Measuring the mass of the neutrino, one atom at the time

status report of the EXO

The EXO Collaboration

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Has 0νββ decay been already discovered ??

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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Part of the Heidelberg-Moscow collaboration
Mod. Phys Lett. A27 (2001) 2409

…this is a controversial matter (see details in)

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
……………

But in any case this (probably false alarm) shows how difficult these measurements are
Traditionally experiments are built with *belt* or *suspenders*
EXO is trying to have *both*

Historically two main approaches have been employed:

- **Final state ID:** 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  - \+ Very specific signature
  - \+ Large live times (particularly for 1)
  - \+ Large masses
  - \- Possible only for a few isotopes (in the case of 1)
  - \- No distinction between 0ν, 2ν or other modes
- **"Real time":** ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  - \+ Energy/some tracking available (can distinguish modes)
  - \+ In principle universal (b)
  - \- Many γ backgrounds can fake signature
  - \- Exposure is limited by human patience

How about combining the two approaches to have a really clean measurement all the way to very high sensitivity?

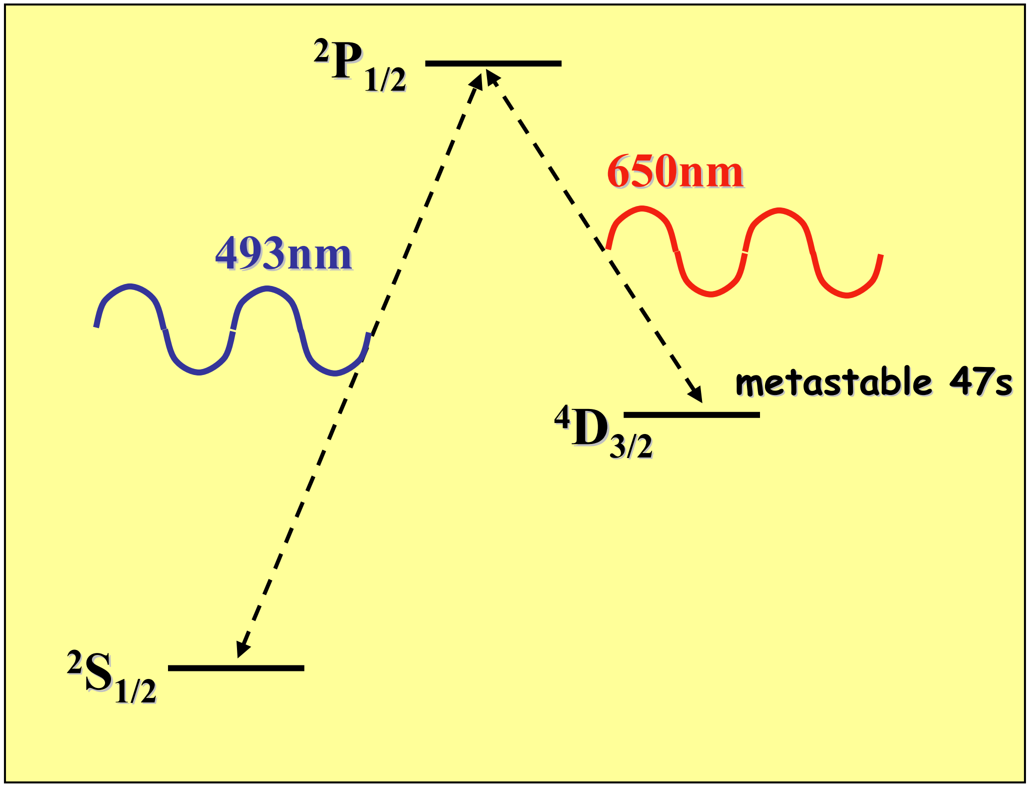
Xe is ideal for a large experiment

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography… a joint enrichment program ?

Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++} e^- e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba$^+$ system best studied
(Neuhauser, Hohenstatt,
Toshek, Dehmelt 1980)
Very specific signature
"shelving"
Single ions can be detected
from a photon rate of 10^7/s

- **Important additional constraint**
- **Drastic background reduction**



The Ba-tagging, added to a high resolution Xe imaging detector provides the tools to develop a background-free next-generation ββ experiment

Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80%

A somewhat natural scale:

- **World production of Xe is ~30 ton/yr**
- **Detector size**
- **$2 \cdot 10^3$ size increase: good match to the 10^{-2} eV mass region**

Mainly going in light bulbs and satellite propulsion

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 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) Use for 2νββ $T_{1/2}>1\cdot10^{22}$yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ 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)	$2*10^{27}$	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	11	15

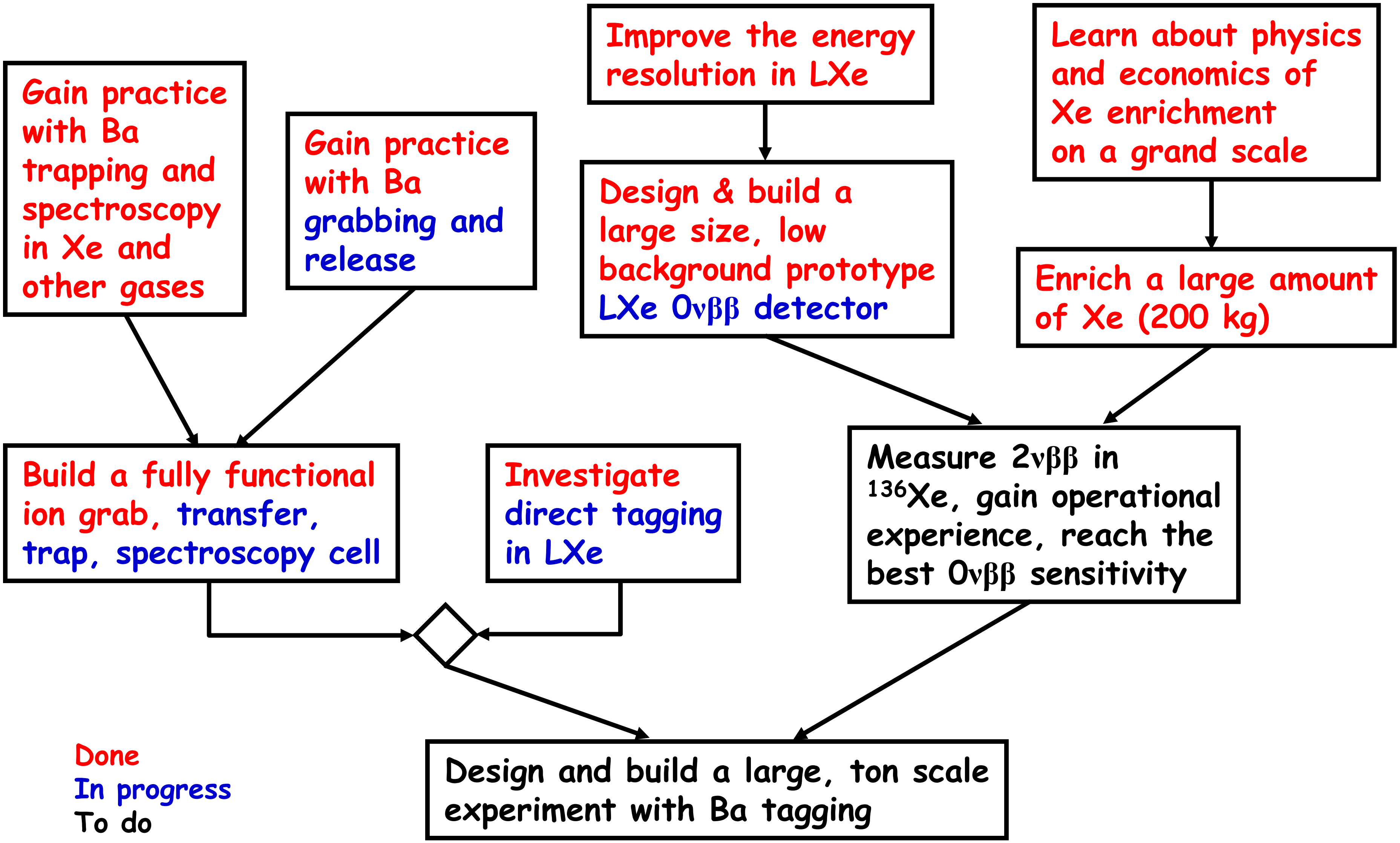
* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† 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

The roadmap to the background free discovery of Majorana neutrinos and the neutrino mass scale



EXO-200:
an intermediate detector <u>without</u> Ba tagging

- **Need to test detector technology, particularly the LXe option:**
  A 200 kg chamber is close to the largest Xe detector ever built and hence good training ground
- **Essential to understand backgrounds from radioactivity:**
  200 kg is the minimum size for which the self-shielding is important and there is negligible surface inefficiency
- **Using ^{136}Xe can hope to measure the "background" $2\nu\beta\beta$ mode:**
  200 kg is needed to have a chance (if do not see the mode then is really good news for the large experiment !!)
- **The production logistics and quality of ^{136}Xe need to be tested:**
  Need a reasonably large quantity to test production
- **Already a respectable (20x) $\beta\beta$ decay experiment**
- **No need for Ba tagging at this scale**

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 2.481MeV 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	Majorana mass (eV) NSM
EXO-200	0.2	70	2	1.6*	40	$6.4 \cdot 10^{25}$	0.27†	0.38♦

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5} \cdot 10^{25}$, ($\pm 3\sigma$)
(Phys. Lett. B 586 (2004) 198-212
consistently use Rodin's matrix elements for both Ge and Xe)

In 200kg EXO, 2yr:
- Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ
- Best case (NSM, lower limit) 162 events on top of 40 bkgd → 11σ

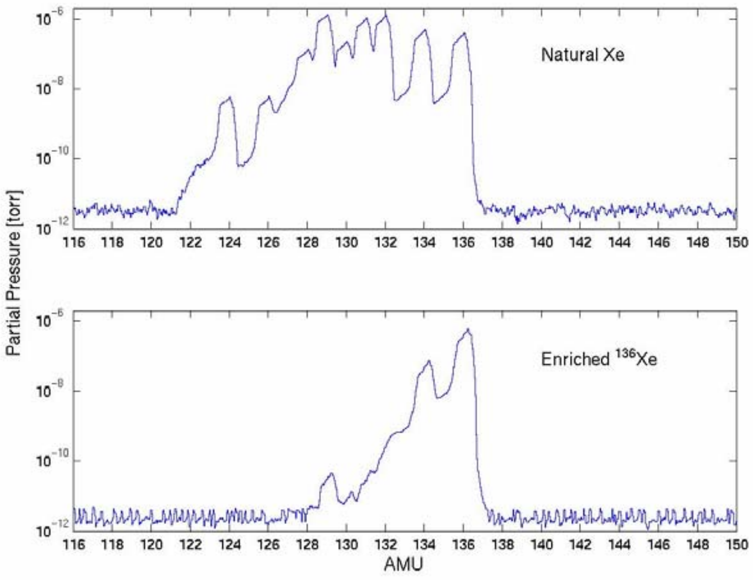
Status of 2ν mode in ^{136}Xe

2νββ decay has never been observed in ^{136}Xe.
Some of the lower limits on its half life are close to (and in one case below) the theoretical expectation.

	$T_{1/2}$ (yr)	evts/year in the 200kg prototype (no efficiency applied)
Experimental limit		
Leuscher et al	$>3.6 \cdot 10^{20}$	<1.3 M
Gavriljuk et al	$>8.1 \cdot 10^{20}$	<0.6 M
Bernabei et al	$>1.0 \cdot 10^{22}$	<48 k
Theoretical prediction		
QRPA (Staudt et al) [$T_{1/2}^{max}$]	$=2.1 \cdot 10^{22}$	=23 k
QRPA (Vogel et al)	$=8.4 \cdot 10^{20}$	=0.58 M
NSM (Caurier et al)	$(=2.1 \cdot 10^{21})$	(=0.23 M)

