The XENON Dark Matter Project
Progress Report

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http://www.astro.columbia.edu/~lxe/XENON/

XENON Progress Report: Outline

- Project Overview and Goals
- Underground Sites for XENON
- Review of Instrument Concept and Discrimination Methods
- Dark Matter Sensitivity Goals of XENON (10kg,100kg,1 ton)
- Review Status of R&D and Results (9/1/02-present)
- Summary of R&D on Alternative Detectors for XENON
- Projected R&D Milestones and Timeline for XENON10 Phase
- Background Simulations (Rick’s talk)
- Requirements for Underground Site and Safety Issues
- Publications, Internal Notes and Conference Talks
- Competing Experiments

The XENON Collaboration

Columbia University

Elena Aprile (PI), Karl-Ludwig Giboni, Sharmila Kamat+,
Pawel Majewski+, Kaixuan Ni*, and Masaki Yamashita+

Brown University

Richard Gaitskell, Peter Sorensen*, Luiz De*Viveiros

University of Florida

Laura Baudis, David Day*

Lawrence Livermore National Laboratory

Adam Bernstein, Chris Hagmann and Celeste Winant+

Princeton University

Tom Shutt, John Kwong*

Rice University

Uwe Oberlack ,Omar Vargas*

Yale University

Daniel McKinsey, Richard Hasty+

Undergraduates, Ph.D.Students and Post-Docs on XENON

- XENON science captivates young postdocs, students and general public alike.
- Collaboration is committed to meet NSF's EPO mission, devoting time and funds to this goal.

Postdocs (average age~30 yr):
Columbia: Masaki Yamashita (NSF) , Pawel Majewski (NATO-NSF Fellow) and Sharmila Kamat (Columbia Teaching Fellow)
Yale: Richard Hasty (McKinsey startup), Celeste Winant (LLNL)

Ph.D. Physics Students
Kaixuan Ni, Min Li and Walter Lippincott ? (Columbia)
Peter Sorensen and Luiz DeVireiros (Brown)
John Kwong (Princeton), Omar Vargas (Rice)

Undergraduates and High Schol working at Nevis Lab (Summer 2003) :
Naresh Kumar (Columbia Rabi scholar), Jamila Hussain (Rochester)
Naomi Kort (Columbia REU student), Shueb Amhed (Bronx High)
plus other undergraduates at Brown, Princeton and Rice

•Undergraduates and High Schol working at Nevis Lab (Summer 2004) :
Christine Zaruba, David Day and Taritree Wongjirad (Columbia REU)
Manuel Donnay (Columbia SEAS), Jamila Hussain (Columbia?)
Jason Li (Great Neck North High), plus more students at other institutions.

XENON Project Overview and Goals

- The XENON concept exploits the excellent ionization and scintillation response of LXe to achieve 16 keV threshold for nuclear recoils and 99.5% background discrimination in a 3D position sensitive TPC, operated in dual phase and at high electric field. With a target mass of 1 tonne (XENON1T) , distributed in 10 independent TPCs, the WIMPs sensitivity goal is $\sigma \sim 10^{-46}$ cm^2 , with < 10 background events/ yr.

- The XENON concept was proposed to NSF in September 2001. A 2 yr R&D phase started a year later. To-date we have demonstrated key technologies with various prototypes and measured many of the quantities necessary to establish the feasibility of XENON. We project to complete the measurements of the ionization and scintillation yields of low energy nuclear recoils by early 2005. Neutrons calibration of dual phase prototype ongoing with Columbia RARAF Van der Graff at Nevis Lab. Neutron recoils down to 15 keV.

- Projecting on a successful R&D phase, a 3yr continuation proposal targeted at the XENON100 phase was submitted in October 2003. Reviews Summary: complete R&D, fully demonstrate LXe discrimination power and consider demonstrating performance with a small prototype running underground.

- Our goal is to have a low background 10 kg scale detector (XENON10) with a LXe active VETO, passive shield and muon veto operating underground by end of 2006 . At present a PMTs readout remains the most reliable and robust for this detector. UV PMTs operating in LXe, are commercially available with very low radioactivity (~20 mBq / PMT) and further improvement is expected.

- XENON10 projected sensitivity of 0.01 ev/kg/day (CDMSII) can be easily reached at Soudan. This underground phase will guide the design of (XENON100). With a sensitivity of $\sigma \sim 10^{-45}$ cm^2 , within reach by 2008, this experiment will be highly competitive with LHC for SUSY particles discovery.

Underground Sites for XENON

- The Collaboration has contacted and visited several underground sites:
  WIPP, SNOLAB, LNGS and SOUDAN.

- Space is available at Soudan and this is a suitable site for XENON10. The plans to make available a low counting facility will benefit many experiments including XENON.

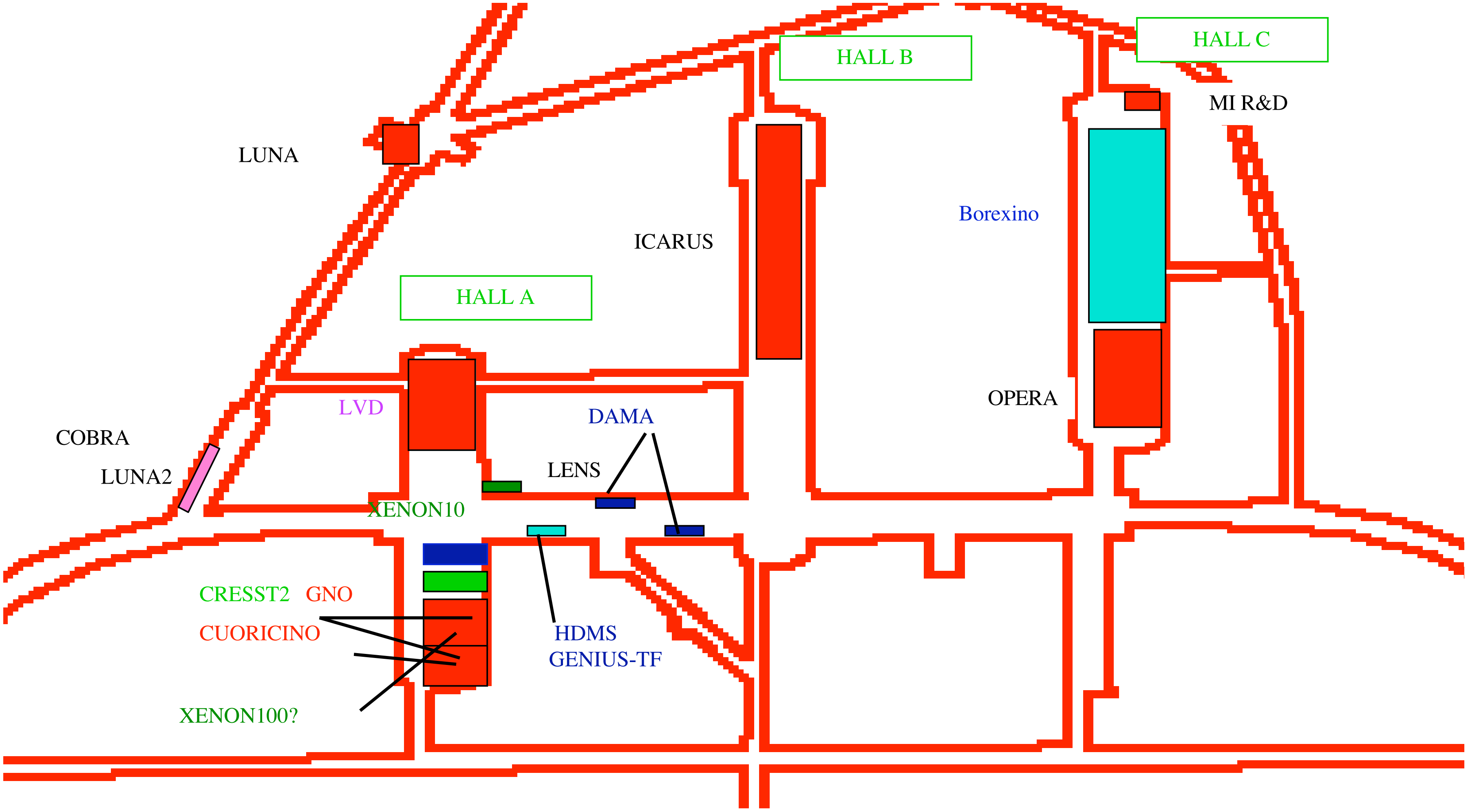
- Space and some level of support is also available at LNGS for a XENON10 phase.

- A LOI for XENON100 at LNGS was submitted and the proposal presented to the Scientific Committee on April1, 2004. The Committee and the Director view XENON an important experiment with high discovery potential. They strongly encouraged the Collaboration to demonstrate the stable operation and the background rejection power with a smaller scale prototype at GS.

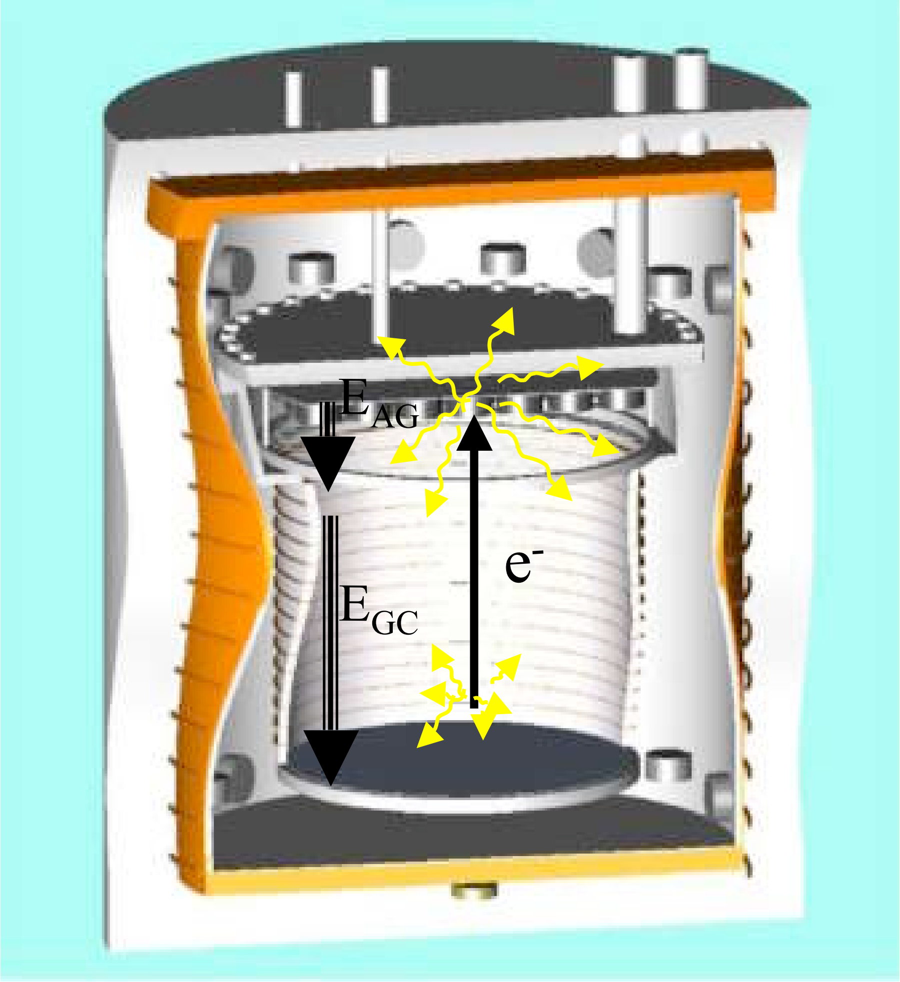
- A LOI to SNOLAB is in preparation and the Collaboration has been encouraged to consider the lab for future XENON phases (>2007).

- Once we demonstrate the background rejection capability with running XENON10 underground, the design of XENON100 will start. The choice of the site will be driven by the goal to achieve the most sensitive direct WIMP search. It is clear that depth will be essential requirement to minimize the irreducible fast neutrons background .

Gran Sasso Lab Occupancy and XENON



XENON Baseline Design Overview



- XENON unit detector is is a 3D position sensitive dual phase XeTPC with a fiducial mass of ~ 100 kg.

  Modular approach allows to optimize single unit, with phased construction over reasonable time. Preferred for reliability and safety underground

  The target LXe volume is embedded in an active LXe VETO. Both target and shield LXe kept at –95.1 ± 0.05 C by a mechanical refrigerator.

  Ionization electrons liberated by an event in the target drift for 30 cm in LXe, under a field >1 V/cm. At the liquid / gas interface, an extraction field ~ 10 kV/cm is applied, inducing proportional light.

  Direct (S1) and proportional (S2) Xe light (178 nm) is simultaneously detected by an array of UV PMTs and by a CsI photocathode operating in LXe.

  Background neutrons (and WIMPs) and γ,α, e background produce distinctly different S2 / S1.

  This is the basis for full event-by-event discrimination. Challenge: a 16 keV nuclear recoil gives very small light and charge signals.

Expected Direct and Proportional Light Signals (10 keV event)

		Zero Field 0 kV/cm	Median Field 1 kV/cm	High Field 5 kV/cm
Electron recoil				
Direct light (S1)	UV Photons (a)	420	160	150
Charge	Electrons (b)	0	510	580
Proportional light (S2)	UV Photons (c)	0	143000	162000
Alpha recoil				
Direct light (S1)	UV Photons (d)	510	480	460
Charge	Electrons (e)	0	17	29
Proportional light (S2)	UV Photons (c)	0	4800	8100
Nuclear recoil				
Direct light (S1)	UV Photons (f)	84		76
Charge	Electrons (g)	0		<6
Proportional light (S2)	UV Photons (c)	0		<1680
Background Discrimination (S2/S1)				
Electron Recoil			890	1080
Alpha Recoil			10	18
Nuclear Recoil				<22

a - W(ph) = 23.7 eV, 38% and 36% light quenching for 1 and 5 kV/cm

b - W = 15.6 eV, 80% and 90% charge collection for 1 and 5 kV/cm

c - N(ph)/N(e)=70*(E/p-1)*p*d, with E=10 kV/cm, p=2 atm and d=0.5 cm in the gas phase

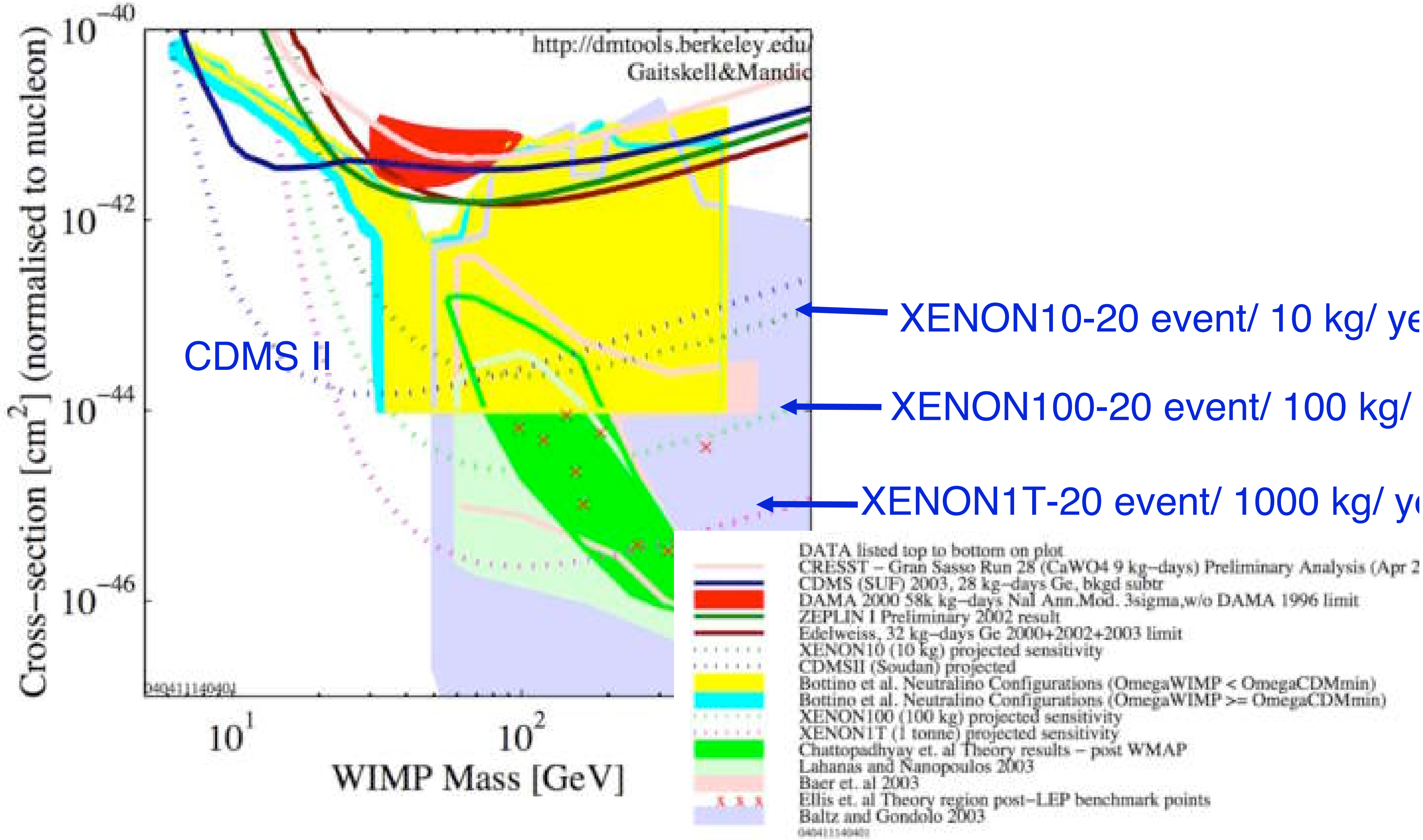
d - W(ph) = 19.6 eV, 95% and 90% light quenching for 1 and 5 kV/cm

e - W = 17.3 eV, 3% and 5% charge collection for 1 and 5 kV/cm

f - assume quenching factor = 20%, compared with electron recoil, and 90% light quenching for 5 kV/cm

g - assume 15.6 eV W value, 20% quenching factor for charge, and < 5% charge collection at 5 kV/cm

XENON Dark Matter Sensitivity Goals



CDMS II

XENON10-20 event/ 10 kg/ ye

XENON100-20 event/ 100 kg/

XENON1T-20 event/ 1000 kg/ y

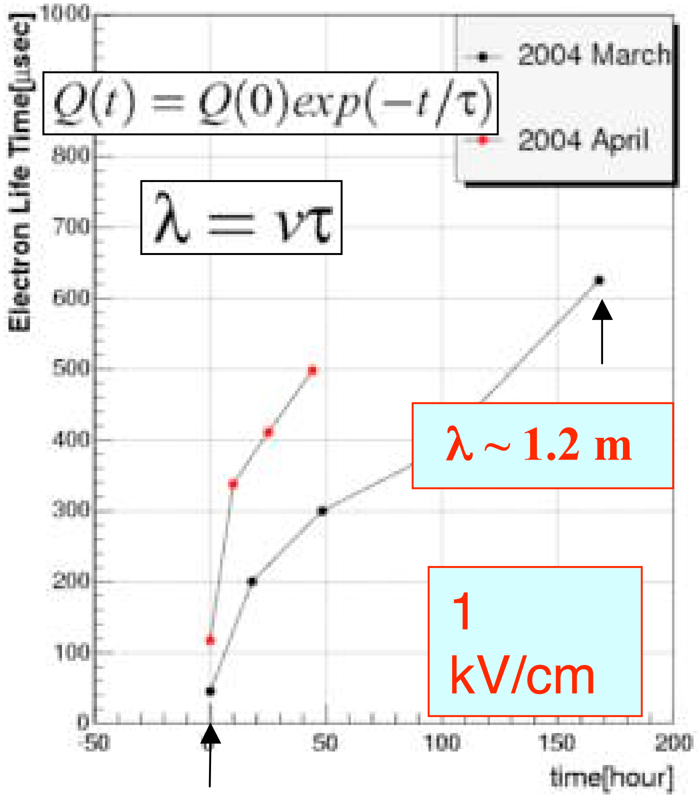
Summary of XENON R&D Goals

- > 1 meter electron attenuation length in LXe → *DEMONSTRATED*
- Reliable Operation of UV PMTs in LXe → *DEMONSTRATED*
- LXe Light Quenching Factor for < 50 keV recoils → **PRELIMIINARY RESULTS**
- LXe Cryogenics System with Pulse Tube Refrigerator→ ***DEMONSTRATED***
- Dual Phase Operation with 100 % Electron Extraction → ***DEMONSTRATED***
- Detector Simulations of E-Fields / Light Collection/ 3D TPC → ***DEMONSTRATED***
- Low Radioactivity PMTs (with ~10 mBq/2" tube) → ***DEMONSTRATED***
- MC Background Simulations → ***DEMONSTRATED***

- Cs I photocathode in LXe, with feedback suppression → R&D **INITIATED (Sep 04)**
- Nuclear Recoils Ionization vs Field and Energy→ R&D **IN PROGRESS (Dec 04))**
- Electron / Nuclear Recoil Discrimination at 16 keV → **R&D IN PROGRESS (Mar 05)**
- **Novel HV Distribution to PMTs Array in LXe→R&D IN PROGRESS**
- Alternative Readout (MCPs,LAAPDs, GEMs & Wires)→ **R&D IN PROGRESS**
- Kr removal from Xe (< 0.1 ppb) → **R&D IN PROGRESS**

R&D Milestone: > 1 m Electron Attenuation Length

- XENON goal: 30 cm drift gap and high E-field to detect <10 e^- ? signal from 16 keV Xe recoil requires extreme purity level, well below 1 ppb O_2 equivalent.
- Commercial Xe: O_2 CO,N_2O,H_2O, etc. plus numerous organic molecules at ppm concentration. e- attachment rate to N_2O like impurities increases with E-field. Typical Oxisorb and molecular sieves columns to be avoided (Radio-purity). High temperature getter and spark method plus UHV and careful materials selection for gas system and detector.
- Built Dedicated Gas Purification System with Continuous Re-Circulation through HT getter. System shown to deliver high purity Xe to a variety of XENON prototypes.

