The PIXeY detector: Progress Toward Imaging Hidden Nuclear Material with Liquid Xenon

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The Problem

The cold war ended. But…

The number of nuclear armed states is increasing.

Some nuclear armed states have unstable governments.

Smuggled weapons are appealing to terrorists as they require no delivery system.

Increasing global trade provides increasing smuggling opportunities.

Traditional deterrence is ineffective.

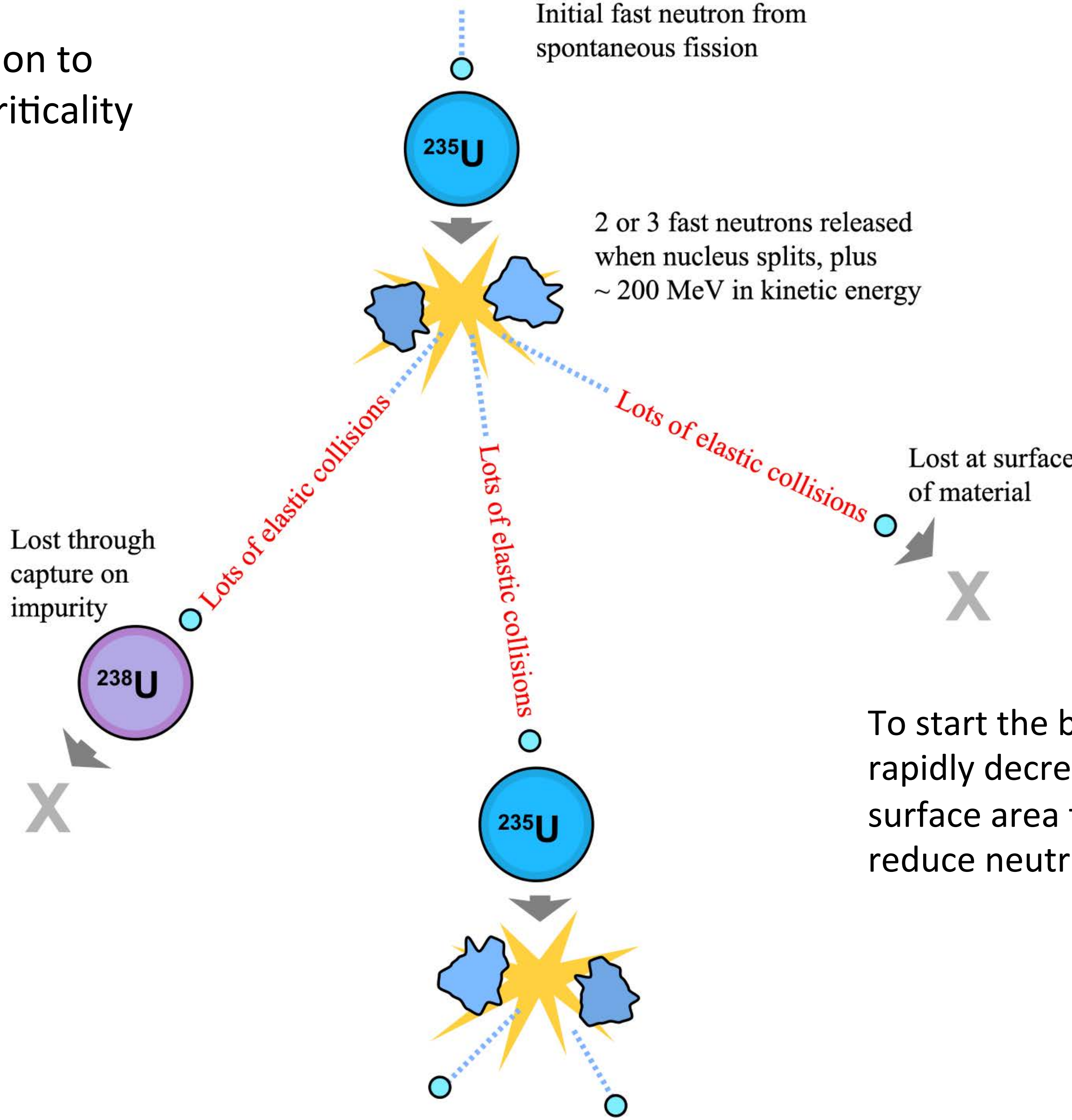
The IAEA has documented 18 cases of actual theft or loss of plutonium or HEU (the materials from which a nuclear bomb could be made), confirmed by the states concerned. Additional thefts are known to have occurred which the relevant states have so far not confirmed to the IAEA.

What is not known, of course, is how many thefts may have occurred that were never detected; it is a sobering fact that *nearly all of the stolen HEU and plutonium that has been seized over the years had never been missed before it was seized*.

-Securing the Bomb, Matthew Bunn (2010)

“There is a 20% chance of a nuclear explosion in a city in the next ten years.”
-Richard Garwin (2007)

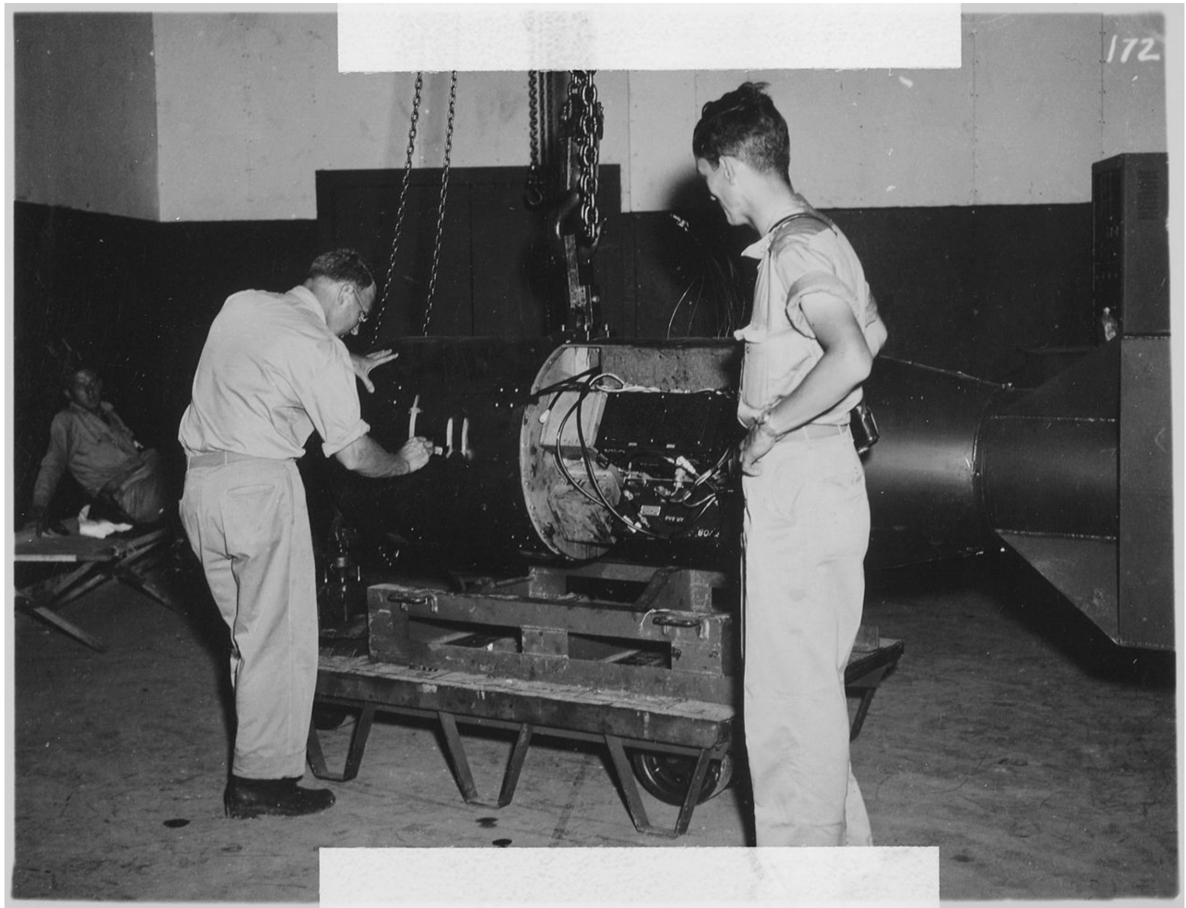
Introduction to Prompt Criticality



To start the bomb, rapidly decrease the surface area to reduce neutron loss.

Four ways to make trouble	Plutonium Obtained by chemical separation of used reactor fuel Bare critical mass: 10 kg	Highly enriched uranium (HEU) Obtained by isotope separation of natural uranium or reprocessed used reactor fuel Bare critical mass: 50 – 100 kg
Implosion assembly Fuel becomes critical in a microsecond Technically challenging	Most modern weapons	A few modern weapons?
Gun-type assembly Fuel becomes critical in a millisecond Technically unsophisticated	"Predetonation" – small explosion, plutonium mess	"Little boy" and other early US weapons Primitive weapons made by nuclear terrorists?

What are we looking for? Primitive Weapons Made by Unsophisticated States or Terrorists

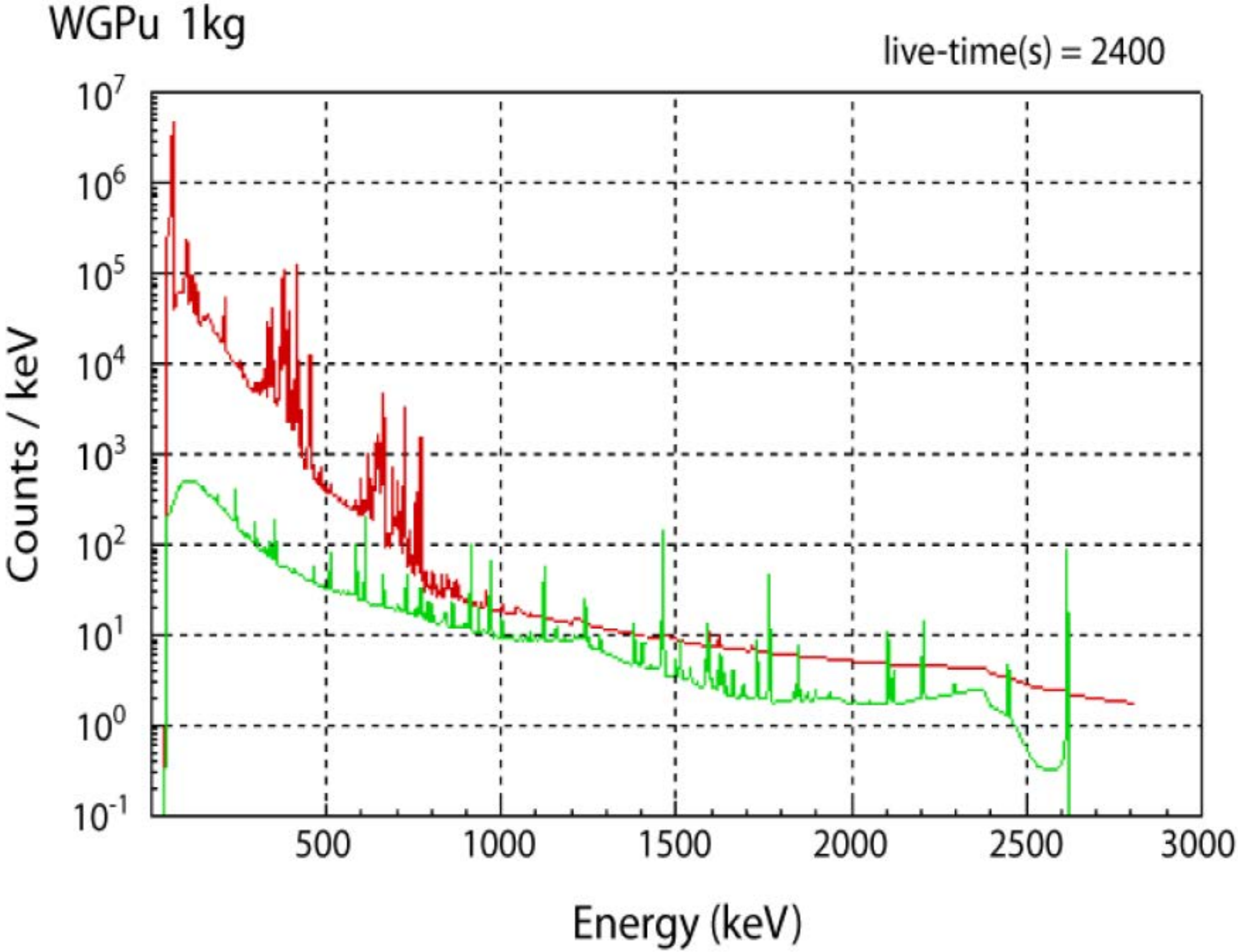


“Little Boy” bomb dropped on Hiroshima
140,000 deaths, half immediate
15 kt energy release
3 m long, 4400 kg
US (1945)

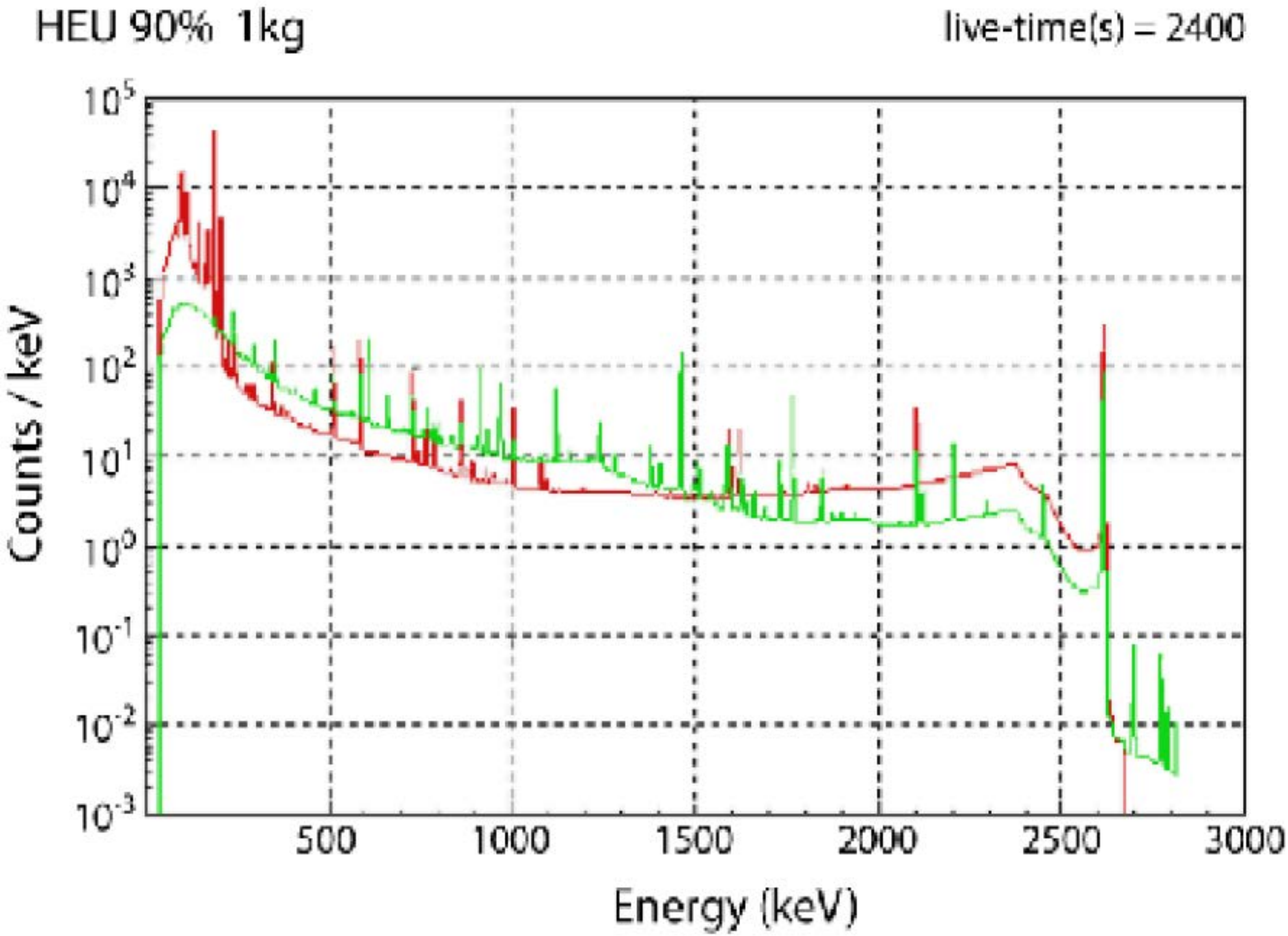
Sen. Millikin: *We... have mine-detecting devices, which are rather effective... I was wondering if anything of that kind might be available to use as a defense against that particular type of use of atomic bombs.*

Dr. Oppenheimer: *If you hired me to walk through the cellars of Washington to see whether there were atomic bombs, I think my most important tool would be a screwdriver to open the crates and look. I think that just walking by, swinging a little gadget would not give me the information.*

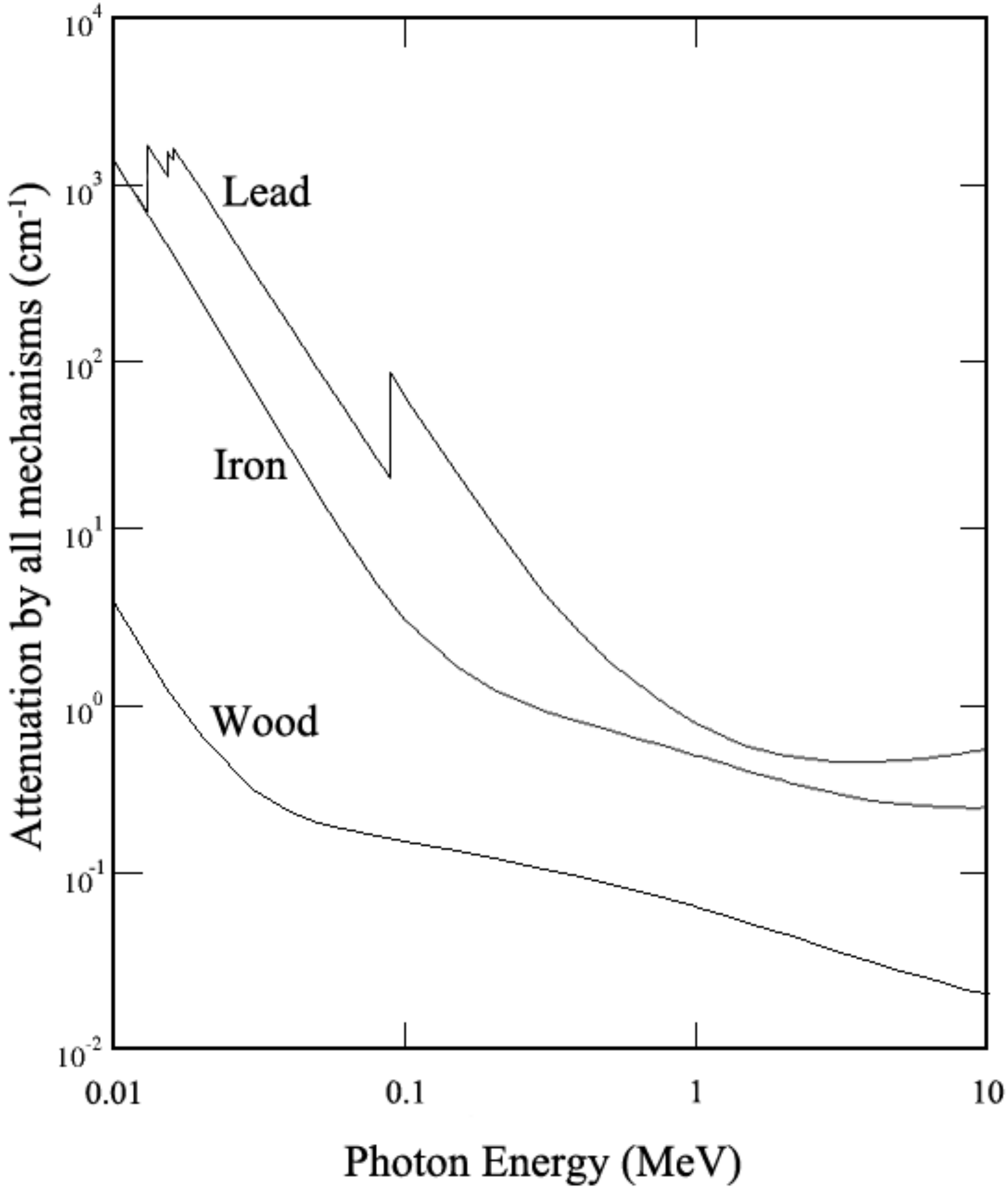
-Senate hearing on nuclear proliferation, 1946



WGPu 1kg
live-time(s) = 2400
Counts / keV
Energy (keV)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
500
1000
1500
2000
2500
3000


HEU 90% 1kg
live-time(s) = 2400
Counts / keV
Energy (keV)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
500
1000
1500
2000
2500
3000

Attenuation by Shielding



Naturally Occurring radioactive Material (NORM)

Uranium-238 (4.5 billion years)

Typically 3 ppm in soil

Thorium-232 (14 billion years)

Typically 6 ppm in soil

Potassium-40 (1.2 billion year half-life)

Typically 1.5 ppm in soil

Lessons from Discussion with Dennis Slaughter, LLNL

At shipping ports, space and time are big money.

