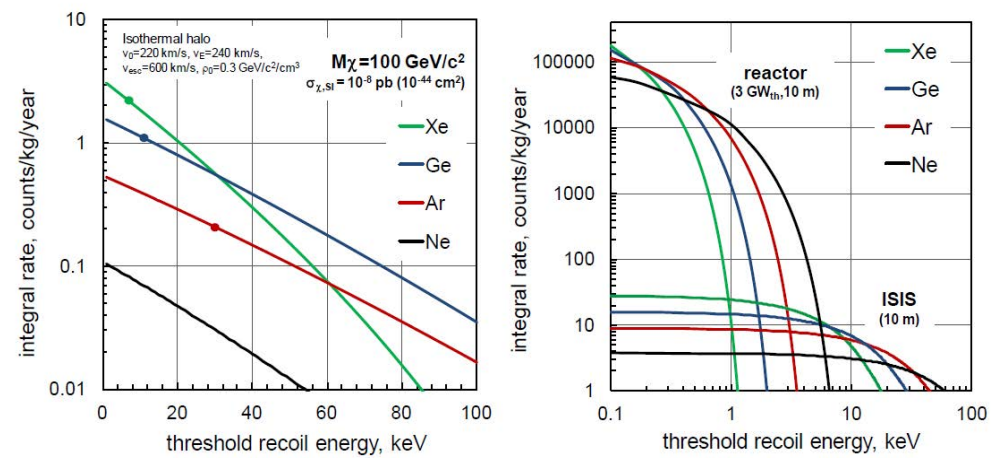
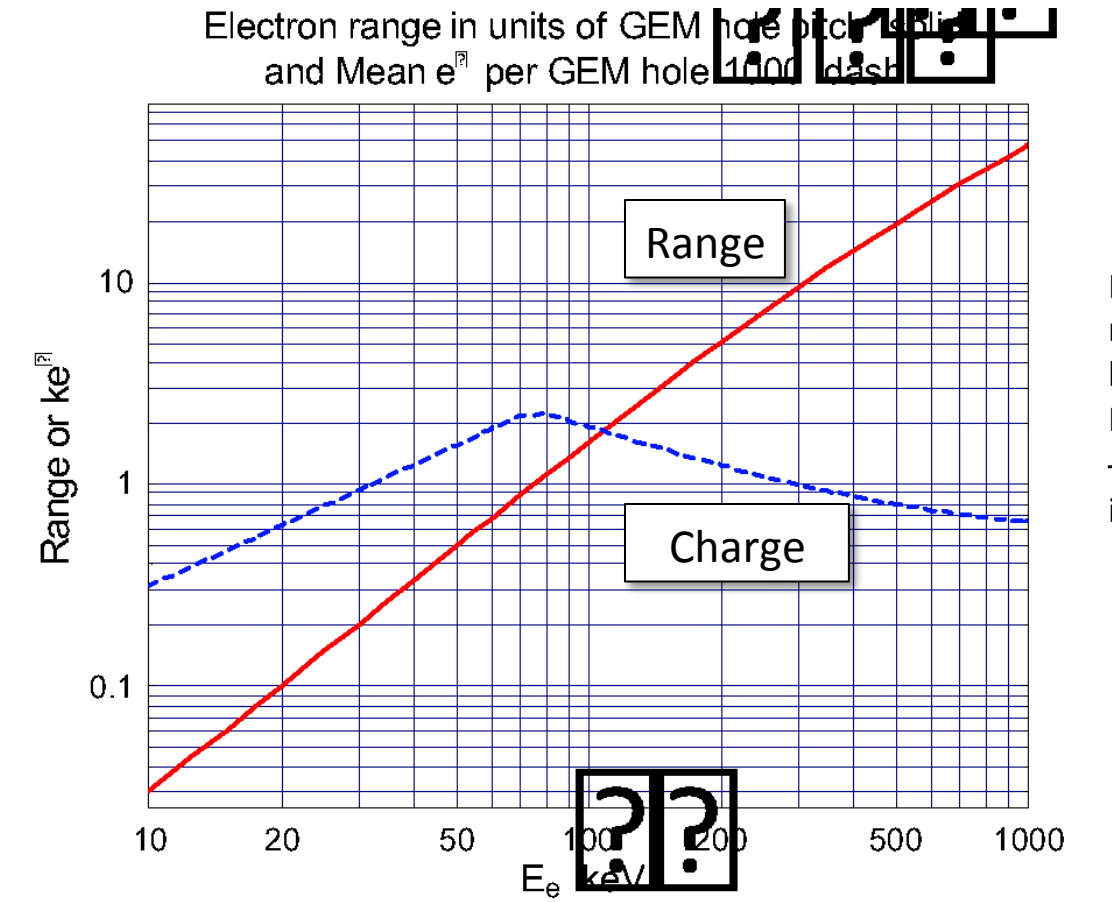


Figure 1: Predicted integral spectra for WIMP elastic scattering (left) and for coherent neutrino-nucleus elastic scattering (right) for Xe, Ge, Ar and Ne (in order of decreasing rate at zero threshold). Both plots assume perfect energy resolution.

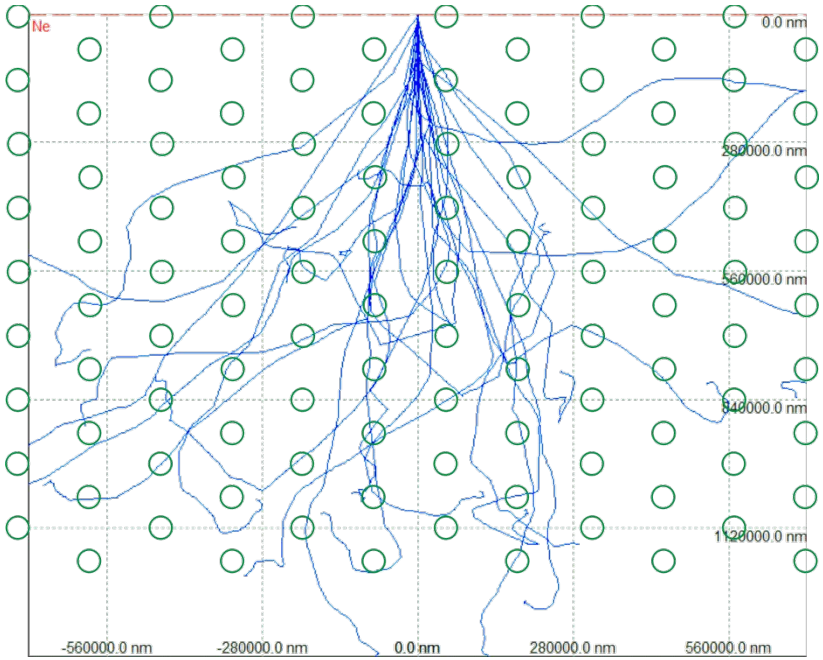
Electron Range and Specific Ionization in Critical Density Neon



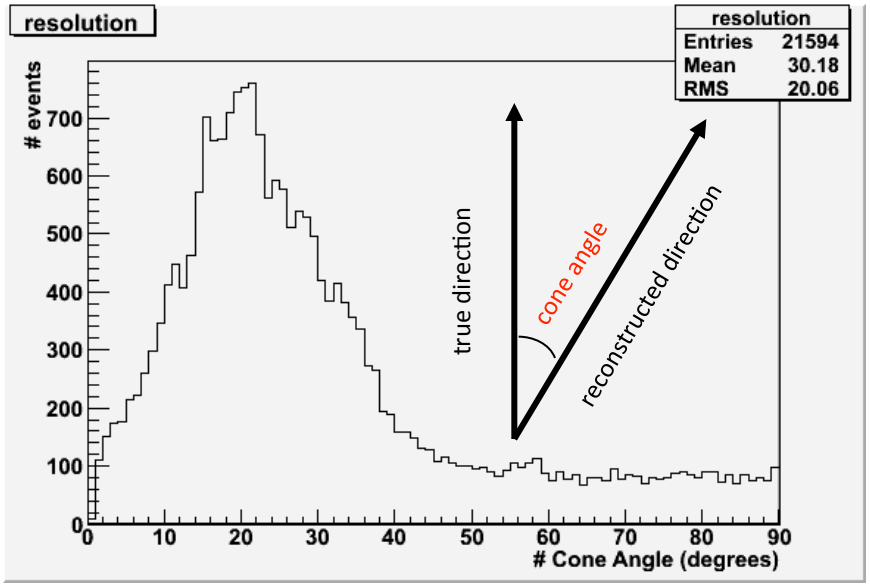
For charge, recombination must be included:
Free electrons are 0.4 – 0.8x initial ionization

Range and specific ionization for electrons in critical density neon from NIST database ESTAR (http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html).