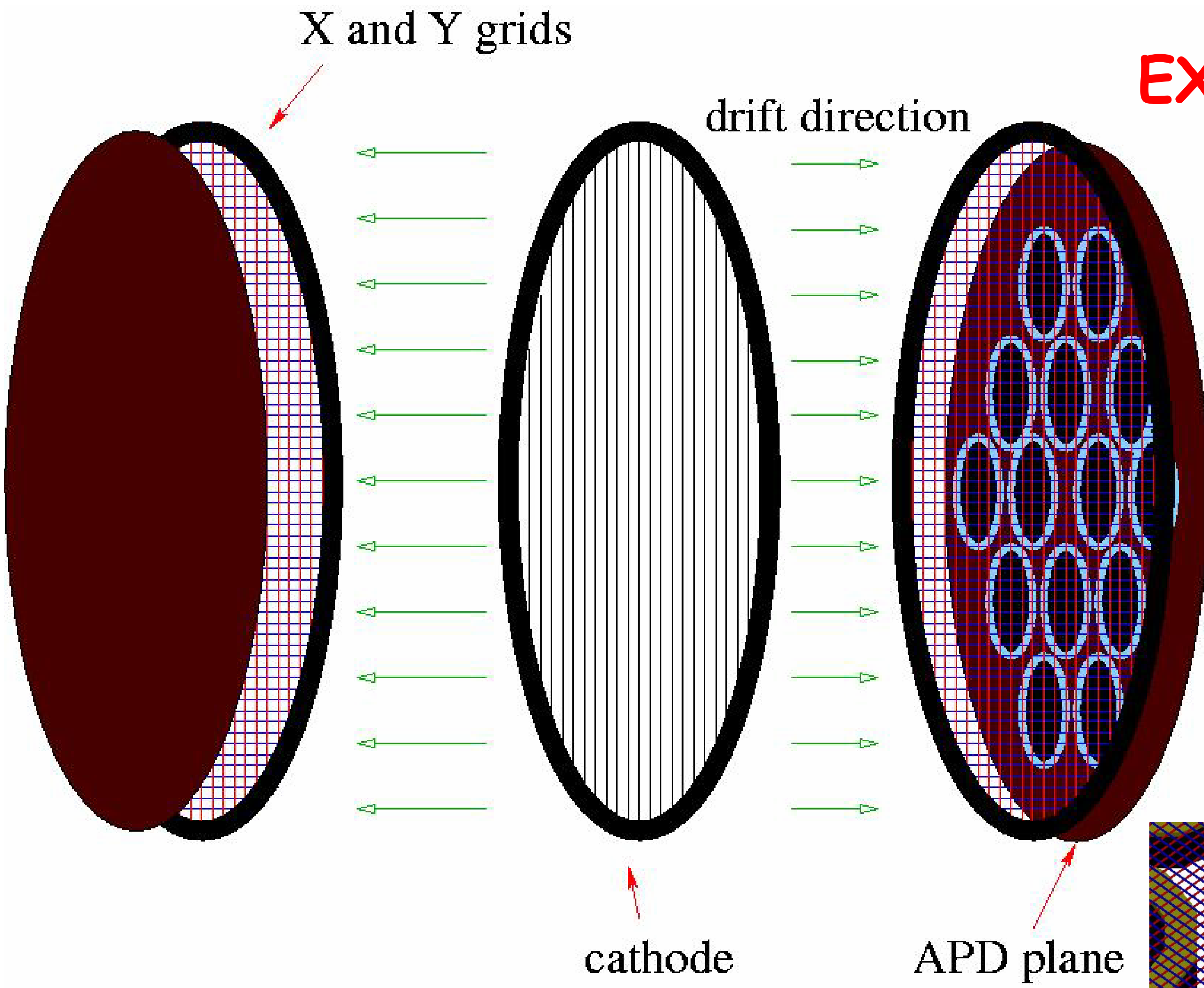
EXO-200 should definitely resolve this issue

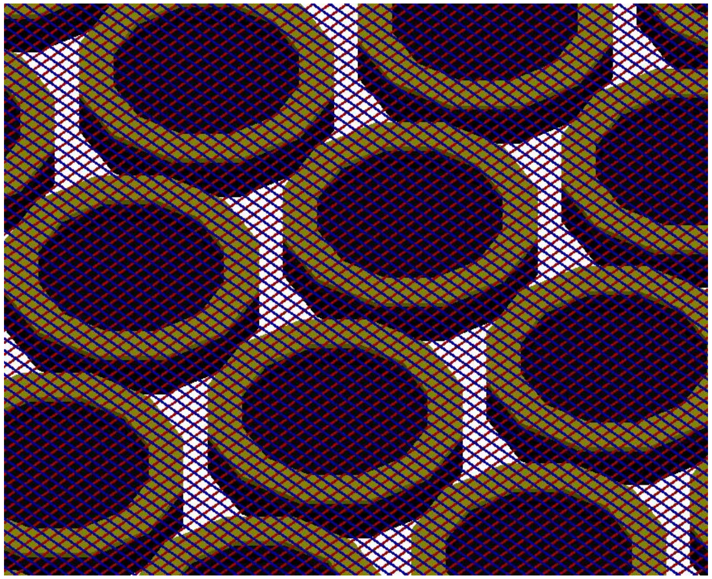
200 kg ^{136}Xe test production completed in spring '03 (80% enrichment)



- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated ββ isotope (by ~factor of 10)

EXO-200 TPC basics

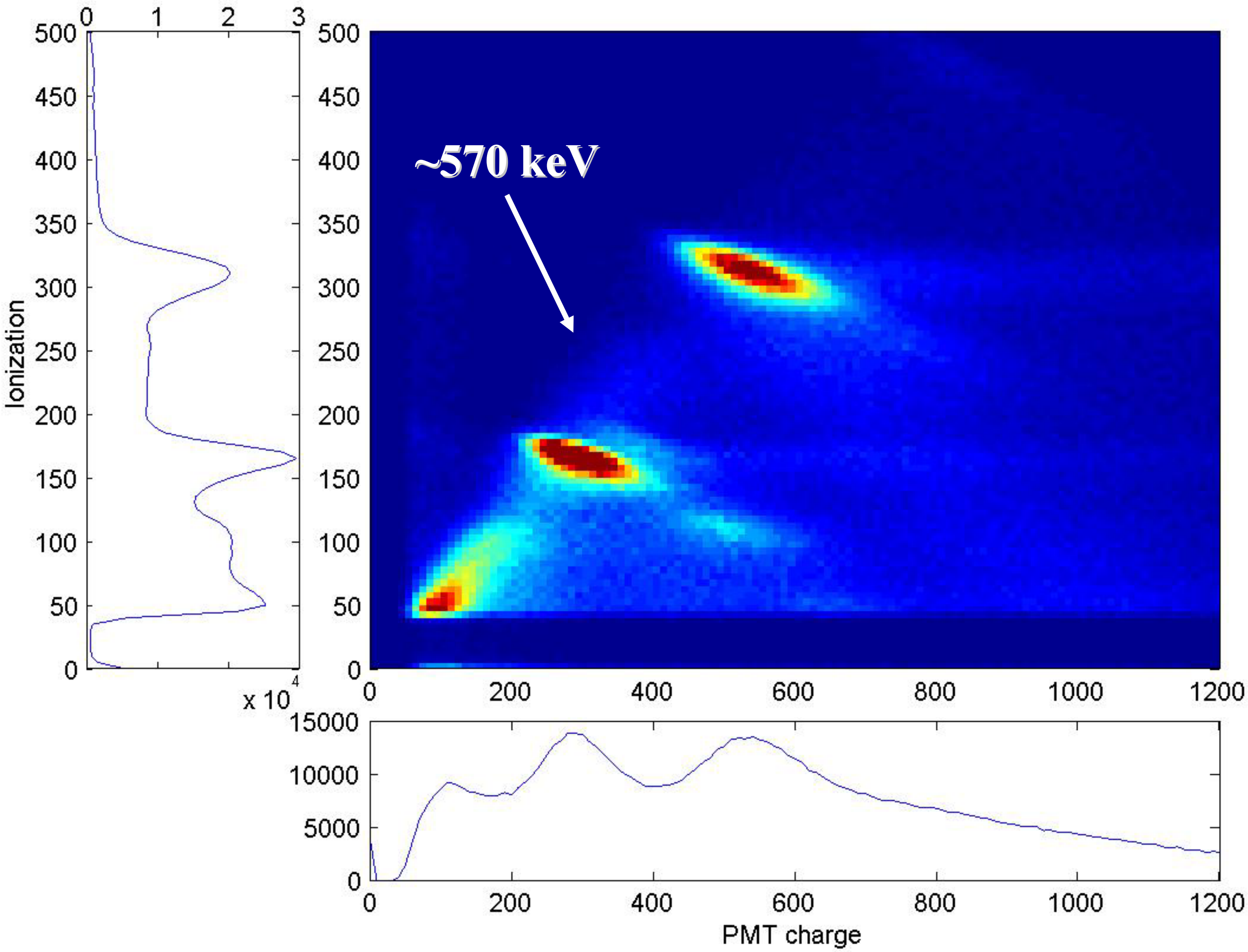




G.Gratta - EXO

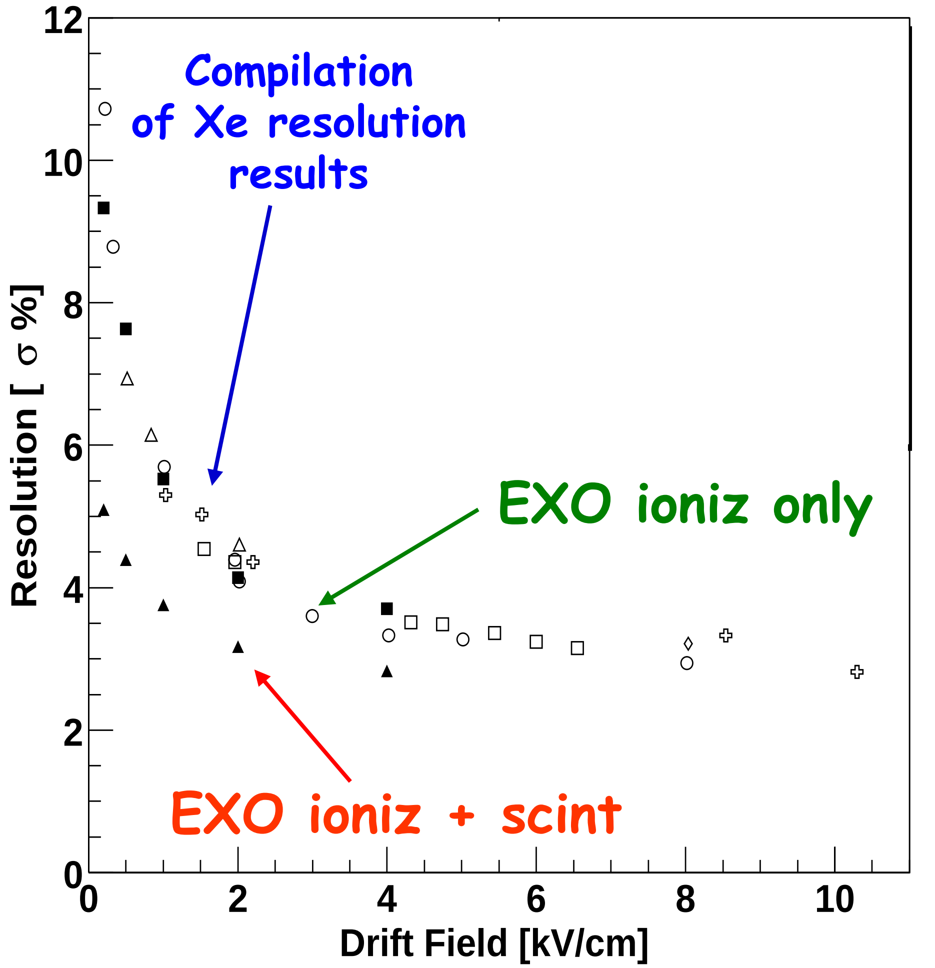
Aspen, Jan 29, 2007

EXO R&D showed the way to improved energy resolution in LXe: *Use (anti)correlations between ionization and scintillation signals*



G.

Anti-correlated ionization and scintillation improves the energy resolution in LXe



Ionization alone:
$\sigma(E)/E$ = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

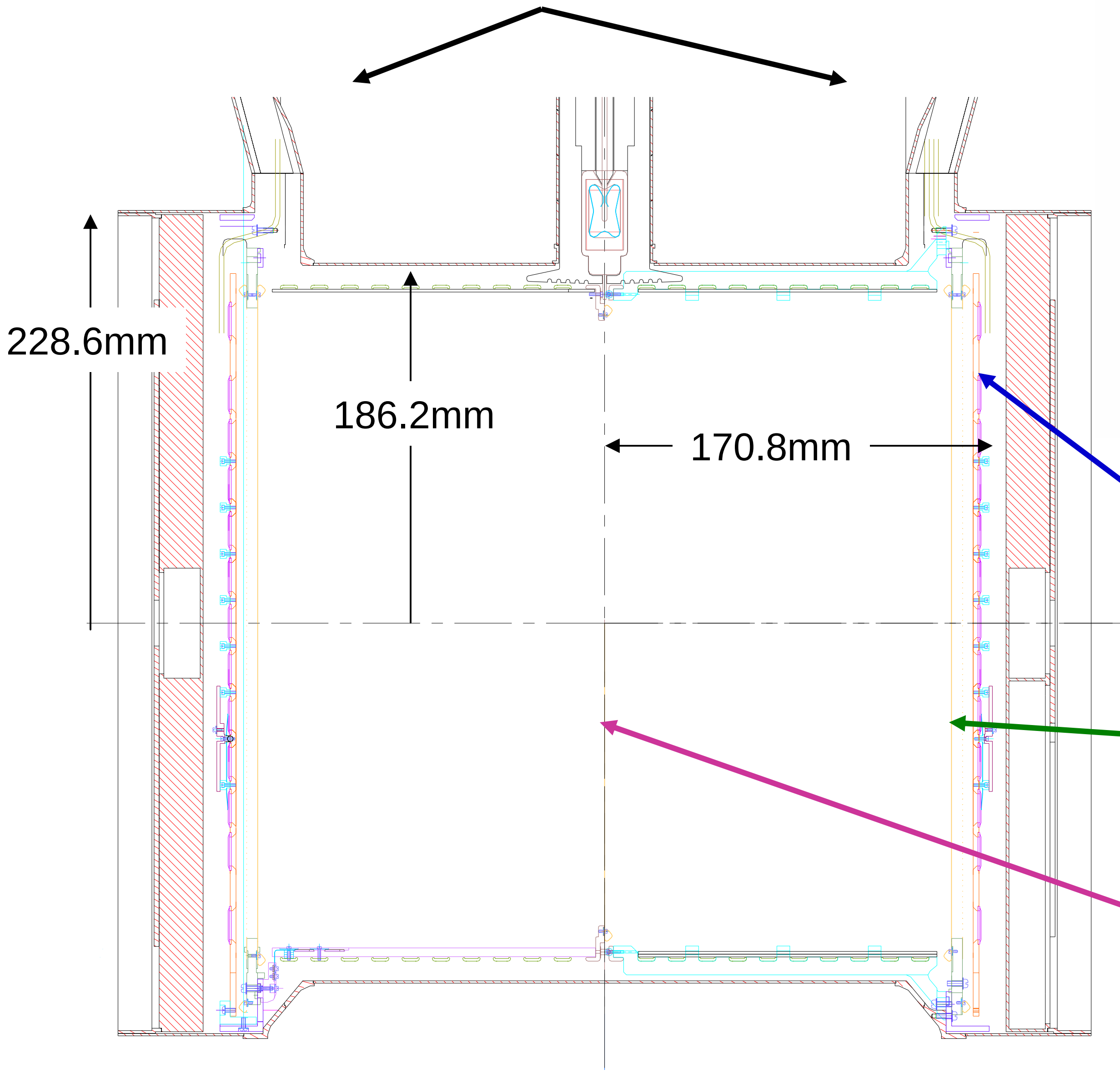
Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$
(a factor of 2 better than the Gotthard TPC)