Therefore:

Any system that frequently false alarms will be ignored.

Any system that requires a large fixed installation will be opposed.

Current systems are crude – Big slabs of plastic scintillator, some sodium iodide detectors. Low energy resolution and no directional capability.

What is needed are mobile devices that discriminate against NORM. These need to fit into a large van or small delivery truck.

11 million containers are shipped to the US each year. As of 2012, only 4% are scanned for radioactivity, selected by an algorithm.

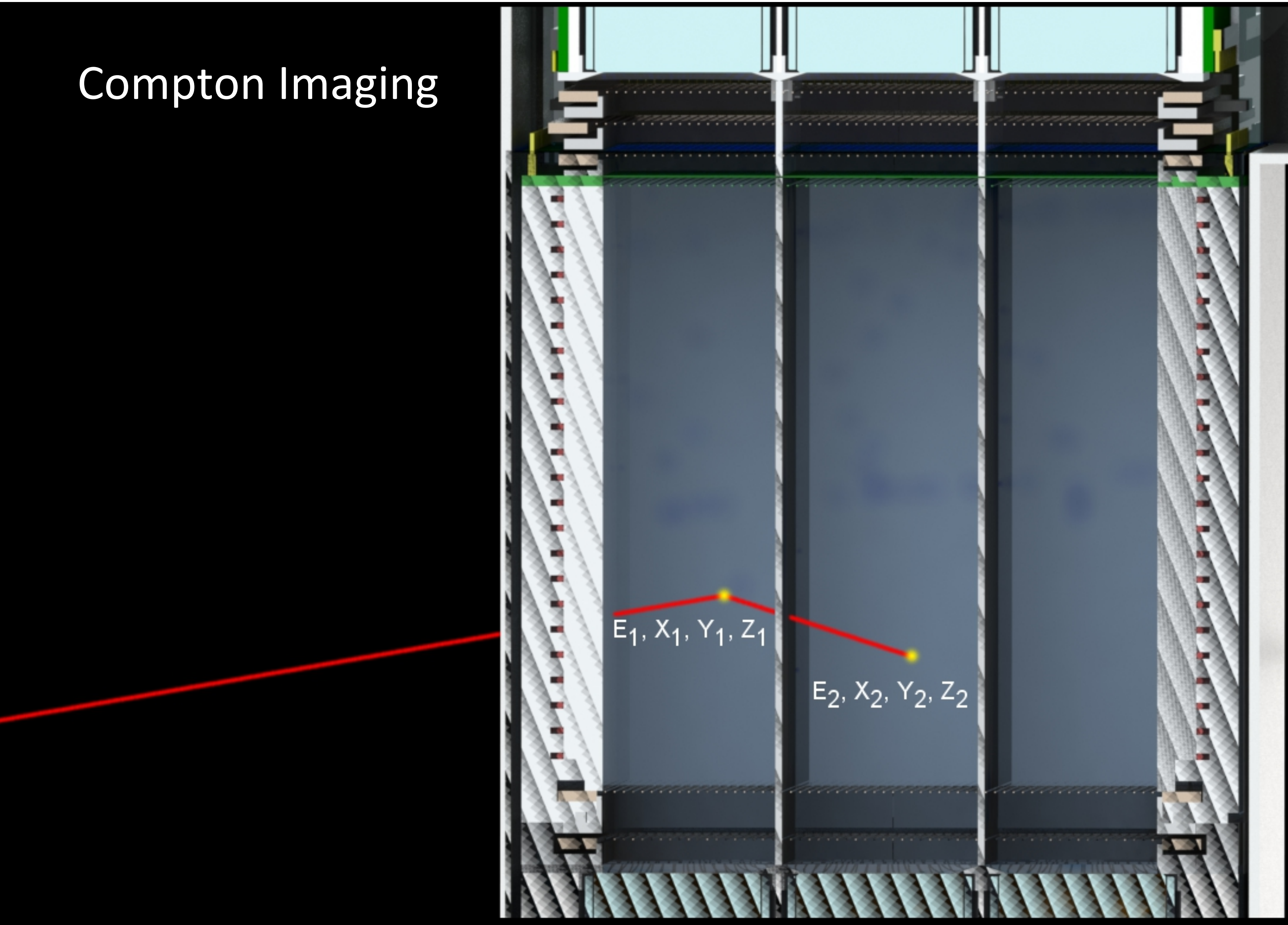
Gamma Imaging for Ignoring NORM and Reducing False Alarms

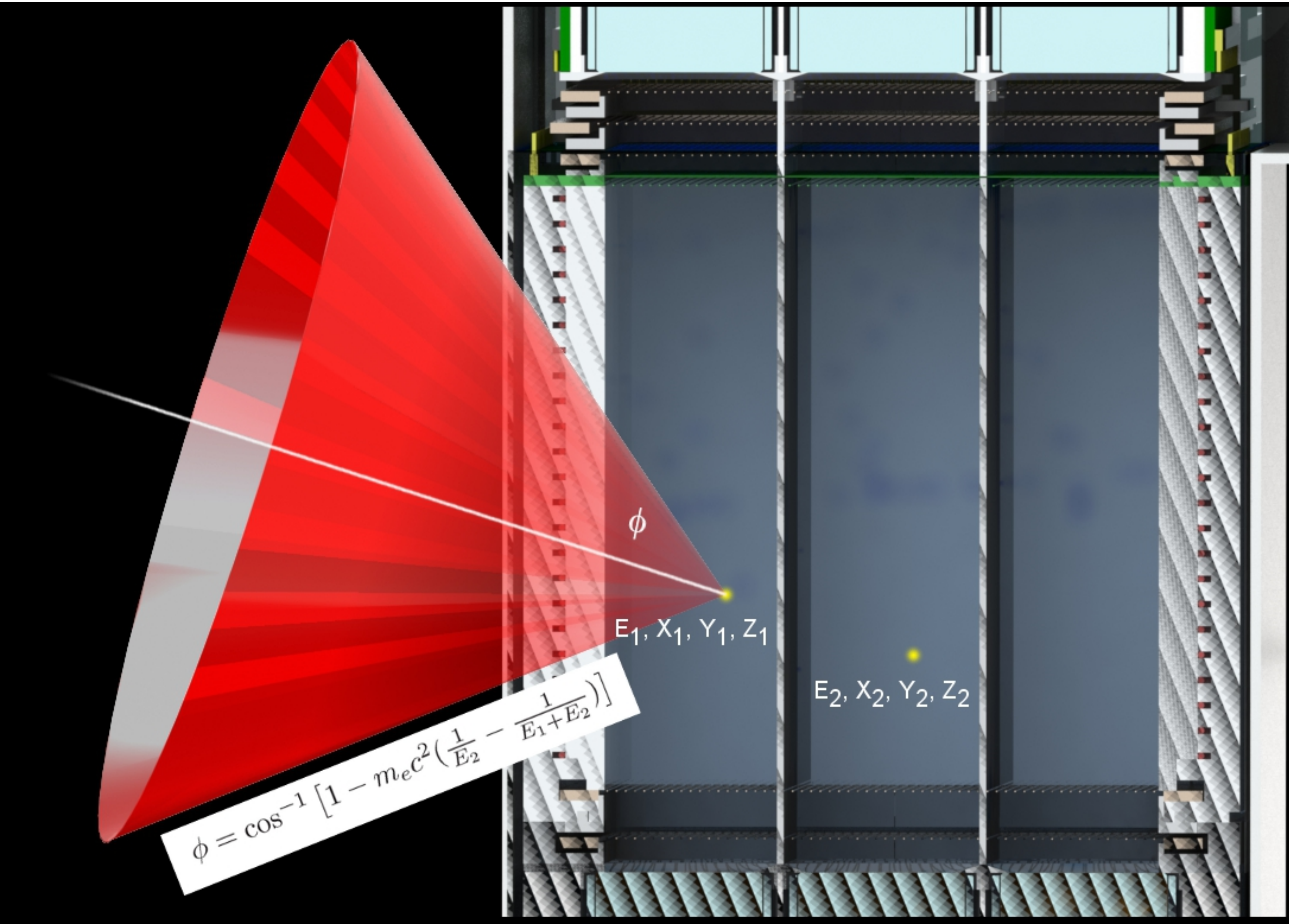
NORM is usually spatially diffuse, whereas a bomb core is always concentrated.

Signals emanating from concentrated sources can be ignored if their energies correspond to harmless isotopes, like potassium and thorium.

But imaging must be efficient. Pinhole cameras and coded apertures absorb most incident gammas and are very inefficient. Compton imaging can produce images without loss of efficiency.

Compton Imaging




ϕ
E_1, X_1, Y_1, Z_1
E_2, X_2, Y_2, Z_2
$\phi = \cos^{-1}\left[1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right)\right]$


NOBLE
TRANSPORT LTD.


NOBLE
TRANSPORT LTD.


NOBLE
TRANSPORT LTD.

Materials for Gamma Imaging

	Energy resolution (662 keV)	Position resolution	Density	Cost	Detector element thickness	n/gamma discrimination
Plastic scintillator	Poor	~ 10 cm	1.0 g/cc	~$30/kg	~ 20 cm	No
Liquid scintillator	20%	~ 10 cm	0.9 g/cc	~$30/kg	~ 20 cm	Yes
Sodium Iodide	6%	~ few cm	3.7 g/cc	~$800/kg	~ 10 cm	No
CZT	1%	~ 1 mm	5.8 g/cc	~$30,000/kg	~ 1 cm	No
Germanium	0.2%	~ 3 mm	5.3 g/cc	~$20,000/kg	~ 5 cm	No
Liquid Xenon	3-6%	~ 1 mm	3.0 g/cc	$1,200/kg	~ 20 cm	Yes

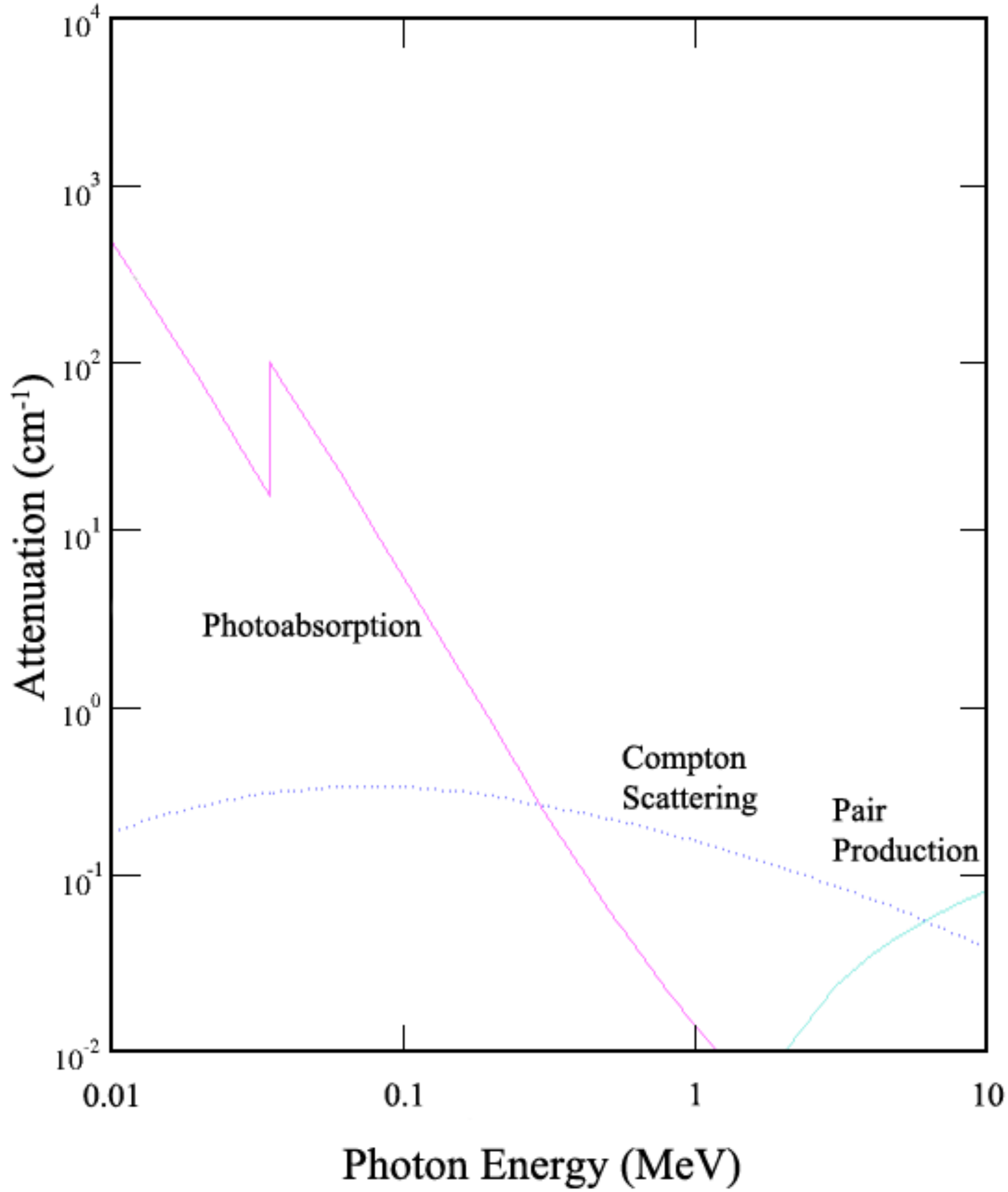
Liquid Xenon combines:

- **Energy resolution between CZT and sodium iodide**
- **Cost of sodium iodide**
- **Position resolution of CZT**
- **Scalability of organic scintillator.**

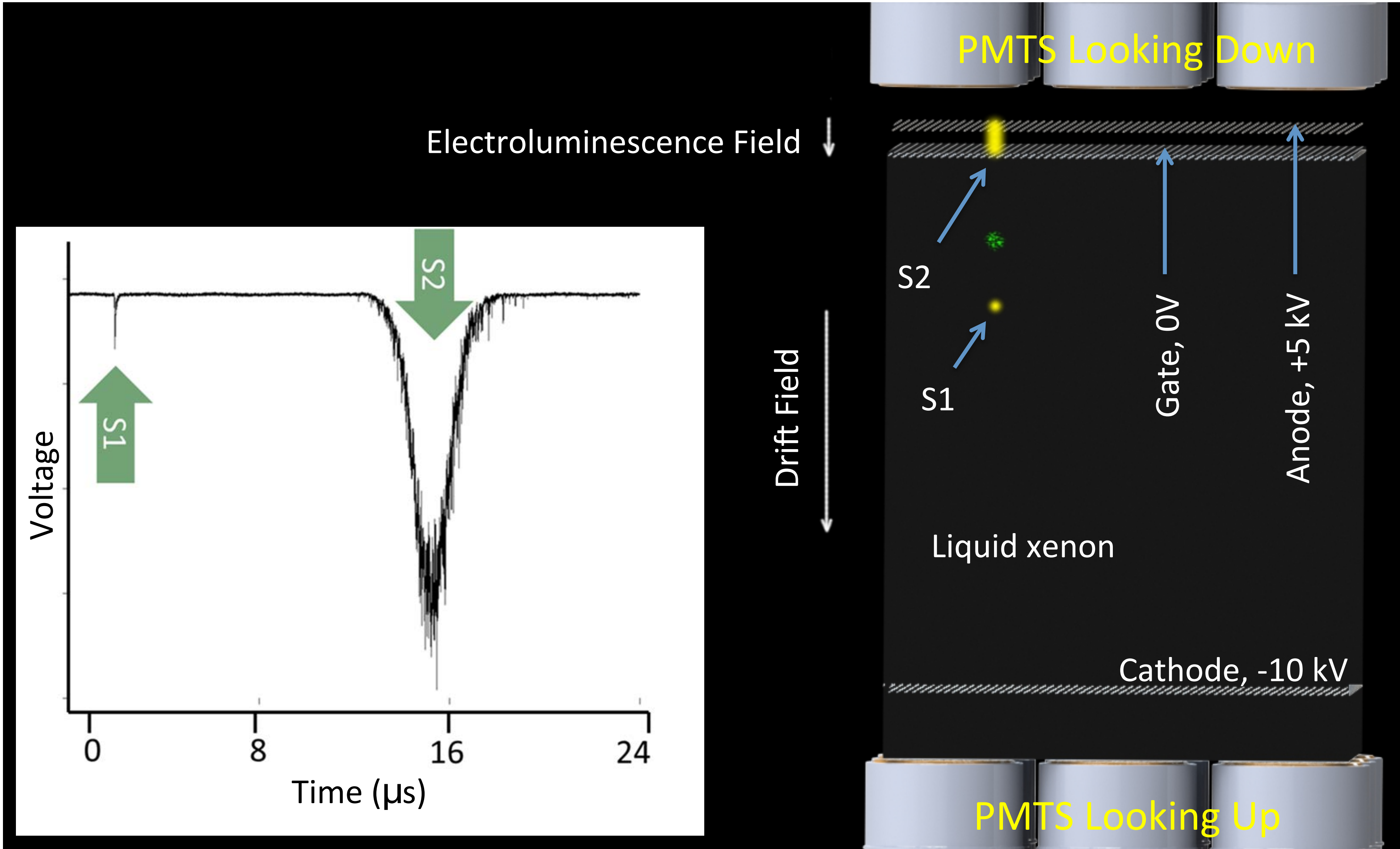
Liquid Xenon Properties

- Strong gamma stopping power: 6 cm attenuation length at 1 MeV.
- Density: 3 kg / L.
- Bright and fast scintillation yield from gammas: 42 photons / keV
- Electrons drift at 1.5 mm / μs.
- Scalable- light and charge travel well.
- Detectors operate at 178 K and 2 bar pressure.
- Photoabsorption dominates Compton scattering up to 300 keV (Z = 54).