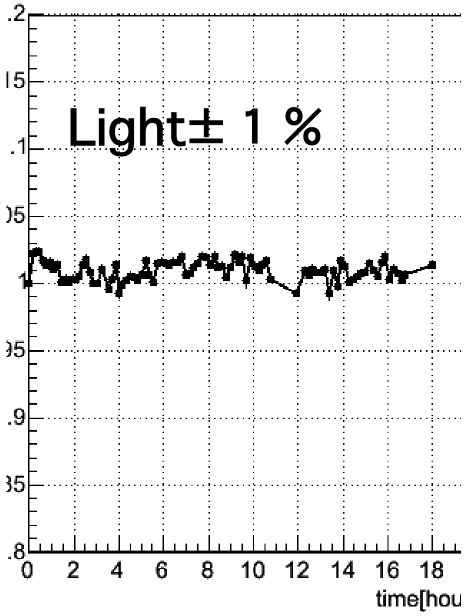


$Q(t) = Q(0)exp(-t/\tau)$

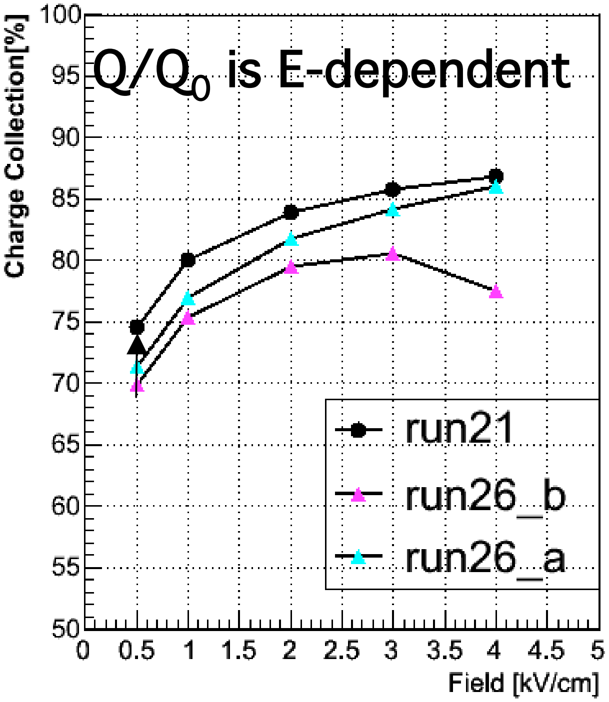
$\lambda = v\tau$

λ ~ 1.2 m

1 kV/cm

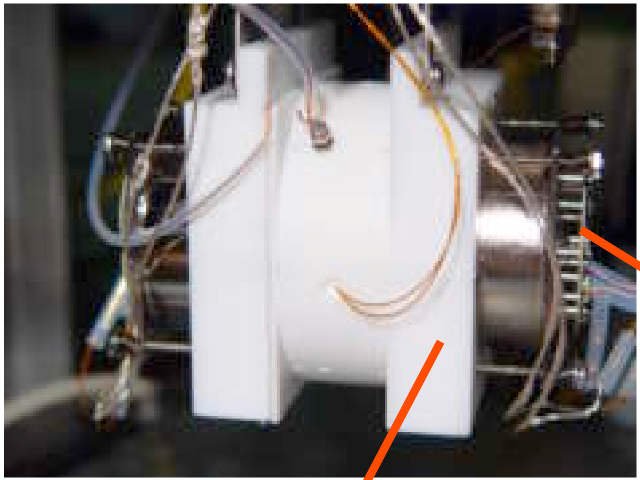


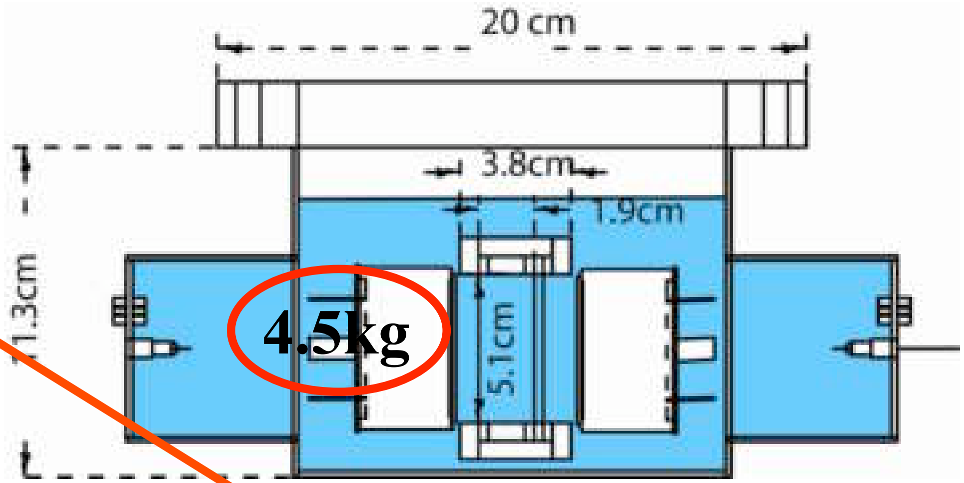
Light± 1 %

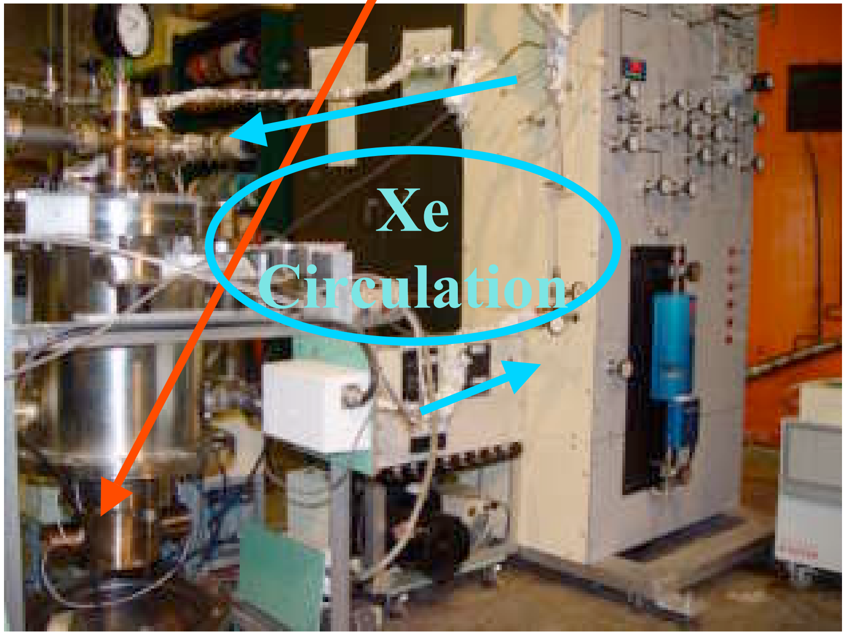


Q/Q_0 is E-dependent

R&D Milestone: Light Detection with UV PMTs in LXe







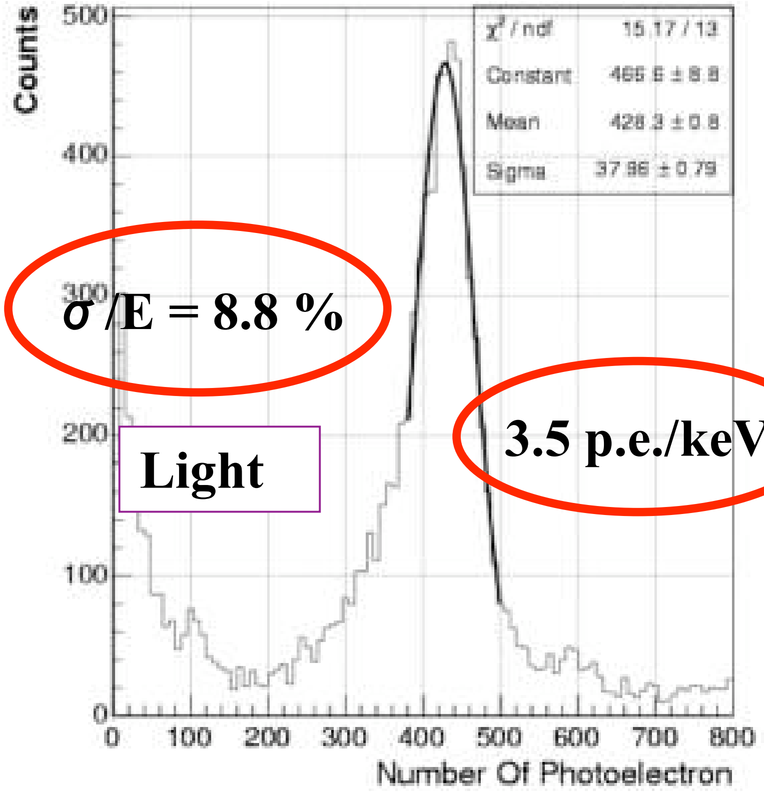
- Gridded Ionization Chamber (2 cm drift) viewed by 2 Hamamatsu R9288 with custom-developed HV divider also in LXe.
- Demonstrated reliability of operation at –100 C and 3 atm. Measured single P.E. level. Gain calibration with blue LEDs.
- Demonstrated compatibility of materials with high purity LXE requirement. Tested and optimized gas circulation performance and effectiveness. T~ 1ms.

Important New Results Obtained from Charge & Light C

Excellent Light Sensitivity Ideal for Quenching Factor Measurement with < 50 keV Neutron Recoils

Best Δ E / E in LXe from simultaneous measurement of anti-correlated charge and light signals

^{57} Co (122keV)

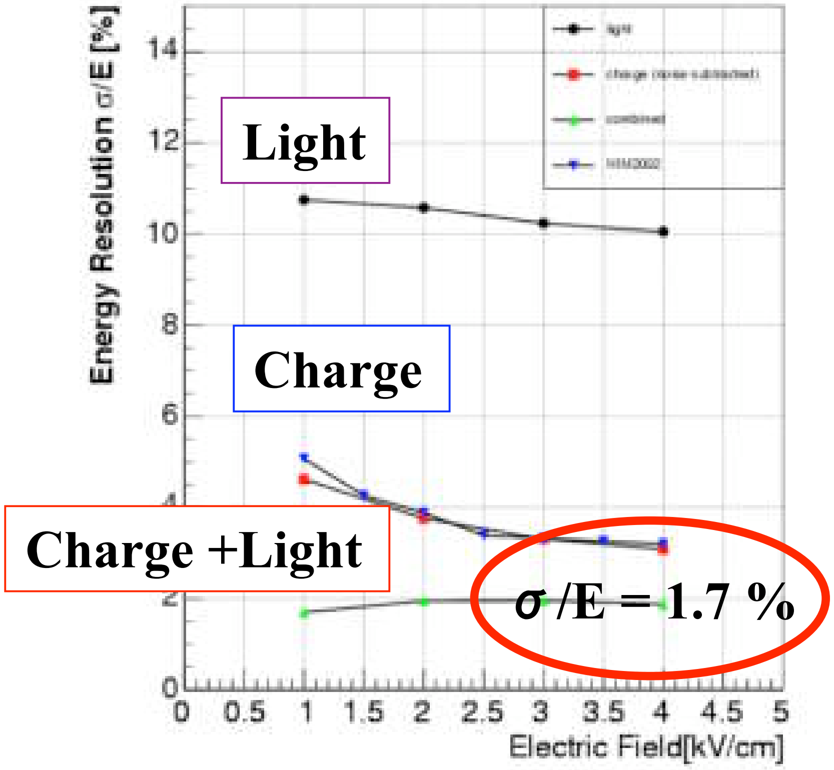


σ /E = 8.8 %

Light

3.5 p.e./keV

^{137} Cs (662keV)



Light

Charge

Charge +Light

σ /E = 1.7 %

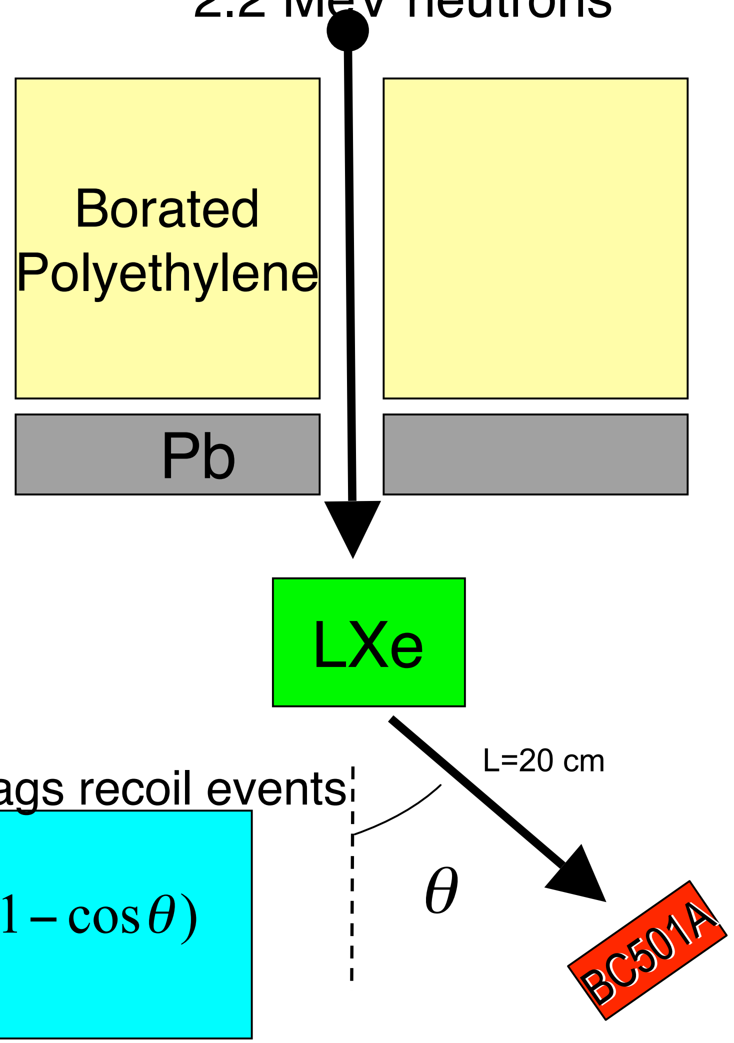
R&D Milestone: LXe Quenching Factor (Columbia/Yale)

$$QF = \frac{\text{nuclear recoil scintillation}}{\text{electron recoil scintillation}}$$

Columbia RARAF
p(t,3He)n
2.2 MeV neutrons

Current data are inconsistent and do not extend to low energy recoils of interest for next generation DM experiments.

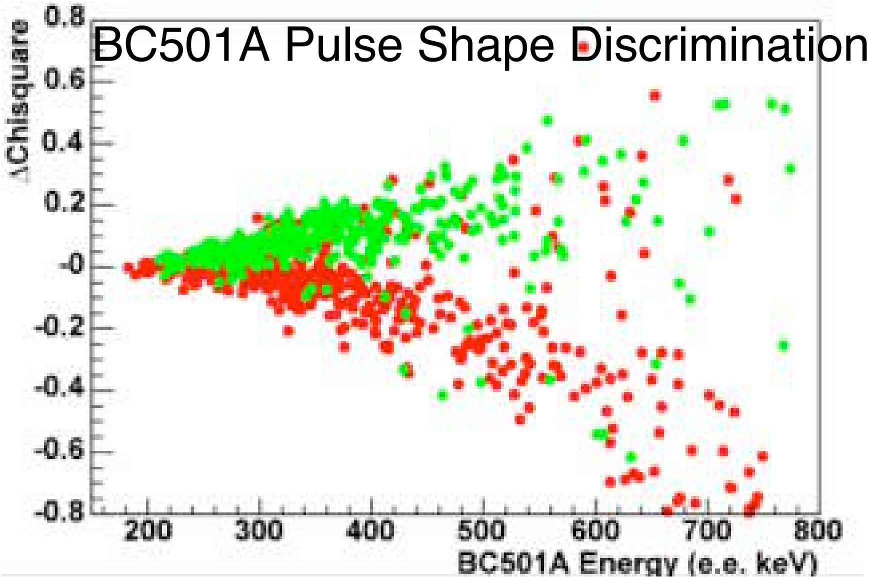
Xe recoil (keV)	QF	
40 to 70	0.22+/- 0.01	Akimov 2002
45 to 110	~0.2	Arneodo 2000
35 to 70	0.45 +/- 0.10	Bernabei 2001

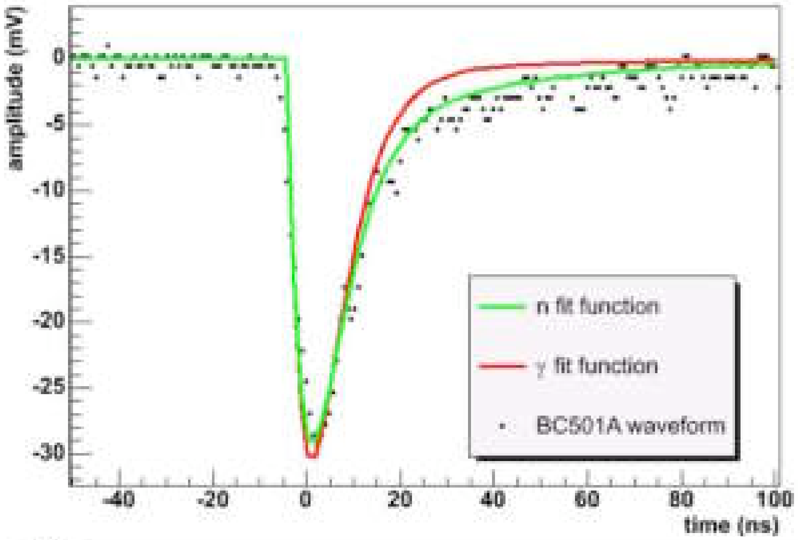


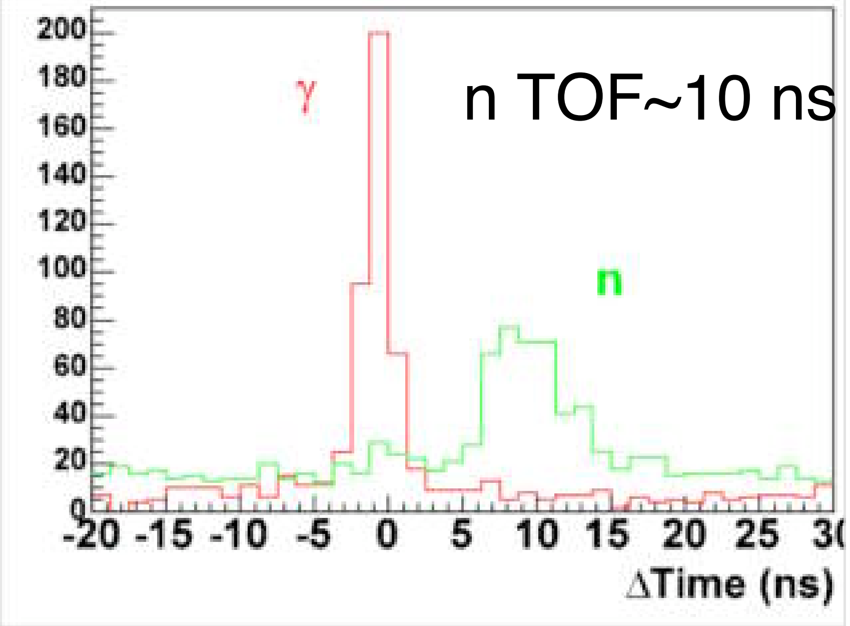
BC501A scintillator tags recoil events

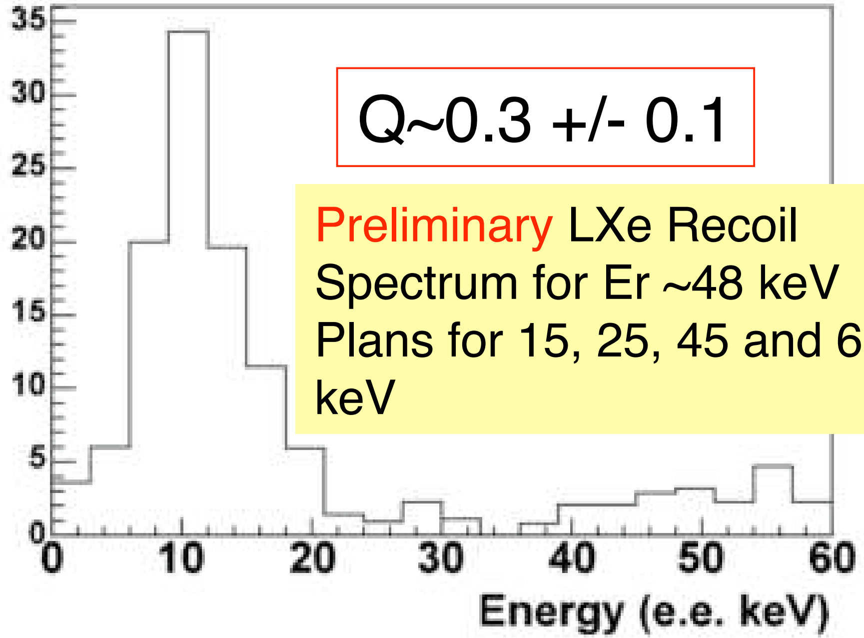
$$E_r \approx E_n \frac{2M_n M_{Xe}}{M_n + M_{Xe}}(1-\cos\theta)$$

Preliminary Quenching Factor Results


BC501A Pulse Shape Discrimination

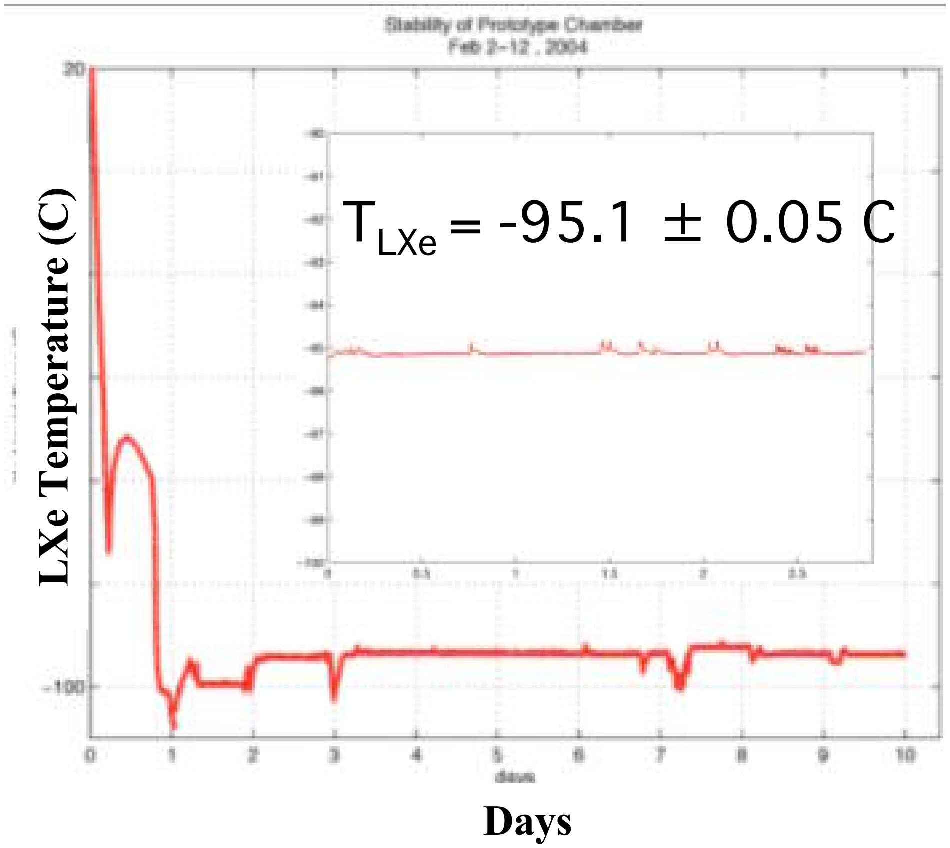



n TOF~10 ns


Q~0.3 +/- 0.1

Preliminary LXe Recoil Spectrum for Er ~48 keV
Plans for 15, 25, 45 and 60 keV

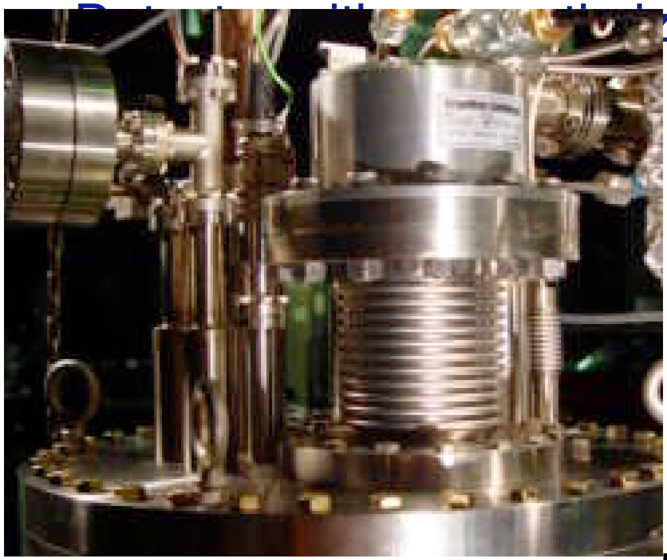
R&D Milestone: Reliable Cryogenic System for LXe



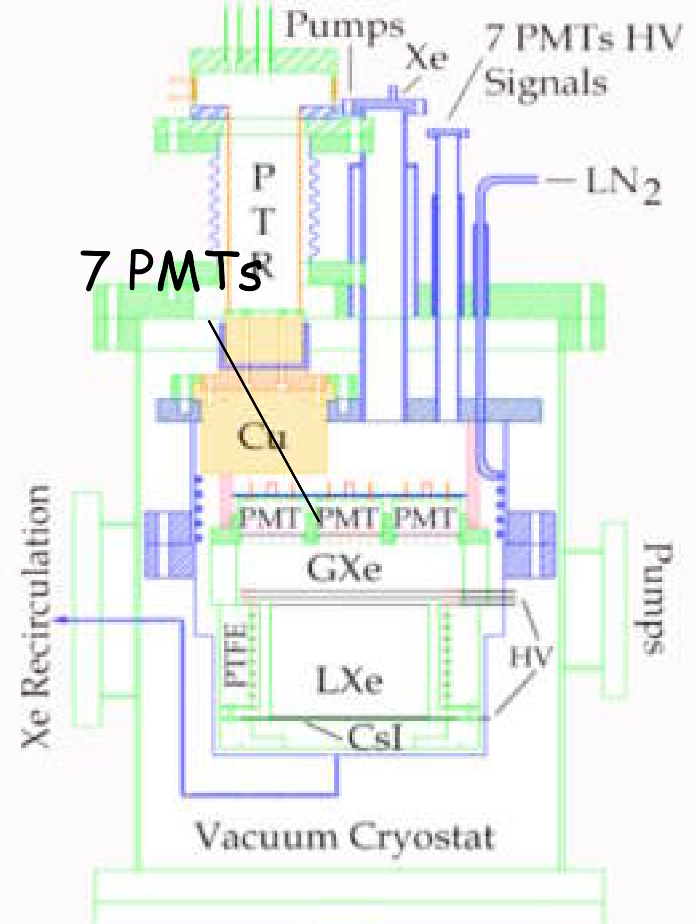
Refrigerator needed for good LXe temperature stability over long term operation underground

