The elusive Neutrino: how double beta decay and the EXO experiment may help unlock its secrets

Andreas Piepke
University of Alabama

Why is this neutrino physics an interesting subject?

Deals with conceptually clear questions.
Neutrino physics allows us to study “new physics”.

It is a field driven by experiment. The findings have sometimes been surprising:
- Neutrinos are massive
- Flavor mixing is large

It impacts multiple disciplines:
- particle physics
- cosmology
- astrophysics

It is even entering the realm of application:
- reactor monitoring, plutonium diversion

Particle physics:

Neutrino masses are zero in the minimal Standard Model.

Extensions of the SM naturally give $m_\nu \neq 0$.

Discovery of neutrino oscillations requires adjustments to the SM. How to build neutrino masses into the Langrangian?

Open questions:

- What are the values of the neutrino masses?
- Are neutrinos their own anti-particles?
- Is CP-violated for neutrinos?
- What are the values of the 3 mixing angle and CP phases (one for Dirac three for Majorana)?

Astrophysics and Cosmology:

Neutrinos are the only probes allowing us to “look” inside our Sun and Supernovae.

Universe contains 330 ν/cm^3 (410 γ/cm^3), from Big Bang.
m_ν important ingredient for Dark Matter problem.
$\Omega_\nu / \Omega_B < 0.3$ (WMAP) $\quad \Omega_\nu / \Omega_B < 3.0$ (Tritium decay)
$\Omega_B = 0.047 \;\; 0.006$, $\Omega_M = 0.29 \pm 0.07$ and $\Omega_{Tot} = 1.02 \pm 0.02$

Laboratory neutrino mass measurements important consistency check that *can* be done.

Observations indicate an unequal number of baryons and anti-baryons in the universe. To the best of our understanding all structures in the universe are made from matter:

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.21 \pm 0.16) \cdot 10^{-10}$$

From big bang nucleo-synthesis predicting abundance of D, ^{3}He, ^{4}He and ^{7}Li and the anisotropy of cosmic ray background radiation.

Baryons and anti-baryons should have been created in equal numbers in big bang → baryon anti-baryon imbalance must have been created dynamically. This hypothesis is called *baryogenesis*. Imbalance poses a puzzle for particle physics.

The SM of particle physics contains the ingredients to explain the imbalance (Sakharov):

- Baryon number violation
- C and CP violation
- Out of equilibrium dynamics

S. Davidson, E. Nardi, Y. Nir, arXiv:0.802.2962

Although these ingredients exist no mechanism strong enough to explain the observed asymmetry has been found.

The observed degree of CP-violation for quarks is insufficient by many orders of magnitude. New physics such as e.g. CP violation for leptons is needed.

A mechanism called *leptogenesis* has been proposed to solve this problem: heavy right handed Majorana ν (inert in SM; weak singlets) provide CP violation. Their decay in early universe created a lepton number asymmetry that is transferred into a baryon asymmetry by the so-called sphaleron process. This scenario requires Majorana neutrinos and thus double beta decay. Some models require: $0.05 \text{ eV} \leq m_3 \leq 0.15 \text{ eV}$.

Perhaps all matter, even our own bodies, are made of the ashes of heavy neutrinos that decayed in the early universe!

What do we know about neutrino mass?

Discovery of neutrino flavor oscillations showed that neutrinos are massive. Oscillation observed with:

- Solar and reactor neutrinos and anti-neutrinos:
- Δm^2_{21}, $m_1 < m_2$, $\sin^2\Theta_{12}$

- Atmospheric and accelerator neutrinos: Δm^2_{23}, $\sin^2\Theta_{23}$

- LSND oscillation evidence not observed in MiniBooNE

Surprisingly small number of parameters suffices to describe variety of experiments using different methods and energies.

How do we weigh a microscopic particle?

- Neutrino flavor oscillations.

$$U_{\ell i}^2 \qquad \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

- Measurement of energy distribution of charged Leptons in weak decays.

$$\langle m \rangle_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

- Neutrino-less double decay (Dirac versus Majorana).

$$\langle m \rangle_{\beta\beta}^2 = \left| \sum_i \eta_i U_{ei}^2 m_i \right|^2$$

It turns out that nuclear double beta decay is the only practical way to distinguish Dirac from Majorana neutrinos.

What do we know about neutrino mass assuming three flavors?

From experiments using solar ν and reactor $\bar{\nu}$:

$$\boxed{\begin{aligned}\Delta m^2_{21} &= \Delta m^2_{sol} = \left(7.67^{+0.16}_{-0.19}\right)\cdot 10^{-5}\ \mathrm{eV}^2 \\ \sin^2\theta_{12} &= \sin^2\theta_{sol} = 0.312^{+0.019}_{-0.018}\end{aligned}}$$

From experiments using atmospheric and accelerator ν:

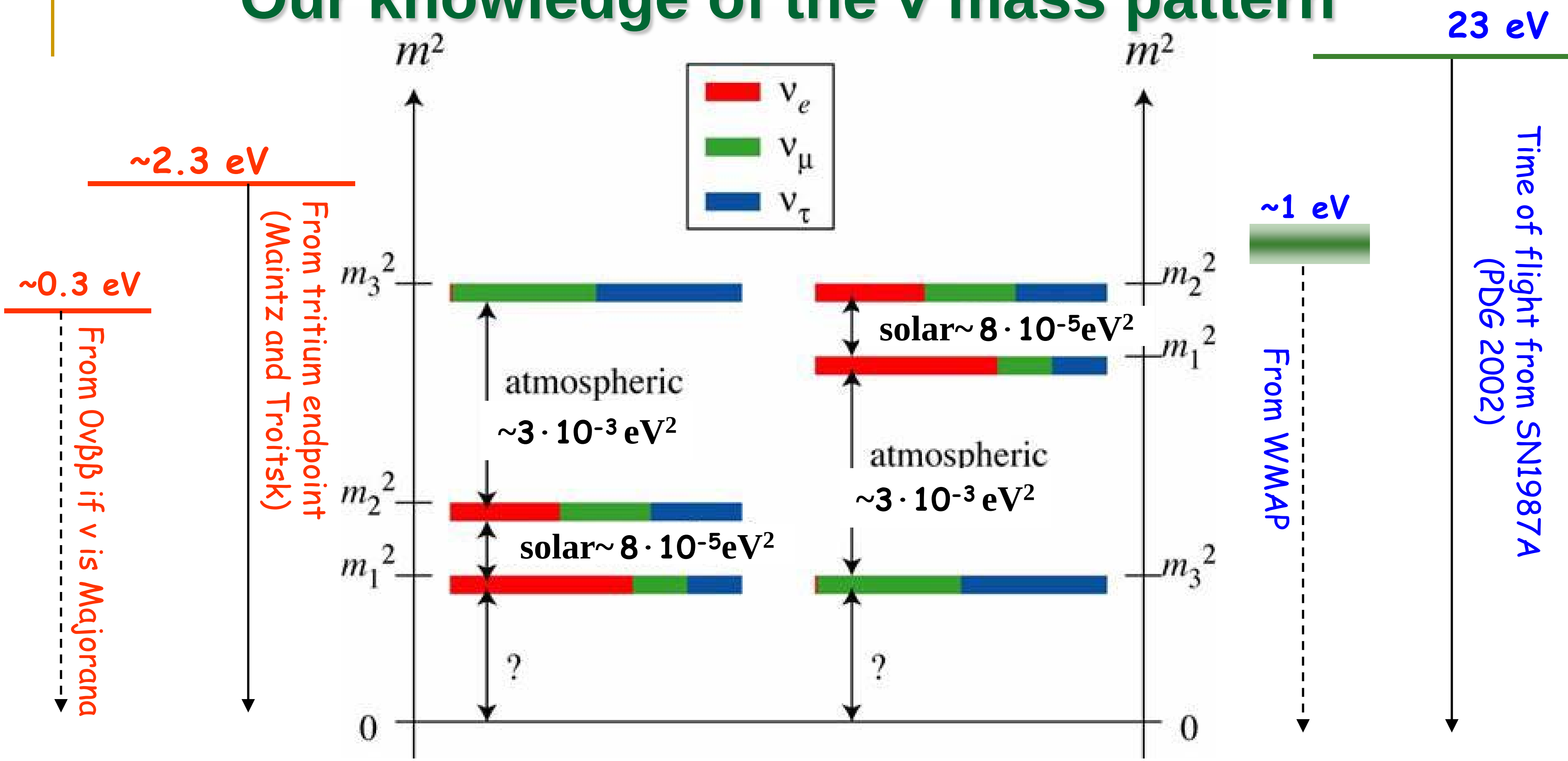
$$\boxed{\begin{aligned}\Delta m^2_{32} &= \Delta m^2_{atm} = \pm\left(2.39^{+0.11}_{-0.08}\right)\cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} &= \sin^2\theta_{atm} = 0.466^{+0.073}_{-0.058}\end{aligned}}$$

From experiments using reactor $\bar{\nu}$:

$$\boxed{\sin^2\theta_{13} = 0.016 \pm 0.01}$$

G.L. Fogli et al., arXiv:0805:2517v3

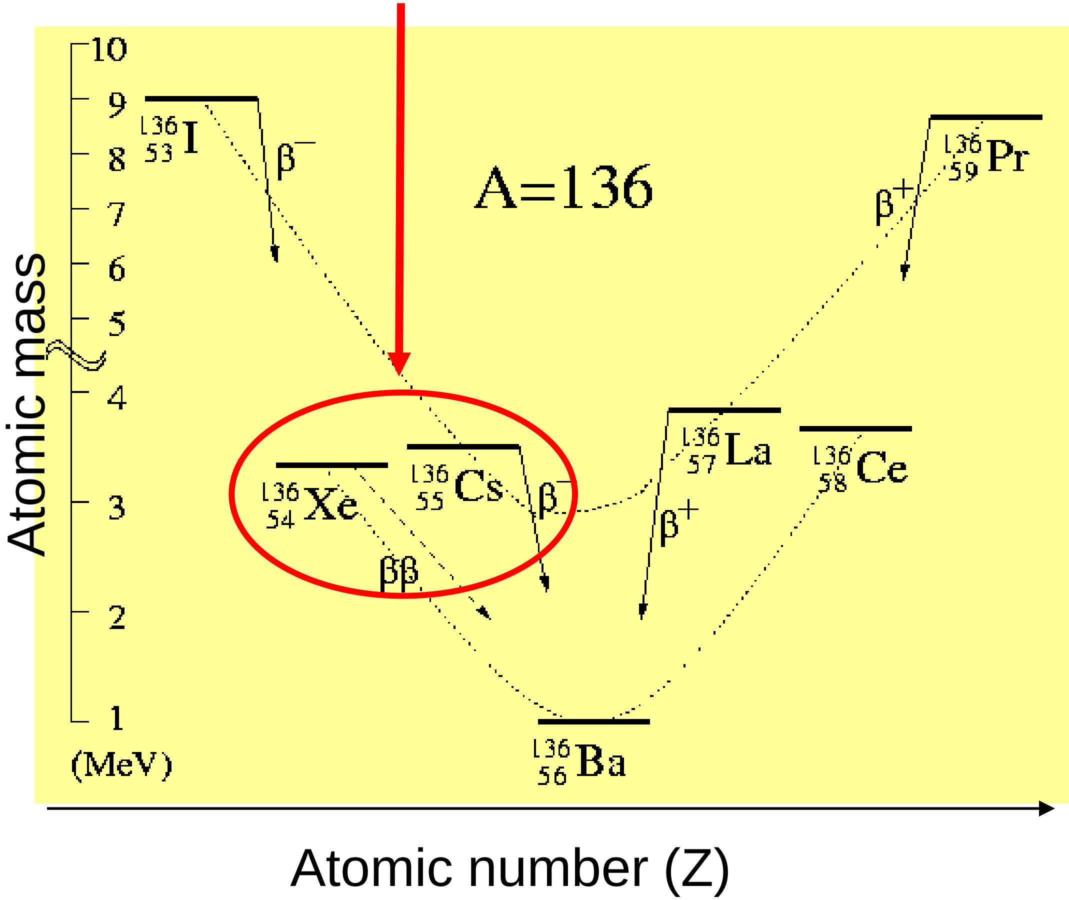
Our knowledge of the ν mass pattern



The measurement of the absolute mass scale, θ_{13} and the choice of hierarchy are the next big challenges in neutrino physics

Double-beta decay:

second-order process,
detectable if first order β-decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Add nuclear matrix element calculations to make such measurements quantitative. Decay rates given as:

ββ2ν-mode:

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} \cdot |\, M^{2\nu}\, |^2$$

Cancellation of contributions of virtual intermediate states.
Measured for many nuclides.
Not directly relevant to ββ0ν, calibrates nuclear models

ββ0ν-mode:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Nuclear matrix element by calculations. Uncertainty?
spread of all values in literature: factor ~3.

Rodin, Faessler, Simkovic and Vogel (Nucl. Phys. A793 (2007)213) studied differences of different calculations.

Most nuclear models use 13 parameters which are tuned to reproduce certain observables (nuclear excitation patterns, giant resonance, quenching of the axial-vector coupling constant,…)

In QRPA and RQRPA calculations $\beta\beta 2\nu$– and $\beta\beta 0\nu$– rates depend on normalized particle-particle interaction strength g_{pp}. g_{pp} fixed to value reproducing $\beta\beta 2\nu$–rate stabilizes calculations.

Consistent choice of input parameters and elimination of clearly off-the-charts calculations results in a 30% spread of nuclear calculations.

Decay rate translates into effective Majorana mass. Requires knowledge of nuclear physics quantities.

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle^2 = \left| \sum_i \eta_i \, U^2_{ei} \, m_i \right|^2$$

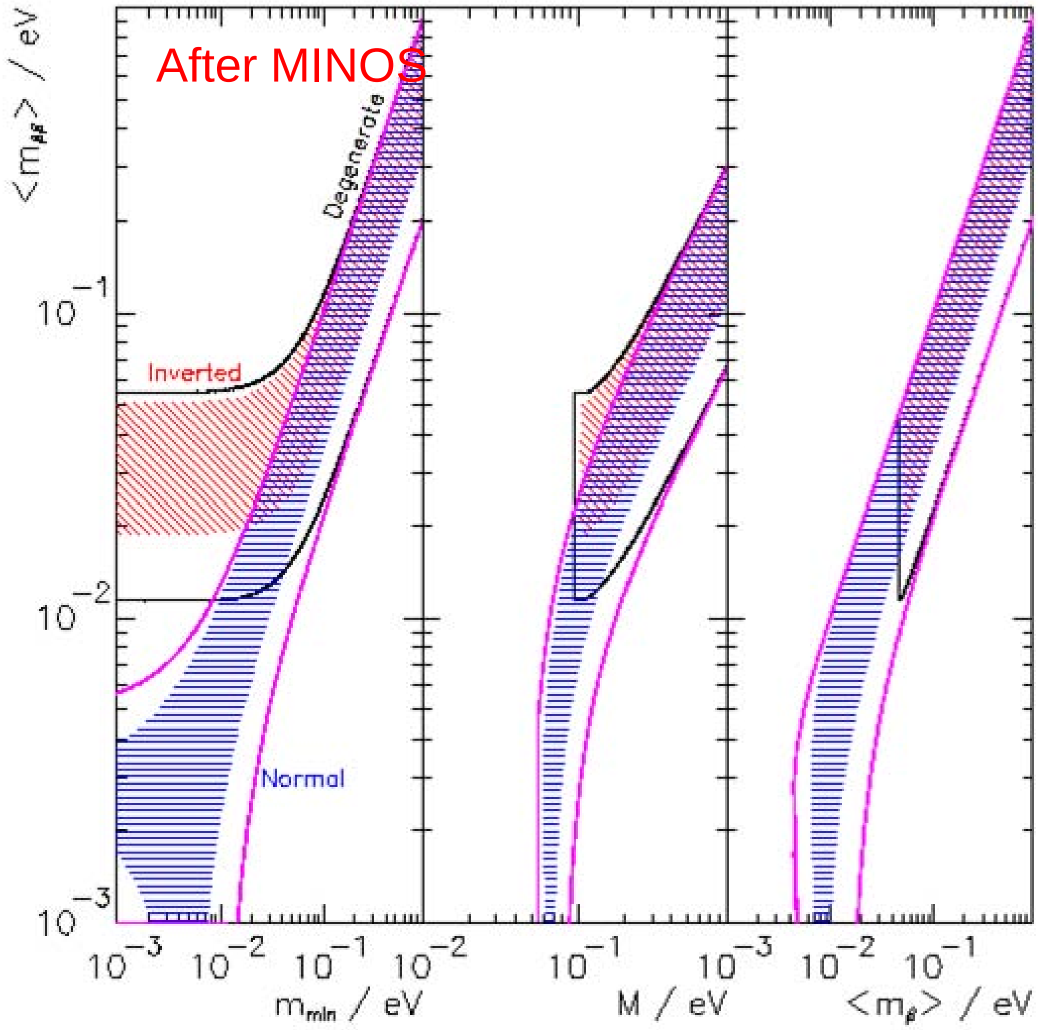
CP-phases: 1

Elements upper row of MNS-matrix

Neutrino masses

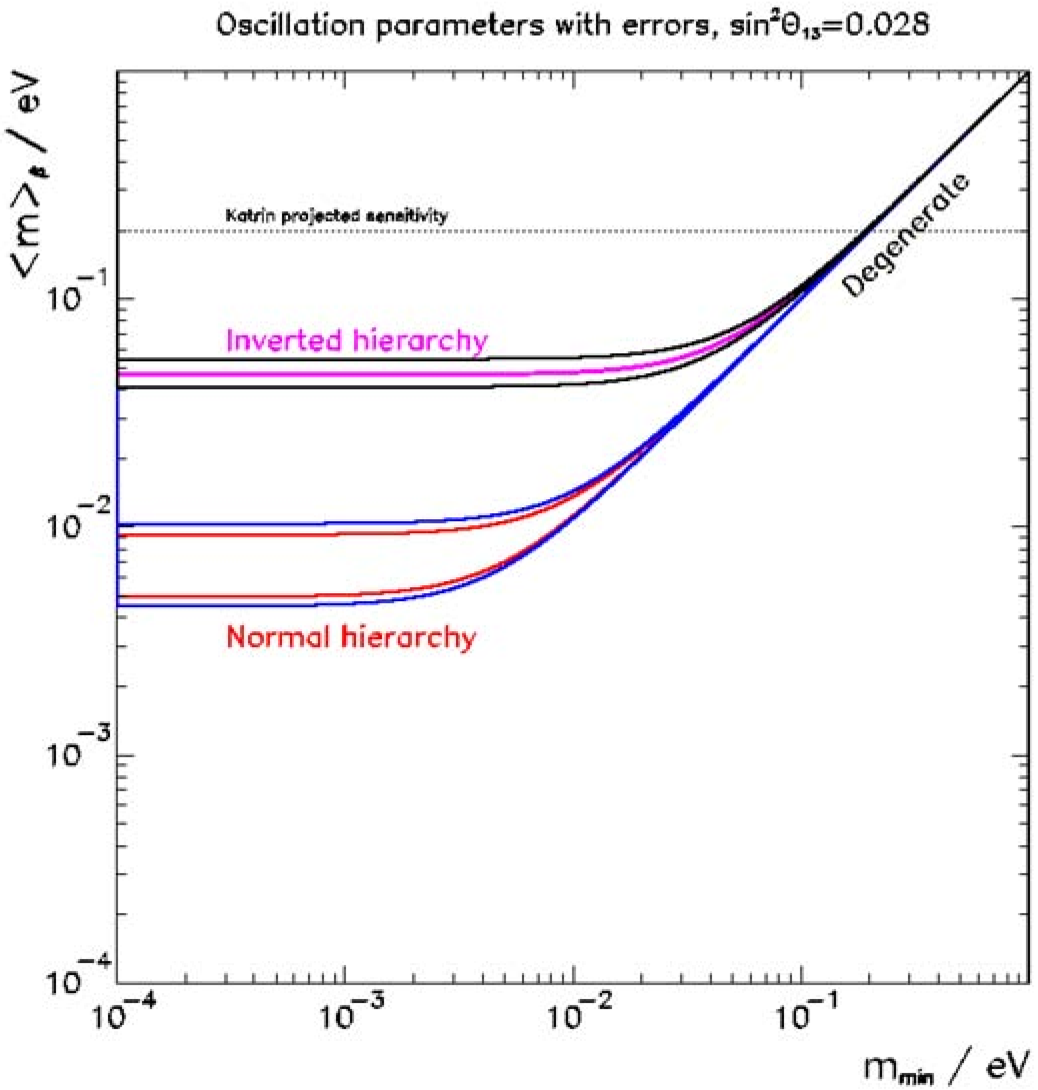
CP-phases can lead to cancellation. But how much? Replace masses by two possible choices of minimal mass m_1 or m_3 and add knowledge of mixing and mass splitting from oscillations.

The problem to be solved:



^{76}Ge : 2.2 10^{28} y
^{100}Mo: 5.9 10^{27} y
^{136}Xe : 1.1 10^{28} y
Rodin et al. PRC68 (2003)

95% CL

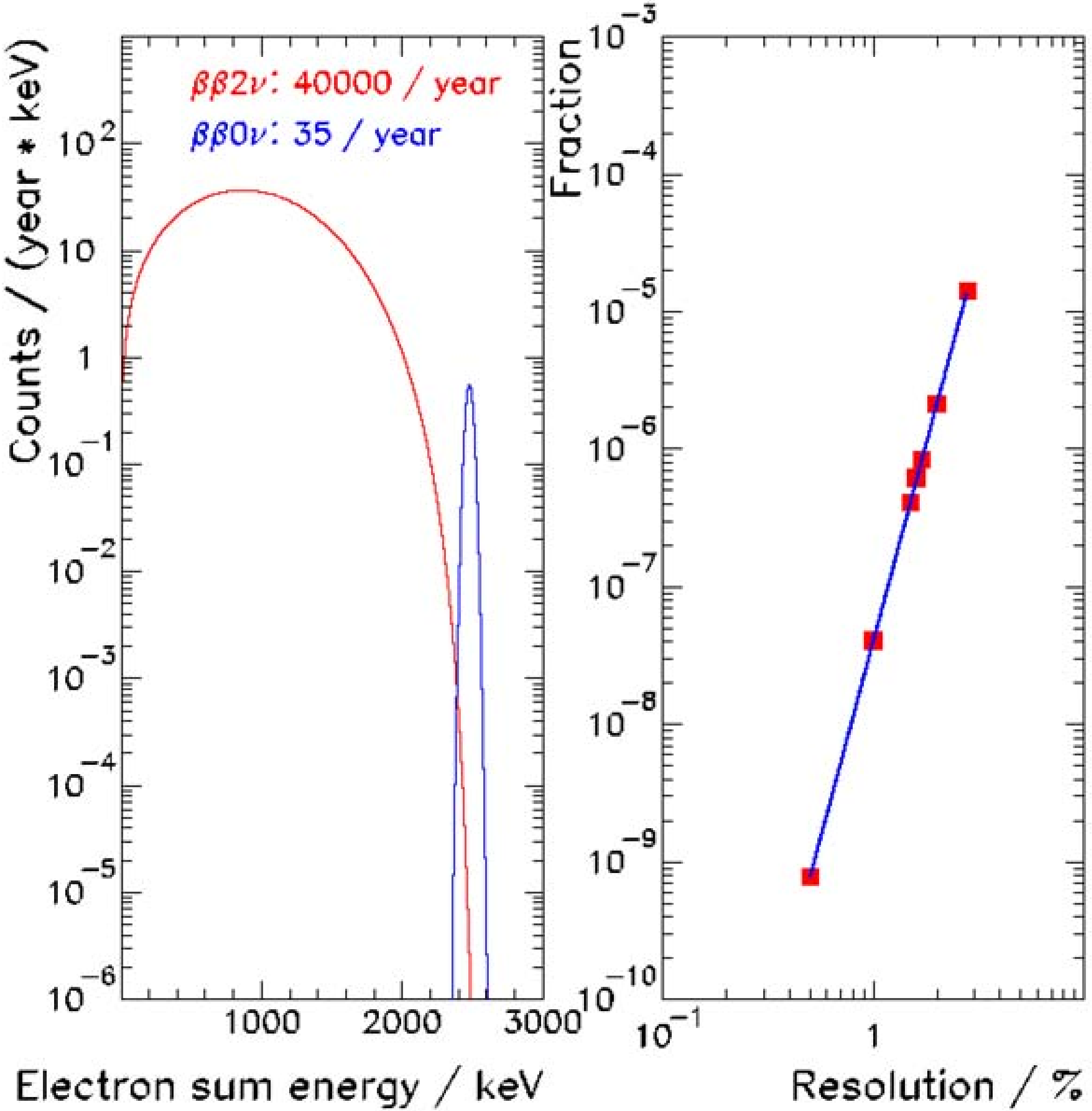


Observable in β–end-pint experiments (KATRIN):

$$\langle m_{\beta} \rangle^2 = \sum_i |U_{ei}|^2 m_i^2$$

Conceptually clean but limited reach.

Decay modes distinguished by measurement of electron sum energy.



Left: expected spectra for 200 kg ^{136}Xe in one year.

Right: leakage of $\beta\beta2\nu$-events into $\beta\beta0\nu$–analysis interval. 5.8th power!

How much isotope is needed to observe a 10 meV neutrino mass? This is very expensive.

Nuclear transition	g_A	$M^{2\nu}_{exp}$ [MeV^{-1}]	$M'^{0\nu}$ RQRPA	QRPA	σ_{exp}	$T^{0\nu}_{1/2}$ (50 meV) [yrs]	
$^{76}Ge \to {}^{76}Se$	1.25	0.15 ± 0.006	3.92(0.12)	4.51(0.17)	±0.05	$0.86^{+0.08}_{-0.07}$	10^{27}
	1.00	0.23 ± 0.01	3.16(0.15)	3.85(0.14)	±0.06	$1.10^{+0.13}_{-0.13}$	10^{27}
$^{82}Se \to {}^{82}Kr$	1.25	0.10 ± 0.009	3.49(0.15)	4.02(0.15)	±0.08	$2.14^{+0.37}_{-0.26}$	10^{26}
	1.00	0.16 ± 0.008	2.91(0.09)	3.29(0.12)	±0.08	$3.50^{+0.46}_{-0.36}$	10^{26}
$^{96}Zr \to {}^{96}Mo$	1.25	$0.11^{+0.03}_{-0.06}$	1.20(0.14)	1.12(0.03)	$^{+0.12}_{-0.24}$	$0.98^{+1.1}_{-0.31}$	10^{27}
	1.00	$0.17^{+0.05}_{-0.1}$	1.12(0.11)	1.21(0.07)	$^{+0.12}_{-0.25}$	$1.12^{+1.5}_{-0.35}$	10^{27}
$^{100}Mo \to {}^{100}Ru$	1.25	0.22 ± 0.01	2.78(0.19)	3.34(0.19)	±0.02	$2.37^{+0.33}_{-0.32}$	10^{26}
	1.00	0.34 ± 0.015	2.30(0.12)	2.71(0.14)	±0.02	$3.55^{+0.45}_{-0.39}$	10^{26}
$^{116}Cd \to {}^{116}Sn$	1.25	0.12 ± 0.006	2.42(0.16)	2.74(0.19)	±0.02	$2.86^{+0.50}_{-0.39}$	10^{26}
	1.00	0.19 ± 0.009	1.96(0.13)	2.18(0.16)	±0.02	$4.30^{+0.71}_{-0.63}$	10^{26}
$^{128}Te \to {}^{128}Xe$	1.25	0.034 ± 0.012	3.23(0.12)	3.64(0.13)	±0.09	$4.53^{+0.44}_{-0.38}$	10^{27}
	1.00	0.053 ± 0.02	2.51(0.08)	2.85(0.08)	±0.10	$7.35^{+1.1}_{-0.88}$	10^{27}
$^{130}Te \to {}^{130}Xe$	1.25	$0.036^{+0.013}_{-0.009}$	2.95(0.12)	3.26(0.12)	$^{+0.26}_{-0.08}$	$2.16^{+0.33}_{-0.16}$	10^{26}
	1.00	$0.056^{+0.05}_{-0.15}$	2.34(0.07)	2.59(0.06)	$^{+0.27}_{-0.08}$	$3.12^{+0.51}_{-0.83}$	10^{26}
$^{136}Xe \to {}^{136}Ba$	1.25	0.030	1.97(0.13)	2.11(0.11)		$4.55^{+0.68}_{-0.56}$	10^{26}
	1.00	0.045	1.59(0.09)	1.70(0.07)		$6.38^{+1.2}_{-0.43}$	10^{26}
	1.25	0	1.67(0.13)	1.78(0.11)		$7.00^{+0.81}_{-0.7}$	10^{26}
	1.00	0	1.26(0.09)	1.35(0.07)		$1.11^{+0.17}_{-0.14}$	10^{27}
$^{150}Nd \to {}^{150}Sm$	1.25	$0.07^{+0.009}_{-0.03}$	4.16(0.16)	4.74(0.20)	$^{+0.06}_{-0.19}$	$2.23^{+0.42}_{-0.21}$	10^{25}
	1.00	$0.11^{+0.014}_{-0.08}$	3.30(0.16)	3.72(0.20)	$^{+0.06}_{-0.19}$	$3.55^{+0.81}_{-0.45}$	10^{25}

Rodin et al., NP A793 (2007) 213.

$$T^{0\nu}_{1/2}\left(\langle m_{\beta\beta}\rangle = 10\,\mathrm{meV}\right)$$

Needs tons of source to have at least few decays per year!

$1.2 \cdot 10^{28}$ yrs

$$T^{0\nu}_{1/2} = T^{0\nu}_{1/2,50\,\mathrm{meV}} \cdot \frac{(50\,\mathrm{meV})^2}{\langle m_{\beta\beta}\rangle^2}$$

Primary Techniques:

- Large amount of decaying material.
- Reduction of intrinsic radioactivity by finding clean materials (VERY DIFFICULT).
- Control cosmogenic activition of materials.
- Passive shielding of cosmic ray showers. (go underground)
- Passive shielding of external radioactivity (ex: lead)
- Active shielding, especially for muons, usually scintillator layers.
  - High resolution calorimetry
    - Includes ionization, scintillation and bolometers.

