The Enriched Xenon Observatory for Double Beta Decay

Francisco LePort
Stanford University

There are two varieties of ββ decay

2ν mode:
a conventional
2nd order process
in nuclear physics

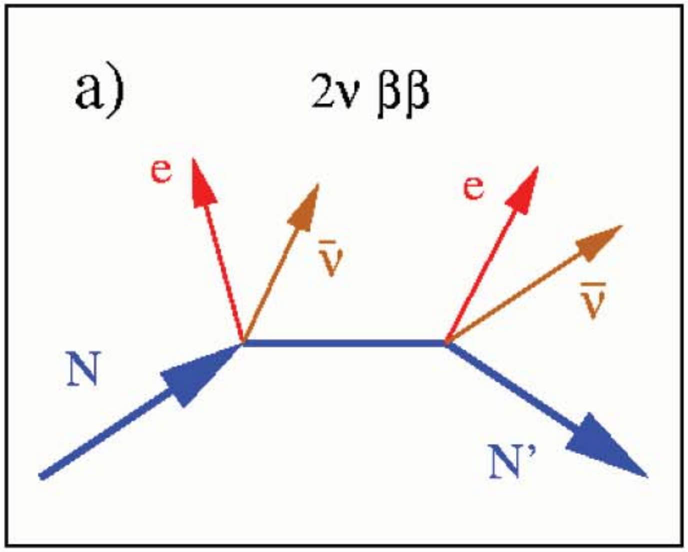
0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$

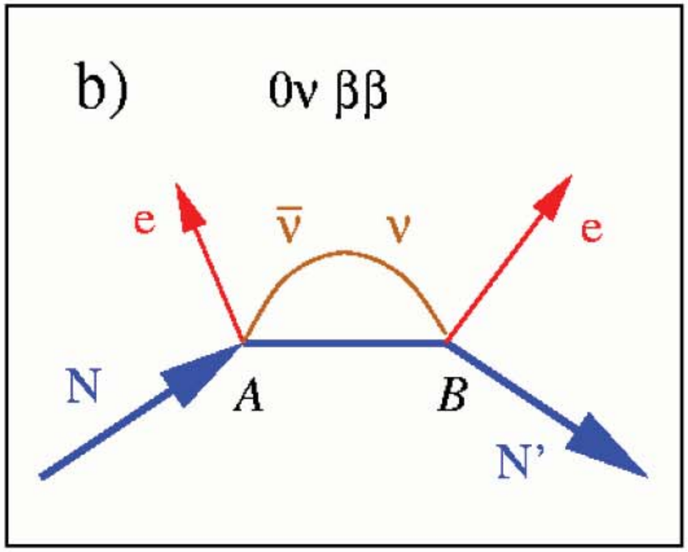
$\nu = \bar{\nu}$

$|\Delta L|=2$

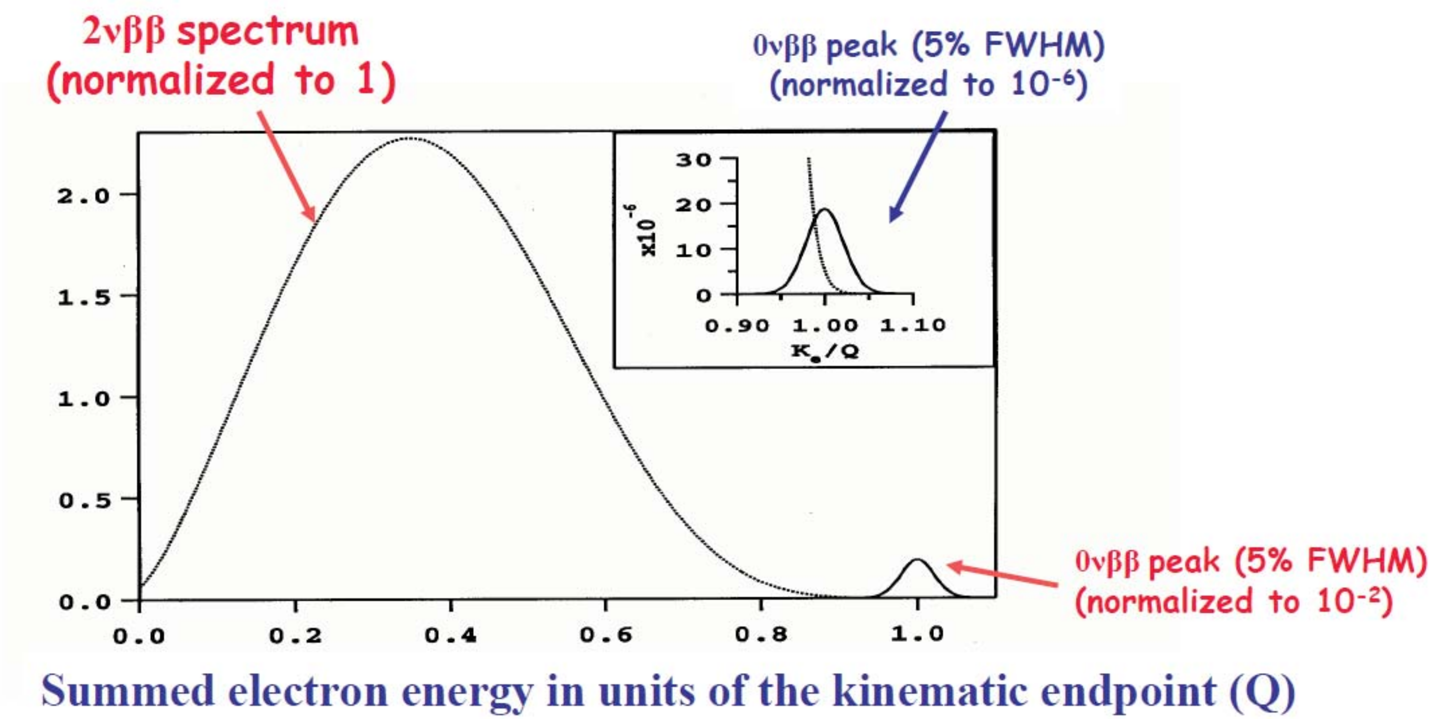
$|\Delta(B-L)|=2$

Since helicity has to "flip"





Detection of 0νββ Decay : e⁻ energy sum is the primary tool



Summed electron energy in units of the kinematic endpoint (Q)

The challenge for this experiment boils down to: Background control.

Good energy resolution is essential. In fact it is the only way to distinguish 2vββ from 0vββ.

Some Advantages of a LXe TPC

Energy resolution is poorer than the crystalline devices (~ factor 10), but

Xenon isotopic enrichment is easier. Xe is already a gas & Xe^{136} is the heaviest isotope.

Xenon is “reusable”. Can be repurified & recycled into new detector (no crystal growth).

Monolithic detector. LXe is self shielding, surface contamination minimized.

Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved. Scintillation light/ionization correlation.

… admits a novel coincidence technique. Background reduction by Ba daughter tagging.

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + e^- + e^-$$

$\longrightarrow$ Identify event-by-event

Described in 1991 by M. Moe (PRC, 44, R931,(1991)).

The method exploits the well-studied spectroscopy of Ba and the demonstrated sensitivity to a *single* Ba^+ ion in an ion trap.

EXO neutrino effective mass sensitivity

Assumptions:

1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0v from 2v modes:
   Select 0v events in a ±2σ interval centered around the 2.458 MeV endpoint¥
4) Use for 2vββ $T_{1/2}>1\cdot10^{22}$yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	24	33
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	5.3	7.3

¥ Redshaw et al. Phys Rev Let 90, 053003 (2007)

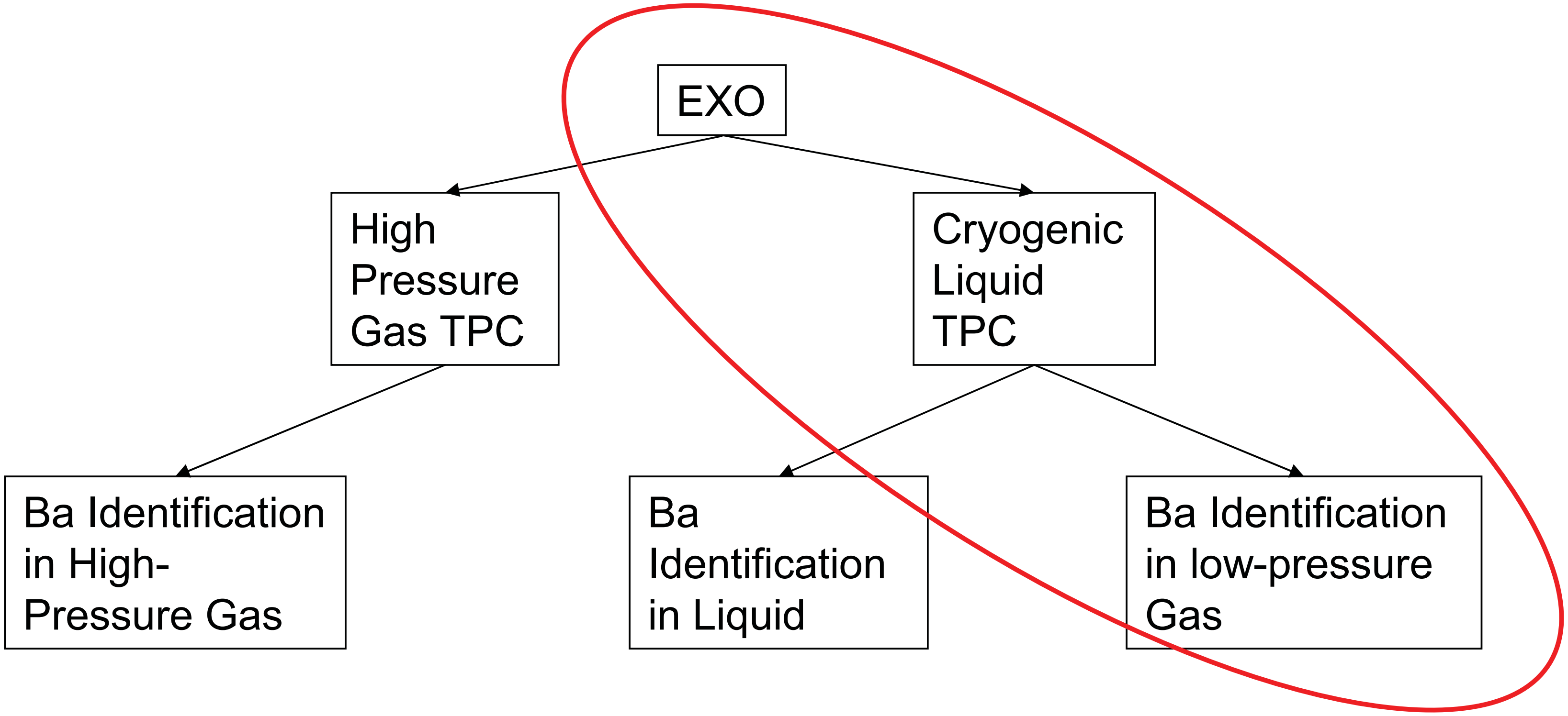
* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ Rodin et al Phys Rev C 68 (2003) 044302

Courier et al. Nucl Phys A 654 (1999) 973c

Multiple Paths to a Background Free Detector



EXO

High Pressure Gas TPC

Cryogenic Liquid TPC

Ba Identification in High-Pressure Gas

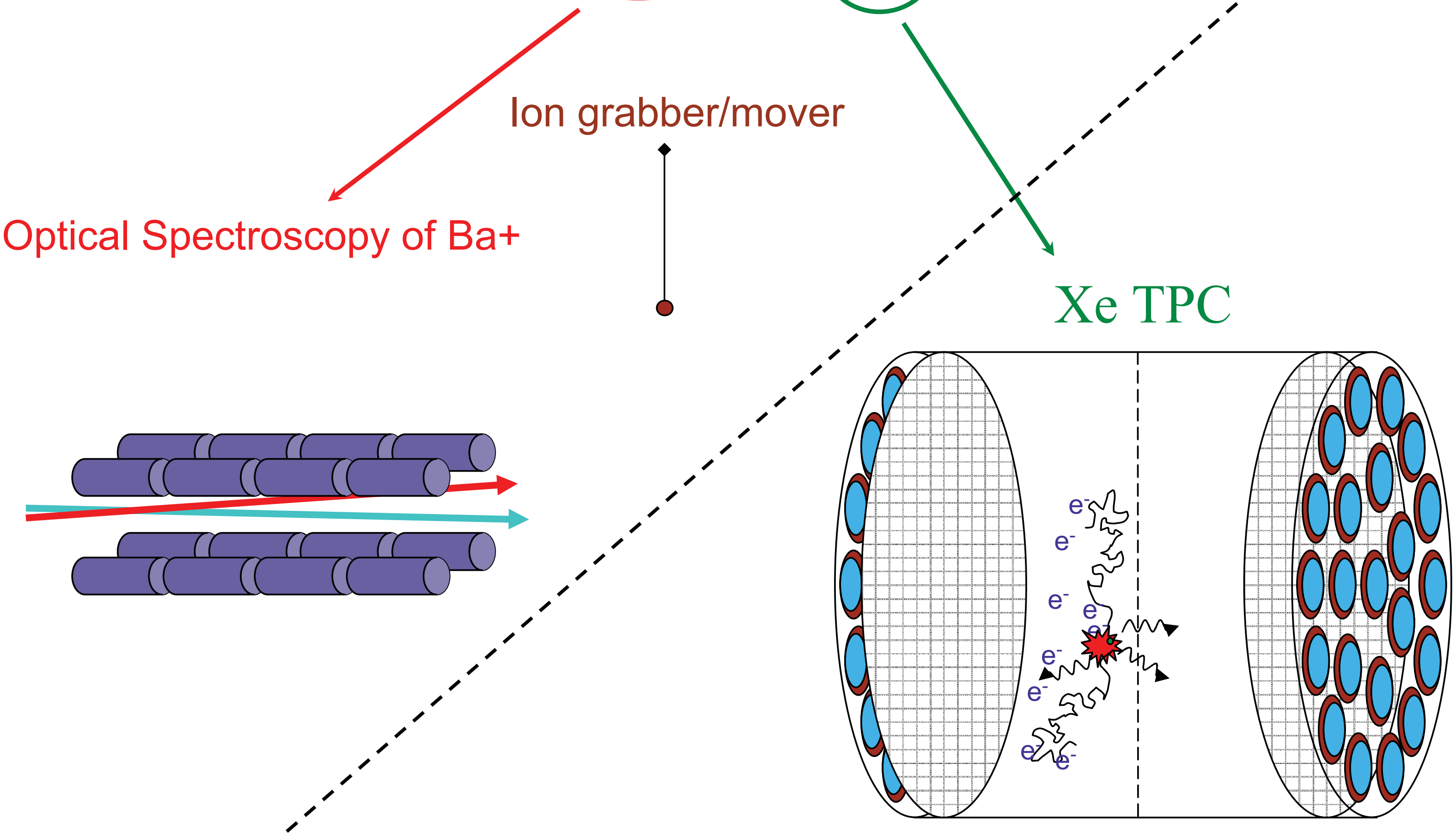
Ba Identification in Liquid

Ba Identification in low-pressure Gas

Detection Method Overview

[M. Moe, Phys. Rev. C 44 (1991) R931]