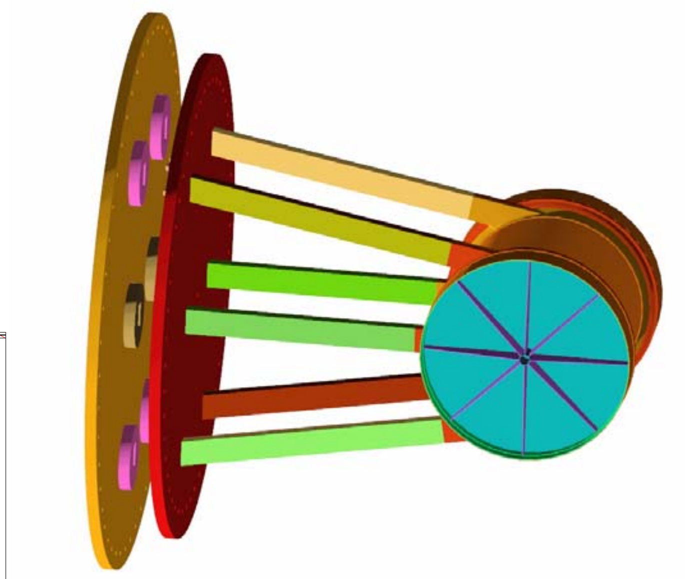
E.Conti et al. Phys. Rev. B: 68 054201

EXO-200 will collect 3-4 times as much scintillation… further improvement possible

EXO chamber “hugs” the fiducial volume very closely!

Mechanical supports and cable/Xe conduits





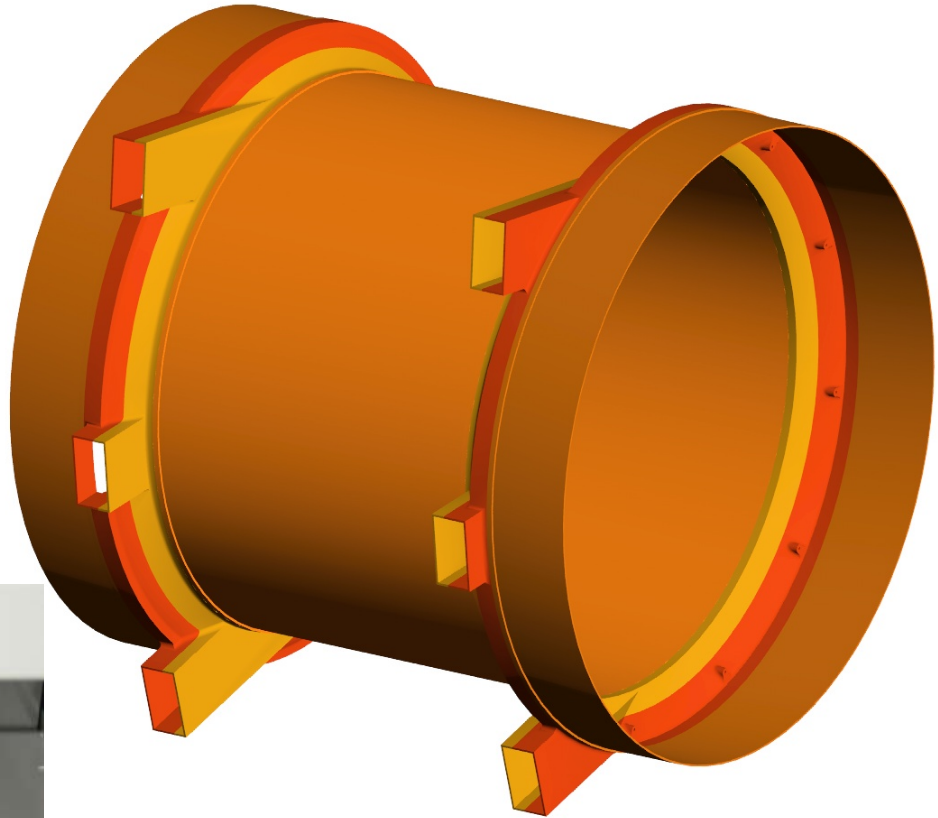
2x300 large area (1.6cm active diameter) unmounted APDs

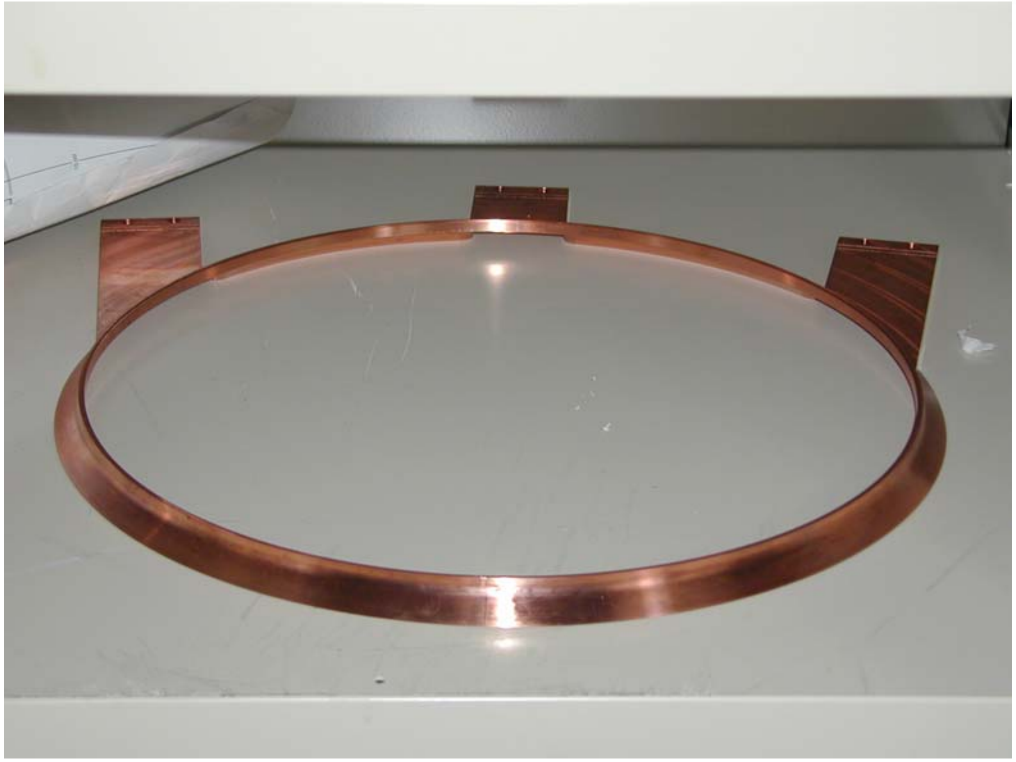
Inductive and charge collecting wire planes

Cathode grid

Ultra-low activity Cu vessel

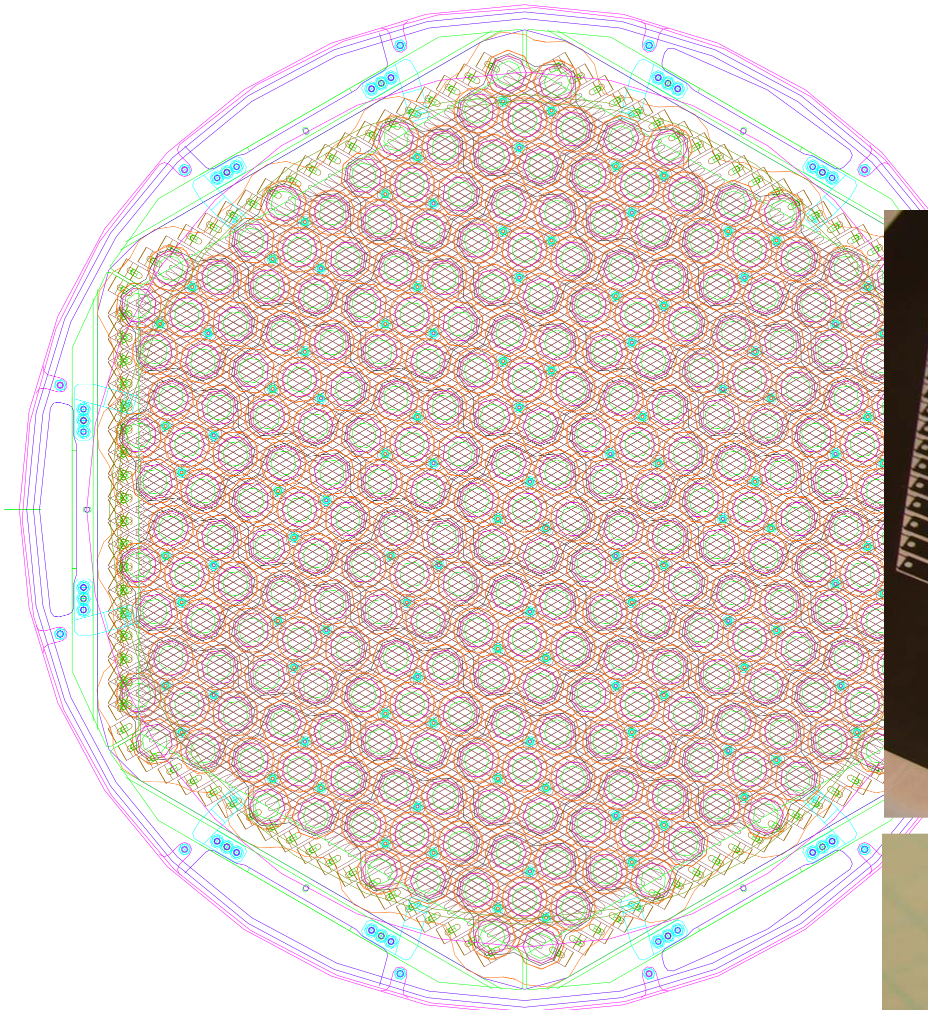
- Very light (~1.5mm thin, ~15kg) to minimize materials
- Low activity copper (shipped from Germany inside a shielded container!)

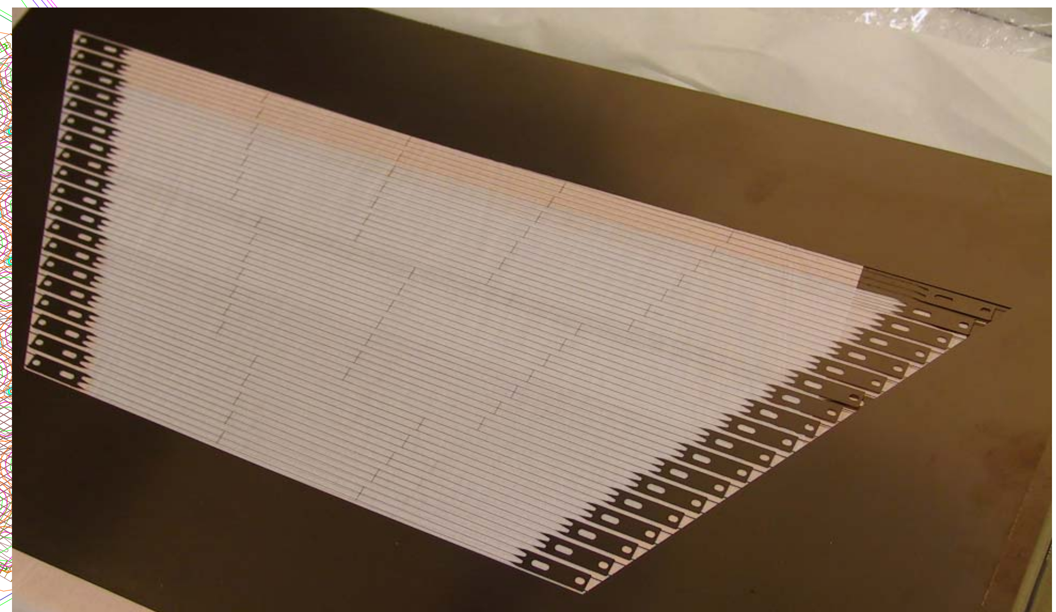


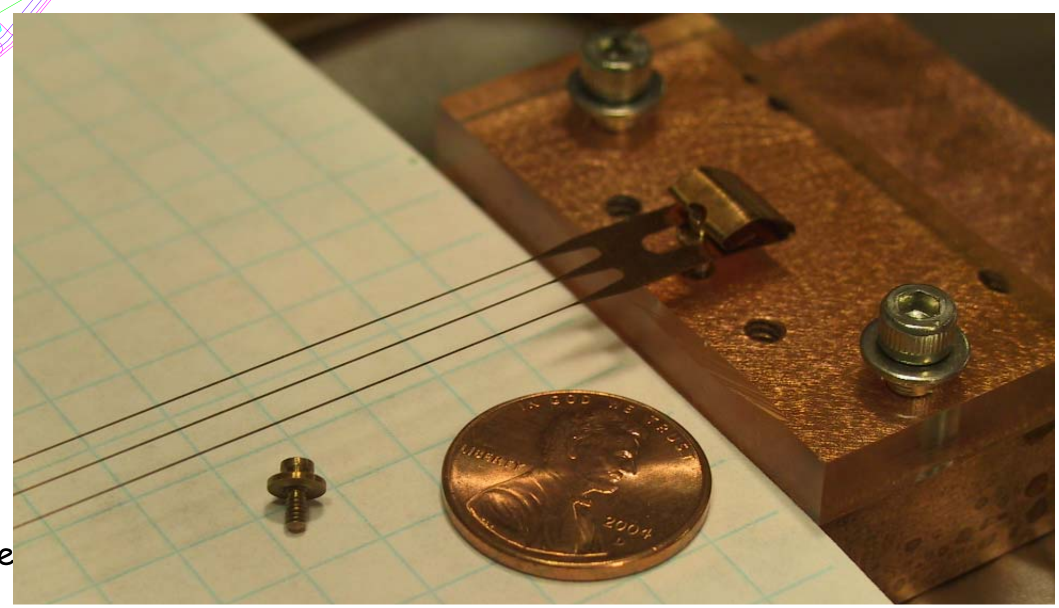


- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)