    With low Backgrounds and no other event discrimination, resolution typically needs to be below a couple of percent
- Spatial tracking:
  - Good single-site discrimination alone can reduce backgrounds significantly.
  - Several techniques: high-resolution wire chambers,…, coarse segmentation.
- Residual nucleus identification (EXO)
- Major Distinctions:
  - Source is Detector? (Improves intrinsic background, but less versatile)
  - Good tracking vs. good calorimetry

K.Barry, D.Leonard, E.Niner, A.Piepke *Physics Dept, University of Alabama, Tuscaloosa AL*
P.Vogel *Physics Dept Caltech, Pasadena CA*
A.Bellerive, M.Bowcock, M.Dixit, 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 University, Fort Collins CO*
M.Moe *Physics Dept UC Irvine, Irvine CA*
D.Akimov, I.Alexandrov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Kovalenko, V.Stekhanov
ITEP Moscow, Russia
J.Farine, D.Hallman, C.Virtue, U.Wichoski *Laurentian University, Canada*
H.Breuer, C.Hall, L.Kaufman, S. Slutsky, Y-R. Yen
University of Maryland, College Park MD
K.Kumar *U. of Massachusetts, Amherst*
M.Auger, R.Gornea, D.Schenker, J-L.Vuilleumier, J-M.Vuilleumier
Physics Dept University of Neuchatel, Switzerland
N.Ackerman, M.Breidenbach, R.Conley, W.Craddock, J.Hodgson, D.McKay, A.Odian, C.Prescott, P.Rowson,
K.Skarpaas, J.Wodin, L.Yang, S.Zalog *SLAC, Menlo Park CA*
J.Anthony, L.Bartoszek, R.DeVoe, P.Fierlinger, B.Flatt, G.Gratta, M.Green, S.Kolkowitz, F.LePort,
M.Montero-Diez, R.Neilson, M. Noske, K.O'Sullivan, A.Pocar, K.Twilker *Physics Dept Stanford U., Stanford CA*

Why ^{136}Xe?

- Reasonable Q-value of **2457.8±0.4 keV**. Based on recent high precision mass measurement at FSU. M. Redshaw, J.McDaniel, E. Wingfield and E.G. Myers, PRL 98 (2007) 053003
- **Active detection medium in both liquid and gaseous phase. Suited for charge collection plus high yield UV scintillator (@ 3 kV/cm ~25 ph/keV, ~50 e/keV, anti-correlated[1]). No crystal growth needed.**
- **Isotope ^{136}Xe has reasonable natural abundance 8.9%.**
- **Noble gas, isotopic enrichment by ultra centrifugation cost effective. No chemistry needed.**
- **Xenon can be re-purified during operation and moved to different detector**

Ionization potentials Xe: 12.130 eV, Ba^{+}: 5.212 eV, Ba^{++}: 10.004 eV
→ ββ–decay product atom remains charged → opens possibility of Ba removal and final state tagging through Ba single ion detection

[1] XENON Collaboration data

EXO detection strategy

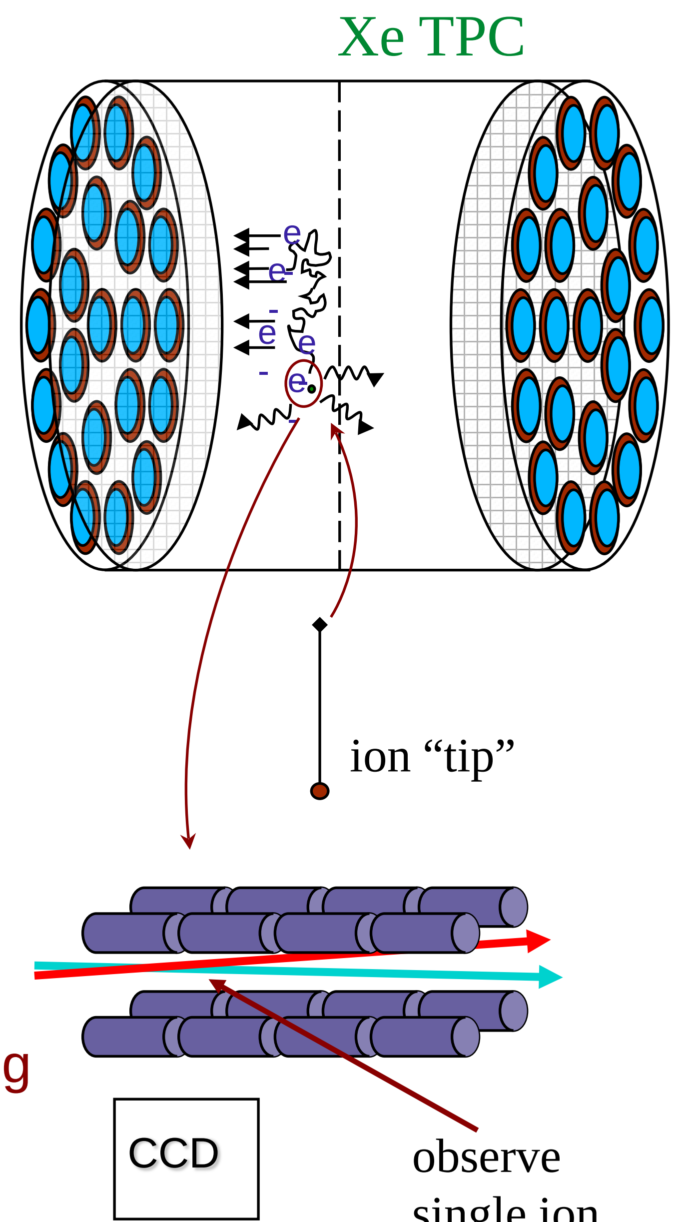
detect the 2 electrons
(ionization + scintillation in xenon detector)

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

positively identify daughter via optical spectroscopy of Ba^{+}

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

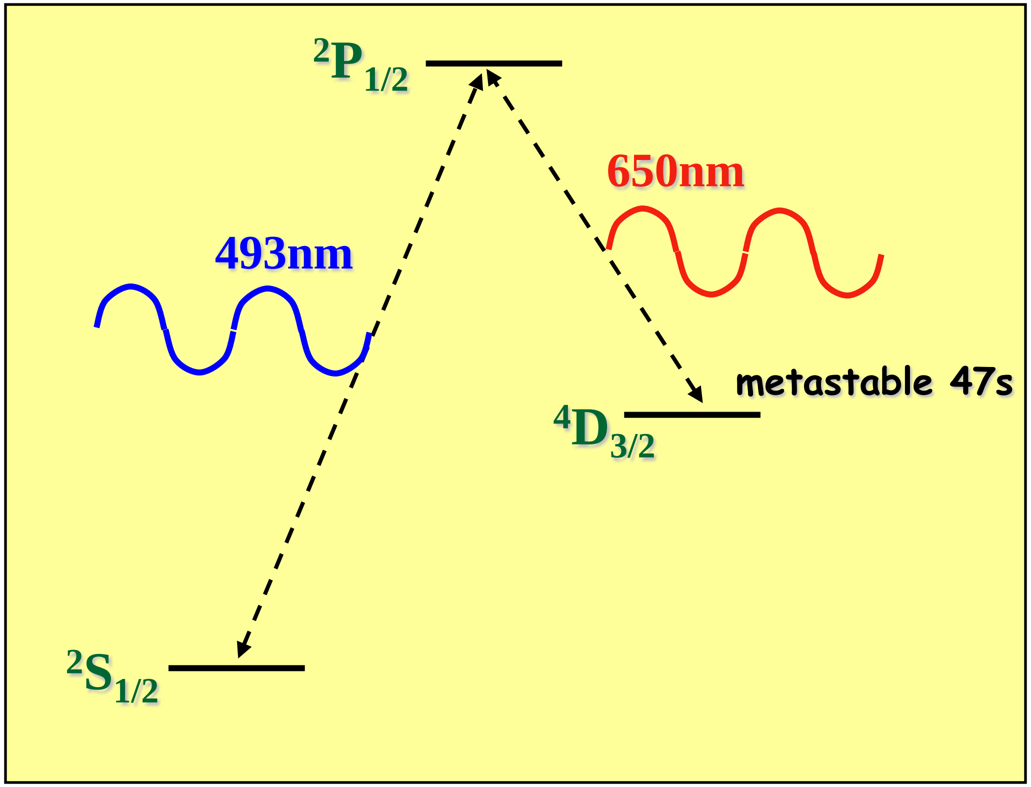
other Ba^{+} identification strategies are also being investigated within the EXO collaboration



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



EXO Road Map

- Goal: build 1 to 10 ton high resolution tracking TPC using enriched ^{136}Xe.
  Equip with Ba-final state tagging. → This should result in extremely small if not zero random background.
  Envisaged sensitivity 10 meV, covers mass range allowed for inverted hierarchy.

- Active R&D program under way. Explores the technical feasibility in phased approach.

- Detect decay and vertex in TPC using liquid Xenon

- Extract Ba ion using a charged probe. Transfer into ion trap, use laser pumping to identify single ion.

- Research on a high pressure gas TPC and in situ detection of Ba in the Xenon gas is being pursued too.

EXO Technical Preparation

Build and operate a smaller scale TPC to demonstrate that required energy resolution and background can be achieved. Demonstrate feasibility of large scale enrichment of ^{136}Xe.

We are building detector using 200 kg enriched Xe (at hand), being installed at WIPP, New Mexico
Will demonstrate background and energy resolution.

Ba extraction, transfer and single ion detection being developed in the lab in parallel.

After successful completion of these parallel research thrusts preparation of full proposal.
In this plan proof of principle does not require the funding of a very costly large experiment up front.

EXO-200:

An intermediate detector without Ba tagging using 200 kg liquid xenon, isotopically enriched to 80% ^{136}Xe

(–108° C, 3.02 g/cm^3)

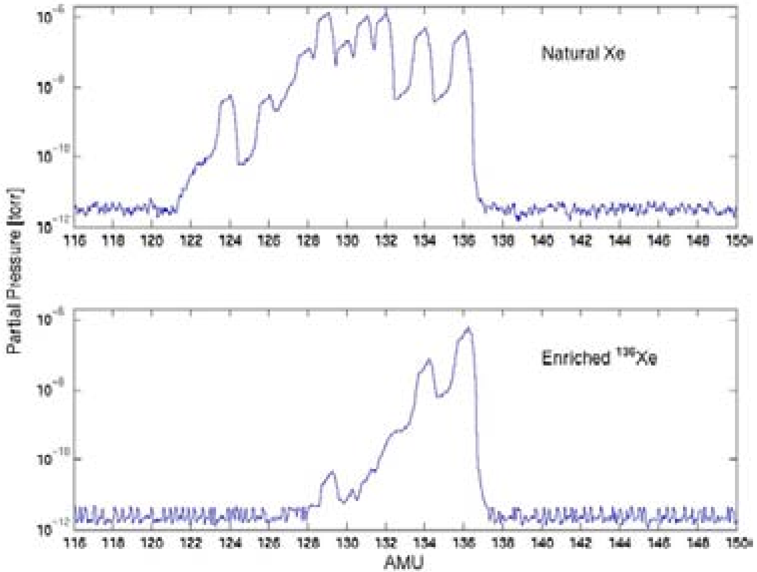
EXO-200

Scientific goals:

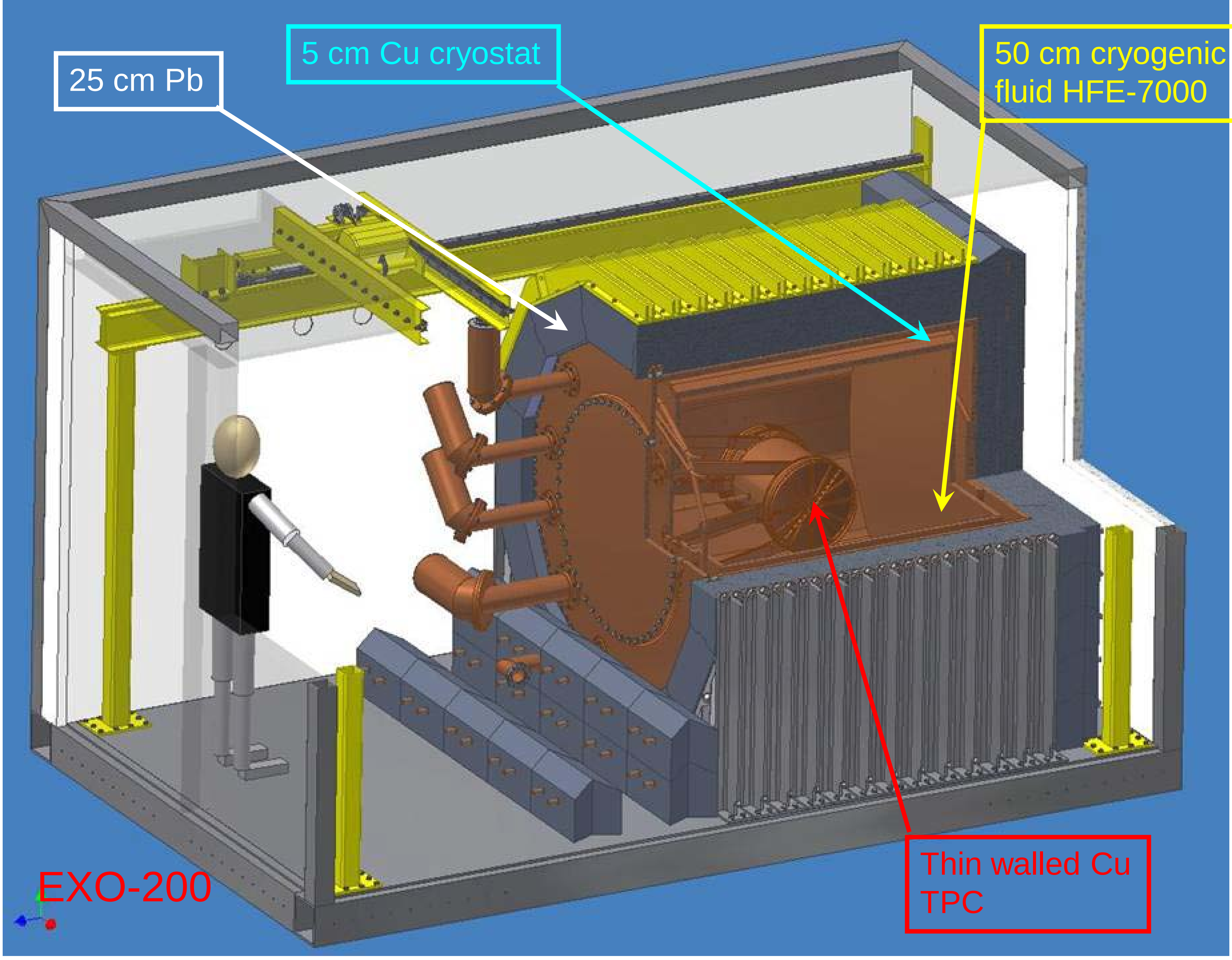
1) Measurement of yet unobserved $\beta\beta2\nu$ decay of ^{136}Xe.
Task: $T_{1/2} > 10^{22}$ y, ~67 dcs / (d 100 kg).
Important background for EXO.

2) Test of the Heidelberg evidence for $\beta\beta0\nu$ decay.
Expectation for ^{136}Xe [Ge range $(1.92\text{-}2.67)\cdot10^{25}$ y, (2006)]:
$T_{1/2} = (1.02\text{–}1.41)\cdot10^{25}$ y [Rodin et al. NPA 793 (07) RQRPA]
17 – 24 dcs / (y 100 kg)
$= (0.38\text{–}0.53)\cdot10^{25}$ y [Caurier et al. arXiv:0709.2137 (07) SM]

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



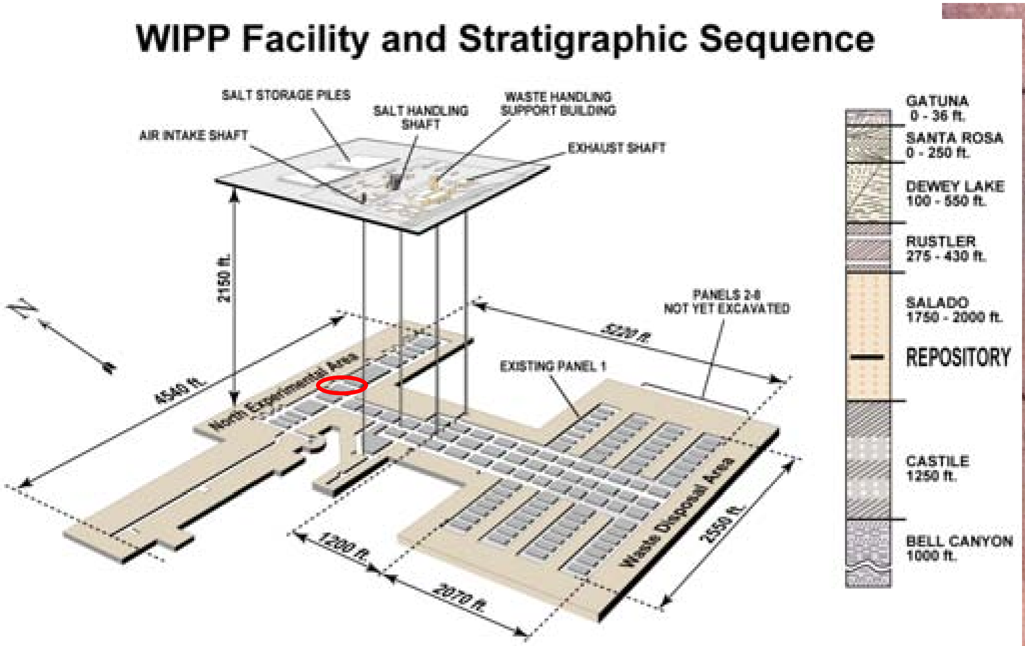
- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated ββ isotope (by ~factor of 10)


5 cm Cu cryostat
25 cm Pb
50 cm cryogenic fluid HFE-7000
Thin walled Cu TPC
EXO-200

Lab preparation

EXO-200 schedule and location

• Jun, 2006	Cryostat and lower Pb installed (Stanford)
• Sep, 2006	First empty cool-down (Stanford)
• May, 2007	Replace super insulation (Stanford)
• June, 2007	Move clean rooms to WIPP
• 2008	Finish underground manufacturing of TPC components. E-beam weld pressure vessel.
• 2009	Assemble and install TPC and veto at WIPP.



October 2007: clean-rooms and gowning area installed at WIPP.

Staging container for component pre-cleaning installed at WIPP.

December 2008 installation of veto support.

Background control

Natural, cosmogenic and anthropogenic radioactivity content of all construction materials quantified using various techniques. EXO testing program: more than 450 material measurements.

Techniques:

Low background γ-counting (Th/U): 1 ppb (UA) 10 ppt (Bern)

Mass spec (Th/U): 10 ppt GDMS, 1 ppt ICPMS (INMS Canada)

NAA utilizing MIT reactor (Th/U): 0.02 to 0.3 ppt (UA)

α counting for ^{210}Pb analysis of shielding lead (via ^{210}Po): 5 Bq/kg (UA)

Rn counting, PIN diode with electrostatic collection:
10 atoms (Laurentian, Canada)

Keep track of results through an elog data base.

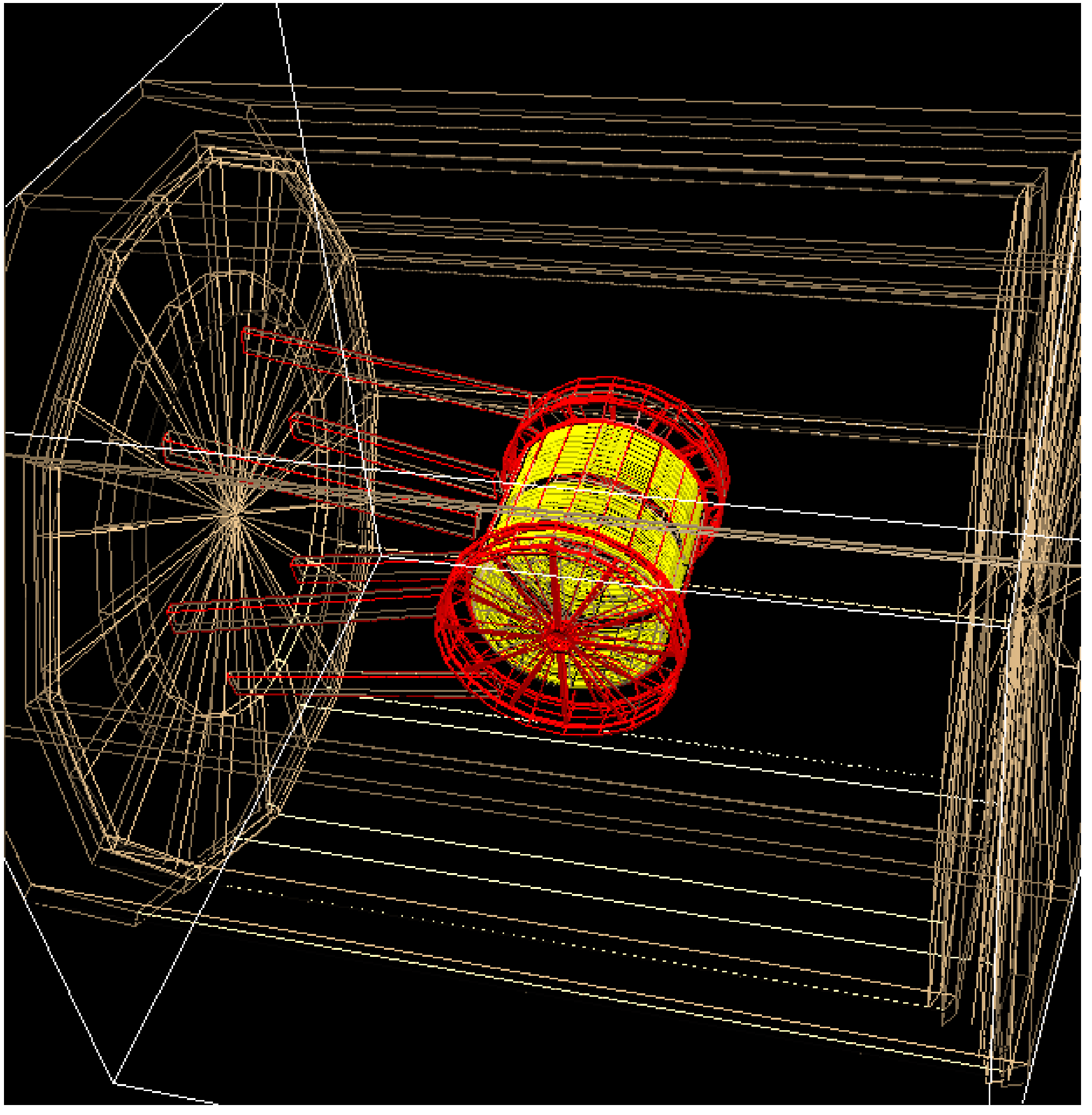
D. Leonard et al., Nucl. Inst. Meth. A 591 (2008) 3.

Calculate the hit efficiency in terms of events per decay for cuts on energy deposit, track length, and distance from detector boundary.

Parametric Monte Carlo: spatial and energy resolution are implemented by folding with energy deposit.
Detailed source generators take into account particle correlations to not over estimate effectiveness of cuts.

Our design goal: the sum of all background contributions and limits will not exceed 20 / y for $\beta\beta0\nu$–analysis and 10 /d for $\beta\beta2\nu$–analysis. Conservative as not all materials for which we have limits will be at or close to the limits.

We keep running log of all backgrounds during installation.



Measurement of radioactivity at ultra trace concentration:

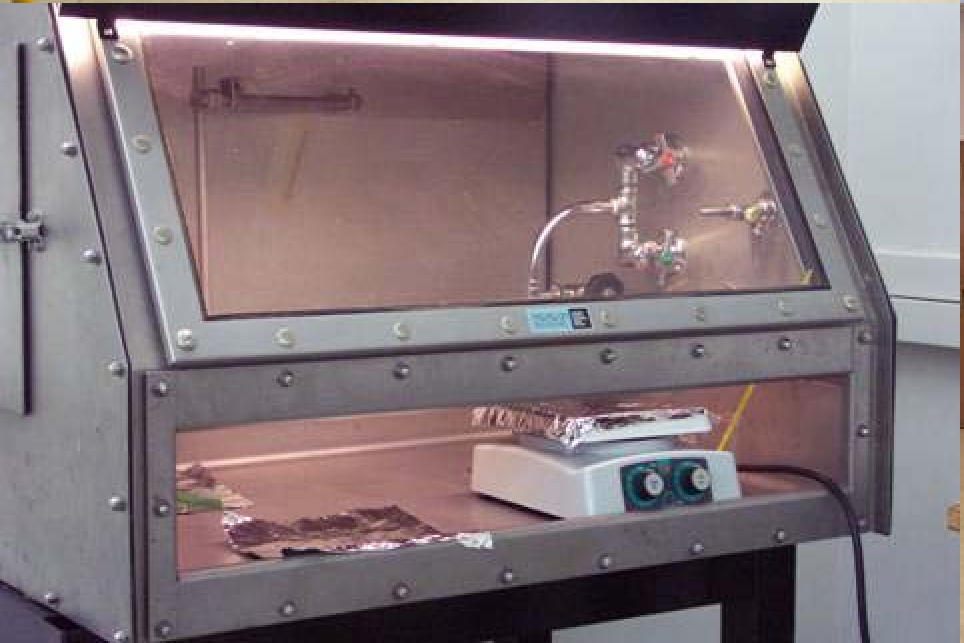
1 ppt Th: 4 μBq/kg or 2.8 days/(decay·kg)

1 ppt U: 12 μBq/kg or 0.9 days/(decay·kg)

ββ2ν-decay of 80% enriched ^{136}Xe:

for $T_{1/2} > 10^{22}$ y specific activity <8 μBq/kg

Facilities available at UA



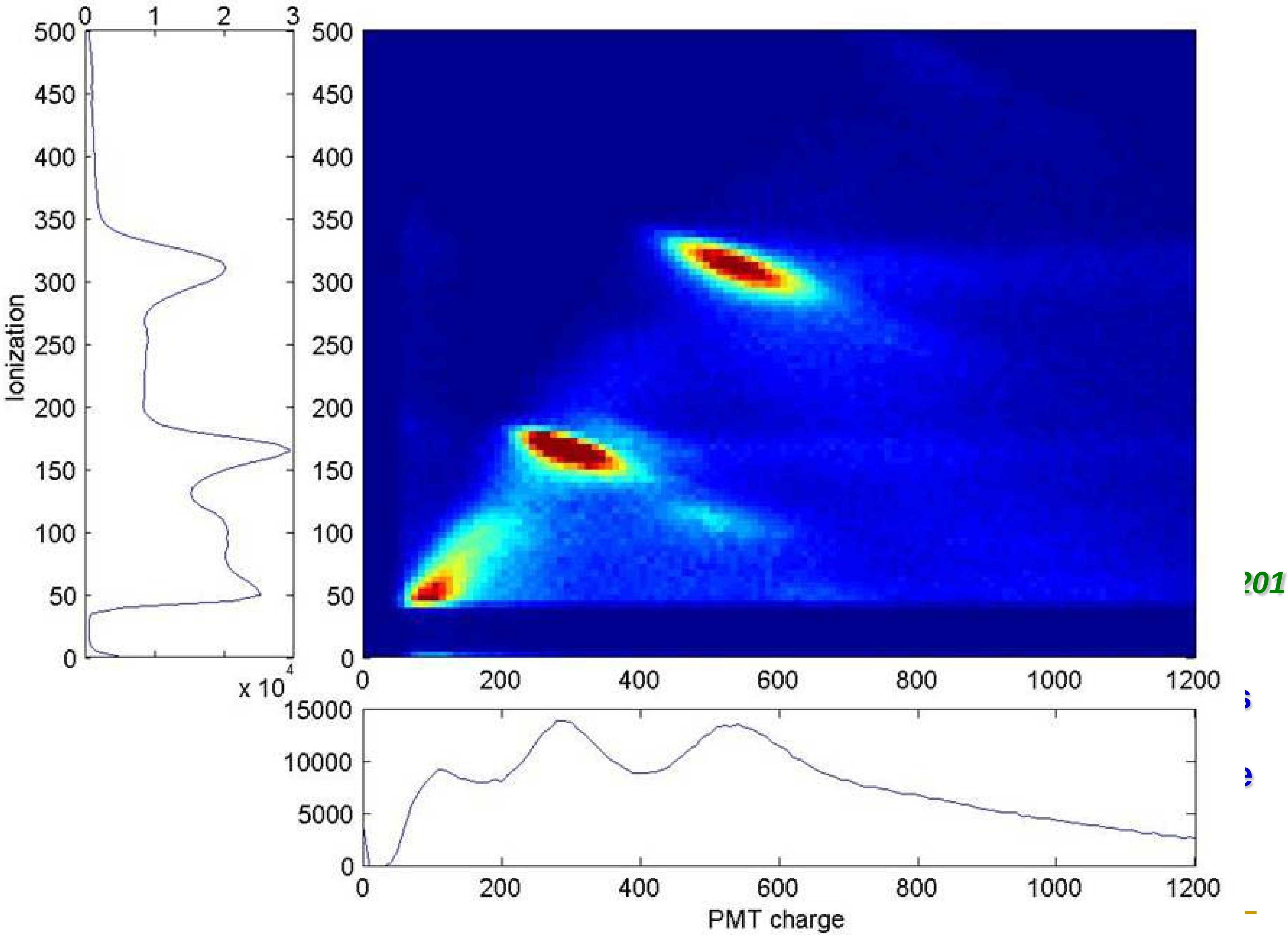
The TPC

Charge Detection

- Double-ended TPC chamber with ~20 cm drift regions. In Xe about 50 e/keV → at 2480 keV results in 124,000 e-, into 1 pF equivalent charge amplifier 20 mV signal → amplify by factor 10 using shaping amplifier. Estimated noise is 500 e.
- Mid-plane cathode biased at -75 kV
- 38 Inductive “Y” wires per side at -4 kV, 100% charge transparent.
- 38 “X” wires at virtual ground to collect the charge.
- LXE electron mobility ~2000 $cm^2/(Vs)$
- Saturation velocity ~ 0.28 cm/μs
- Electron lifetime goal of 3 ms → 2.4% loss at 20 cm.