Gamma Interaction Mechanisms in Liquid Xenon

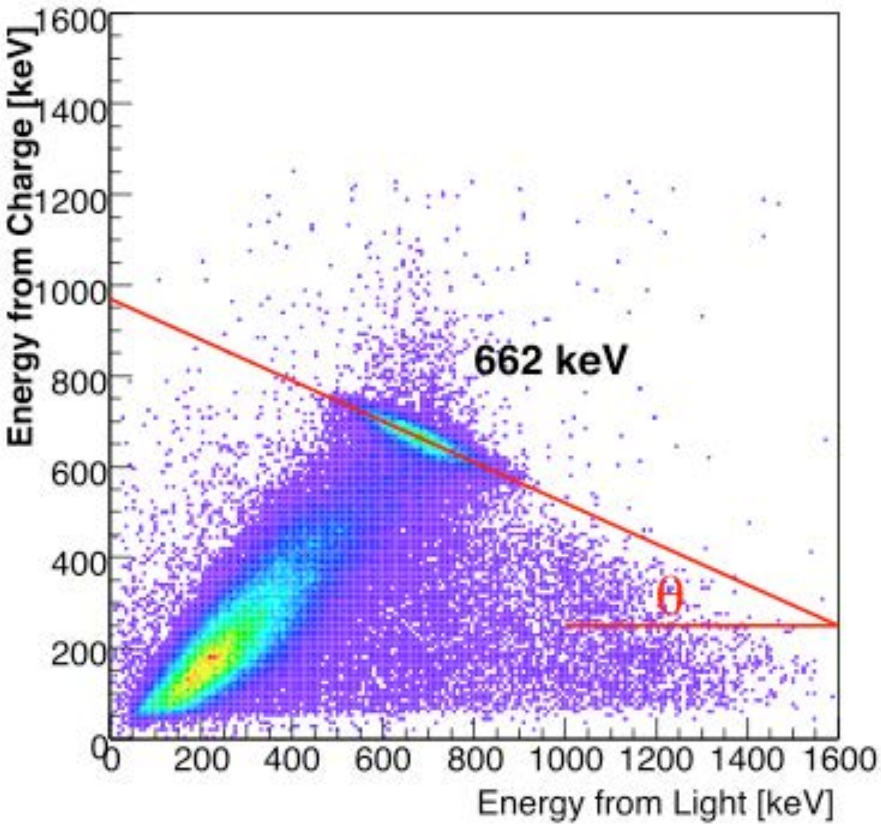


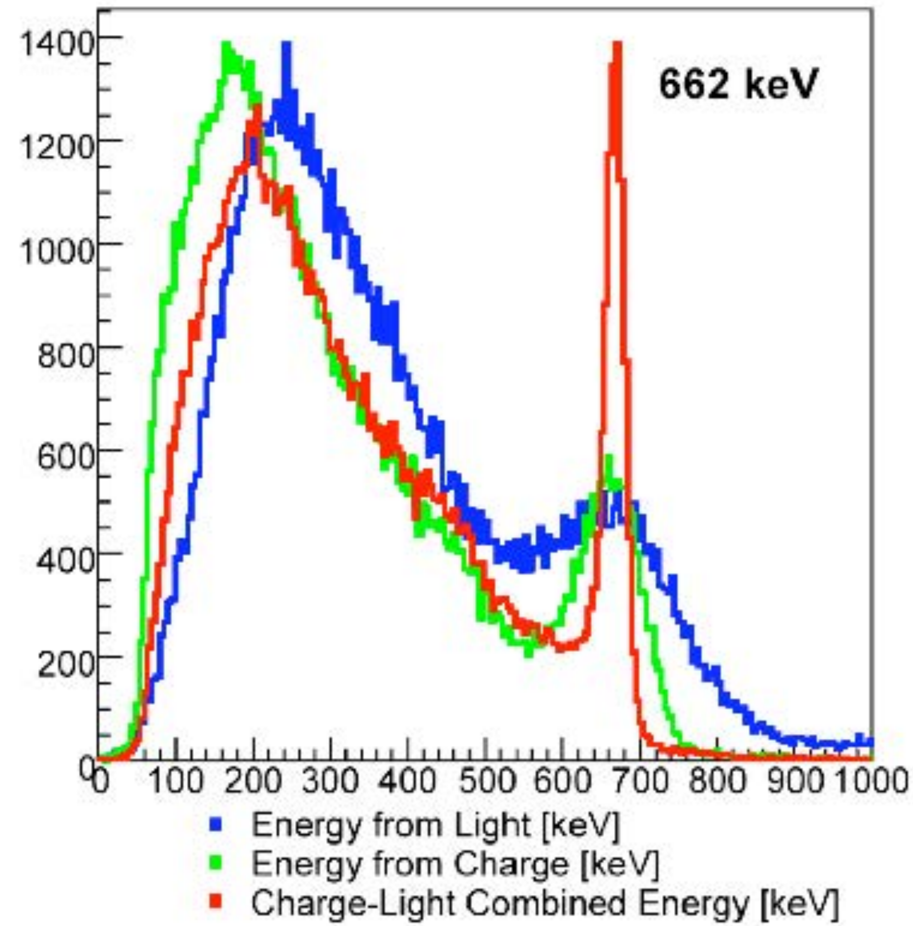
Two-Phase Xenon TPC Operation



Energy Resolution of the Xenon10 Dark Matter Detector

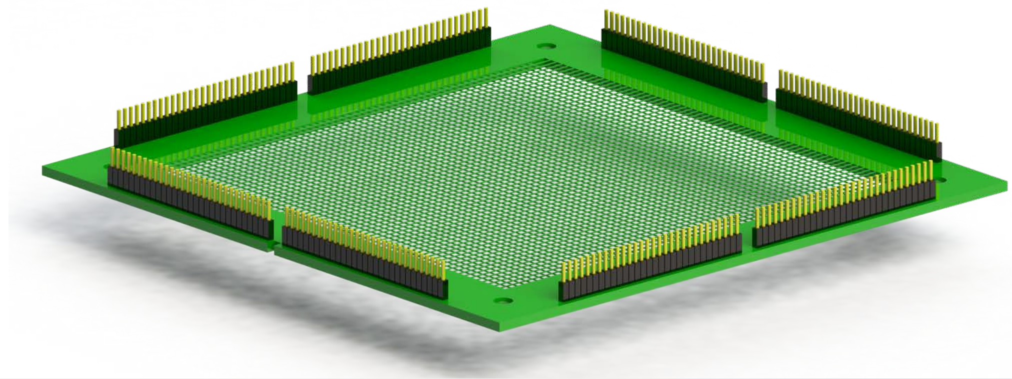
- Charge and light signals are strongly anticorrelated.
- Combination allowed for 4% FWHM resolution at 662 keV.
- 2.6% FWHM at 662 keV projected with improved light collection.

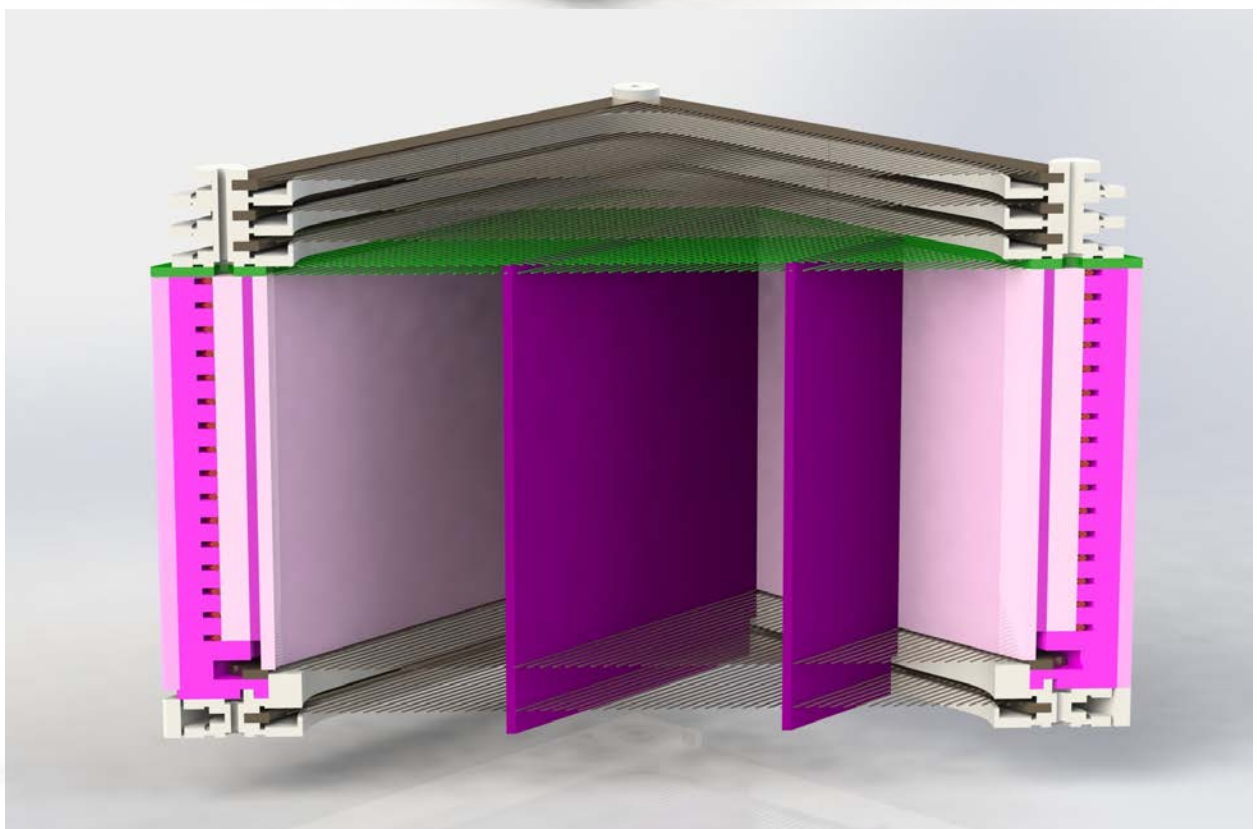


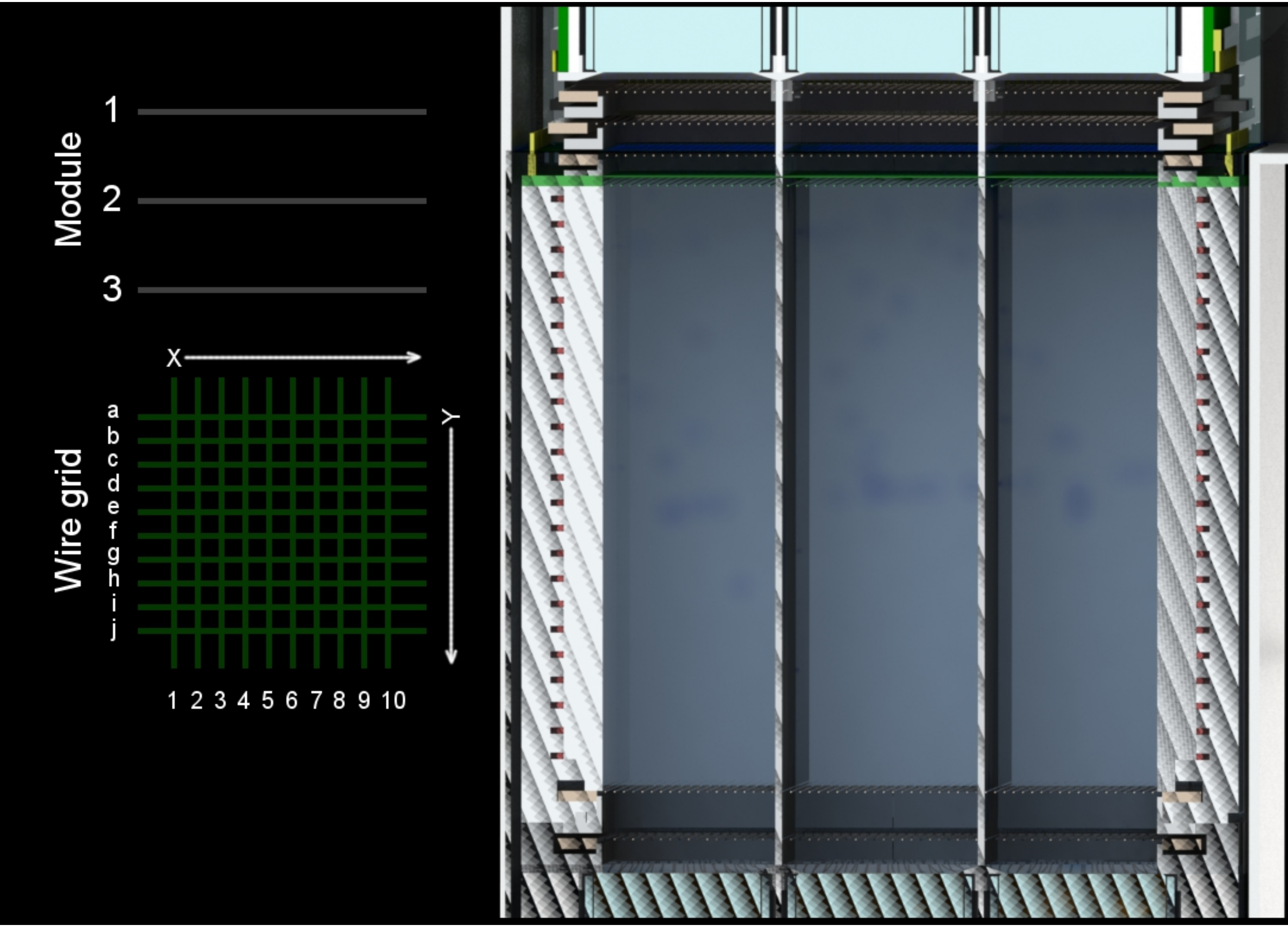


Aprile et al, Phys. Rev. B 76, 014115 (2007)

Add Walls for Energy Resolution, Wire Readout for Horizontal Position



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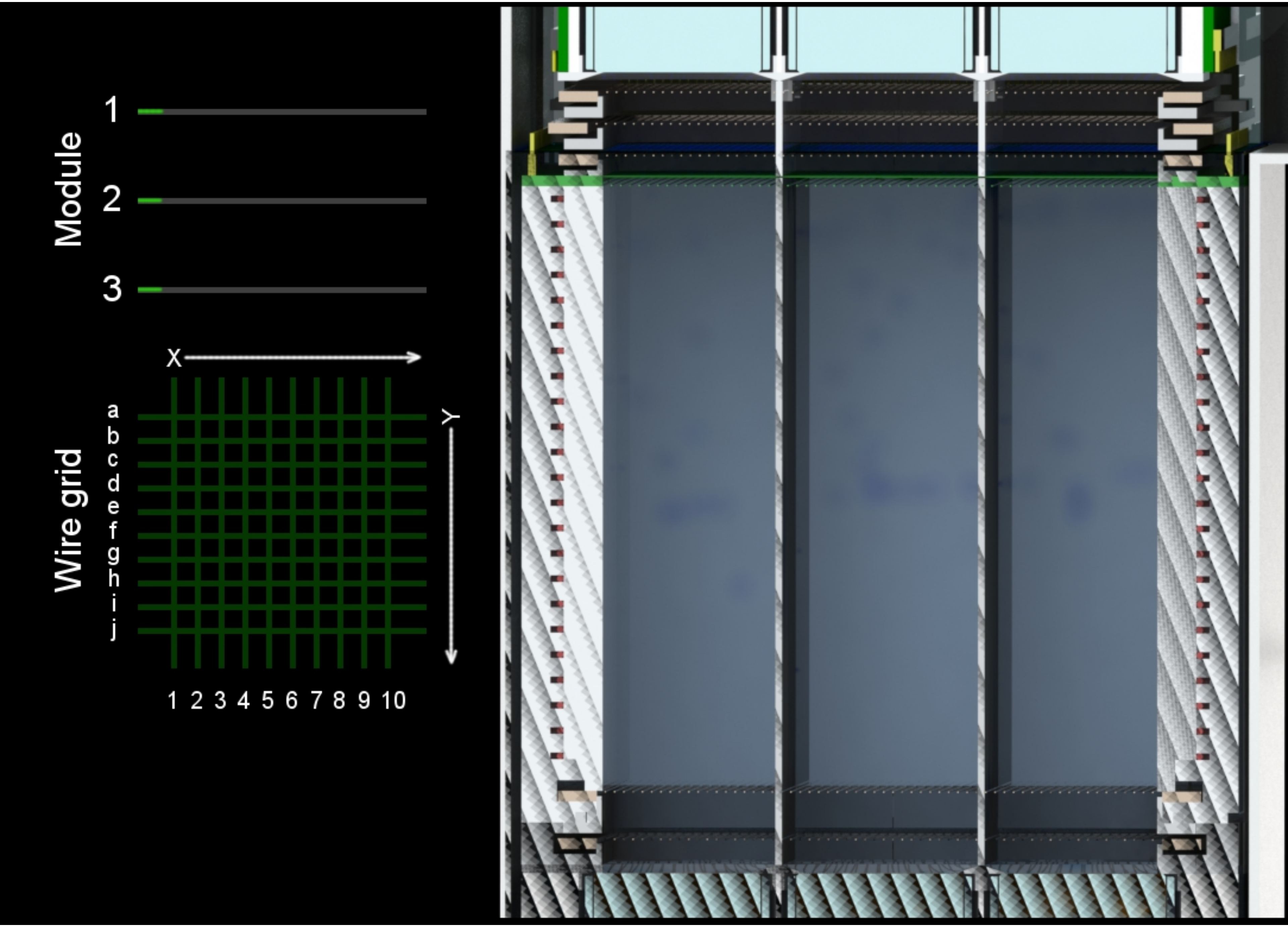