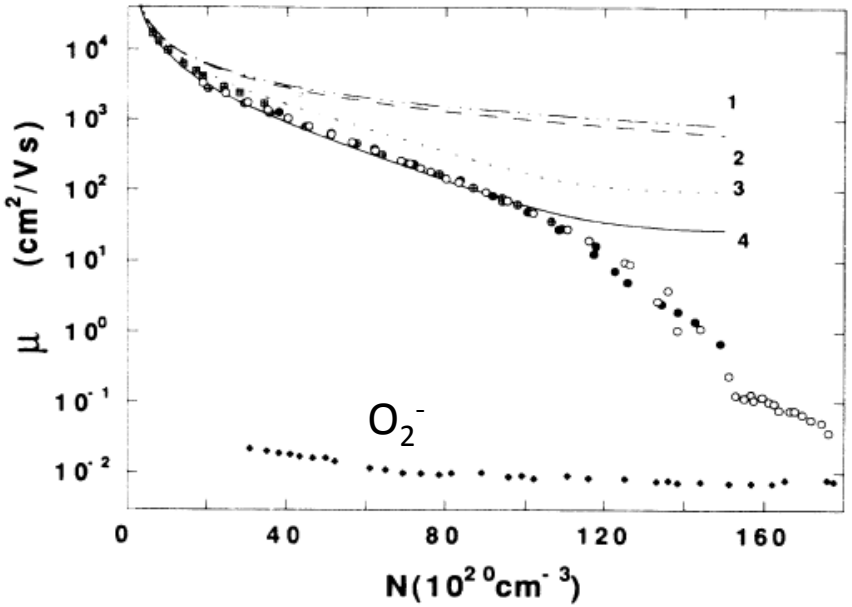
Pointing Resolution : CASINO simulation of 250 keV electrons in 0.483g/cc of Ne



- Fit projections xy, yz, xz. errors weighted by energy of pixels/total
- first 3 or 4 pixels



The eBubble State

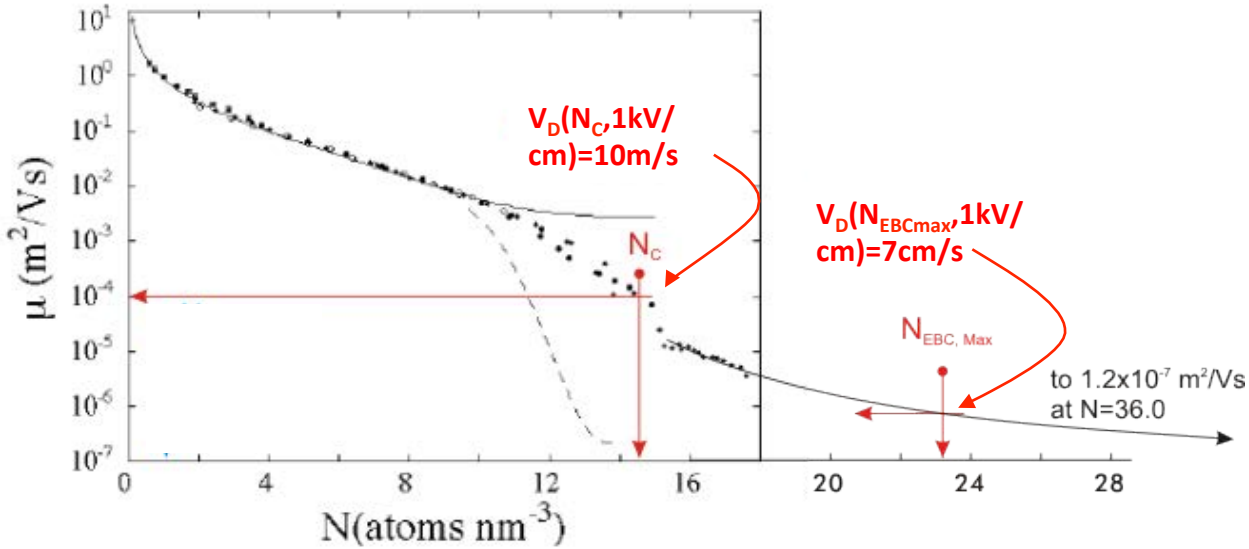


A.F.Borghesani and M.Santini, *Electron mobility and localization effects in high-density Ne gas,* **Phys. Rev. A42**, 7377, (1990).

- Free electrons in high density helium and neon have been shown to be localized in bubbles in the fluids consisting of an electron in an atomic void.
- The formation of electron-bubbles (ebubbles) is due to the Pauli repulsion between the electron and the atomic electrons of the bulk fluid.
- The increasing polarizability and surface tension of heavier noble liquids (Ar, Kr, Xe) prevents the formation of an ebubble state.
- The ebubbles are thermal and therefore have minimum diffusion.
- Mobility can be varied by changing fluid density
- eBubble state is destroyed at high electric fields (as in GEM holes)

Mobility and Diffusion of Electrons in High-Density Neon

$kT_{FLUID}=D/\mu$ for eBubbles



Zero-field mobility in Ne at 45K vs. density, extrapolated to the liquid state

N_C is the critical density
$N_{EBC,Max}$ is the maximum density obtainable in the EBC (40 atm)

Data from
Borghesani, IEEE Trans Dielectrics **13** (2006) 492 (Fig. 8)
and
Bruschi *et al.*, PRL **28** (1972) 1504

Normal boiling point

$\rho_{NBP} = 1.207\, g/ml = 36.03\, atoms/nm^3$

At maximum density in EBC

$T = 45K,\ P = 40\, ATM$

$\rho = 0.77683\, g/ml = 23.19\, atoms/nm^3$

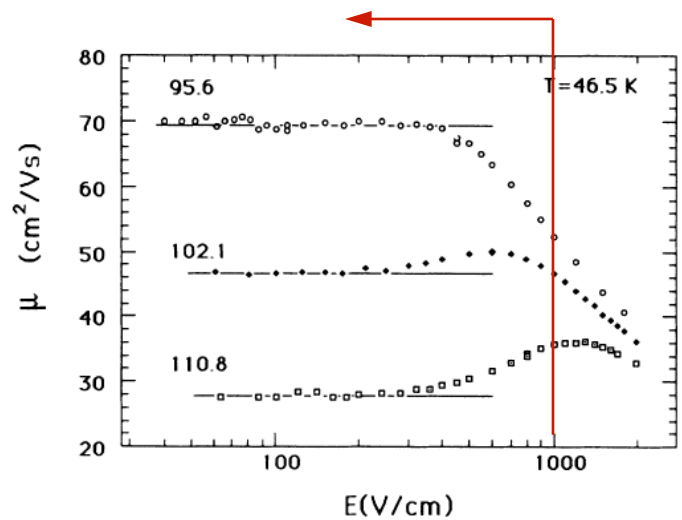
$E_{Drift} = 1kV/cm$

$v_{Drift} = 0.07\, m/s$

$\Delta t_{Drift} = 14\, s\ \ for\ 1\, m\ drift$

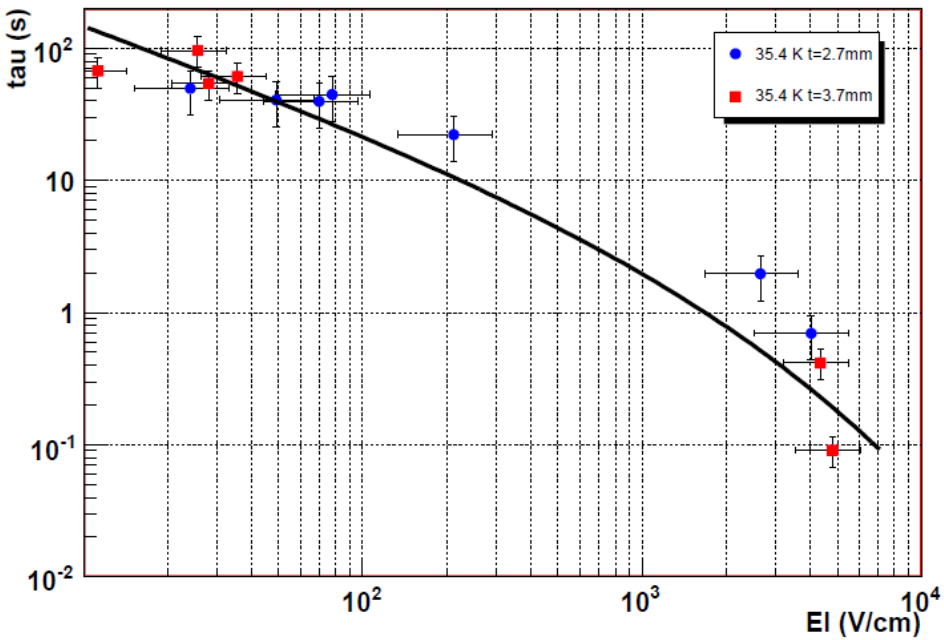
$D_{Einstein} = 2.7\times10^{-9}\, m^2/s$