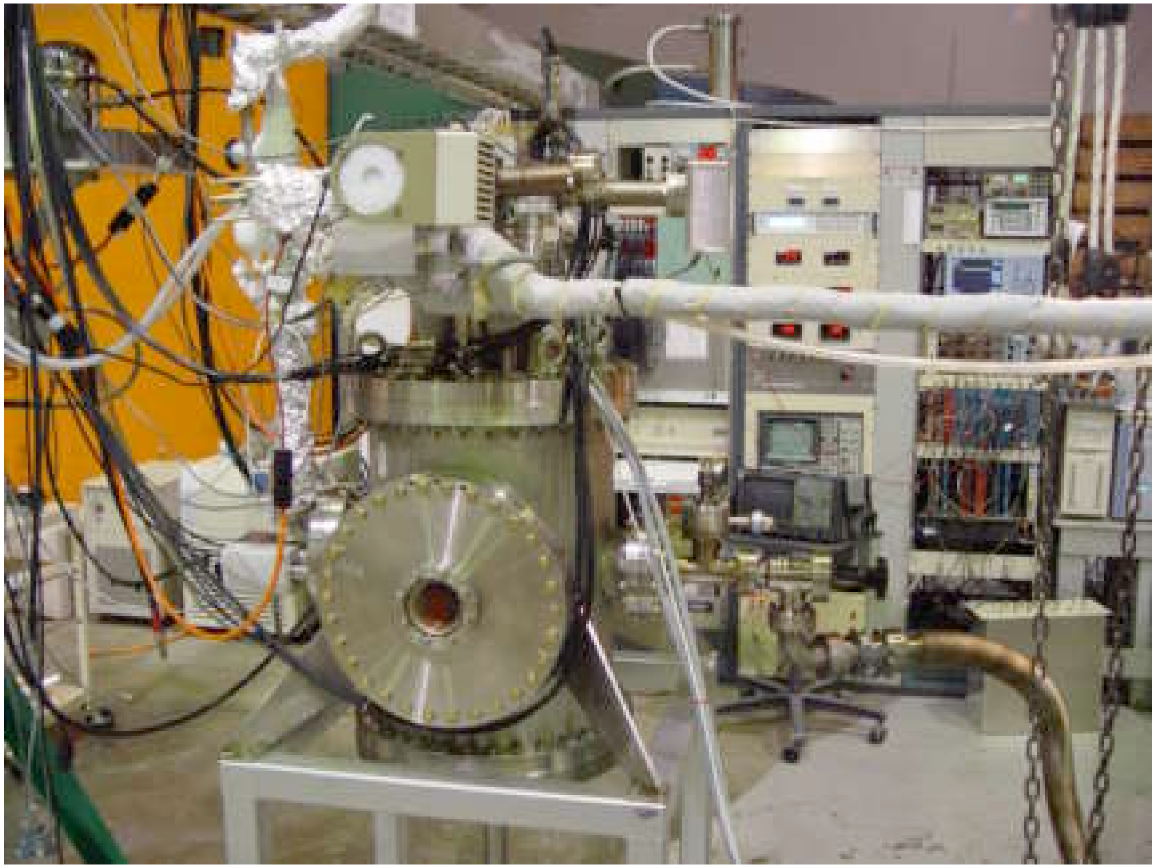
- Pulse Tube Cryocooler (Iwatani)
- 100W Cooling Power at 165 K
- 3.5kW He Compressor, water cooled
- Refrigerator used for cooling (10W) and liquefaction (45W) at 5 slpm (limited by purifier)
- 20W Heat Loss of Present

zed



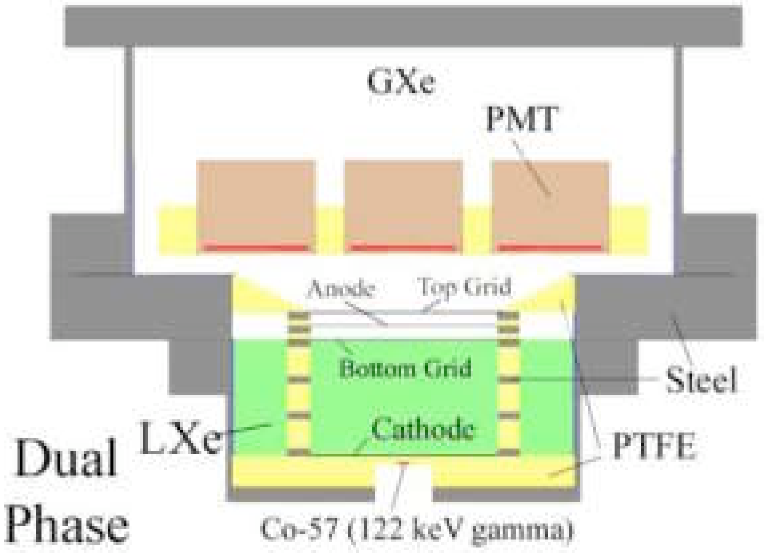
R&D Milestone: Dual Phase 3D XeTPC Prototype

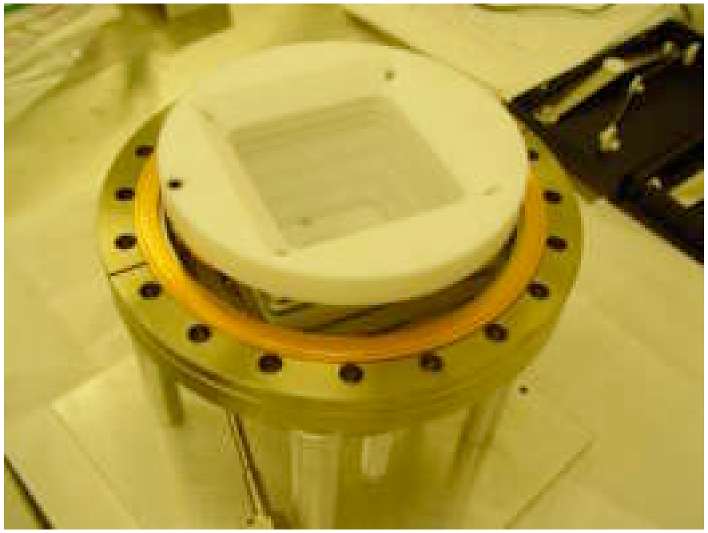


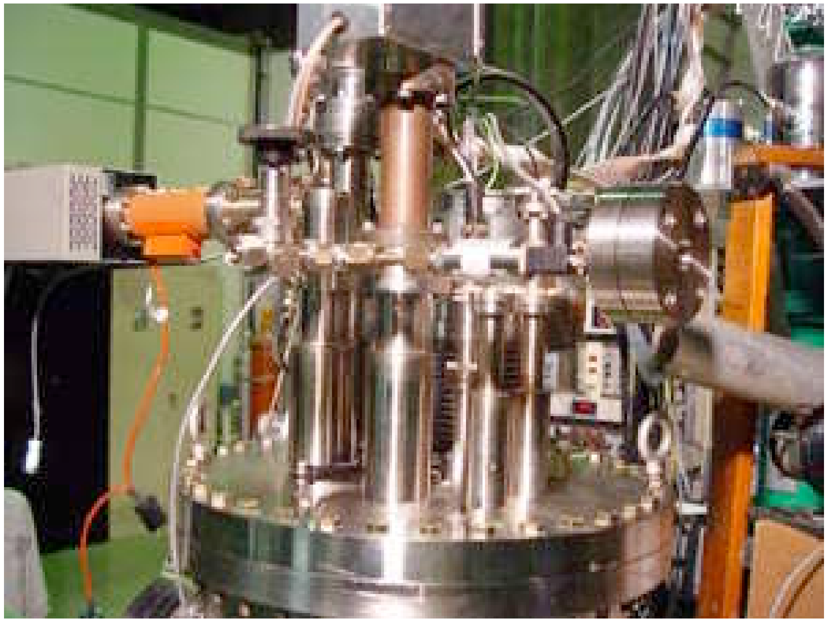


- 4 Experiments to-date with continuous optimization for charge and light response at high field.
- 7 PMTs (Hamamtsu R9288) array now fully working with dedicated DAQ System (see attachment). For current run, April 9- present, DAQ changed to full digitization of direct and proportional light waveforms (7 ch of LeCroy 1GHz scopes, 8 bit for S1+ 7 Ch CAMAC digitizers 10 bit, for S2). Goal of current data taking: measure XY response with alpha particles, operate at E> 1kV/cm and 1st try at S2/S1 with neutron sources.

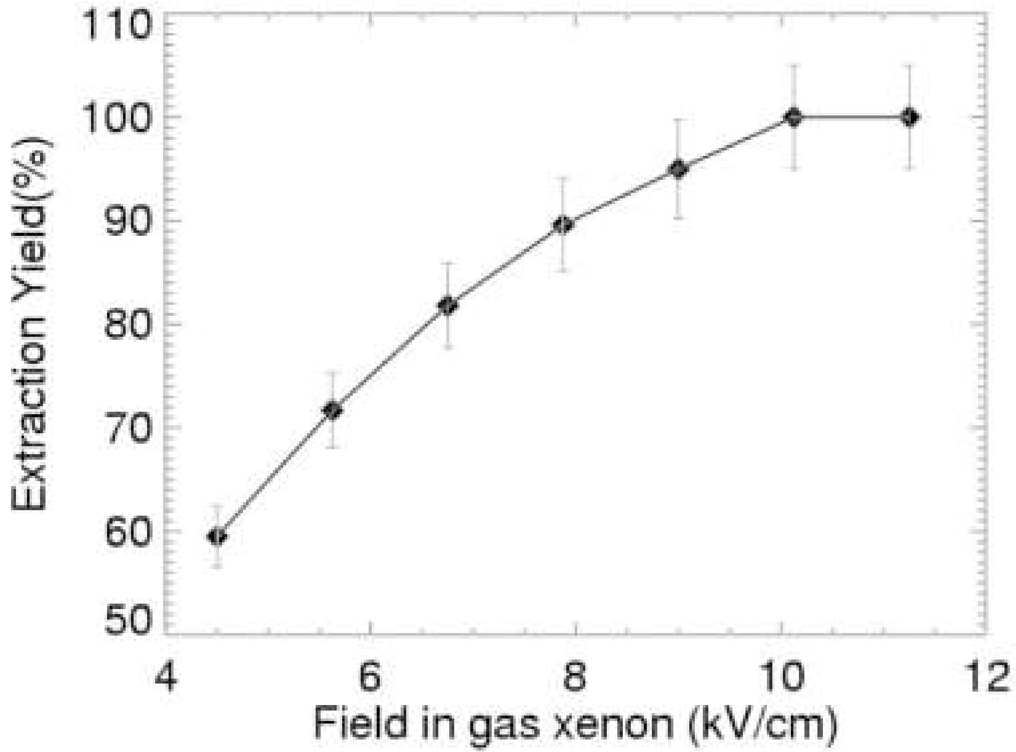
Details of TPC with 7 PMTs Array and Cryostat

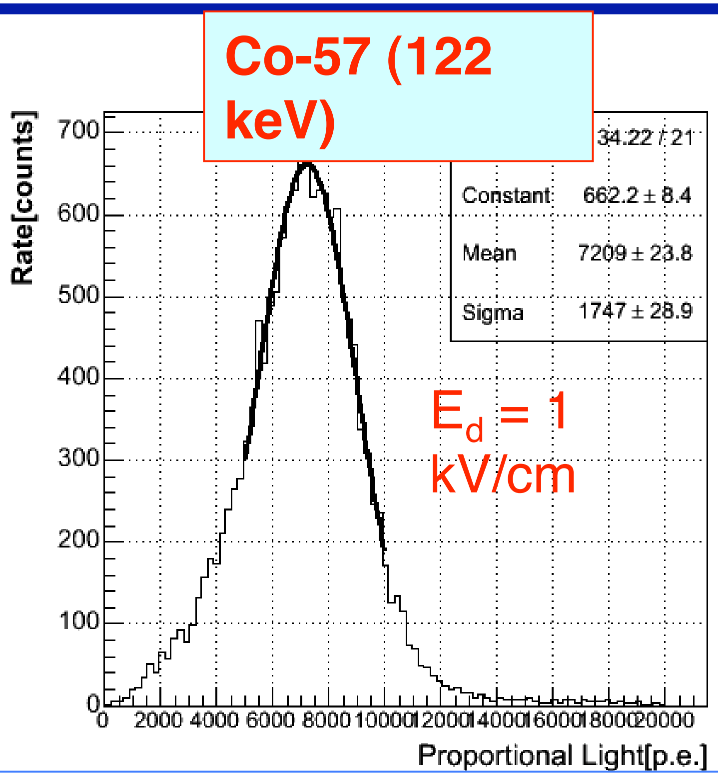






R&D Milestone: Electron Extraction & Proportional Light





Co-57 (122 keV)

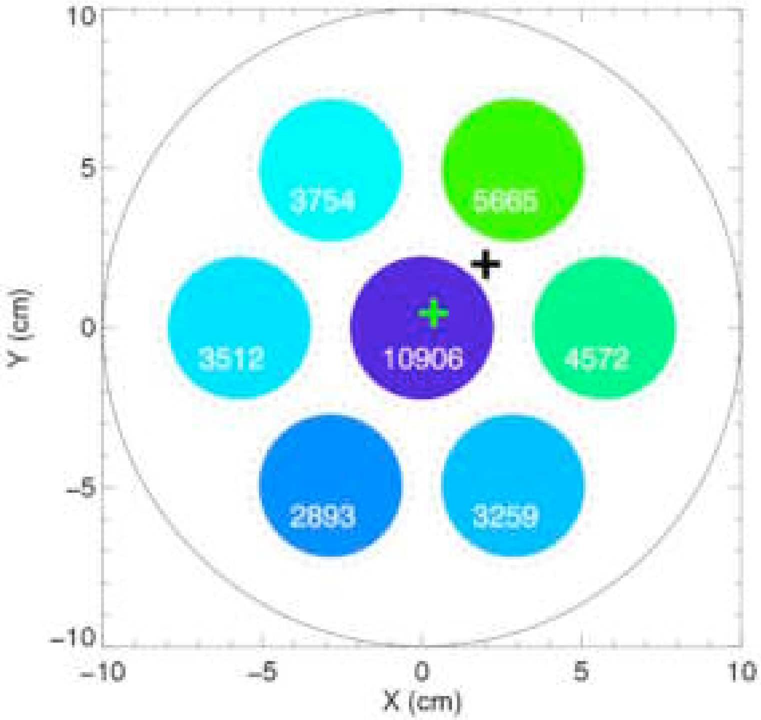
The negative ground state energy of quasi-free electrons in LXe requires an accelerating electric field to extract them through the liquid-gas interface. We find that at E> 10 kV/cm extraction is near 100%.

Proportional Light Spectrum : p.e. from 122 keV in LXe localized within mm of TPC bottom→ charges drift entire 5 cm gap under 1kV/cm →efficiently extracted to the gas accelerating gap (10 kV/cm), producing large proportional light signal

Simulation: X-Y Position Reconstruction for the Current Chamber

$$\vec{r}_{res} = \frac{\sum_i N_i(pe) \times \vec{r}_i(pmt)}{\sum_i N_i(pe)}$$

- position reconstructed from proportional light hit pattern using a simple center-of-gravity method
- better position resolution expected with more sophisticated algorithm
- 100 keV electron recoil, 1kV/cm drift field
- 10 kV/cm amplification field, 2 atm, 5 mm gap
- # of photoelectrons are showed on each PMT



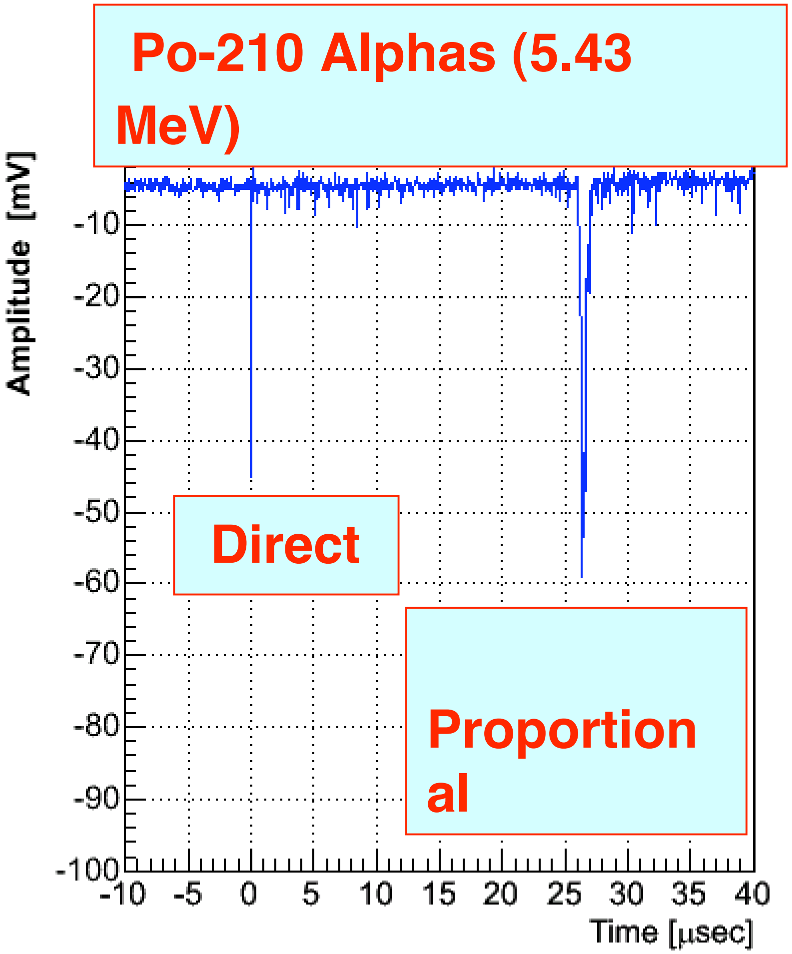
Event position (black cross): (2, 2) cm

Reconstructed position: green cross

X position error: 1.65 cm

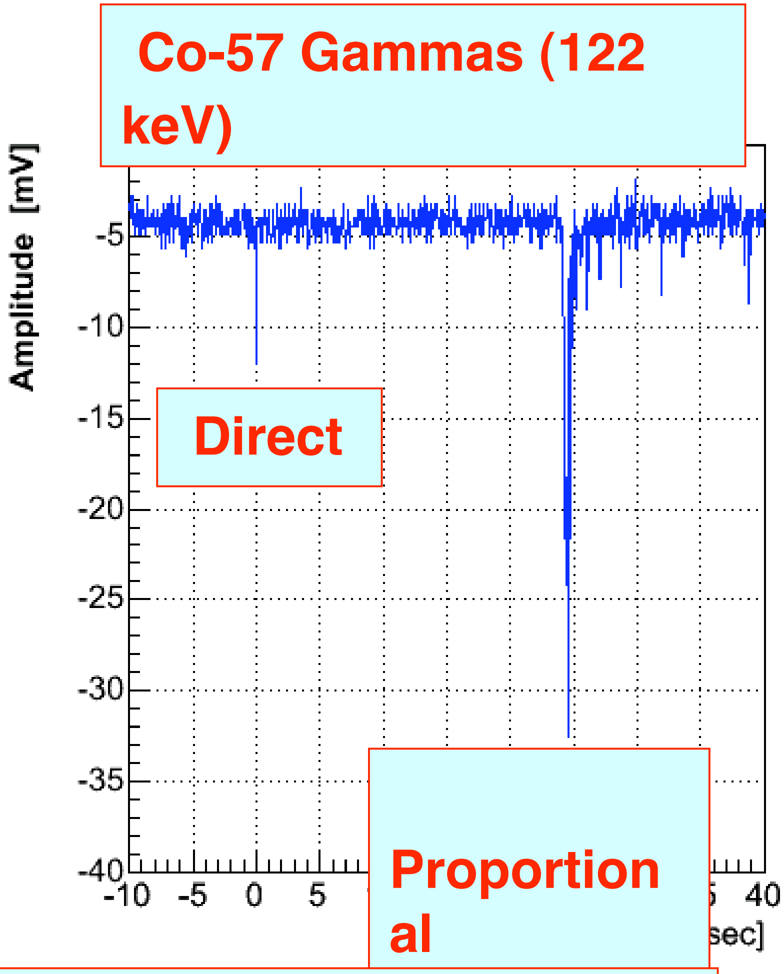
Y position error: 1.54 cm

Typical Light Waveforms from Dual Phase Chamber


Po-210 Alphas (5.43 MeV)

Direct

Proportional


Co-57 Gammas (122 keV)

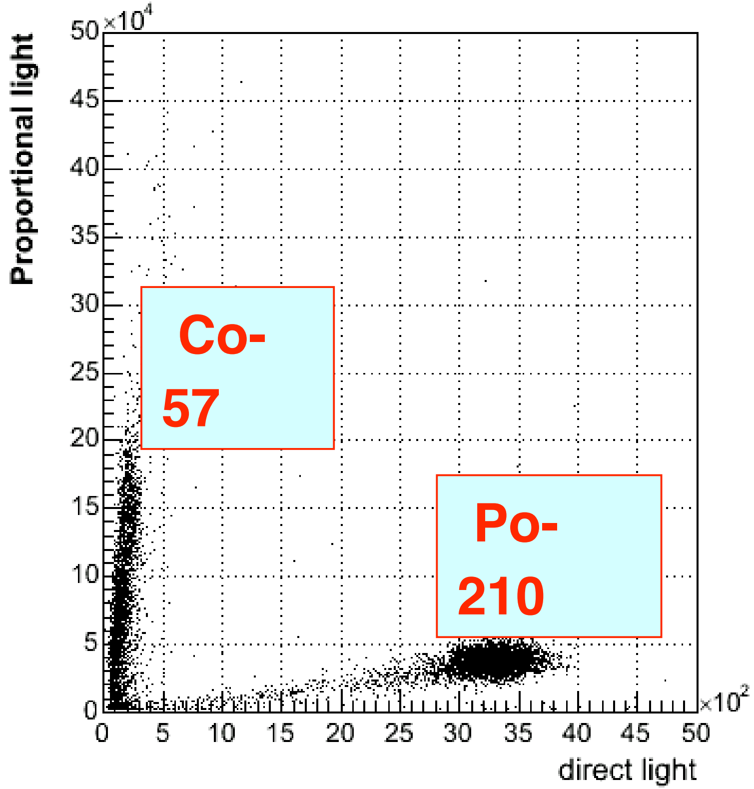
Direct

Proportional

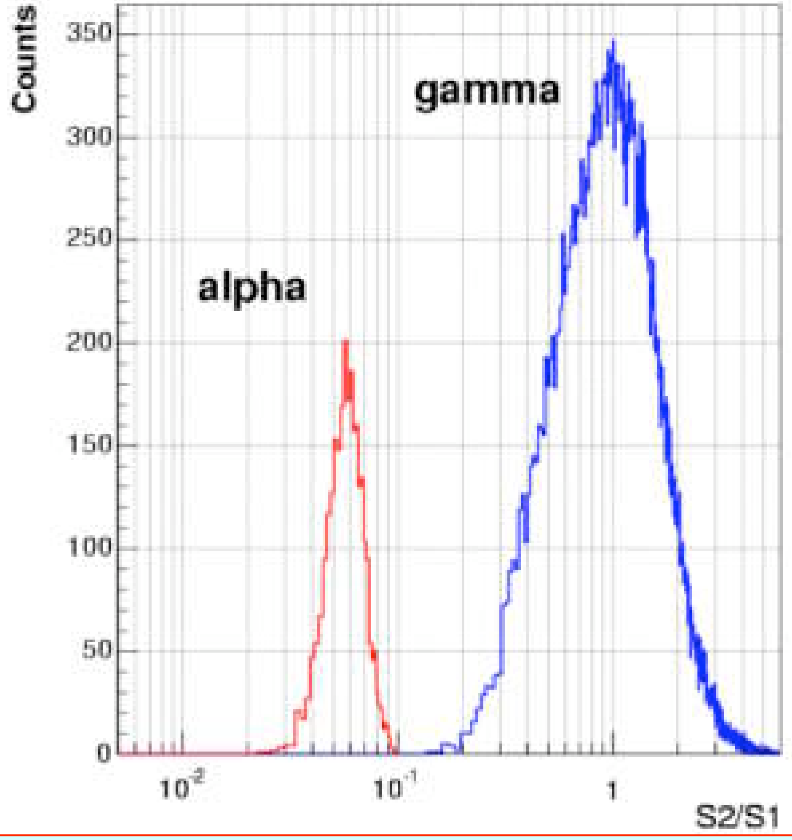
Localized Ionization clouds liberated by alphas and 122 keV gamma photoelectric absorptions drift entire LXe gap (~25 μs)

R&D Milestone: Alpha and Electron Recoils Discrimination

Dual Phase TPC Data

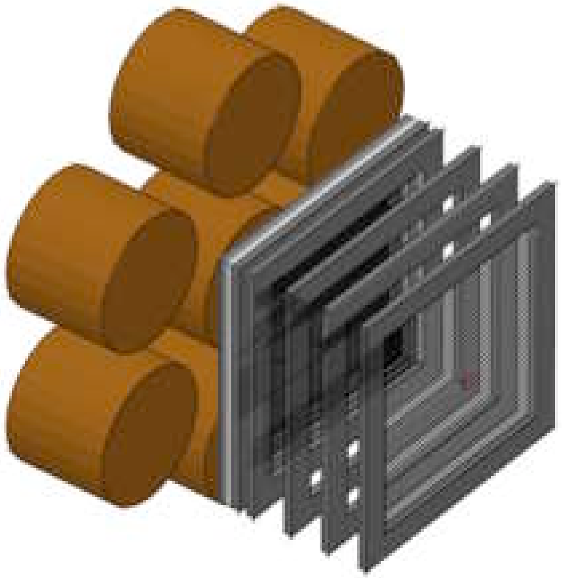


S2/S1 Ratio for α/γ Recoils



Two peaks clearly separated: S2/S1~ 20 / 1 as expected, taking into account loss of alpha direct light due to absorption by source plate