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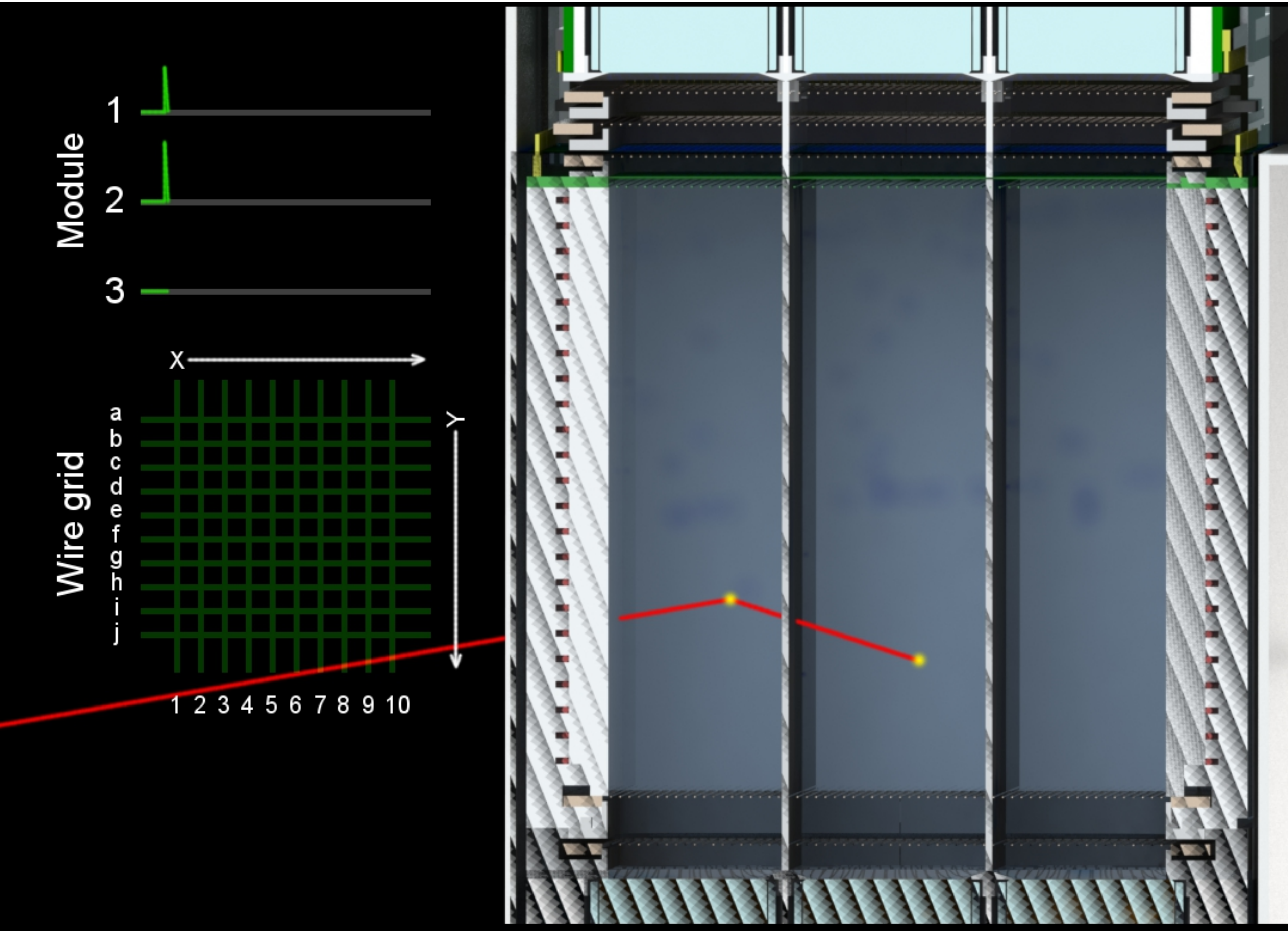

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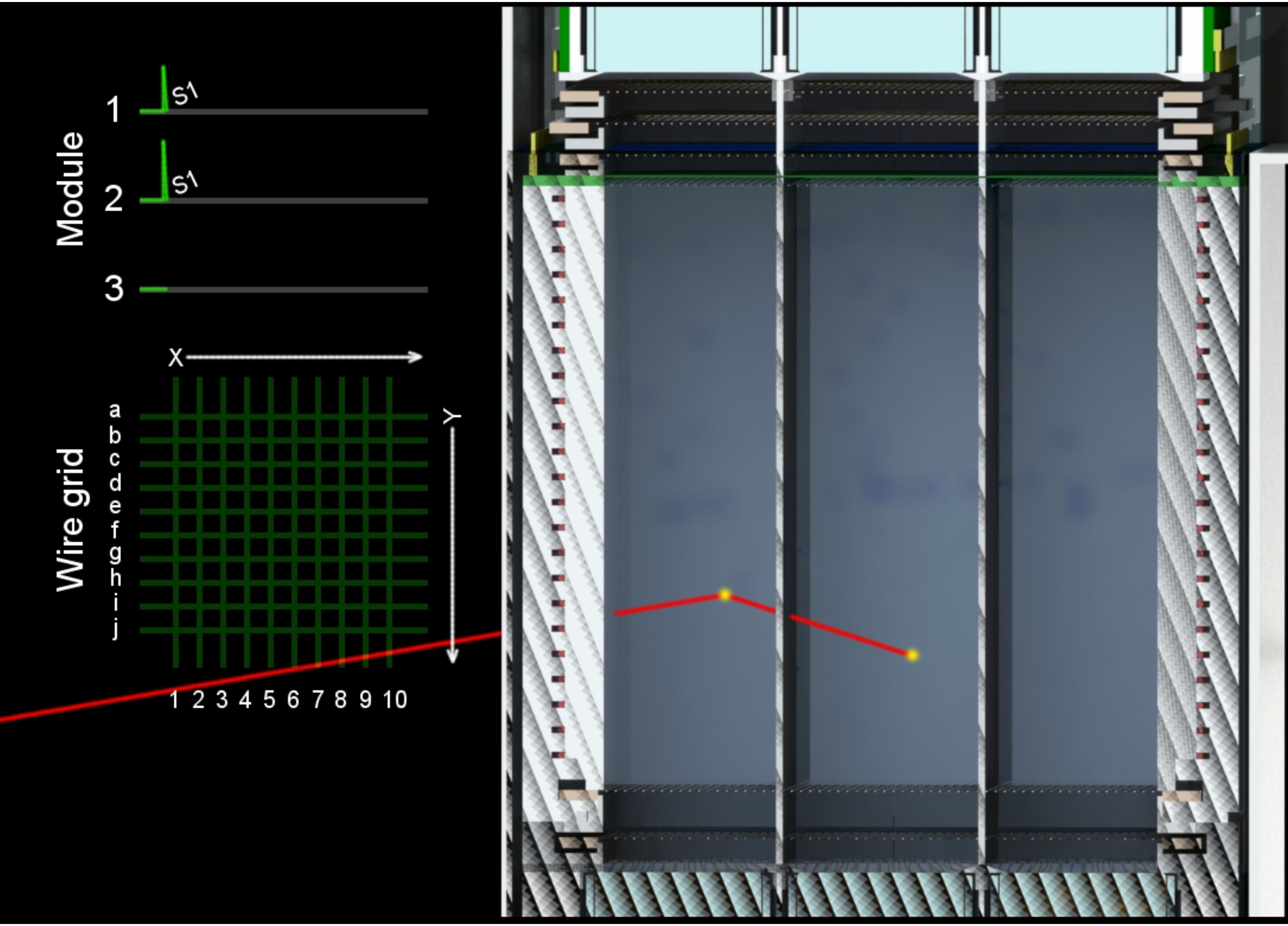

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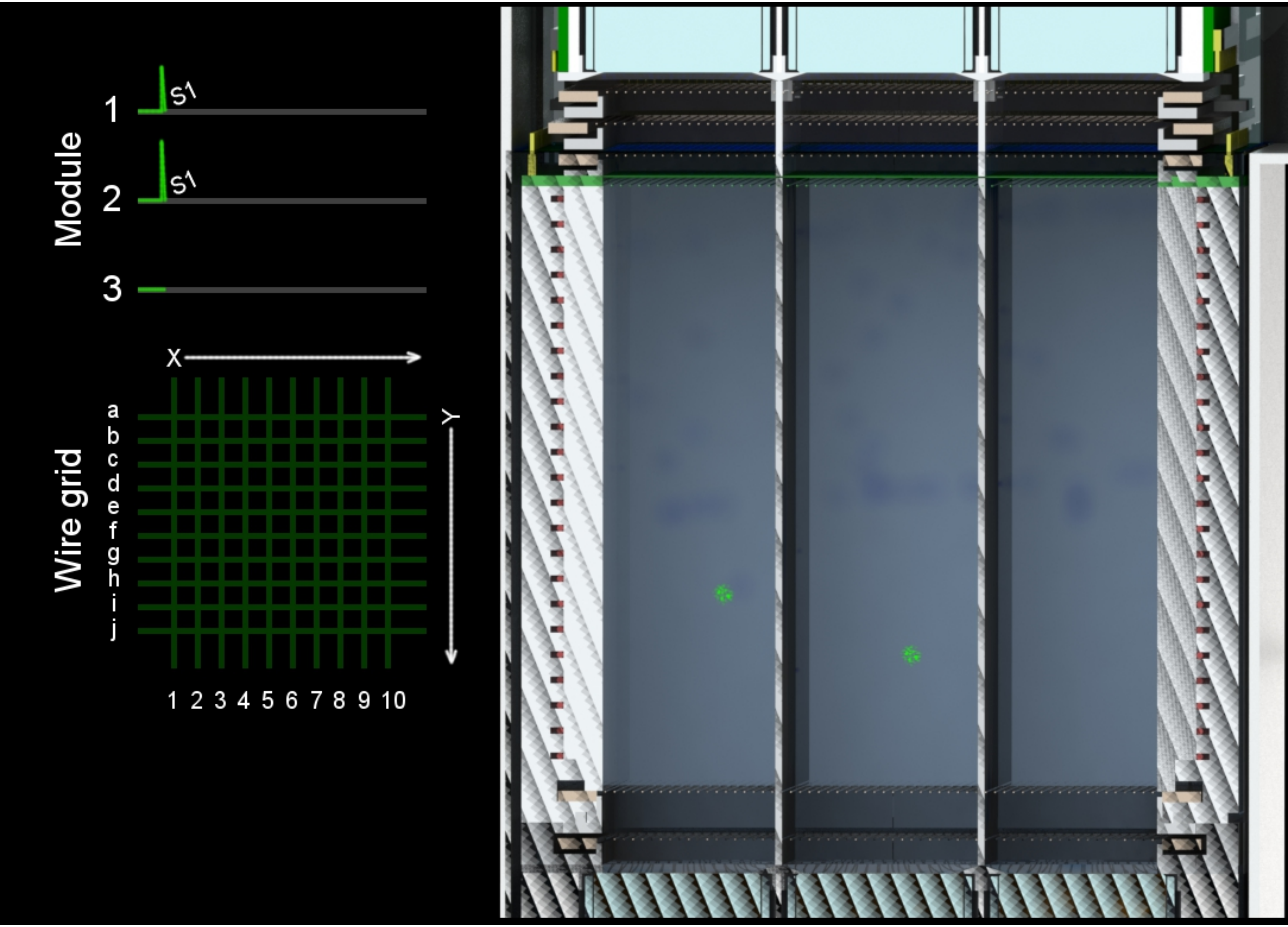
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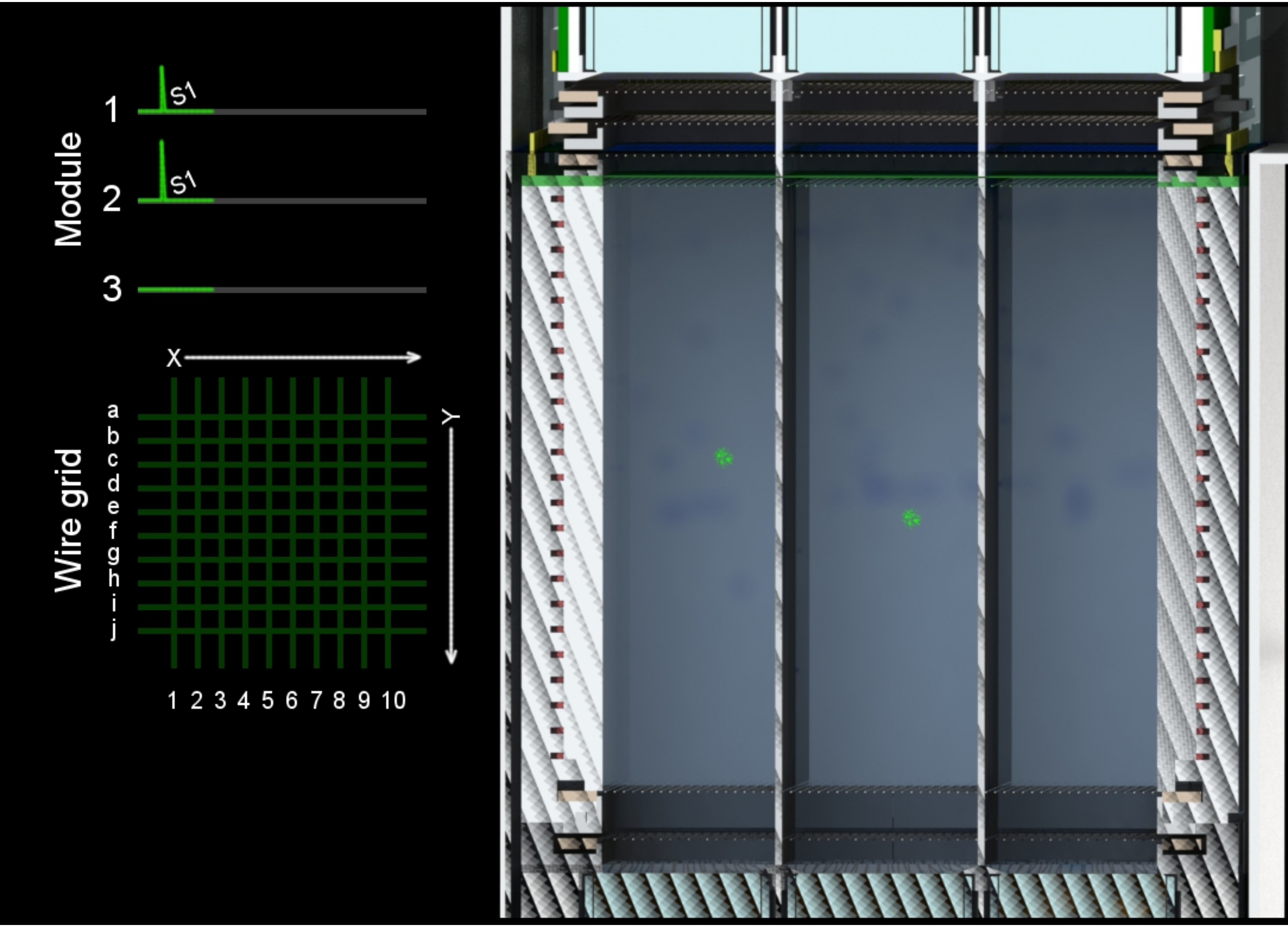

Module
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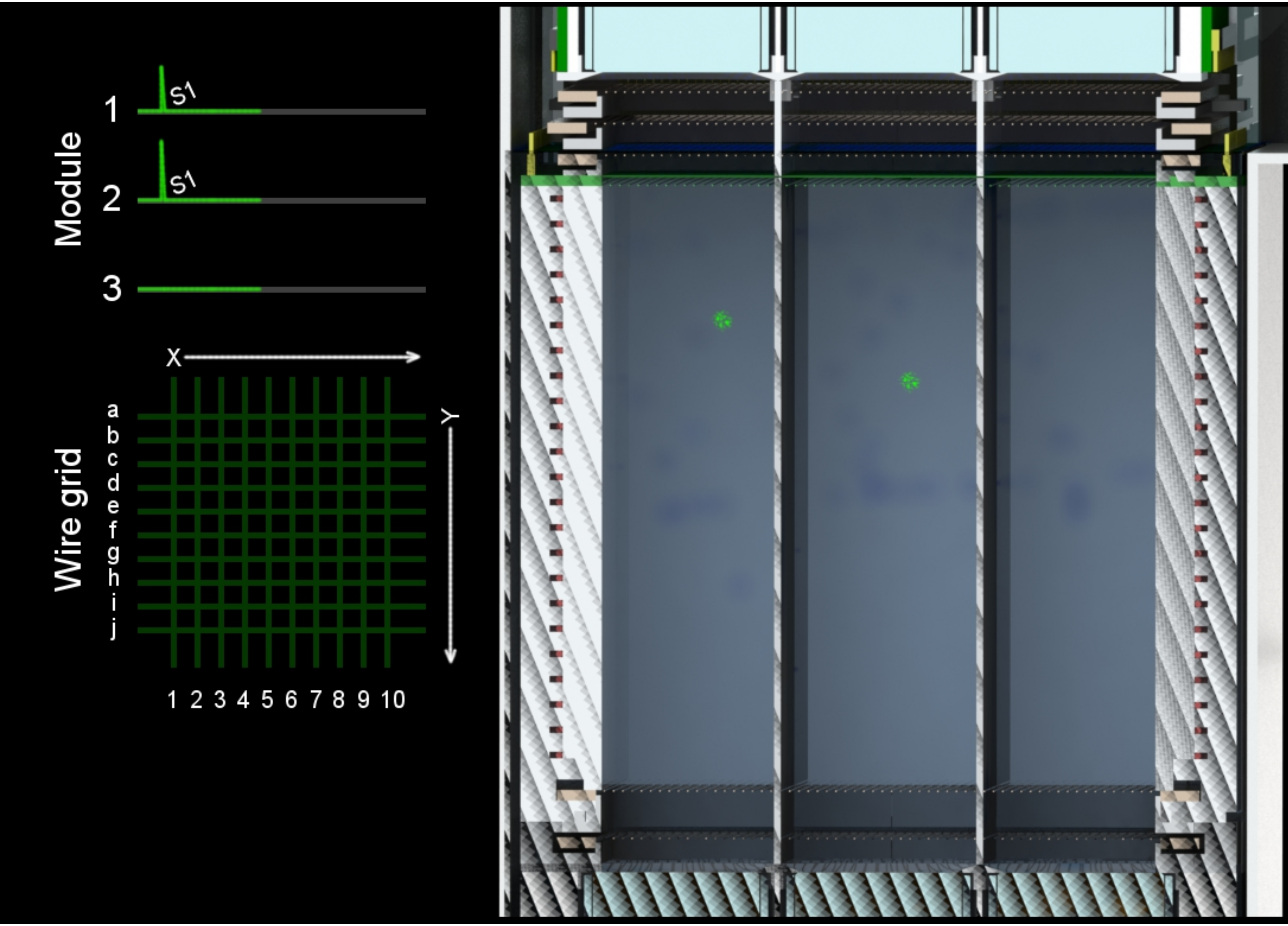
Module
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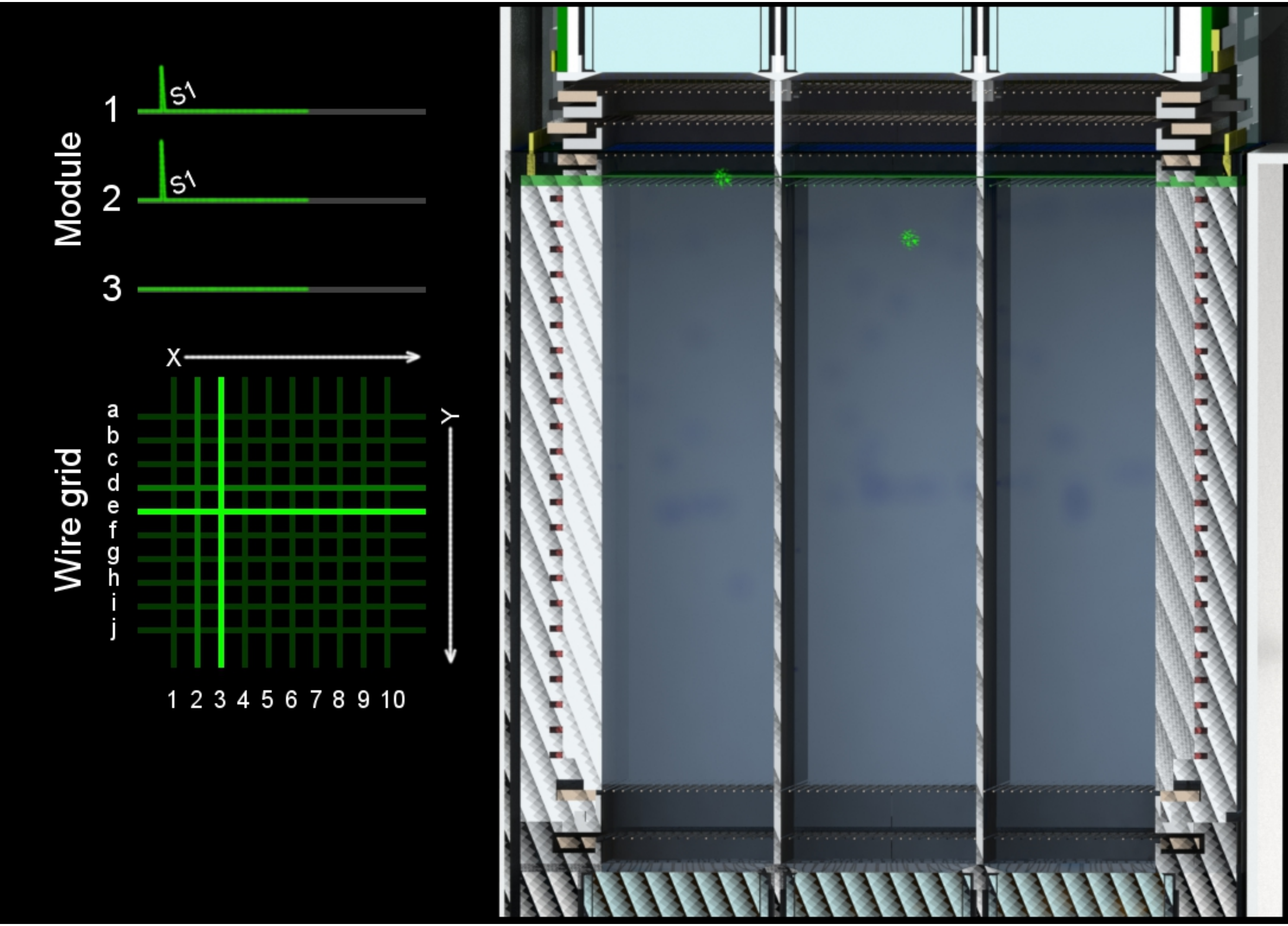