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-} \; (+\, 2\nu_e)$$



Ion grabber/mover

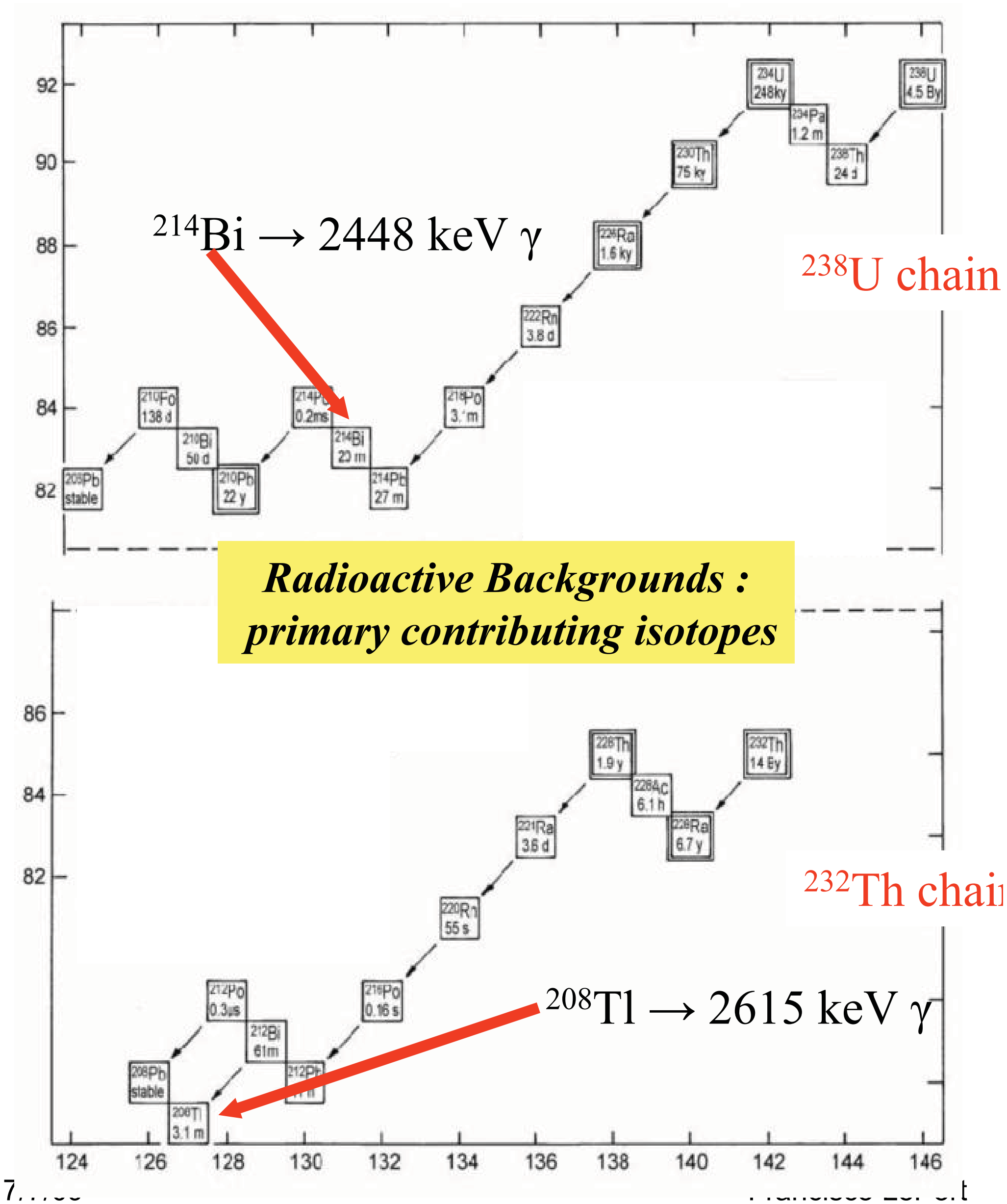
Optical Spectroscopy of Ba+

Xe TPC

EXO-200 Goals

- Search for 0νββ in ^{136}Xe with competitive sensitivity
- Measure 2νββ half life of ^{136}Xe (best limit currently set by Bernabei et al, 1×10^{22}y)
- Understand the operation of a large LXe detector
  - Understand backgrounds / characterize detector materials
  - Learn about large scale Xe enrichment
  - Understand Xe handling, purification, resolution

Our Challenge



^{214}Bi → 2448 keV γ

^{238}U chain

Radioactive Backgrounds :
primary contributing isotopes

^{232}Th chai

^{208}Tl → 2615 keV γ

^{40}K → 1461 keV γ’s, a background for 2νββ only

^{222}Rn produces (^{214}Bi) γ bkgrd, & daughter β, α emitters can move throughout the apparatus with deadly results.

^{60}Co results from cosmogenic activation of Cu, which is essentially the only metal we use. Thus all Cu components with line of sight to the detector must remain sheilded during storage.

Main γ (external) backgrounds

- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (a concern for the $2\nu\beta\beta$)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- other γ's in ^{238}U and ^{232}Th chains
- other cosmogenics of Cu (a concern for the $2\nu\beta\beta$)

Qualification of low background materials (U.of Ala., Neuchatel, INMS, Laurentian)

Assay @ U. of A. Ge detector following neutron activation @ the MIT research reactor, Neuchatel Ge counter and INMS (Canada) mass spectrometry (ICPMS and GDMS methods). Radon counting (Laurentian).

Material requirements for ββ2ν-bkg < 10 events/day and ββ0ν-bkg < 3 events/year **(no tracking cuts)**

Material	Mass [kg]	K [ppt]	Th [ppt]	U [ppt]
Xenon	200	30 / na	0.1 / 0.04	0.02 / 0.0008
Teflon*	100	790 / na	0.6 / 0.6	0.2 / 0.2
HFE	4681	520 / na /	0.4 / 0.03	0.2 / 0.02
Copper	2956	37000 / na /	35 / 1	13 / 2.5

* Large teflon mass shown here reflects an earlier teflon TPC vessel design. TPC vessel for EXO200 is constructed from high purity copper (small teflon mass is used).

NAA/Ge counter measurements are in some cases only limits – the required purities can exceed our sensitivity.

This is true in the case of the heat transfer fluid (*HFE-7000*) where limits are the best seen (less than 1 ppt), but still above the target. “Liquid organics”, if handled carefully, can be very pure, based on experience with KamLAND scintillator. For the *xenon* purity we rely on the enrichment and purification procedures (no NAA or counting measurement possible).

Massive effort on material radioactive qualification using:

- NAA
- Low background γ-spectroscopy
- α-counting
- Radon counting
- High sensitivity GD-MS and ICP-MS

At present the database of characterized materials includes >300 entries

MC simulation of backgrounds

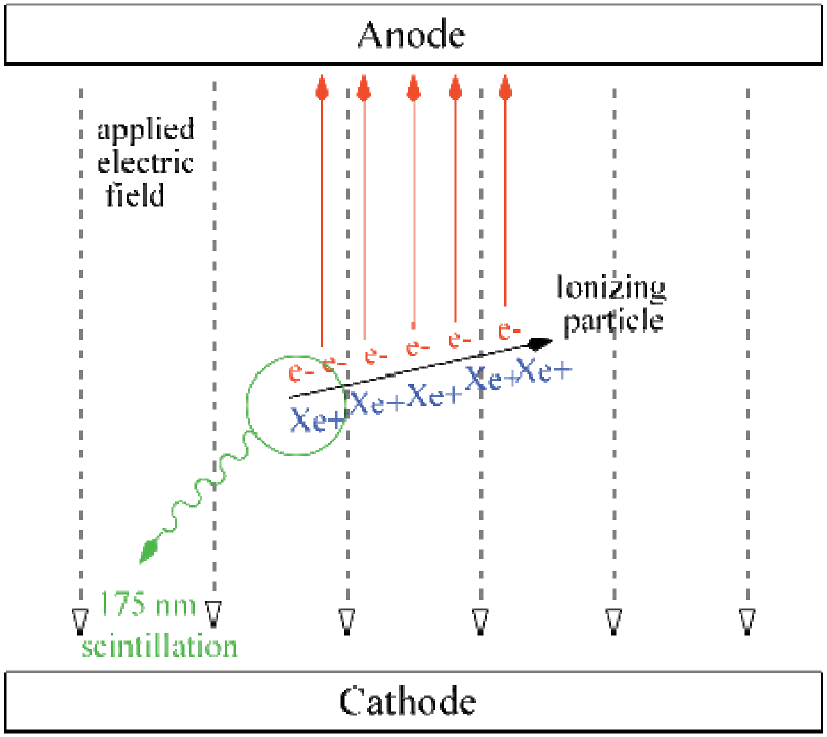
The impact of every screw within the Pb shielding is evaluated before acceptance

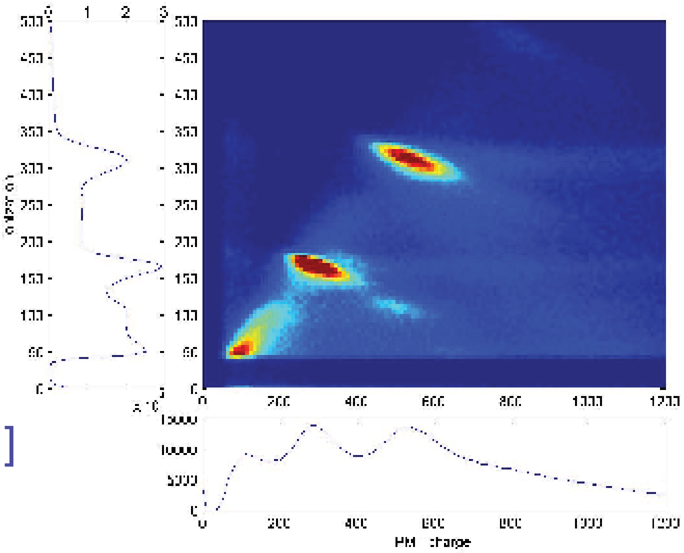
NIM article published on the subject with entries for 225 materials [D.Leonard et al., Nucl. Inst. and Meth. A 591 3 (2008)]

EXO-200 Detector

Improve energy resolution via simultaneous collection of ionized electrons and scintillation light (confirmed by others)

E. Conti et al. (EXO Collab), PRB: **68**(2003)054201]





Ionization and Scintillation results using ^{207}Bi

Ionization alone:

σ(E)/E = 3.8% @ 570 keV

or 1.8% @ $Q_{\beta\beta}$

Ionization & Scintillation:

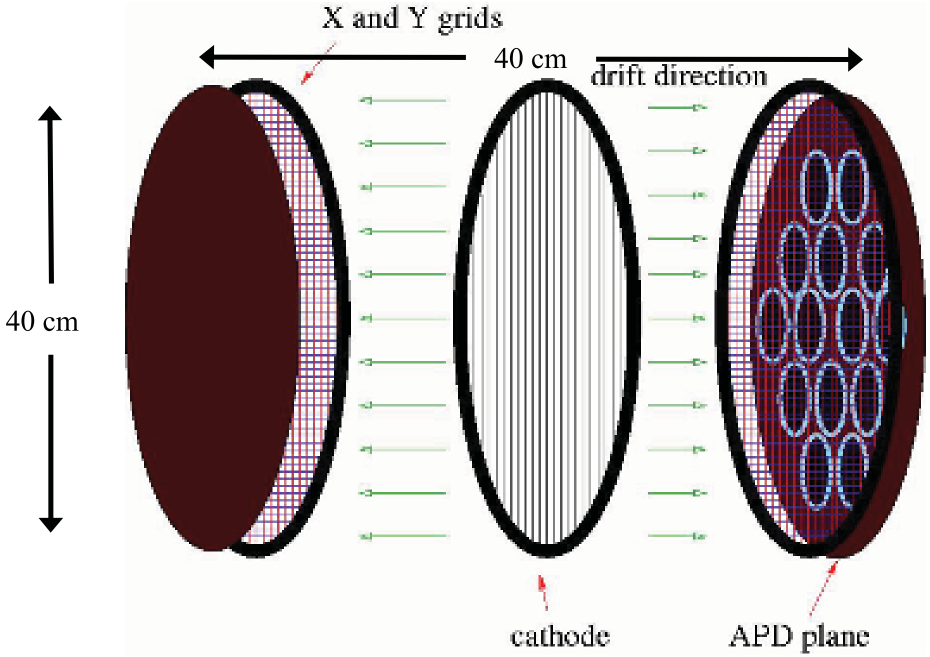
σ(E)/E = 3.0% @ 570 keV

or 1.4% @ $Q_{\beta\beta}$

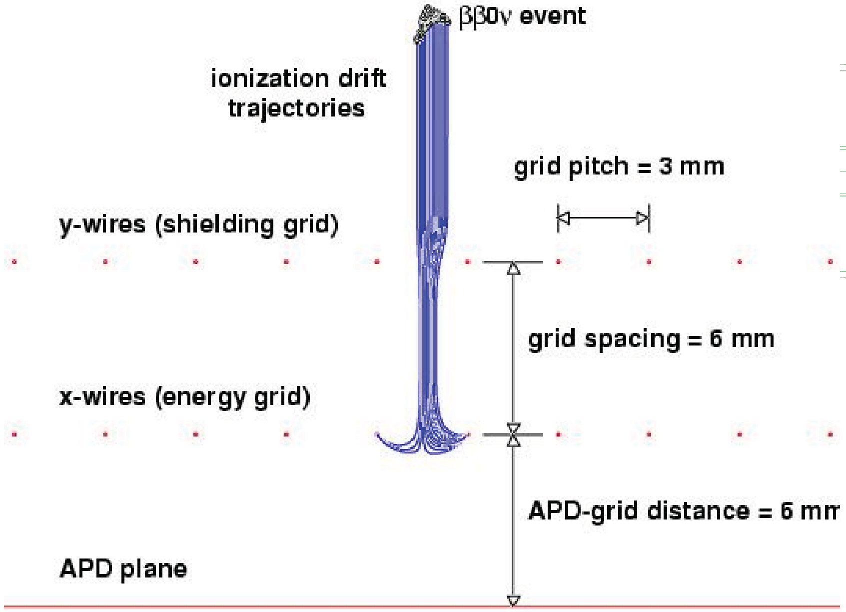
(a factor of 2 better than the Gotthard TPC)