One readout pancake







~600 “Bare” LAAPD from Advanced Photonix

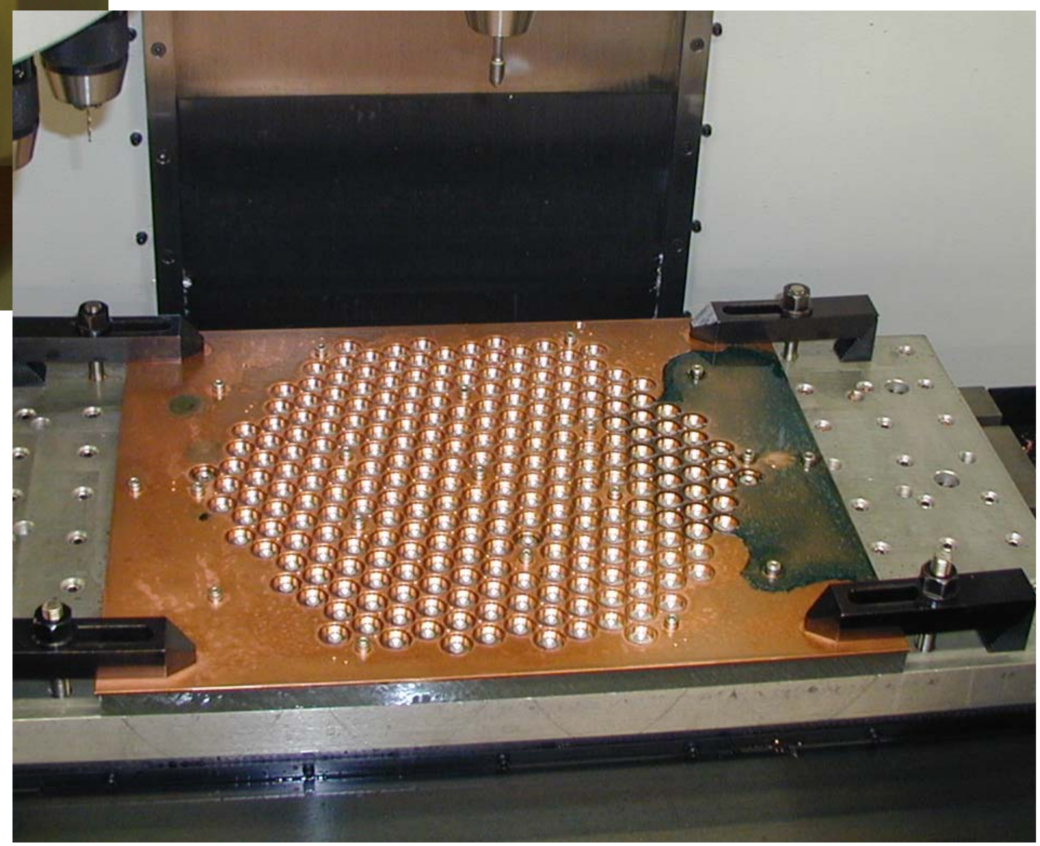
APDs are ideal for our application:

- very clean & light-weight,
- very sensitive to VUV

QE > 1 at 175nm

Gain set at 100-150

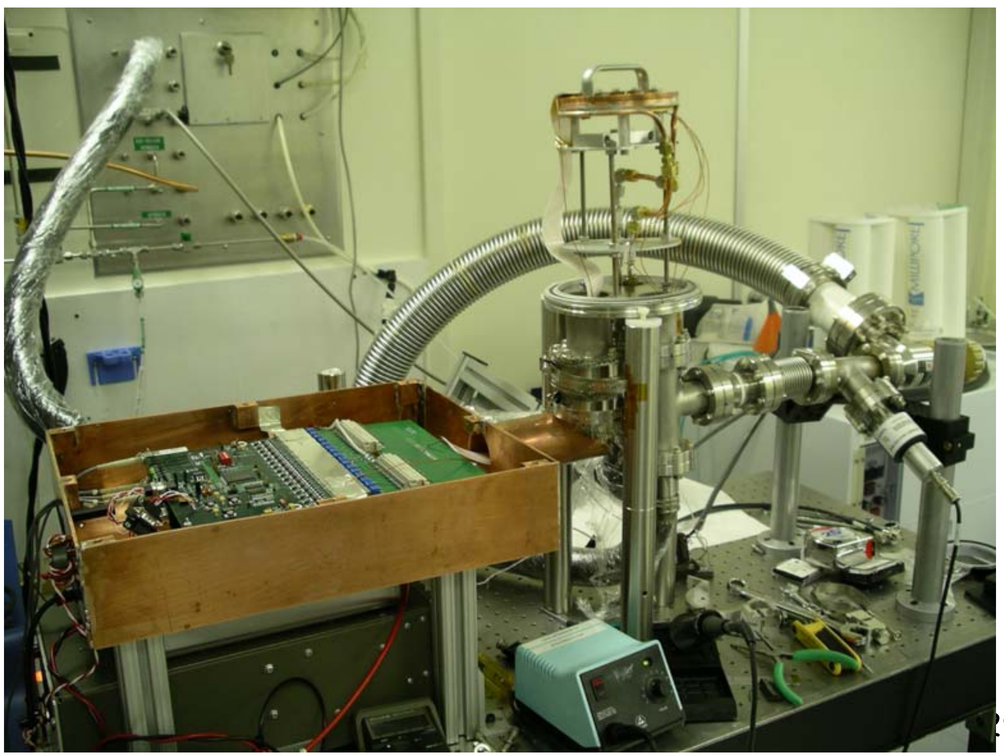
V~1500V
ΔV < ±0.5V
ΔT < ±1K   APD is the driver for temperature stability
Leakage current OK cold

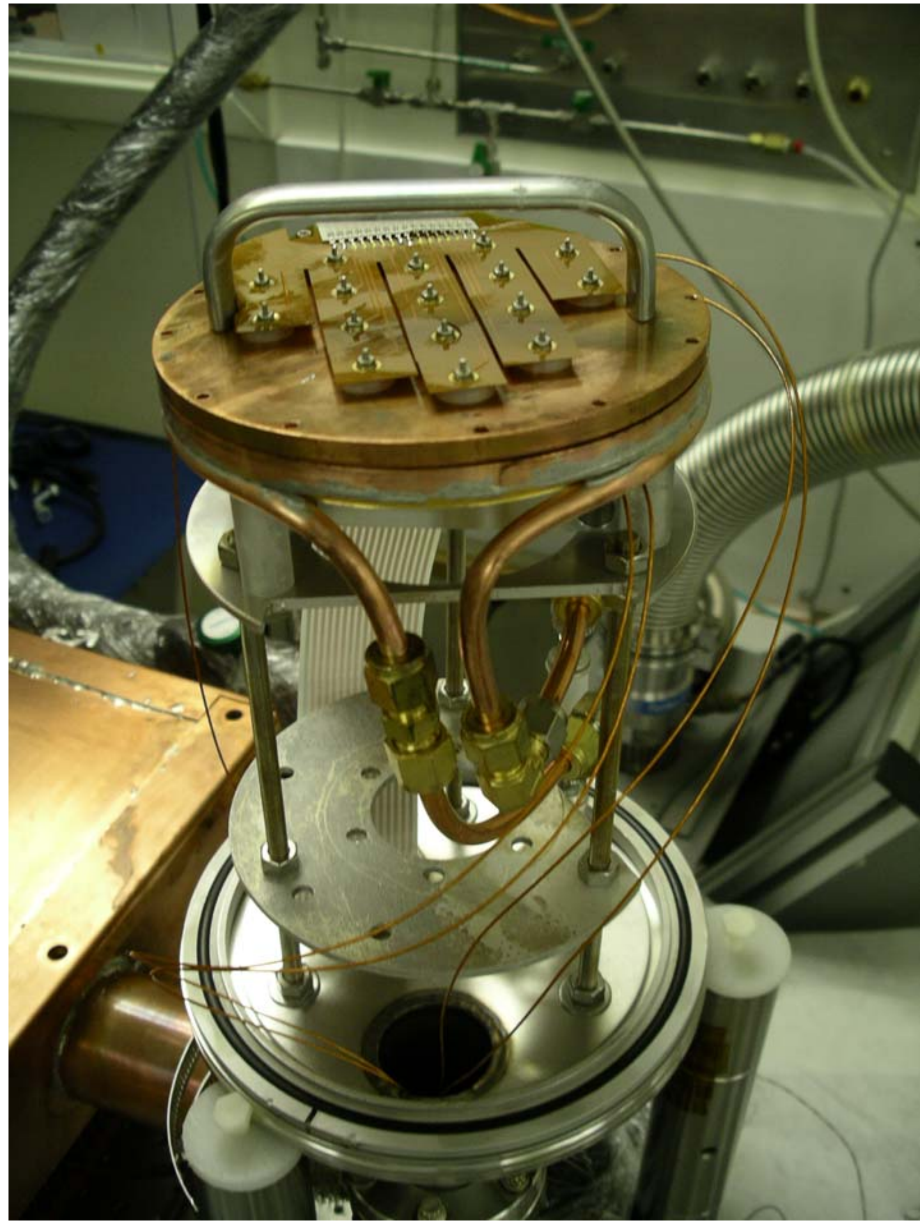


APD testing rig to measure
16 APDs at the time in vacuum
At -100C.

For each APD gain, leakage
current, QE will be measured

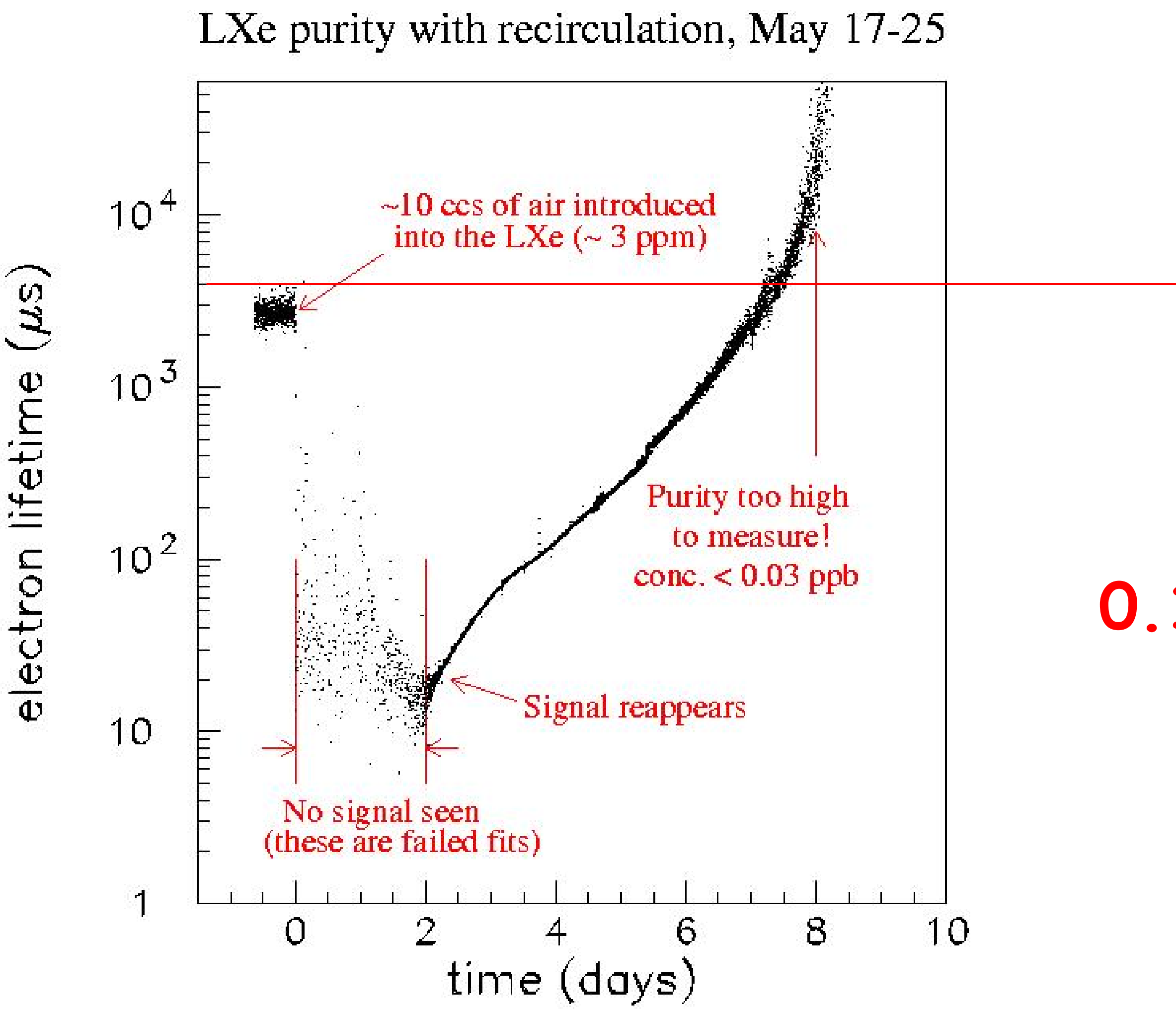
Readout using production
EXO-200 electronics (one card)