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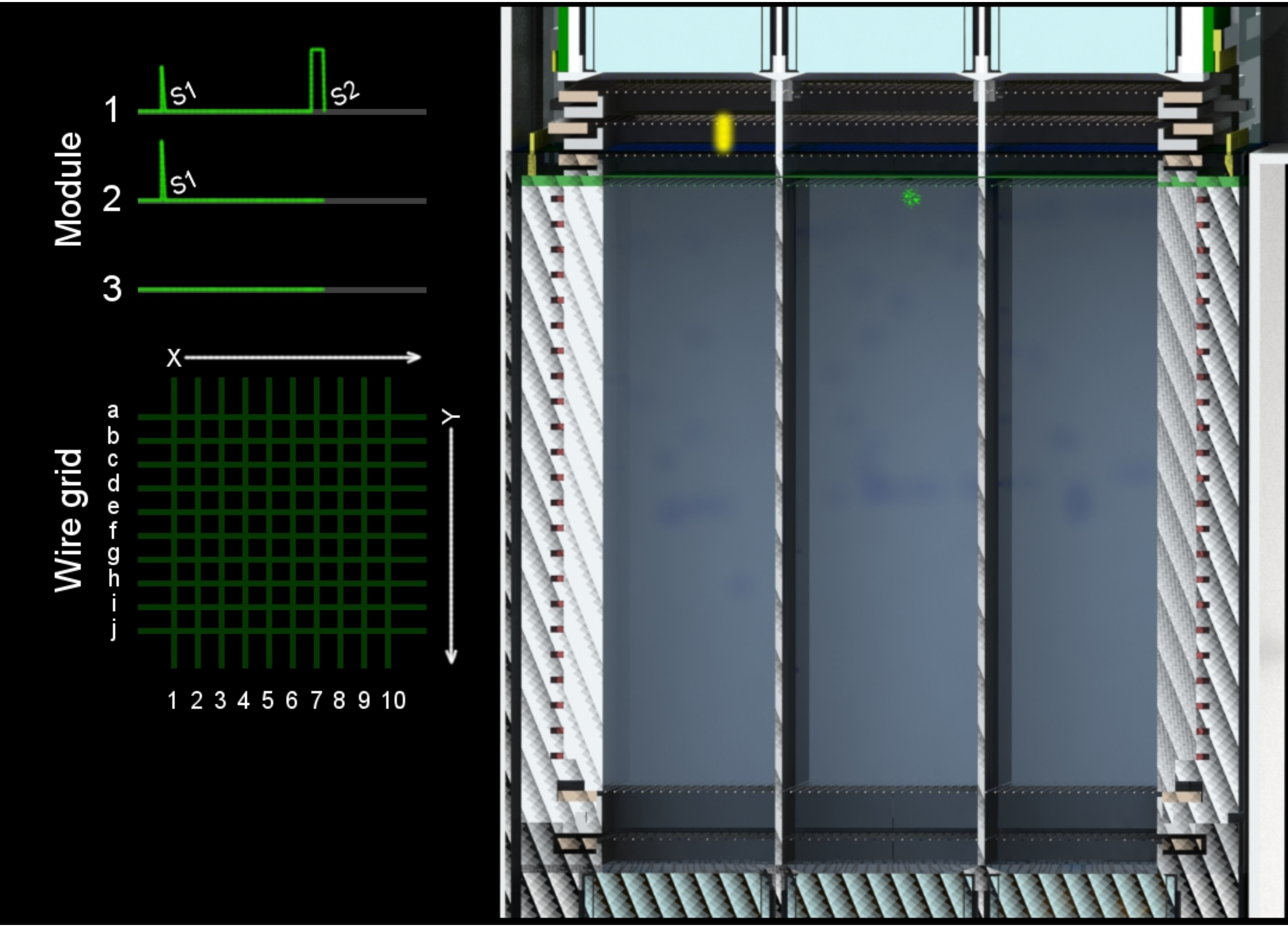
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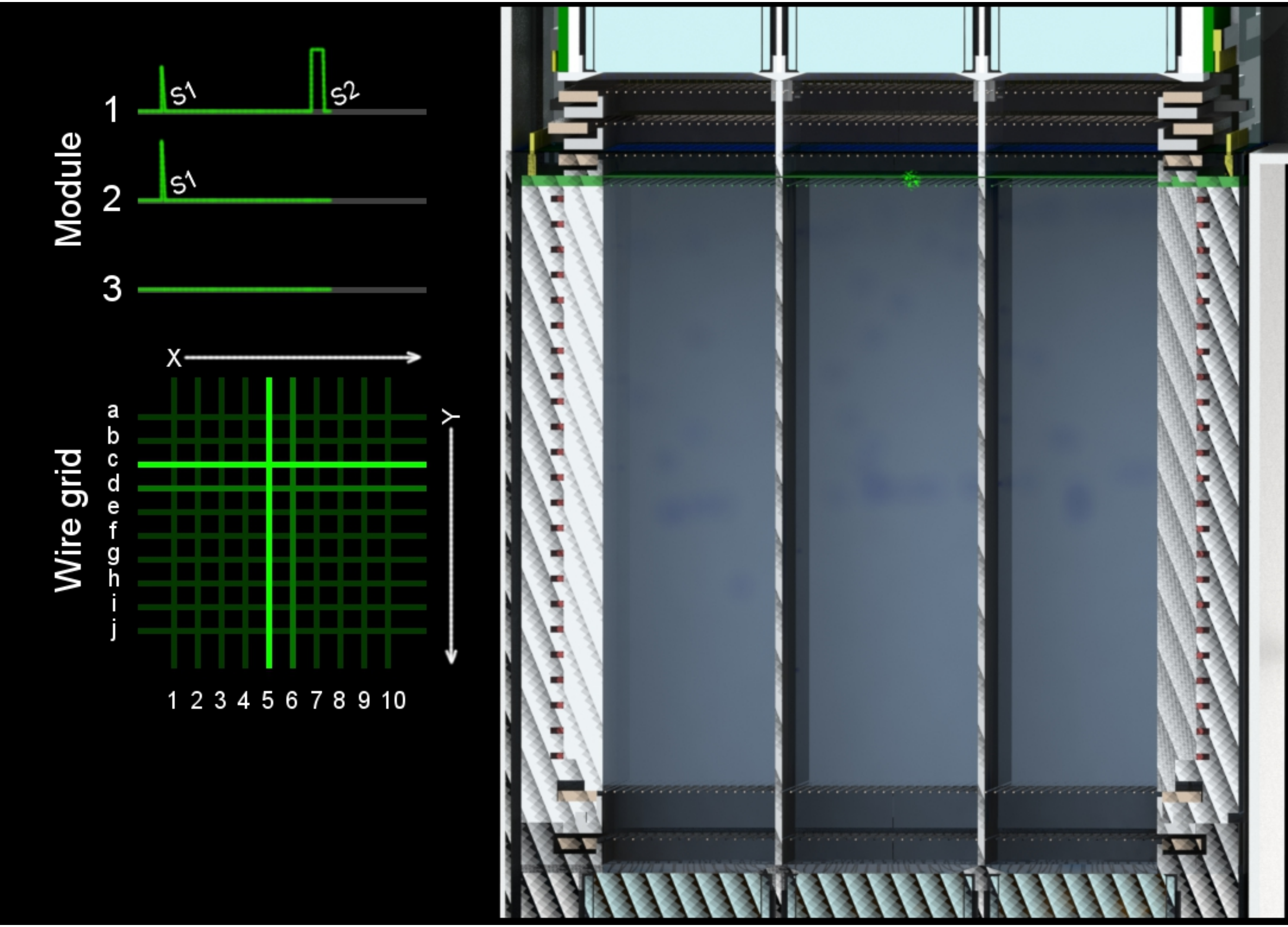
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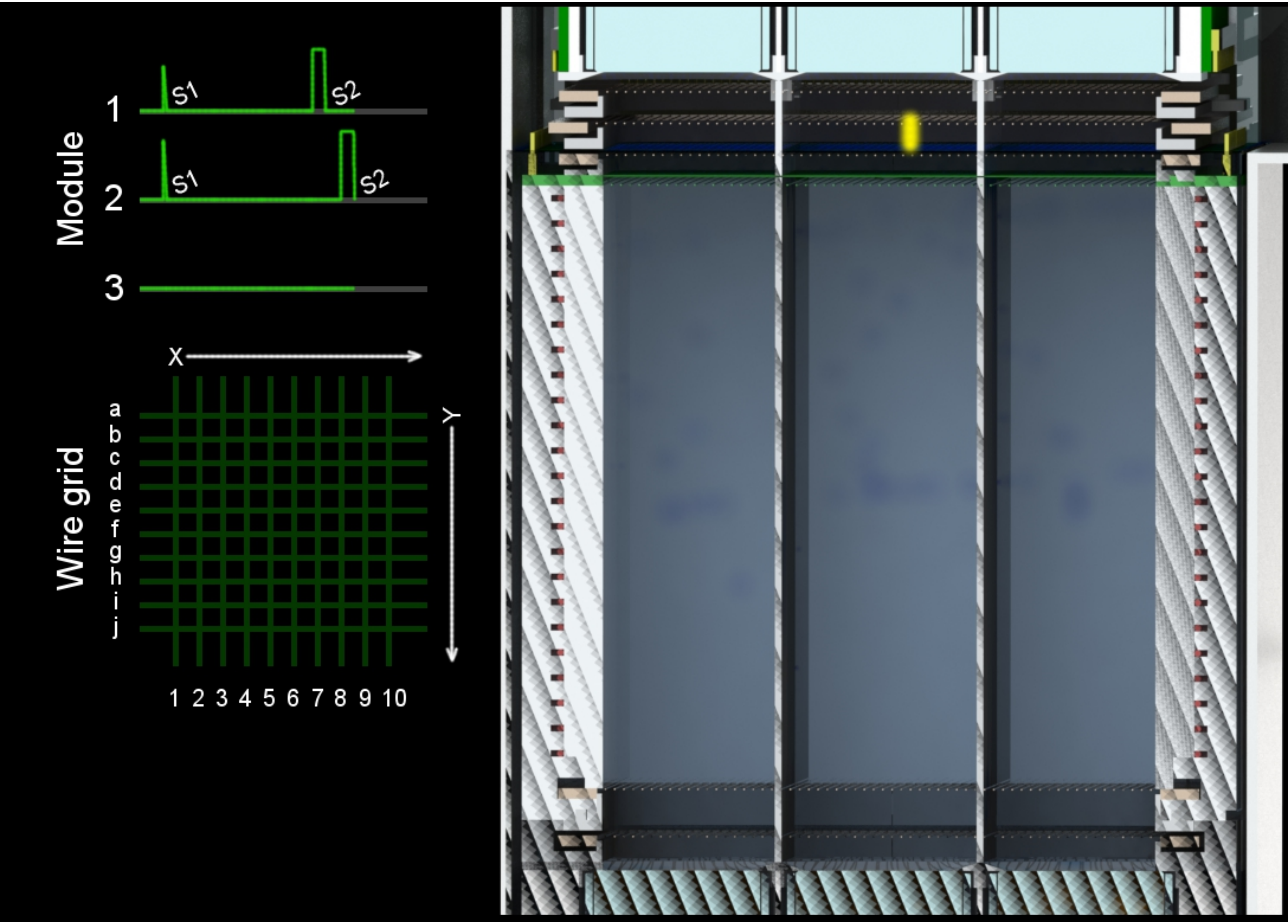
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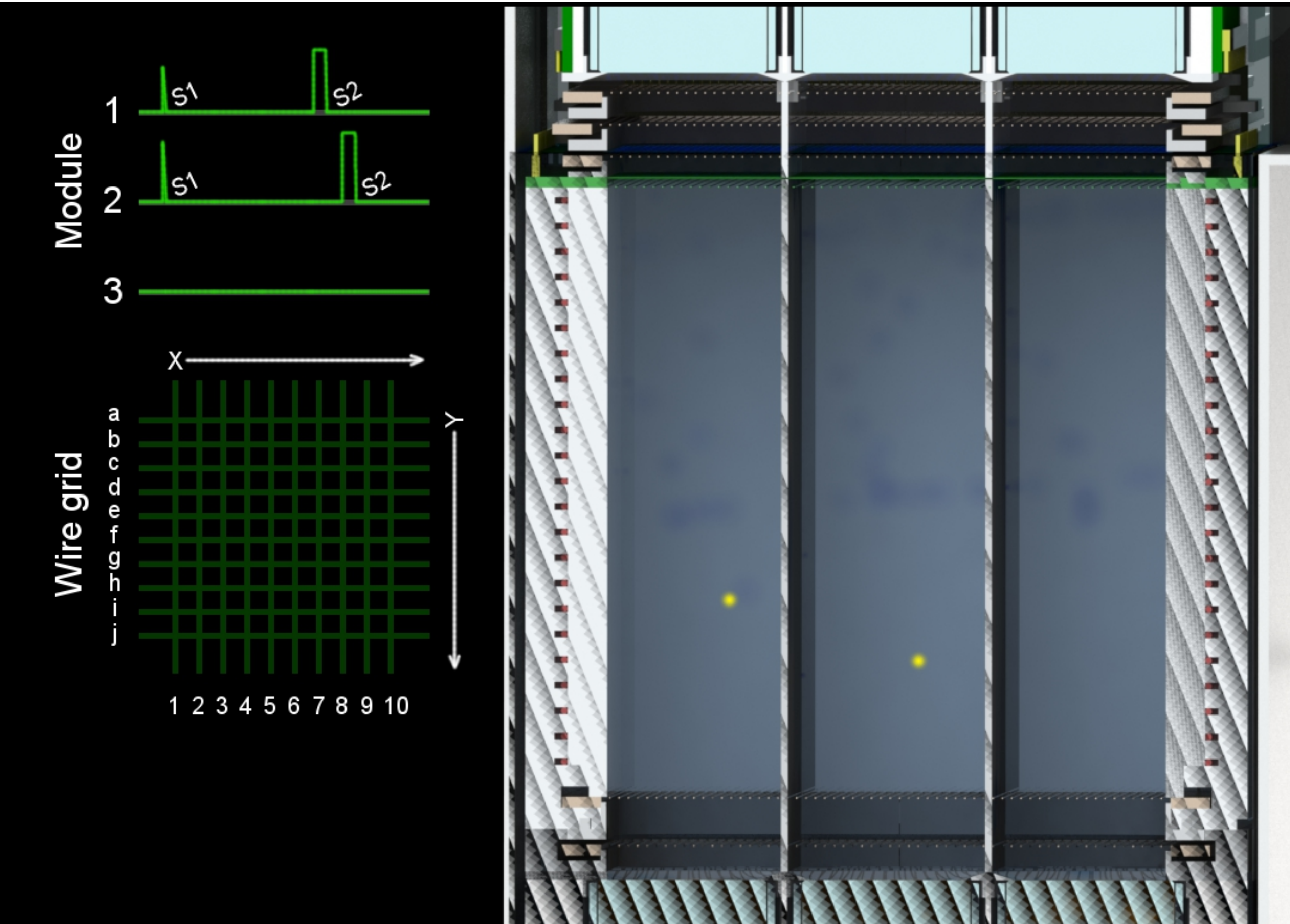
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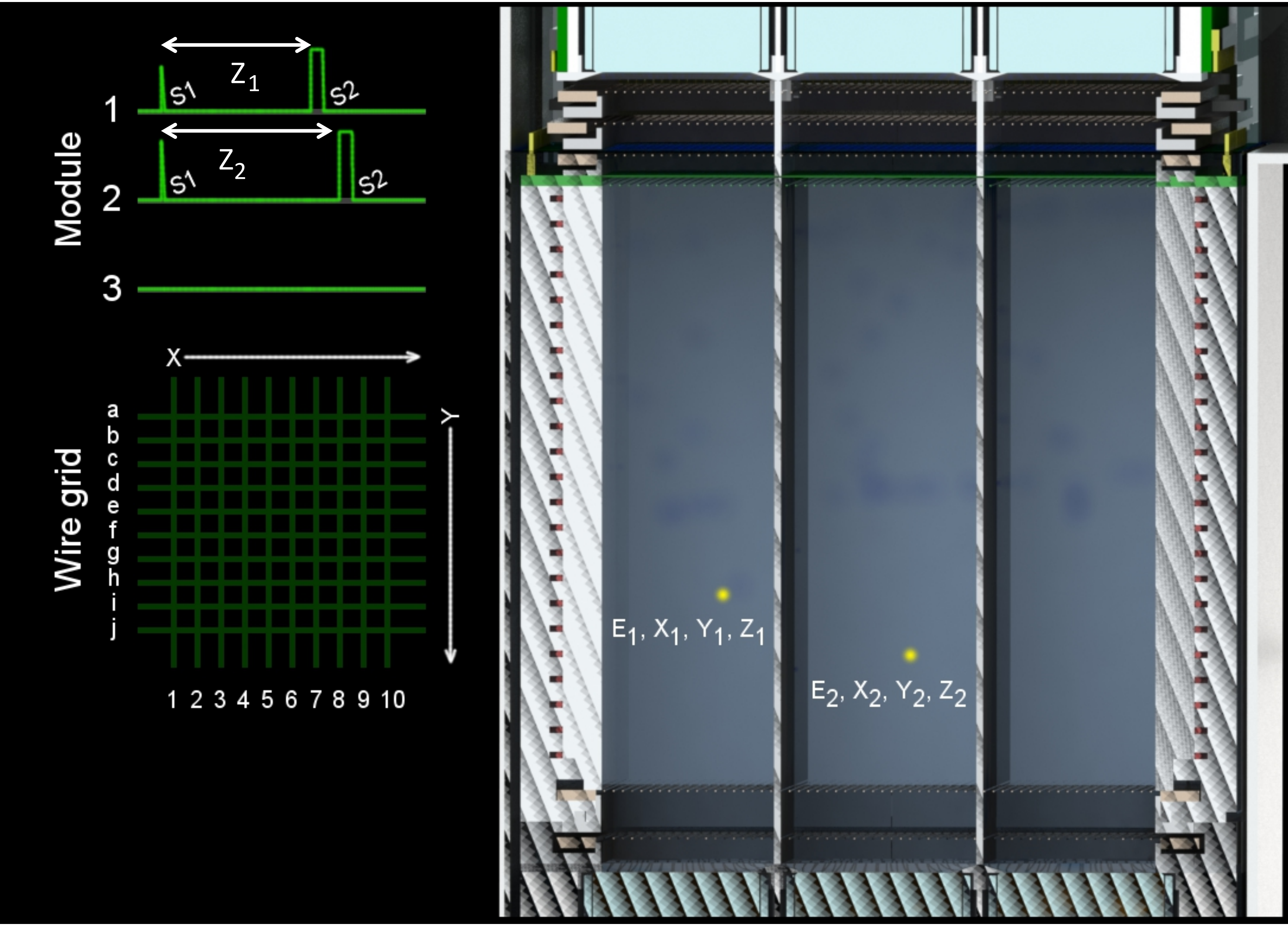