$\sigma_T = 280\, \mu m\ \ for\ 1\, m\ drift$

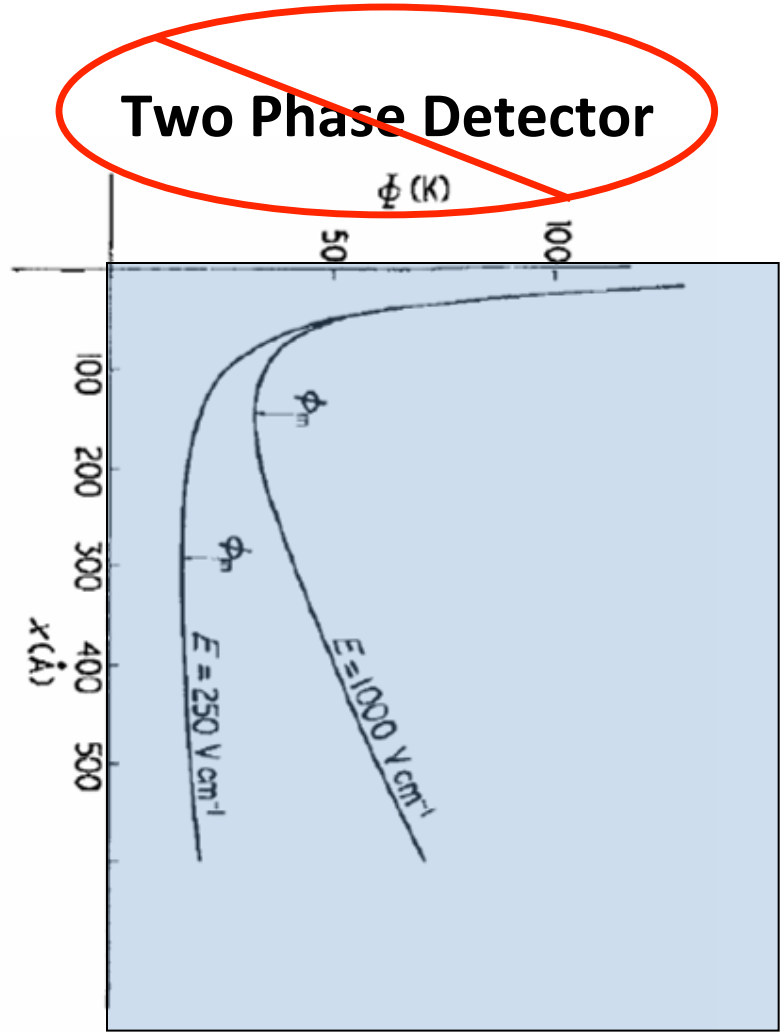


eBubbles Trap at the Liquid-Vapor Interface

- Dielectric discontinuity at the interface ($\varepsilon_{liq} > \varepsilon_{gas}$) due to dielectric constants
- Potential well just beneath surface
- eBubble has low probability of tunneling through this potential barrier per unit time



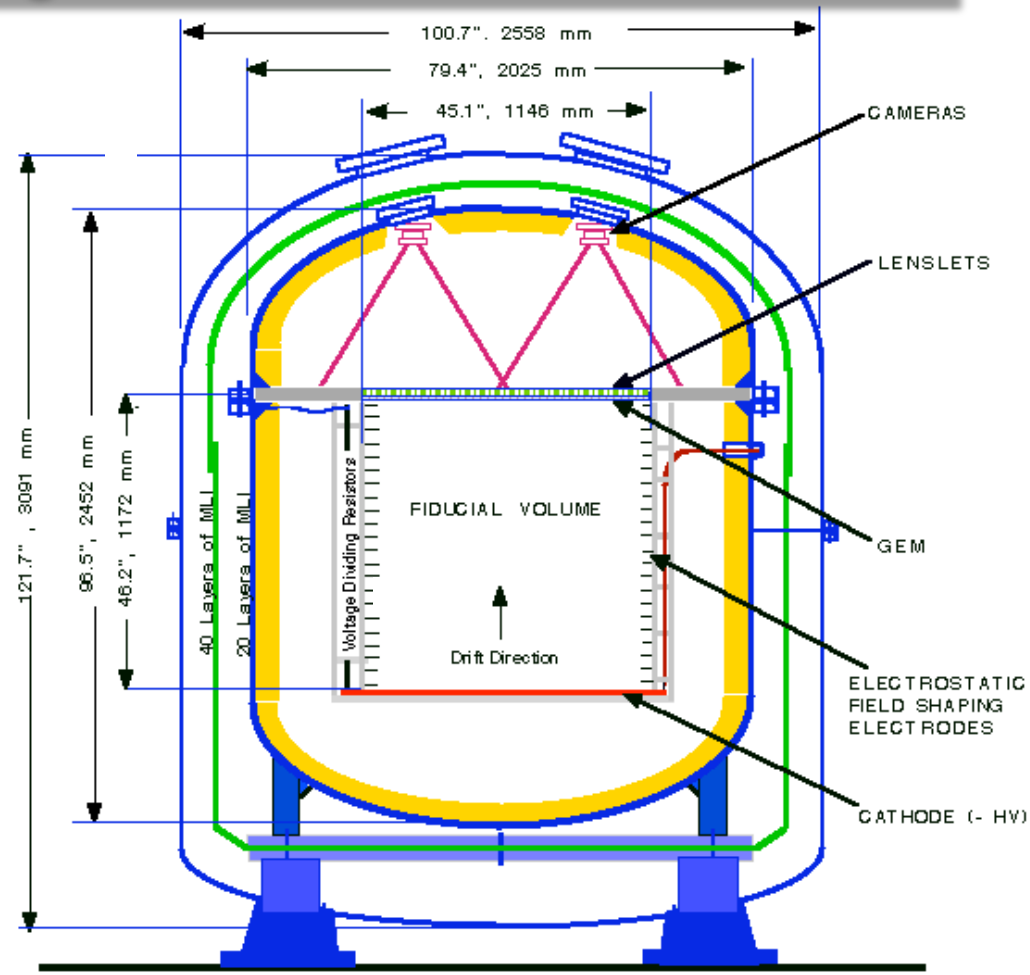
The trapping times t as a function of the electric field EL at 35.4 K. Galea, et al., *Charge transmission through liquid neon and helium surfaces*, JINST 2 (2007) P04007



Schoepe, W. and G.W. Rayfield, *Tunneling from Electronic Buble States in Liquid Heium through the Liquid-Vapor Interface*, PR A7 (1973) 2111

eBubble: Development of a Neutrino Tracking Detector Using GEM Avalanche Light Production in Neon

- $1m^3$ demonstrator
- High pressure cryostat operating for 35-45 K, up to 40atm
- Readout plane is GEM foils, imaged by CCDs
- CCDs provide high pixel count at low cost/pixel for cost effective readout ***if enough light is produced in avalanches***.
- Baseline – Critical density Ne; 0.48kg/l (~26atm @ 44K)
- Goal – supercritical Ne: 1kg/l (40 atm @ 40K)