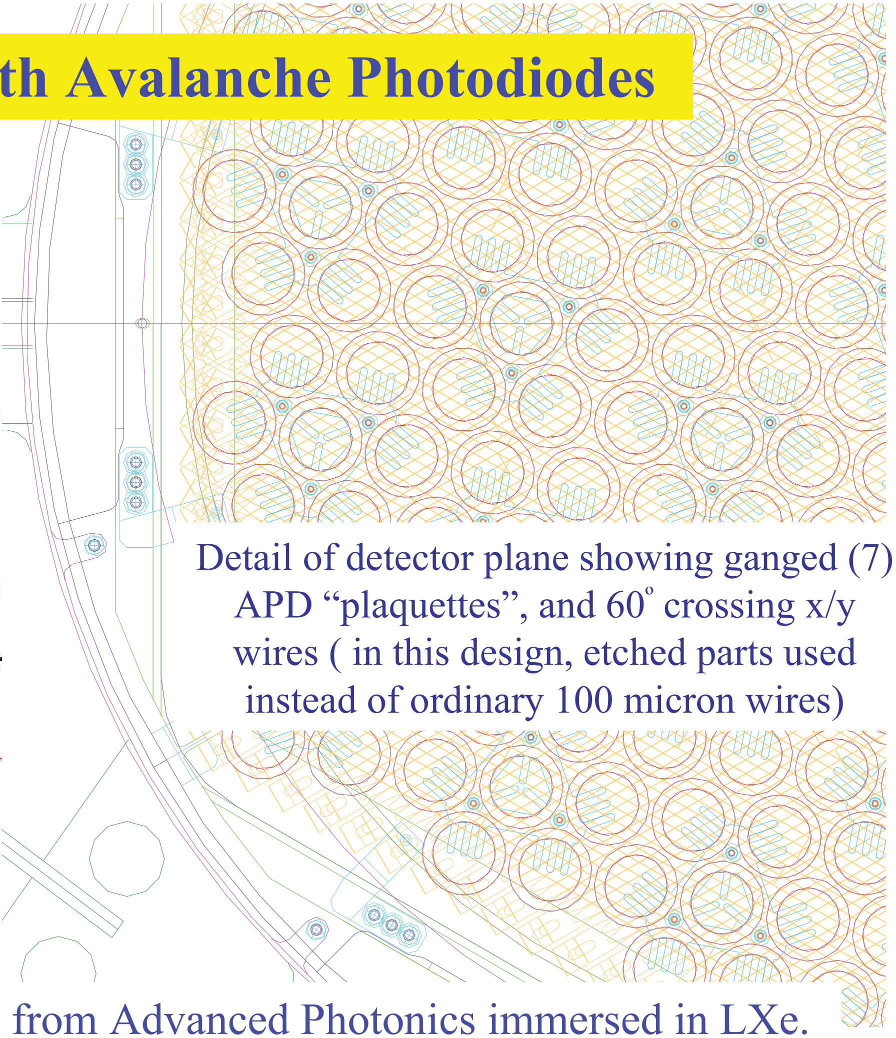
Detector details

- **Cylindrical detector split into two halves by HV plane (75 kV max, running potential to be optimized)**
- **Crossed wires, 100μm diameter, 3mm pitch, ganged in groups of 3 at either end (ionization, 48chx48ch => 1 cm^3 resolution)**
- **Avalanche Photodiodes, ganged in groups of 7, at either end (scintillation, 37ch, ~15% collection efficiency not including reflections)**
- **Low background flex cables carry signals out (can't put electronics inside LXe due to radiopurity requirements)**

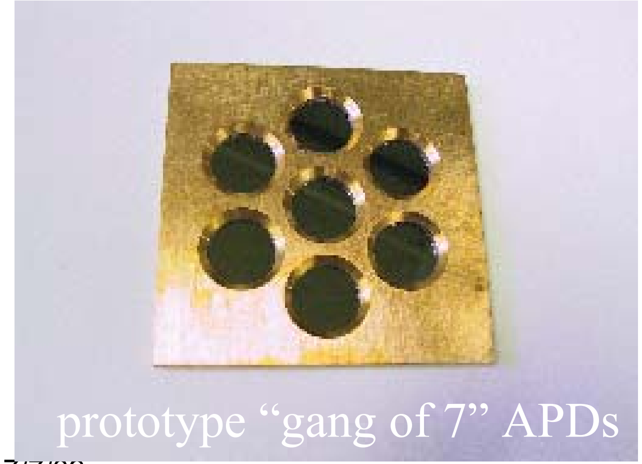


A Liquid Xenon TPC with Avalanche Photodiodes





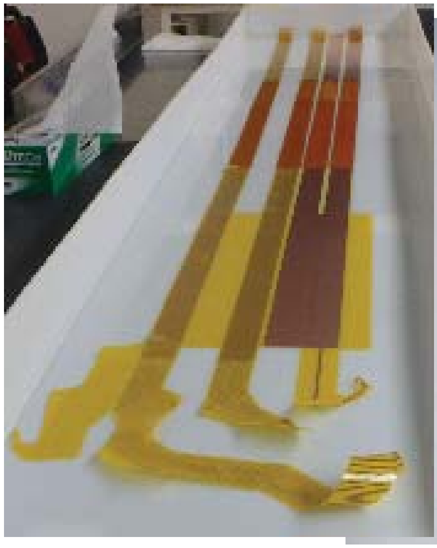
Detail of detector plane showing ganged (7) APD “plaquettes”, and 60° crossing x/y wires (in this design, etched parts used instead of ordinary 100 micron wires)

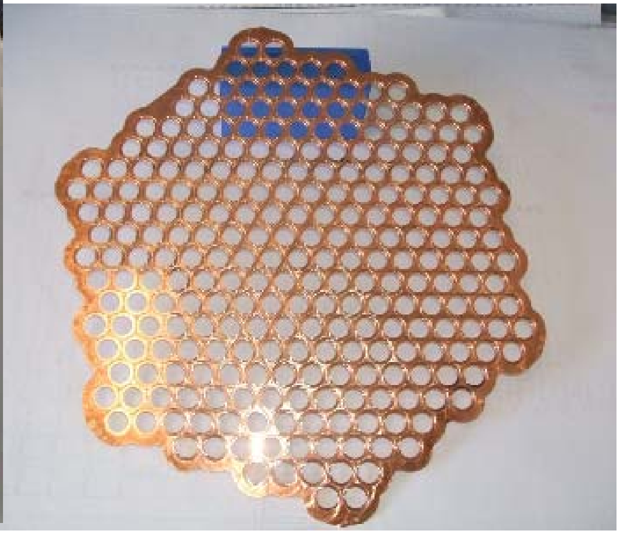


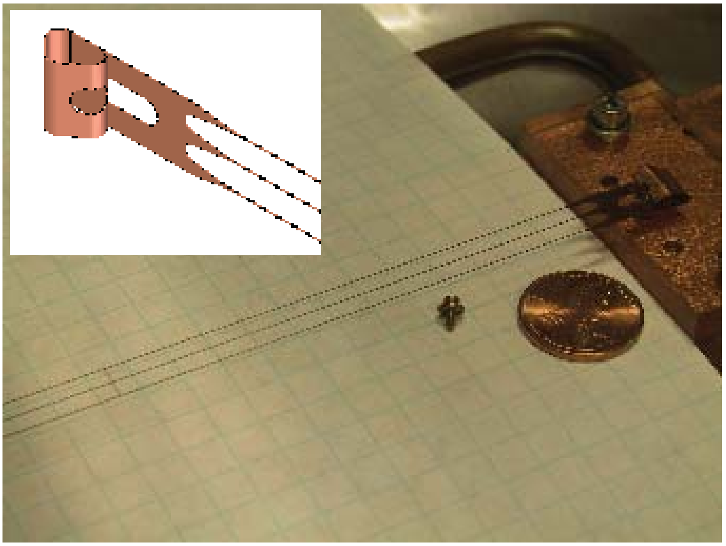
prototype “gang of 7” APDs

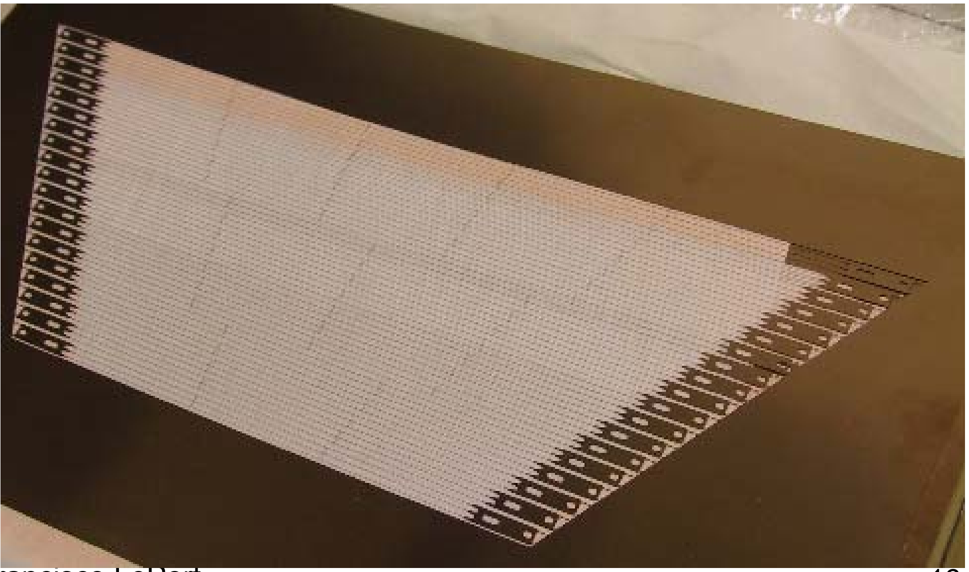
LAAPDs from Advanced Photonics immersed in LXe.
High radiopurity, High QE (>100%) in VUV (175 nm)
Operated at ~-1.4kV, Gain ~ 100. Noise for gang of 7 ~2000 electrons is acceptable.
For charge channels, 800 electrons is the target.

Detector Components

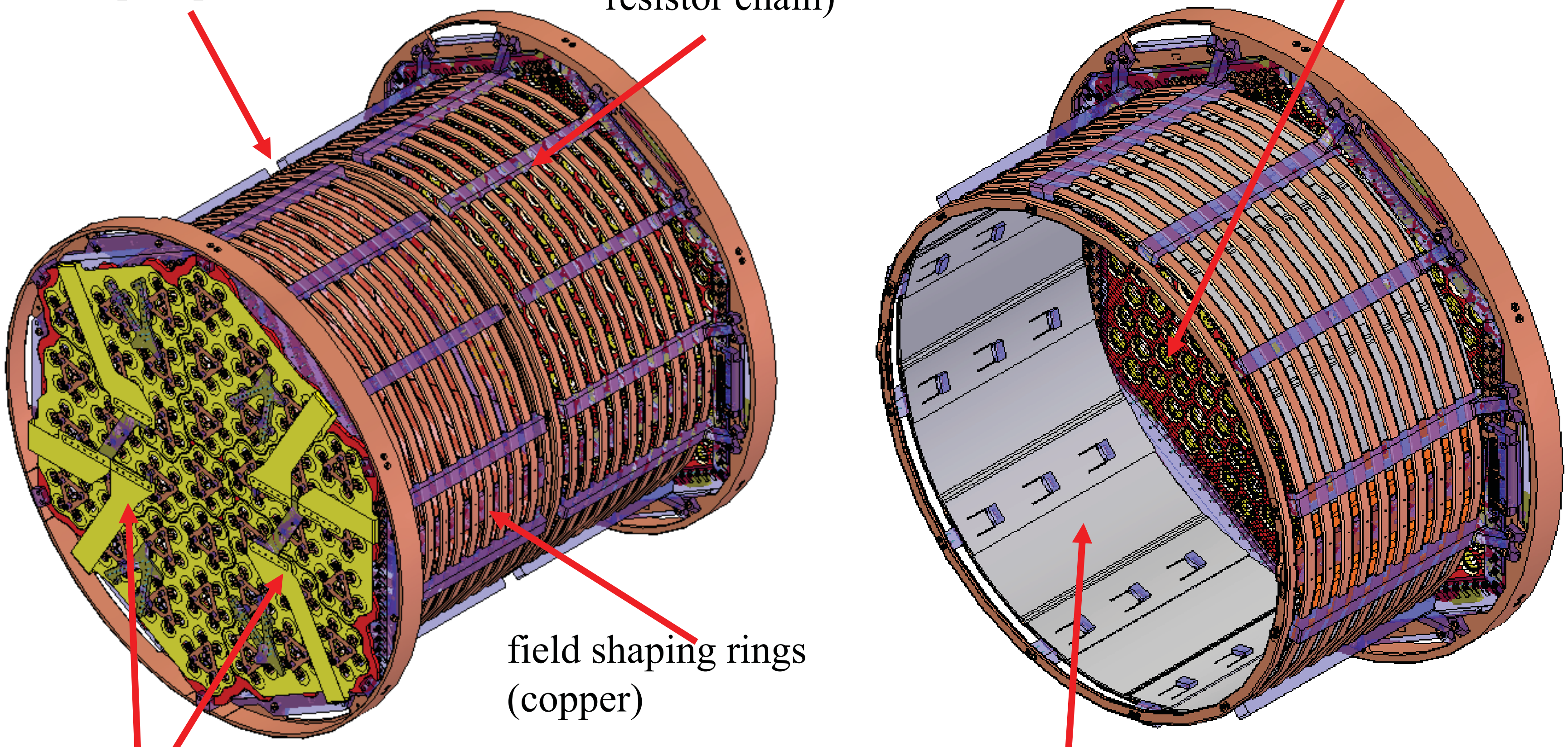








EXO-200 TPC



Central HV plane (photo-etched phosphor bronze)

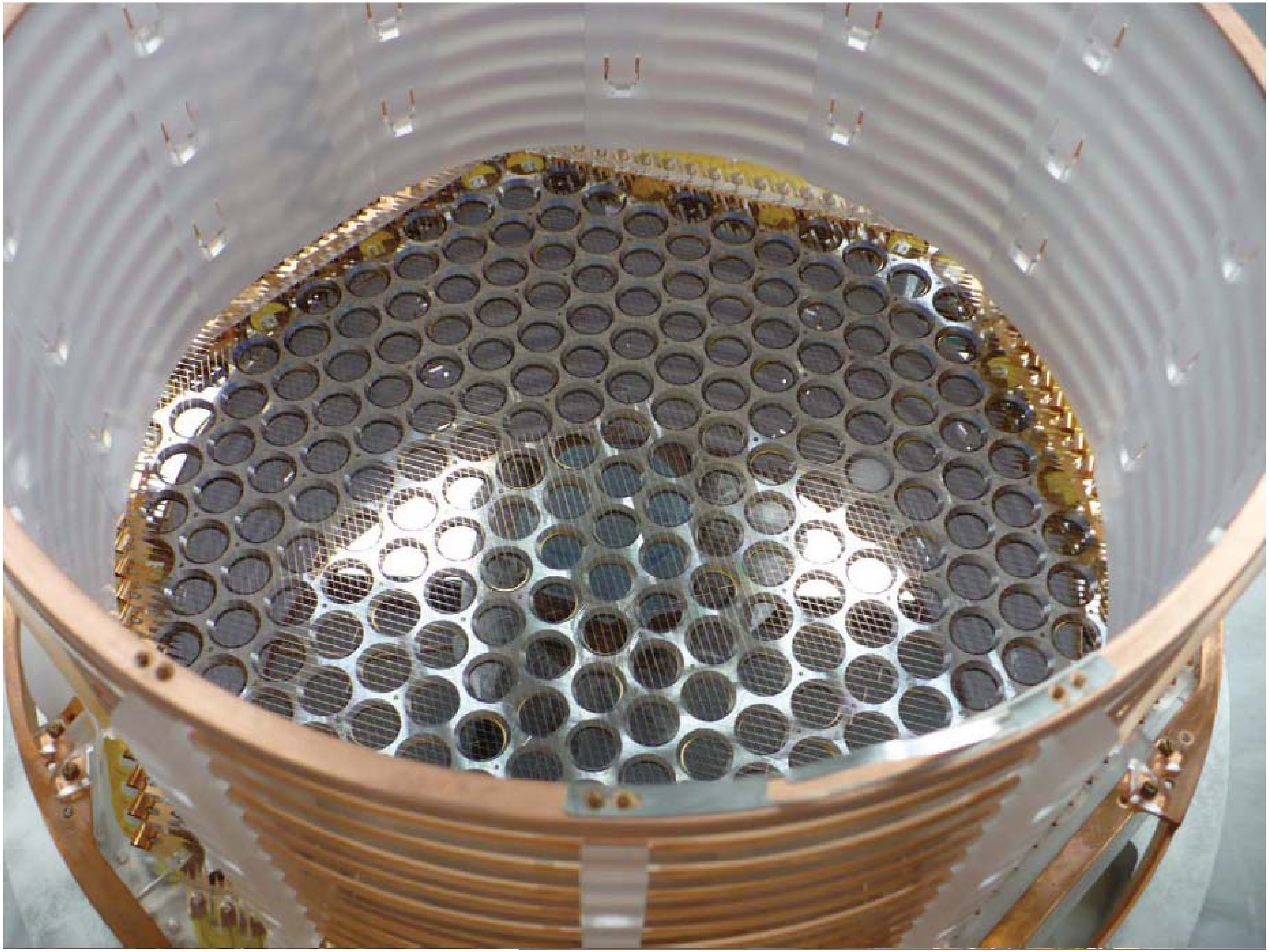
acrylic supports (one holds the field divider resistor chain)