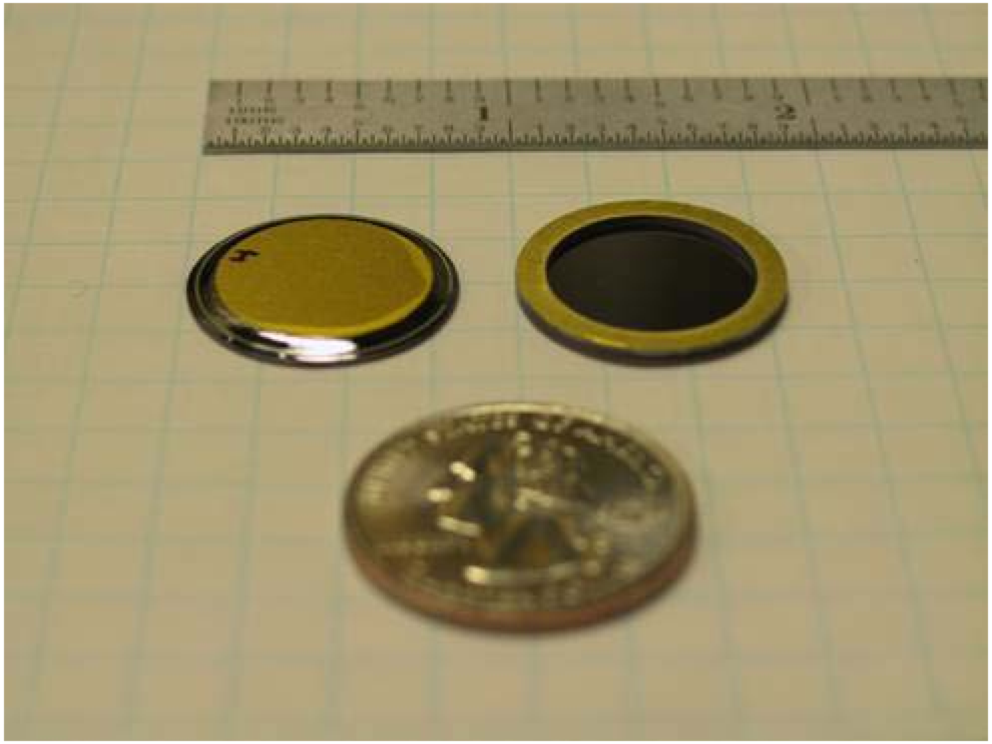
Light Detection

- 516 16 mm (active area) APD's (Avalanche Photo Diodes).
- QE measured to be 120% at 175 nm by NIST.
- Geometrical photo-coverage ~17%. Compared to PMTs with about 30% QE corresponds to 70% coverage.
- Read-out: gangs of seven APD's
- Yield enhanced by reflective Teflon reflectors in TPC.
- Chare amplifier 5 pF per gang of seven.
- Low gain (compared to PMT's), of ~100.
- Clean materials, mostly refined silicon.
- Connections made by contact springs for easy maintenance.

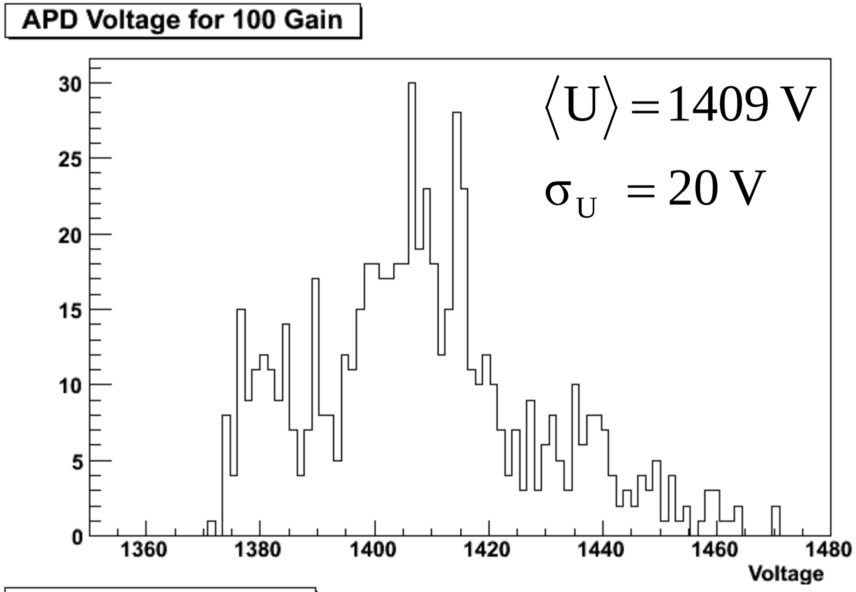

Ionization
PMT charge
x 10^4

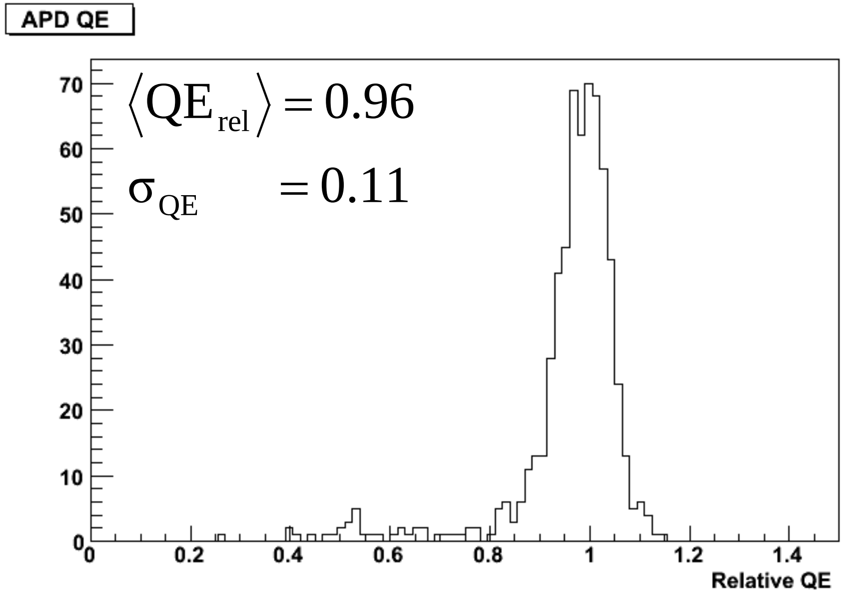
APD delivery status

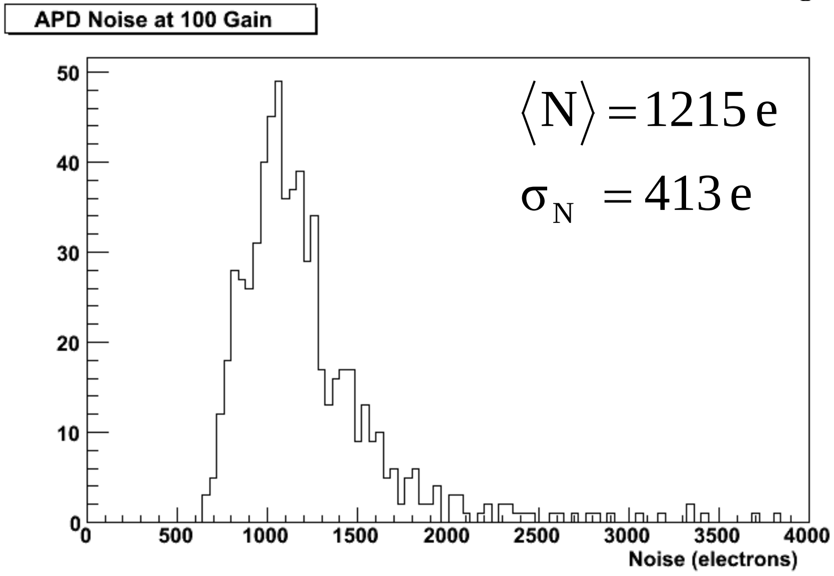
- 815 APDs delivered out of 849.
- 812 tested.
- 596 working (relative QE > 0.7, noise < 3000 electrons).



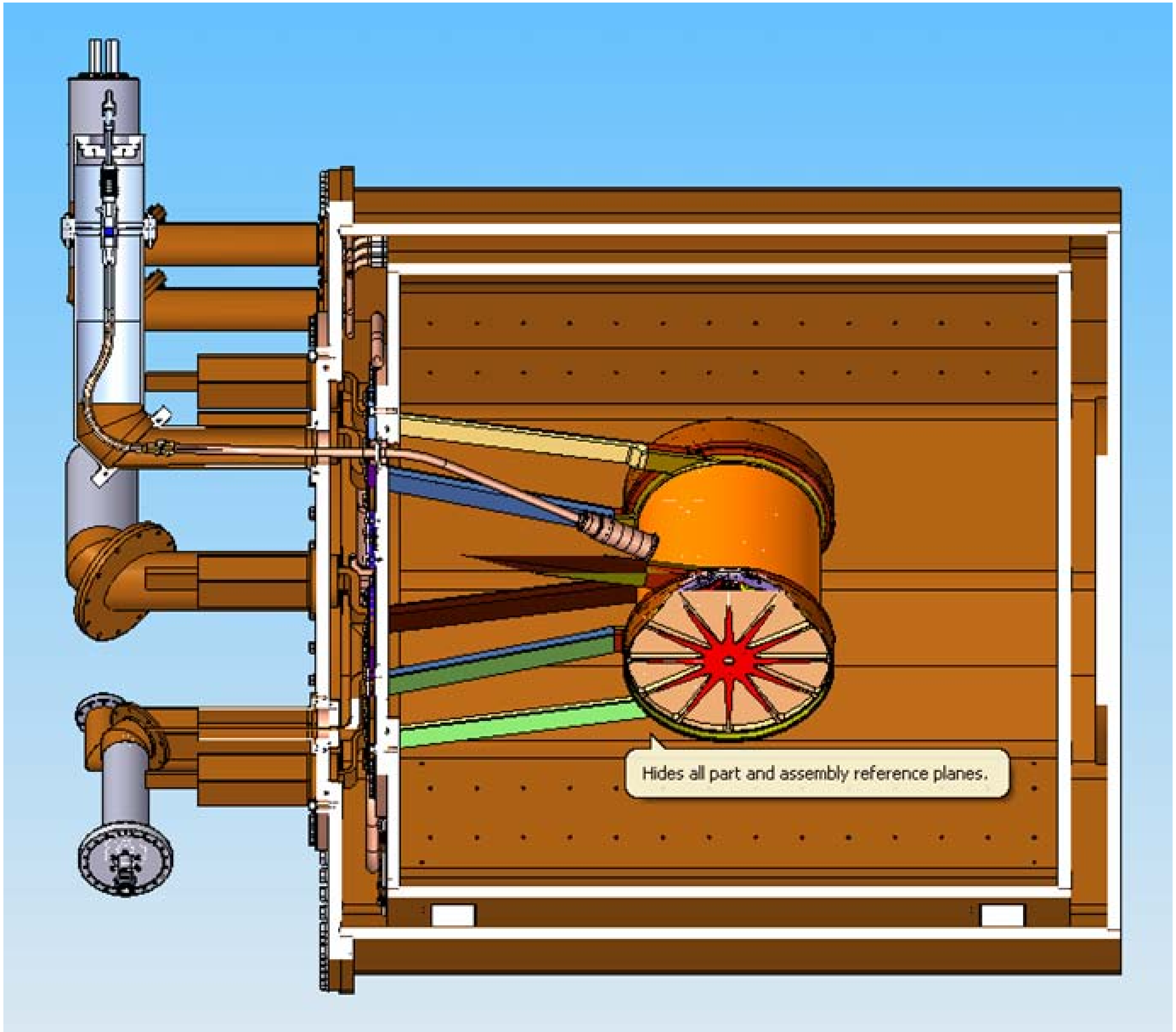
- 516 needed
  - 258 at each end
    - 36 gangs of 7, one gang of 6.



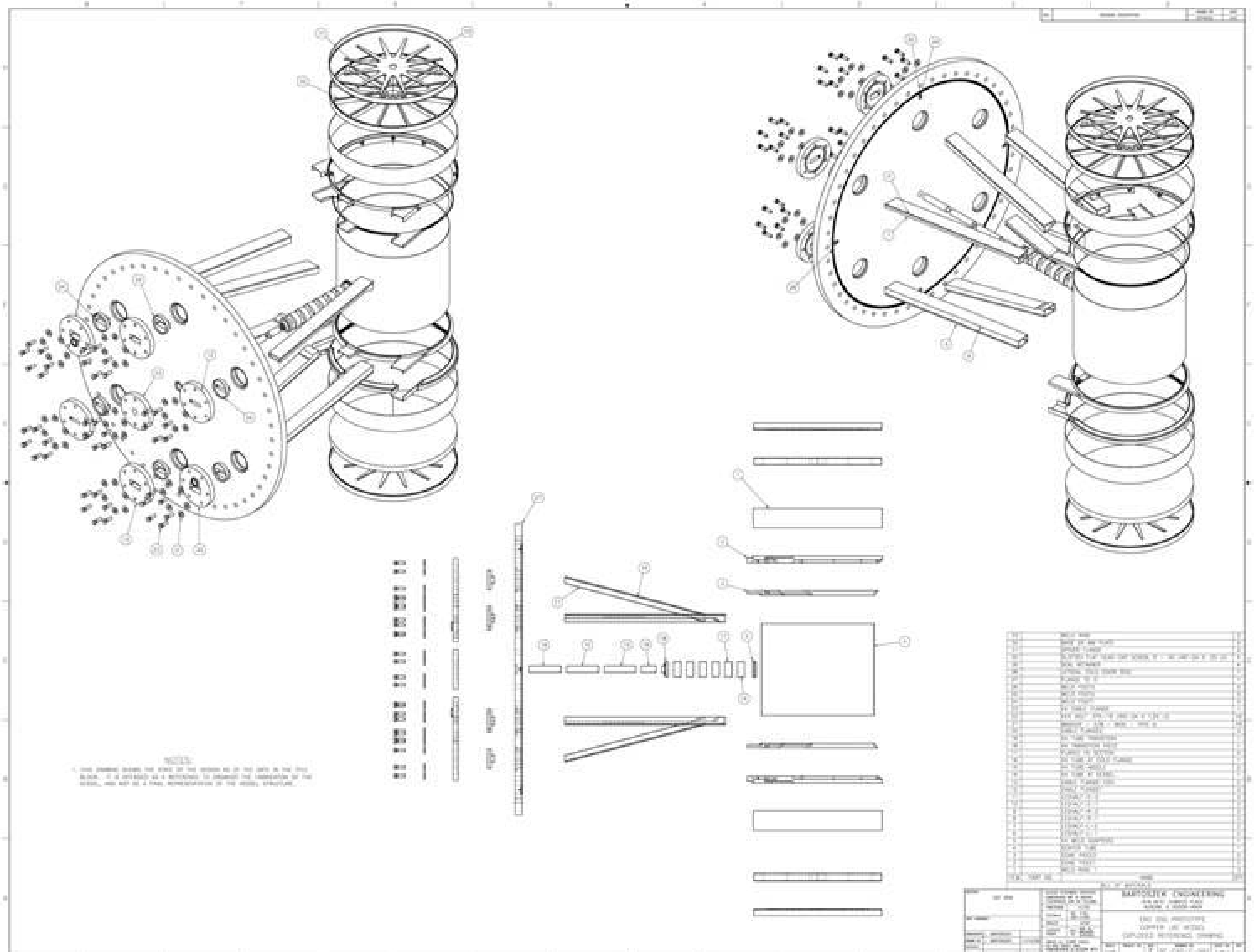


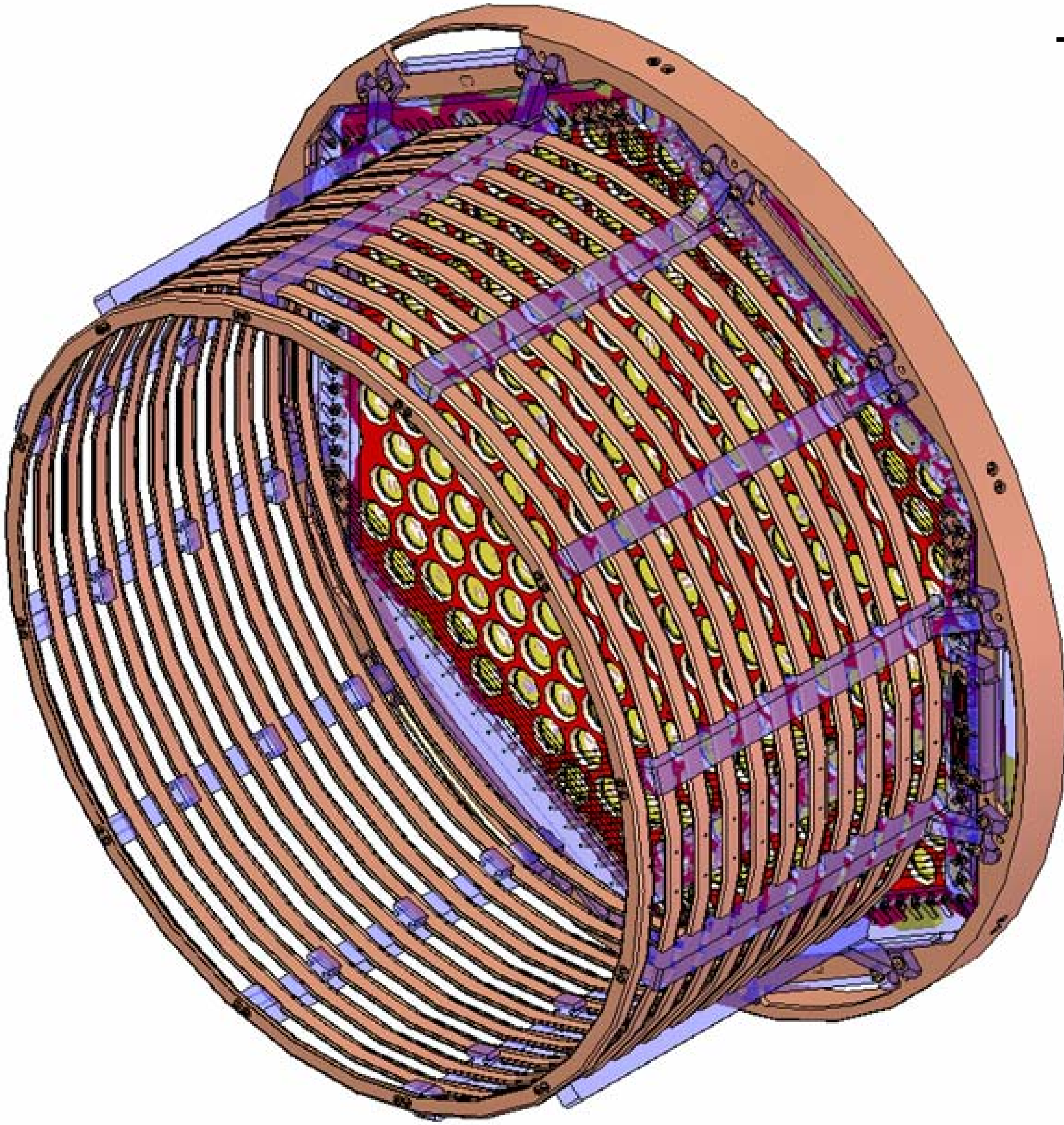


All tests done at liquid Xe temperature (-108° C).



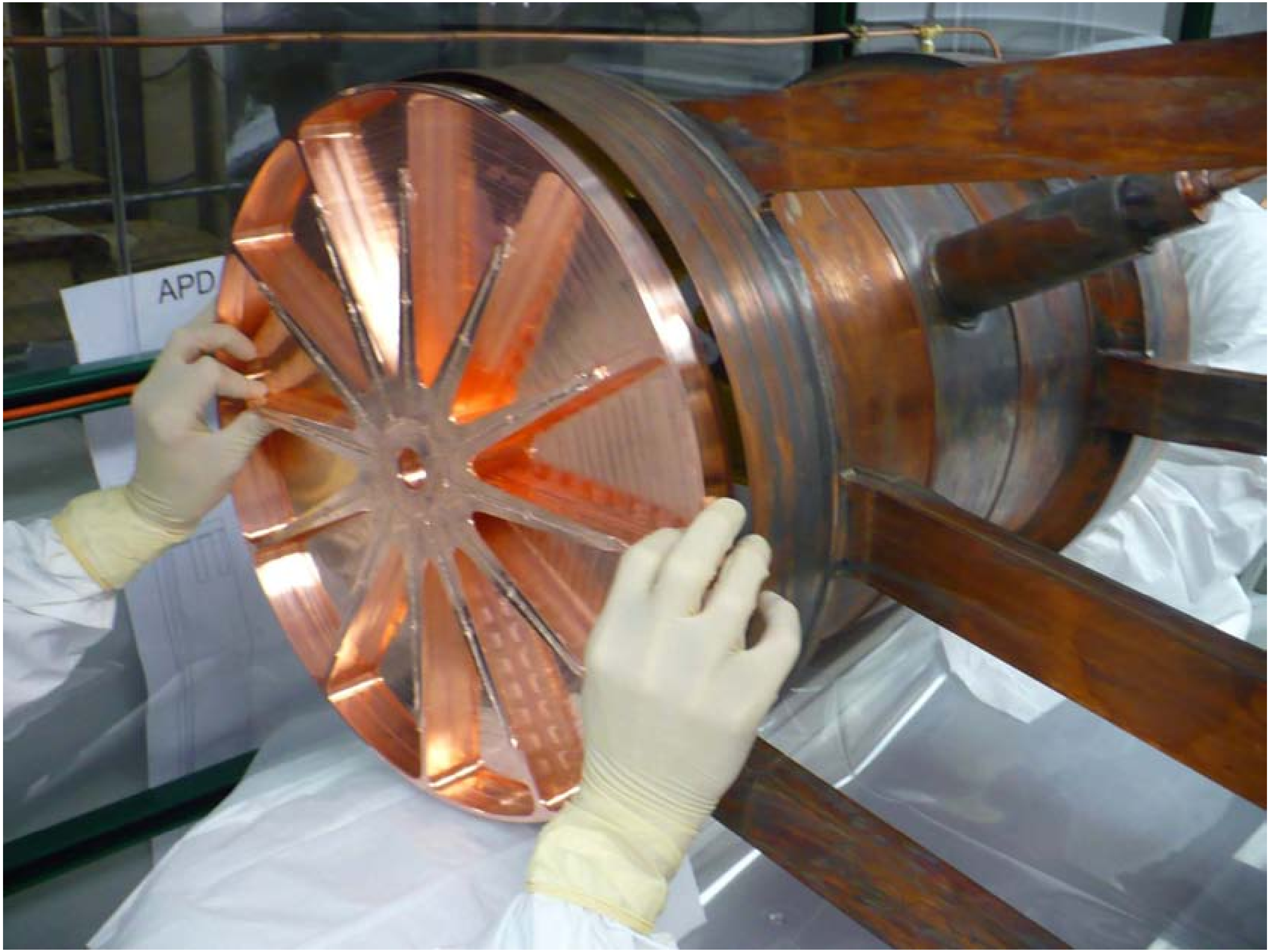
Thin walled Cu pressure vessel.
Active parts (wires, APDs) are attached to a removable inner structure.

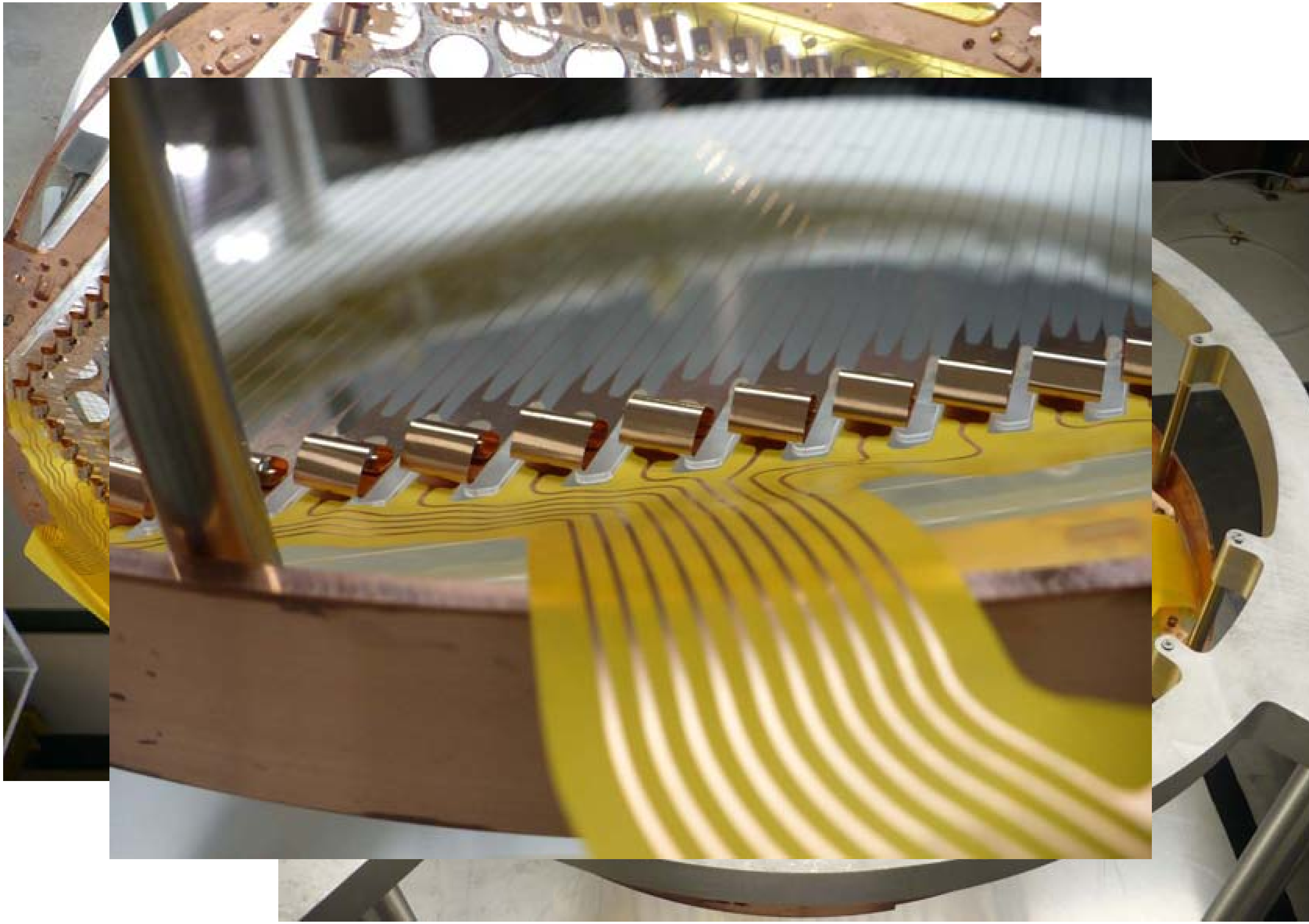




TPC internal structure


Kimwipes


APD



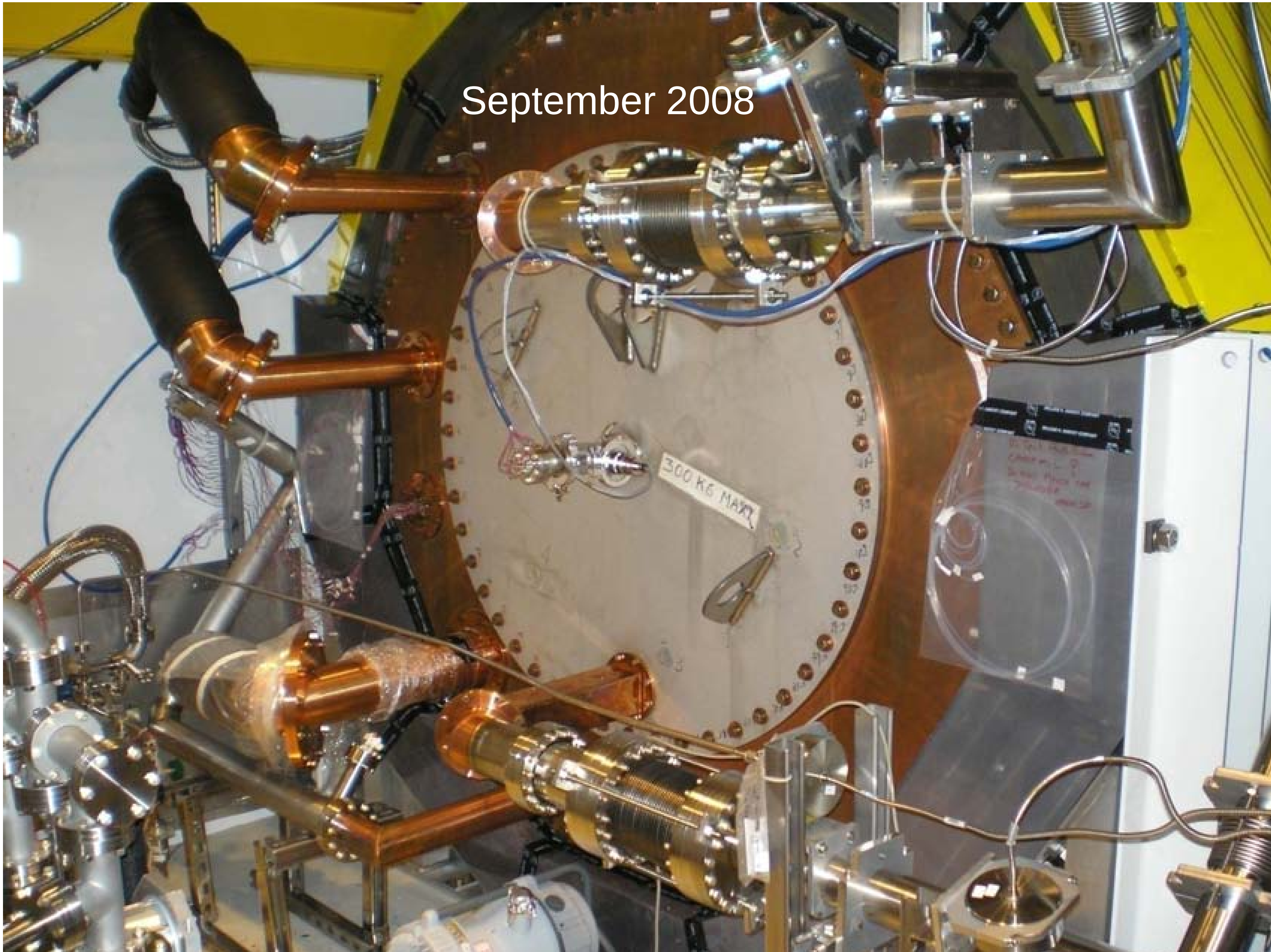
The Cryostat

Etching with dilute HNO_3 after receipt in 2006.

Superinsulation

Application of new SI after it was found that original SI was too radio-active (2007).