Module
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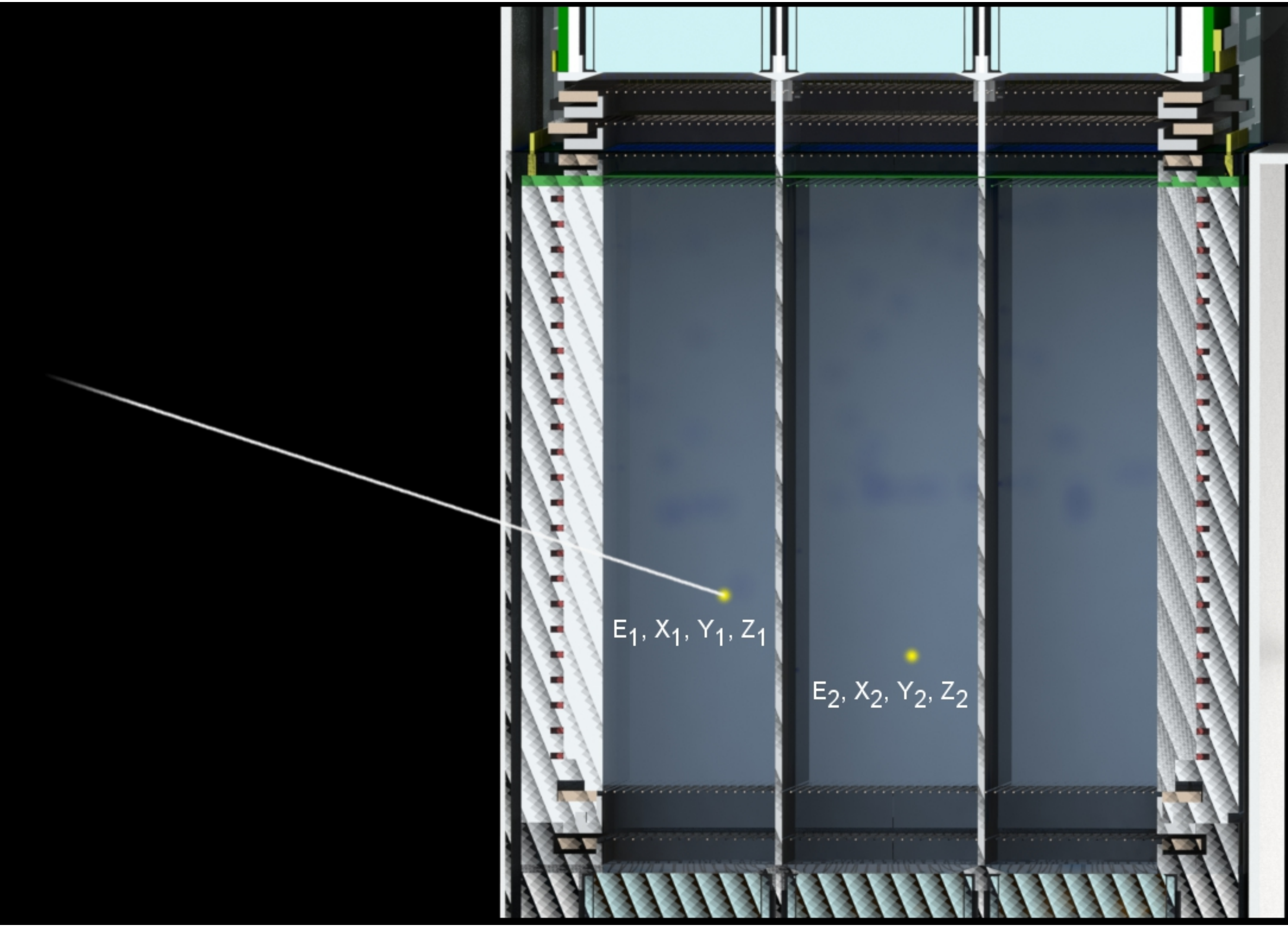
E_1, X_1, Y_1, Z_1
E_2, X_2, Y_2, Z_2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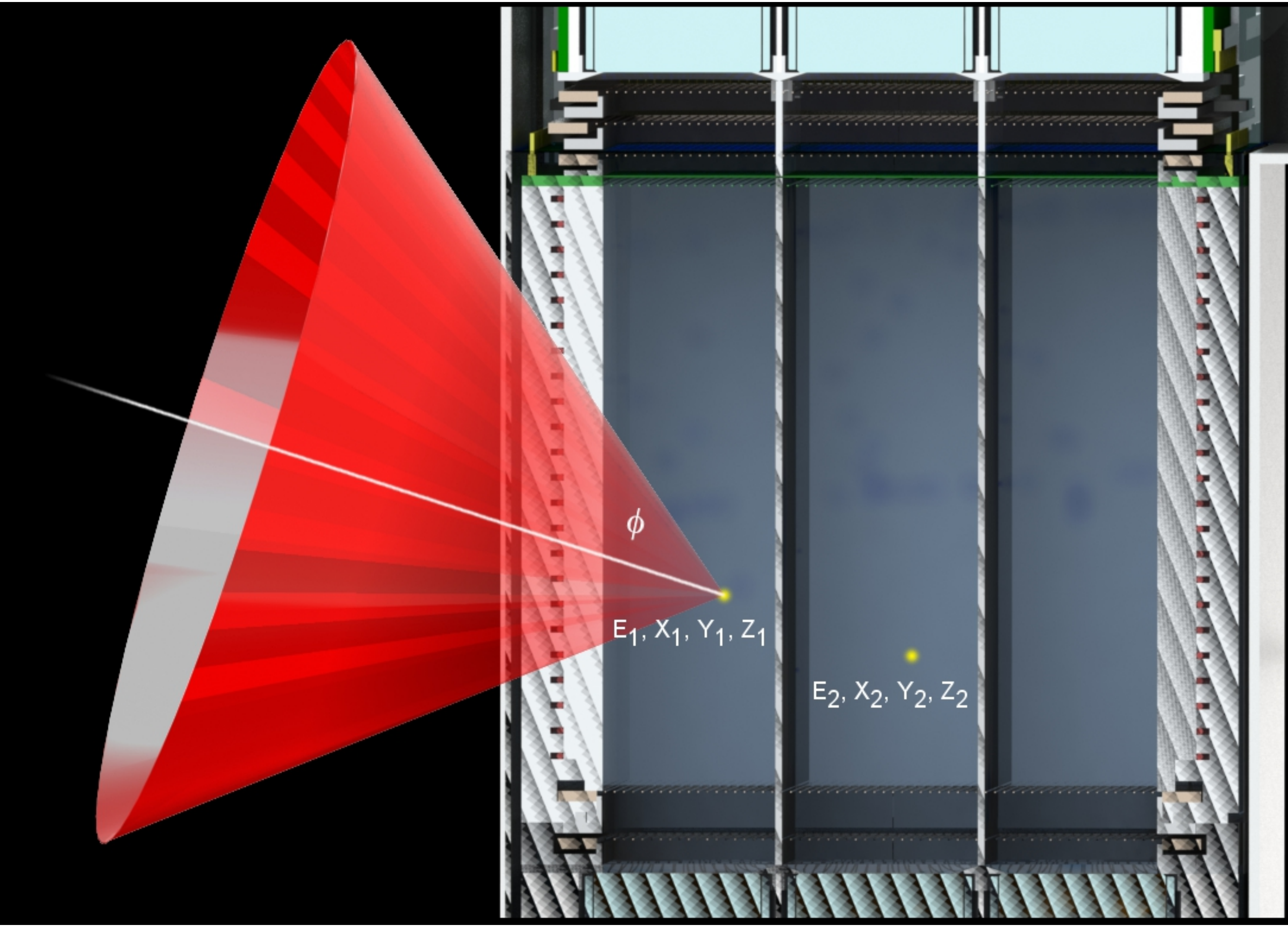
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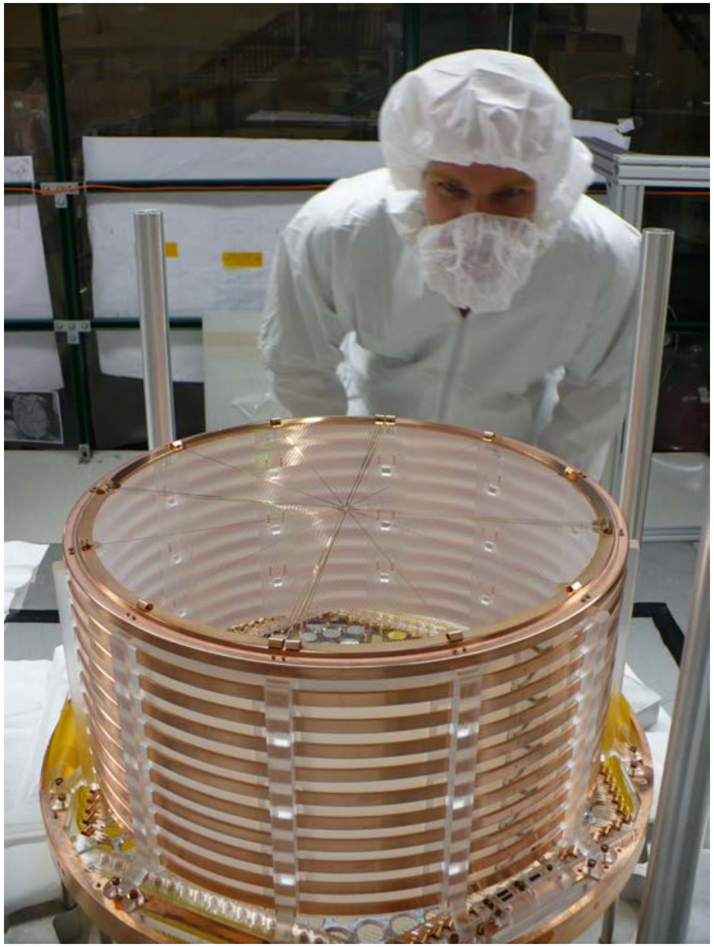
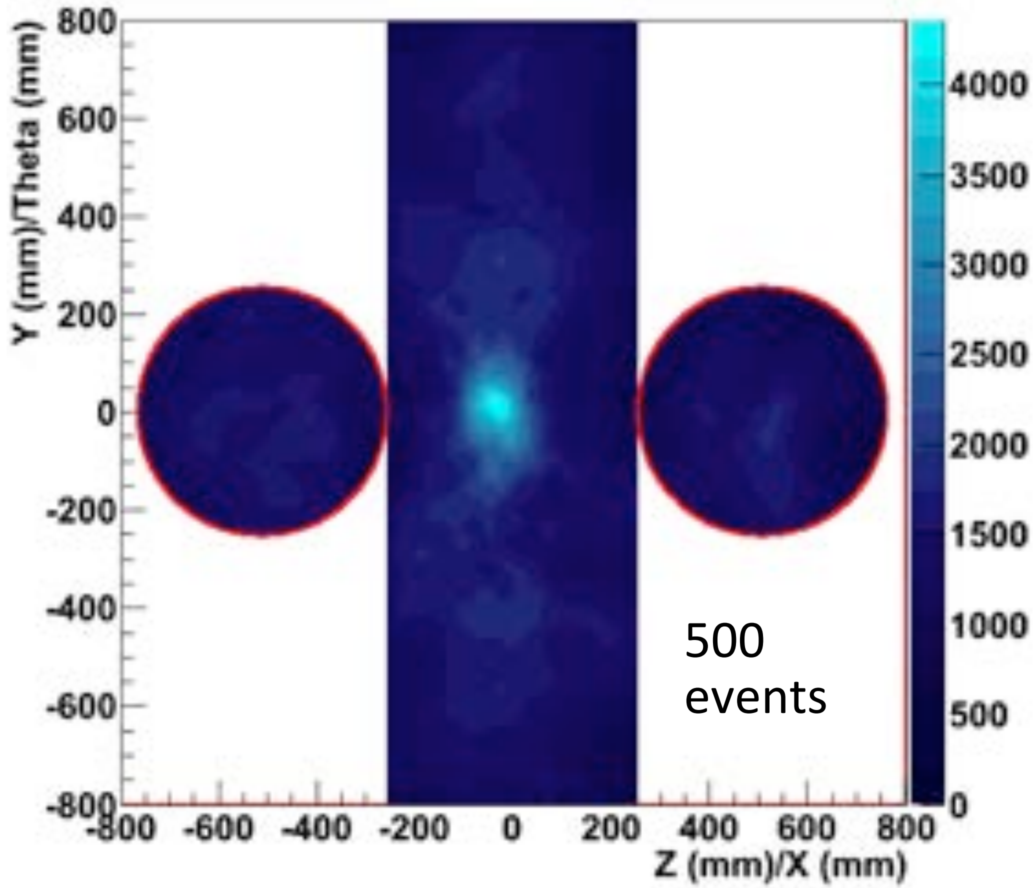
E_2, X_2, Y_2, Z_2

Compton Imaging in Liquid Xenon – the EXO Detector





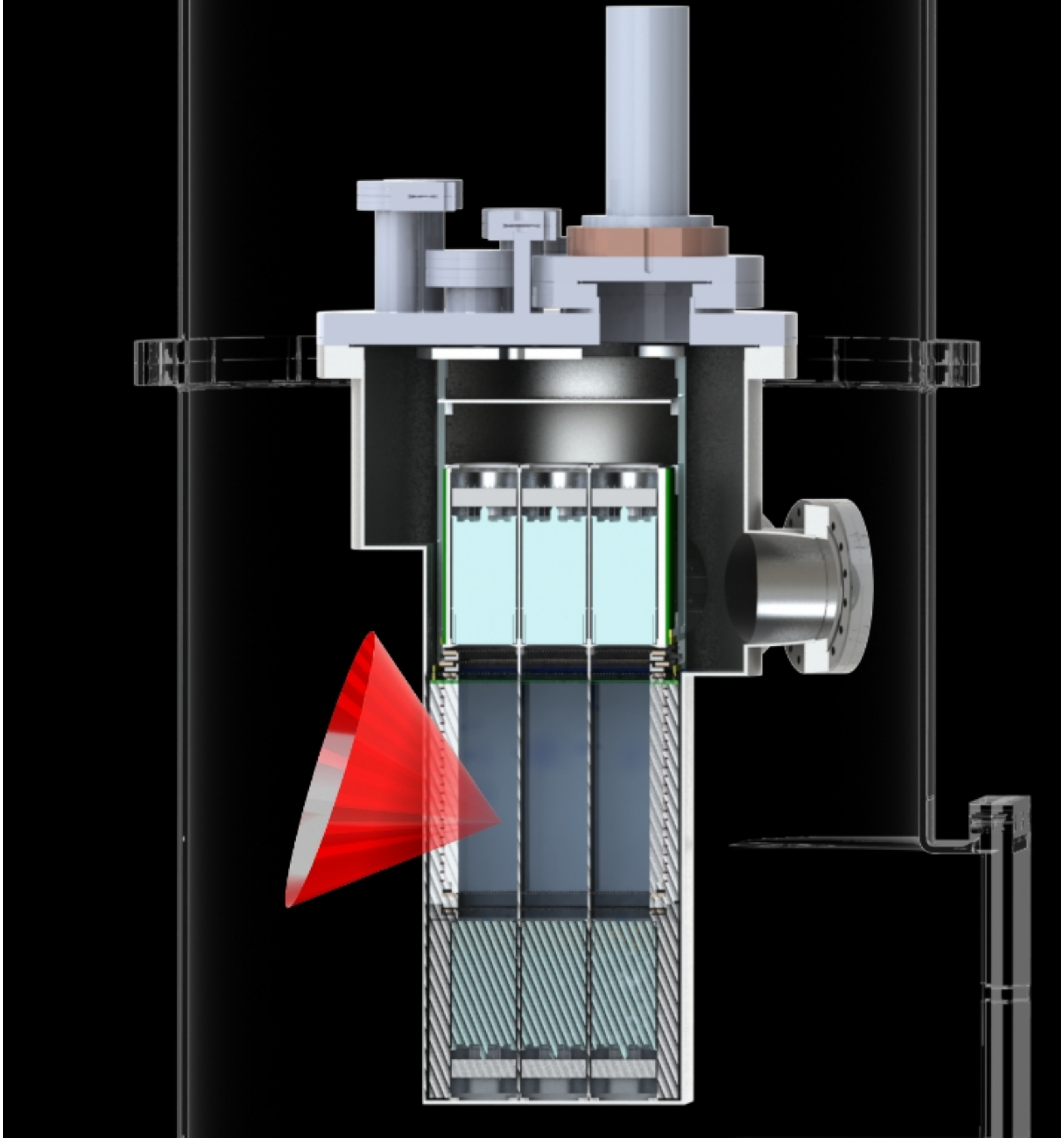
LXeGRIT Gamma Astronomy Telescope

- Single-phase, all-liquid xenon TPC.
- Durable, balloon borne for operation in the upper atmosphere.
- 5.9% FWHM energy resolution at 1 MeV
- 4.7 degree FWHM angular resolution