~200 APDs tested
receiving ~100 APDs/month

Recirculation essential



EXO-200 goal

l > 400 cm

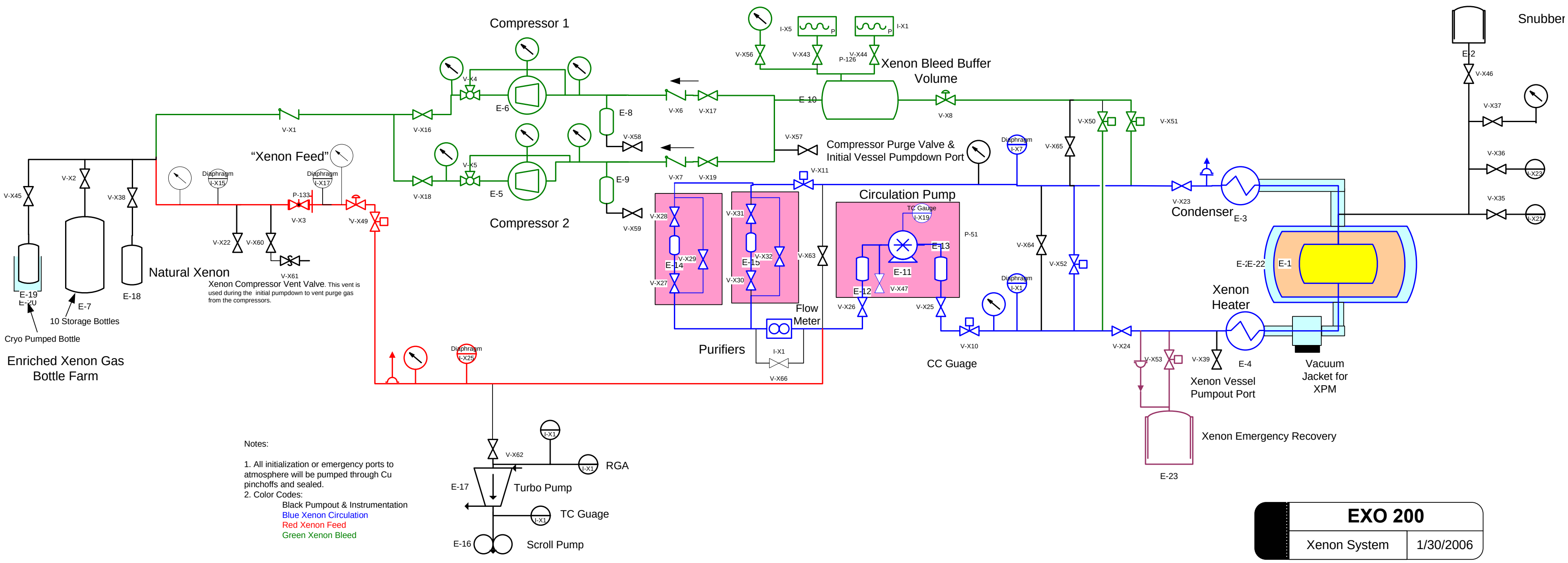
t ~ 4 ms

0.1 ppb O_2 equivalent

Conclusion: common impurities (O_2, H_2O, CO_2) efficiently removed by purifier, recirculation.

Cryogenics/fluidics

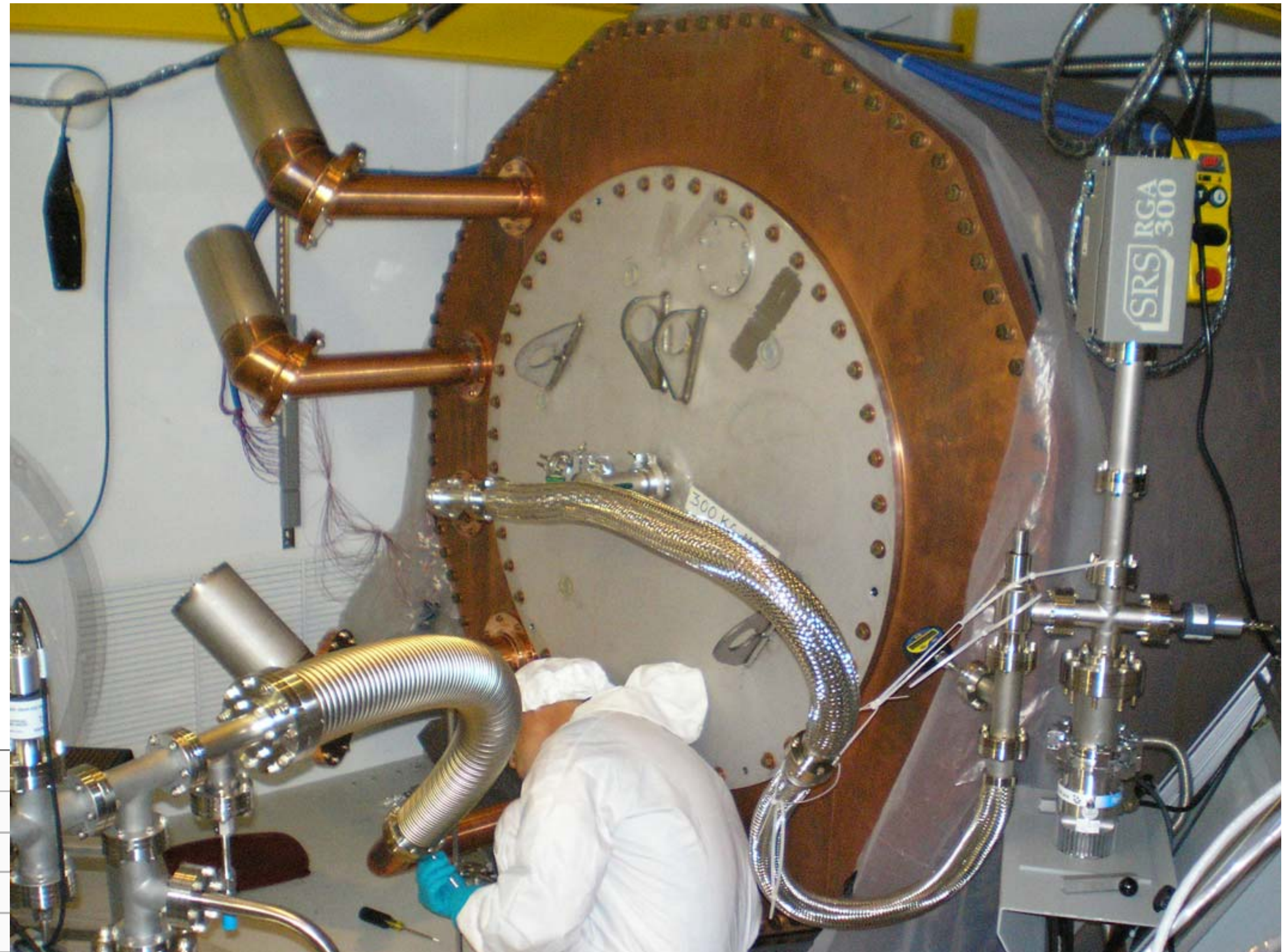
Must maintain ΔP = ±0.3 bar across the thin copper vessel

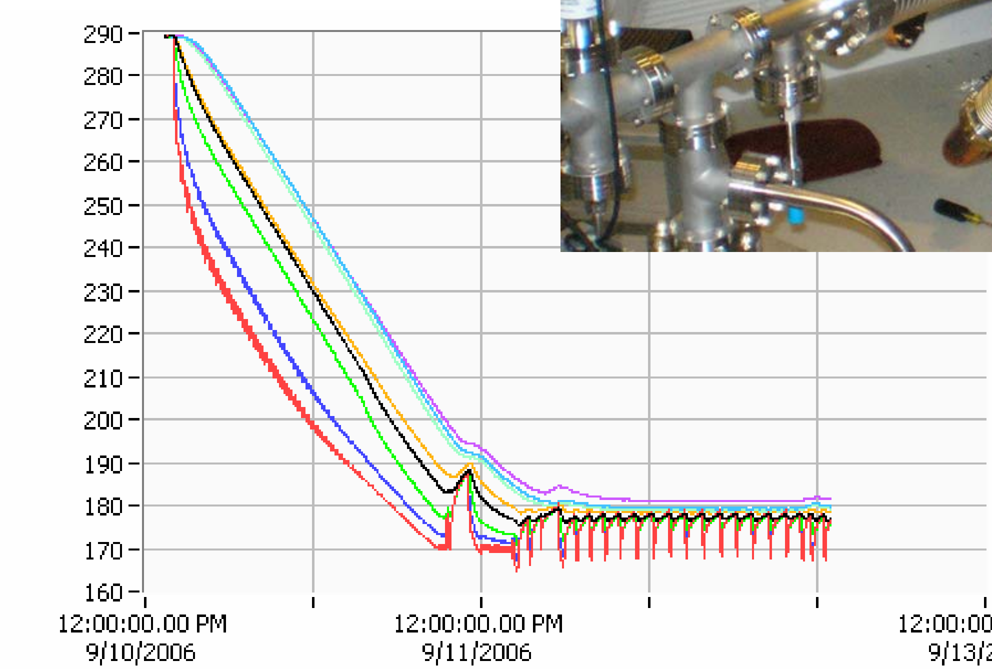


Cryostat was fabricated at SDMS (Grenoble)

First cryostat cooldown

Sept 10-17, 2006





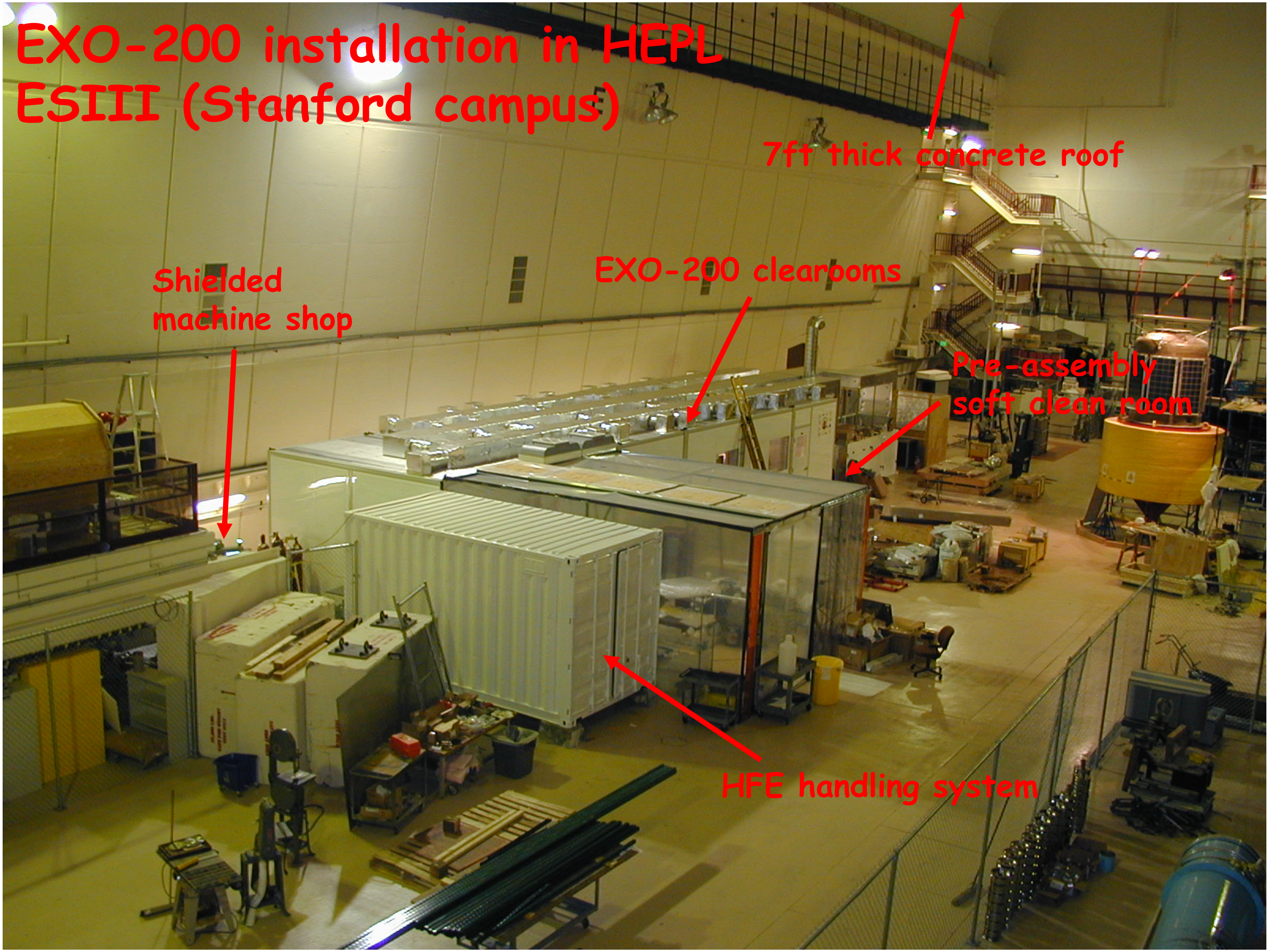
Massive effort on material radioactive qualification using:

- NAA (MIT-Alabama)
- Low background γ-spectroscopy (Neuchatel, Alabama)
- α-counting (Alabama, Stanford, SLAC, Carleton)
- Radon counting (Laurentian)
- High performance GD-MS and ICP-MS (Canadian Inst. Standards)

At present the database of characterized materials includes >100 entries

MC simulation of backgrounds at Alabama and Stanford/SLAC

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


EXO-200 installation in HEPL
ESIII (Stanford campus)
7ft thick concrete roof
Shielded
machine shop
EXO-200 clearooms
Pre-assembly
soft clean room
HFE handling system

Plan for Ba grabbing and tagging R&D

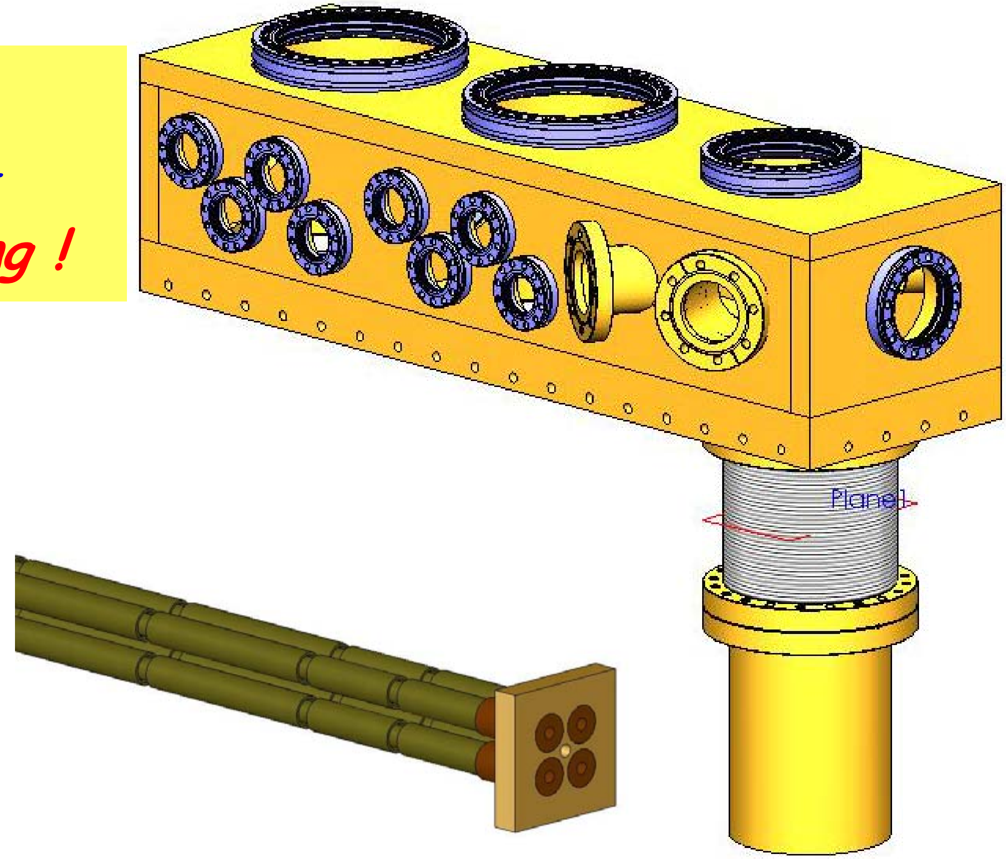
- We have developed the atomic physics and spectroscopy techniques to achieve good quality tagging in presence of some Xe gas
- Gained experience with using He to stabilize traps and counter some of the ill effects of Xe
- Have a scheme to load a linear trap with high efficiency
- Developing a single Ba ion source in LXe for testing
- Have built a linear trap designed for high loading efficiency. Very similar to final device.
- Developing different "grabbing" techniques in parallel:
    - *Xe ice tip*
    - *Starting development of very promising RIS tip*
- Continue R&D on tagging in LXe: high rewards is successful but hard

Done
In progress

RFQ linear trap

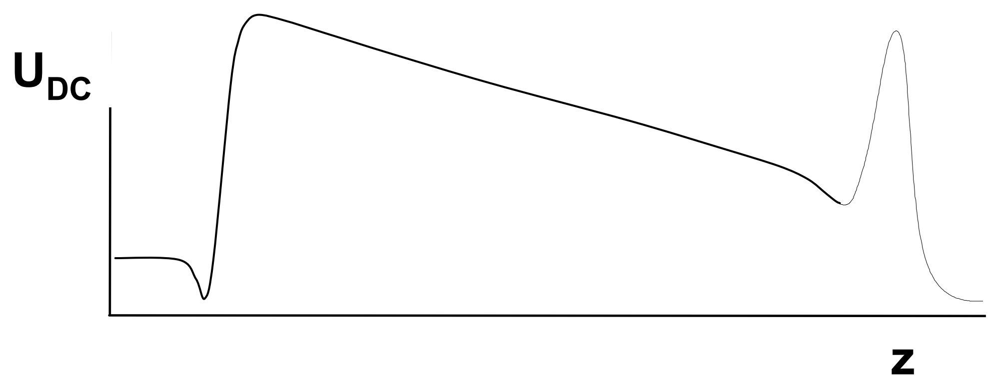
Grabbing/releasing with Ba+

This is built like the final thing !

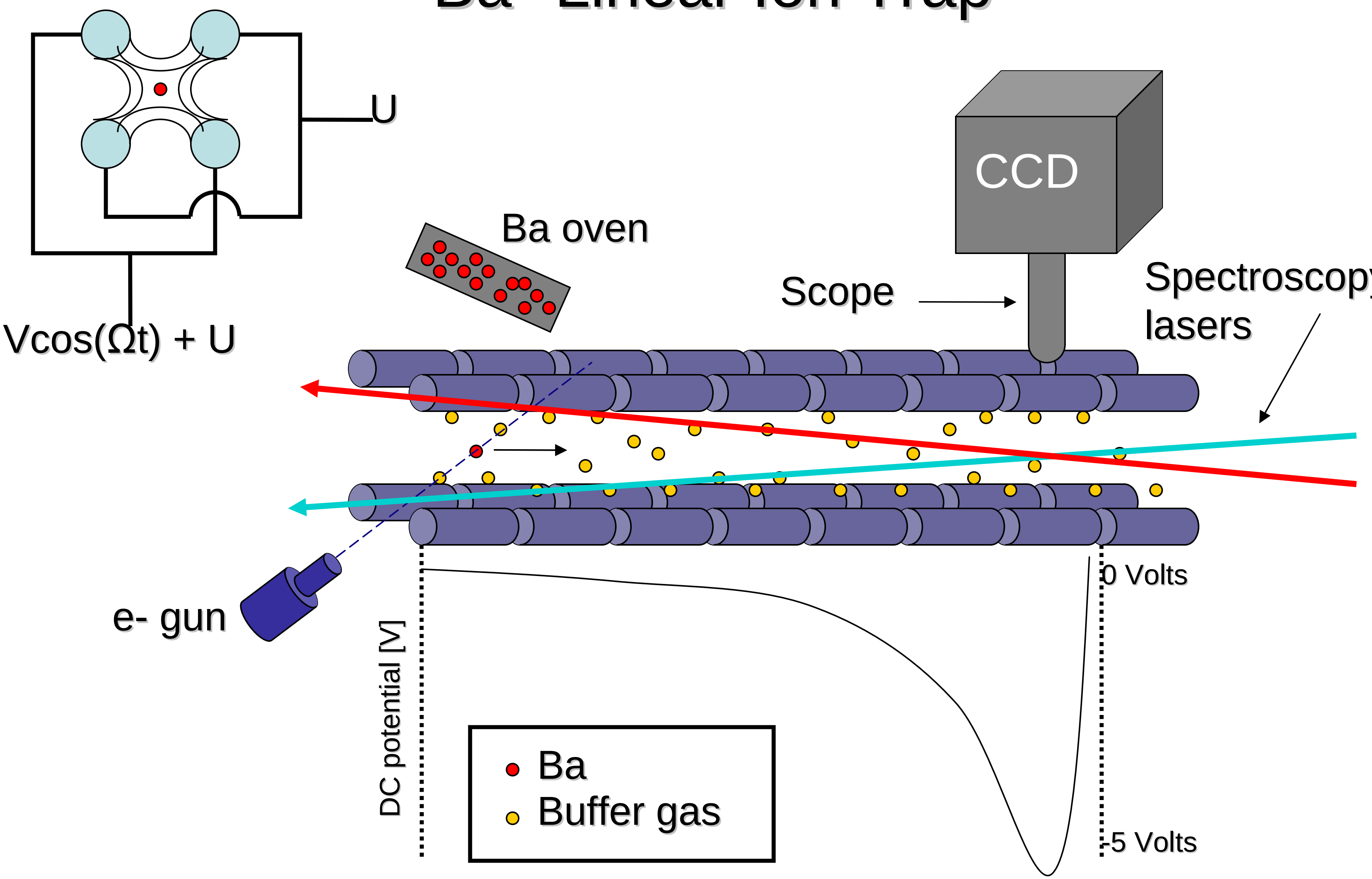


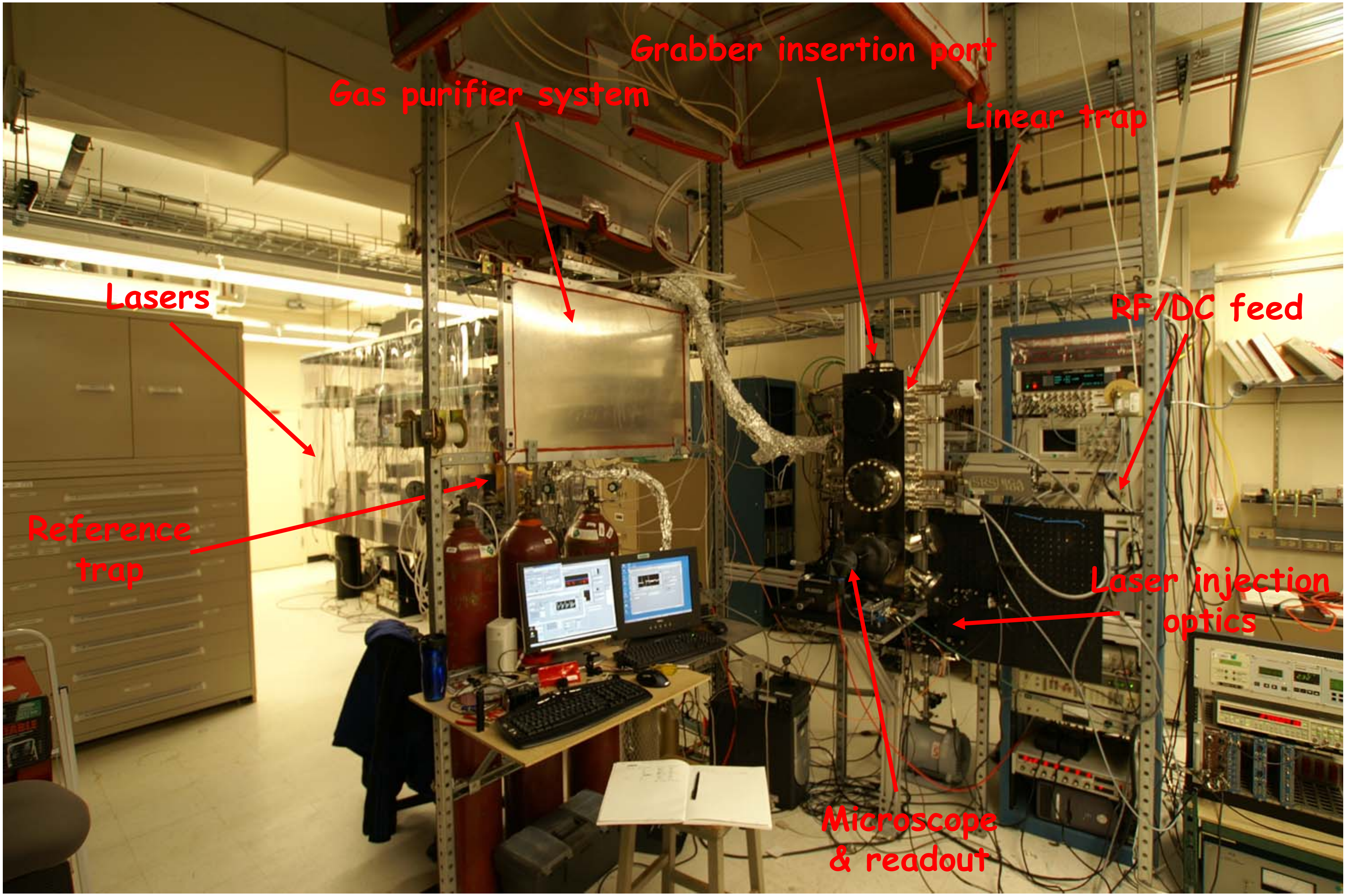
Electrostatic z-field, RF xy field

- *High loading efficiency*
- *Longitudinal gas (He/Ar) cooling*
- *length: 600 mm (~15 segments)*
- *$r_{electrode}$: 20mm, shorter in the trapping region*
- *Can load from tip in Xe/He atmosphere and move ion in laser spectroscopy region*
- *Can "shoot" ion from trap to "grabber probe"*
- *Can load/trap with residual Xe pressure (differentially pumped in different z regions)*