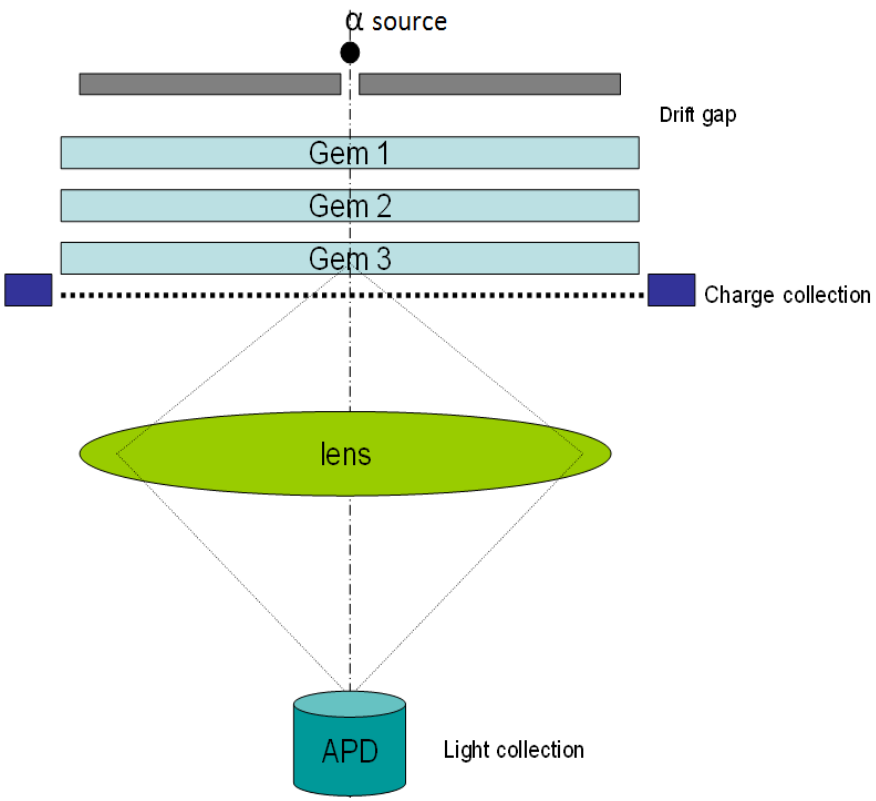


A schematic drawing of full-size 1T eBubble Chamber

Work Toward a Practical eBubble Detector

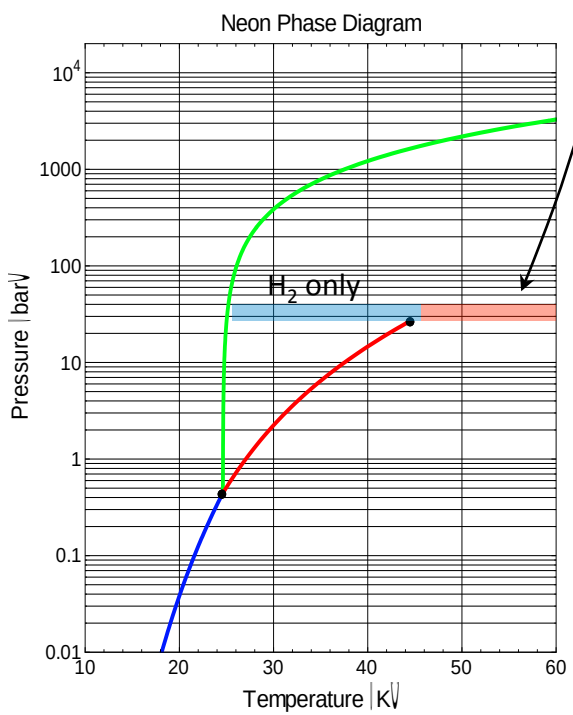
Measure charge and light output of GEMs in high density neon

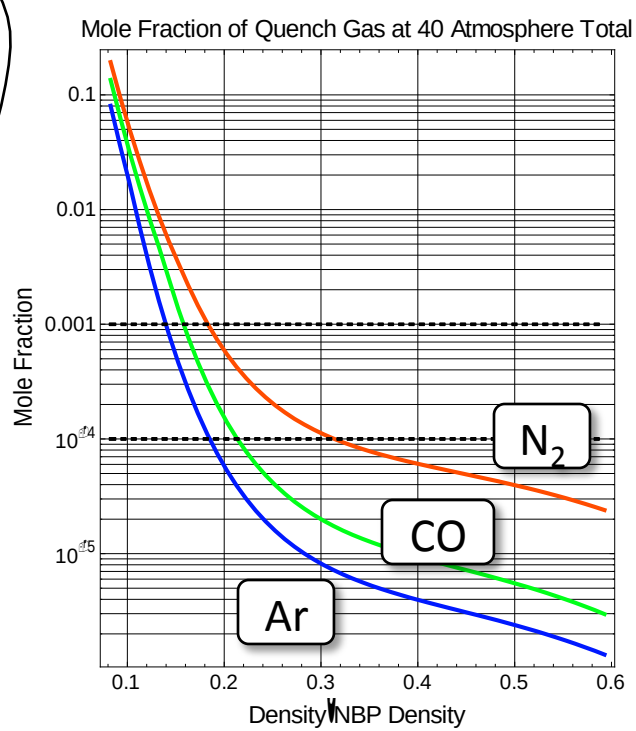
Determine conditions to maximize light output from GEMs