APD plane (copper) and grid plane (photo-etched phosphor bronze)

field shaping rings (copper)

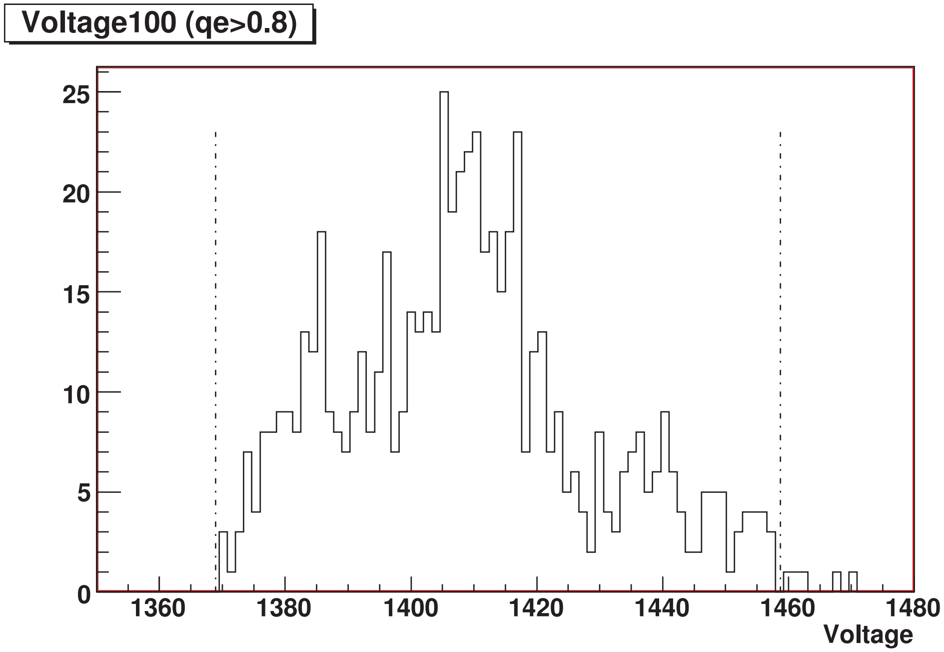
flex cables on back of APD plane (copper on kapton, no glue)

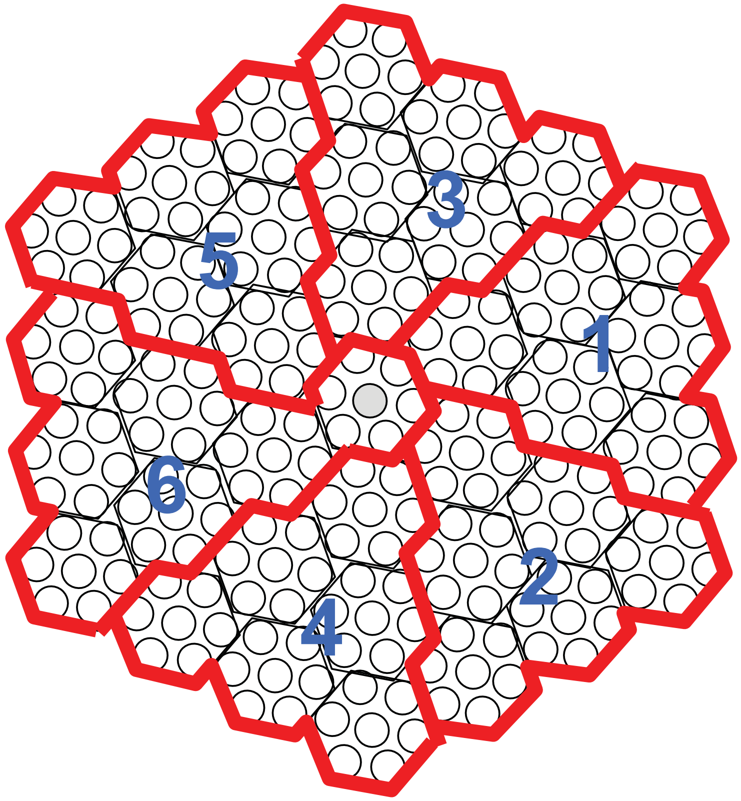
teflon light reflectors/diffusers



APD testing

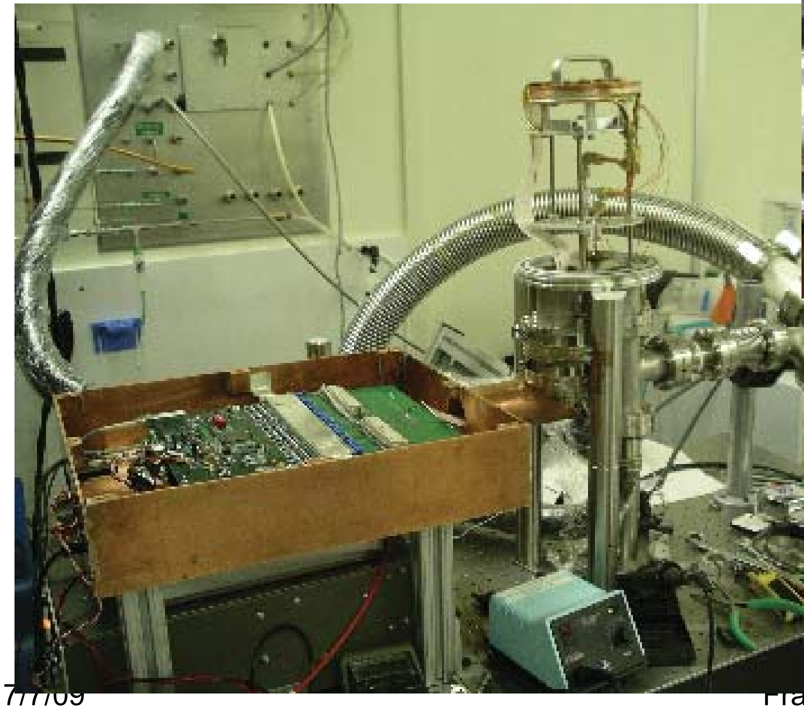
- 851 APDs were tested, the best (QE and noise) 468 were chosen
- APDs are voltage matched in 12 groups of ~40
- Results published in NIMA (http://arxiv.org/abs/0906.2499)

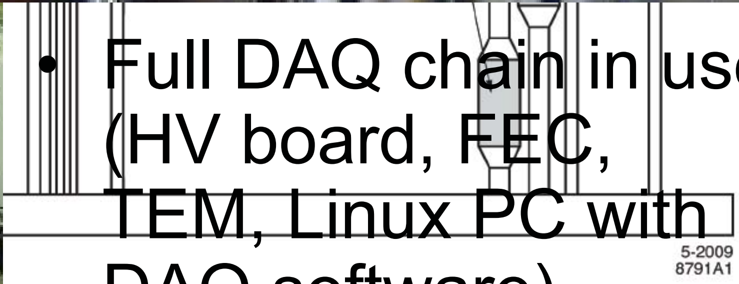




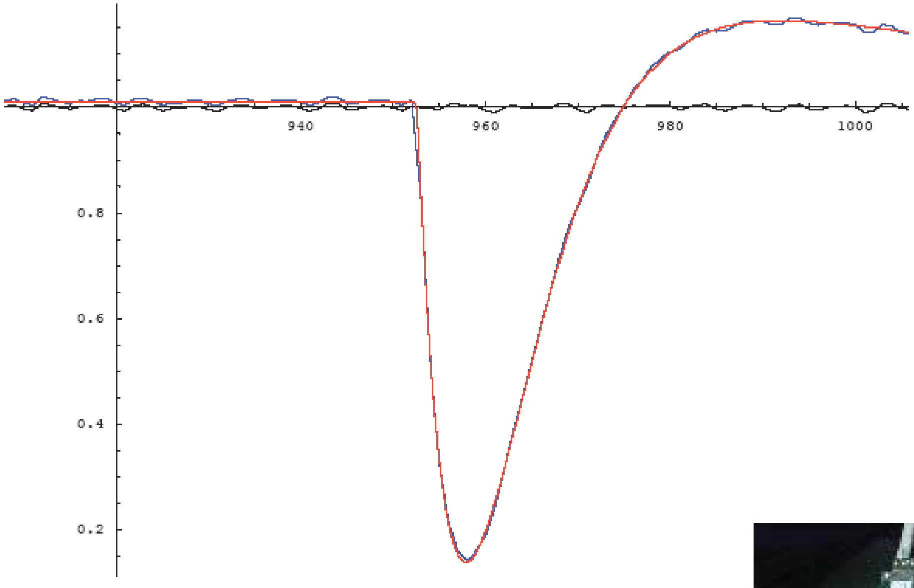
APD and Electronics commissioning

- Test 16 APDs simultaeously using a Xe scintillation source (^{148}Gd) and an ^{55}Fe source



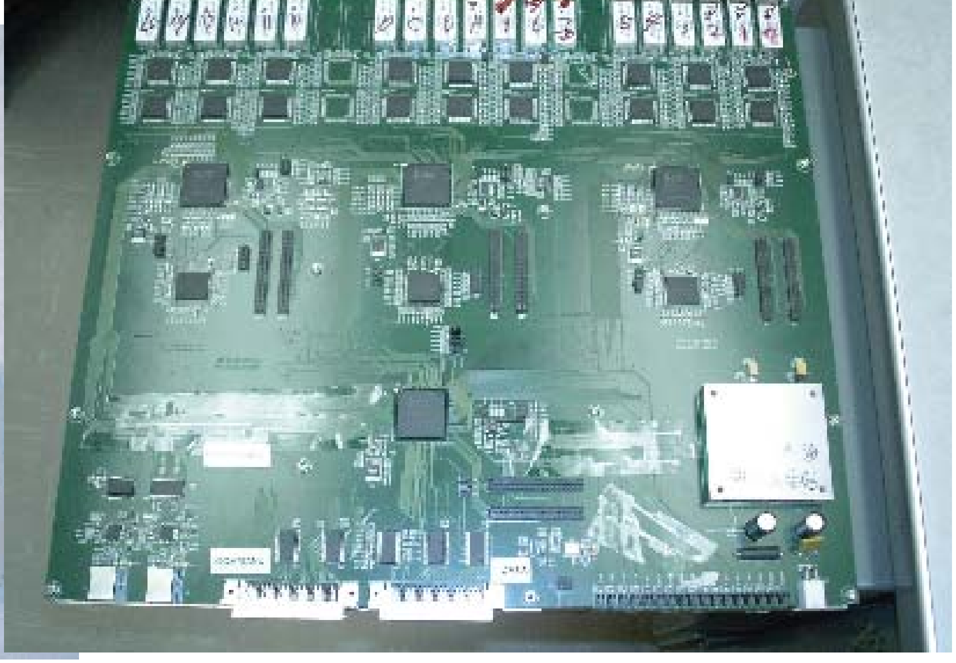


- Full DAQ chain in use (HV board, FEC, TEM, Linux PC with DAQ software)

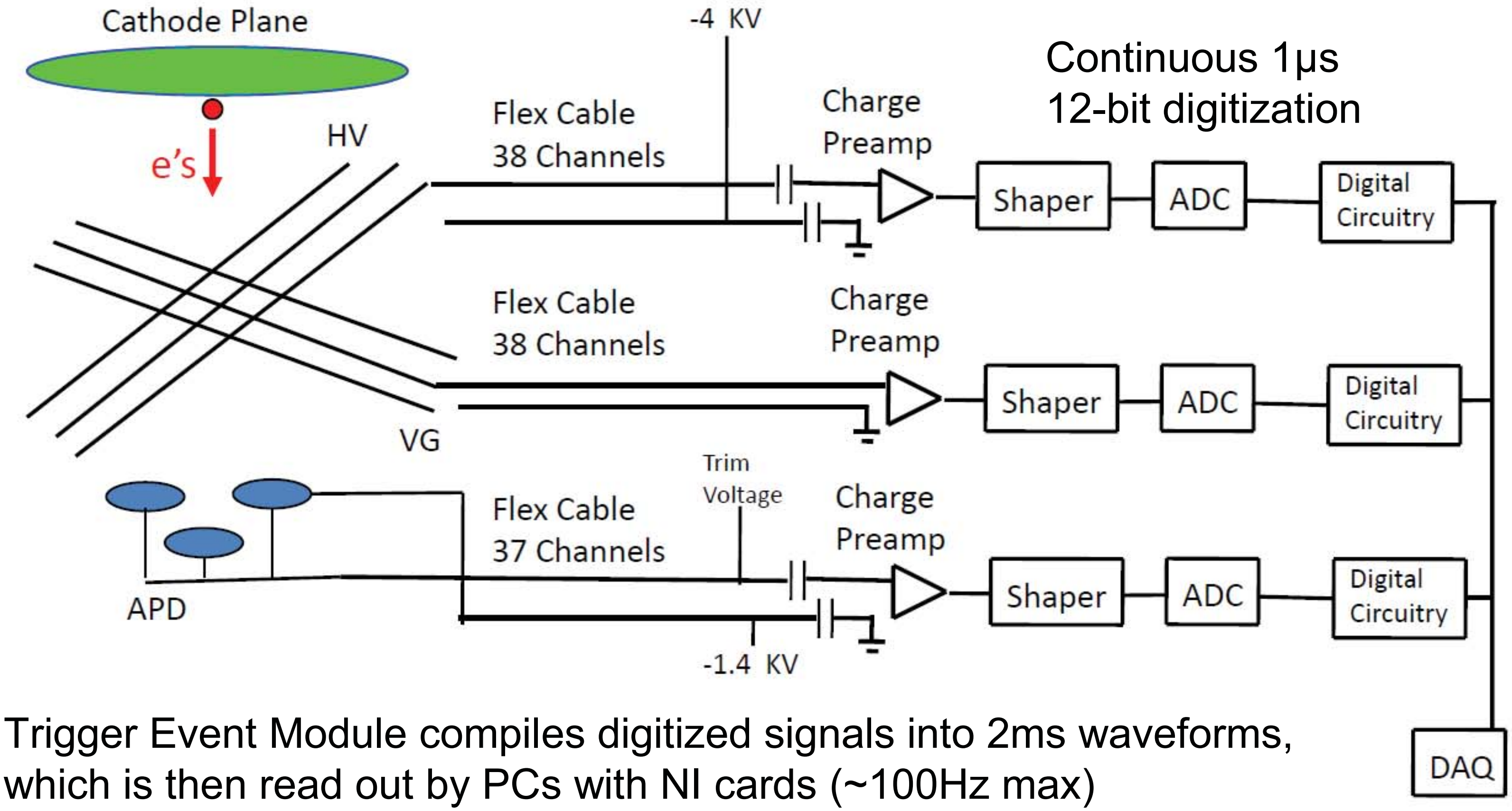


Electronics

-Fully designed and produced
-DAQ software has been written
-Fine tuning of shaping times and other parameters underway