7 PMTs Array: MC Simulations of Direct Light Collection

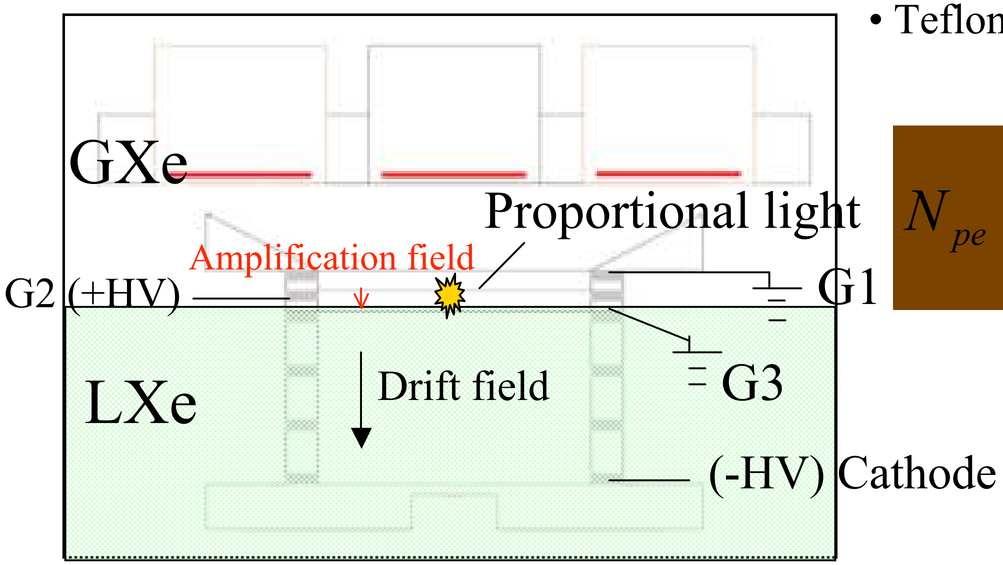


Detector Parameters

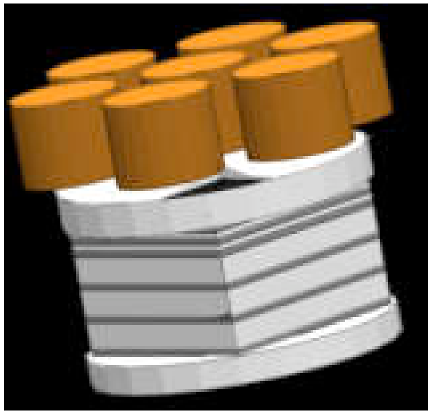
- wire grids, 0.12 mm diameter and 2 mm spacing
- sensitive volume: 5 cm * 8 cm * 8 cm
- amplification gap : 5.5 mm

Simulation Assumptions

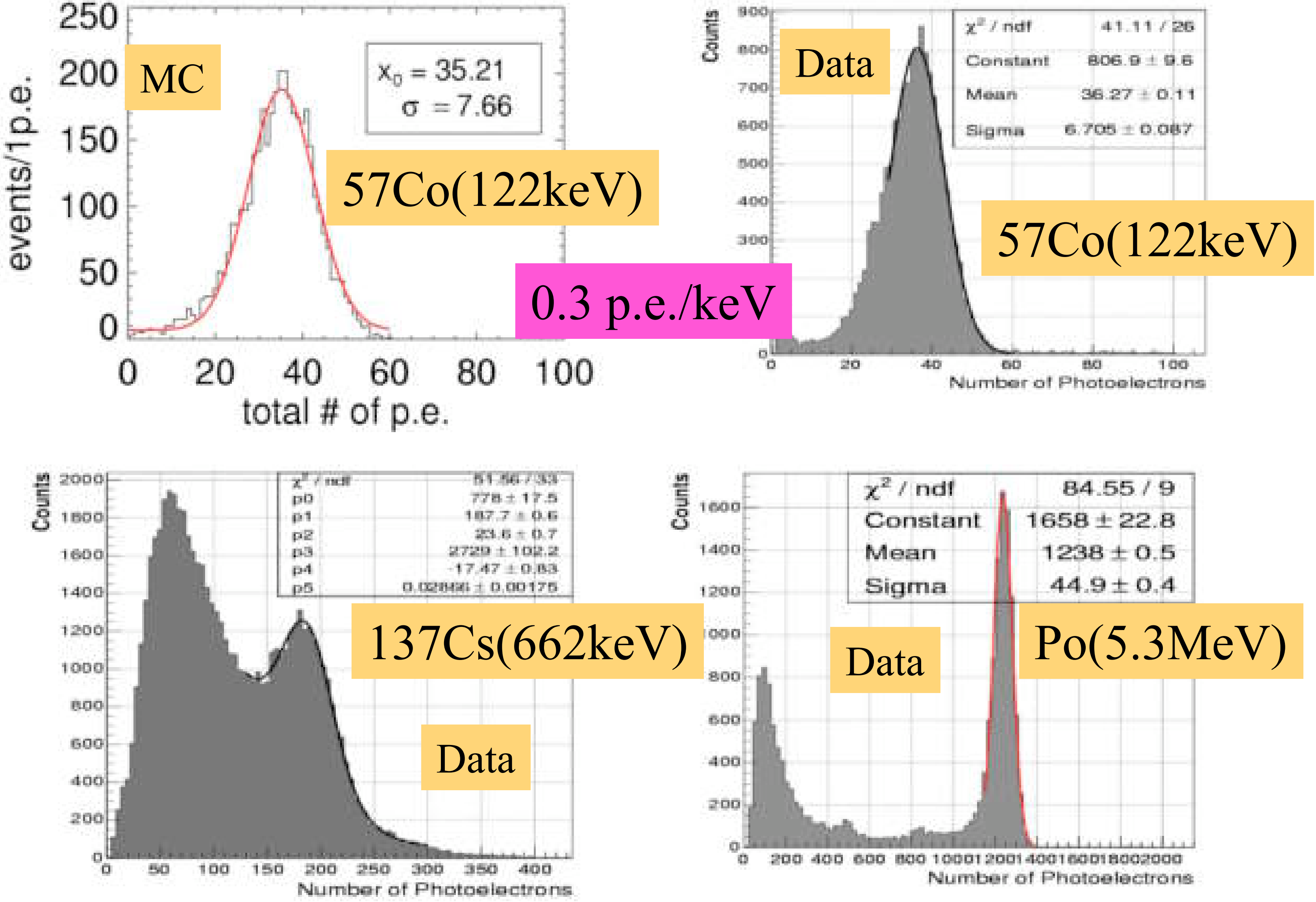
- W value for electron recoil : 23.7 eV
- LXe absorption length : 100 cm
- LXe index of refraction : 1.61
- PMT quantum efficiency : 20%
- PMT p.e. collection efficiency : 60%
- Quartz window index of refraction : 1.56
- Teflon reflectivity : 95%



$$N_{pe} = \frac{E_{\gamma} \cdot Q_{f}}{W_{ph}} \times P_{ce} \times Q_{e}$$



R&D Milestone : Direct Light Detection for γ/α (Data & MC)



MC

57Co(122keV)

Data

57Co(122keV)

0.3 p.e./keV

137Cs(662keV)

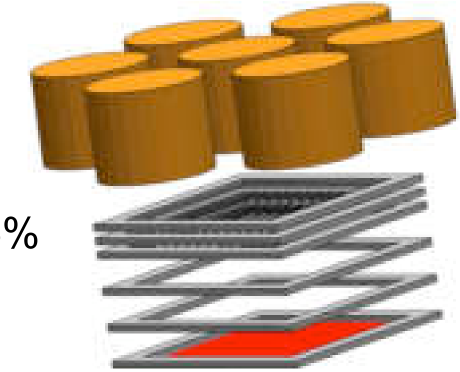
Data

Data

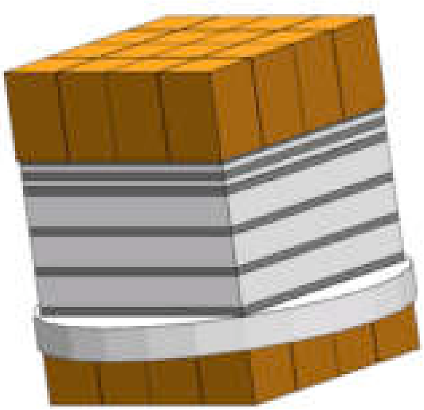
Po(5.3MeV)

How to Increase Light Collection in this TPC prototype?

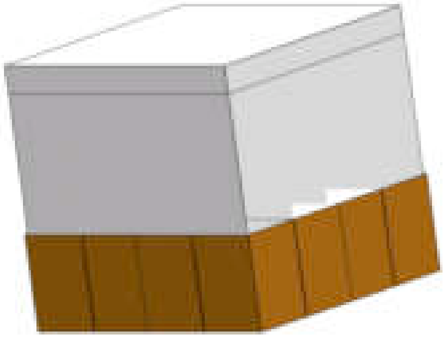
Current chamber with seven R9288 PMTs
→ 0.3 p.e./keV
→- 0.6 p.e./keV
with seven R8778 (26% QE, 90% C.E.):



Chamber with CsI photocathode (31% QE) on the bottom and same PMTs as current chamber on top (PTFE not shown): 0.15 p.e./keV for PMTs; 6.2 p.e./keV for CsI



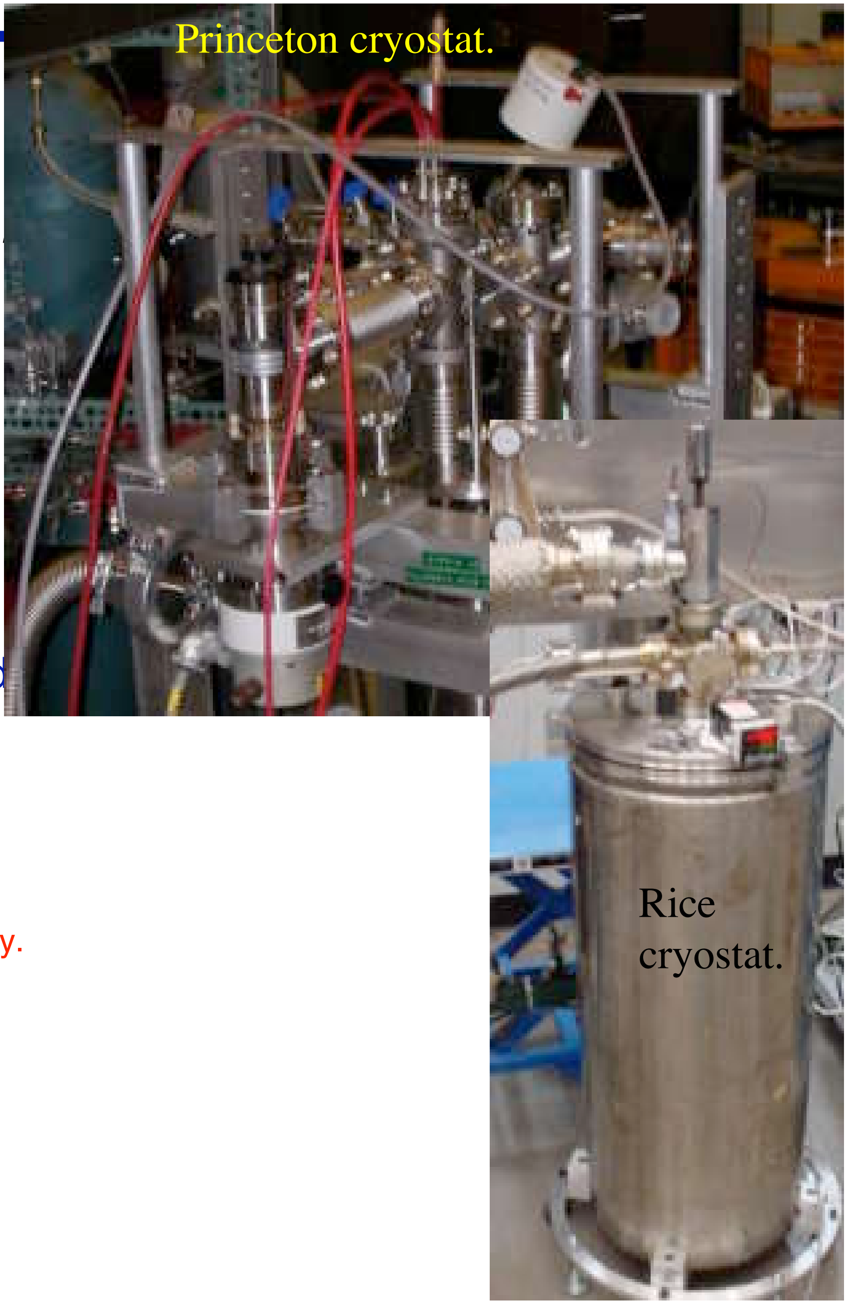
Chamber with 16 R8520 square PMTs (24% QE, 70% C.E.) on top and 16 on bottom: 2.5 p.e./keV



Chamber with 16 R8520 square PMTs (24% QE, 70% C.E.) only on bottom: 2.5 p.e./keV

We will investigate all these possibilities in the coming months

Other chamber / Cryostats for XENON R&D



- CsI feedback
  - Three CsI photocathodes ready for testing, for small and large chambers (CERN, *V. Peskov*; Bari, *Singh*).
  - Remove electrons with "Gate" grid

    Switch 10 kV in < 1 μs.
  - Shielding to reduce x-talk to PMT

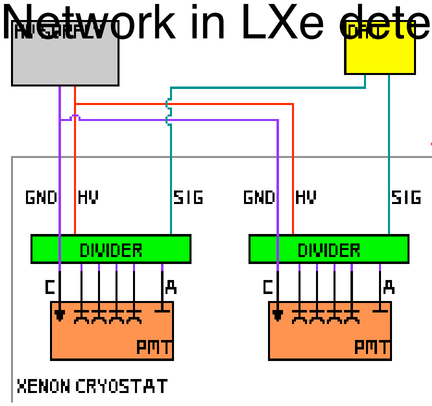
    1 pF, 1 μS, 5000 V $\Rightarrow$ 5 mA, 5 nC.
  - CsI handling and stability to be studied

    (production capability in Princeton HEP)
  - CsI radioactivity negligible for < μm photocathod
- Princeton cryostat
  - CsI tests
  - Stretched Wire Grids
    - Tested from 180 °C to 77K, for liquid Xe purity.
    - New Cirlex for patterned circuits. Now testing for LXe purity.
  - Precision liquid capacitance sensor: level + tilt measurement < 100 μm
  - Wire readout development
- Rice cryostat
  - GEM development

R&D on Novel HV bias distribution for PMTs array (LLNL)

Usual method

- One HV supply per PMT biases dynodes across resistive Network in LXe detector

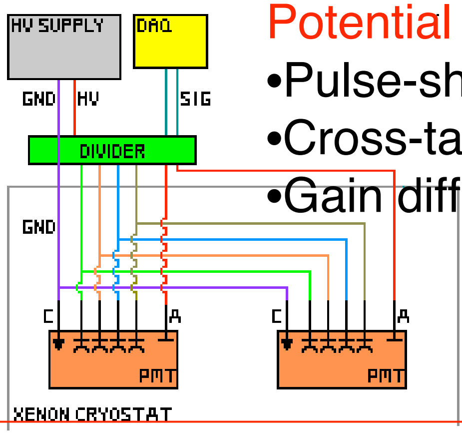


Problems:

- Heat-dissipation (~50mW/ch)
- radio-impurities of resistors
- Many feedthroughs for ge array

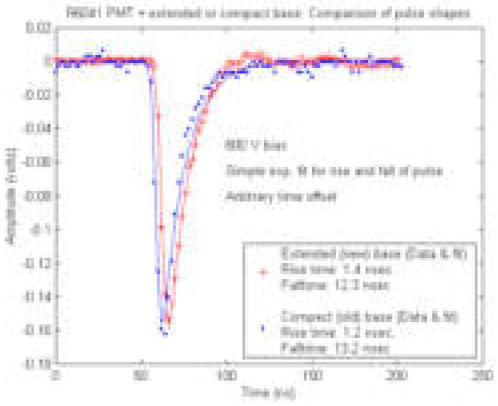
New method

- Move network outside cryostat
- Deliver each dynode bias throug cable harness
- # of FT reduced for large array



Potential Problems:

- Pulse-shape degradation
- Cross-talk between PMTs
- Gain differences of PMTs

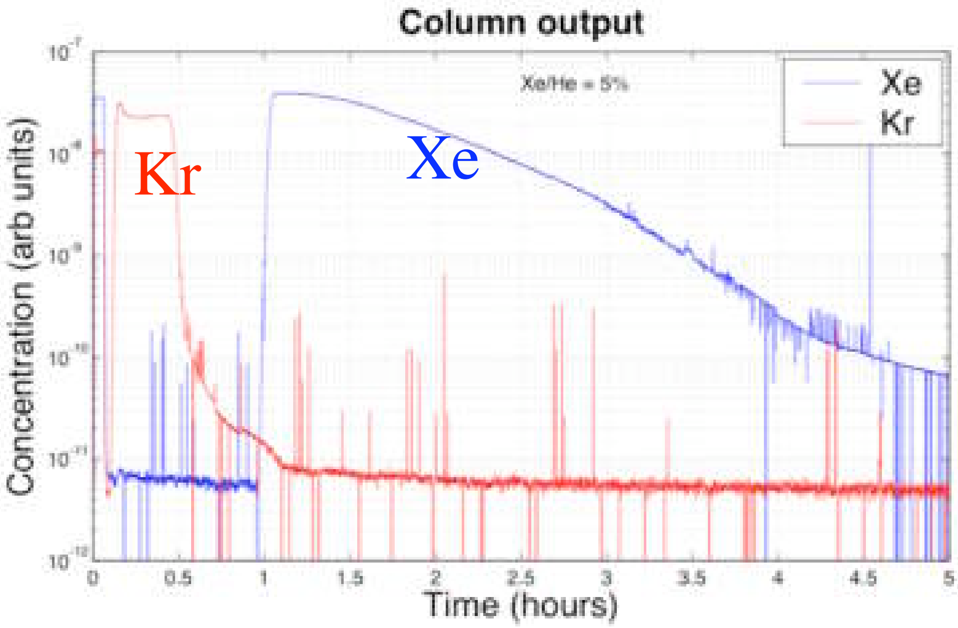


NO DEGRADION OF PULSE SHAPE

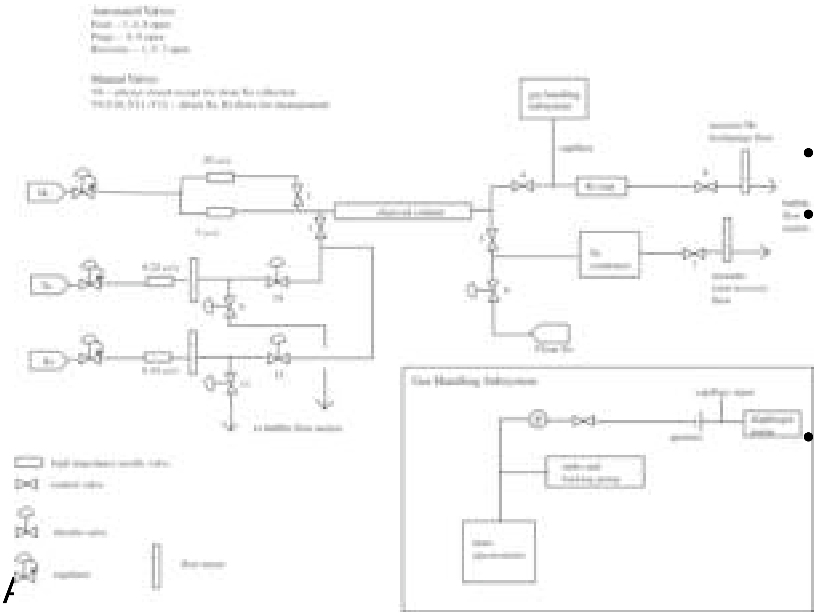
- Next Steps:
- add 2nd PMT to external divider & cable harness.
- Characterize power consumption, pulse shape, termination, cross-talk
- Replace resistive network with separate supplies for each dynode.
- Design harness for PMTs of choice in prototype detector

R&D on Kr Removal (Princeton)

- ^{85}Kr. 687 keV endpoint β decay.
  Rate: 280 kBq/Kg(Kr).
- XENON100: need 0.1 ppb Kr/Xe.
- Industry (SpectraGas) can produce ≈ 10 ppb Kr/Xe.
- Chromatographic separation with activated charcoal
  - Separate NSF funding at Princeton
- Separation demonstrated with 60 gm charcoal column.



Kr separation ≈ 99.9 % (Preliminary)



- Full processing system now being tested.
- Projected performance, 1 Kg charcoal column:
  - 1.8 Kg Xe/day
  - Purification ≈ 10^3 (PRELIMINARY)
  - Use 14 stp m^3 He/ Kg Xe processed.
- High purity system: completed Summer 05.

Material screening (University of Florida)

First step (~ 6 months):

SOLO facility (coordinated by Brown): gamma screening for Majorana, CDMS & XENON

Second step:

enlarge SOLO facility with additional ULB, 100 % eff HPGe detector,

read-out electronics + software (U Florida) and operate facility jointly

Future: Soudan Low Background Lab proposal - SOLO will be integrated into the proposed larger Low

Background Lab

Priority of screening (over ~ 1 year):

PMTs: inner parts, ancillary parts, glass

Resistive material (RuO_2) and substrate

PFTE, Grid materials,E-shaping rings

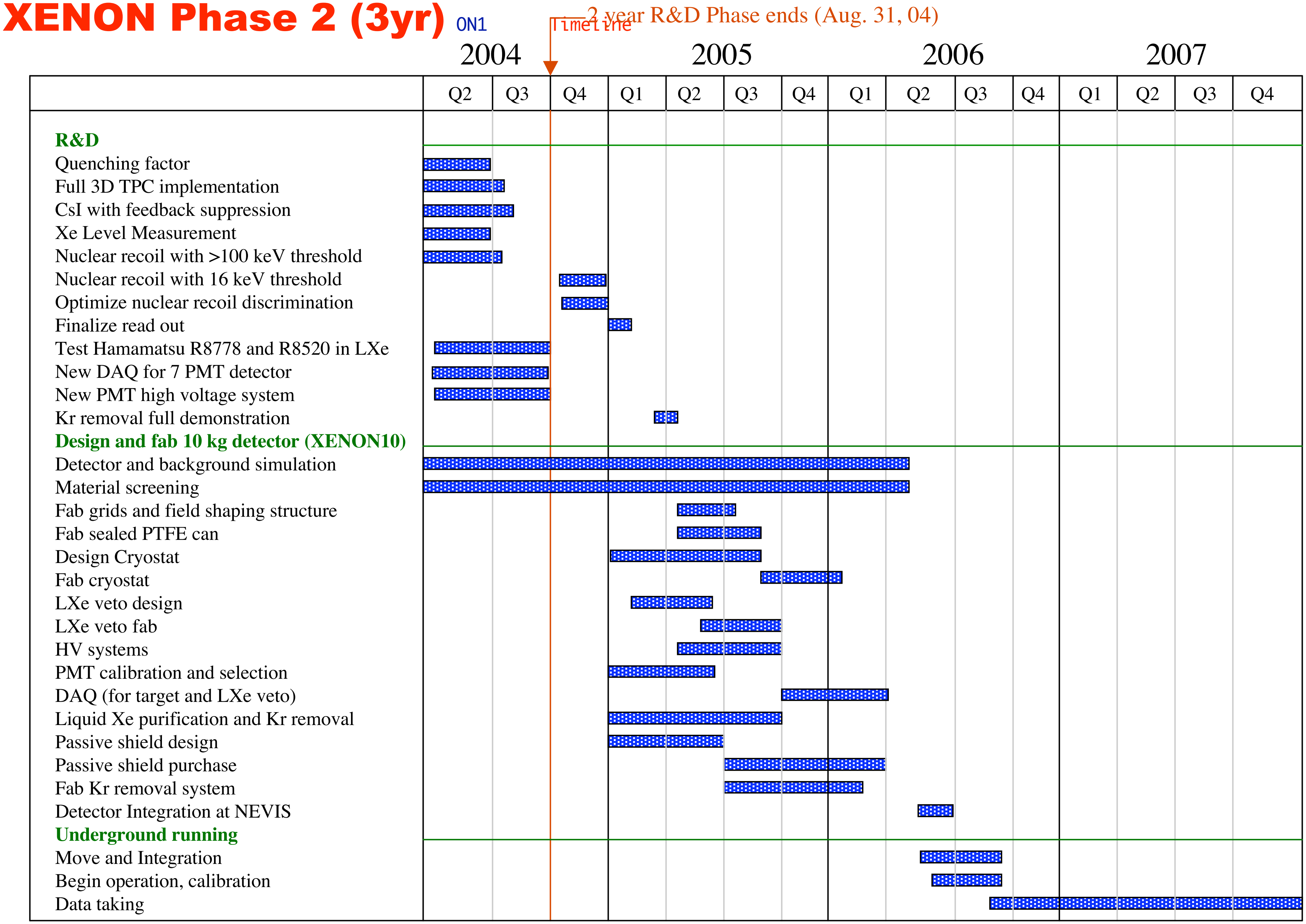
Shielding materials, cables, connectors, insulation material, outer vessel