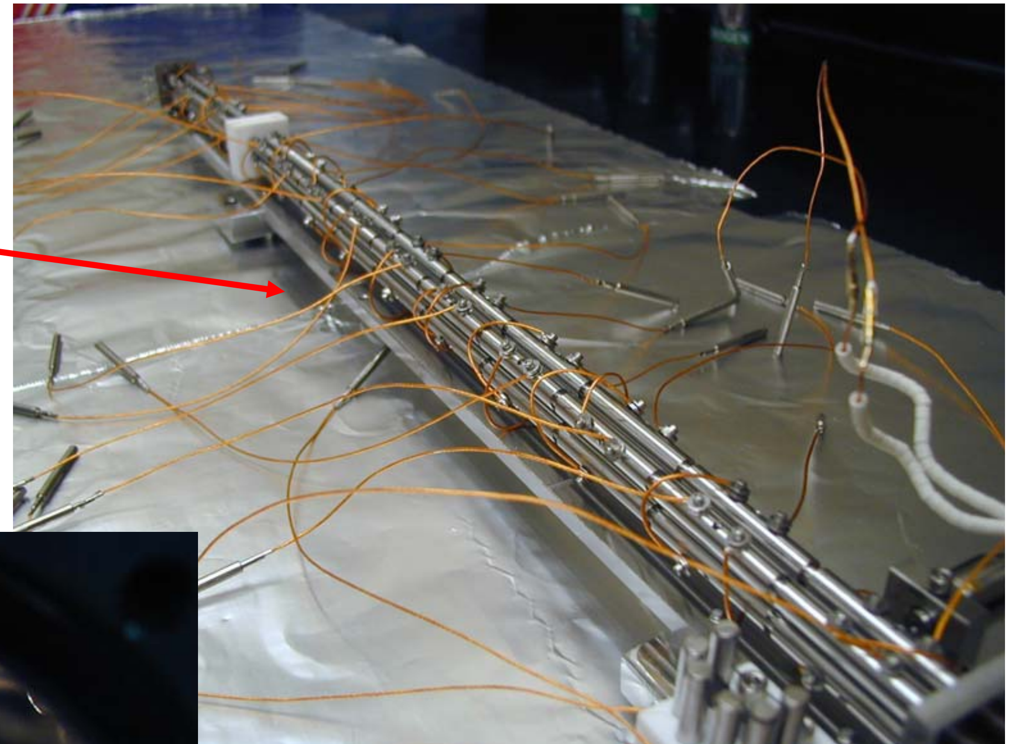


Ba$^+$ Linear Ion Trap



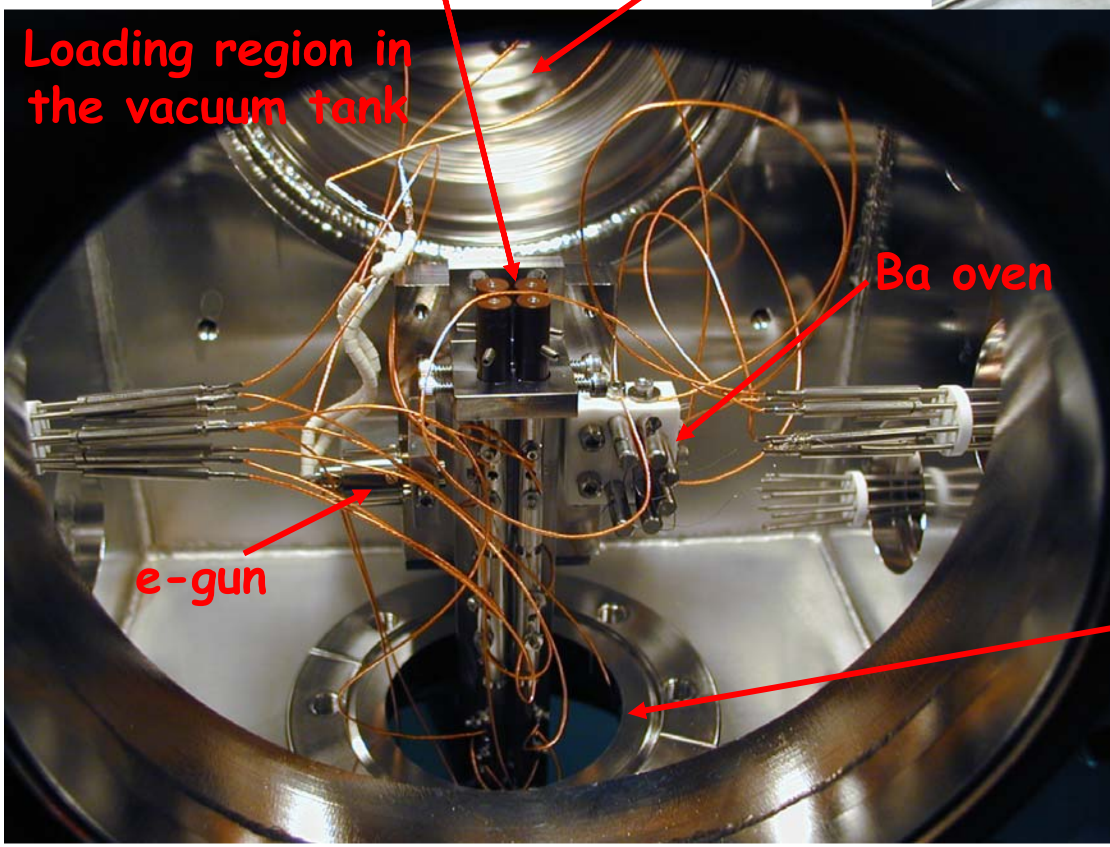

Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference
trap
Laser injection
optics
Microscope
& readout

Electrode structure being prepared

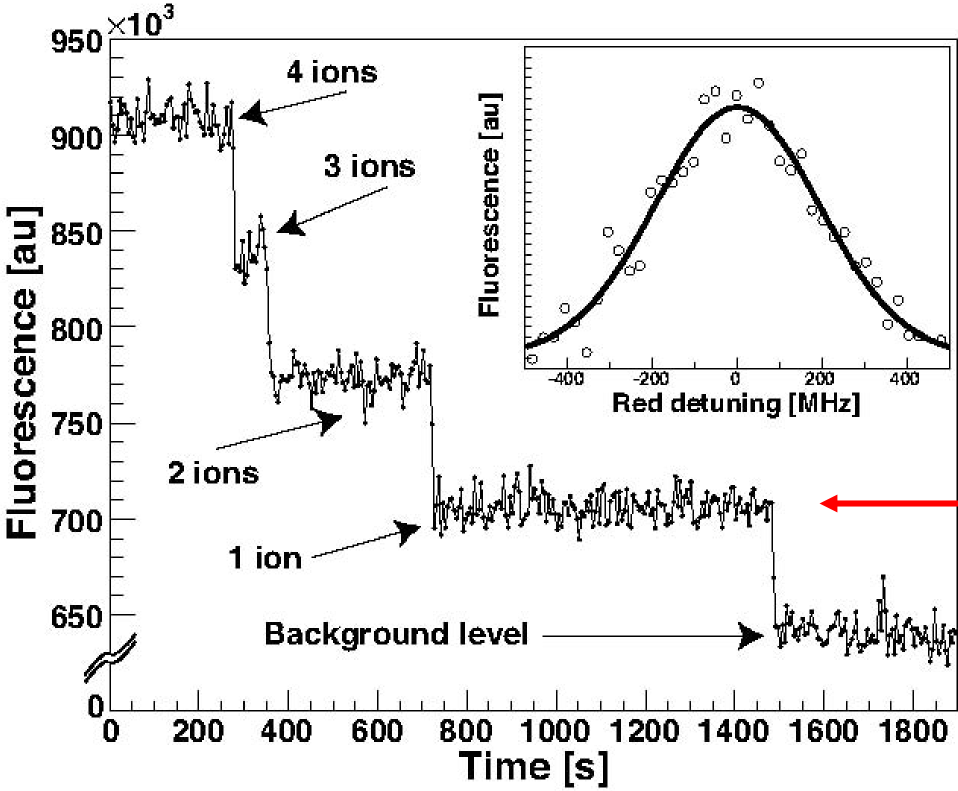


Tip loading access

Main turbo port



Differentially pumped aperture

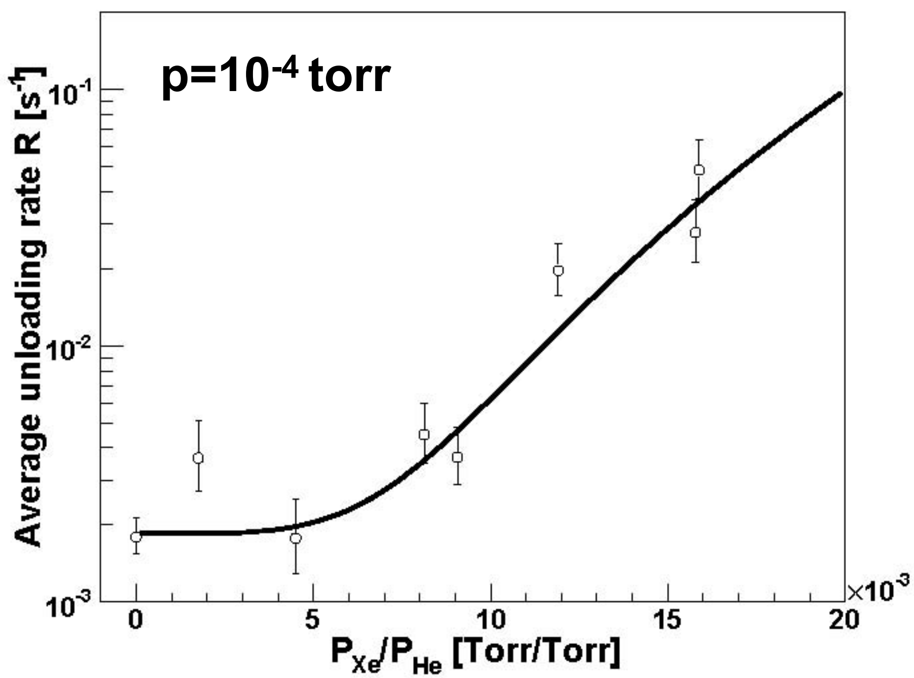


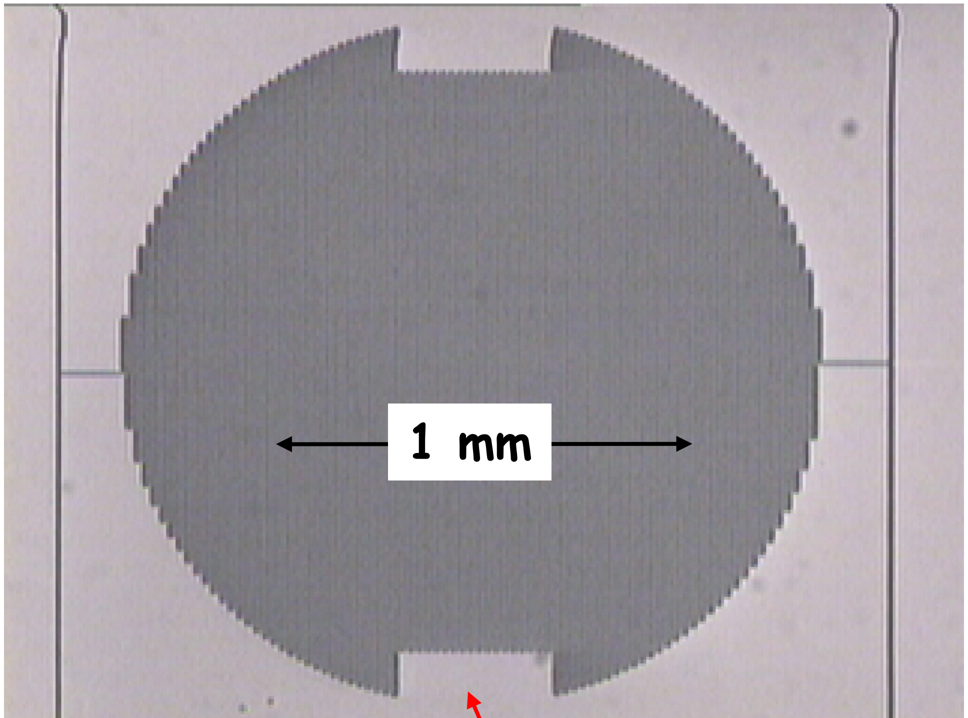
First single ion detection in high pressure gas (He, Ar)

(to be submitted to PRL in the next ~week)