Electronics



Continuous 1μs
12-bit digitization

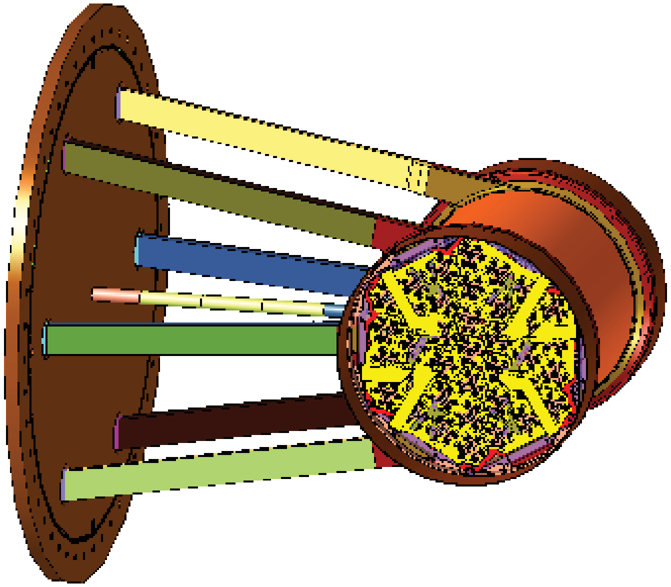
Trigger Event Module compiles digitized signals into 2ms waveforms, which is then read out by PCs with NI cards (~100Hz max)

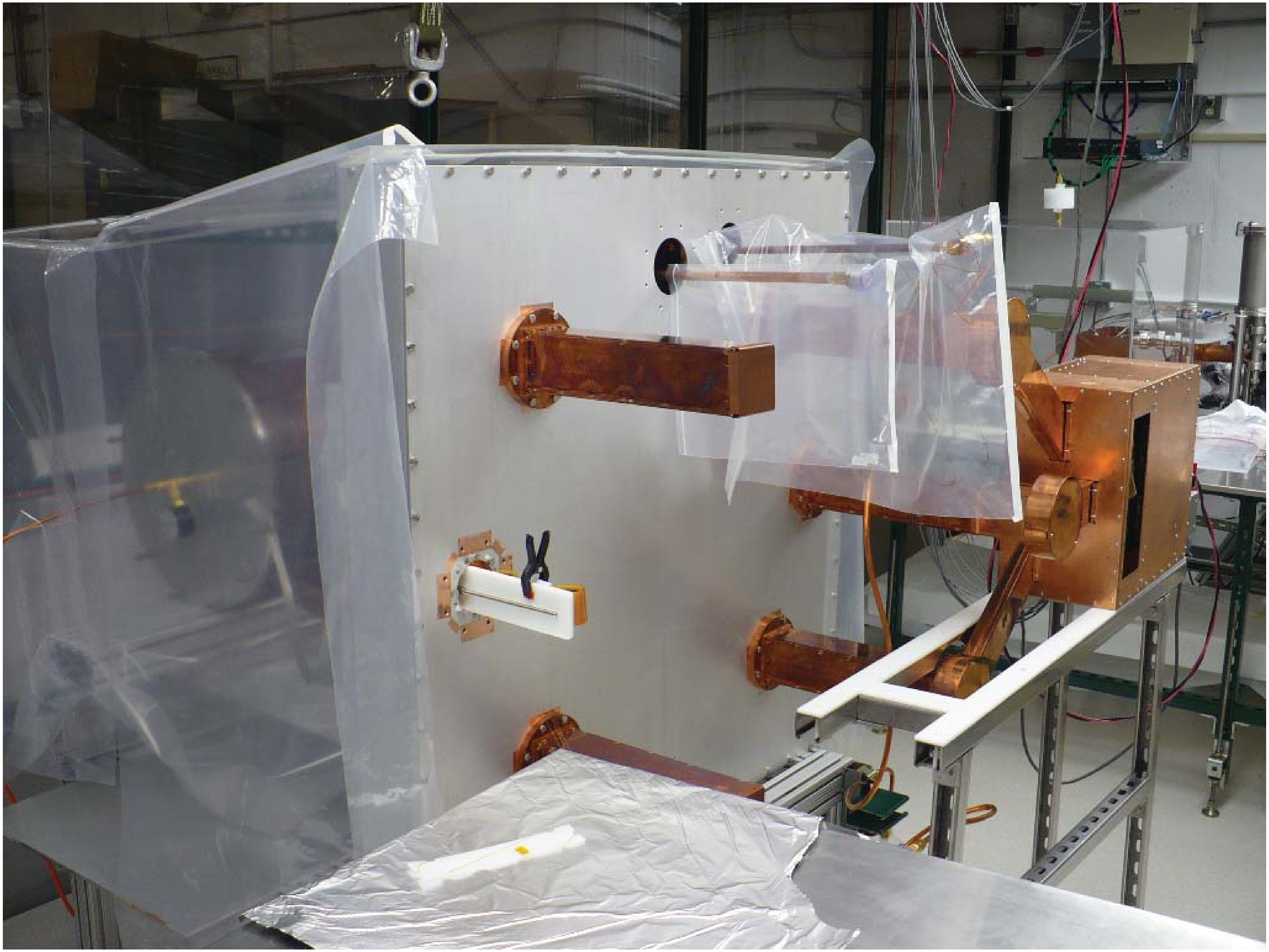
All of our electronics exists outside lead shielding. This makes things very hard, in particular cabling and noise issues!

Chamber

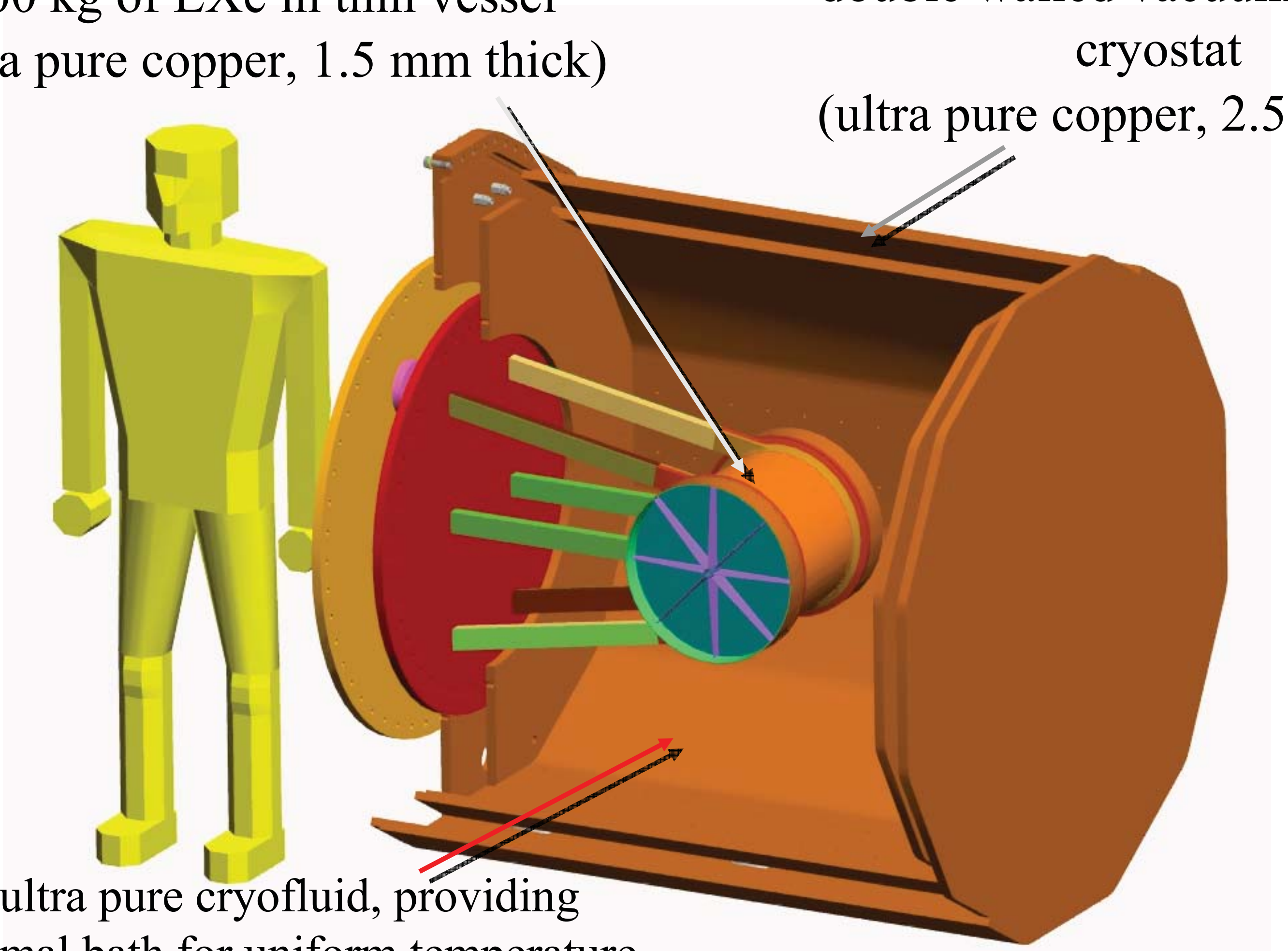
Chamber was machined at Stanford University under 7 m.w.e shielding

E-beam used for all but final weld to minimize introduction of radioactive background





The EXO-200 detector



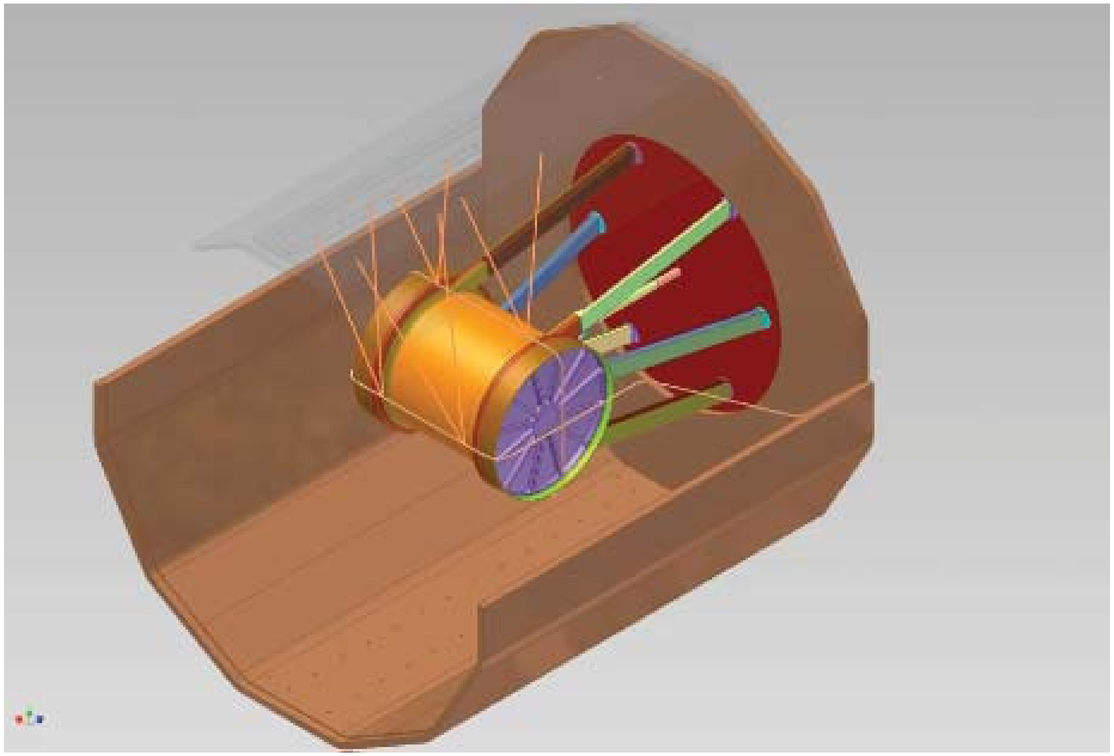
200 kg of LXe in thin vessel
(ultra pure copper, 1.5 mm thick)

double walled vacuum insulated
cryostat
(ultra pure copper, 2.5 cm thick)

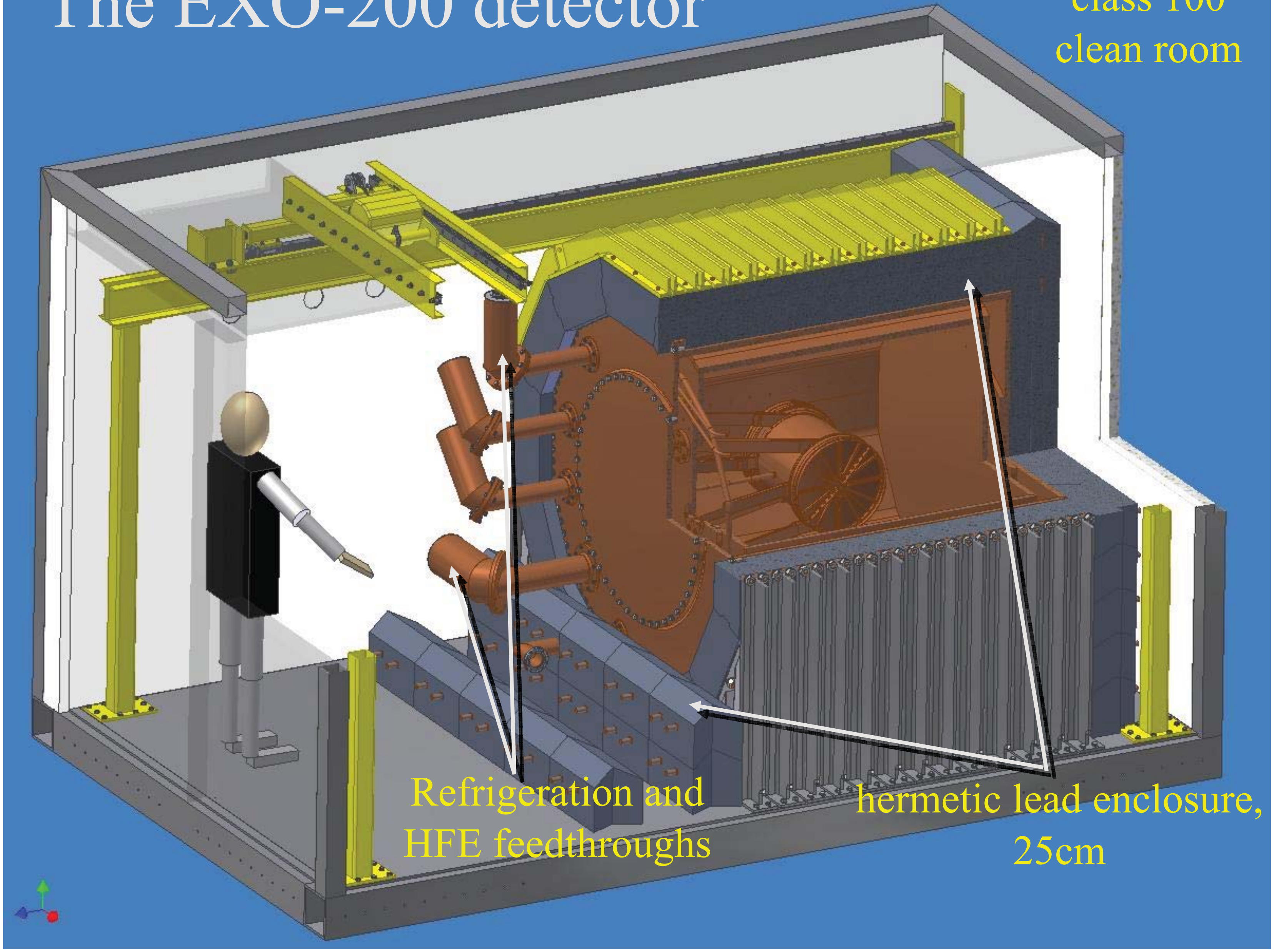
50 cm of ultra pure cryofluid, providing
large thermal bath for uniform temperature
and excellent screening from external γ rays (density = 1.8 at -100 C), neutrons
(3M HFE-7000, hydrofluoroether $C_3F_7OCH_3$)