Results from screening will be integrated into Monte Carlo background studies

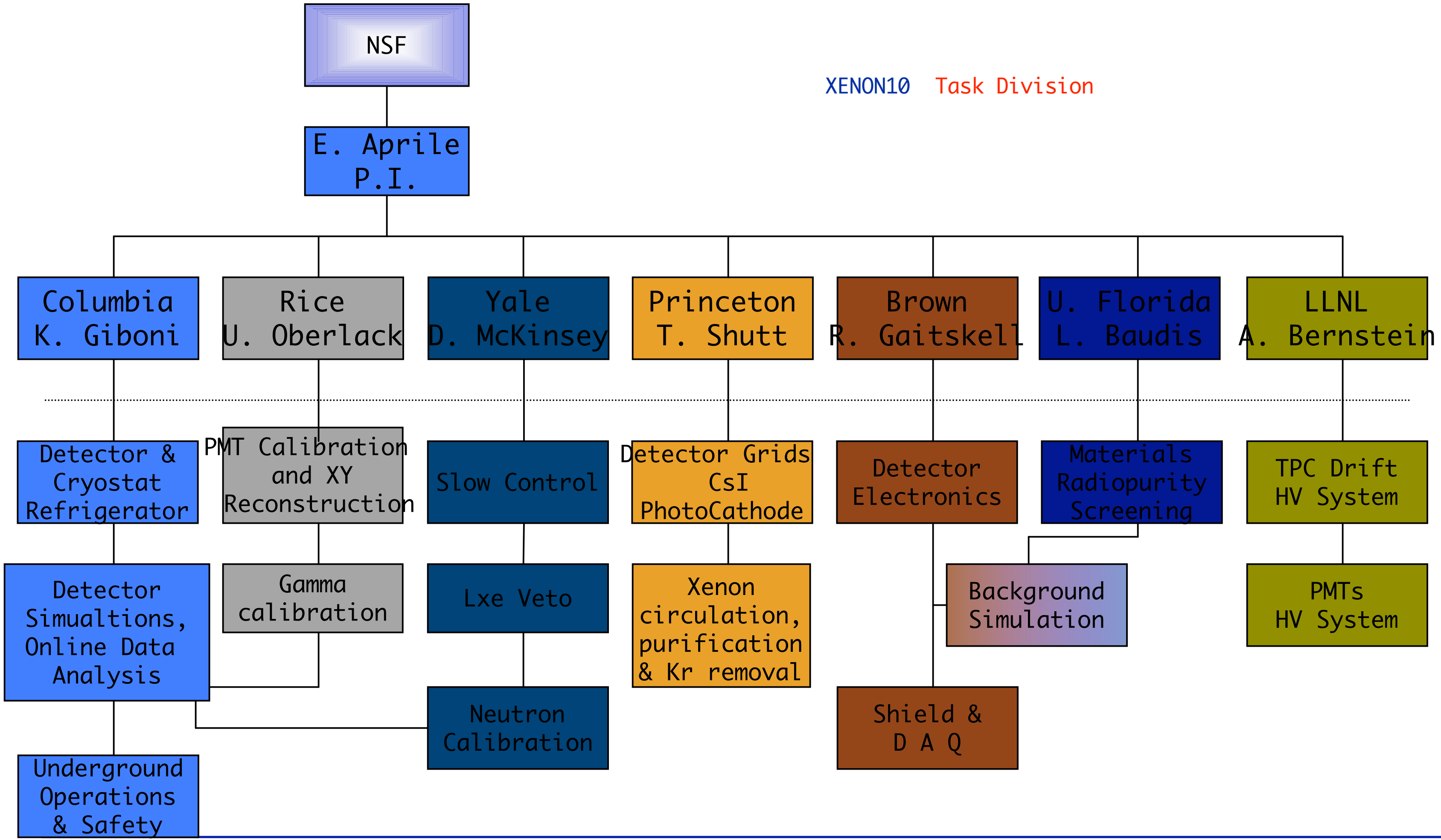
Alternative Light and Charge Detectors

- MCP PMT (Burle). Alternative to Hamamatsu. (Brown).
  - Gain Demonstrated $2x10^5$, single PE, QE=8% with program to improve -> 30%
  - Operated in LXe single and dual phase small chamber, very fast time response, segmented anode, favorable packing geometry. Still problems with LXe purity.
  - Radioactivity ≈ 5 x Hamamatsu PMT, program to reduce 10-100x
- Gas gain charge readout.
  - Motivation: radioactivity << from PMTs, unambiguous x-y position, PMT cost.
  - Prerequisites for single electron detection appear to be met:
    - Gain $G=2x10^4$ wires (Princeton, also Sakurai, NIMA313,155 1992), $G=3x10^3$ GEMs (Bondar, NIMA481, 200 2002)
      - At room temperature, but final gas density.
    - Theoretical noise limit (Radeka) = 50 e^- rms. (10 pF, 2 μs, 160K).
  - Requires CsI photocathode to work
  - Wire grid (Princeton)
    - Cirlex circuit board technology developed. Now testing for LXe purity.
    - Low noise electronics with stripline readout. (similar to CDMS charge readout).
  - GEMs (Rice).
    - Possible front-side CsI for additional light collection. (or reflective coating).
    - Sub mm x-y readout possible
    - Glue-free mounting method tested. LXe purity still under study.
- Decision on XENON10 Readout finalized in Spring 2005. R&D on alternative readout schemes continued at low level, mostly with startup and other funding.

XENON Phase 2 (3yr)



XENON Organization Chart



XENON10 Task Division

NSF

E. Aprile
P.I.

Columbia
K. Giboni

Rice
U. Oberlack

Yale
D. McKinsey

Princeton
T. Shutt

Brown
R. Gaitskell

U. Florida
L. Baudis

LLNL
A. Bernstein

Detector & Cryostat Refrigerator

PMT Calibration and XY Reconstruction

Slow Control

Detector Grids CsI PhotoCathode

Detector Electronics

Materials Radiopurity Screening

TPC Drift HV System

Detector Simualtions, Online Data Analysis

Gamma calibration

Lxe Veto

Xenon circulation, purification & Kr removal

Background Simulation

PMTs HV System

Neutron Calibration

Shield & D A Q

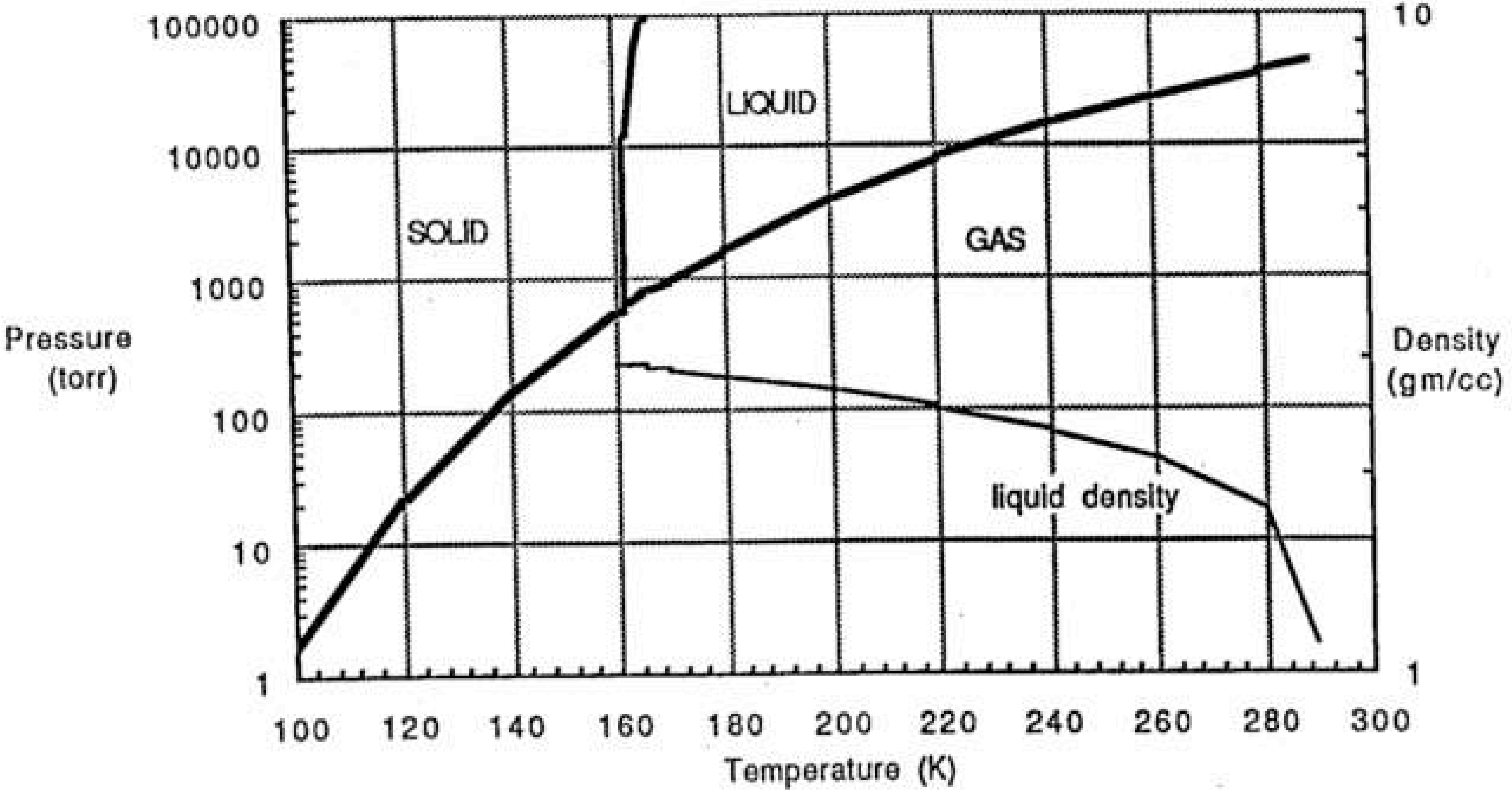
Underground Operations & Safety

XENON SAGENAP Presentation: Additional Slides

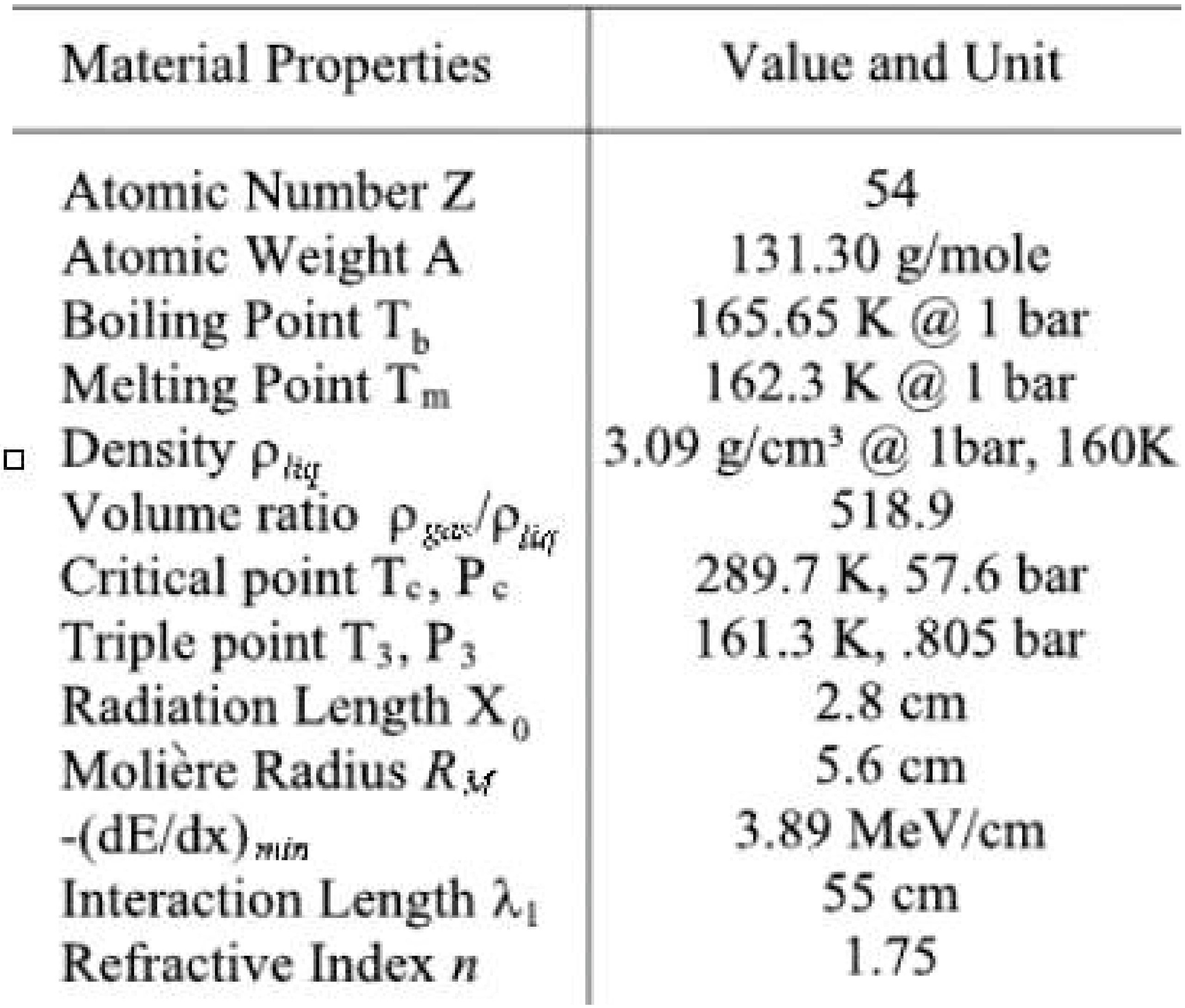
Promise of Liquid Xenon for Dark Matter Detection

- **High atomic number (Z=54) and density (ρ=3g/cc) permit a compact self-shielding detector geometry.** Presence of even / odd Isotopes allows for spin-independent / spin-dependent interactions.
- **Simultaneous measurement of ionization and scintillation signals produced by WIMP interactions and the different amplitude/time response of these signals for e/n recoils provide powerful and efficient background discrimination.**
- **Additional background suppression with 3D position sensitive TPC and active LXe VETO. Requirement for passive shielding largely reduced.**
- **It is available in large quantities at a reasonable cost (~1k$/kg). "Easy" cryogenics at –100 °C.**
- **It can be purified to achieve > 1 meter drift of free ionization electrons . Additional processing can reduce traces of radioactive ^{85}Kr , ^{42}Ar, Ra to the low level required. No long-lived radioactive Xe isotopes.**

Xenon Phase Diagram

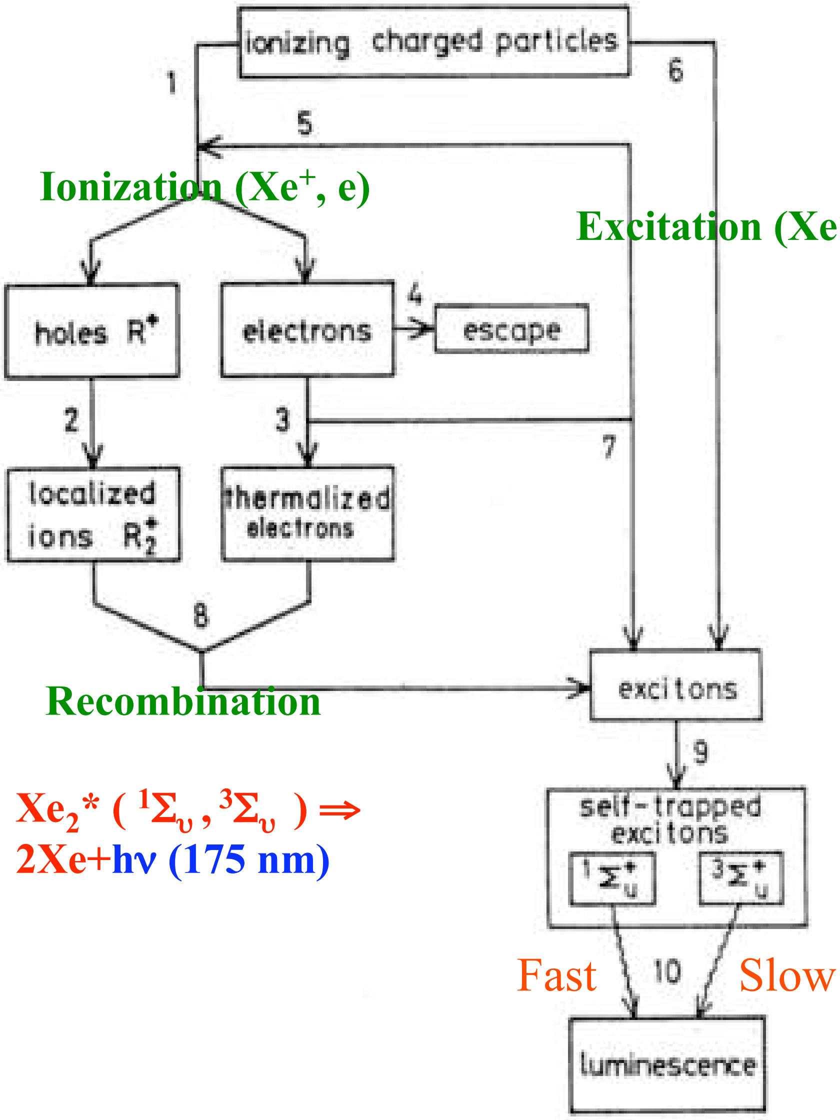


Xenon Physical Properties



Material Properties	Value and Unit
Atomic Number Z	54
Atomic Weight A	131.30 g/mole
Boiling Point T_b	165.65 K @ 1 bar
Melting Point T_m	162.3 K @ 1 bar
☐ Density ρ_{liq}	3.09 g/cm³ @ 1bar, 160K
Volume ratio ρ_{gas}/ρ_{liq}	518.9
Critical point T_c, P_c	289.7 K, 57.6 bar
Triple point T_3, P_3	161.3 K, .805 bar
Radiation Length X_0	2.8 cm
Molière Radius R_M	5.6 cm
$-(dE/dx)_{min}$	3.89 MeV/cm
Interaction Length λ_I	55 cm
Refractive Index n	1.75

Ionization and Scintillation in Liquid Xenon



Ionization (Xe^+, e)

Excitation (Xe^*)

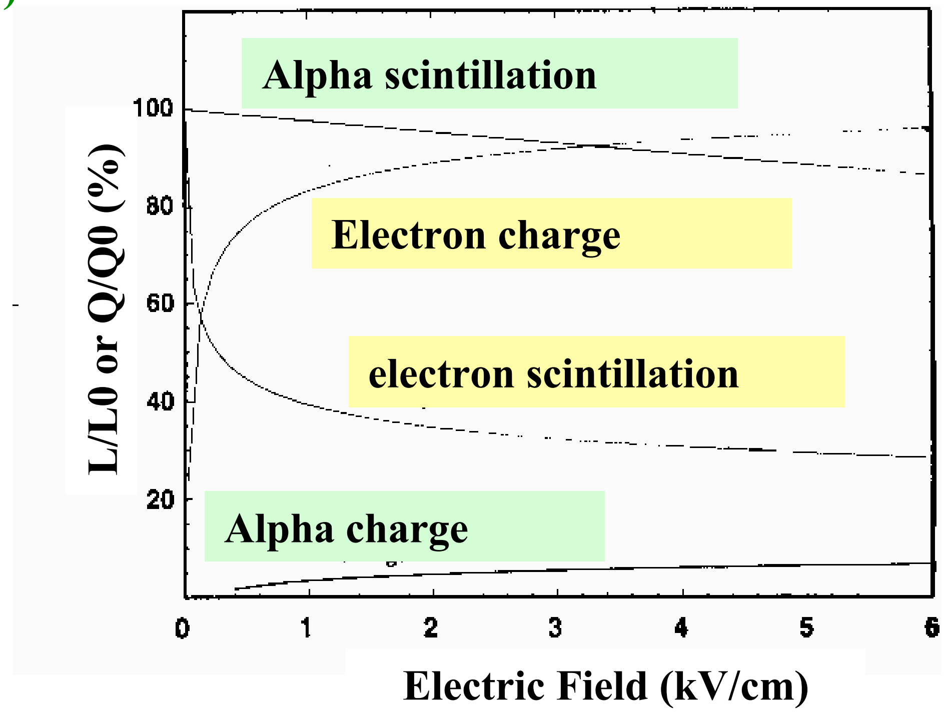
Recombination

Fast

Slow

$Xe_2^* ({}^1\Sigma_\upsilon , {}^3\Sigma_\upsilon) \Rightarrow$
$2Xe + h\nu$ (175 nm)

I/S (electron) >> I/S (non relativistic particle)



Alpha scintillation

Electron charge

electron scintillation

Alpha charge

L/L0 or Q/Q0 (%)

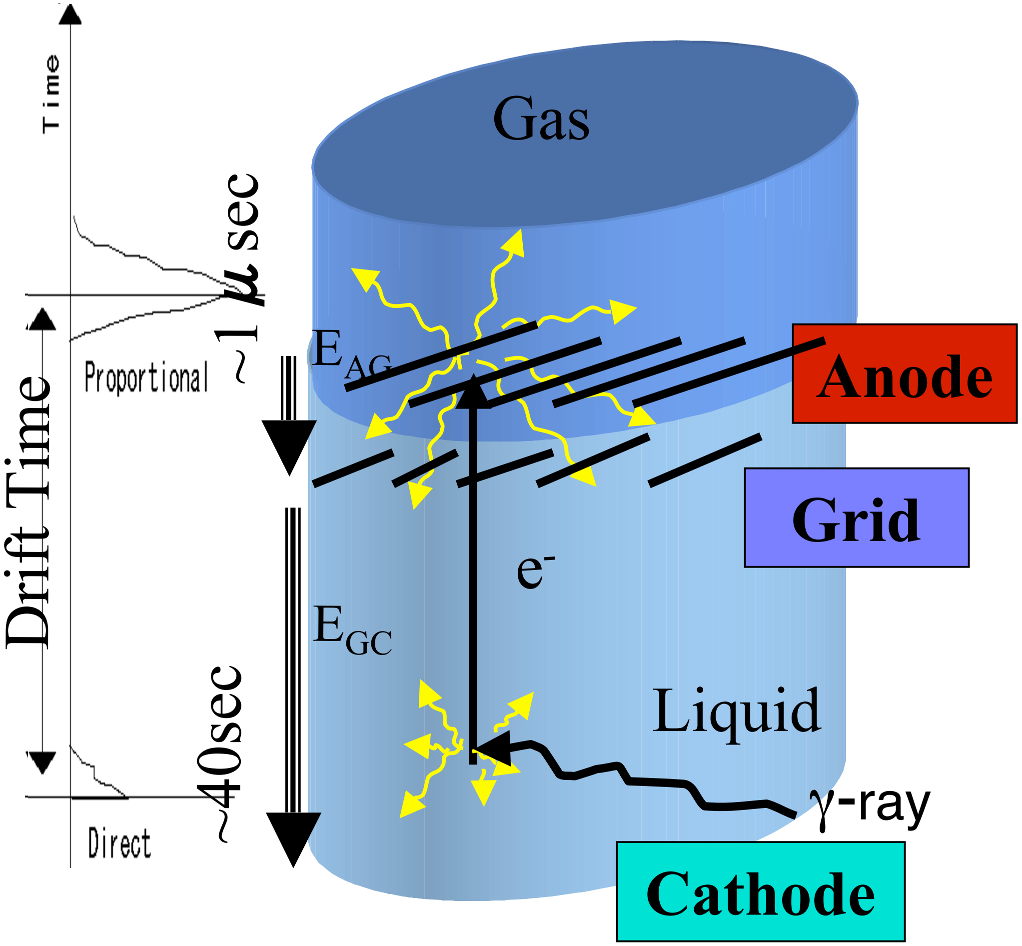
Electric Field (kV/cm)

XENON Event-by-Event Discrimination

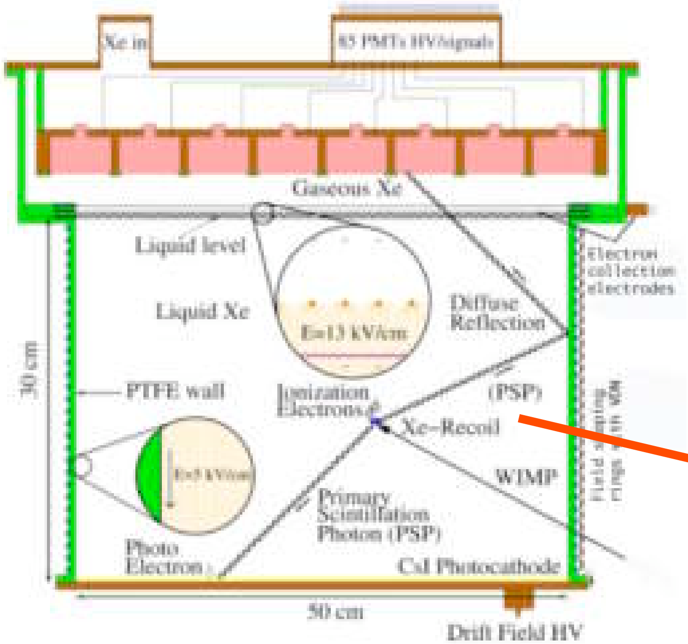
Inside the LXe Target:
WIMPs , Neutrons →
Nuclear type recoils
g, e, a (background) →
Electron type recoils

For each type of event measure simultaneously direct scintillation (S1) and ionization (proportional scintillation) (S2)

Scintillation Signals strongly dependent on type of recoil and applied fields:
S2/S1 >>0→Electron Recoil
S2/S1 ~0→ Nuclear Recoil



The XENON 100kg Module



Drift Field : maximum 5kV/cm
Drift Gap: maximum 30 cm
Prop. Gap: 4 mm (2 atm)
Prop. Field: minimum 13 kV/cm
Target PMTs: 85 (2 ‘’, 30% QE)
Sensitivity : 5 p.e. / keV ee
Target & Shield LXe: 120 liters

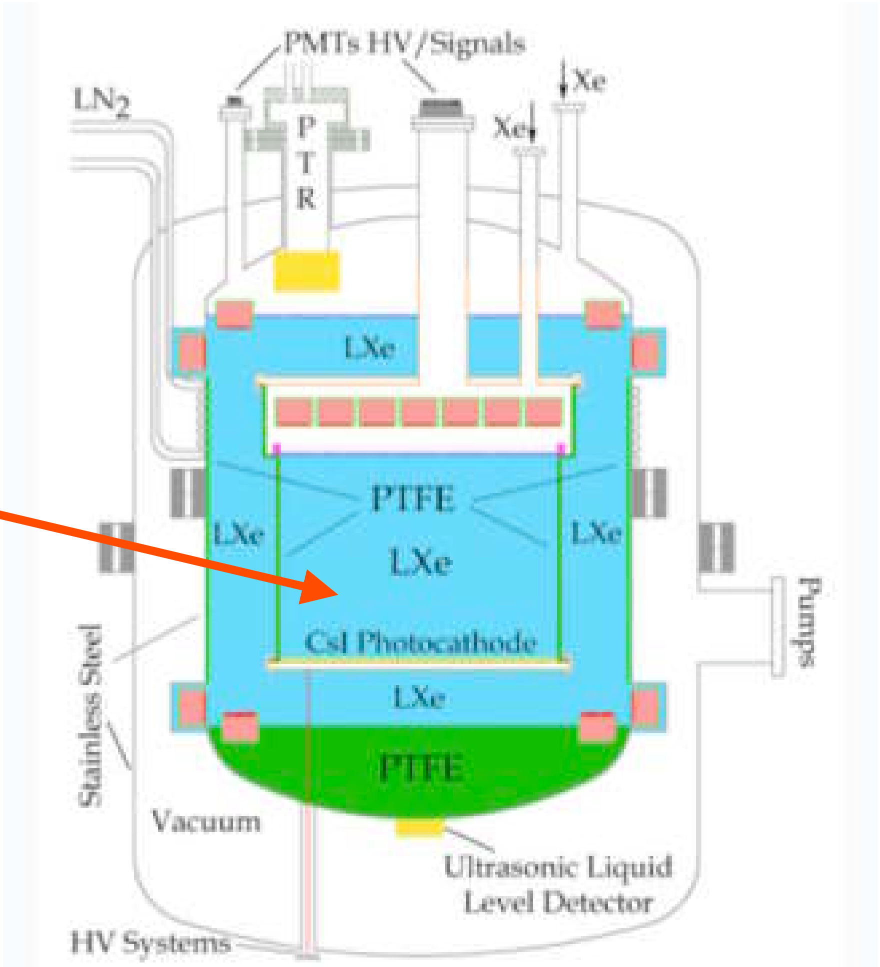


Figure 6. Schematic of XENON100 Detector

XENON100:Cryogenic System and Xe Purification

~ 120 liters of LXe for target and shield. Pulse Tube Refrigerator with ~ 120 W cooling power (heat load on the XENON100 detector estimated at ~ 50W), used for keeping LXe at – 100 C within 0.1 degree. Pre-cooling (~1 day) and Xe liquefaction (~2 days) with same PTR.