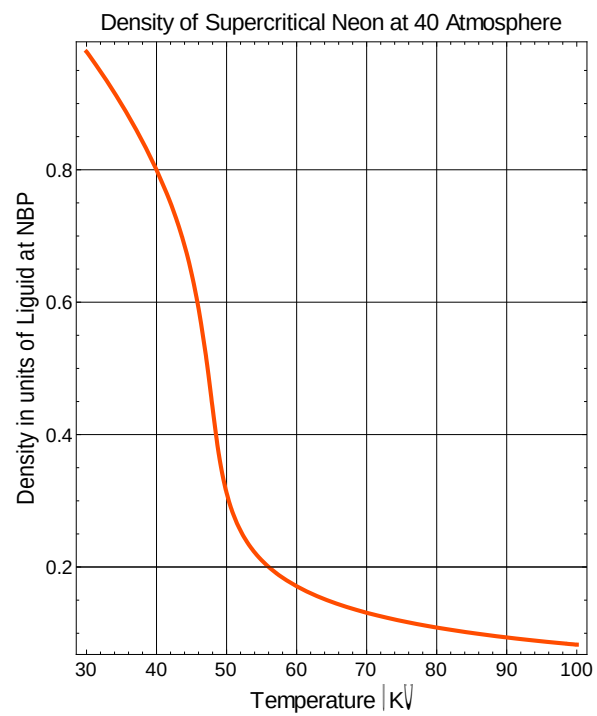


Possible Penning Gases

Operating Range:
- Above critical pressure
- Below 40 atm
- Above freezing line







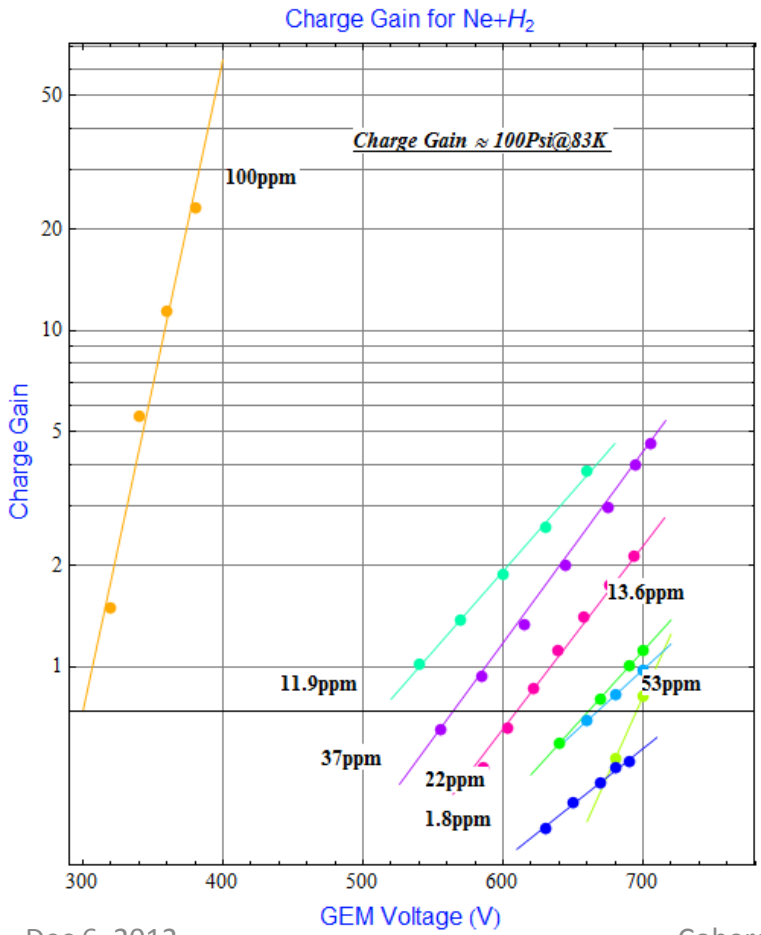
Charge gain in Ne + H_2 mixtures

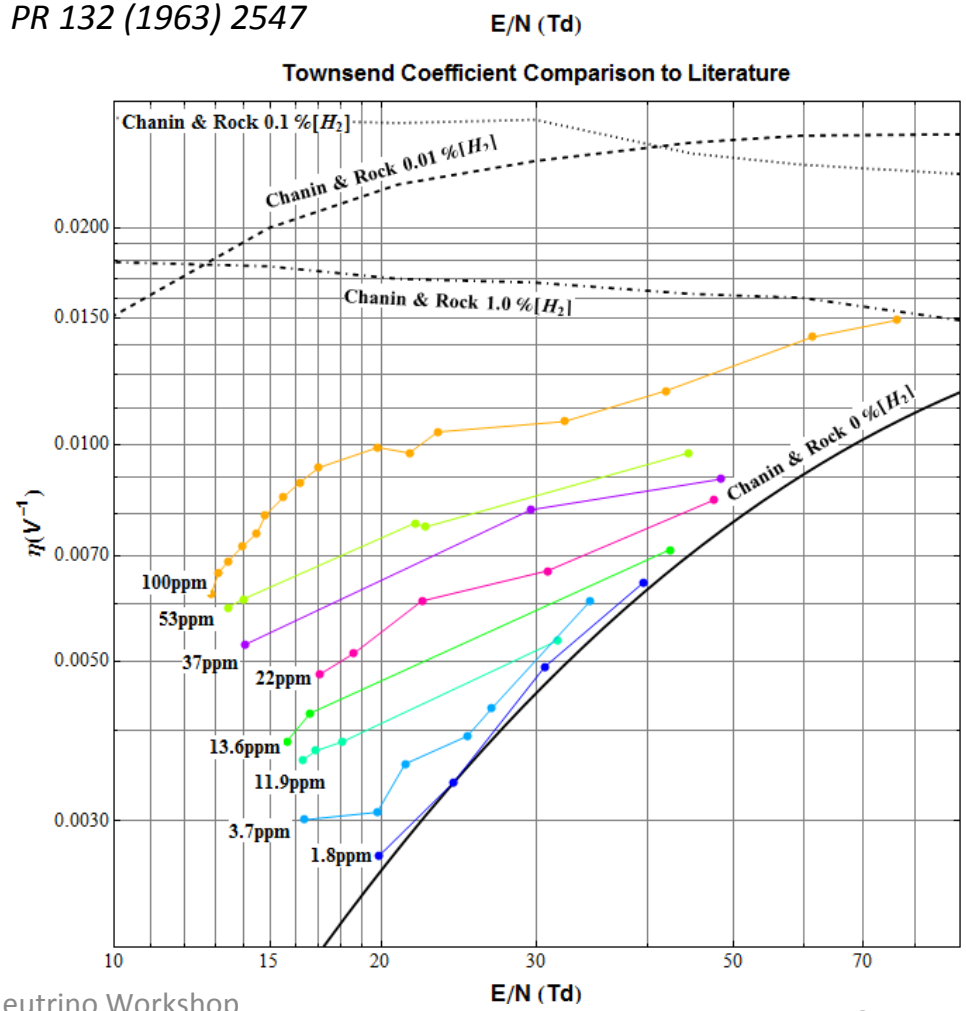
- Charge gain achieved by electron-impact ionization and Penning ionization:
- Ne+H_2 makes a good Penning pair.

$$Ne + e \rightarrow Ne^{+} + 2e$$
$$Ne^{*} + H_2 \rightarrow Ne + H_2^{+} + e$$

$$Gain = \frac{N_{av,e}}{N_0} = e^{\alpha d} = e^{\eta V}$$

- Our results agree with the literature: *Chanin and Rork, PR 132 (1963) 2547*

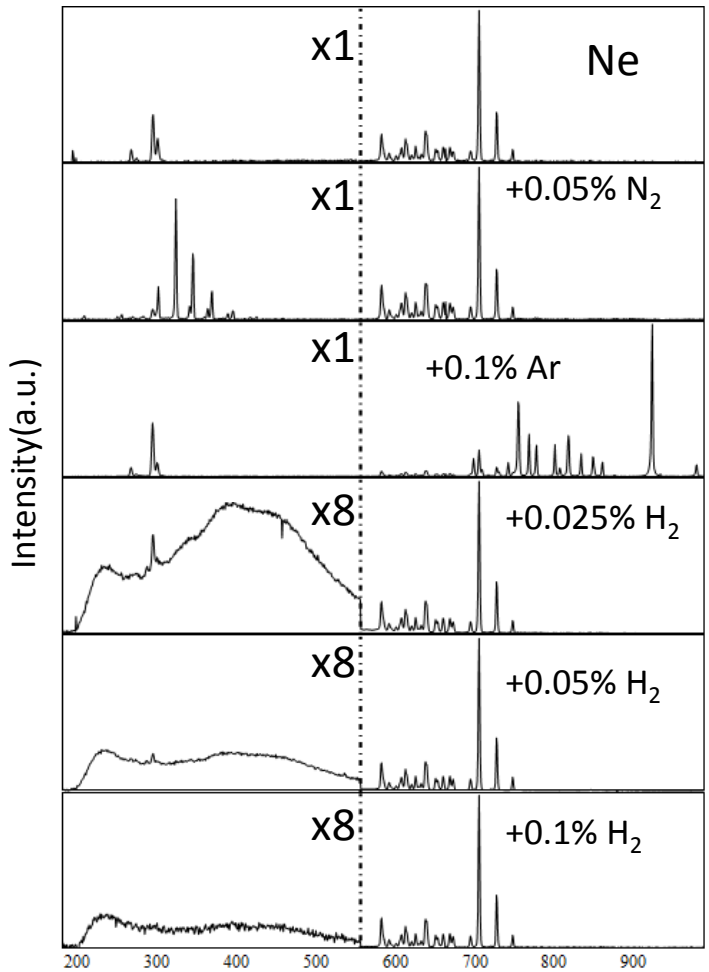




Optical Spectra of GEM Avalanches in Ne

At low H2 concentrations and high total pressure, a continuum emission extending into the UV dominated the optical content of GEM avalanches.

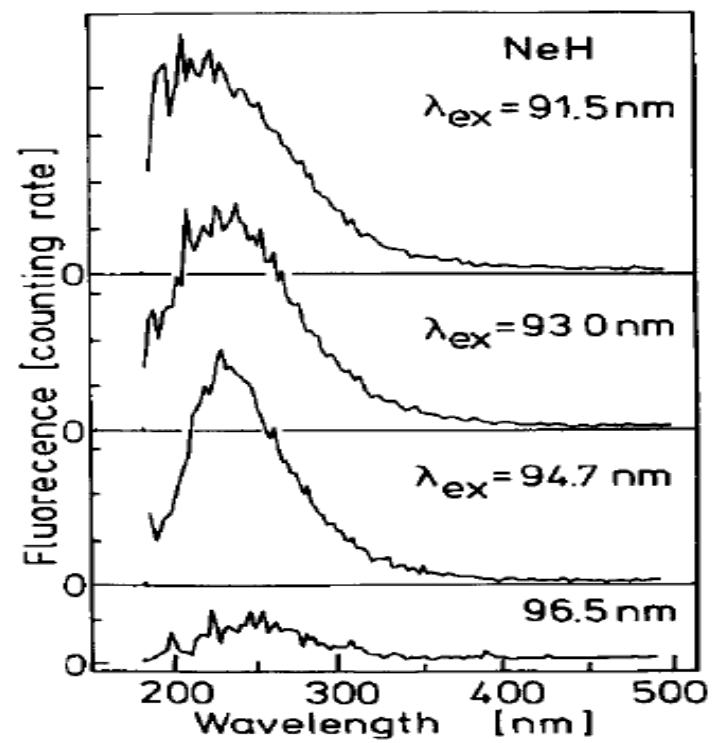
Measured Spectra for Gem Avalanches in NE + X



*The continuum part is magnified for visualization.