Calibration

- Calibration system designed, tubing in hand, sources in hand or being procured
- MC simulations have determined (to some extent) locations and duration of exposure
- A deployment system has been tested at cryogenic temperatures



The EXO-200 detector



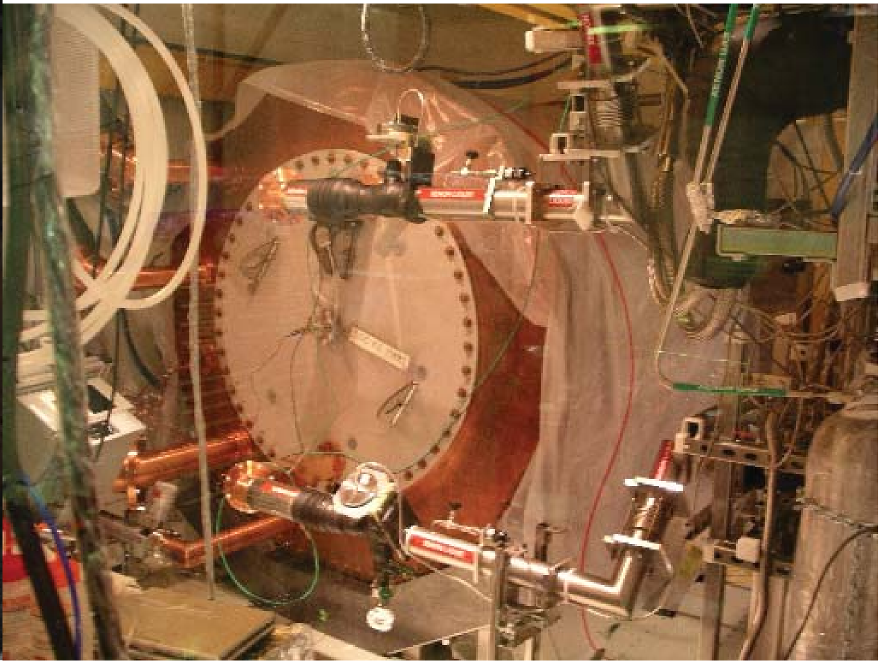
class 100 clean room

Refrigeration and HFE feedthroughs

hermetic lead enclosure, 25cm

Commissioning LXe and Refrigeration Systems

Successfully liquefied 30 kg of Natural Xe in a “dummy” stainless steel vessel at Stanford. After major improvements and move to WIPP, now repeating this test.



The EXO-200 modular clean rooms

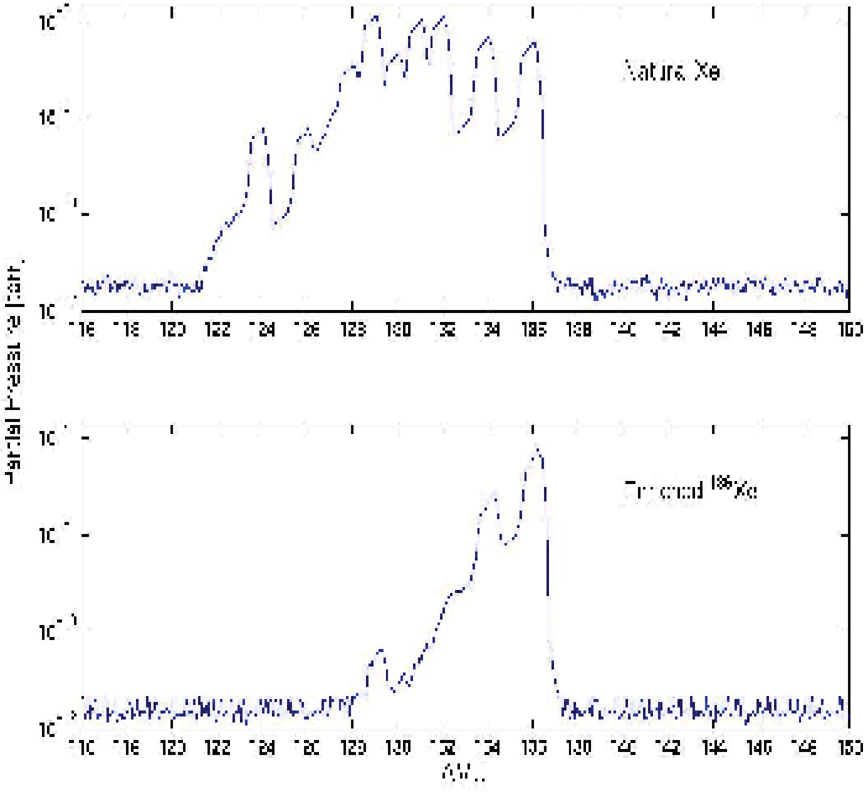
2m thick concrete roof

Sheilded shipping container for Cu and Detector

soft wall clean room: pre-assembly and cleaning

HFE storage dewar in shipping container

^{136}Xe stockpile in shipping container



200 kg of xenon enriched to 80% in ^{136}Xe : the largest isotope possession by any ββ collaboration

EXO-200kg Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.458MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV)	
							QRPA	NSM
Prototype	0.2	70	2	1.6*	40	$6.4 \cdot 10^{25}$	0.13	0.19

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $2.23^{+.044}_{-0.31} \cdot 10^{25}$, ($\pm 3\sigma$)

In 200kg EXO, 2yr:

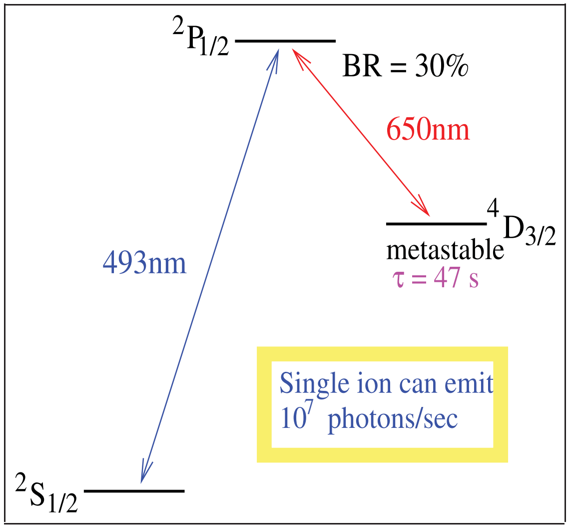
- **Worst case (QRPA, upper limit) 46 events on top of 40 events bkgd → 5σ**
- **Best case (NSM, lower limit) 170 events on top of 40 bkgd → 11.7σ**

Ba Retrieval and Tagging Goals

- Identify the Ba daughter of the ββ decay with high efficiency
- One method:
  - Retrieve Ba daughter from LXe
  - Release Ba daughter into a linear RF quadrupole trap
  - Positively identify Ba daughter via laser spectroscopy, possibly in the presence of Xe gas
- Other methods under development:
  - Spectroscopy of Ba directly in LXe
  - Spectroscopy of Ba in high pressure GXe

Laser fluorescence barium identification

A well-studied technique pioneered by atomic physicists in the 1980's for the detection of single atoms and ions, in particular, alkali and alkaline-earth metals.



Single ion can emit 10^7 photons/sec

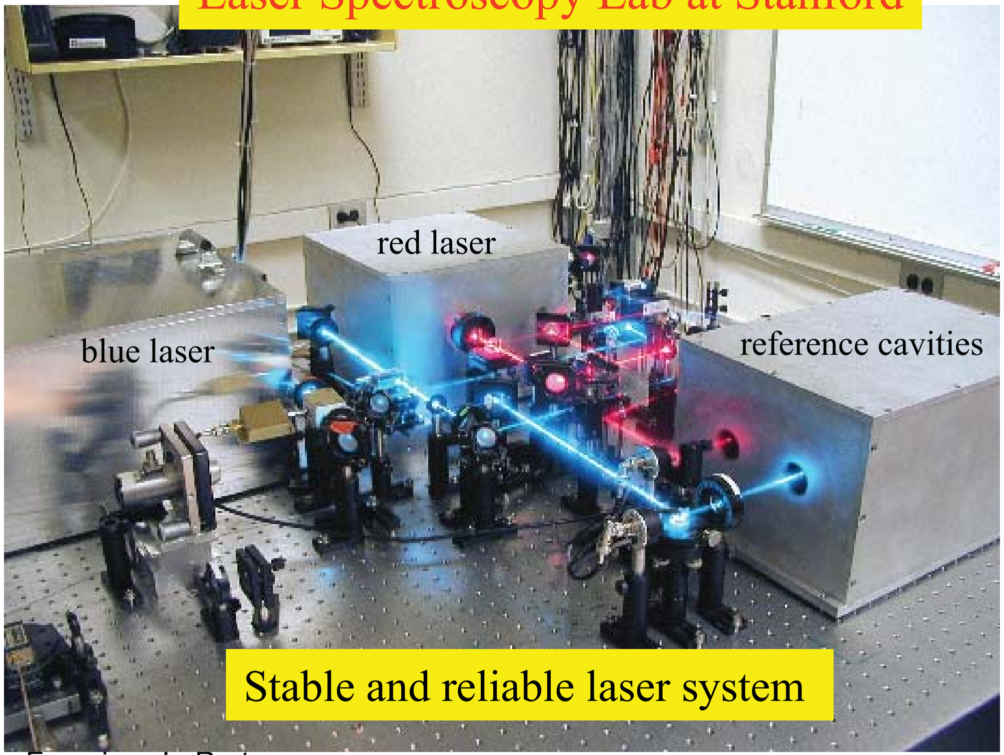
Level structure for Ba^+

Ba^{++} lines in the UV – convert ion to Ba^+ or neutral Ba.

"Intermodulation"

"Shelving" into metastable D state allows for modulation of 650nm light to induce modulated 493nm emission *out of synch.* with excitation (493nm) light – improves S/N

Laser Spectroscopy Lab at Stanford



Stable and reliable laser system

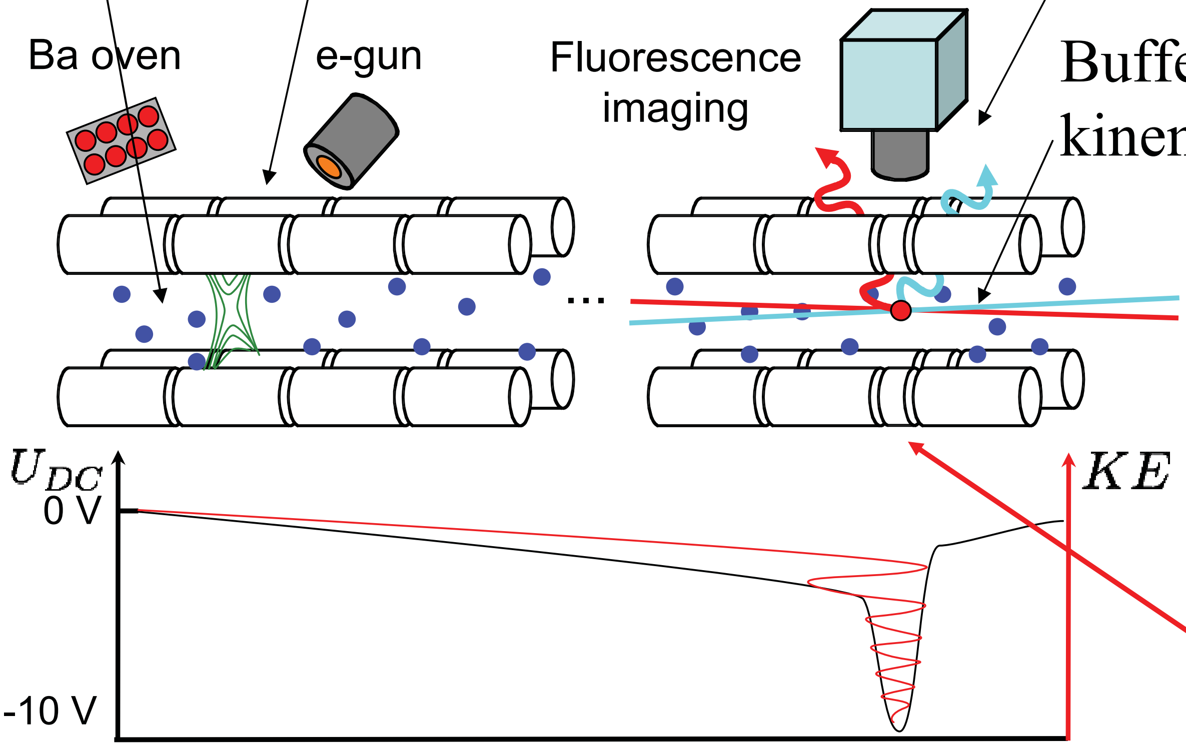
Single Ba ion trapping

Create Ions

Hyperbolic field traps ions radially

Spectroscopy is done

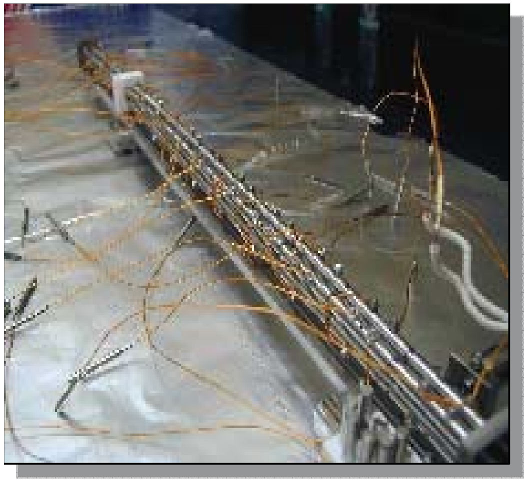
Buffer gas (He/Xe) kinematically cools Ion