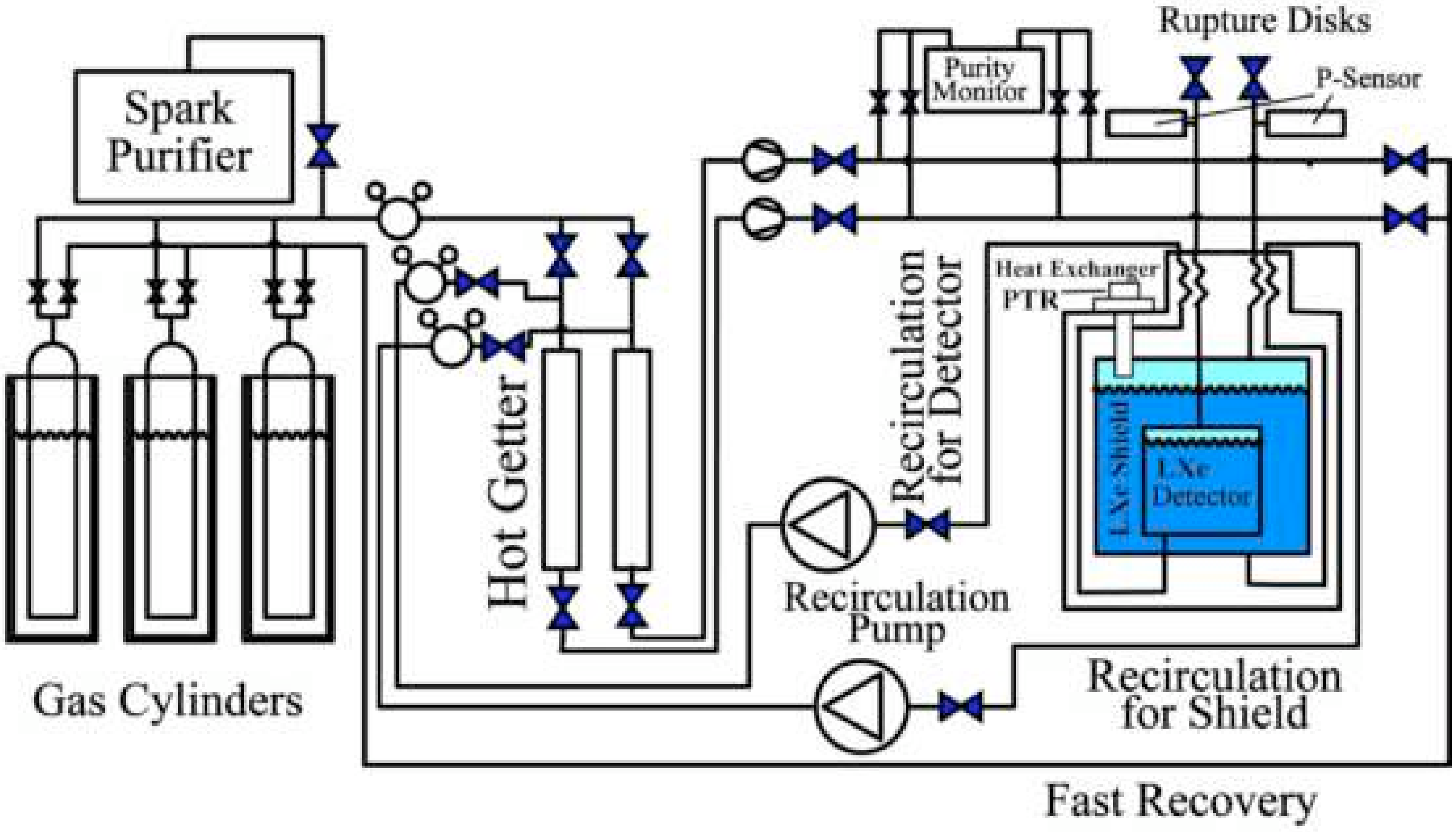
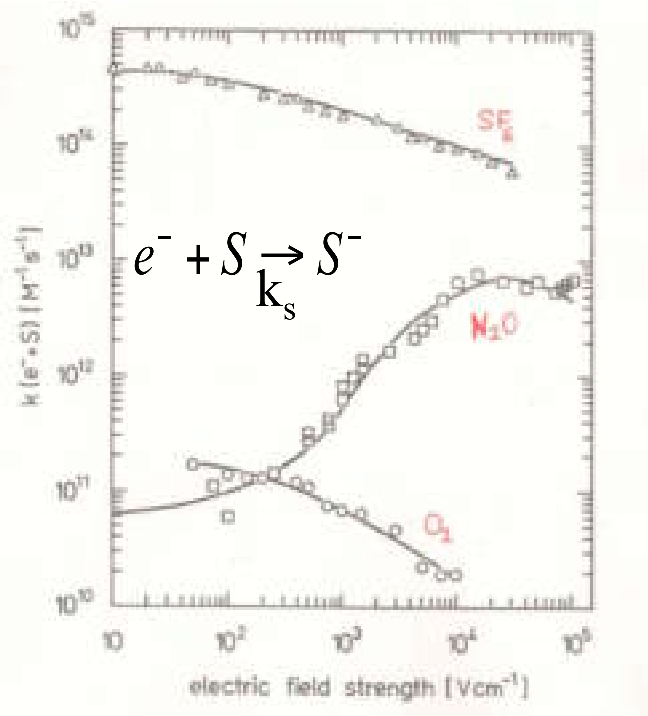


Figure 11. Purification and Recirculation System

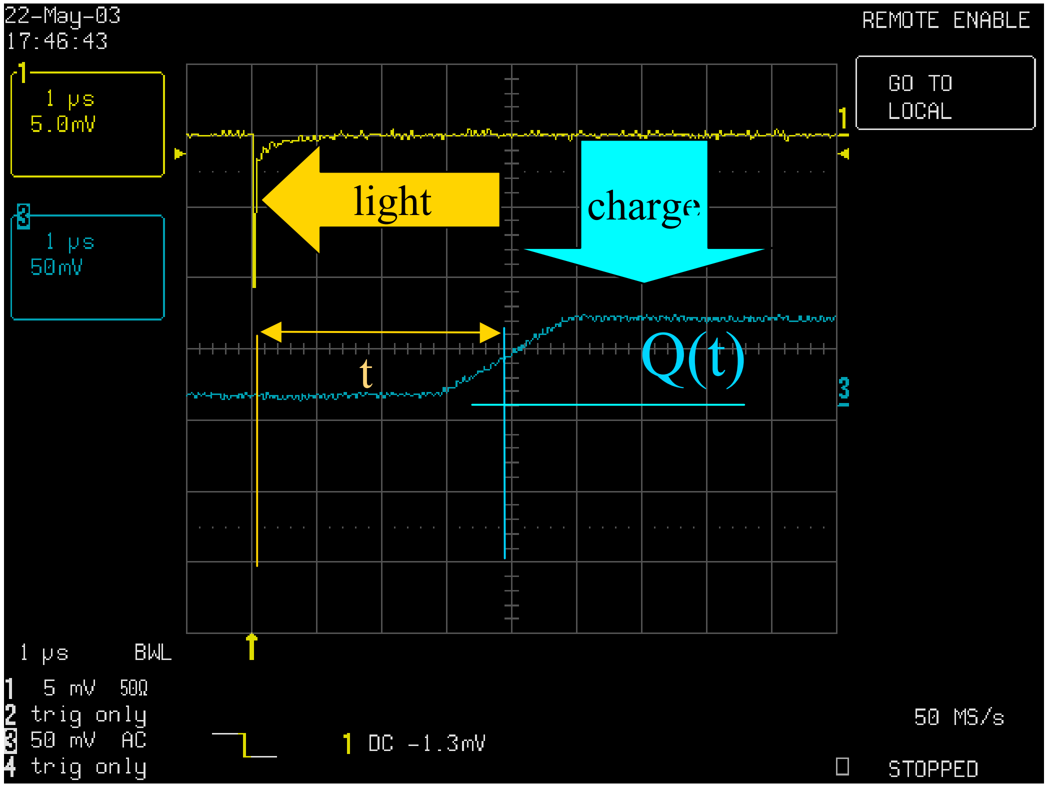
Xe Purification: Electronegative Impurities

- Xe : difficult to purify because of its high affinity for polar molecules
- XENON goal: 30 cm drift gap and <20 e^- signal from 16 keV Xe recoil require extreme purity level, well below 1 ppb O_2 equivalent.
- Commercial Xe: ppm concentration of many impurities (O_2 CO,N_2O,H_2O, etc.) plus numerous organic molecules which also absorb UV light!. At high field, attachment rate to certain impurities increases.

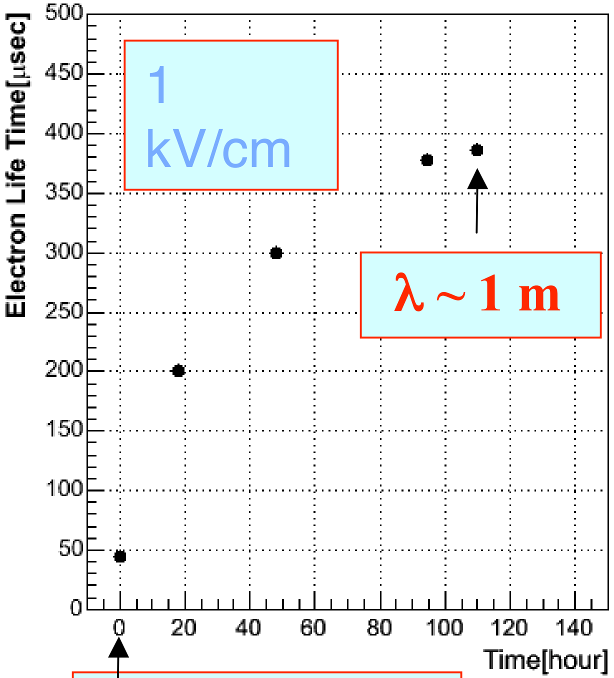


$$e^- + S \xrightarrow[k_s]{} S^-$$

Principle of Electron Lifetime Measurement



22-May-03
17:46:43
REMOTE ENABLE
GO TO LOCAL
1 μs 5.0mV
1 μs 50mV
1 μs BWL
1 5 mV 50Ω
2 trig only
3 50 mV AC
4 trig only
1 DC -1.3mV
50 MS/s
STOPPED



1 kV/cm

λ ~ 1 m

Start Circulation

$$Q(t) = Q(0)exp(-t/\tau)$$

$$\lambda = v\tau$$

attenuation length

Electron life time

drift velocity ~ 2 mm/_s

XENON TPC Signals Time Structure

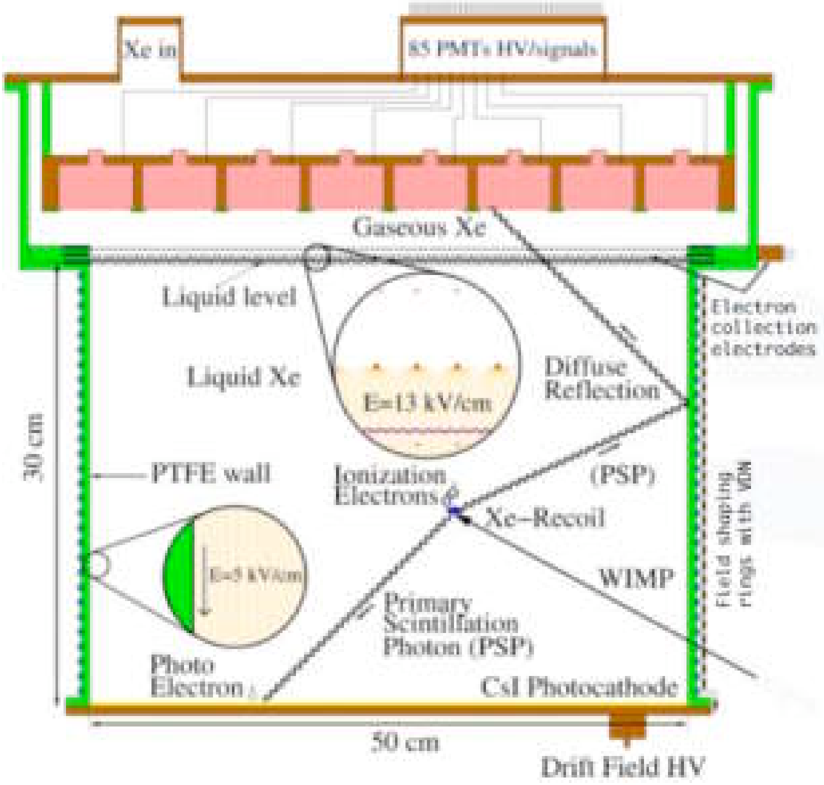
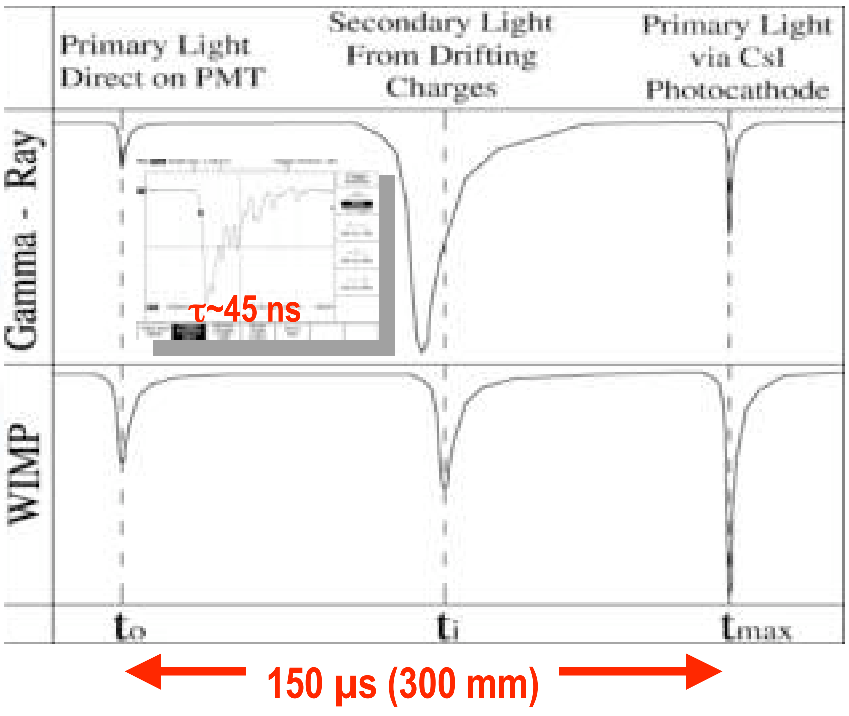


Figure 8. Schematic of 100 kg Detector



- Three distinct light signals; CsI important for low threshold and trigger
- Z from drift time; XY from proportional light signals on PMTs array.
- 3D event localization gives additional background rejection capability

Light Collection Efficiency

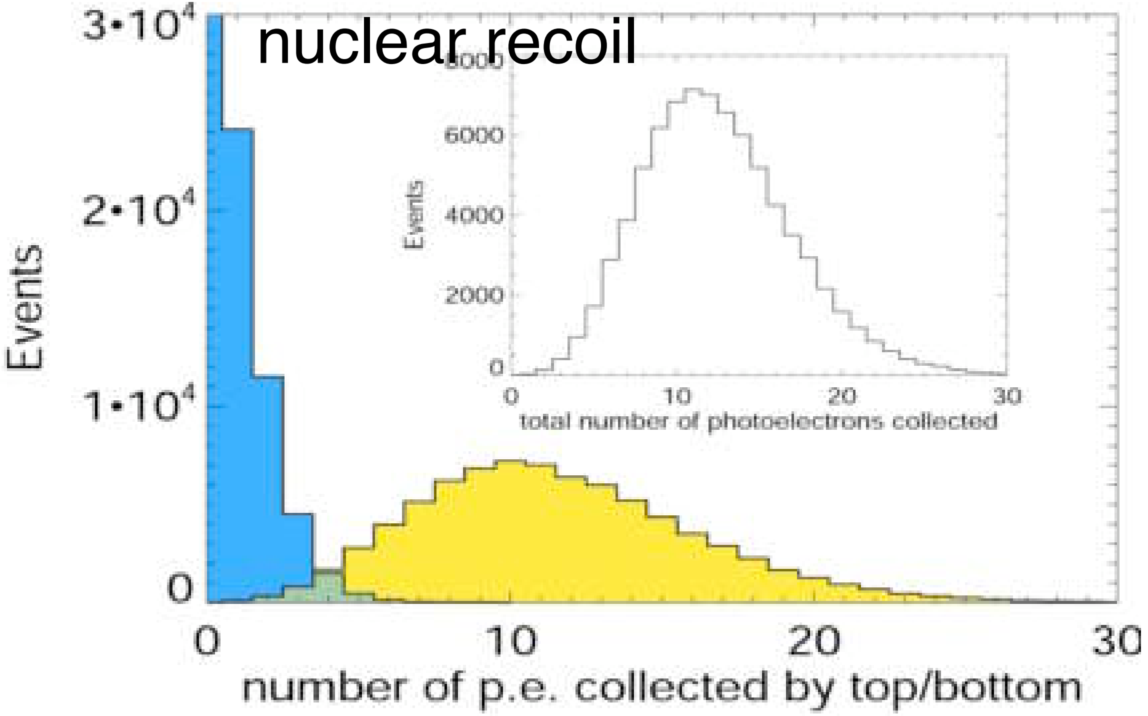
Assumptions (16 keV nuclear recoil) :

- **W_{ph} : 23.7 eV**
- **Absorption Length: 1 m**
- **Scattering Length: 3**
cm
- **Quenching Factor: 2**
- **Q.E. of PMTs: 20%**
- **Q.E. of CsI : 30%**
- **PTFE Reflectivity : 9**
- **Wires Transparency 90%**
- **85 PMTs (2 inch) arra**

Results:

Total light collection efficiency ~40%.

Sensitivity = 5p.e./ keV for nuclear recoil



X-Y Position Resolution - Simulation Results

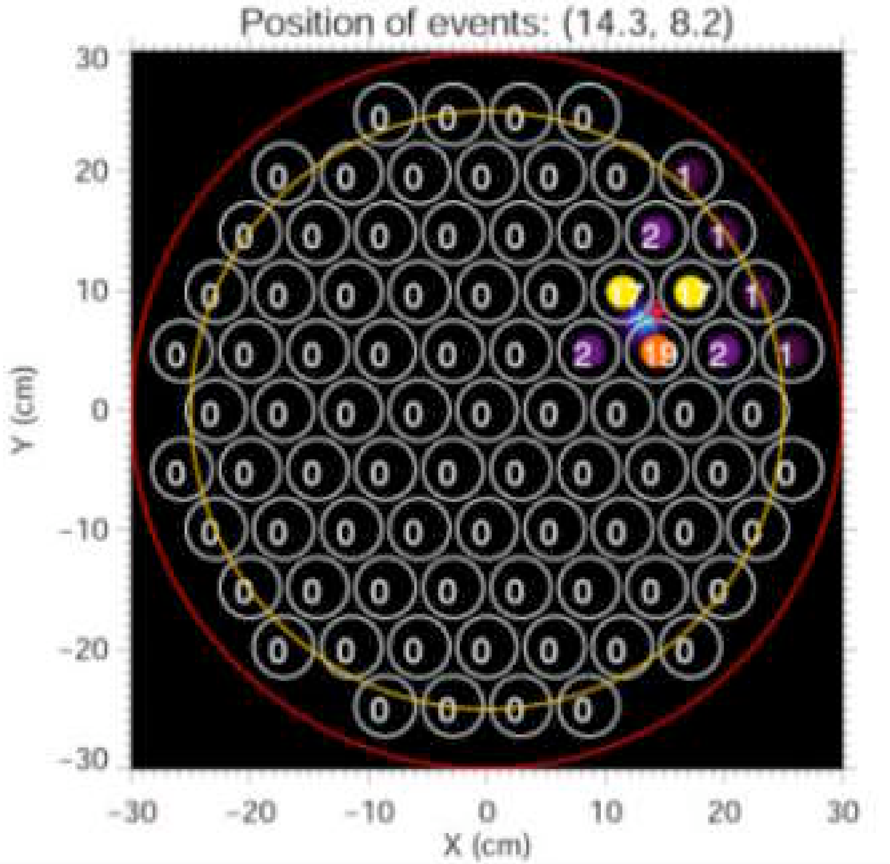


Figure 10. Reconstructed X-Y Position

TPC Parameters:

- **$E_{d,}$: 5kV/cm**
- **Prop. Gap: 4 mm (2 atm)**
- **Prop. Field: 13 kV/cm**
- **PMTs: 1cm above Gap**

Results:

1.2 cm position resolution for uniformly distributed nuclear recoils with 16 keV

Detection of Xe Light with a CsI Photocathode

- Stable performance of reflective CsI photocathodes with high QE of 31% in LXe has been demonstrated by the Columbia measurements

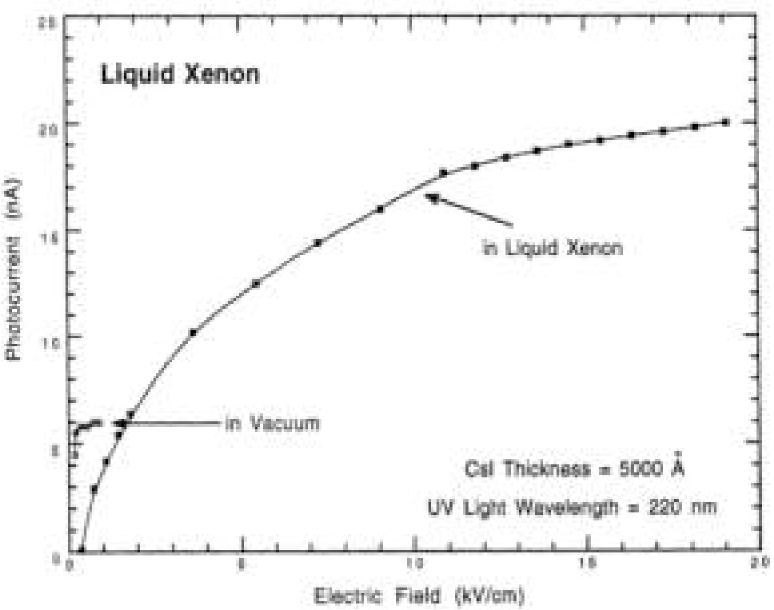
- CsI photocathodes can be made

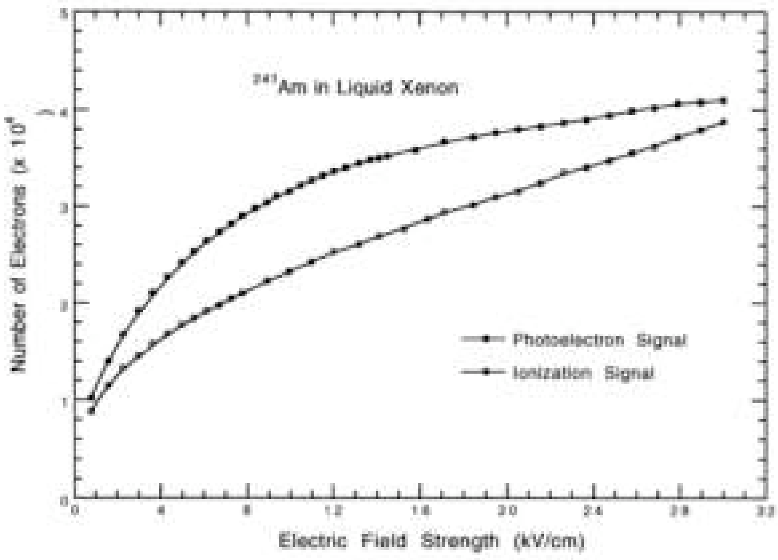
  in any size/shape with uniform response, and are inexpensive.