The emitting is presumed to be NeH* produced in the Penning reaction

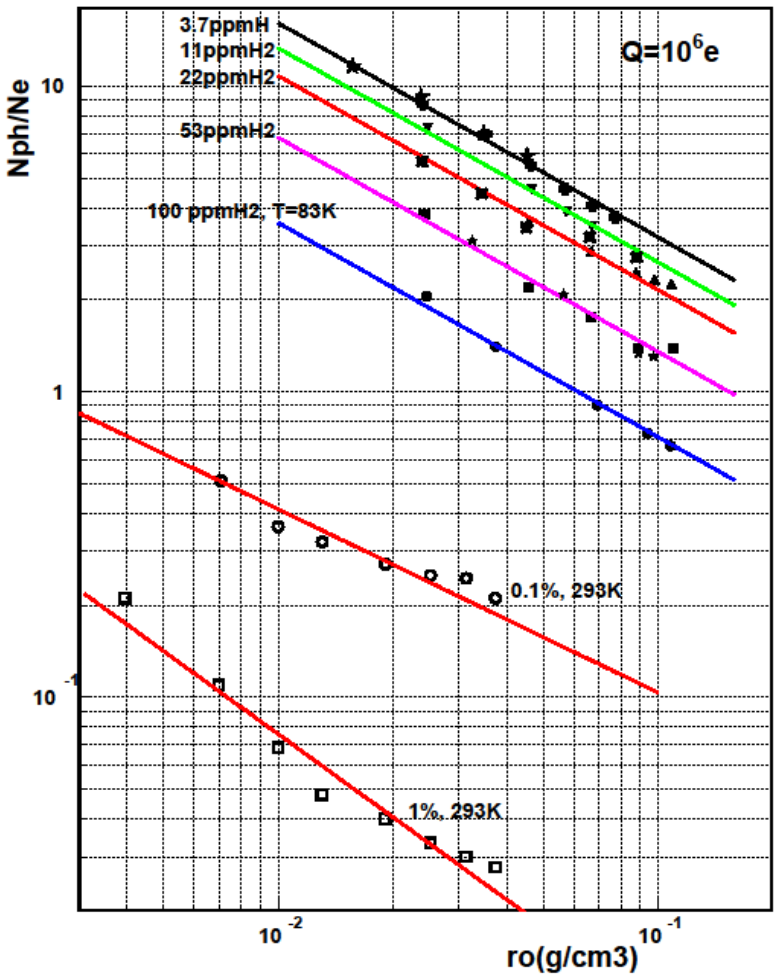
$$Ne^* + H_2 \rightarrow NeH^* + H^+ + e^-$$



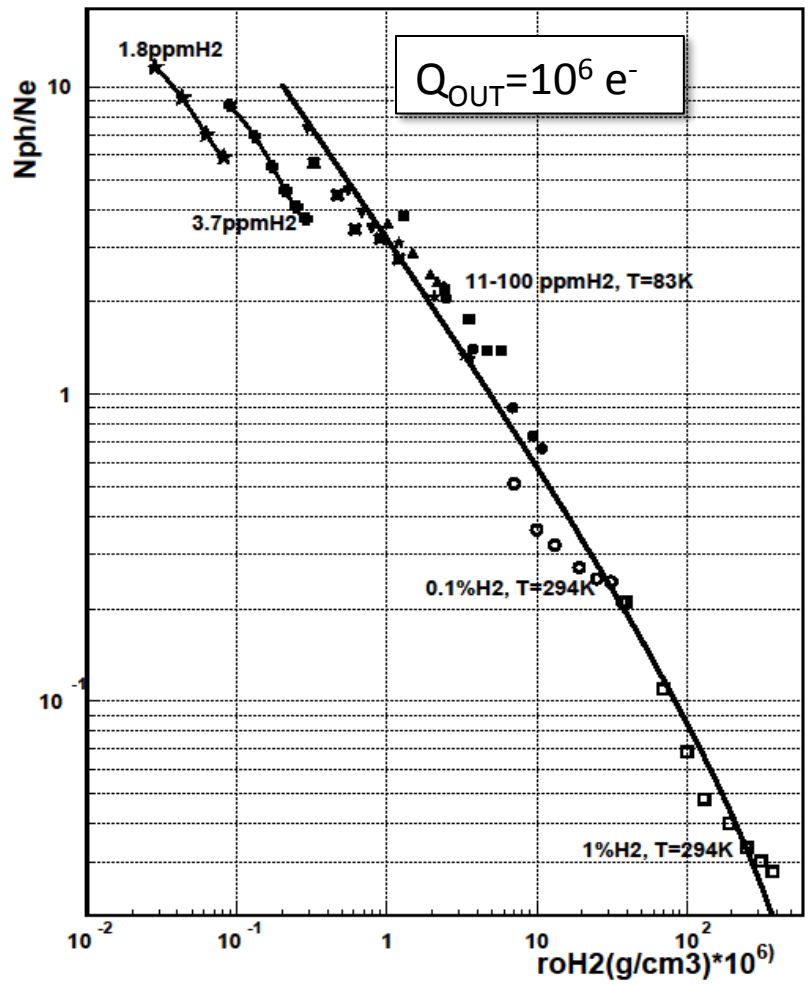
Bound-free fluorescence of NeH as a function of excitation energy *(from Thomas Möller el at. Chem. Phys. Lett.136(1987)551)*

Light Output for GEM Avalanches in Ne as the ratio of photons to electrons

Light yield (n_γ/n_e) *vs.* Ne density



Light yield (n_γ/n_e) *vs.* H_2 density



Light Gain in Ne+H2 and Model Prediction

- Charge Gain and Light Yield both depend on H_2 concentration, but are relatively independent of temperature
- High Light Yield is maximized by varying both pressure and H_2 concentration
- 10 photons/electron at maximum
- A gas kinetic model can qualitatively predict the charge/light production

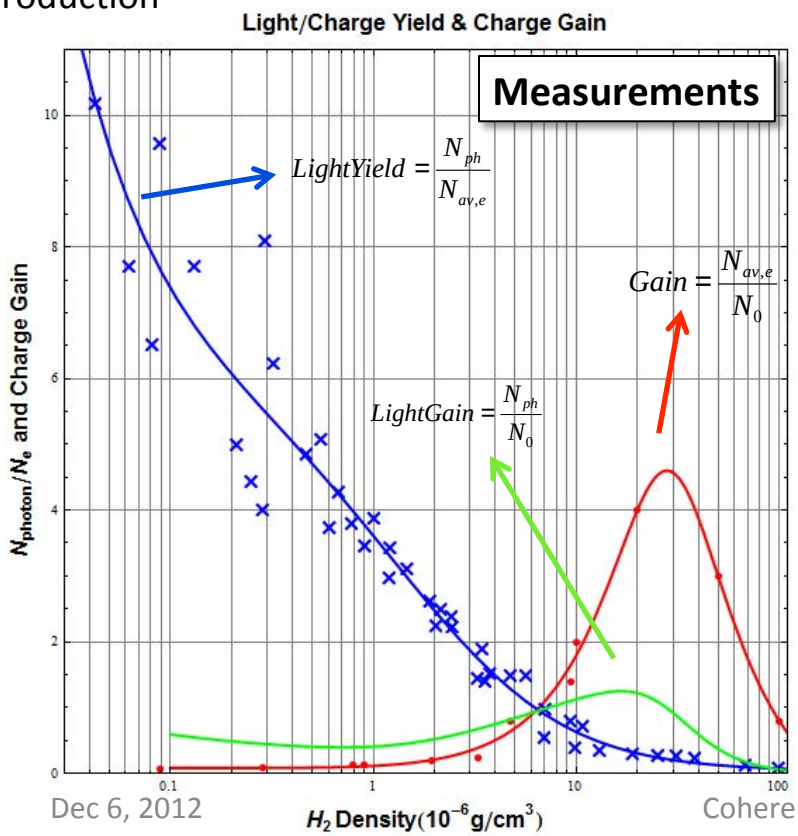
$$LightGain = Gain \times LightYield = \frac{N_{ph}}{N_0}$$