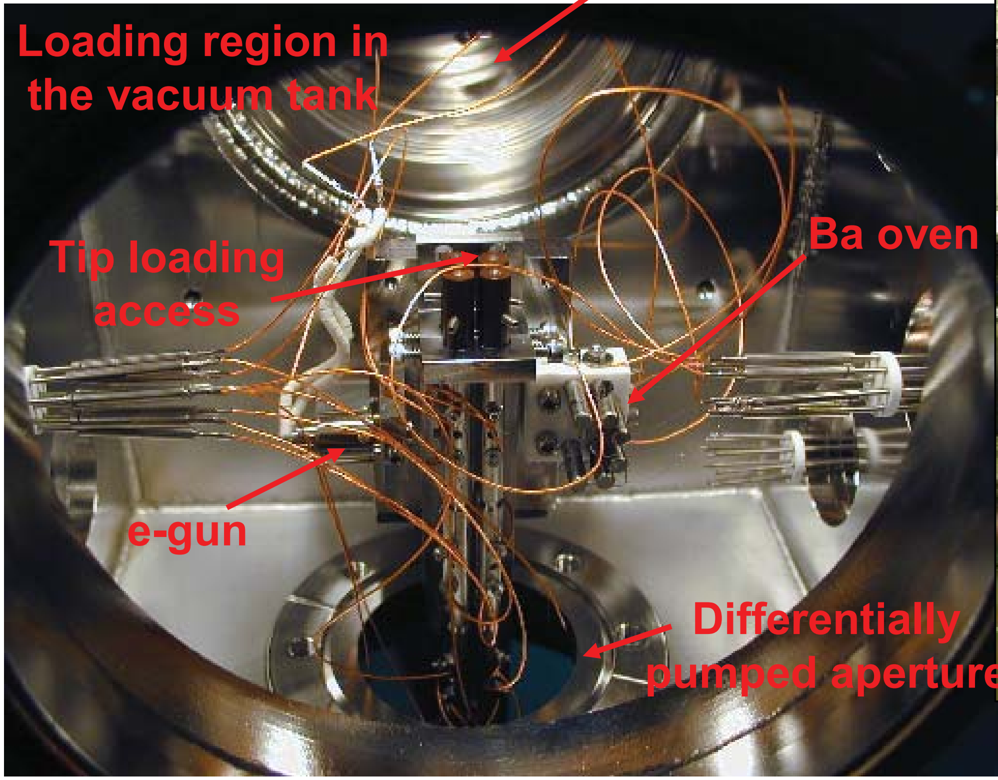


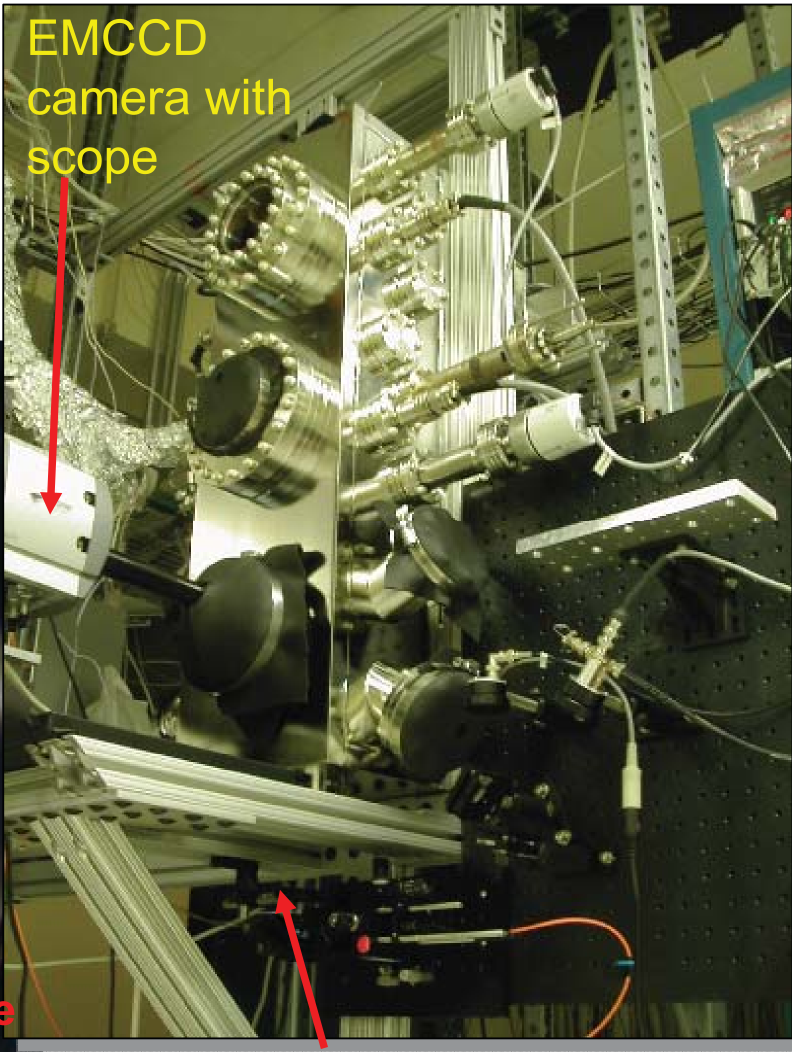
short longitudinal trapping segment

DC field is graded to trap Ions axially

Linear ion trap at Stanford

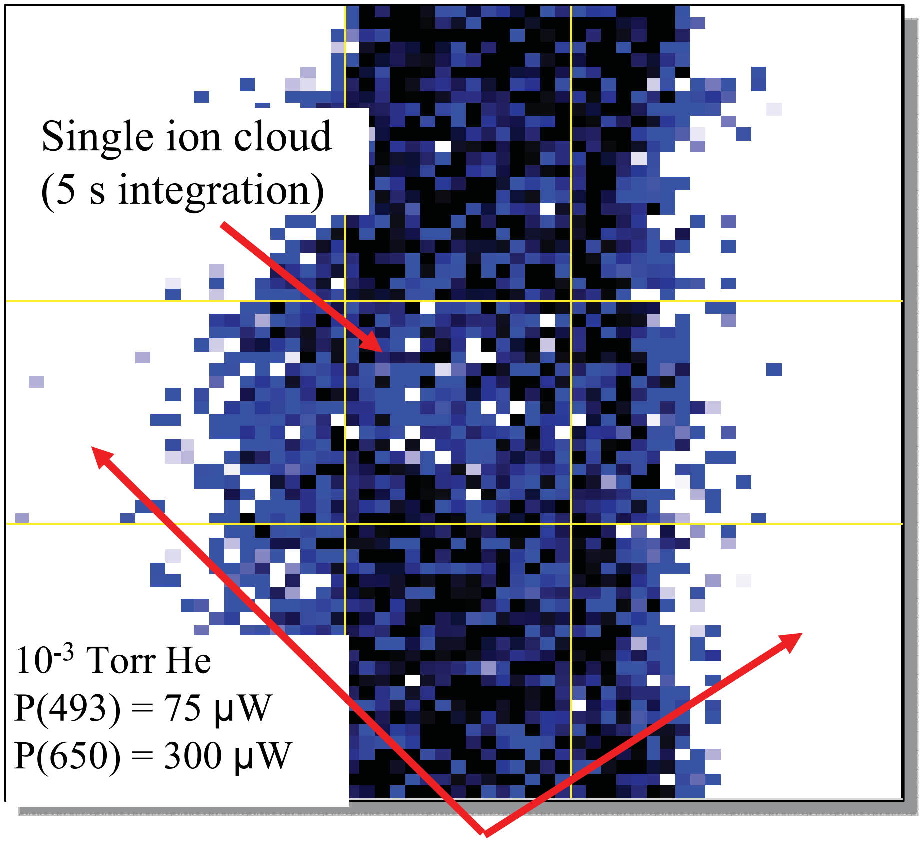






Input optics (493 nm, 650 nm beams on single fiber)

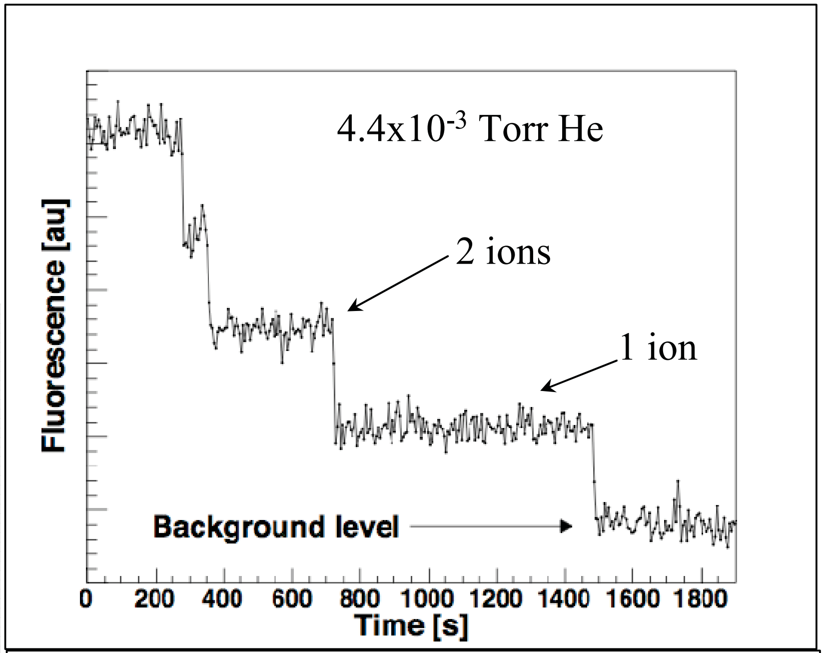
First detection of single ions in buffer gas!

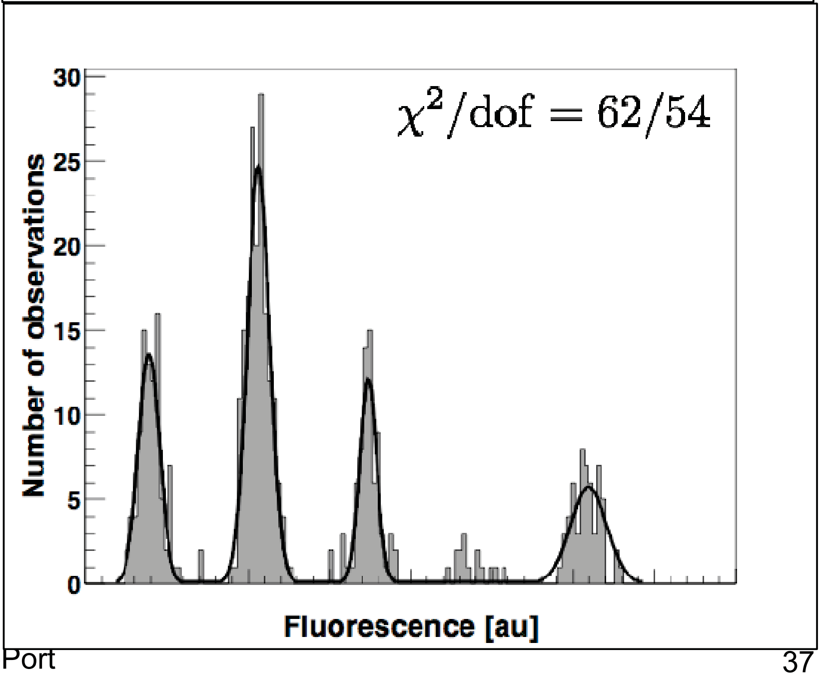


Single ion cloud
(5 s integration)

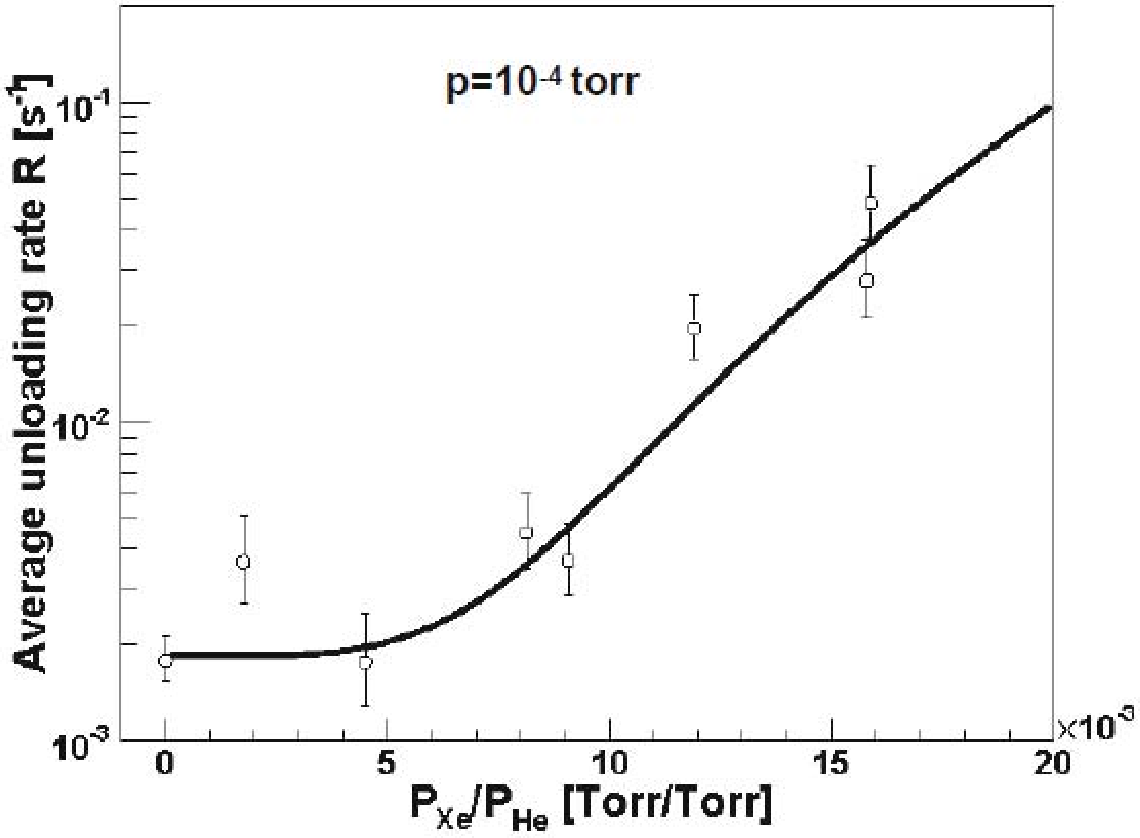
10^{-3} Torr He
P(493) = 75 μW
P(650) = 300 μW

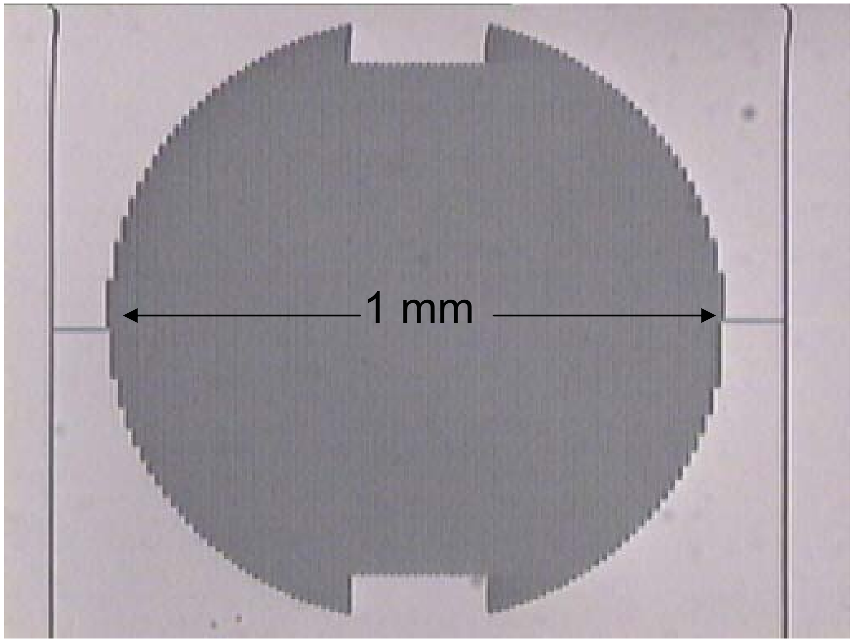
Electrodes glowing from scattered laser light