- LXe negative electron affinity Vo(LXe)= - 0.67 eV and the applied electric field explain the favorable electron extraction at the CsI-liquid interface.

Aprile et al. NIMA 338(1994)

Aprile et al. NIMA 343(1994)



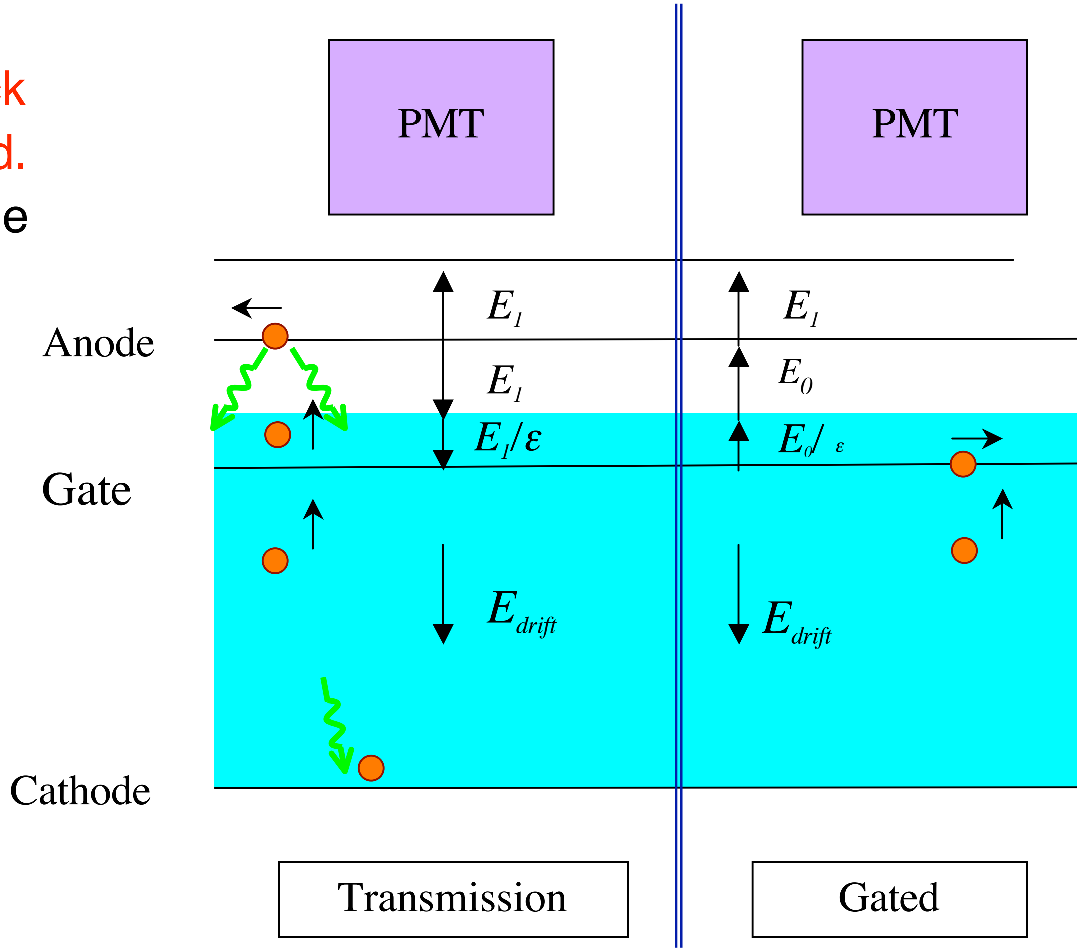


CsI Photocathode for XENON: Feedback Suppression Scheme

- CsI PC on bottom will increase light collection (QE= 30% @ 178 nm).
- Question: Expect Positive Feedback
- Answer: Remove e$^-$ with "Gate" grid.
- HV switching commercially available
  - up to 10 kV in ≈ 50 ns
  - 10 kHz rep rates
- Status
  - Chamber/Cryostat Design complete
  - HV switching unit acquired.
- Cross talk to PMT, other grids:
  - Assume C=1 pF, Δt =1 μS, ΔV=5kV
  - I = 5 mA. Q = 5 nC.
- Next Steps:

  Integrate Princeton chamber with Columbia Xe gas recirculation system (May 2004) .

  Tests with CsI PC (Summer 2004)



R&D Milestone: Dual Phase 3D XeTPC Prototype

Pulse Tube Refrigerator

7 PMTs

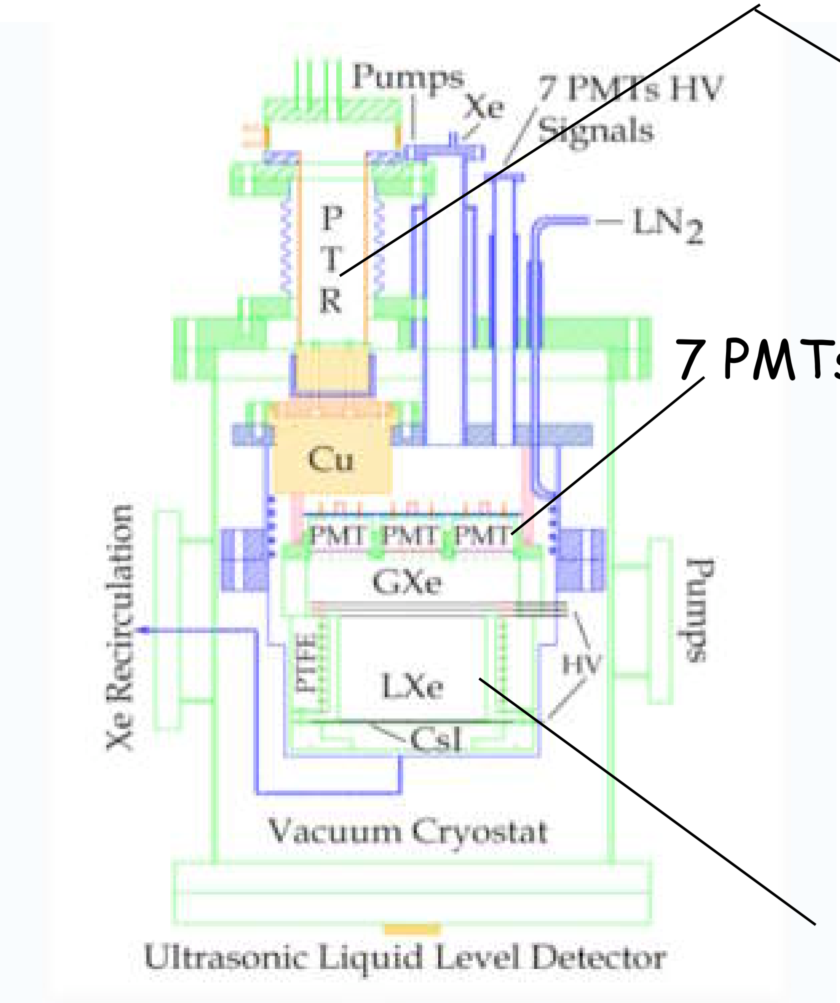


Figure 4. Schematic of 10 kg Prototype

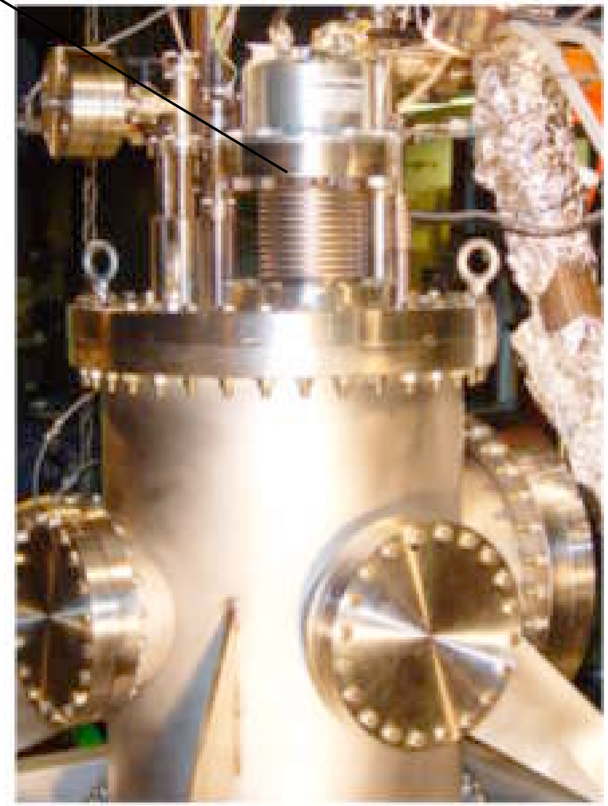
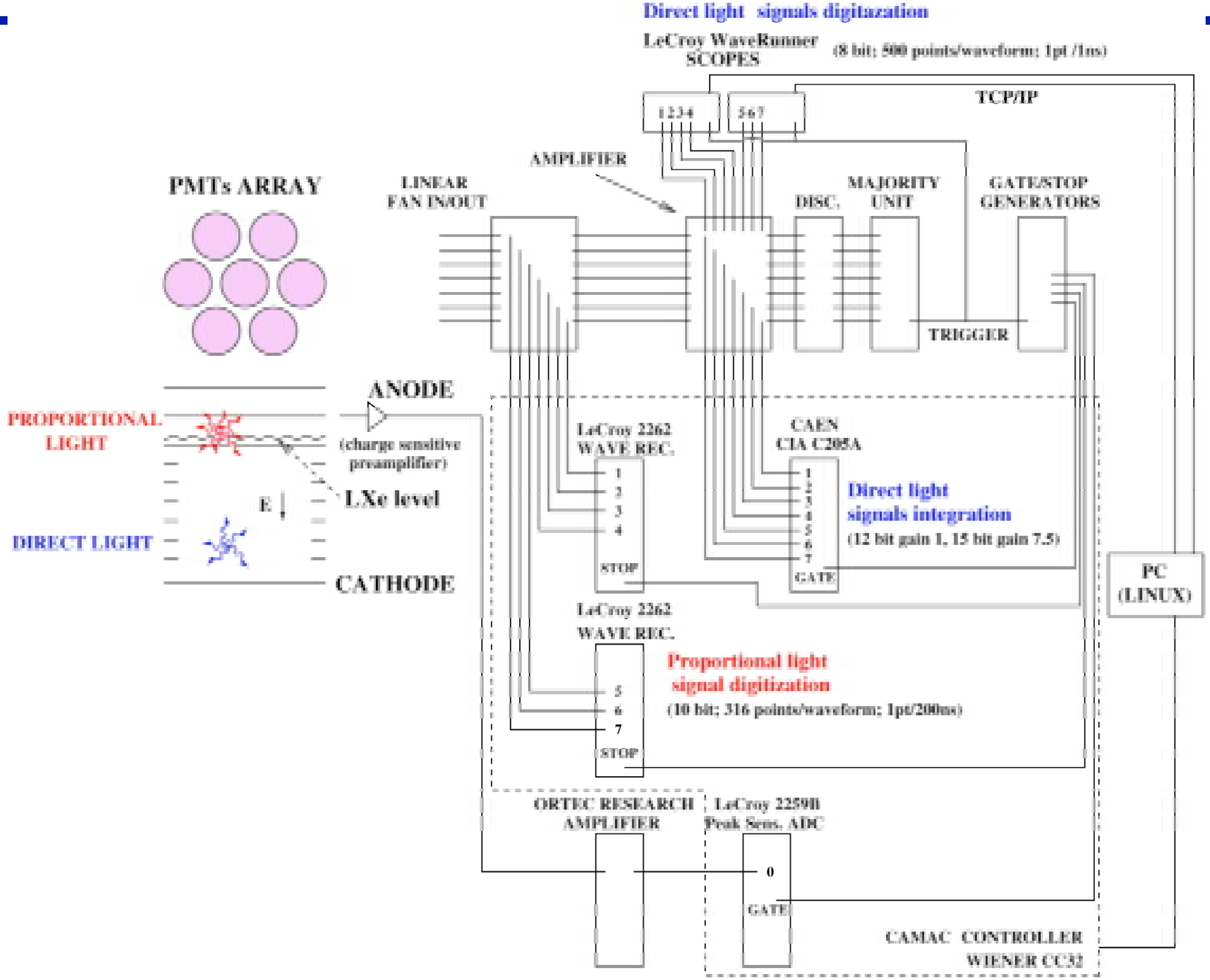


Figure 5. Photo of 10 kg Prototype

Max 10 cm drift gap with 5kV/cm.



Direct light signals digitazation

LeCroy WaveRunner SCOPES

(8 bit; 500 points/waveform; 1pt /1ns)

TCP/IP

PMTs ARRAY

LINEAR FAN IN/OUT

AMPLIFIER

DISC.

MAJORITY UNIT

GATE/STOP GENERATORS

TRIGGER

PROPORTIONAL LIGHT

DIRECT LIGHT

ANODE

(charge sensitive preamplifier)

LXe level

CATHODE

LeCroy 2262 WAVE REC.

CAEN CIA C205A

Direct light signals integration

(12 bit gain 1, 15 bit gain 7.5)

PC (LINUX)

LeCroy 2262 WAVE REC.

Proportional light signal digitization

(10 bit; 316 points/waveform; 1pt/200ns)

ORTEC RESEARCH AMPLIFIER

LeCroy 2259B Peak Sens. ADC

CAMAC CONTROLLER WIENER CC32

XENON Baseline PMTs Readout

- Hamamatsu Low Temperature Tube (R9288)
  - Developed for LXe detectors. Shown to work reliably at low T and at P= 5 atm
  - 2” Metal channel (12 stages, Amplification 10^6), compact design (4 cm long)
  - Low Background version under study by Hamamatsu
  - Quantum Efficiency > 20%
  - Pulse Rise Time = 2.3 ns, transit time spread = 750ps

- Hamamatsu Low Background Tube (R8778)
  - Developed for XMASS Collaboration
  - Box and Line Dynodes, 2”, 112 cm long, 5x10^6 amplifi
  - Low background
    - Current value ≈ 70 mBq / PMT (K / U / Th = 60 / 7 / 4)
    - Goal ≈ 10 mBq/PMT (K / U / Th = 4 / 2 / 4)
  - Quantum Efficiency >26%
  - Pulse Rise Time = 5 ns, transit time spread = 4ns

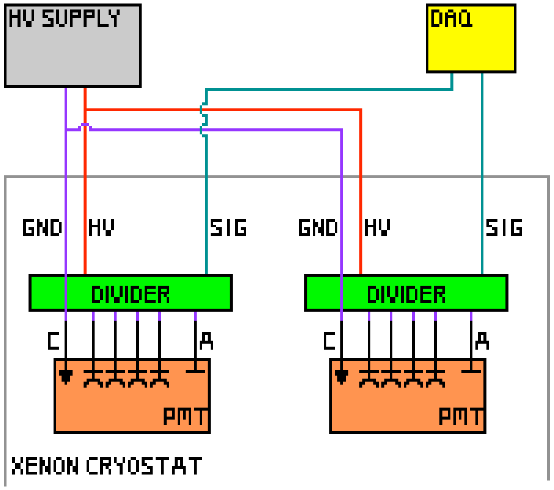
R&D on Novel HV bias distribution for PMTs array

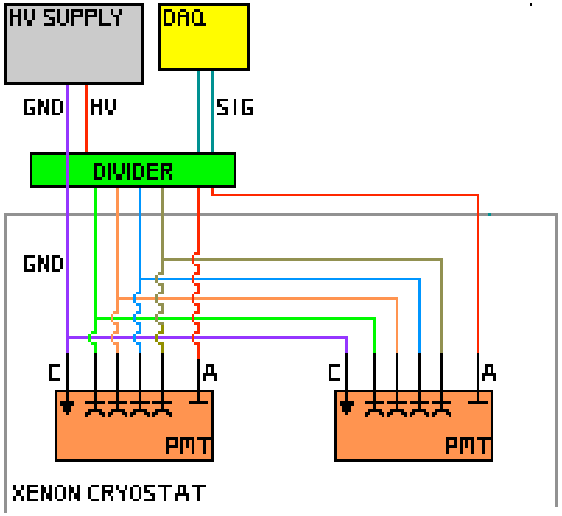
Usual method

- One HV supply per PMT biases dynodes across resistive Network in LXe detector

New method

- Move network outside cryostat
- Deliver each dynode bias through fanned-out cable harness
- # of FT reduced for large array





Problems:

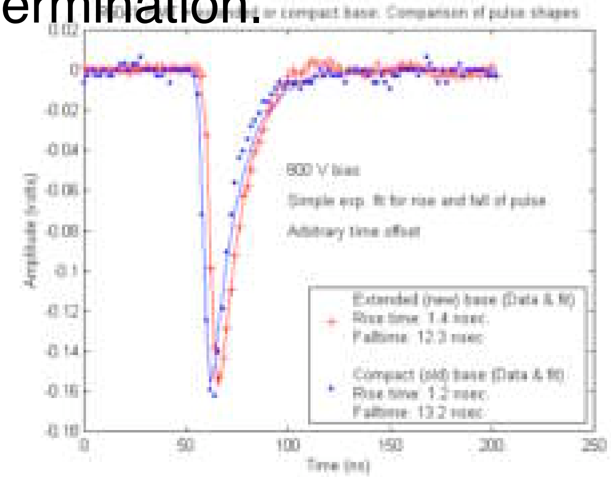
- Heat-dissipation (~50mW/ch)
- radio-impurities of resistors
- Many feedthroughs for large array

Potential Problems:

- Pulse-shape degradation
- Cross-talk between PMTs
- Gain differences of PMTs

Remote bias preserves single PMT signal integrity (LLNL)

- Separate resistive divider and PMT base with 1.5m coax cable harness.
- Compare old (compact) and new (extended) bases with PMT at room temperature
- Test pulse shape integrity: characterize reflections, intrinsic gain, termination.

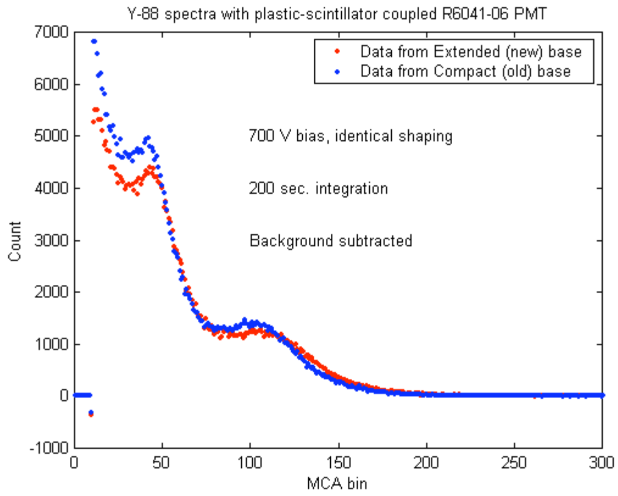


NO DEGRADATION

Pulse shapes are similar within error (left):

- ~1 ns edge resolution
- ~1 mV noise

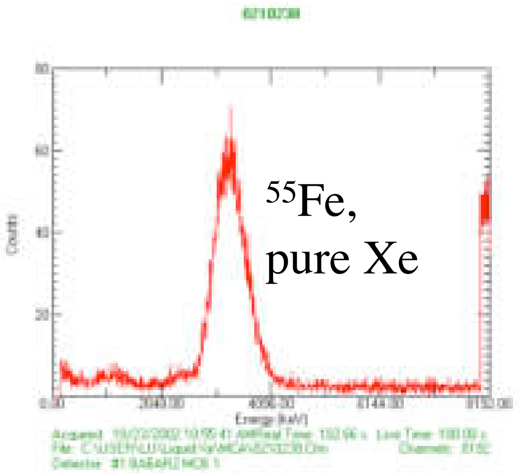
- Intrinsic gain of PMT+base unchanged, within ~5% error (right)



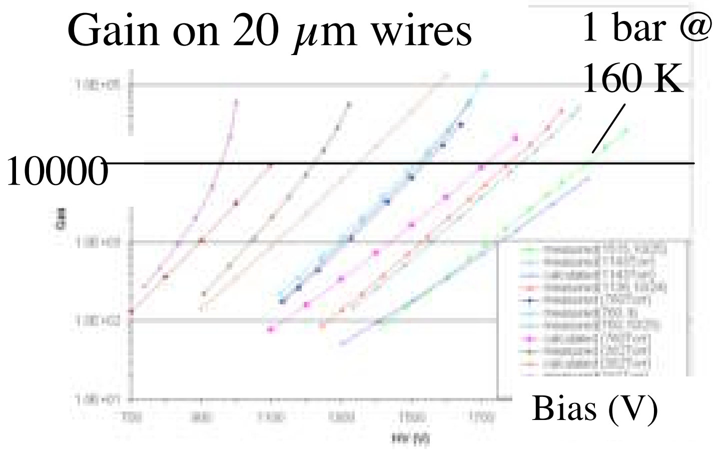
- Next: add 2nd PMT to external divider & cable harness. Characterize power consumption, pulse shape, termination, cross-talk. (April 2004)
- Long term plan:
  - Replace resistive network with separate supplies for each dynode (May 2004)
  - Design and build cryogenic prototype (Summer 2004)

Wire readout with gas gain (Princeton)

- Motivation:
    - PMT radioactivity dominates.
    - PMTs expensive.
- Gas gain in pure Xe appears compatible with single electron measurement.
    - Measured Gain > 10^4 (2 atm). (NIMA 313, p155 (1992))
    - Electronics noise limit: 10 pF, 1 $\mu s \approx$ 50 e^- rms (e.g, Radeka, Ann.Rev.Nucl.Part.Sci, 38 (1998))
- Mechanics: soldered wires on Cirlex (Kapton) substrate.
    - Tested at high field, final gas density.
    - Key issue: Poisoning of LXe? Tests starting.
    - Attractive technology for grids in any case.
- Hybrid charge readout. In progress.
    - FETs at optimal temperature.
    - Kapton stripline with buried HV decoupling capacitor.
    - Radioactivity: ≈ mBq for 40 cm Ø (PMTS: ≈ 1 Bq).
- Single electron measurement. In progress
    - Literature hints at favorable single electron response.