$$Ne^* + H_2 \rightarrow NeH_2^*$$
$$NeH_2^* \rightarrow Ne^* + H_2^+ + e^-$$

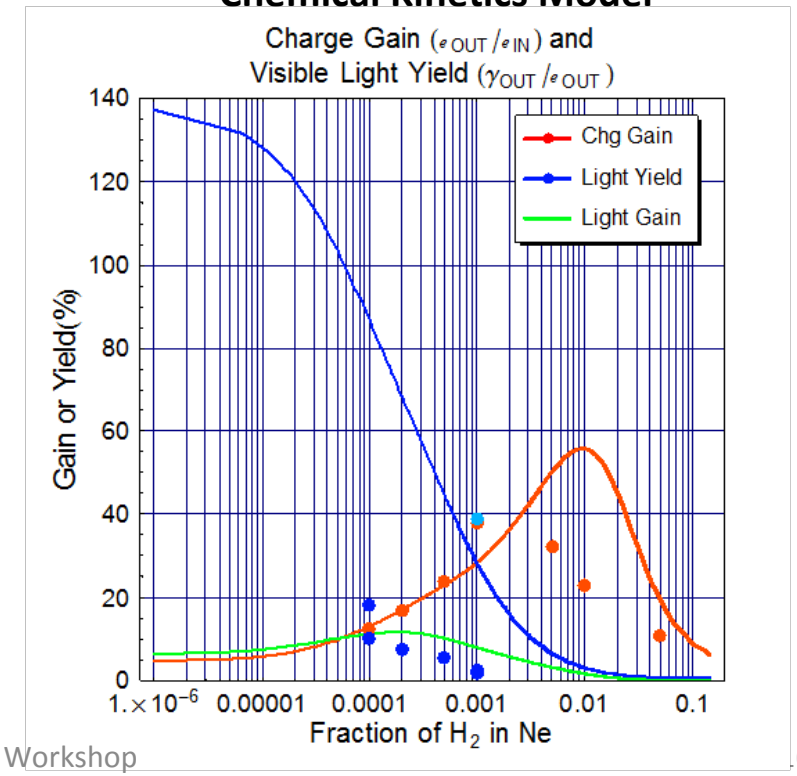
High $[H_2]$

$$Ne^+ + H_2 \rightarrow NeH_2^+$$
$$NeH_2^+ \rightarrow NeH^* + H^+ + e^-$$

Low $[H_2]$



Chemical Kinetics Model



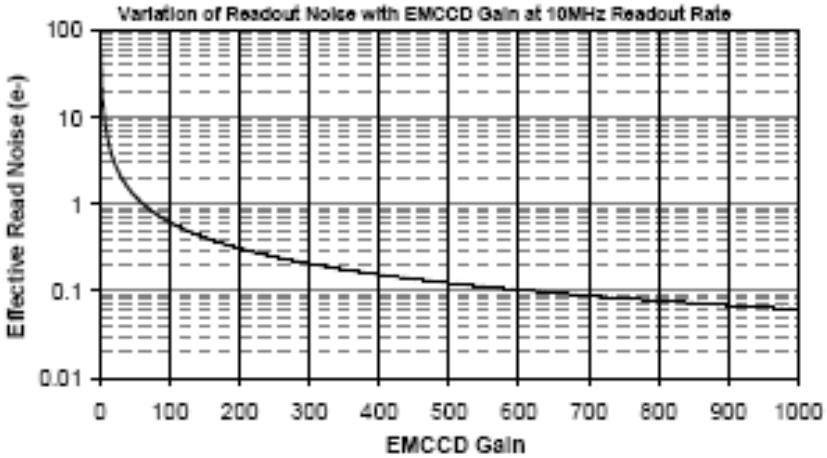
CCD camera, with internal electronic gain

Want to be fast enough and sensitive enough to demonstrate the TPC technique using e-bubbles in Critical density Ne (26atm & 44K).

		Full frame rate: (NxN) [Hz]		
DU-897	Pixel size(um)	512x512	256x256	128x128
1x1	16	35	68	132
2x2	32	68	132	248
4x4	64	131	246	439

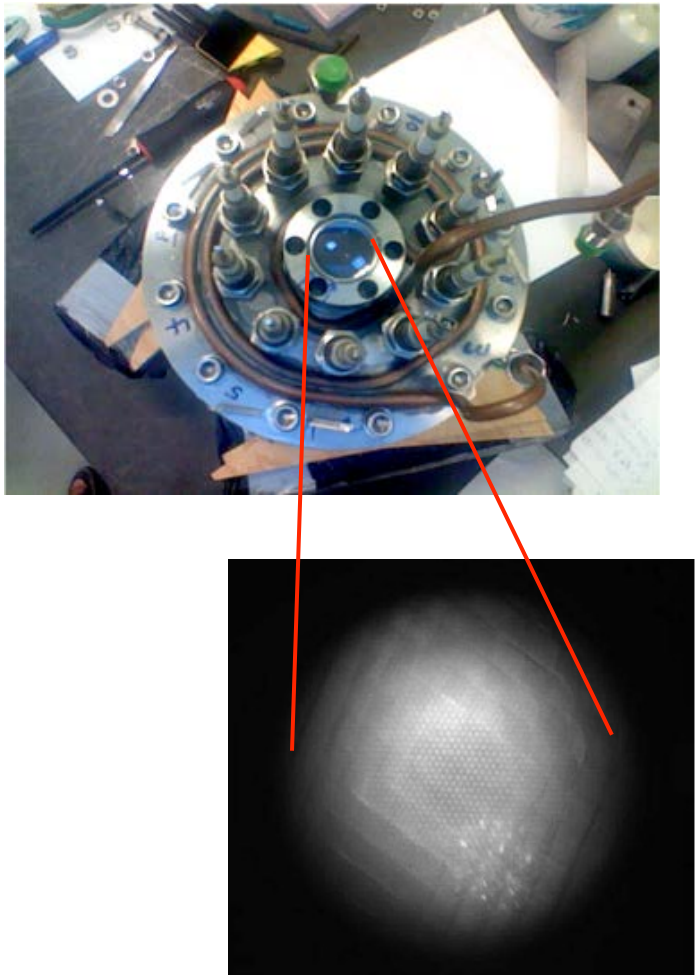
Andor technology:
iXon with EMCCD
DU-897

- Noise & EMCCD Gain

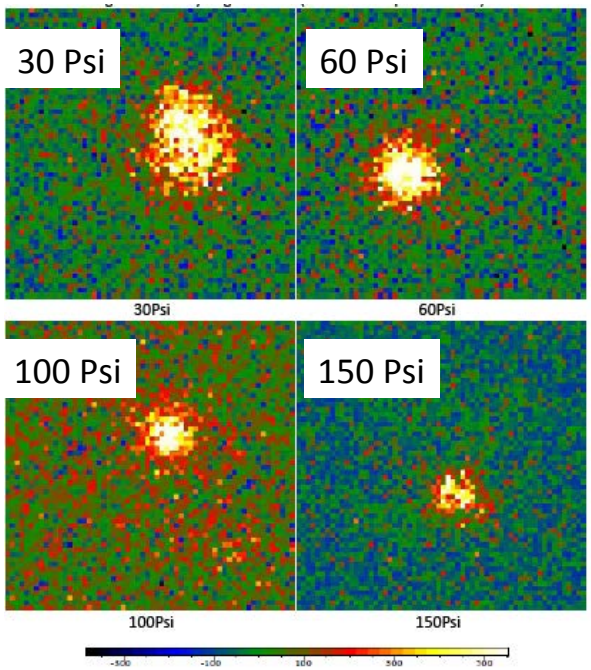


Back Illuminated :
QE=92.5% at 600nm
Dark current <0.1pe/pixel

Optical Readout by EMCCD



- The CCD optical readout has been tested at room temperature.
- The EMCCD image shows good spatial resolution of GEM holes
- The cost of the optical readout can be significantly lower than electronic readout.