*E. Aprile *et al.*, *New Astronomy Reviews,* **48**, *1-4, p. 257-262 (2004)*

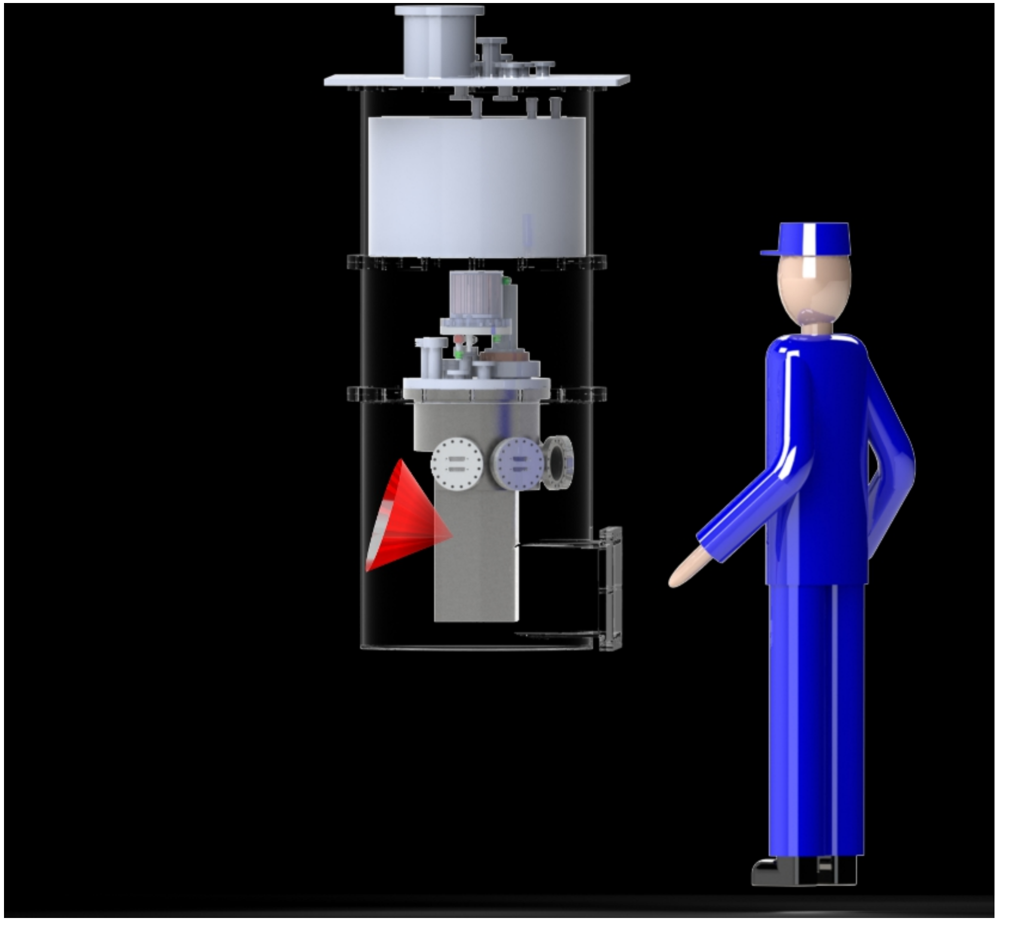
Existing

Under Construction



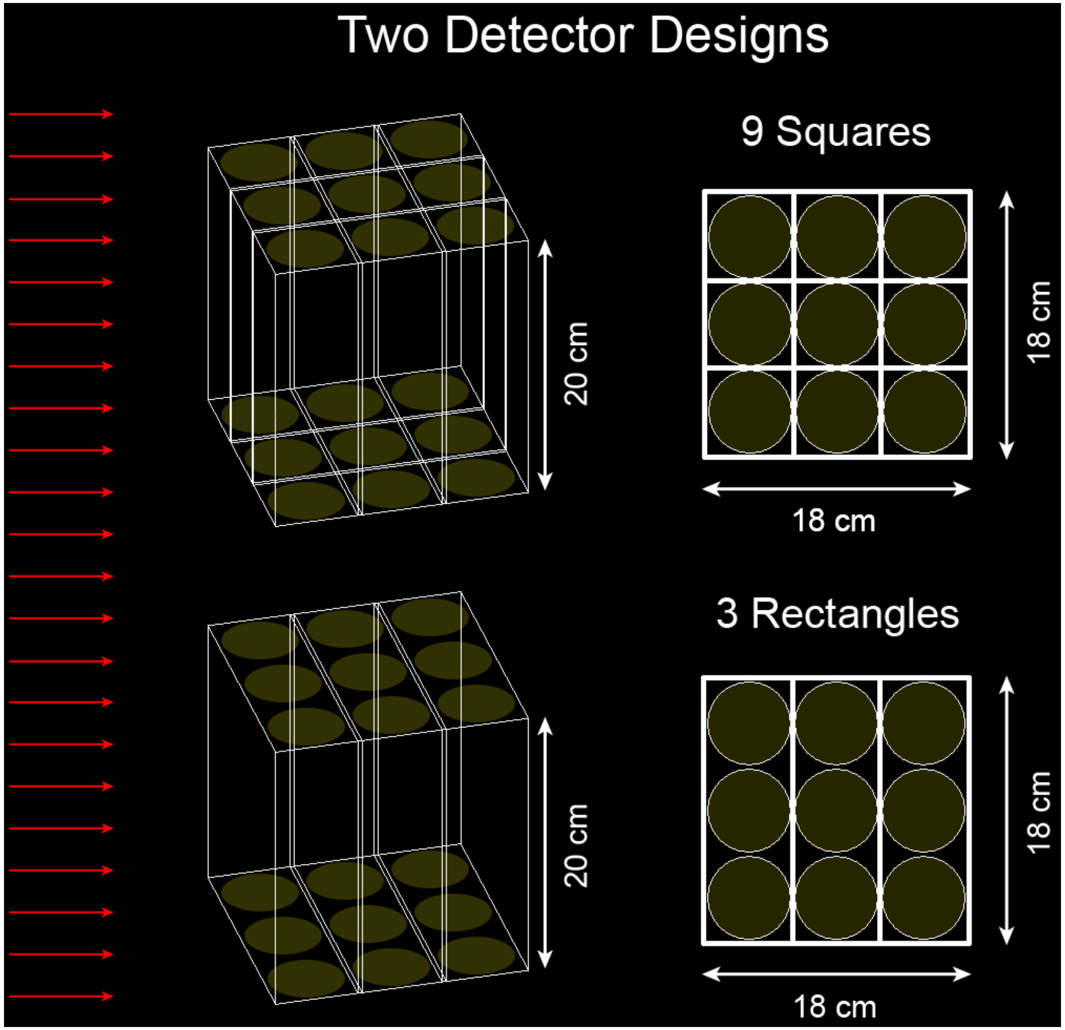
The PIXeY Compton Imager

- 18 kg of xenon in 6 liters of active volume.
- Three optical modules of 6 cm width.
- 18 PMTs (6 per module).
- 120 charge readout channels at 3 mm pitch.
- Operates under existing cryogenic platform.
- Full GEANT4 gamma and optical simulation.
- Detailed 3D CAD design is complete.
- Fabrication just beginning.
- Will use data analysis software from professor Zhong He's group at Michigan.



Modeling for Design Optimization

Ten detector geometries modeled with GEANT4 to optimize efficiency and resolution



Model parameters

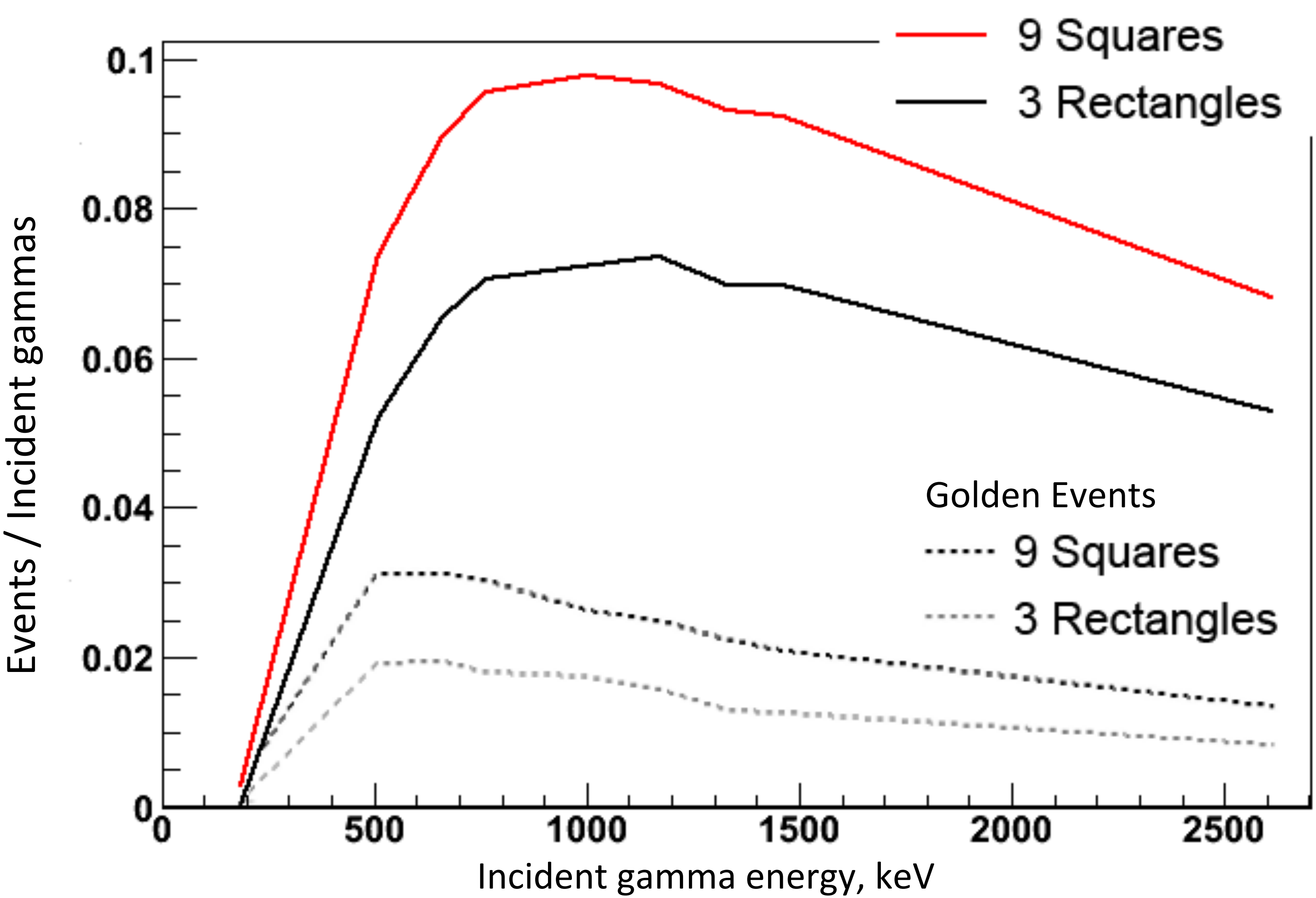
1 mm σ wire grid resolution

Light collection model from the ZEPLIN dark matter collaboration

90% transparent field establishing grids. All others 95%.

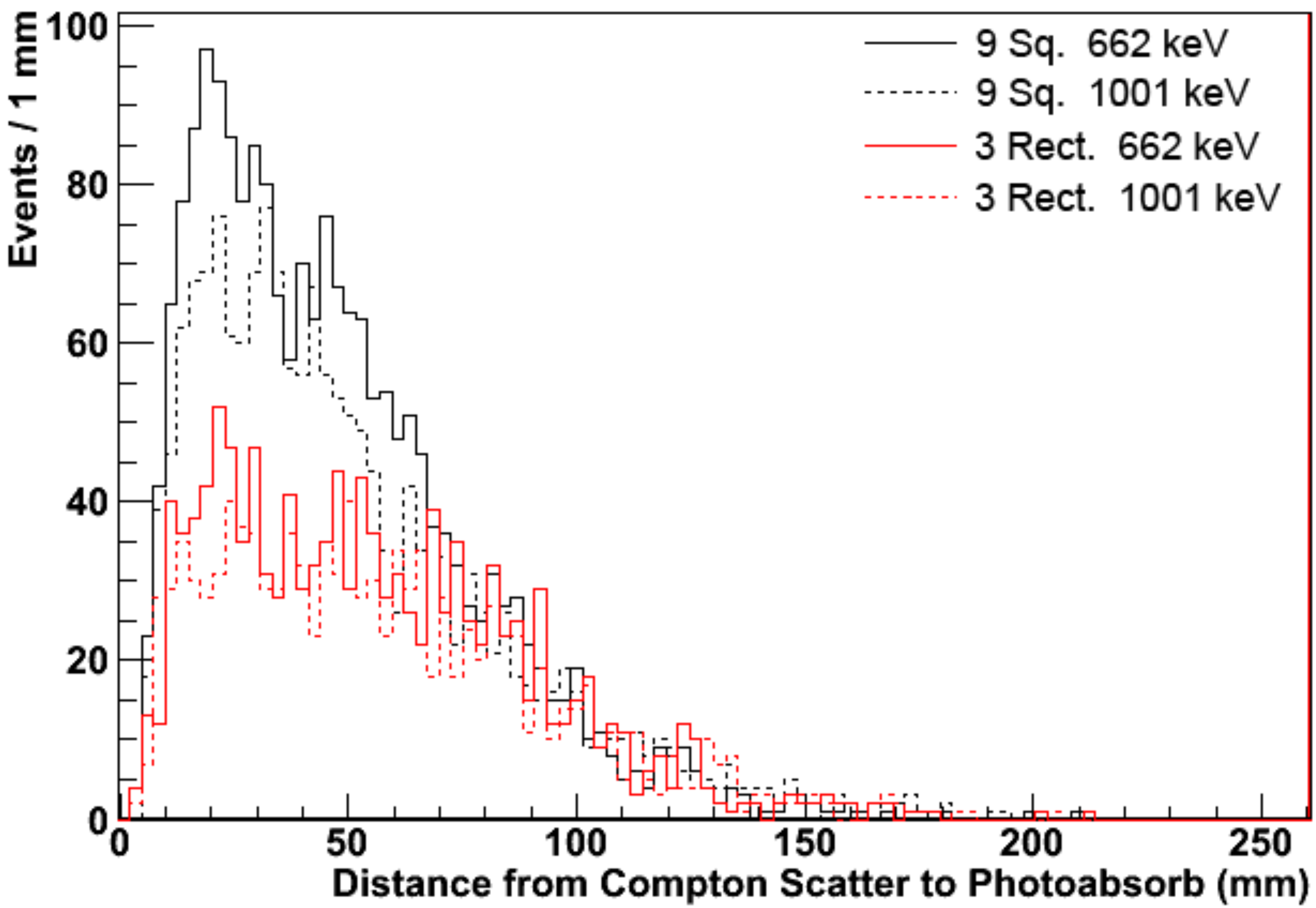
Energy resolution calculated from
E. Aprile *et al*., Phys. Rev. B **76,** 014115 (2007)

Efficiency of Compton Imager Designs

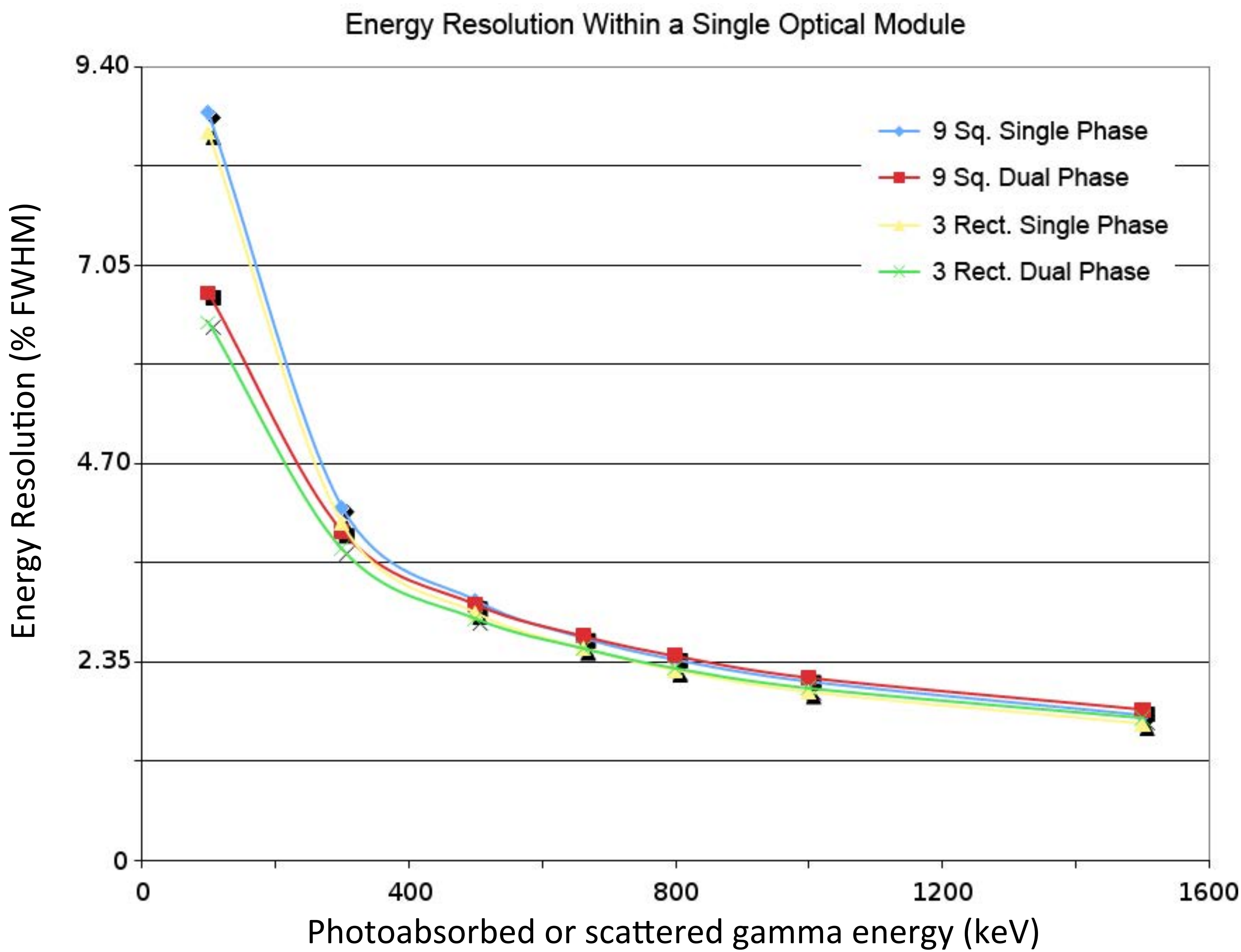


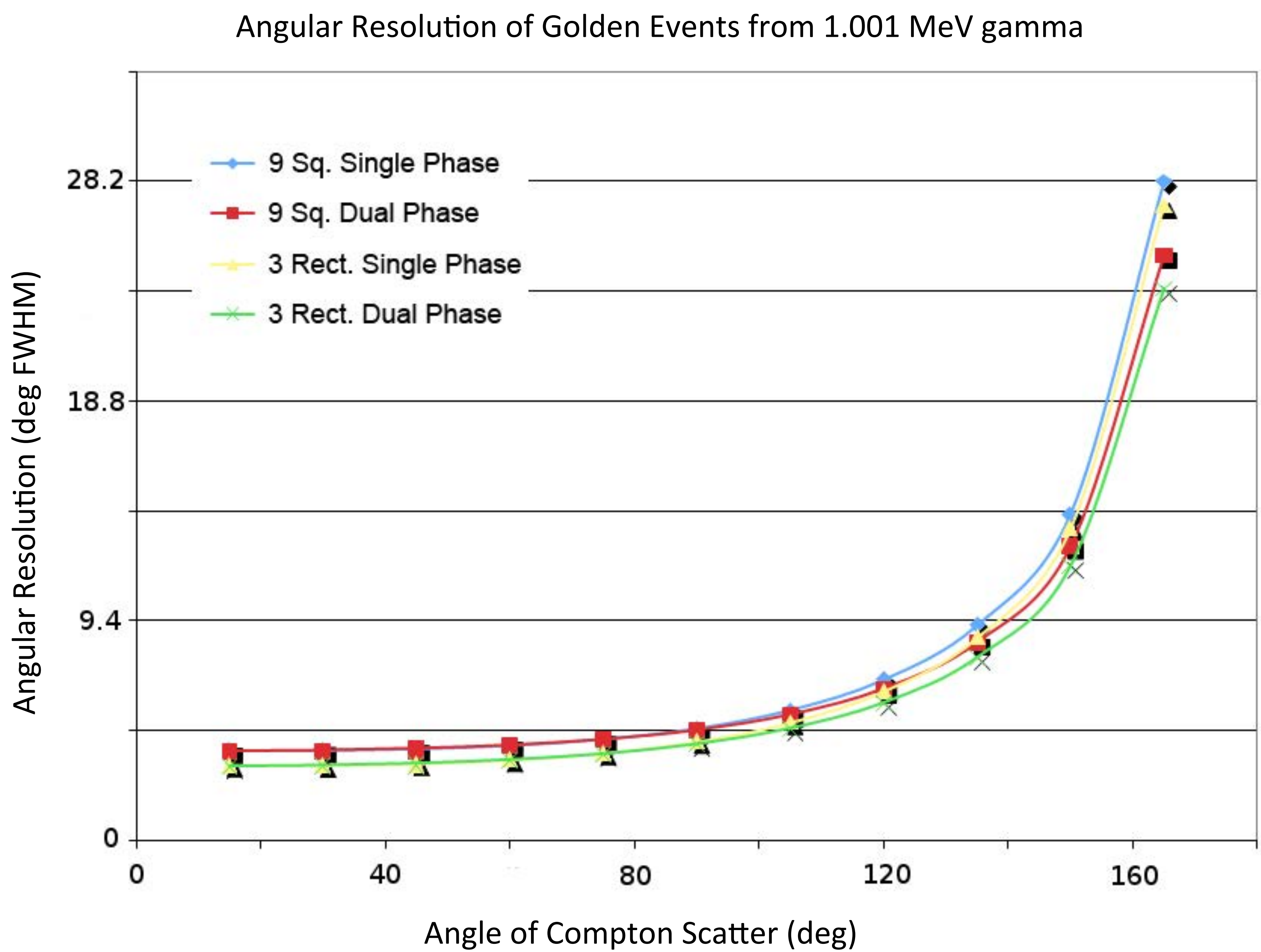
Golden events: Single isolated Compton scatter followed by photoabsorption.