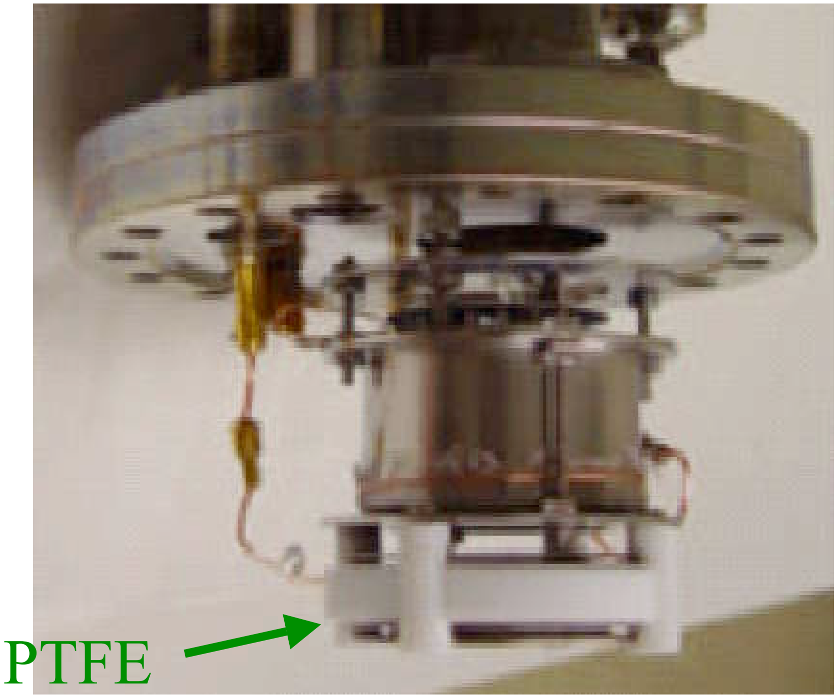


Gain on 20 μm wires

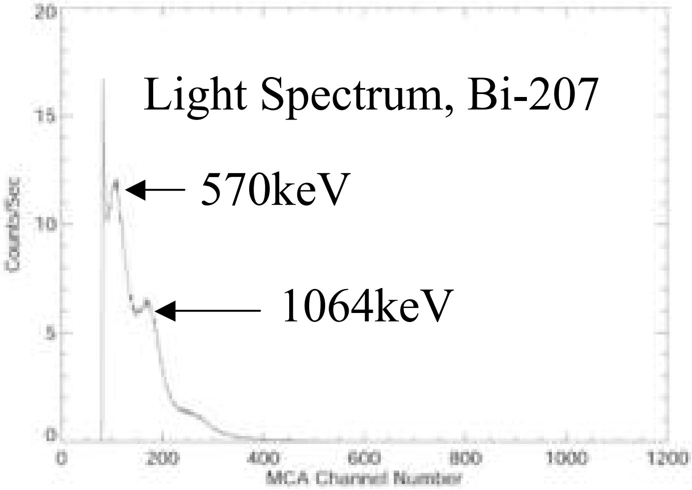


Cirlex wire grids

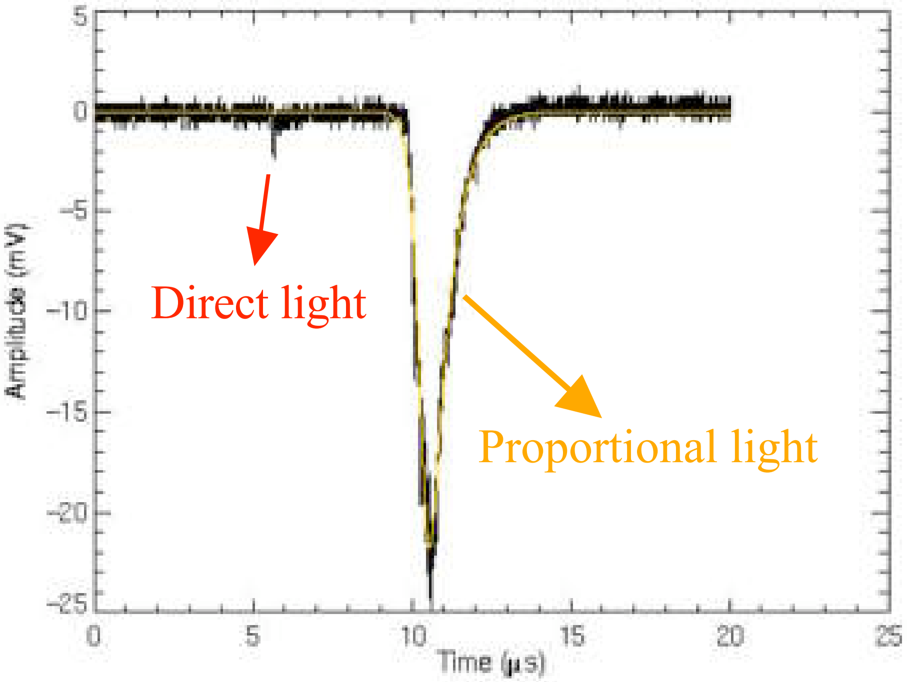
Light collection improvement with PTFE



- Adding PTFE wall and PTFE piece on the bottom improved the light collection efficiency.
- The purity level of liquid xenon is not affected by PTFE.
- Light spectrum of Bi-207 at zero field was obtained with the PTFE structure.

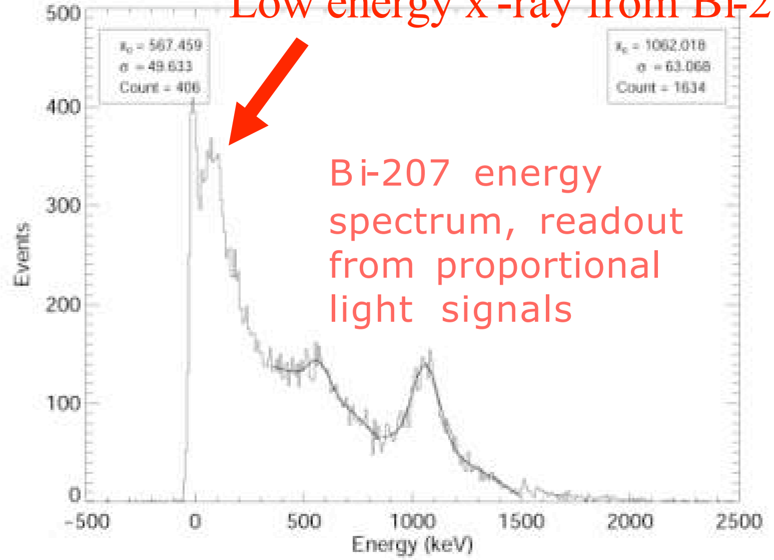


Method of analysis of waveforms



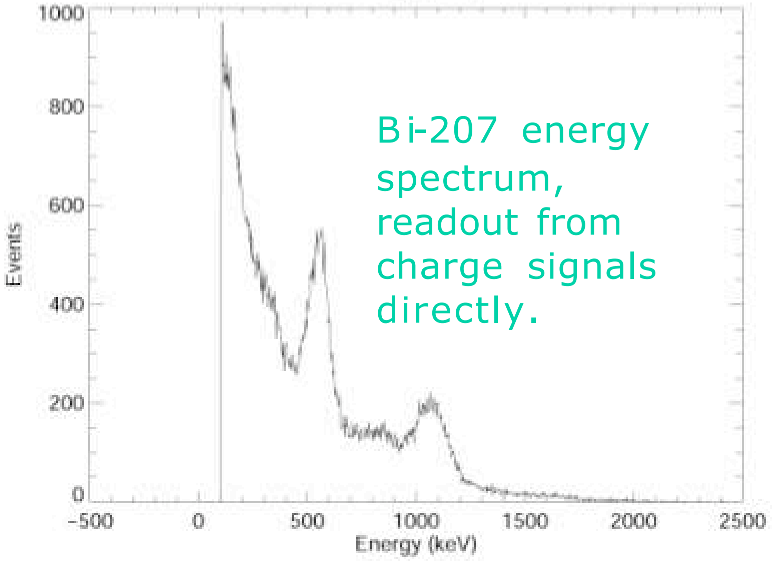
Direct light

Proportional light



Low energy x -ray from Bi-207

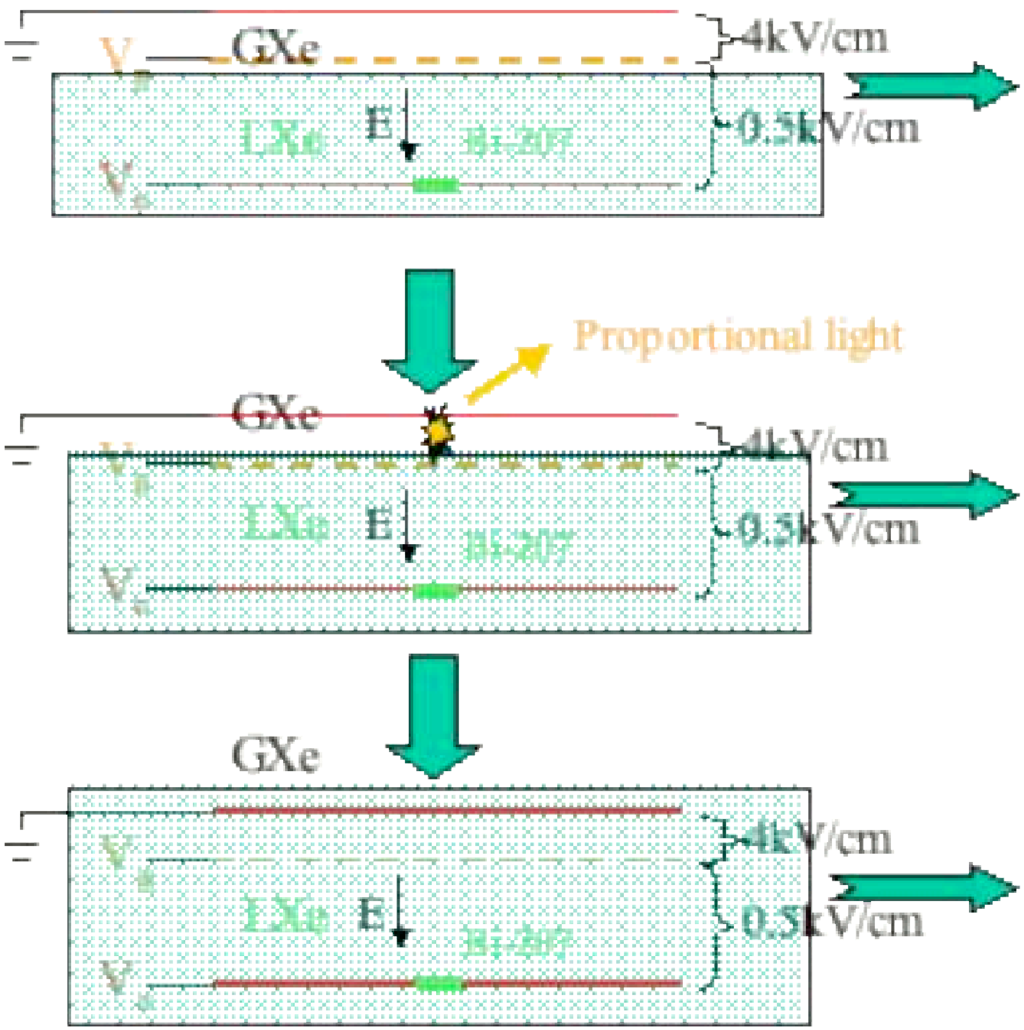
Bi-207 energy spectrum, readout from proportional light signals



Bi-207 energy spectrum, readout from charge signals directly.

- Event waveform shows both direct and proportional light signals
- The area of the proportional light pulse is proportional to the ionization electrons. Spectrum of Bi-207 from the proportional light is compared with charge spectrum in a single phase operation (right)
- Lower energy threshold can be reached from proportional light

Operation of a dual phase xenon chamber

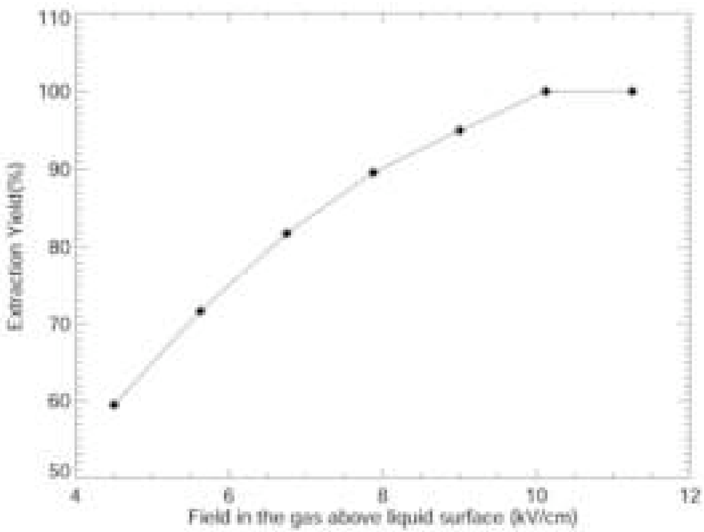


- Liquid level is below the Grid
- No ionization electron can escape from LXe to GXe at low extraction field (0.5kV/cm) => No proportional light is produced

- Liquid level is above the Grid and below the Anode
- Ionization electron can be extracted from LXe to GXe at high extraction field (4kV/cm) => proportional light is abundantly produced

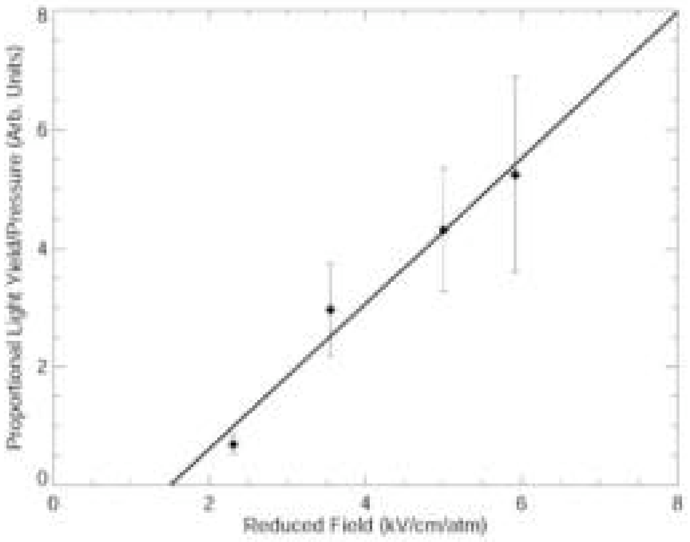
- Liquid level is above the Anode
- Ionization electrons are collected by the Anode, no GXe => no proportional light is produced

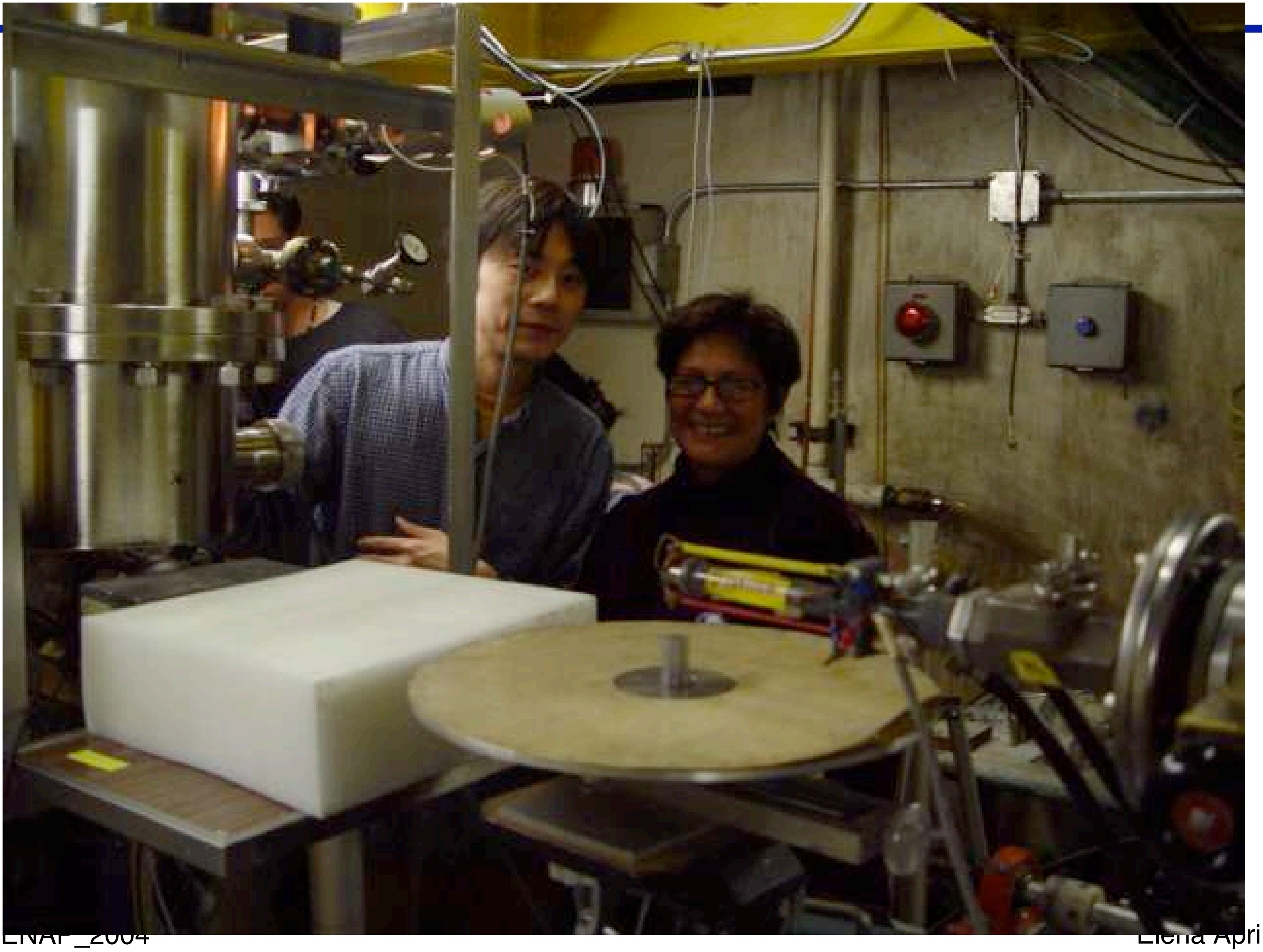
Electron emission and proportional scintillation



- The negative ground state energy of quasi-free electron in liquid xenon requires an electric field to extract electron from LXe to GXe.
- For a full extraction of ionization electrons to gas phase, a field of 10kV/cm in the gas xenon is needed from our data.

- The proportional light yield is related to the field in the gas, the gas gap and the gas pressure [Bolozdynya, NIM A 99]
- The proportional light yield has been measured as a function of reduced field (field/pressure)





Slow Control for 10 kg Prototype

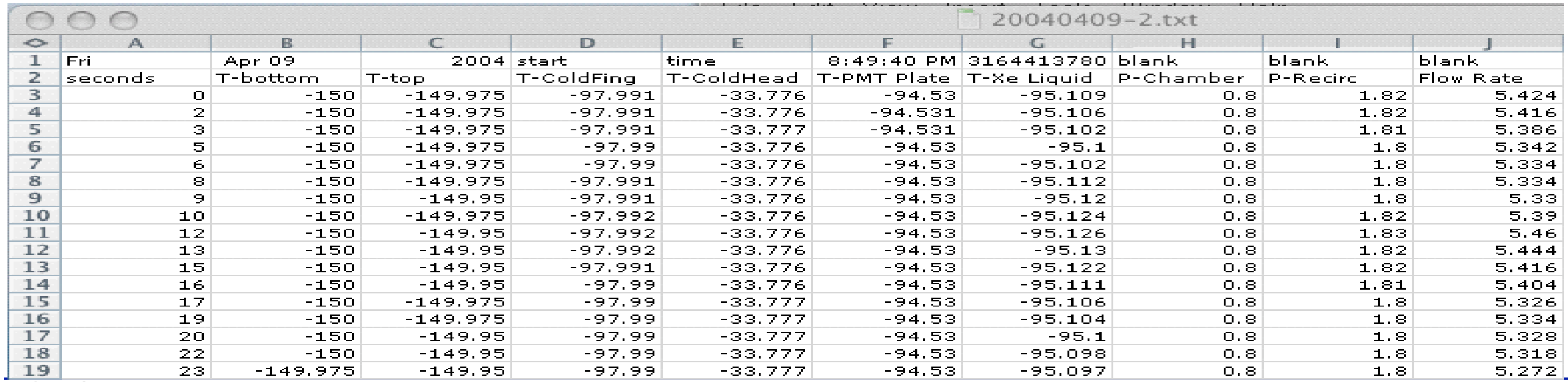
Real-Time Monitoring Systems:

PTR Chiller Supply Temperature
PTR Chiller Return Temperature
PTR Top Temperature
Chamber Turbo Pump Temperature
Cryostat Turbo Pump Temperature
Recirculation Pump Temperature
Pump Chiller Supply Temperature
Pump Chiller Return Temperature
Grid HV
Cathode HV

Monitor Screen (above), and
LogFile Example (below).

Monitoring AND Real-Time Logging (Labview):

PTR Cold Head Temperature
Cold finger Temperature
PMT Plate Temperature
Xe Liquid Temperature
Chamber Temperature (Top)
Chamber Temperature (Bottom)
Chamber Pressure
Recirculation Pressure
Recirculation Flow Rate
PMT HV



20040409-2.txt

	A	B	C	D	E	F	G	H	I	J
1	Fri	Apr 09	2004	start	time	8:49:40 PM	3164413780	blank	blank	blank
2	seconds	T-bottom	T-top	T-ColdFing	T-ColdHead	T-PMT Plate	T-Xe Liquid	P-Chamber	P-Recirc	Flow Rate
3	0	-150	-149.975	-97.991	-33.776	-94.53	-95.109	0.8	1.82	5.424
4	2	-150	-149.975	-97.991	-33.776	-94.531	-95.106	0.8	1.82	5.416
5	3	-150	-149.975	-97.991	-33.777	-94.531	-95.102	0.8	1.81	5.386
6	5	-150	-149.975	-97.99	-33.776	-94.53	-95.1	0.8	1.8	5.342
7	6	-150	-149.975	-97.99	-33.776	-94.53	-95.102	0.8	1.8	5.334
8	8	-150	-149.975	-97.991	-33.776	-94.53	-95.112	0.8	1.8	5.334
9	9	-150	-149.95	-97.991	-33.776	-94.53	-95.12	0.8	1.8	5.33
10	10	-150	-149.975	-97.992	-33.776	-94.53	-95.124	0.8	1.82	5.39
11	12	-150	-149.95	-97.992	-33.776	-94.53	-95.126	0.8	1.83	5.46
12	13	-150	-149.95	-97.992	-33.776	-94.53	-95.13	0.8	1.82	5.444
13	15	-150	-149.95	-97.991	-33.776	-94.53	-95.122	0.8	1.82	5.416
14	16	-150	-149.95	-97.99	-33.776	-94.53	-95.111	0.8	1.81	5.404
15	17	-150	-149.975	-97.99	-33.777	-94.53	-95.106	0.8	1.8	5.326
16	19	-150	-149.975	-97.99	-33.777	-94.53	-95.104	0.8	1.8	5.334
17	20	-150	-149.95	-97.99	-33.777	-94.53	-95.1	0.8	1.8	5.328
18	22	-150	-149.95	-97.99	-33.777	-94.53	-95.098	0.8	1.8	5.318
19	23	-149.975	-149.95	-97.99	-33.777	-94.53	-95.097	0.8	1.8	5.272

Requirements to an Underground Lab

Space:
5 x 5 x 6 m^3 experimental room
3 x 3 m^2 clean room (class 100) and 3 x 3 m^2 control room (computers + electronics with internet to surface)
Weight loading: XENON10 15 t Pb / 25 t total, XENON100 24 t Pb / 40 t total

Electrical power:
30 kW for 10 kg prototype, 100 kW for 100 kg module; + UPS (20 kW on emergency generator)

Liquid Nitrogen:
200 l/week for 10 kg, 500 l/week for 100 kg module

Above ground office space with 5 yr occupancy time
Access to existing infrastructure such as machine shop, low background facility,chemical lab, library

Safety Issues for XENON Underground

XENON operates:

Liquid Xe: condensed noble gas at T = -95 C, inert, non flammable, non toxic

(XENON10: total 60 kg Xe, XENON100 total: 300 kg Xe)

Mechanical equipment and electronics

No hazardous materials or chemicals

Primary cooling: mechanical cooler, LN_2 for recovery

Primary hazard: failure of LXe cryogenic system

In case of a catastrophic failure: amount of liquid xenon released < 300 kg, or ~ 60 m^3

XENON Safety System

- Xe gas is stored in stainless steel vessels mounted in stainless steel dewars. Dewars are kept constantly cold (- 196C) for gas emergency recovery
- Condensed liquid for target and VETO contained in double walled cryostat and is kept at the operating temperature by a refrigerator (or by LN_2 cooling in case of power loss)
- Emergency case: Any abnormal situation will open the gas line for automatic recovery of the Xe into storage vessels
- Extreme failure: Rupture discs will vent the evaporated Xe into the storage vessels (kept always at LN_2 temperature when LXe is in detector)
- The storage vessels also have rupture discs, venting into an additional battery of storage vessels for the case of accidental overfilling of the storage vessels

Another Chamber & Cryostat for XENON R&D (Princeton)

Three different CsI Photocathodes prepared by V. Peskov at CERN and by B.Singh at University of Bari

- CsI feedback
  - ◆ Remove electrons with "Gate" grid.
    - Commercial HV switch (Directed Energy)
      10 kV, 50 ns, 10 KHz rep rate.
  - ◆ Shielding to reduce x-talk to PMT
    1 pF, 1 μS, 5000 V $\Rightarrow$ 5 mA, 5 nC.
  - ◆ CsI handling and stability to be studied
    (productin capability in Princeton HEP)
  - ◆ CsI radioactivity. Negligible for < μm photocathode
    (^{127}Cs, ^{39}K ≈ 0.2 Bq/Kg)
- Test in new temperature controlled cryostat
  - ◆ Fast turnaround, LN cooled, low vibration environment, 3 liter volume, configured for 2-phase measurement.
- Stretched Wire Grids
  - ◆ High transparency. Use Pb-free, high T solder, tested from 180 °C to 77 K, and for LXe purity.
  - ◆ New Cirlex for patterned circuits. Now testing for LXe purity.
  - ◆ Precision liquid level + tilt measurement < 100 μm
    - Capacitance readout chip (Smartech UTI): ≈ 10^{-3} pF with 100 pF stray capacitance.