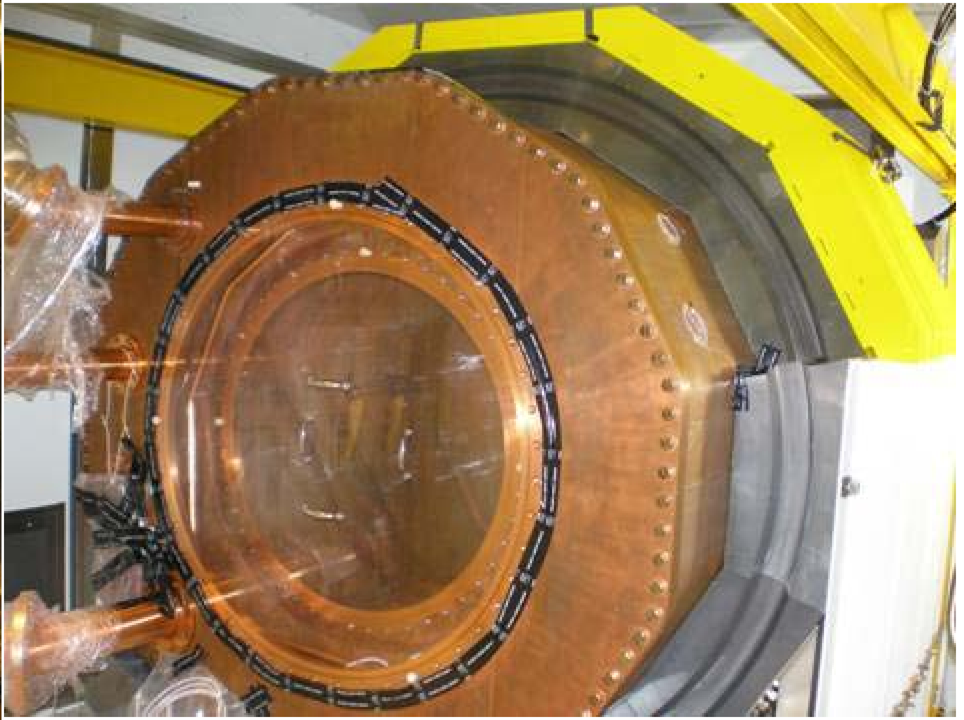
Required design of a large extraction device.


September 2008
300 KG MAX

Lead Shield

2006

May 2008: installation of the "barrel section" of the lead, at WIPP.



The Cosmic Ray Muon Veto

EXO-200 is being installed at WIPP at a depth of 665 m of rock/salt. The corresponding overburden is 1585 mw.w.

The vertical muon intensity has been measured to be: $268 \pm 6\ m^{-2}\ d^{-1}\ sr^{-1}$ by Esch et al., astro-ph/0408486.

The flux through a horizontal surface is $332\ m^{-2}\ d^{-1}$

Monte Carlo estimated muon related background:

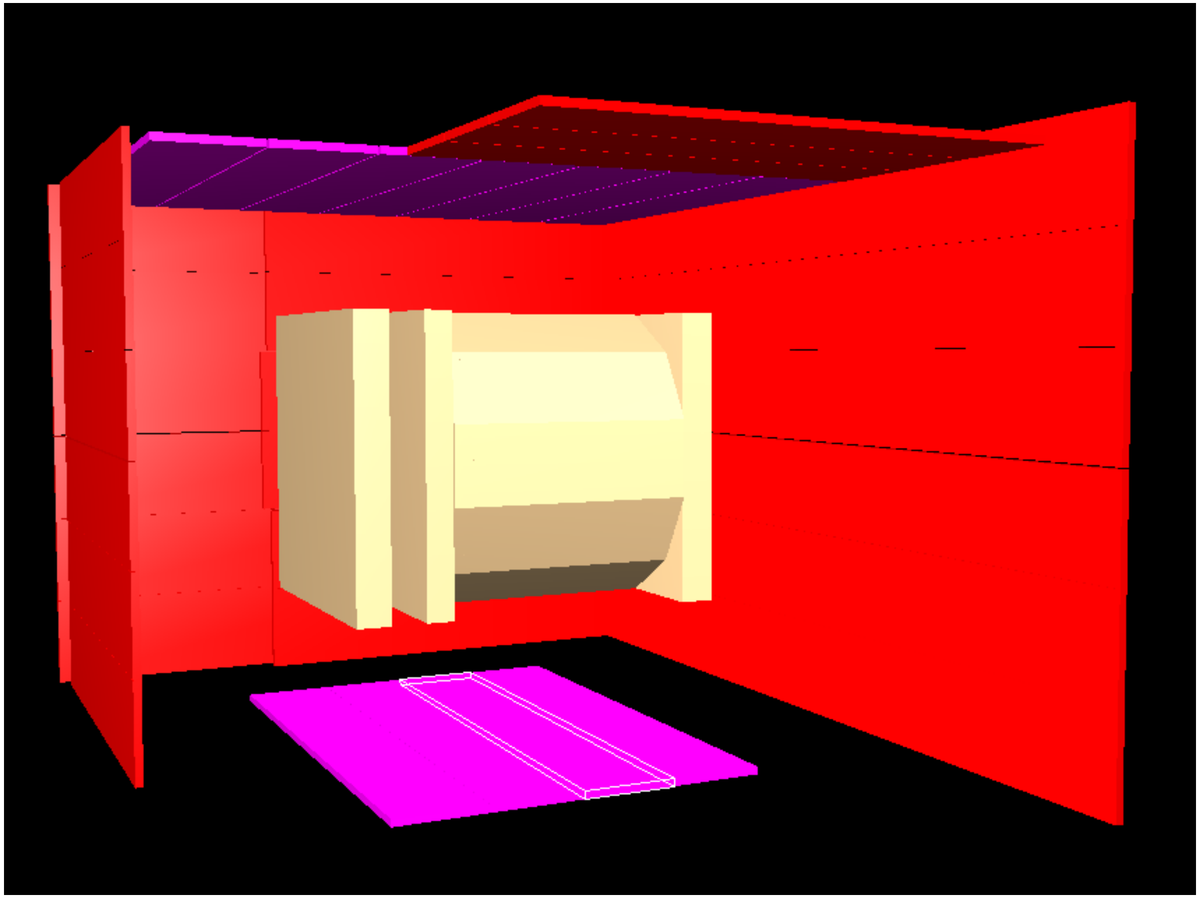
$\beta\beta0\nu$: 15 cnts/year

$\beta\beta2\nu$: 1100 cnts/year

These are due to secondaries with the muon missing the TPC.

Muon veto with at least 90% efficiency needed to meet background goal.

EXO-200 active scintillation muon veto



Geometrical placement is optimized by Monte Carlo.

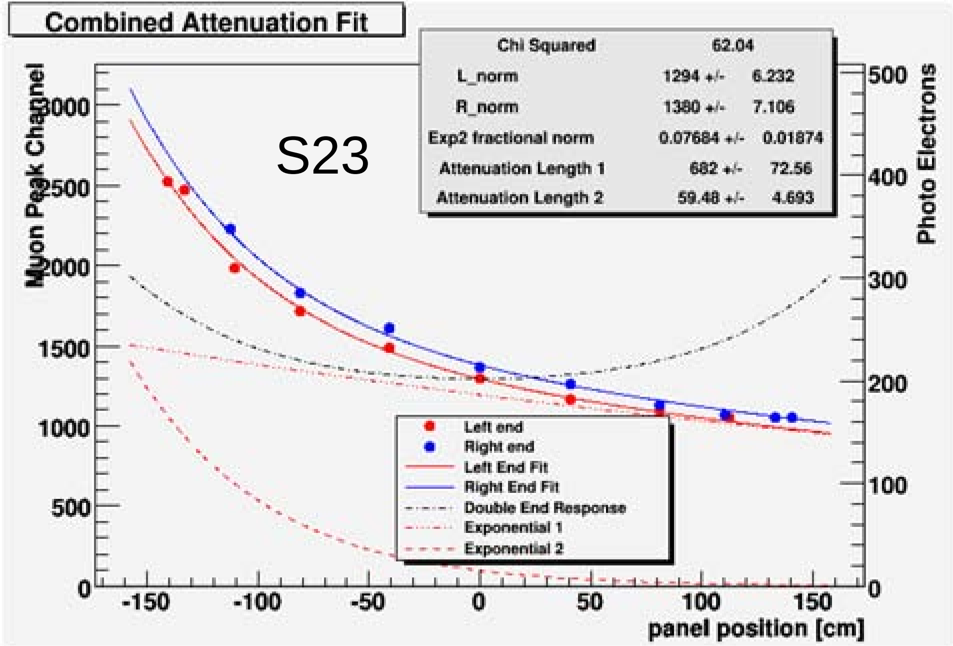
To stay within background budget we need 90% efficiency. For the chosen design we estimate 99.2% efficiency.

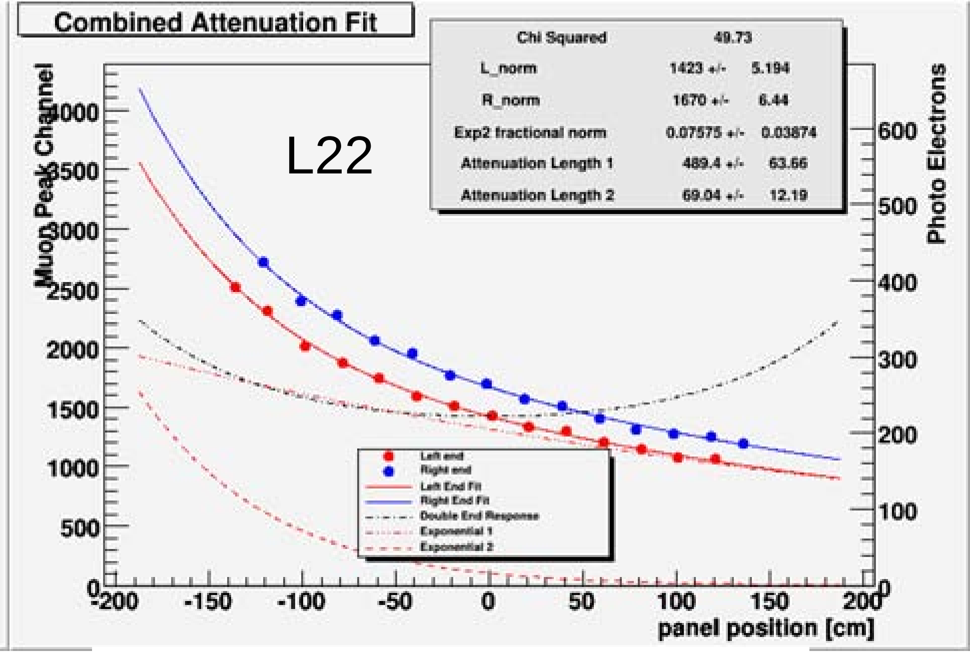
31 large plastic scintillator panels, left over from the concluded KAREMEN neutrino oscillation experiment, have been acquired.

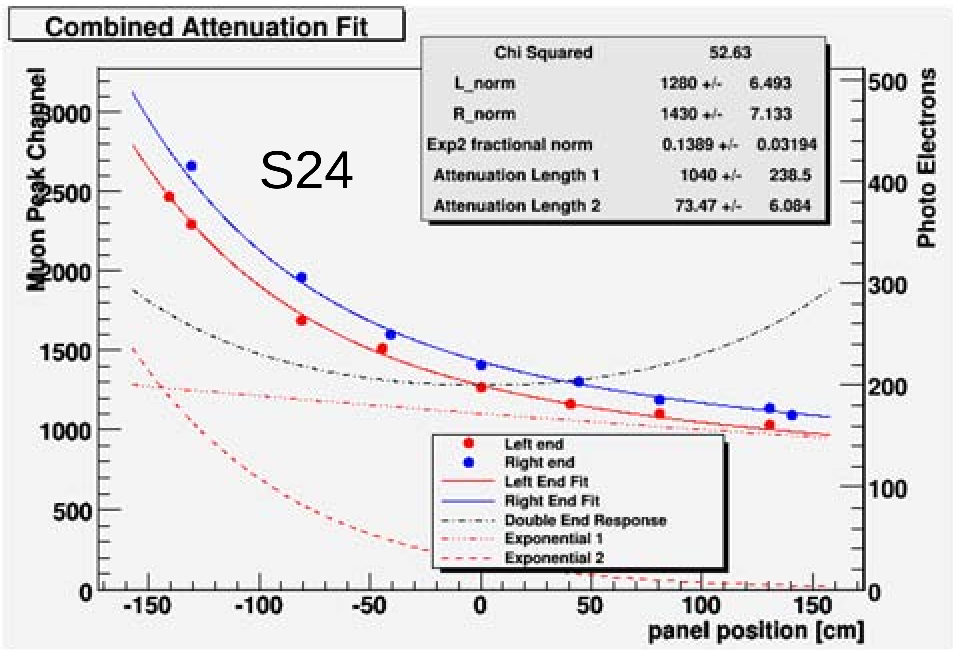
They have been refurbished, tested, and calibrated at UA. Includes gain matching of about 280 PMTs.

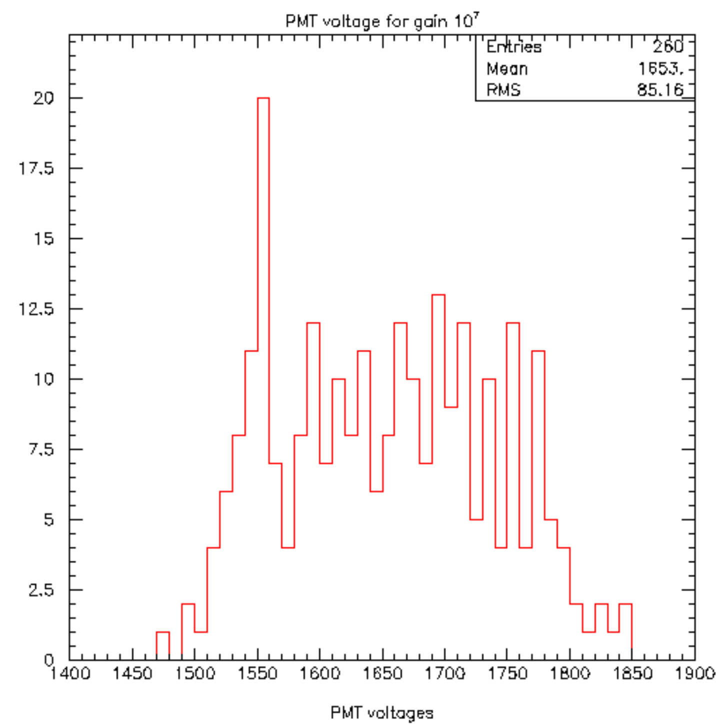

ALABAMA

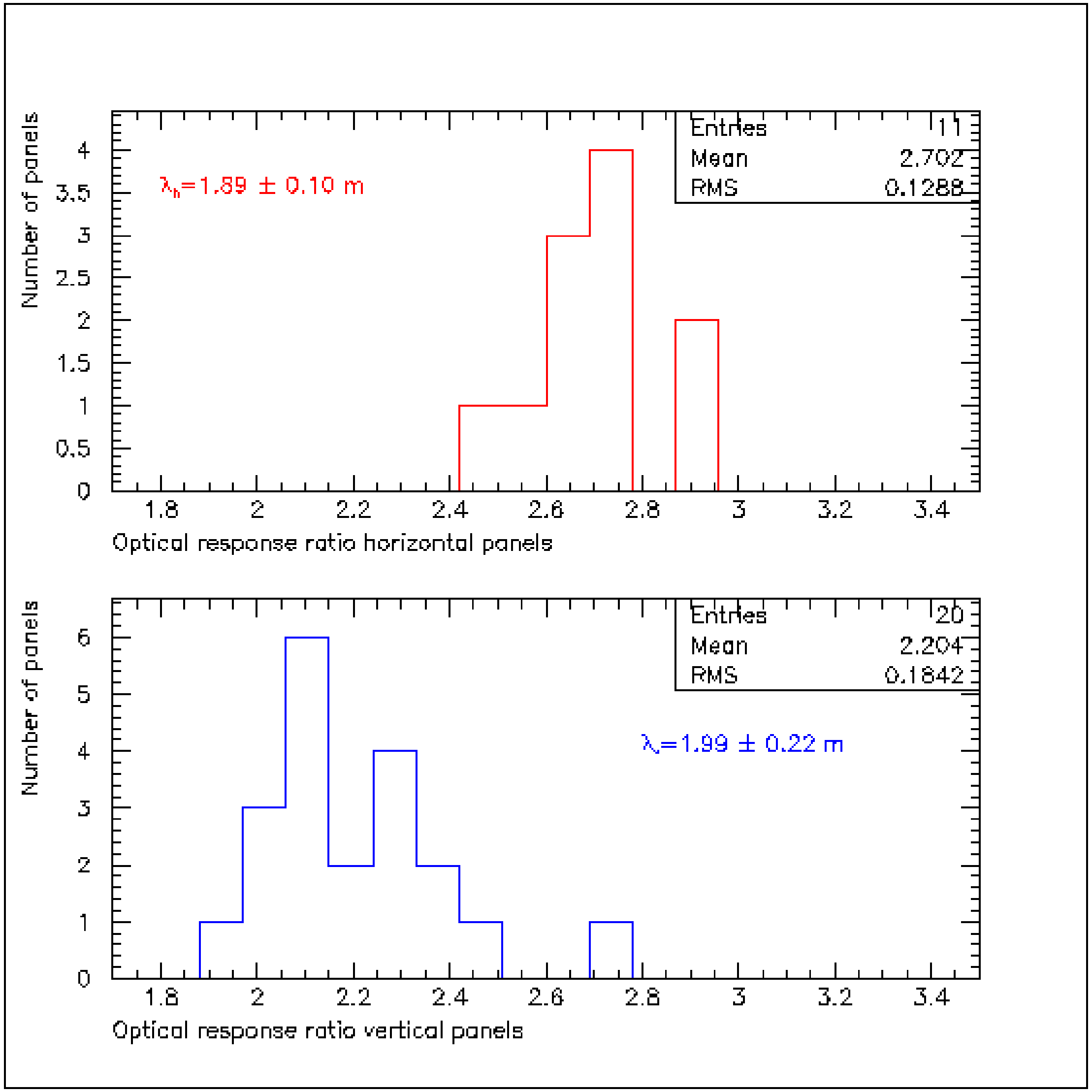

CarlStahl

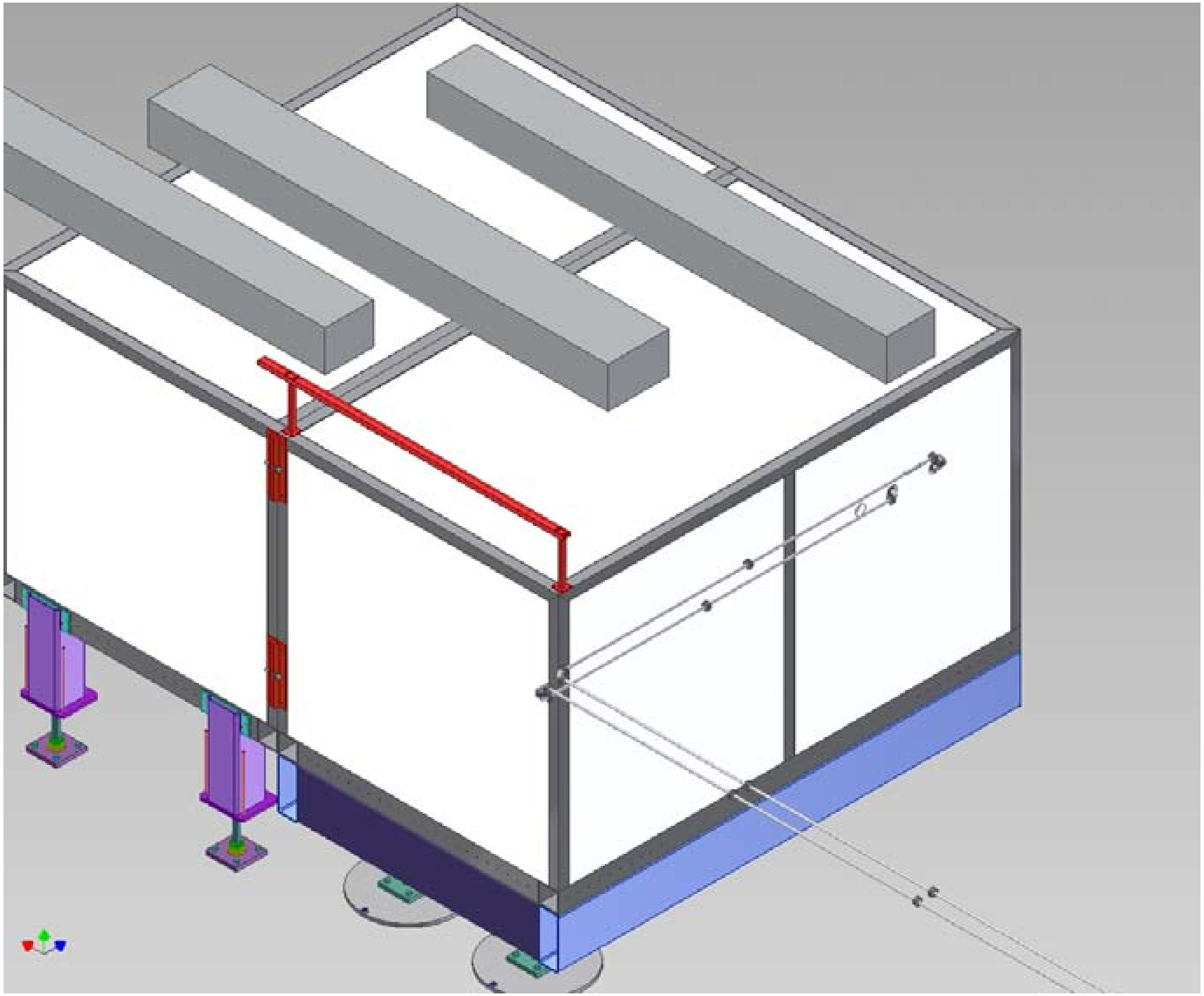

Combined Attenuation Fit
S23
Chi Squared 62.04
L_norm 1294 +/- 6.232
R_norm 1380 +/- 7.106
Exp2 fractional norm 0.07684 +/- 0.01874
Attenuation Length 1 682 +/- 72.56
Attenuation Length 2 59.48 +/- 4.693
Left end
Right end
Left End Fit
Right End Fit
Double End Response
Exponential 1
Exponential 2
Muon Peak Channel
Photo Electrons
panel position [cm]


Combined Attenuation Fit
L22
Chi Squared 49.73
L_norm 1423 +/- 5.194
R_norm 1670 +/- 6.44
Exp2 fractional norm 0.07575 +/- 0.03874
Attenuation Length 1 489.4 +/- 63.66
Attenuation Length 2 69.04 +/- 12.19
Left end
Right end
Left End Fit
Right End Fit
Double End Response
Exponential 1
Exponential 2
Muon Peak Channel
Photo Electrons
panel position [cm]

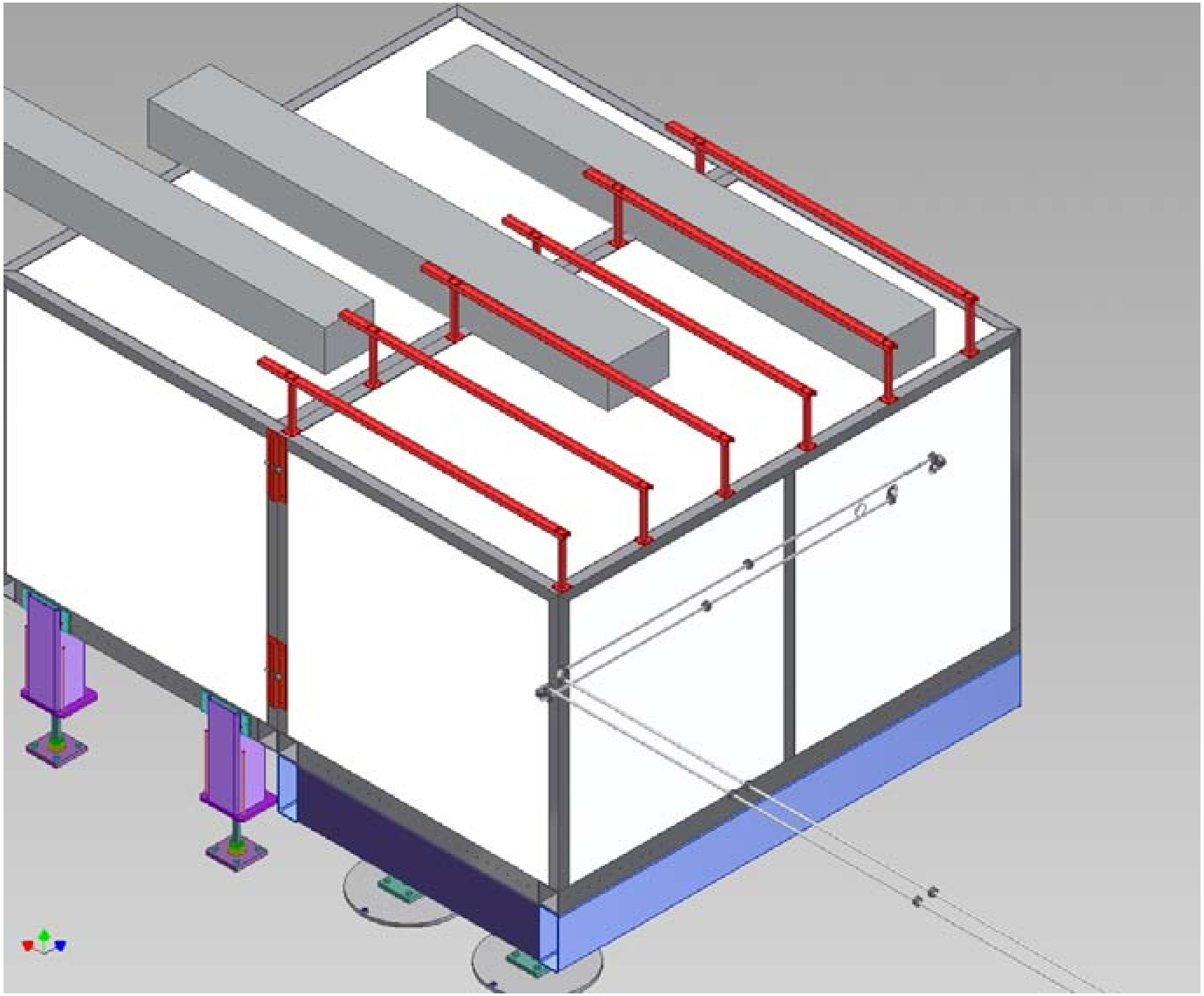

Combined Attenuation Fit
S24
Chi Squared 52.63
L_norm 1280 +/- 6.493
R_norm 1430 +/- 7.133
Exp2 fractional norm 0.1389 +/- 0.03194
Attenuation Length 1 1040 +/- 238.5
Attenuation Length 2 73.47 +/- 6.084
Left end
Right end
Left End Fit
Right End Fit
Double End Response
Exponential 1
Exponential 2
Muon Peak Channel
Photo Electrons
panel position [cm]

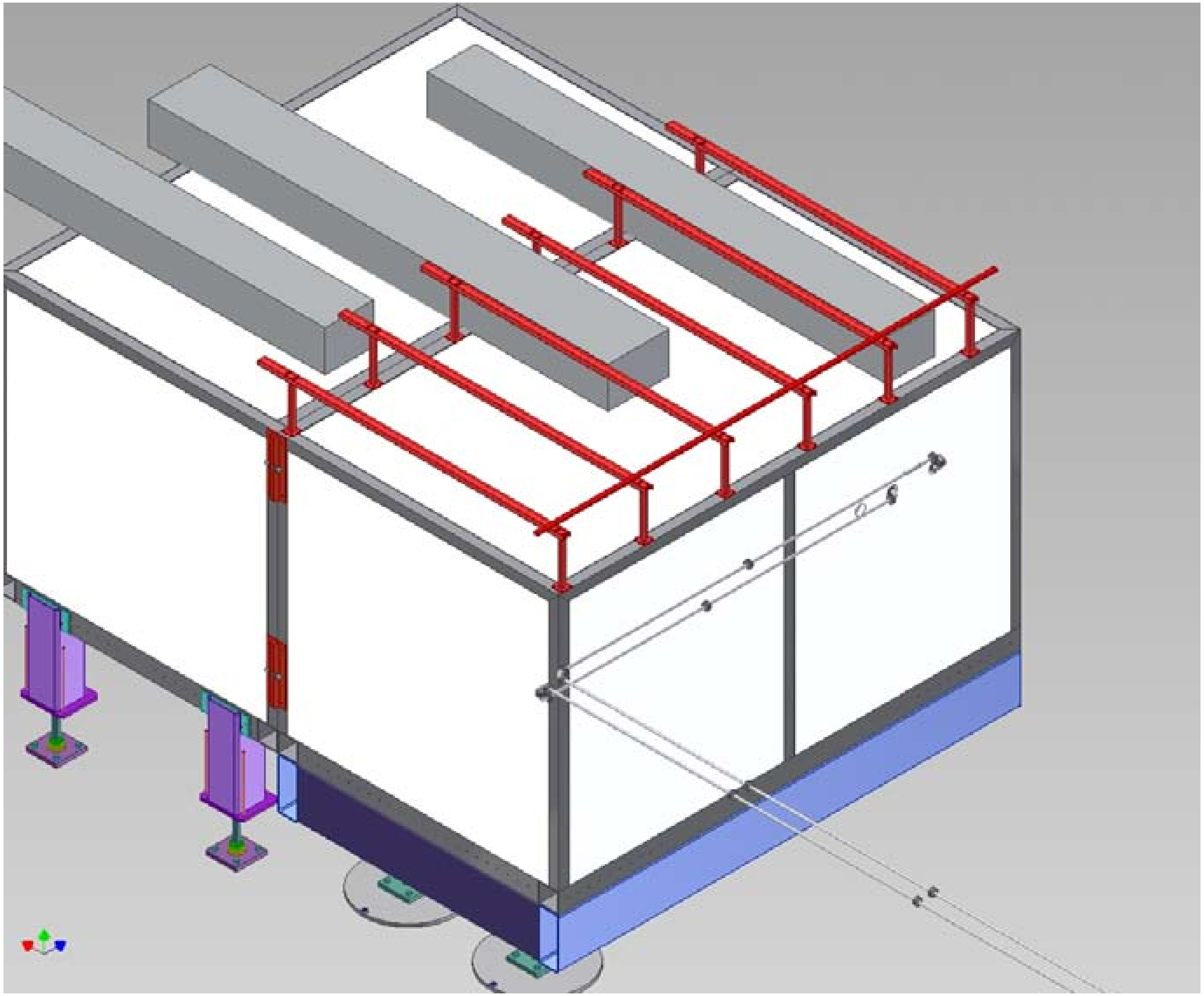

PMT voltage for gain 10^7
Entries 260
Mean 1653.
RMS 85.16
PMT voltages

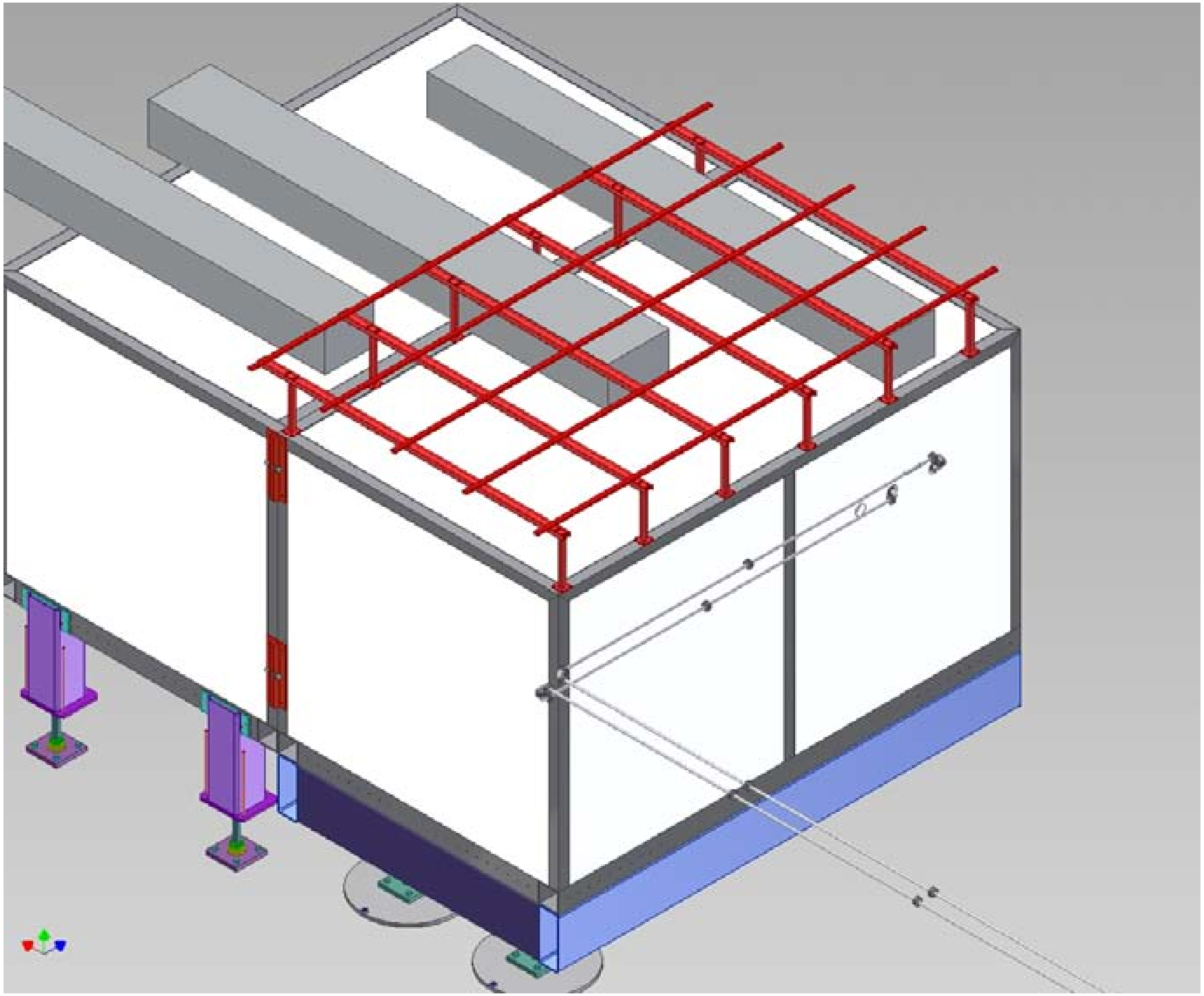

Number of panels
Entries 11
Mean 2.702
RMS 0.1288
λh=1.89 ± 0.10 m
Optical response ratio horizontal panels
Number of panels
Entries 20
Mean 2.204
RMS 0.1842
λv=1.99 ± 0.22 m
Optical response ratio vertical panels