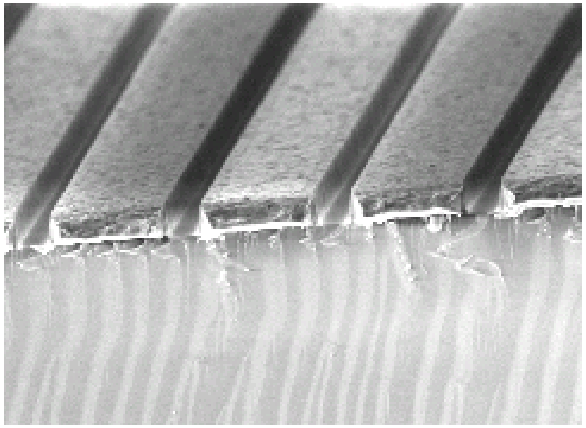


Single ion spectroscopy & identification possible in some Xe atmosphere provided He is added to the trap





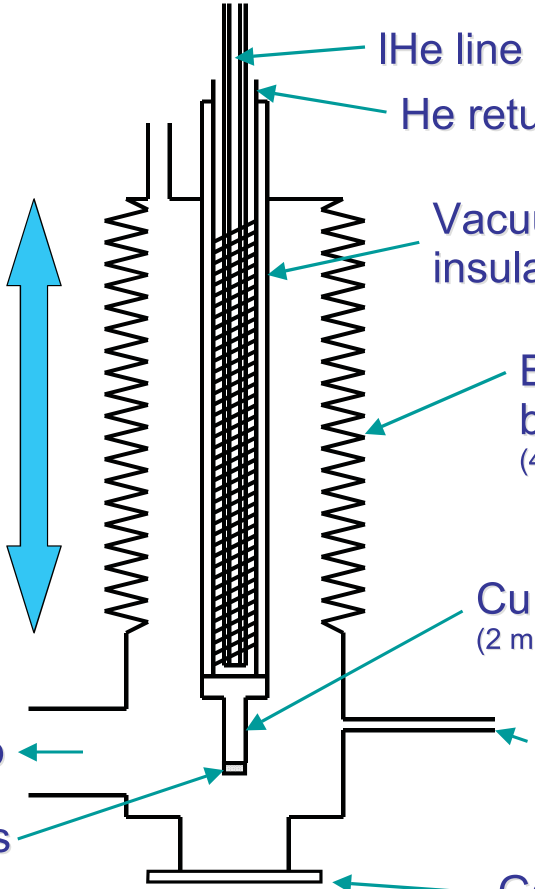
Capacitive cryo-tip (one of many methods being investigated)



Fingers for dielectric ice-thickness measurement:

ε_r(Xe,liquid) = 1.88

ε_r(Xe,solid) = 2.25



lHe line

He return

Vacuum insulation

Edge welded bellows
(400mm travel)

Cu cold-finger
(2 mm diameter)

Turbo pump

Ice thickness sensor

Gate valve

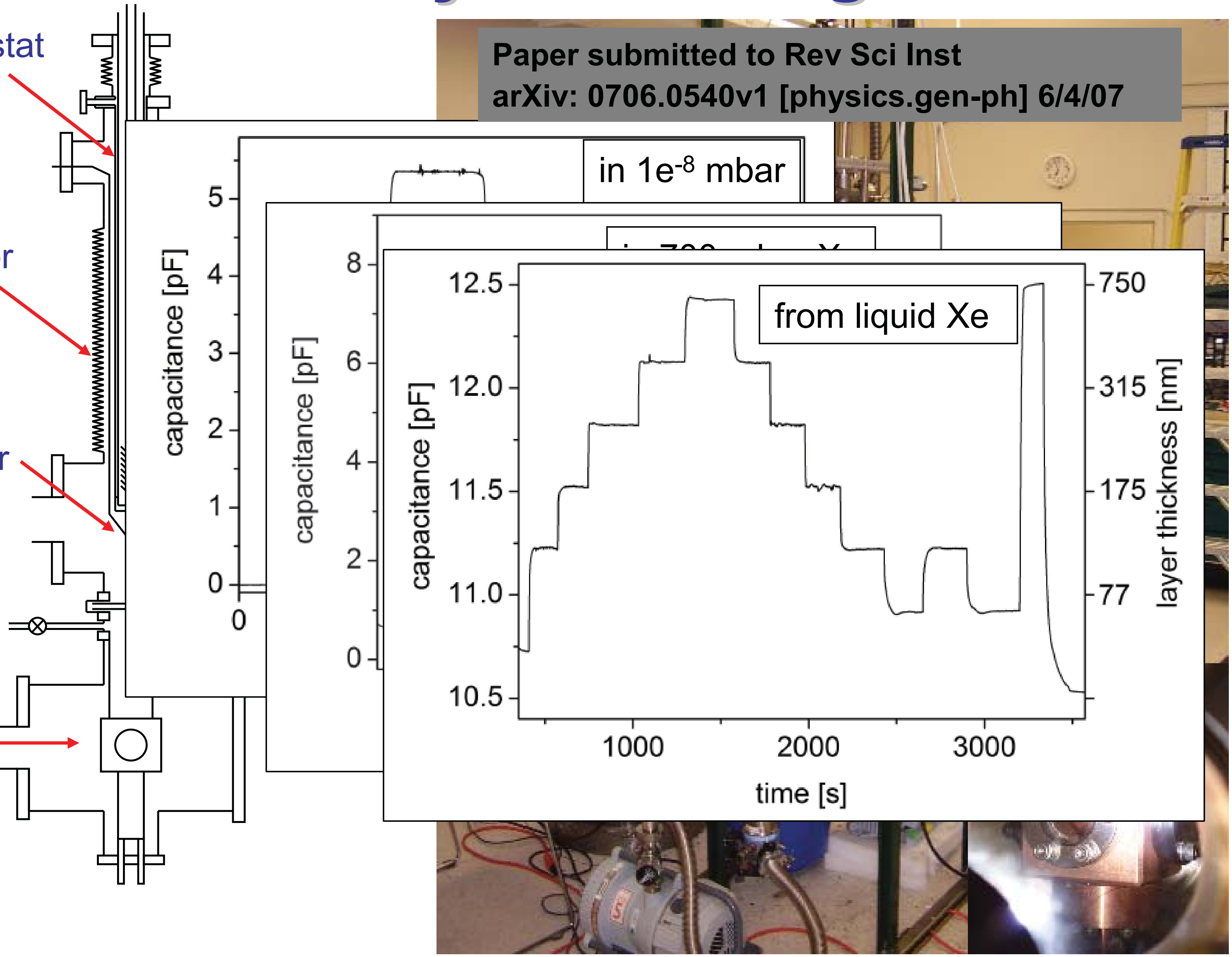
Thin layer freezing

lHe cryostat

Actuator

Ice sensor

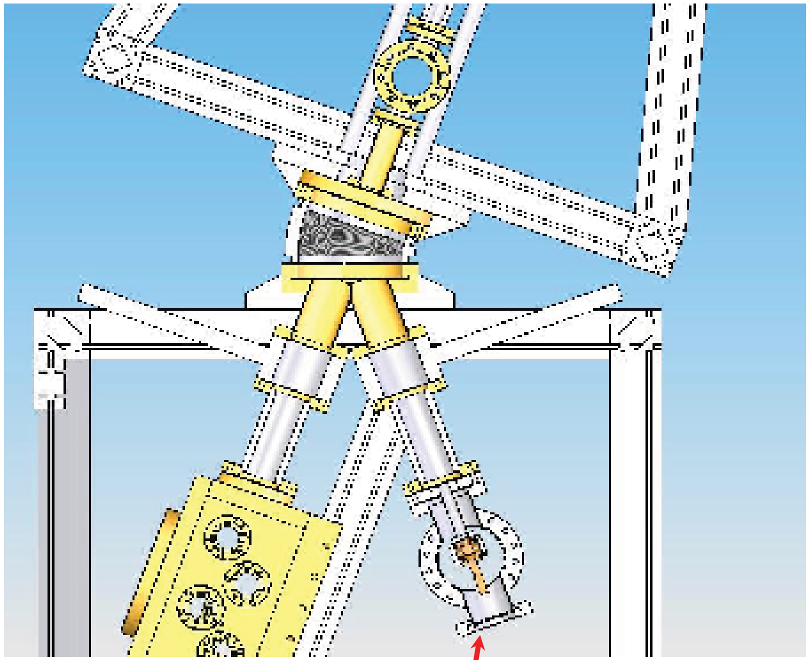
lXe cell

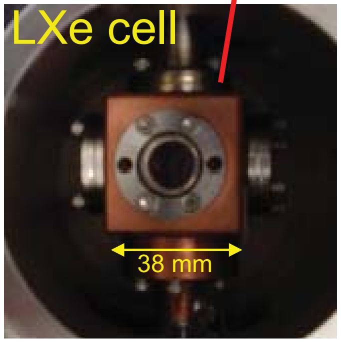


Paper submitted to Rev Sci Inst
arXiv: 0706.0540v1 [physics.gen-ph] 6/4/07

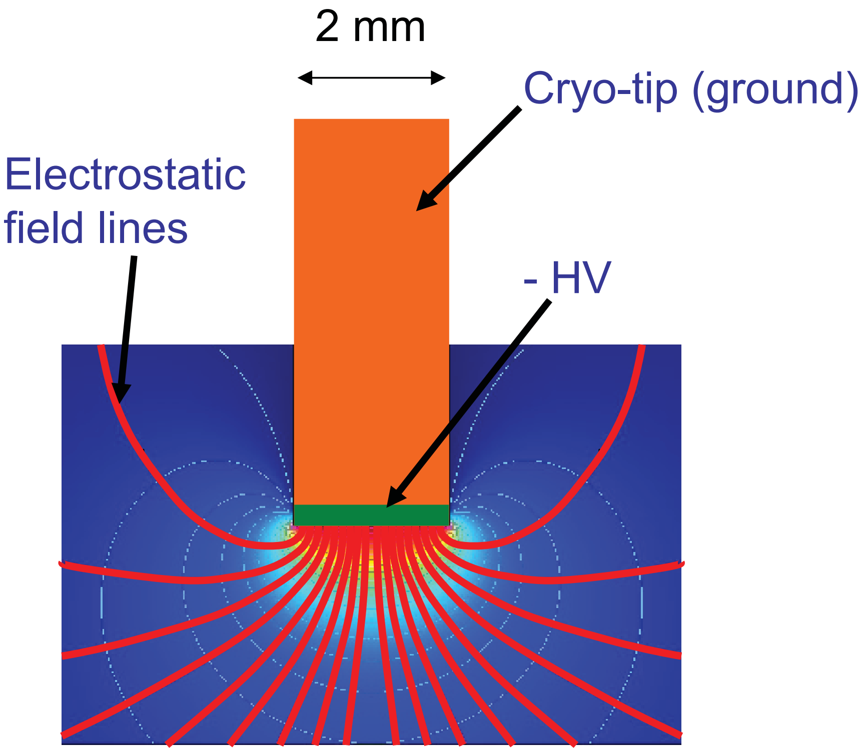
In progress

Tip moving robot





Ion trap



Ion mobility: $\mu \sim 0.3\ \mathrm{cm}^2/\mathrm{kVs}$

$v = \mu \times 1\,\mathrm{kV/cm} \sim 0.3\ \mathrm{cm/s}$

K. Wamba et al. (EXO Collab), NIM A 555 (2005) 205

Conclusions

- EXO-200 detector will be installed before 2010
  - Re-commissioning of all detector support systems at WIPP underway
  - Detector is built and being tested at Stanford
- Ba retrieval and identification along the path to completion
  - Single Ion Ba spectroscopy in buffer gas well understood
  - Retrieval system being pursued with good success
  - Integrated system designed and in early stages of assembly
- Full EXO is on the horizon!

Collaboration

K.Barry, E.Niner, A.Piepke
Physics Dept., U. of Alabama, Tuscaloosa AL, USA
P.Vogel
Physics Dept., Caltech, Pasadena CA, USA
A.Bellerive, M.Bowcock, M.Dixit, K.Graham, C.Hargrove, E.Rollin, D.Sinclair, V.Strickland
Carleton University, Ottawa, Canada
C.Benitez-Medina, S.Cook, W.Fairbank Jr., K.Hall, B.Mong
Colorado State U., Fort Collins CO, USA
M.Moe
Physics Dept., UC Irvine, Irvine CA, USA
D.Akimov, I.Alexandrov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Karelin, A.Kovalenko, A.Kuchenkov, V.Stekhanov, O.Zeldovich
ITEP Moscow, Russia
B.Aharmin, K.Donato, J.Farine, D.Hallman, U.Wichoski
Laurentian U., Canada
H.Breuer, C.Hall, L.Kaufman, D.Leonard, S.Slutsky, Y-R.Yen
U. of Maryland, College Park MD, USA
K.Kumar, A.Pocar
U. of Massachusetts, Amherst, Amherst MA, USA
M.Auger, G.Giroux, R.Gornea, F.Juget, G.Lutter, J-L.Vuilleumier
Laboratory for High Energy Physics, Bern, Switzerland
N.Ackerman, M.Breidenbach, R.Conley, W.Craddock, S.Herrin, J.Hodgson, D.Mackay, A.Odian, C.Prescott, P.Rowson, K.Skarpaas, J.Wodin, L.Yang, S.Zalog
SLAC, Menlo Park CA, USA
L.Bartoszek, R.Cooper, R.DeVoe, M.Dolinski, B.Flatt, G.Gratta, M.Green, F.LePort, M.Montero-Diez, R.Neilson, A.Reimer-Muller, A.Rivas, K.O'Sullivan, K.Twelker
Physics Dept., Stanford University, Stanford CA USA

QuickTime™ and a
decompressor
are needed to see this picture.

Single Ba ion trapping

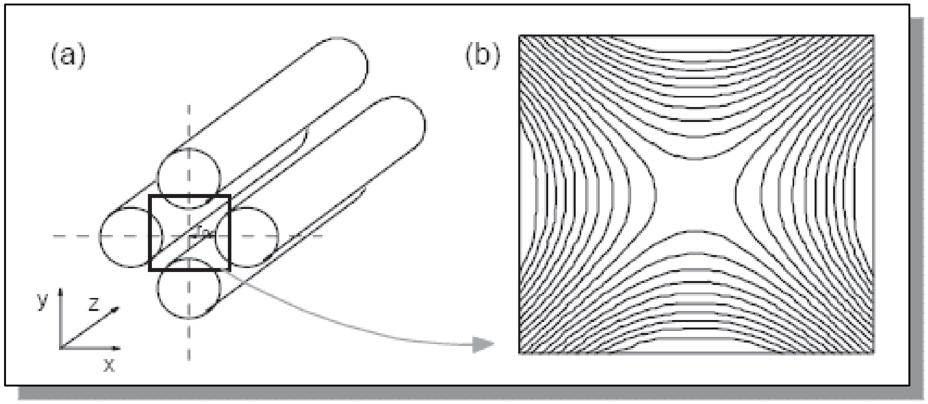
Build an AC quadrupole potential:

$$\Phi = \frac{\varphi_0}{2}\left(1 + \frac{x^2 - y^2}{r_0^2}\right)$$

$$\varphi_0 = U_{DC} + V_{RF}\cos\Omega t$$

longitudinal trapping

radial trapping



write: $\vec{F} = q\vec{E} = m\vec{a}$

$$m\begin{pmatrix}\ddot{x}\\ \ddot{y}\end{pmatrix} = \begin{pmatrix}-\frac{e\varphi_0}{r_0^2}x\\ +\frac{e\varphi_0}{r_0^2}y\end{pmatrix}$$

trap parameters:

$$V_{RF} = 150V_{pk}, \quad f = 1.1\text{MHz}$$
$$U_{DC} = 10V$$