Imaging alpha tracks

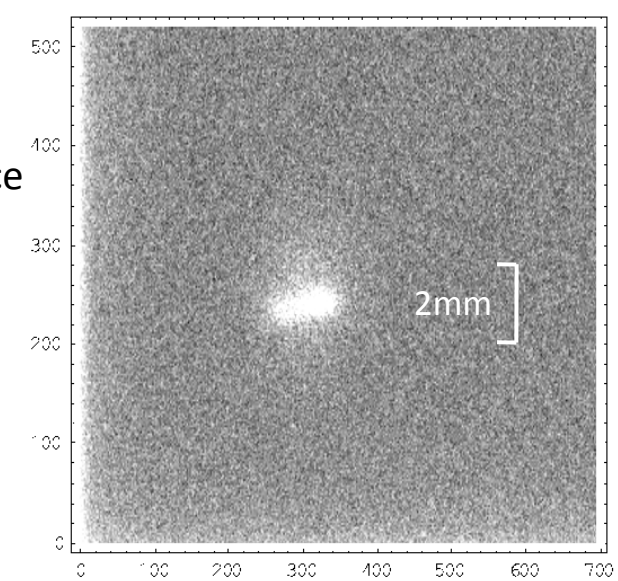
- ✓ Pressure of 7 atm of neon at 298 K
- ✓ Cm244 source behind collimator (5.902 MeV alpha)
- ✓ About 6 mm of track visible, remainder in collimator and source (3.685 MeV alpha has a 6 mm range)
- ✓ 175500 pairs/cm at 35 eV/ion-pair with no recombination
- ✓ 6.6 mm drift distance
- ✓ 1kV/cm drift field

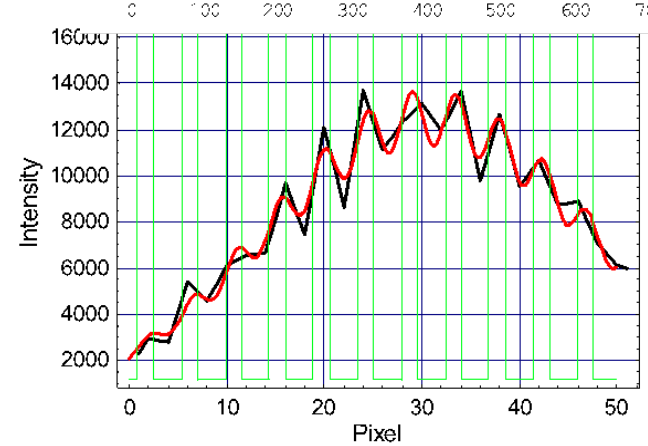
For these conditions
Coulomb broadening is:

$$\sigma_{COUL} = \sqrt{y_0^{\,2} + \frac{N\,e\,z_{DRIFT}}{\pi\,\varepsilon_0\,E_{APPLIED}}}$$

Transverse diffusion (from Magboltz) is:

$$\sigma_{DIFFUSE} = \sqrt{\frac{2\,kT_e\,z_{DRIFT}}{E_{APPLIED}}}$$

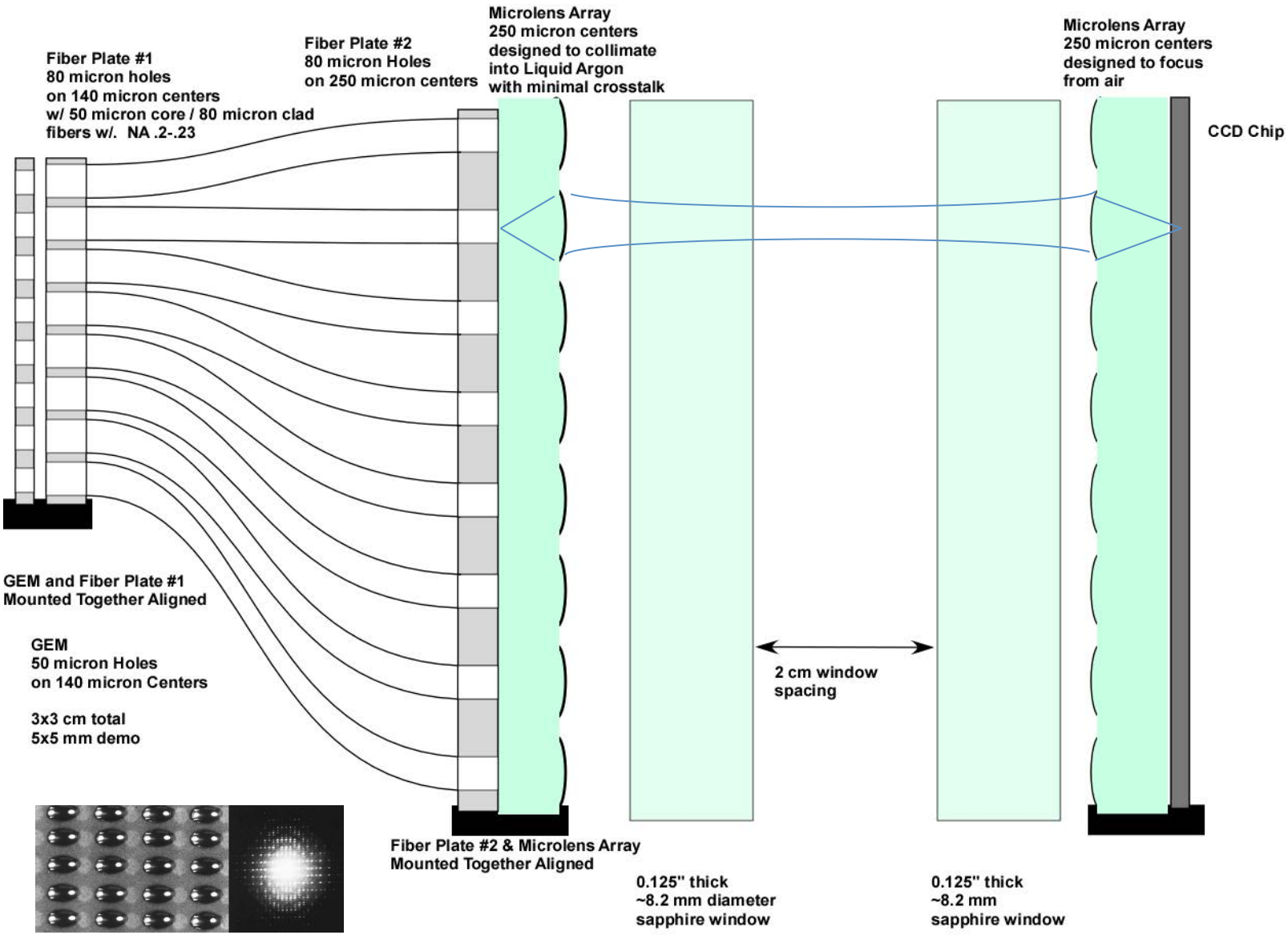




4.50 pixels per GEM hole spacing

The computed track width due to the coulomb force is 0.0817 mm
The computed width due to transverse diffusion is 0.442 mm
The measured track width is 0.326 ± 0.074 mm

Optical transport from GEM to CCD



Prototype & Final Optical System Similarities

- Fiber light collection
  - NA 0.23, half angle ~13.3 degrees, 2.2% of GEM light into half sphere
- Flexibility in placement of GEM, windows, CCD.
- Throw distance of collimated free-space part of link.
- Cryogenic and high pressure environment of fiber and microlens arrays.

Differences in Prototype & Final Optical Systems

- Sparse image on CCD
- Expand to 250 micron pitch at microlenses
- Small size of GEM, window, and CCD utilized

- Use demagnification and/or fiber tapering to improve density of information on CCD
- Maintain 140 micron pitch at microlenses
- Design to match GEM to CCD

Summary

- Estimated system gain: $0.01 \times 5 \times 10^3 \times 0.5 = 50$ pe per ionization electron
- High spatial resolution (140 um)
- Variable density can be used to tune range and ionization per GEM hole
- Threshold should sub kev for electron recoils, somewhat more for nuclear recoils