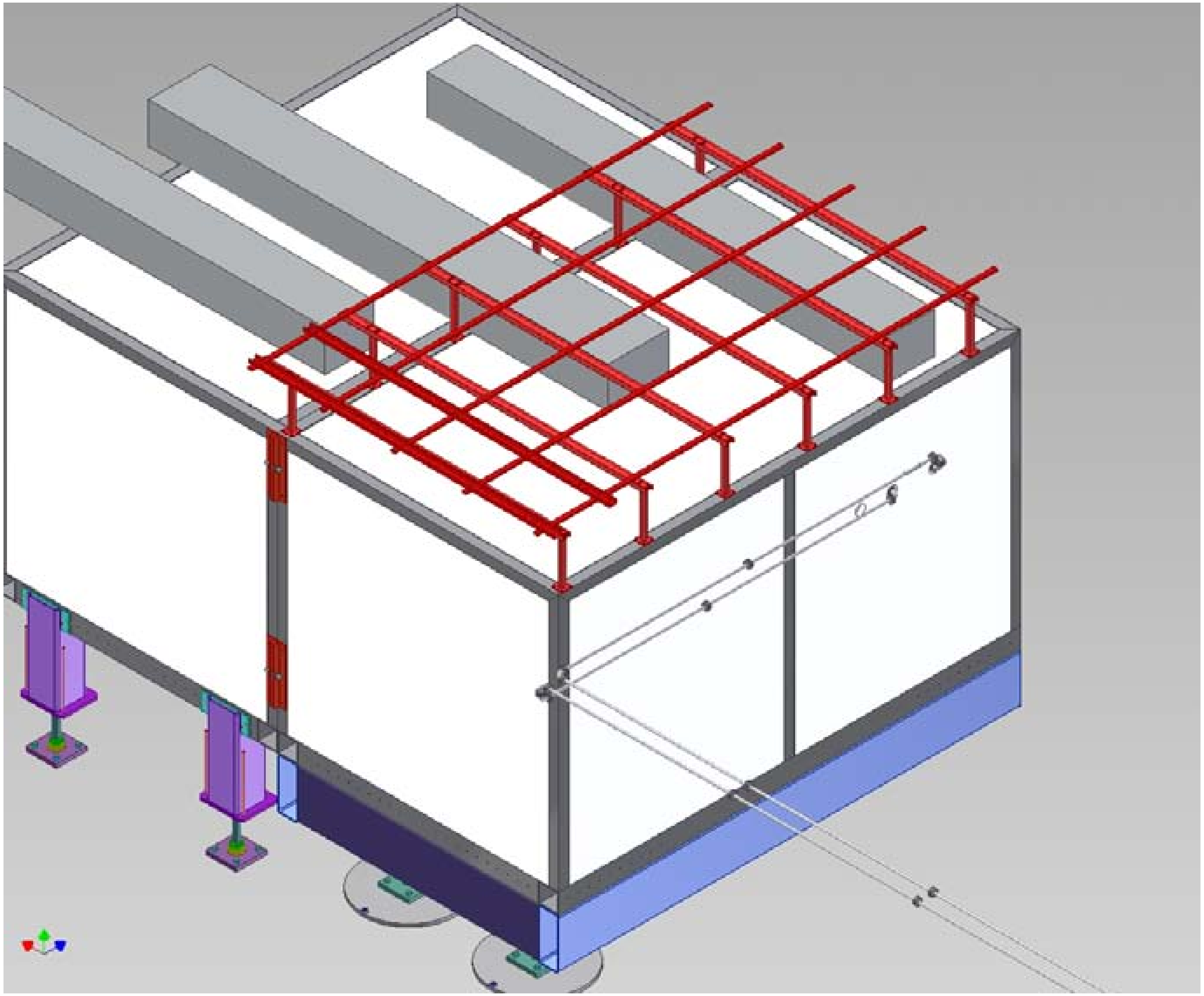


Assemble roof
supports first.

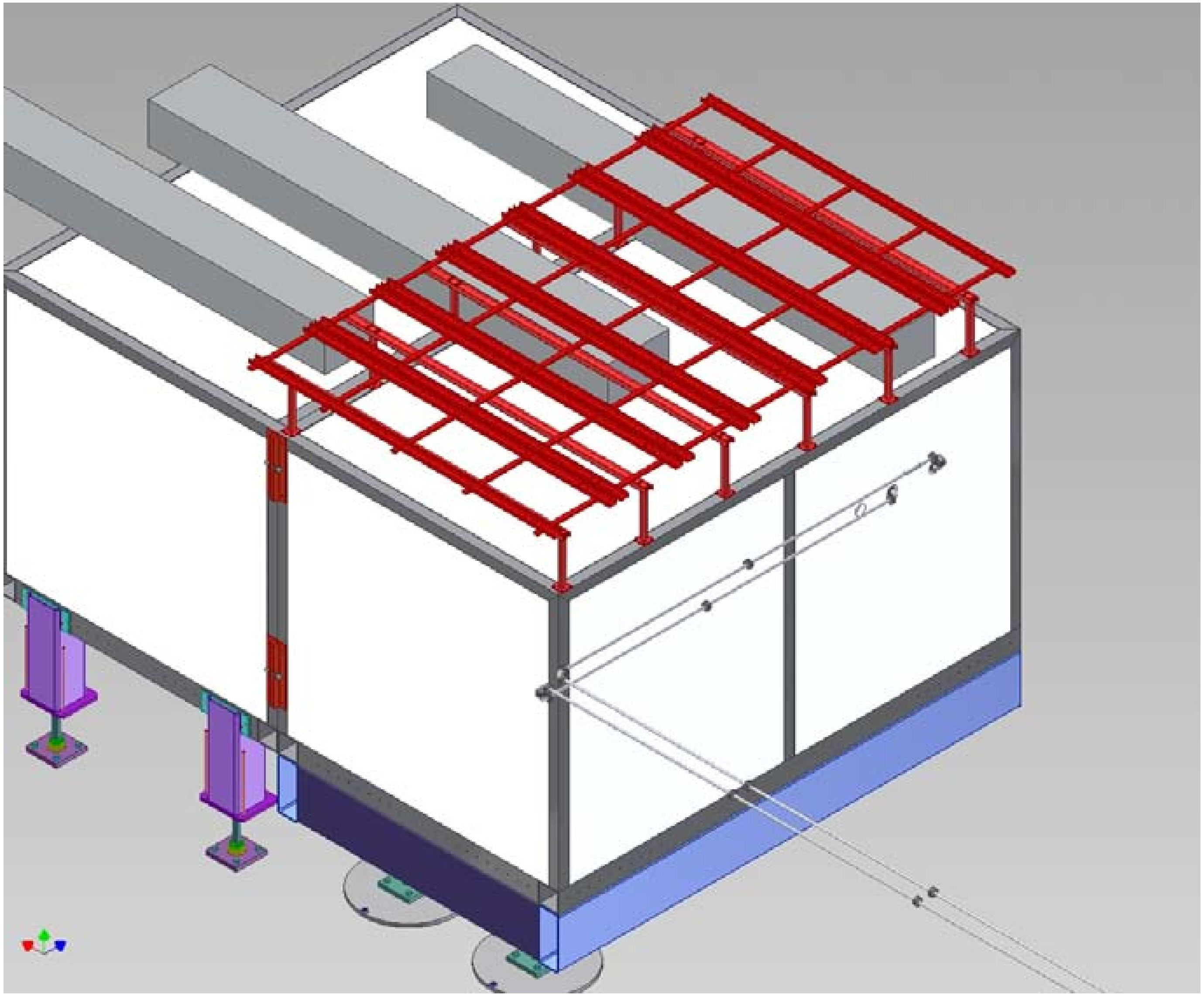


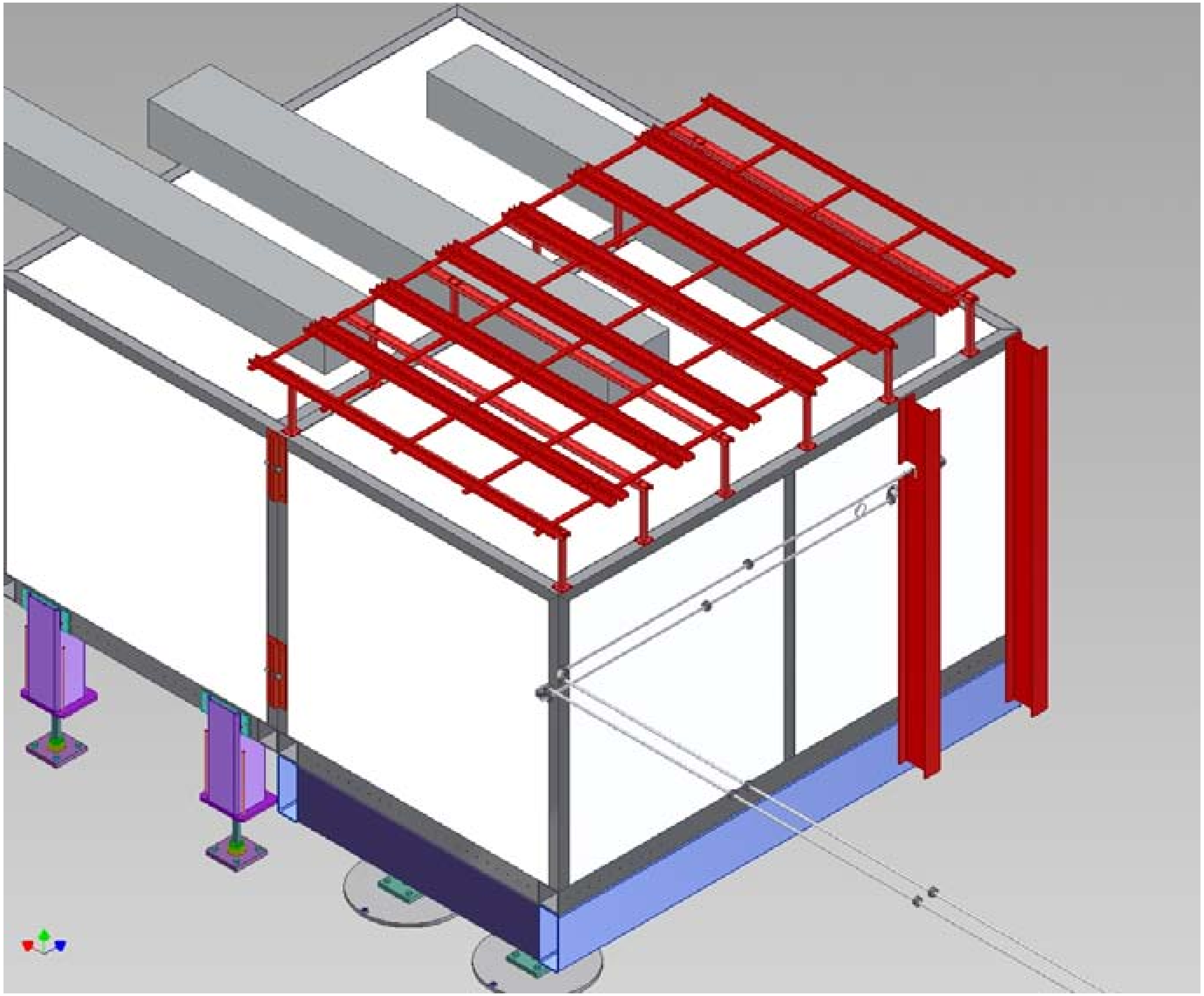






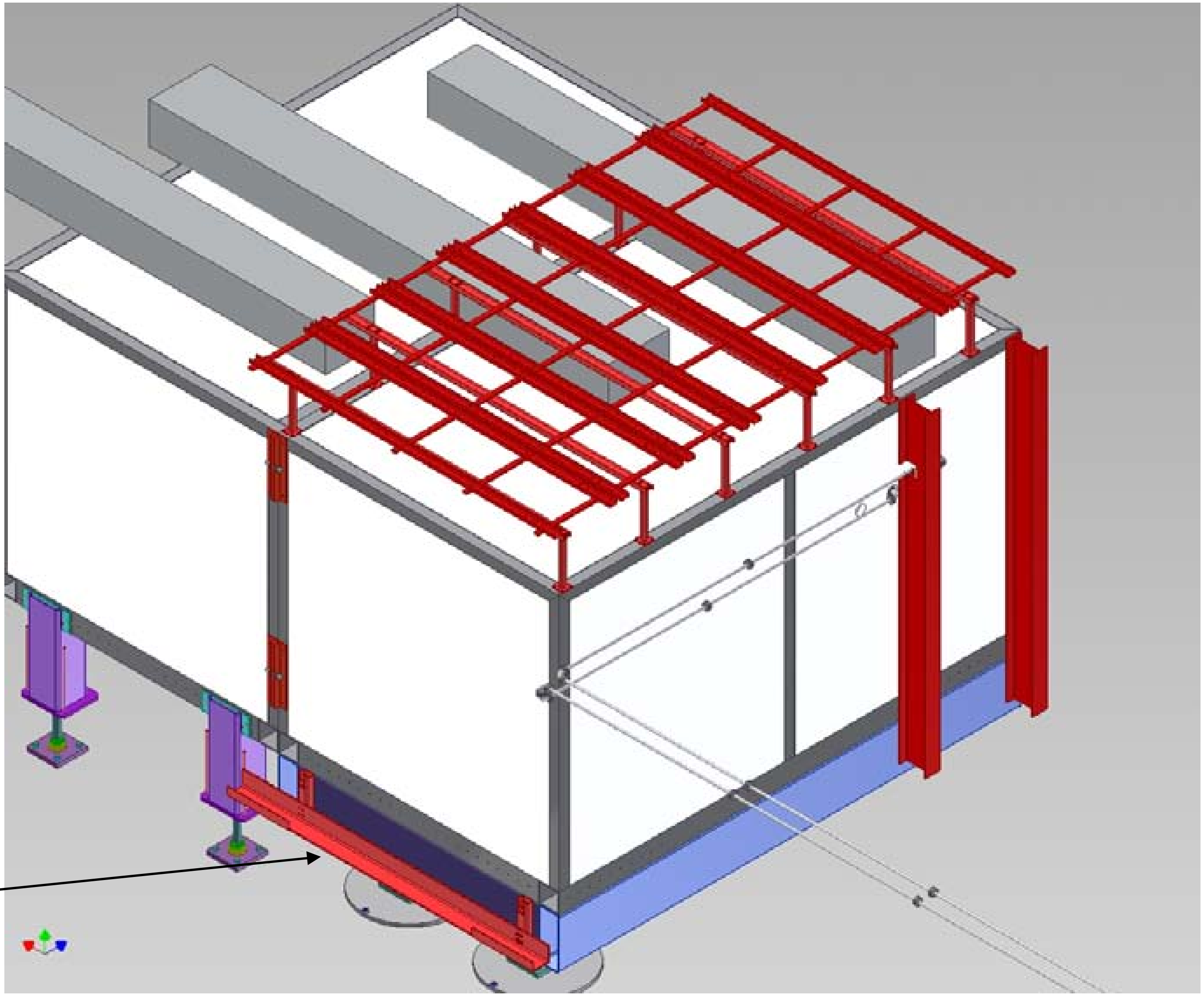
Add panel tracks for south face loading.



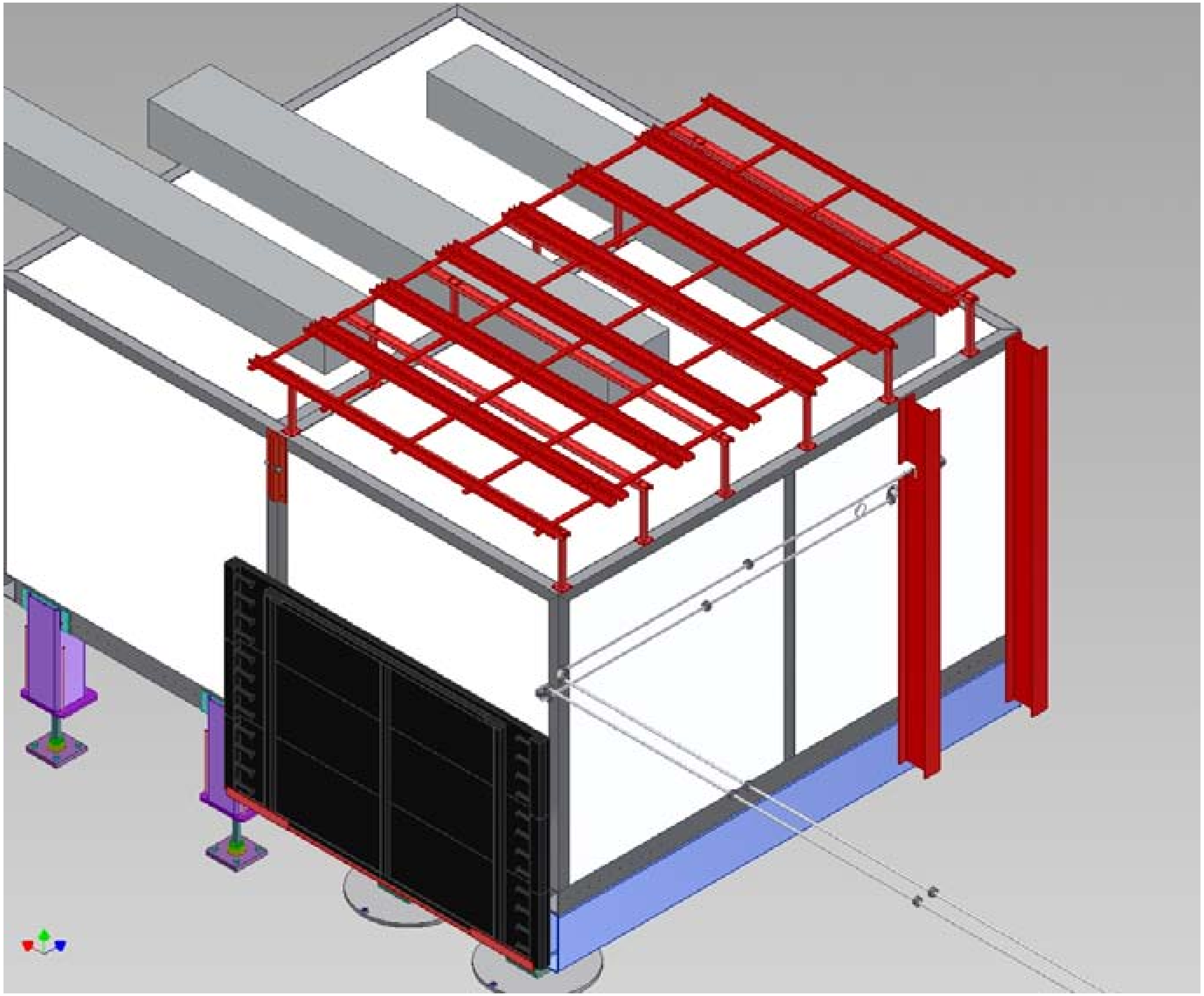


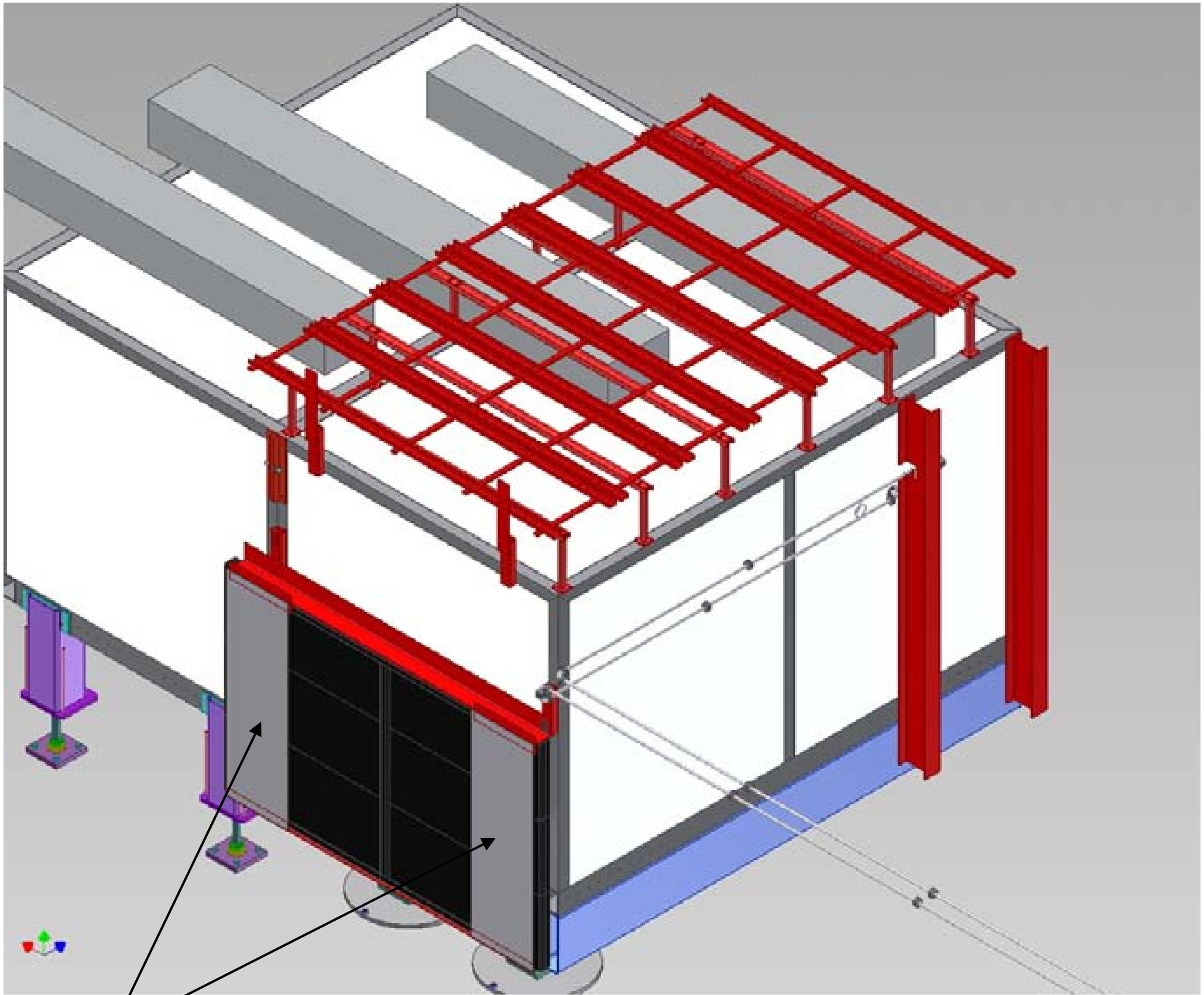
Install overlapping panel supports.

Lowest edge of all panels is 5” above the bottom of Mod. 1 support frame.

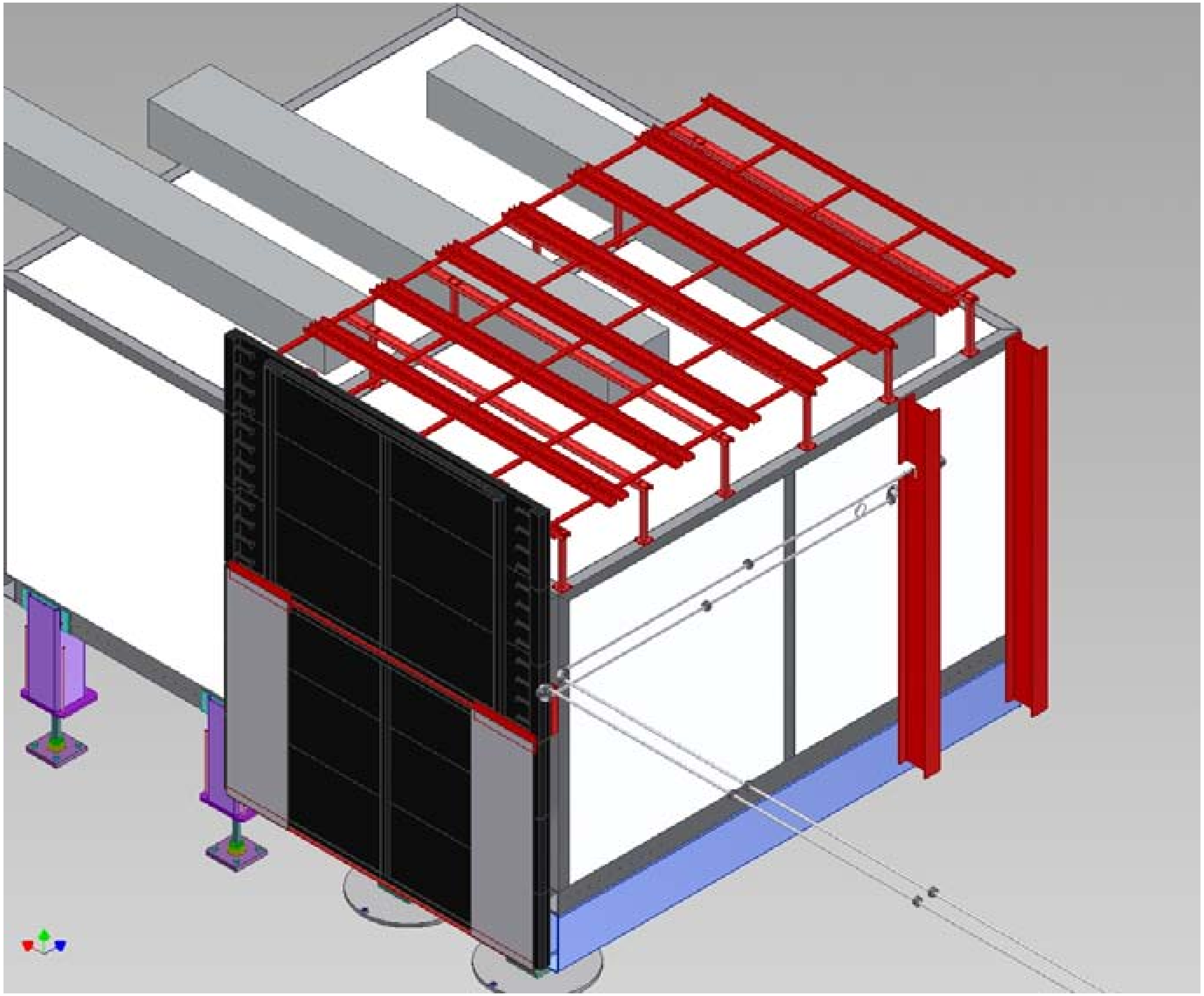


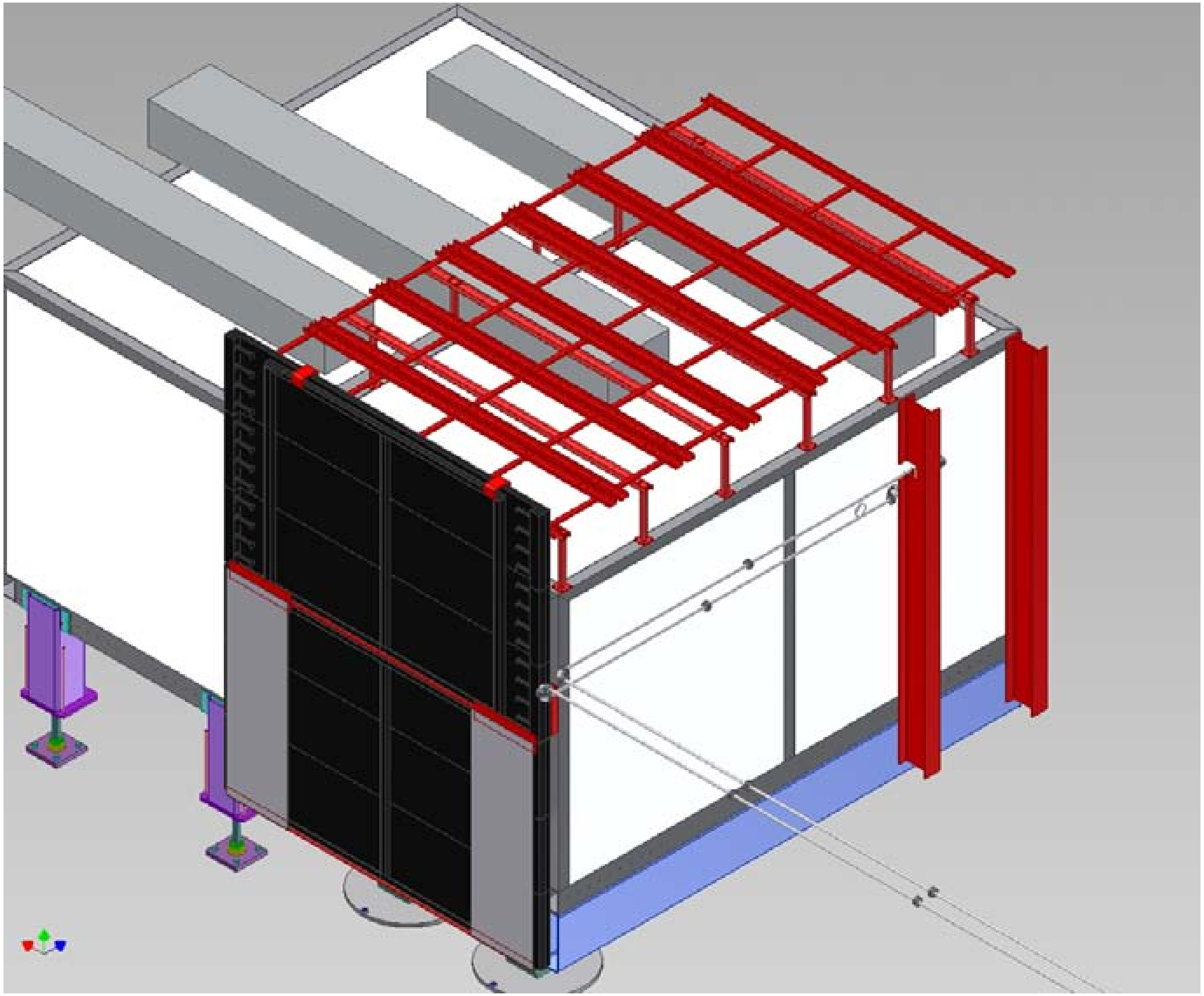
Assemble West face shelves and panels.