~9σ discimination in 25s integration

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



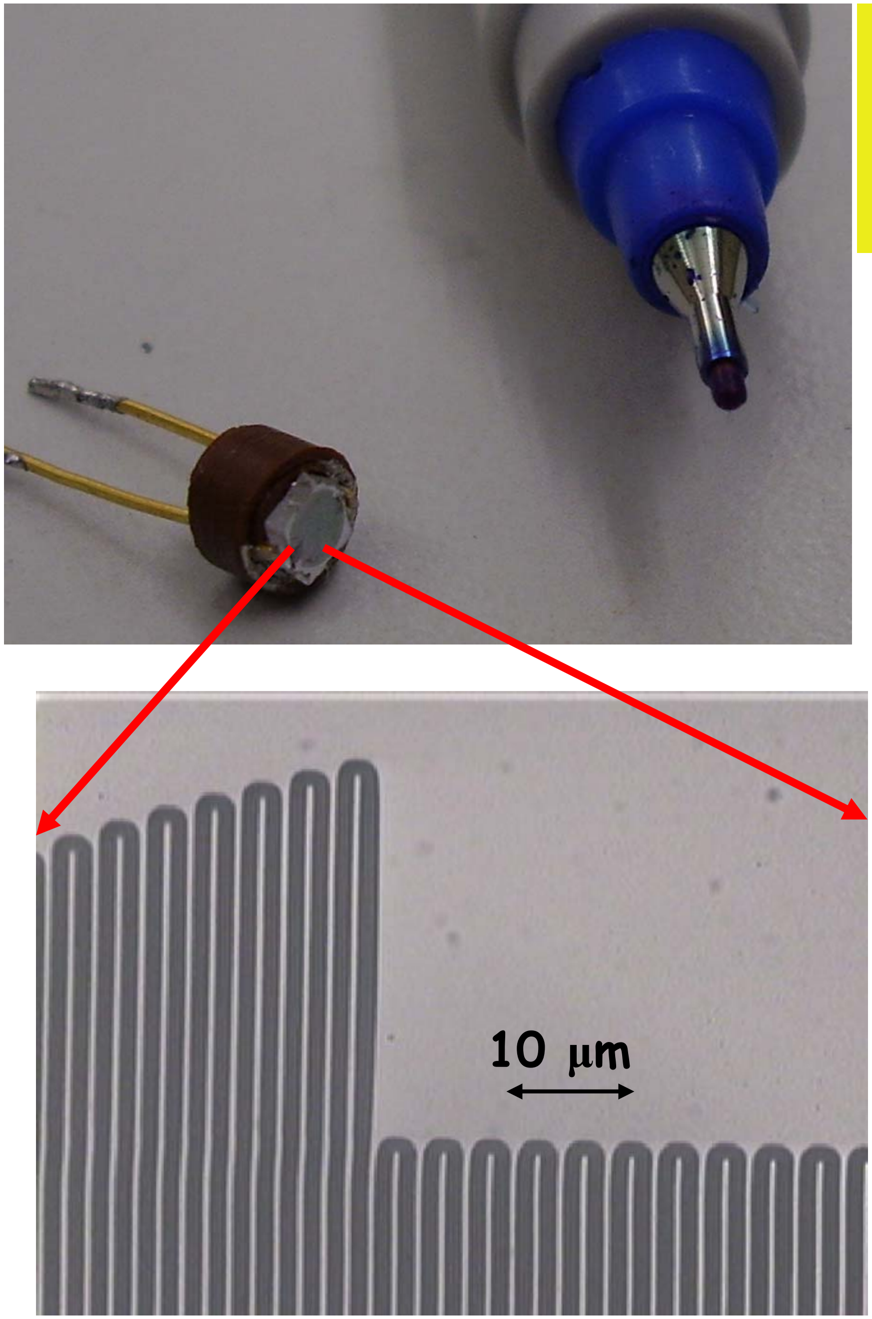


Build a microcapacitor on the tip and detect the chance in ε between liquid and solid Xe

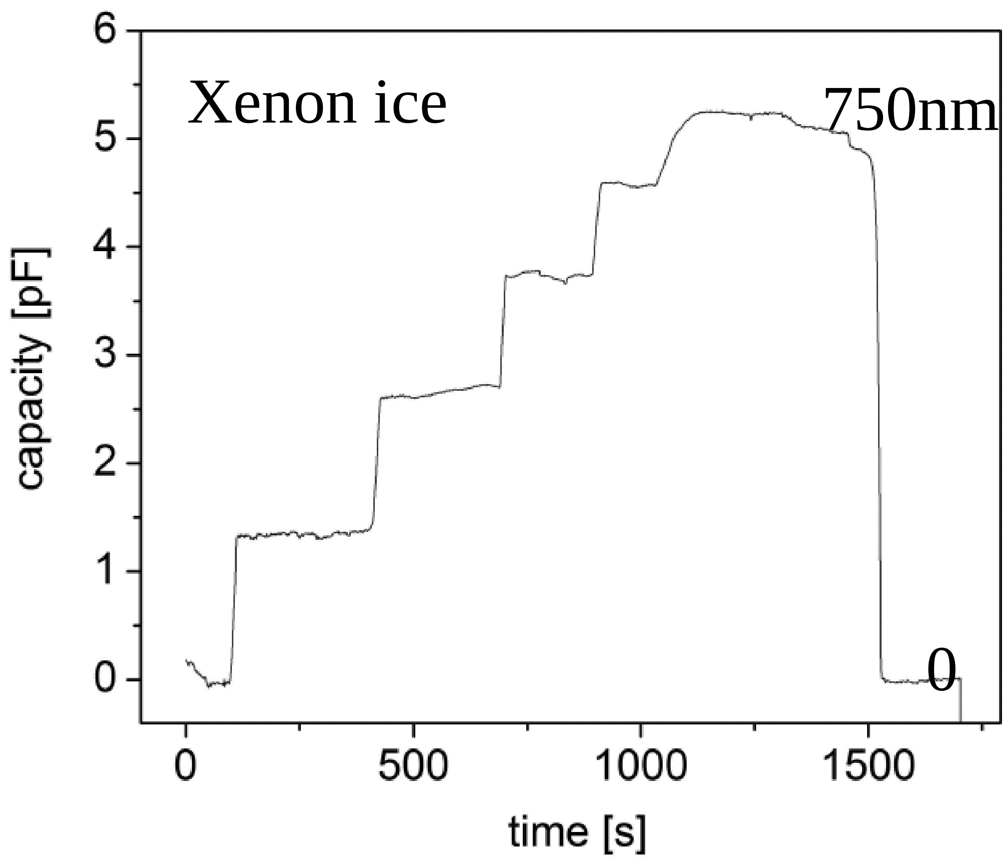
Bonding pads

Measured sensitivity
~10 SXe layers in LXe

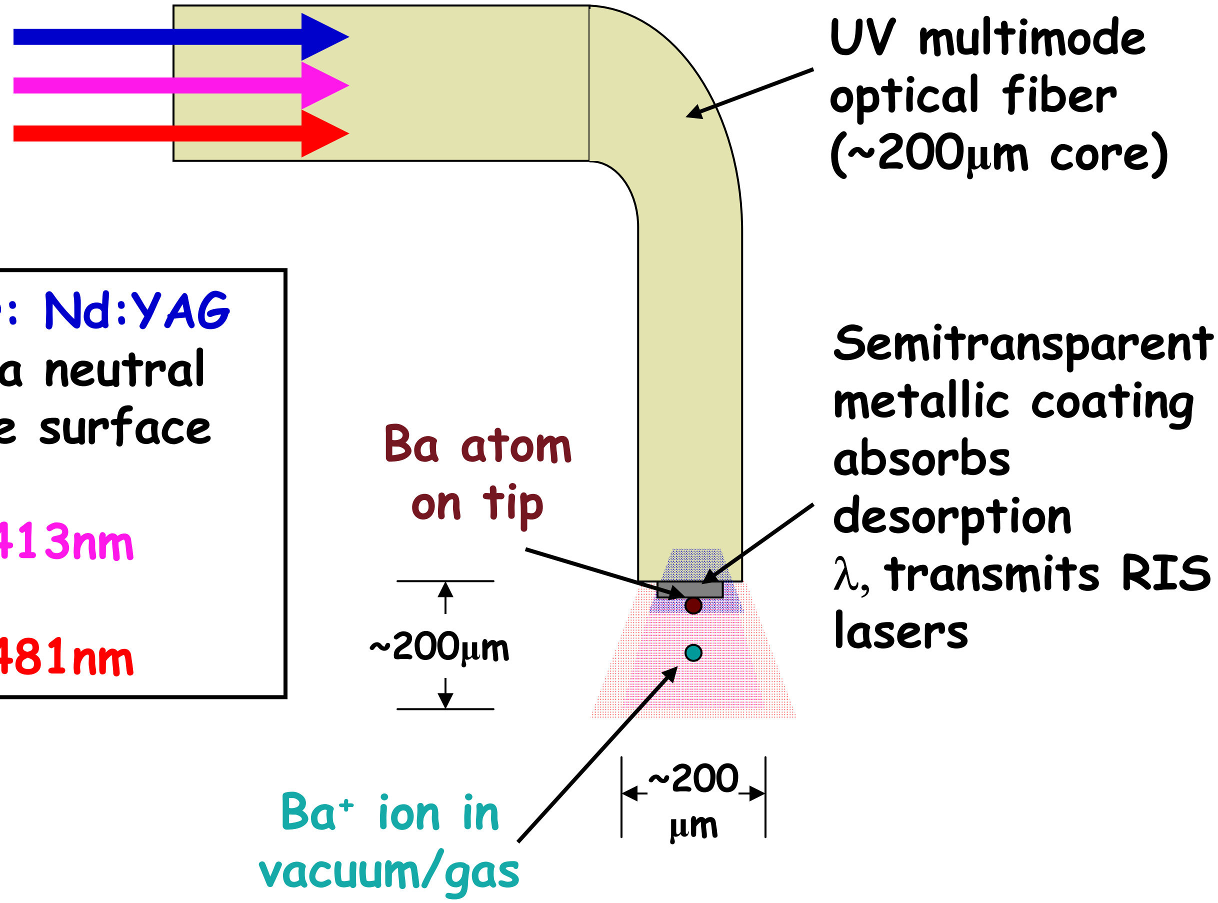
Collect and move to the trap single Ba^+ ions: Use a "dip stick" coated with Xe-ice



How to measure and control thin layers of Xe ice



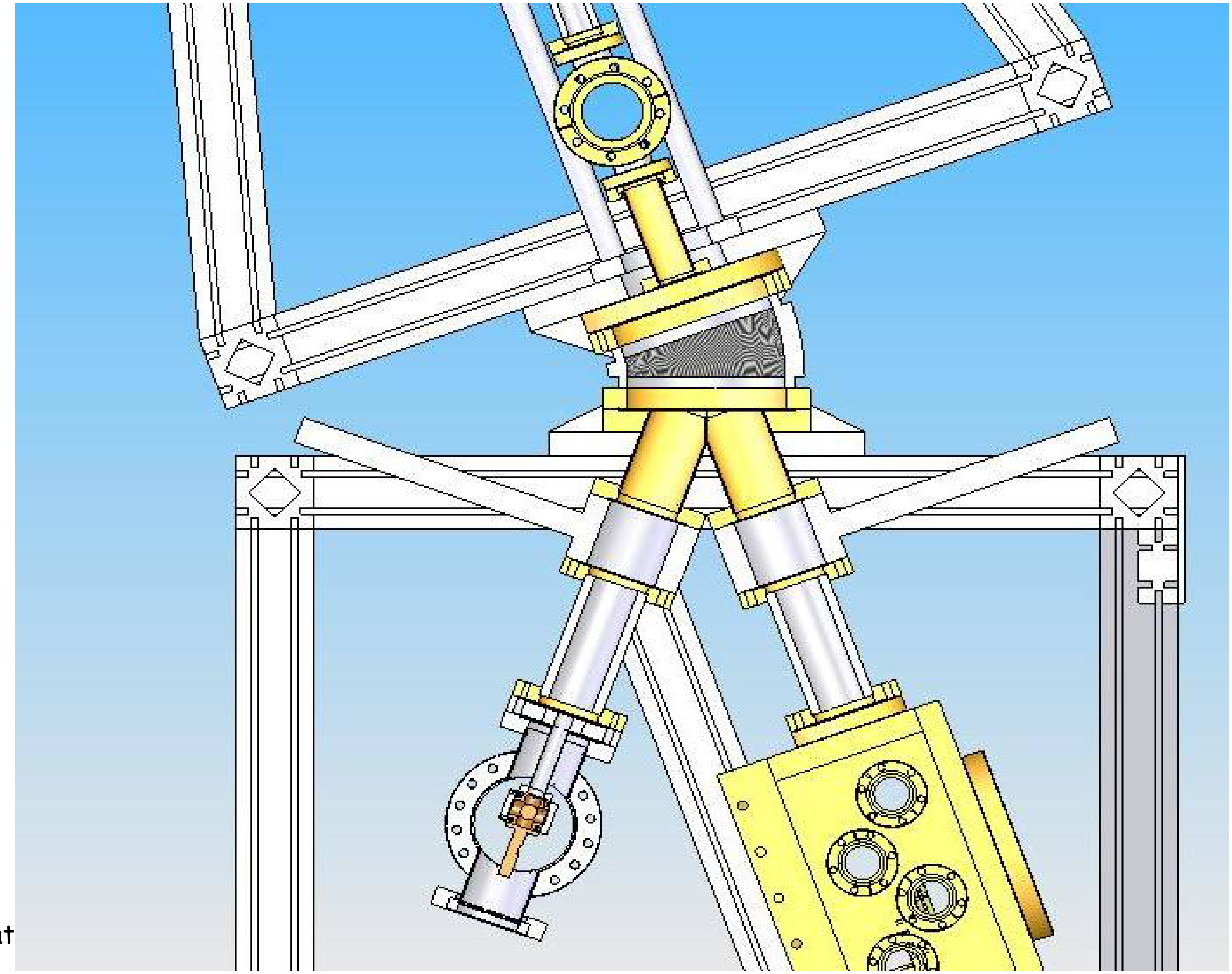
RIS tip



1. Pulsed desorption laser: Nd:YAG
2. ~10ns delay to allow Ba neutral atom to leave the surface
3. -Resonant step: pulsed laser @ 413nm
   -Autoionizing step: pulsed laser @ 481nm

In this case *each step* can be documented to work with high efficiency in the literature !

LXe "fishing" device under construction



Conclusions

Over its glorious history neutrino physics has provided plenty of surprises and has required forays in many different areas of science and technology

EXO really belongs to this tradition!

Isotope enrichment at an unprecedented scale (for science) is a reality

EXO-200 is scheduled to install in the WIPP underground in the Spring-Summer 2007

Ba tagging for EXO is using bag of tricks borrowed from nuclear and particle physics, AMO and surface science

Stay tuned for results!