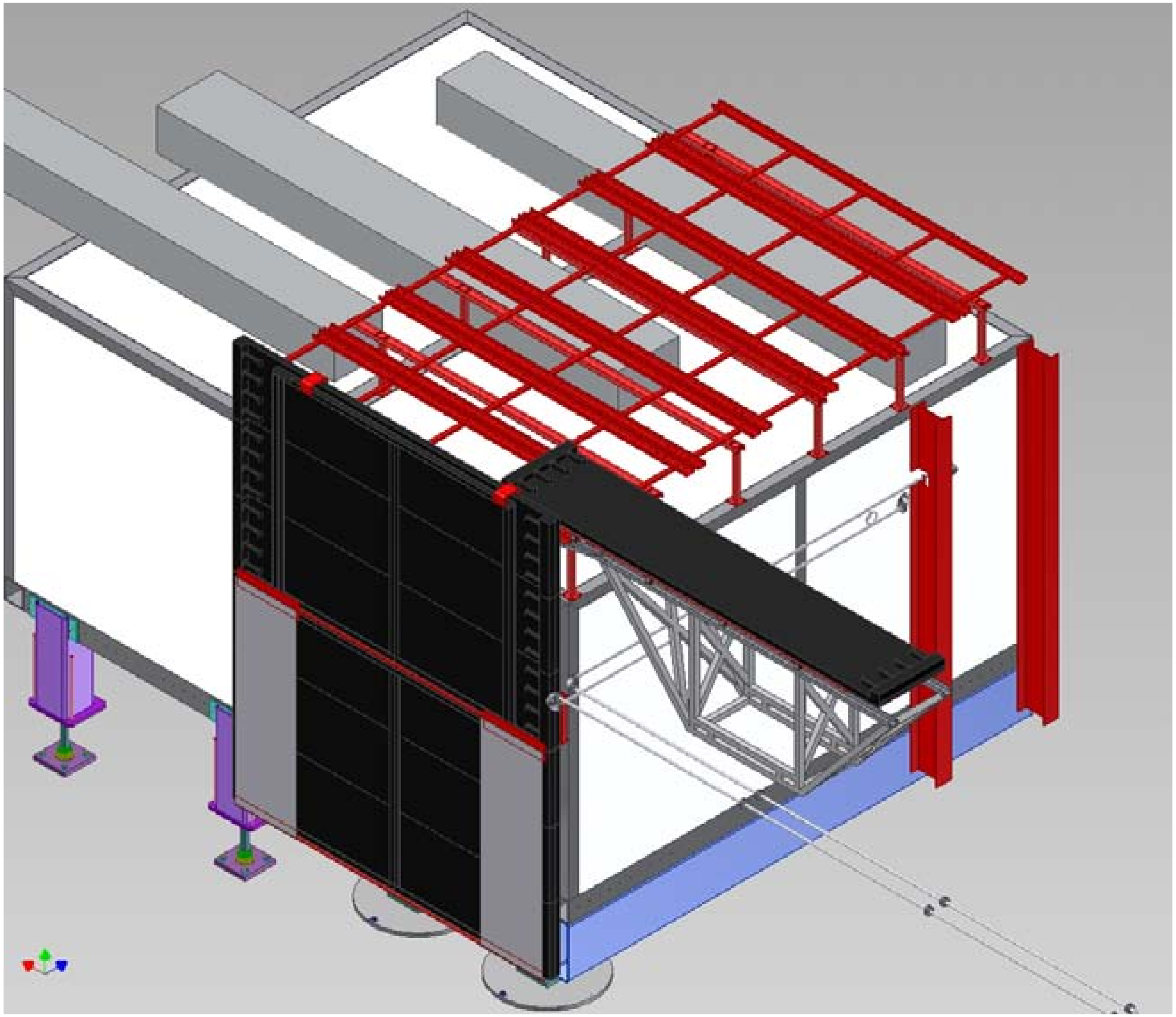




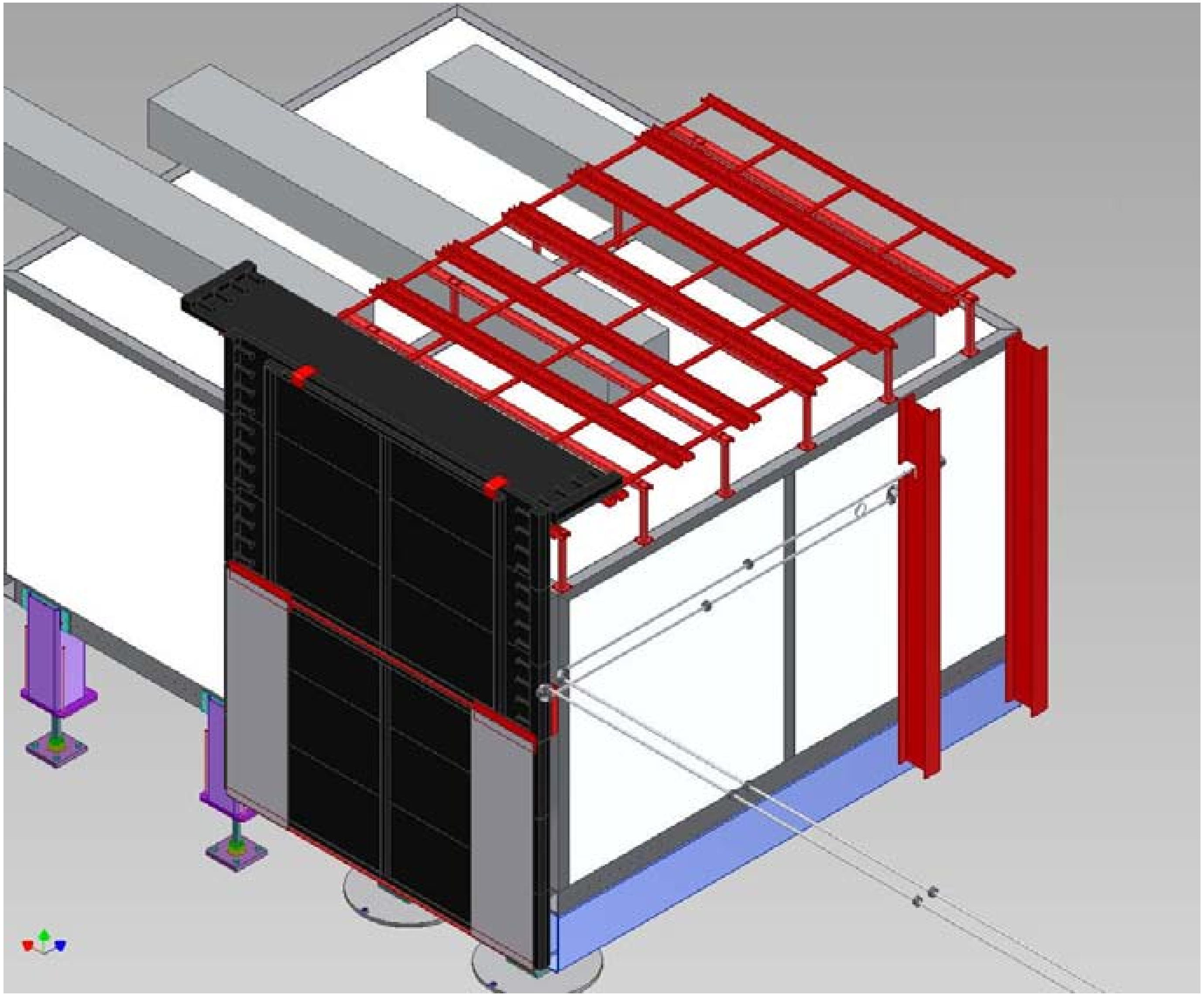
Protective
covers

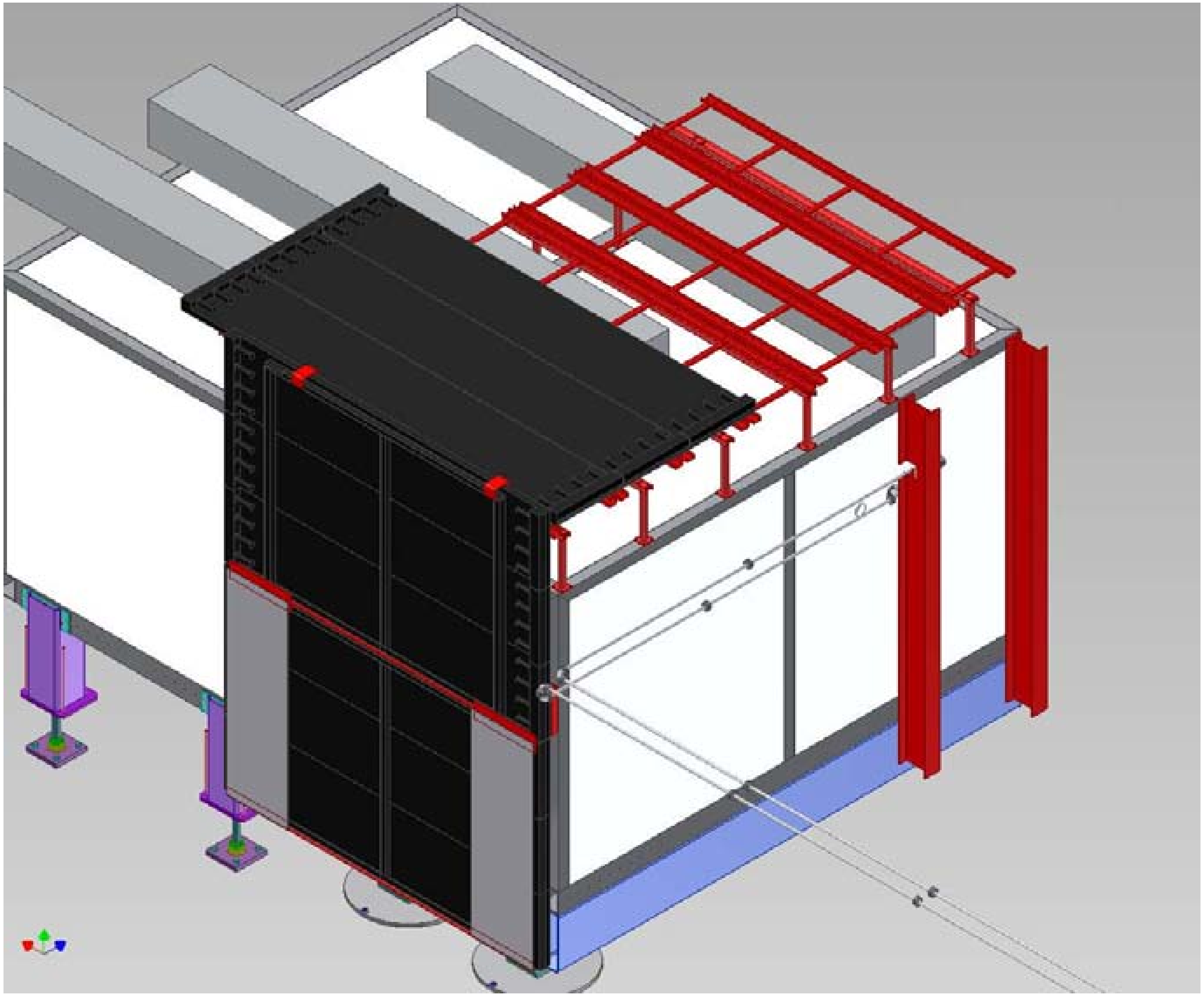


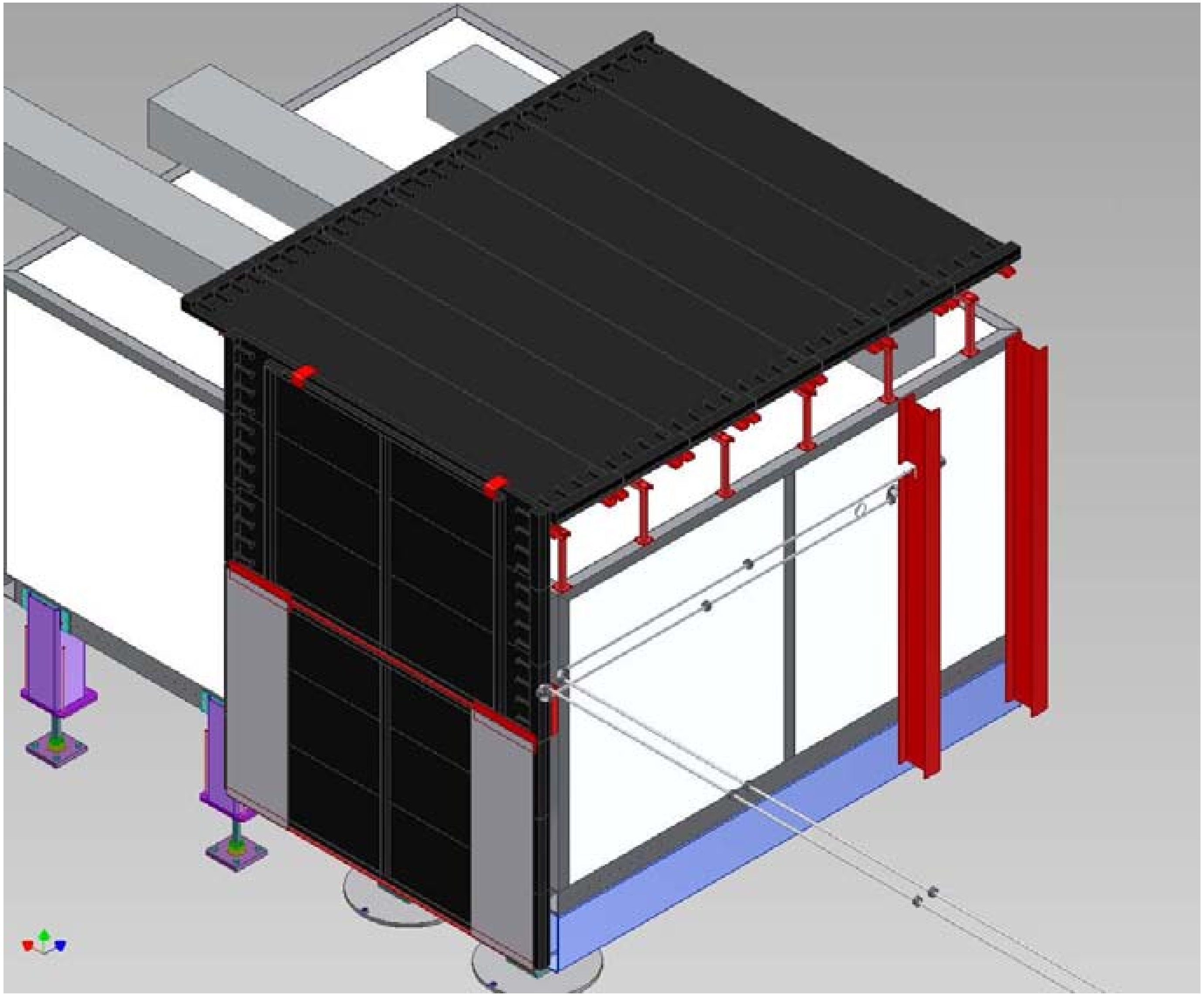


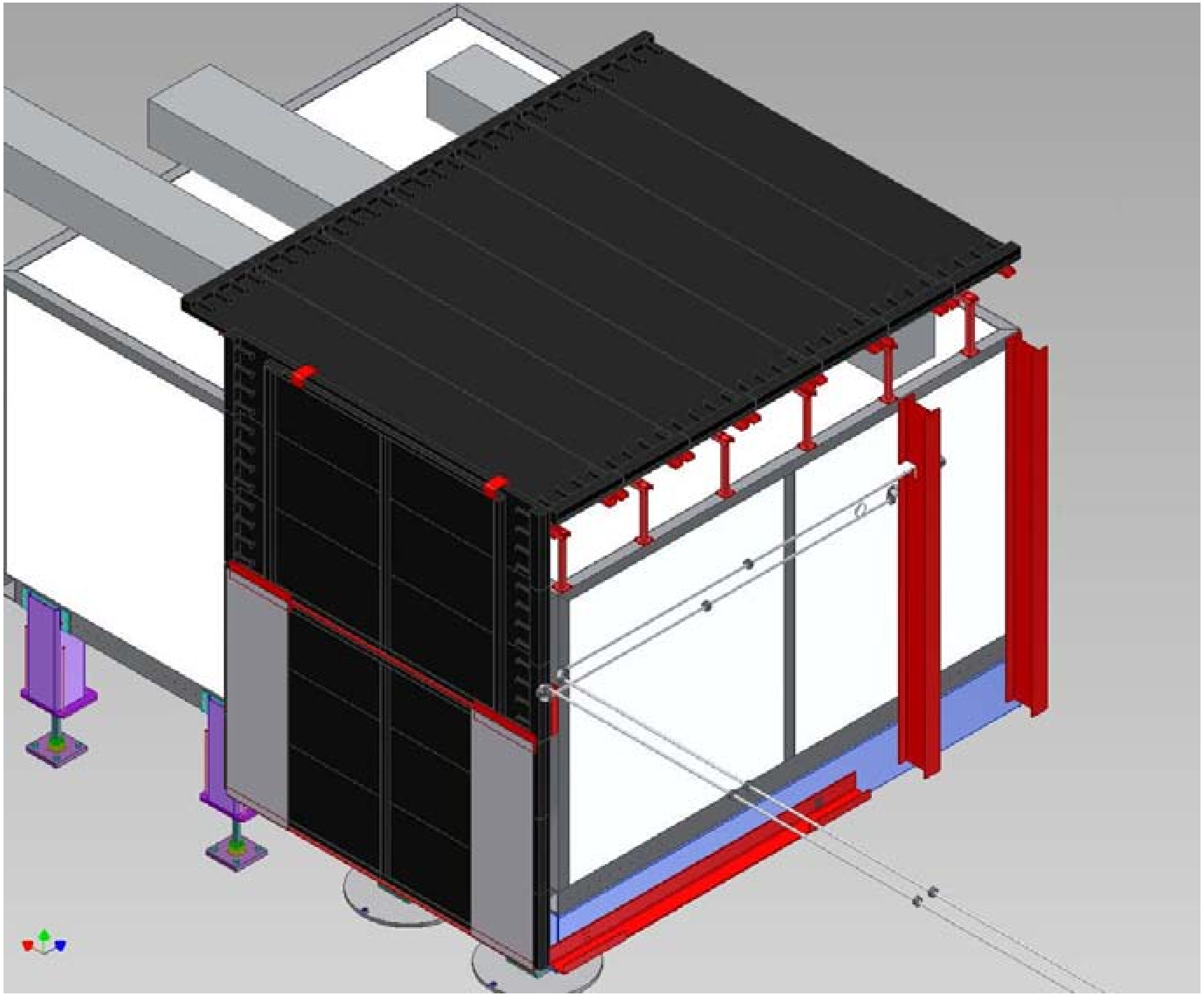


Lifting jig concept for South face loading of roof panels.

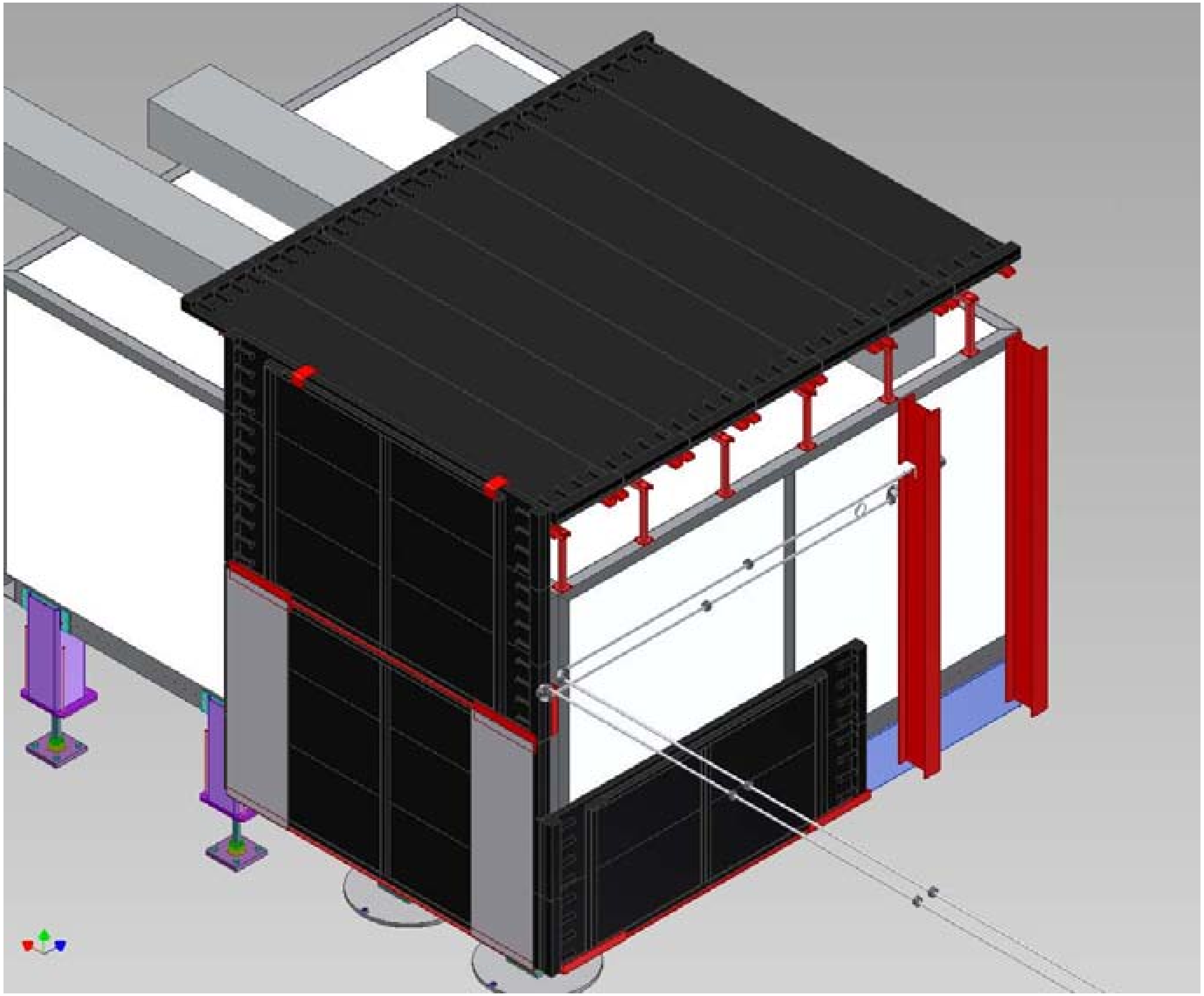


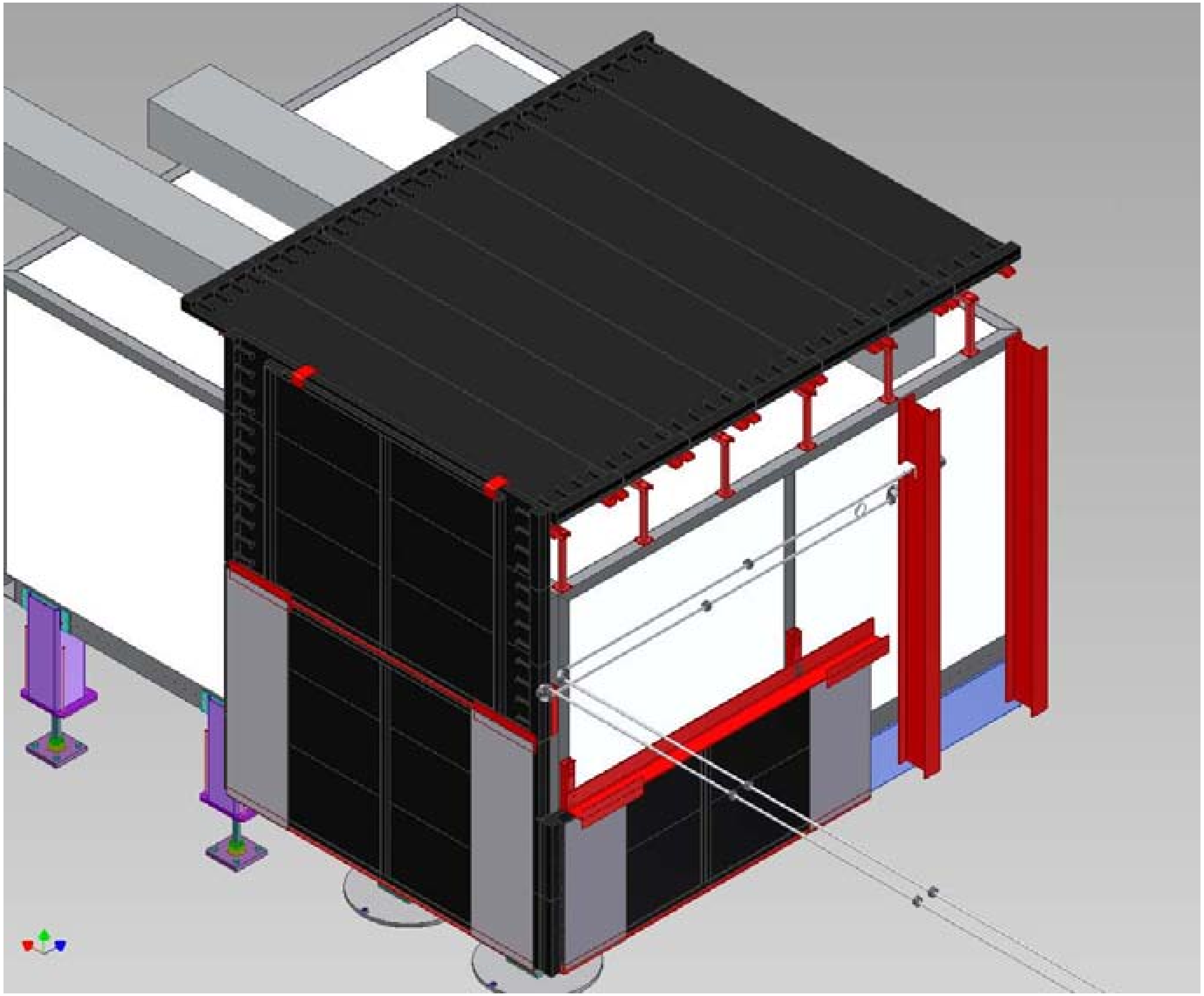


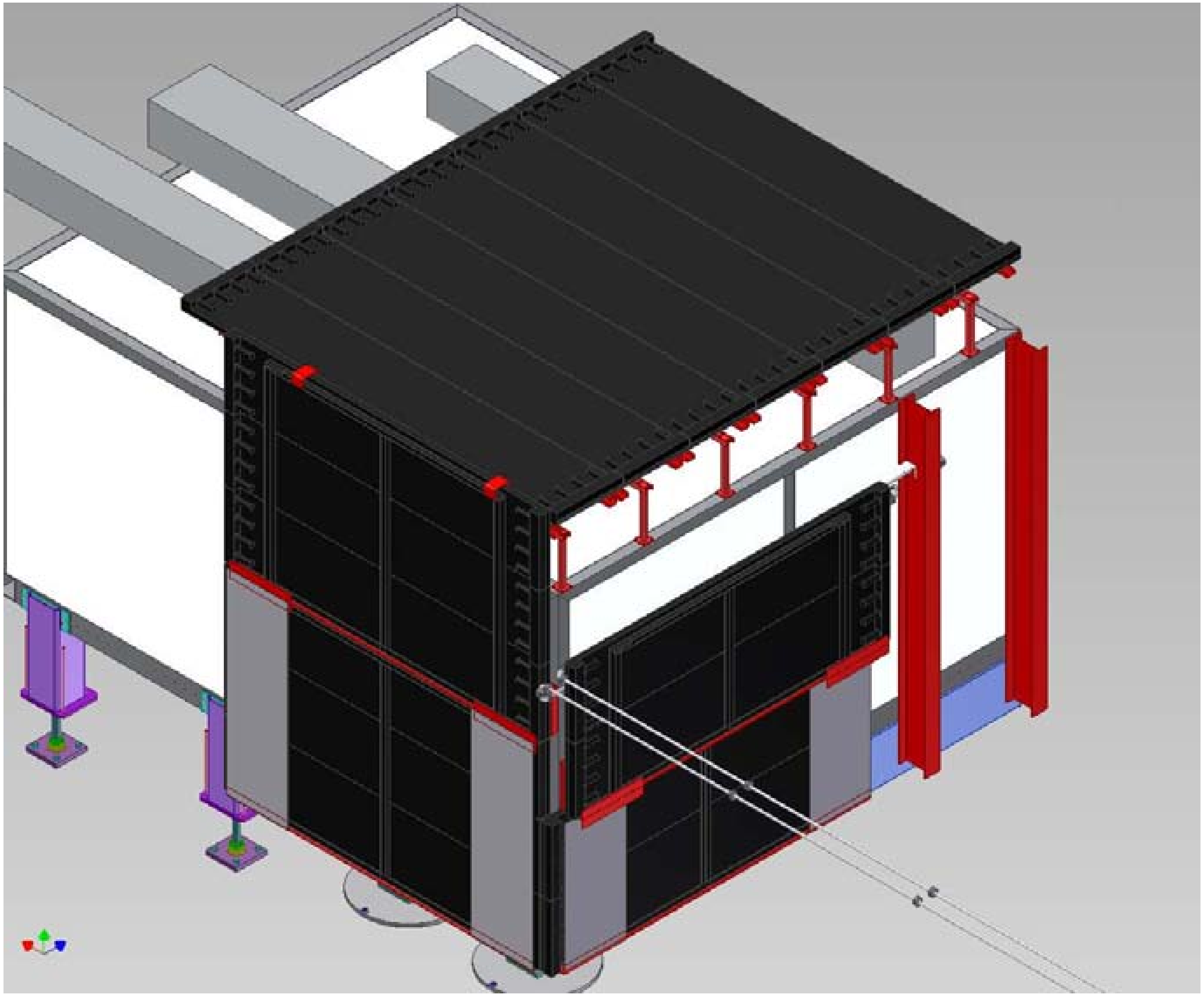


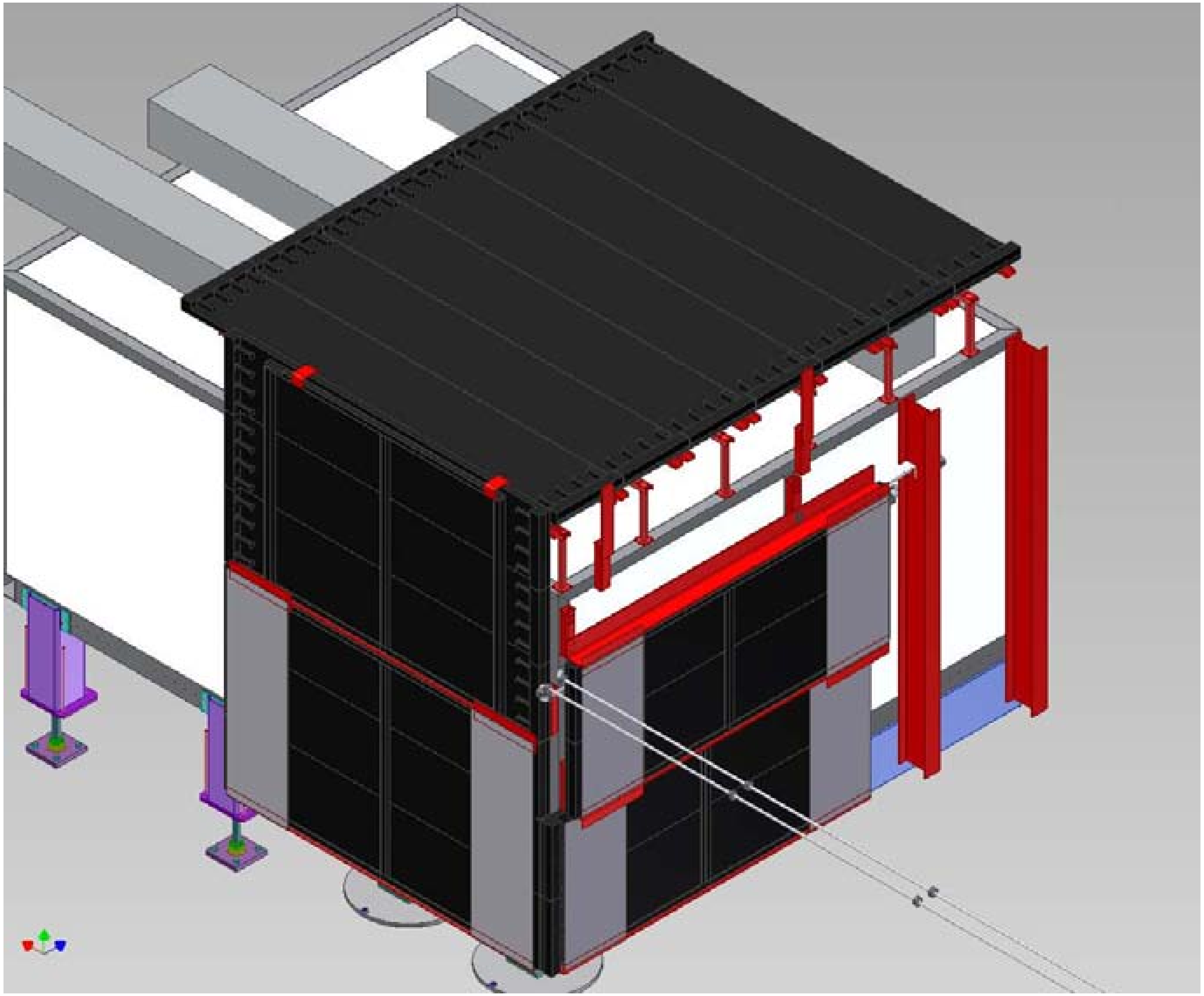


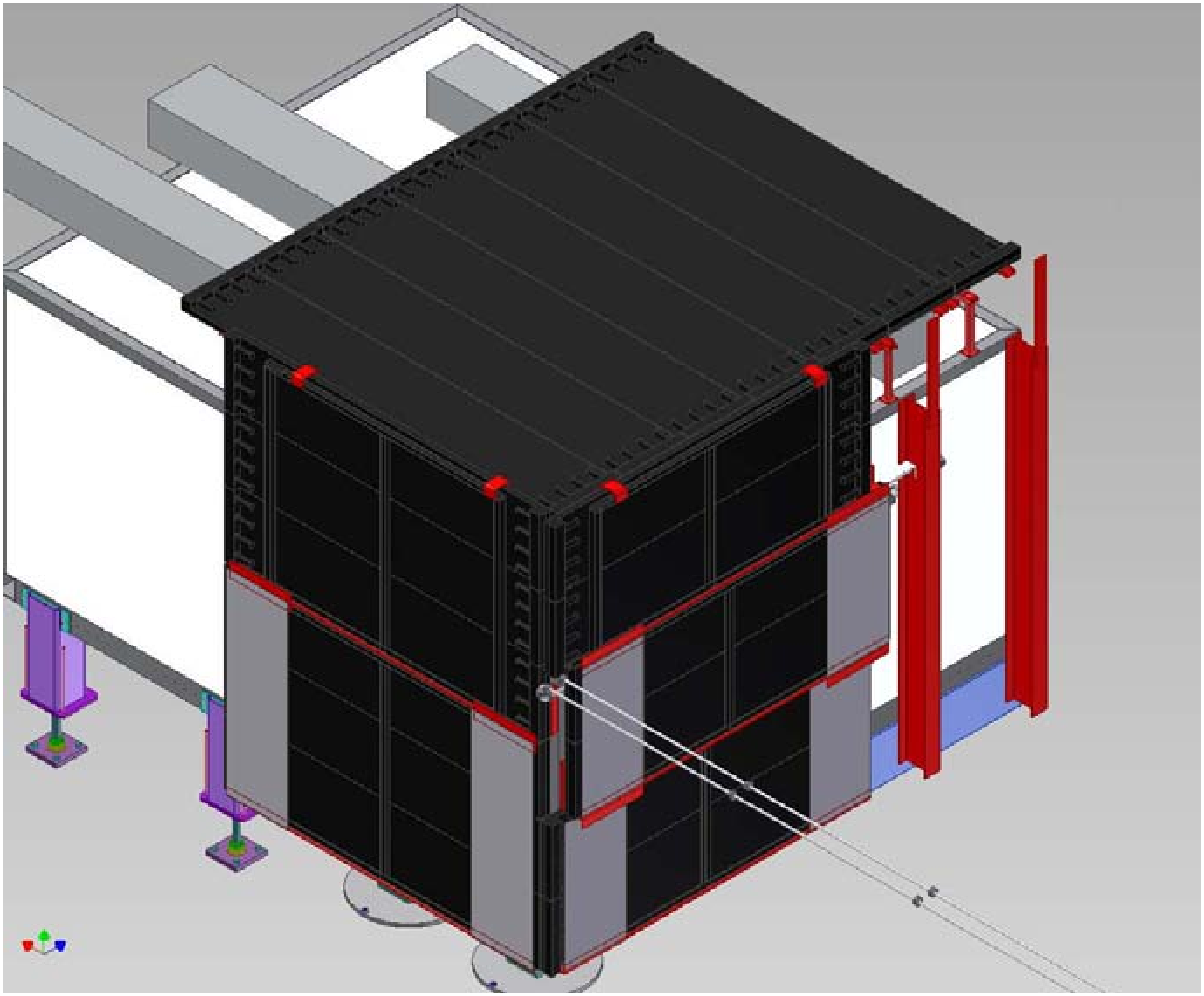
Install south face shelves
and panels.

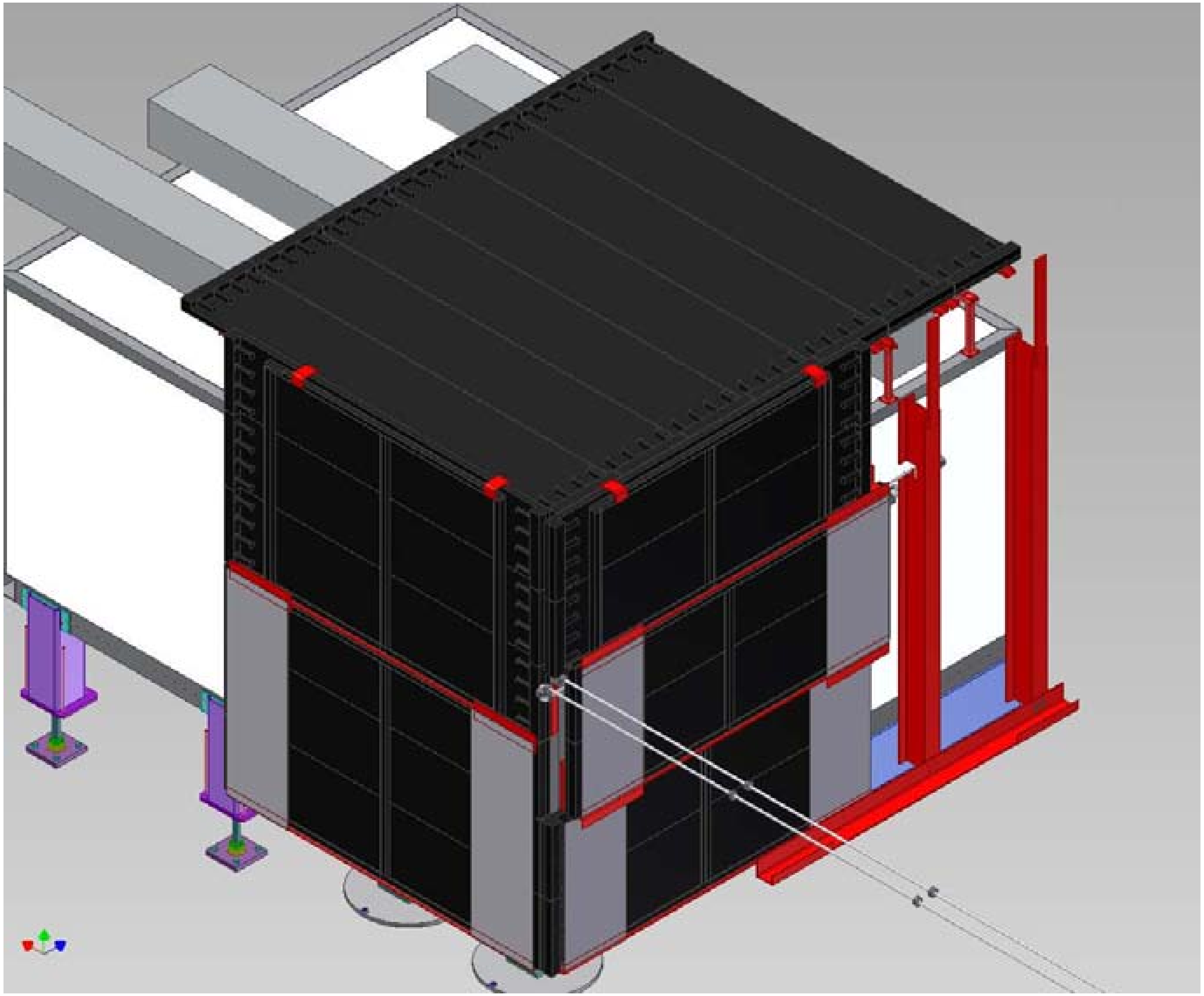




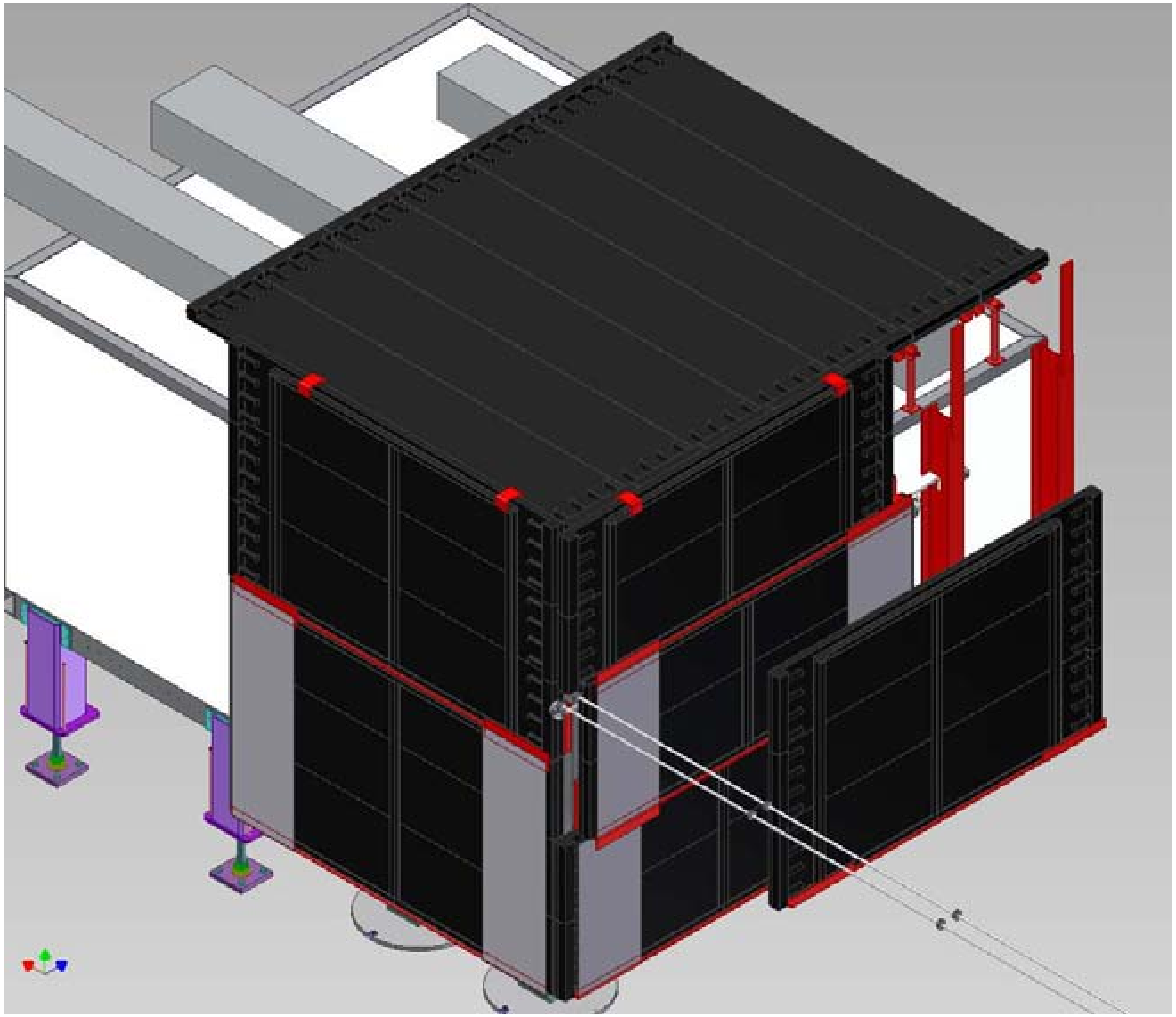


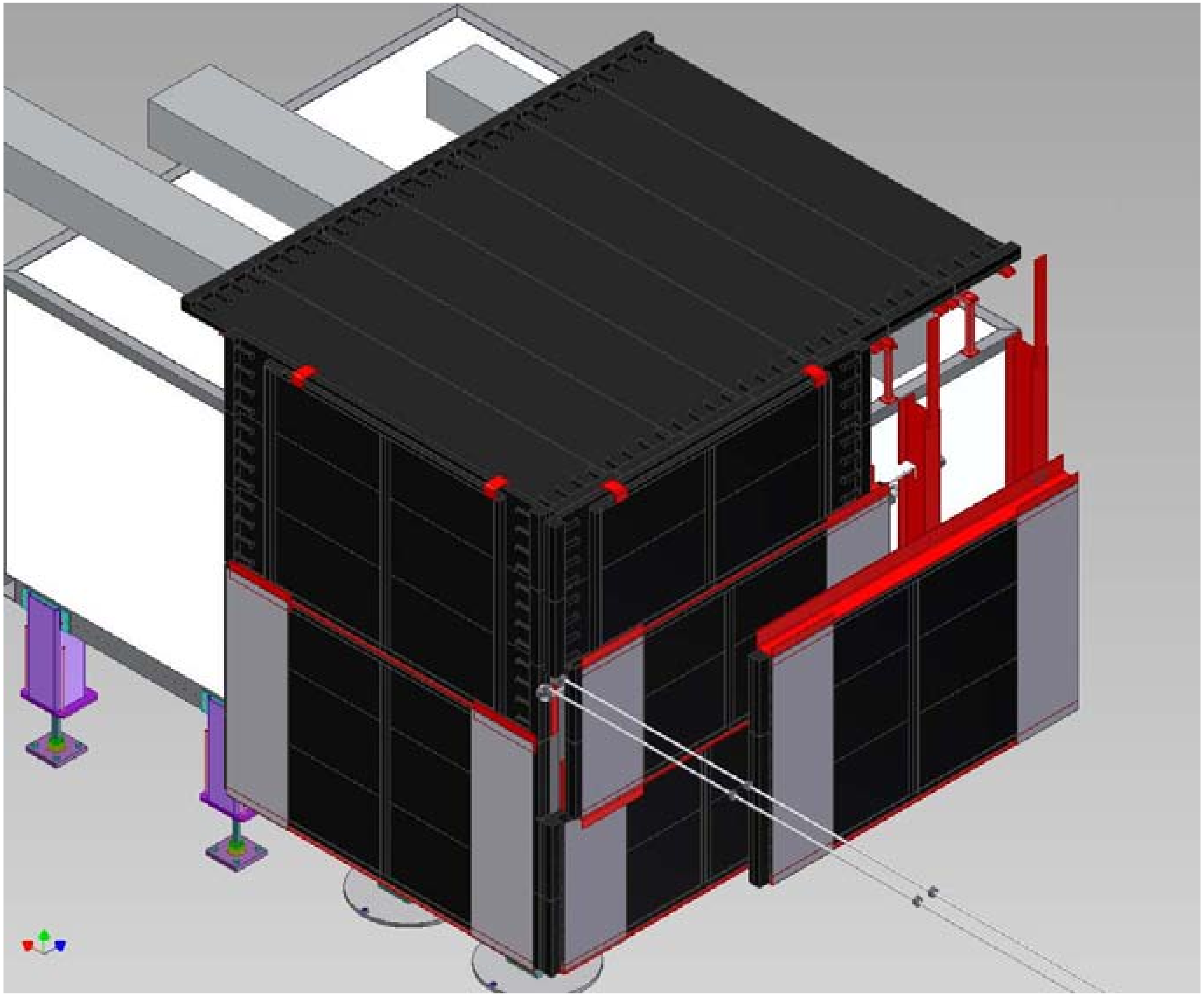


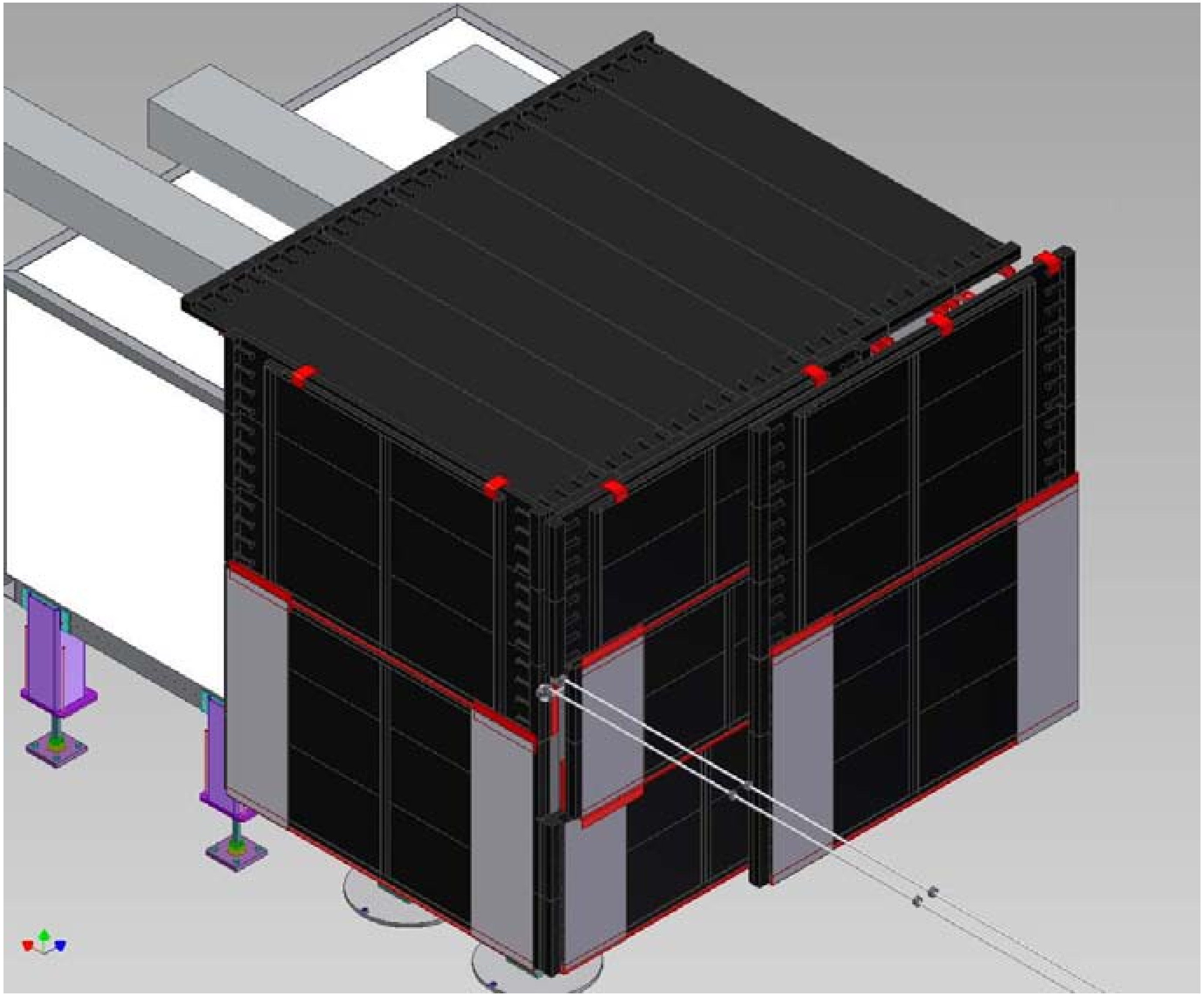




Install overlapping shelves
and panels.







EXO-200 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 2.46MeV endpoint
4) **Negligible background from $2\nu\beta\beta$ ($T_{1/2}$>$1\cdot10^{22}$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 (meV) QRPA[1]	NSM[2]
EXO-200	0.2	70	2	1.6*	40	$6.4 \ 10^{25}$	133	186

1) Rodin, *et. al.*, Nucl. Phys. A **793** (2007) 213-215
2) Caurier, *et. al.*, arXiv:0709.2137v2

What if the Heidelberg signal is due to $\beta\beta 0\nu$–decay ?

Central value $T_{1/2}$ (Ge) = $2.23^{+0.44}_{-0.31} \cdot 10^{25}$, ($\pm 3\sigma$) (MPL A 1547 (06))

A Ge and Xe experiment have the neutrino mass in common:

$$T^{0\nu}_{1/2,Xe} = \frac{G^{0\nu}_{Ge} \cdot \left|M^{0\nu}_{Ge}\right|^2}{G^{0\nu}_{Xe} \cdot \left|M^{0\nu}_{Xe}\right|^2} \cdot T^{0\nu}_{1/2,Ge} = \alpha \cdot T^{0\nu}_{1/2,Ge}$$

In 200 kg EXO, after 2 yrs of life time:

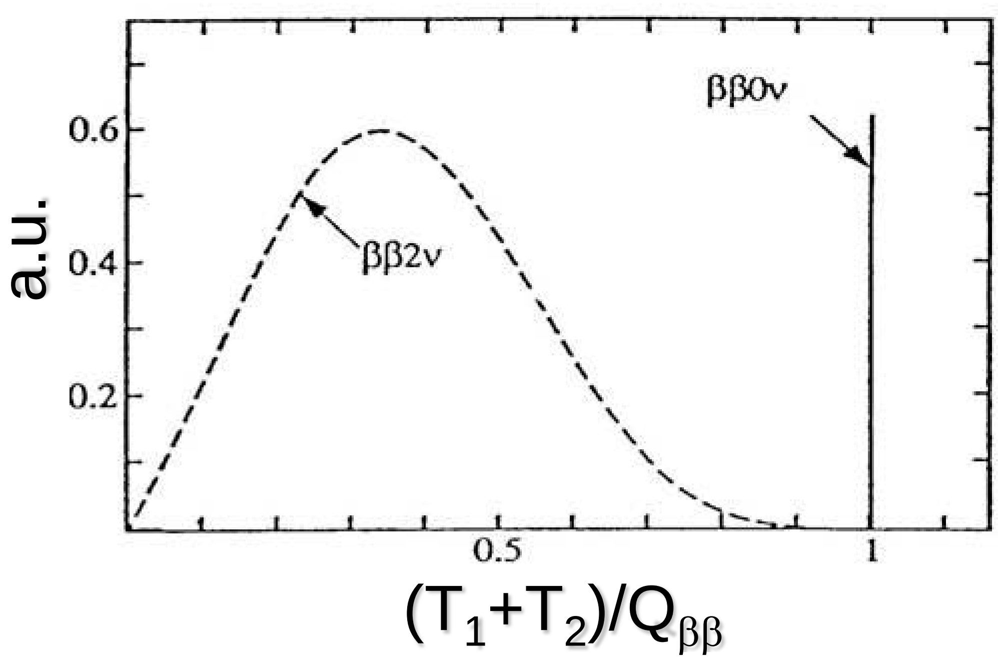
Worst case (RQRPA, upper limit, α=0.53):
46 events on top of 40 events bkgd → 5.0 σ

Best case (NSM, lower limit, α=0.20):
170 events on top of 40 bkgd → 11.7 σ

Ba single ion detection

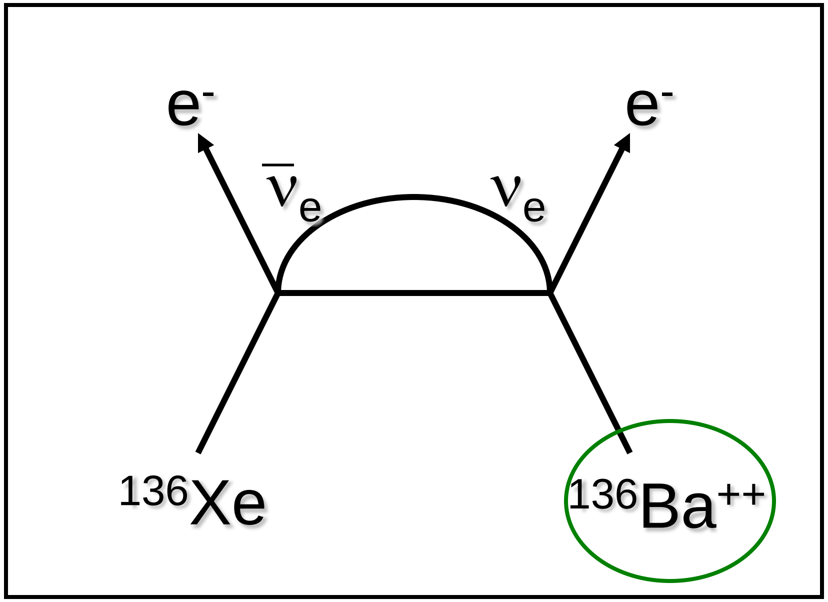
Out of time?
Skip to end

ββ decay observables



Energy deposition from two e^-

Daughter nucleus



Ba Grabber

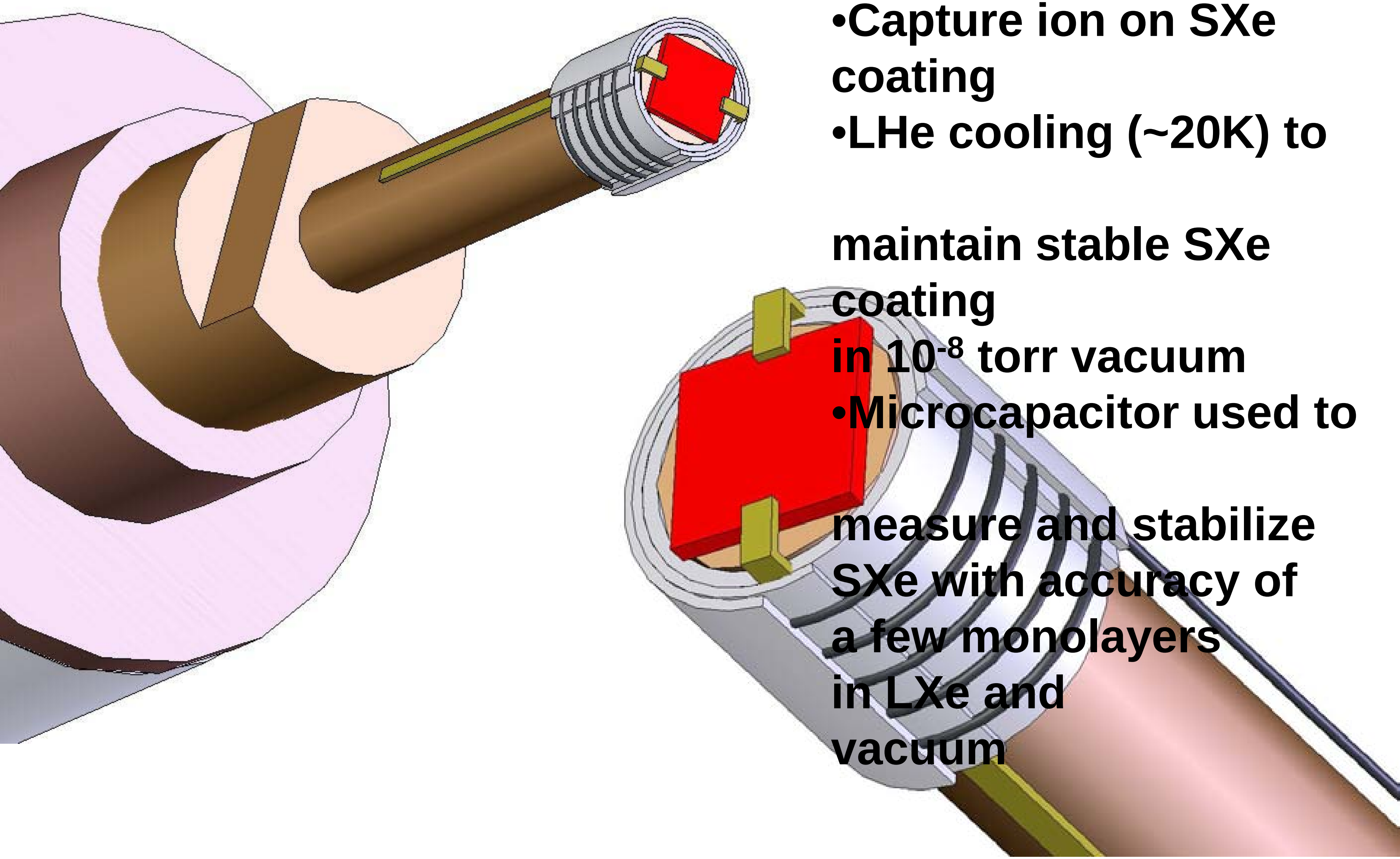
Problem: efficiently remove Ba++ ion from Xenon and release it into an ion trap for laser detection.

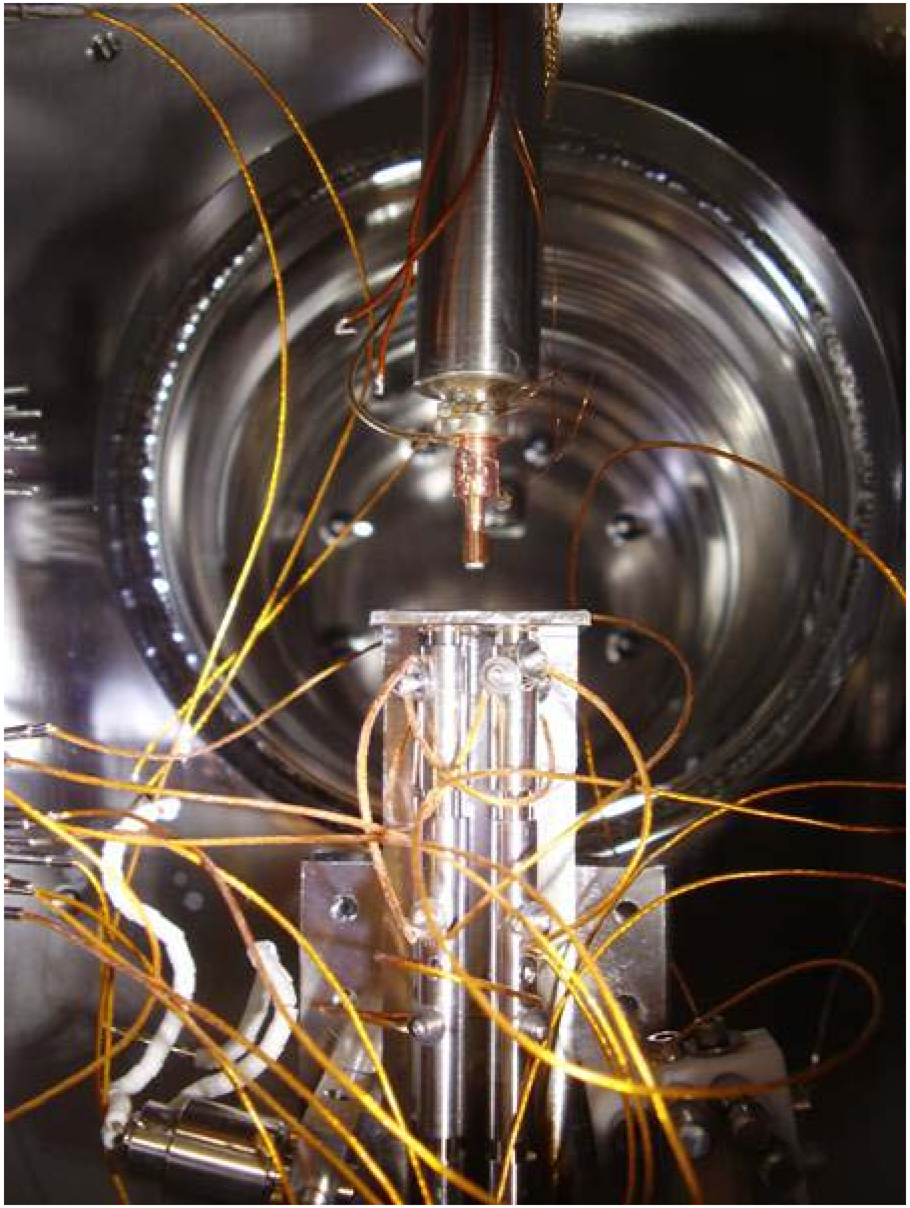
Several approaches have been explored, field emission, ice coating, resonance ionization…

It turns out that not the "attraction" part is the biggest problem but the release. Answer: cover a charged tip with a very thin layer of Xe ice (few mono-layers) which is thawed for release.

Cryogenic dipstick

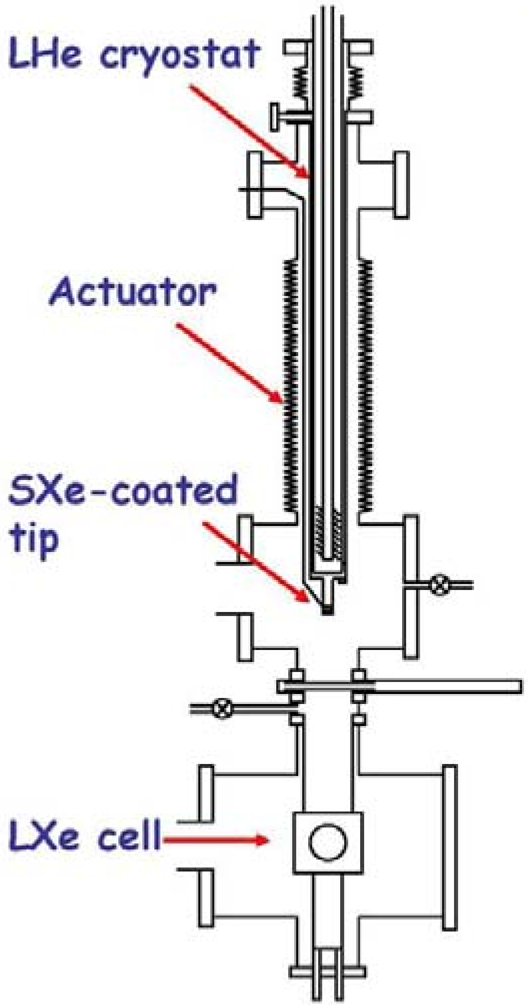
- Capture ion on SXe coating
- LHe cooling (~20K) to maintain stable SXe coating in 10^{-8} torr vacuum
- Microcapacitor used to measure and stabilize SXe with accuracy of a few monolayers in LXe and vacuum





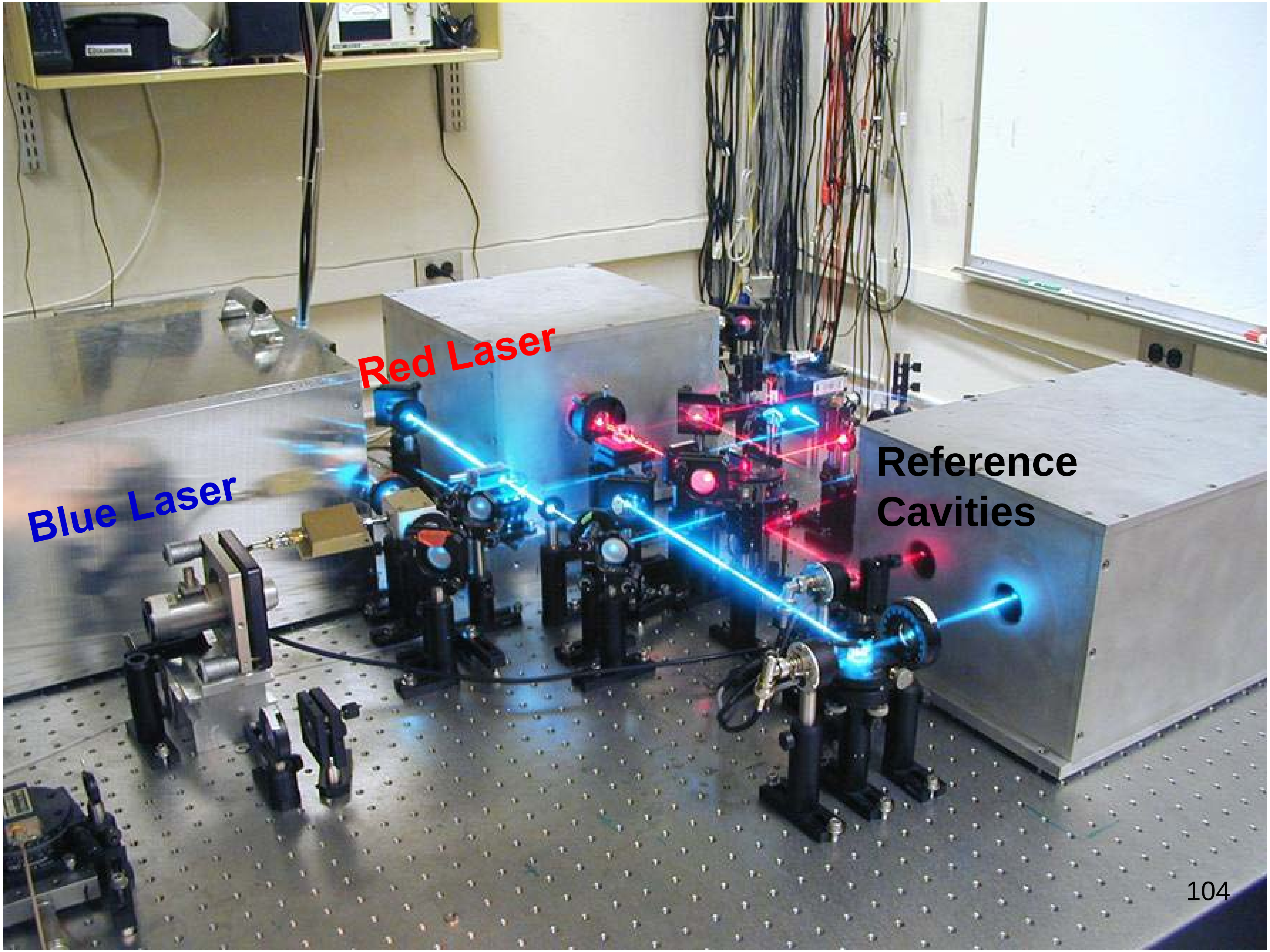
Prototype grabber and linear ion trap at Stanford.

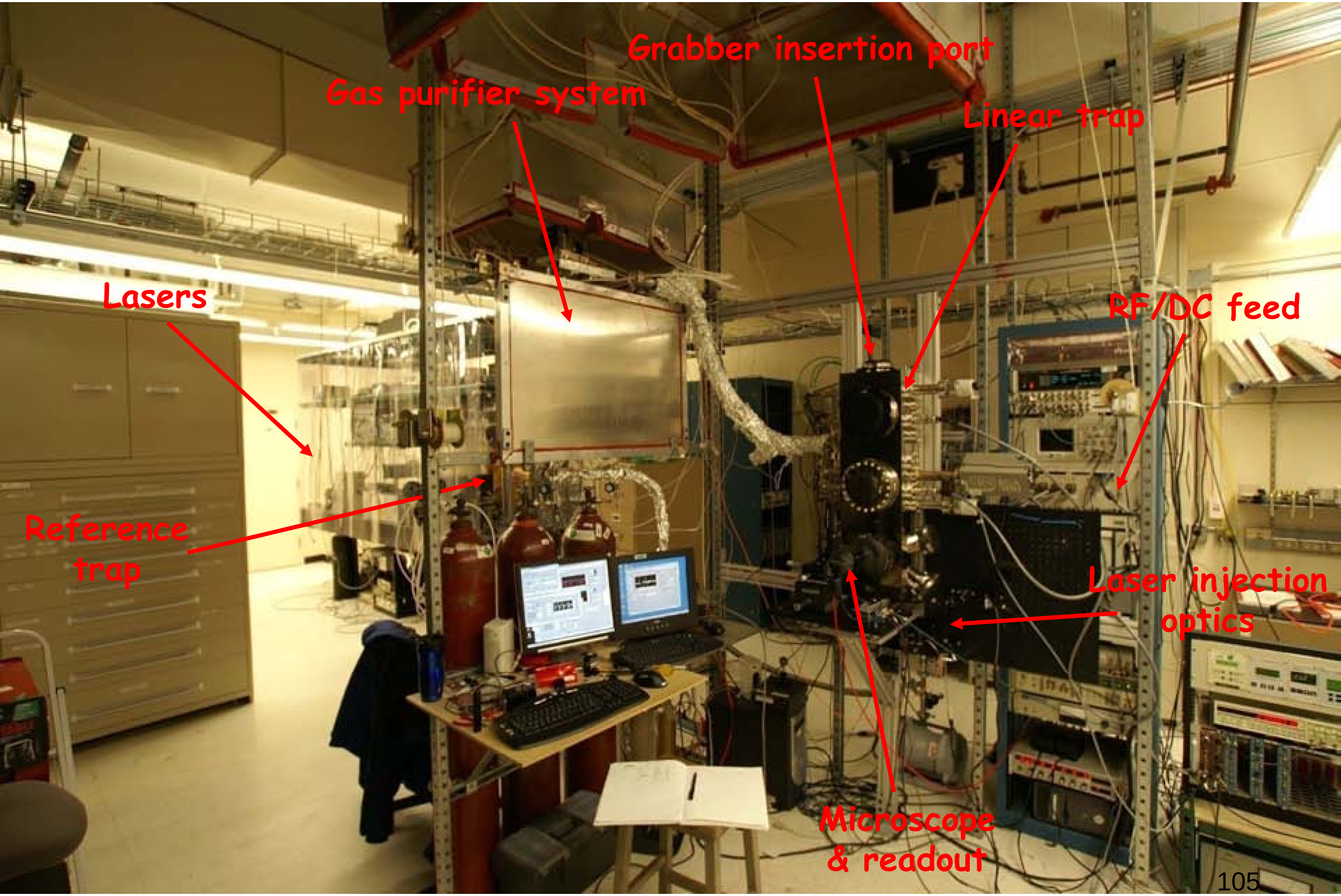
Complete setup



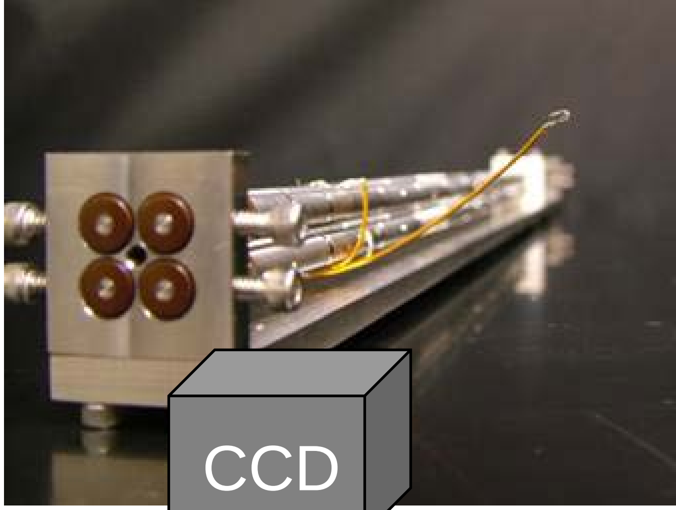
Single Ion Detection

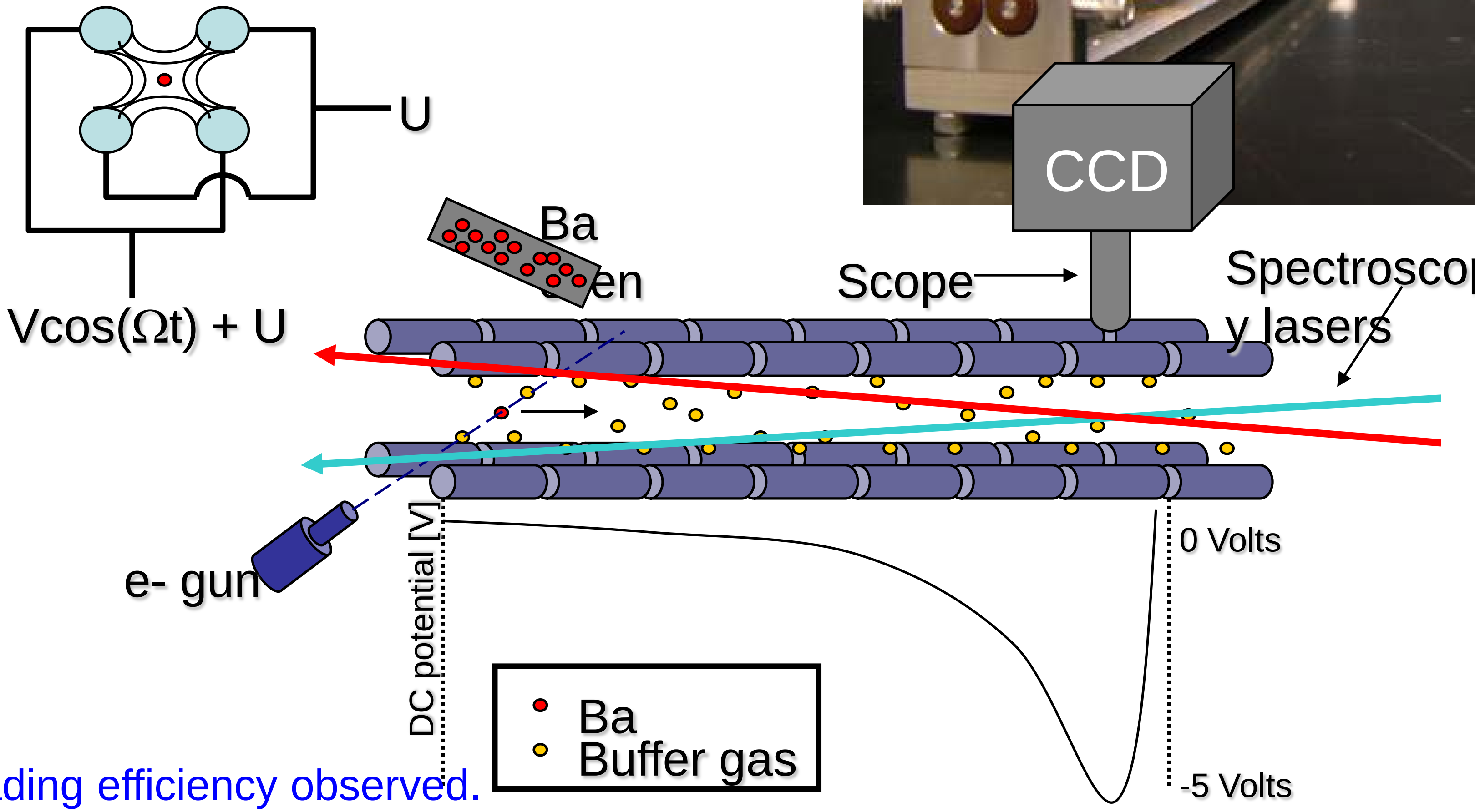
Stable laser tagging system



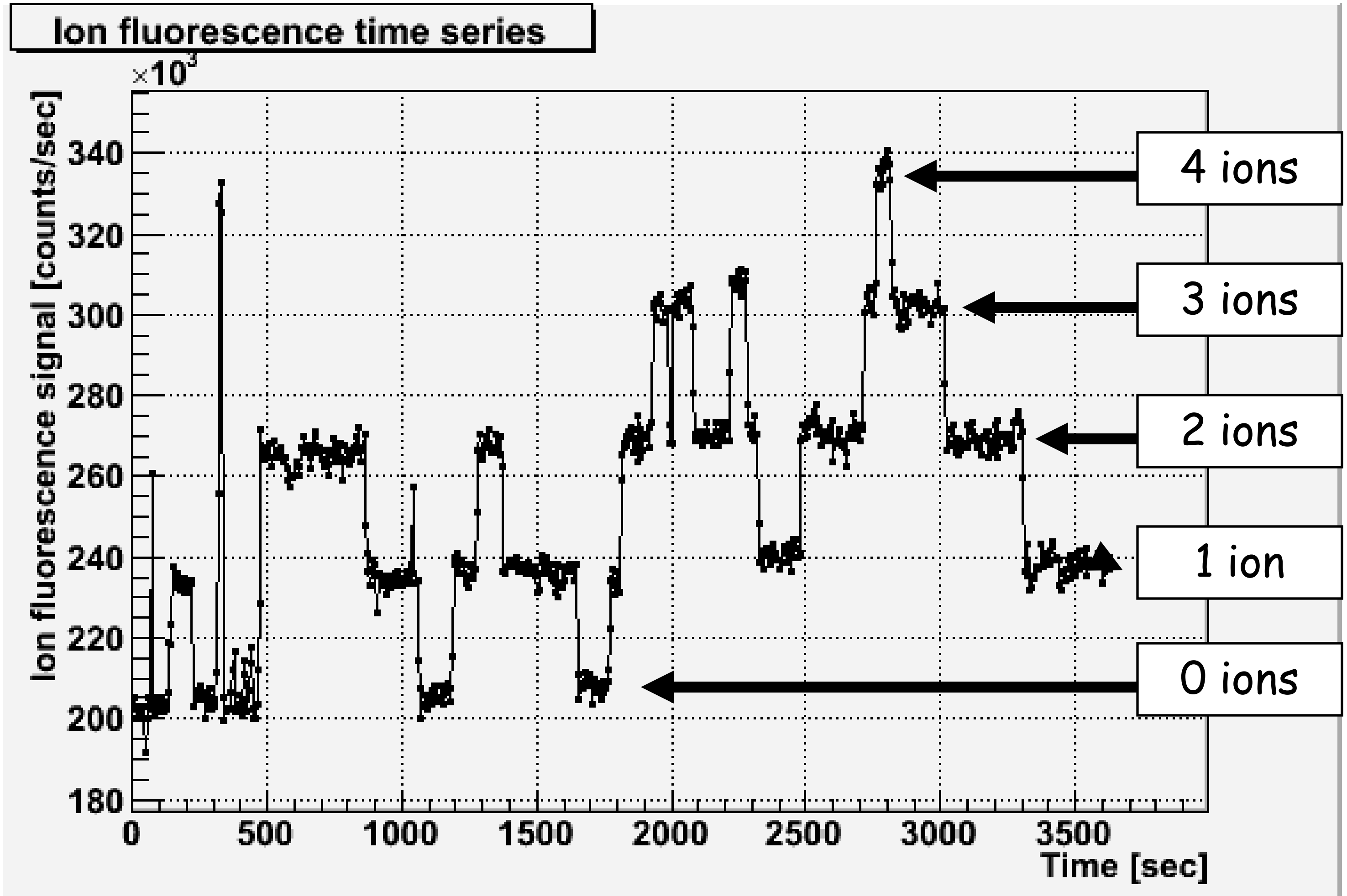

Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference trap
Laser injection optics
Microscope & readout

Ba^{+} Linear Ion Trap

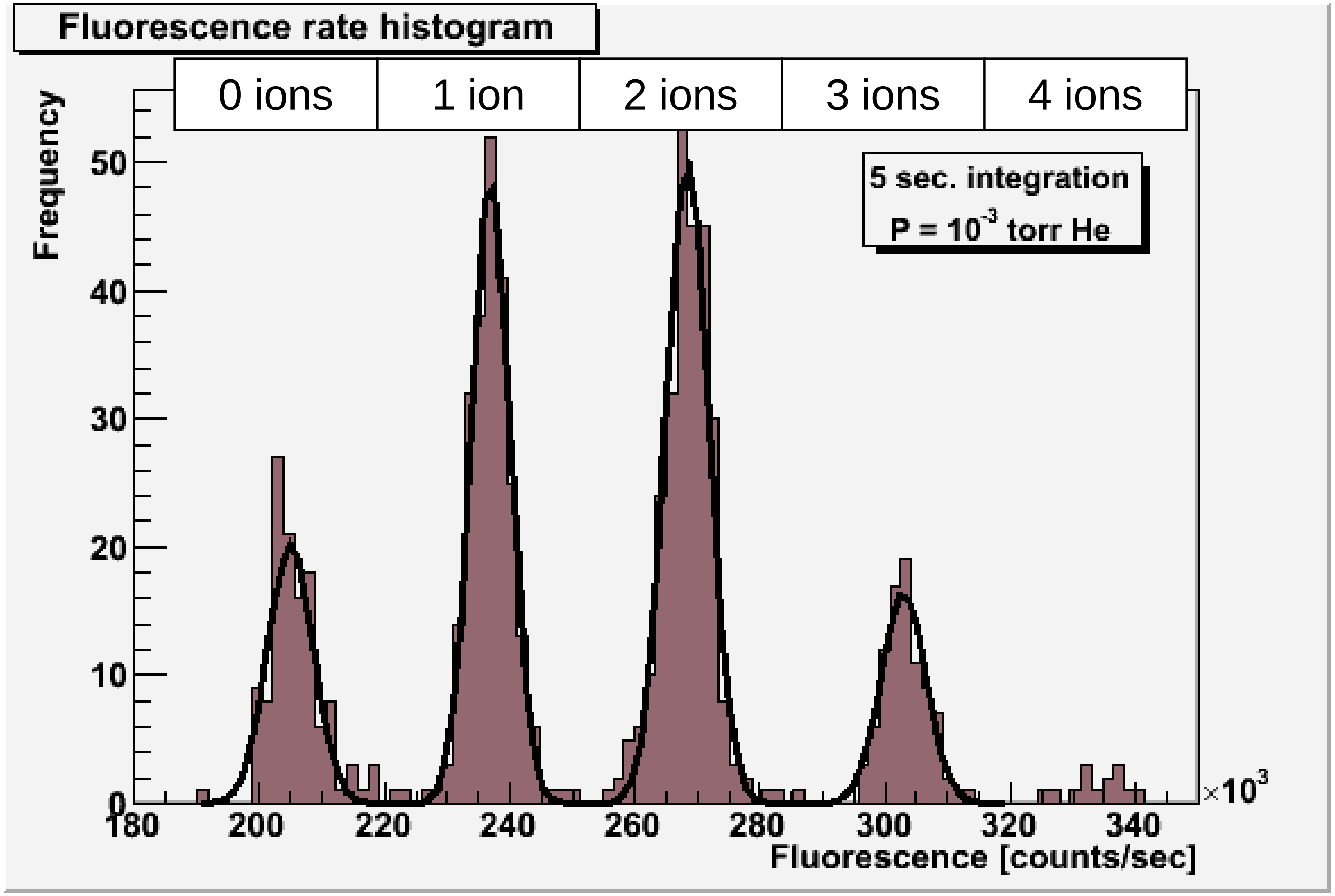




- High ion loading efficiency observed.
- Ions loaded at one end will travel to the other.
- Ions can be manipulated by changing DC potential configuration.



Ion signal as a function of time as ions are loaded and unloaded from the linear trap. The quantized structure demonstrates our ability to detect single atoms in a buffer gas with high S/N.



Histogram of ion fluorescence signal. With a 5 sec integration the signal from 1 ion is distinguishable from background at the 8.7**σ** level.

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 2.46 MeV endpoint
4) **Use for 2vββ $T_{1/2} > 1 \cdot 10^{22}$ yr (Bernabei et al. measurement)**

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2vββ Background (events)	$T_{1/2}^{0v}$ (yr, 90%CL)	Majorana mass (meV) QRPA[1]	NSM[2]
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

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

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

1) Rodin, *et. al.*, Nucl. Phys. A **793** (2007) 213-215

2) Caurier, *et. al*., arXiv:0709.2137v2

Conclusion

The next generation ββ–experiments hope to observe this decay.

Unambiguous evidence will be important for making a clear case that Neutrinos are Majorana particles.

To achieve this we will need experiments using different methods and different nuclides. In case of success this would give some handle on the matrix element calculations and their spread.

This goal requires both high resolution calorimetric and tracking detectors. EXO is the only project with an independent decay tag.

Both EXO-200 and the atom tagging technique are under active development. EXO-200 is fully funded and under construction.

Stay tuned! First data will come soon.

The EXO team