Silver events: Single isolated Compton scatter followed by capture of the remaining energy within the active xenon.

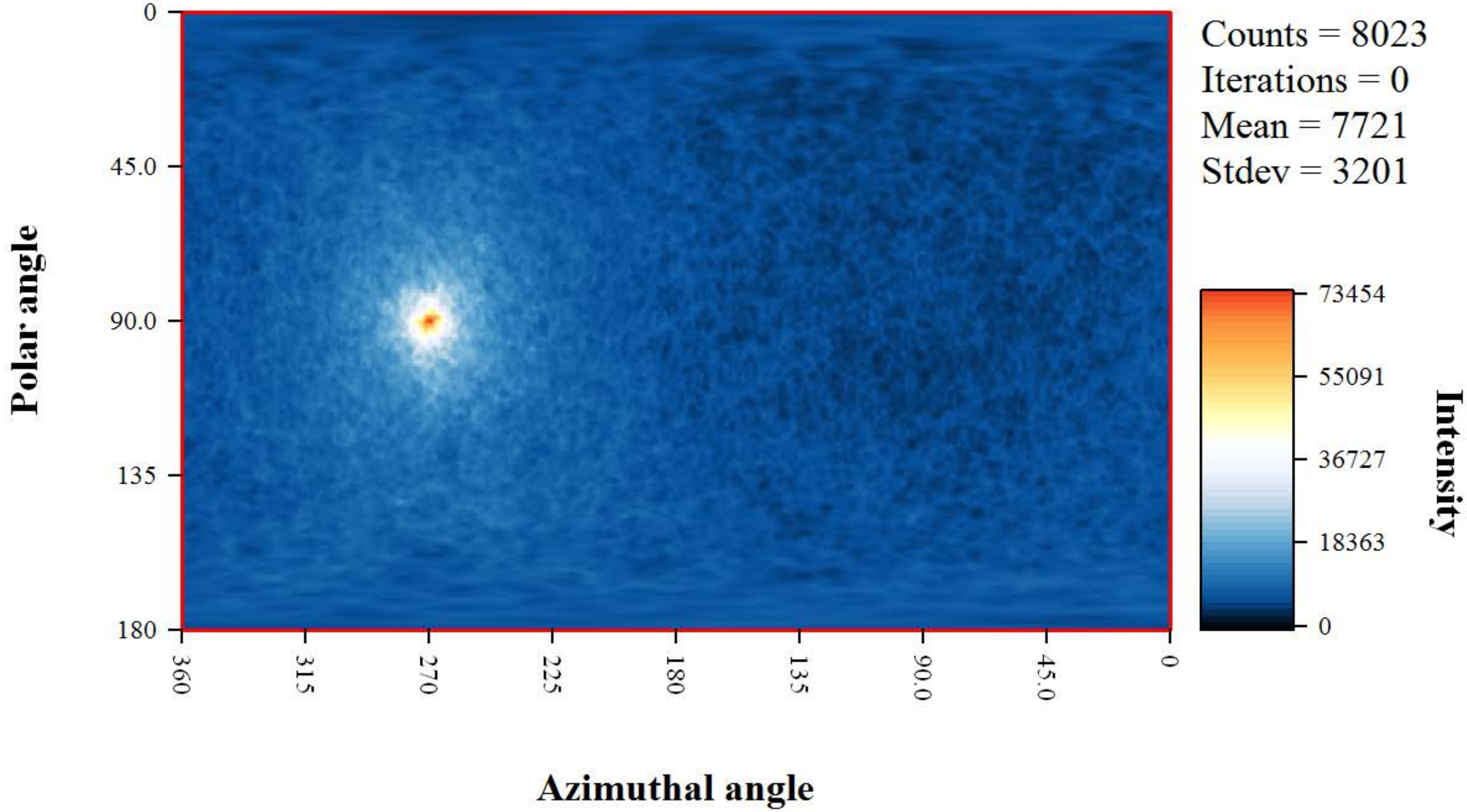


Events / 1 mm
Distance from Compton Scatter to Photoabsorb (mm)
9 Sq. 662 keV
9 Sq. 1001 keV
3 Rect. 662 keV
3 Rect. 1001 keV
0
20
40
60
80
100
0
50
100
150
200
250


Energy Resolution Within a Single Optical Module
9 Sq. Single Phase
9 Sq. Dual Phase
3 Rect. Single Phase
3 Rect. Dual Phase
9.40
7.05
4.70
2.35
0
0
400
800
1200
1600
Energy Resolution (% FWHM)
Photoabsorbed or scattered gamma energy (keV)


Angular Resolution of Golden Events from 1.001 MeV gamma
9 Sq. Single Phase
9 Sq. Dual Phase
3 Rect. Single Phase
3 Rect. Dual Phase
28.2
18.8
9.4
0
0
40
80
120
160
Angular Resolution (deg FWHM)
Angle of Compton Scatter (deg)

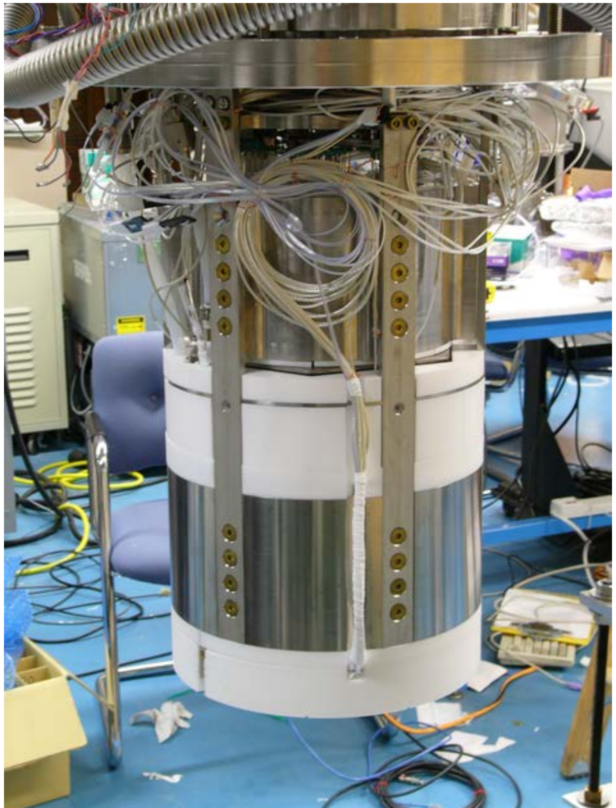
Projected Performance



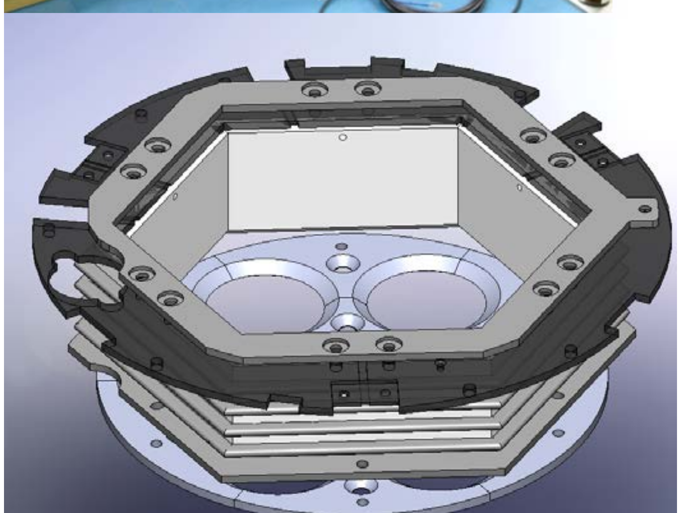
Perfect position resolution: 6° FWHM
Best case: 0.5 mm position resolution: 10.8° FWHM
Worst case: 1.5 mm position resolution: 13.5° FWHM

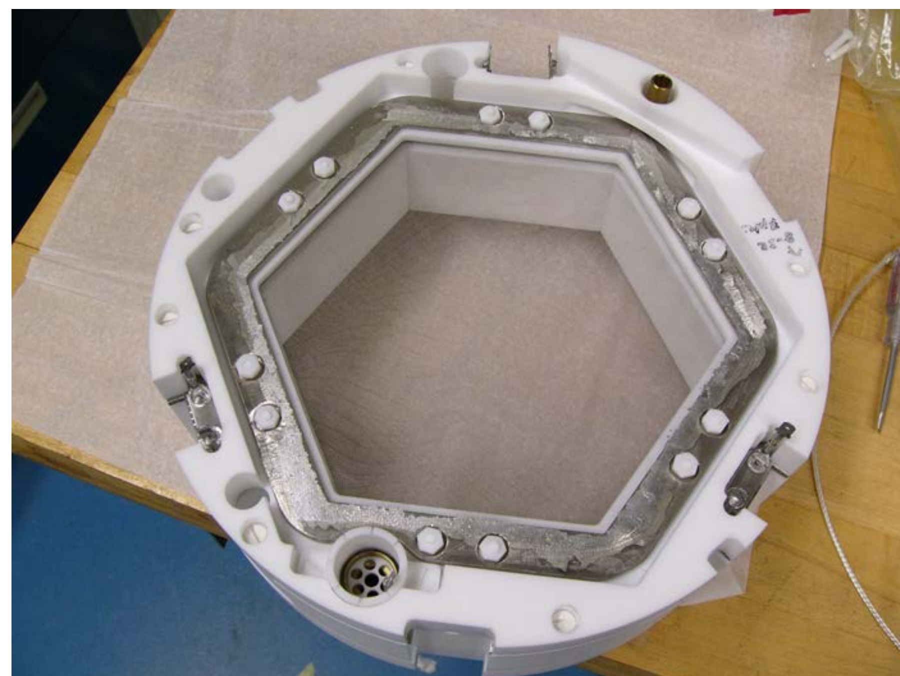
Worst case localizes source to 1/200 of total solid angle!

PIXeY – Particle Identification in Xenon at Yale

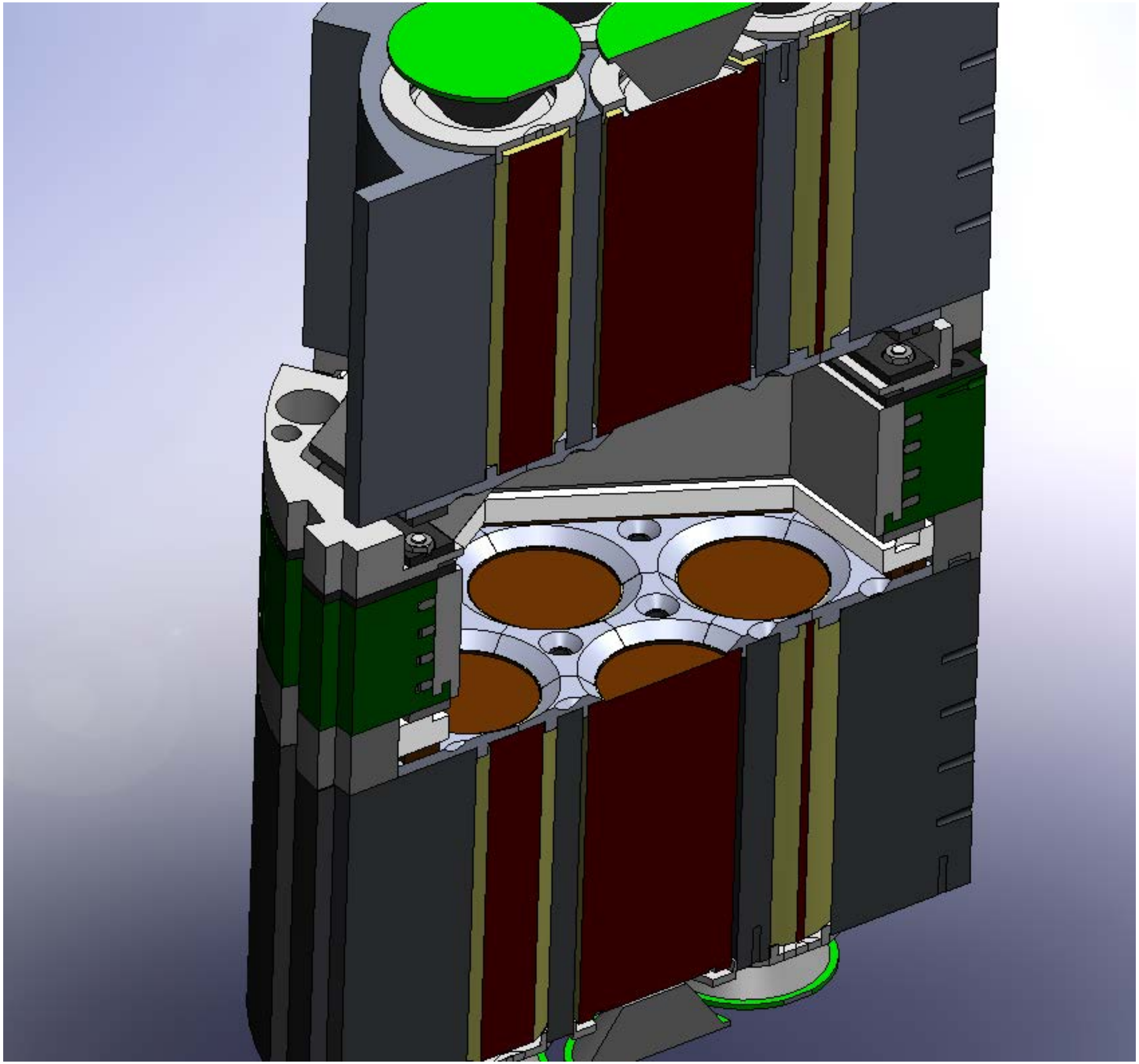


- Two-phase Xe detector; 3 kg active xenon volume.
- TPC is 5 cm tall by 18 cm across far corners. Teflon clad.
- Designed for optimal light collection and strong drift field.
- Has been running for 3 months at Yale, also ran 3 months last year.
- Test platform for technologies supporting Compton imaging:
  - Uniform, transparent grids.
  - Cryogenic and xenon circulation platform.
  - PMT readout and data processing software.

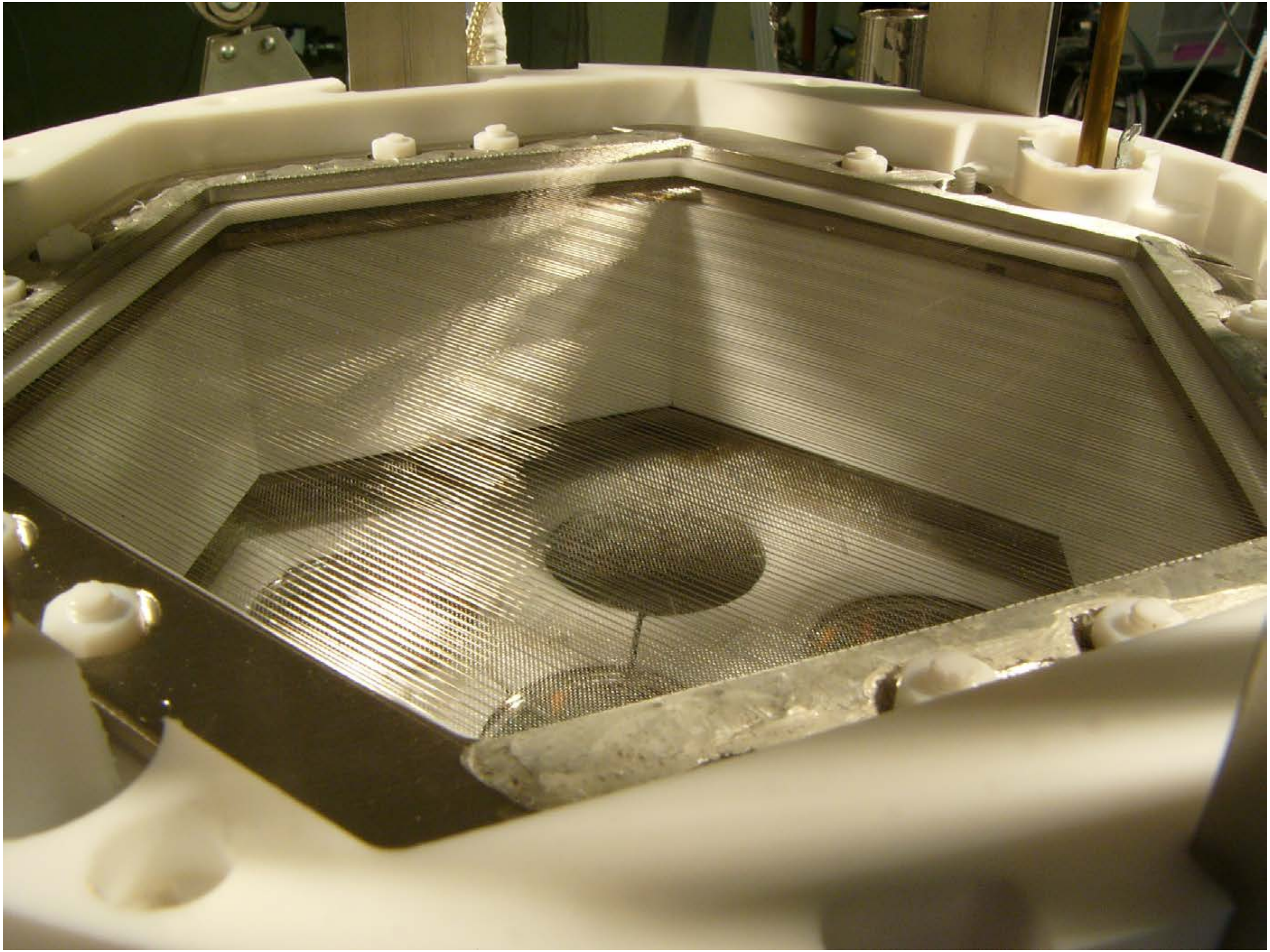


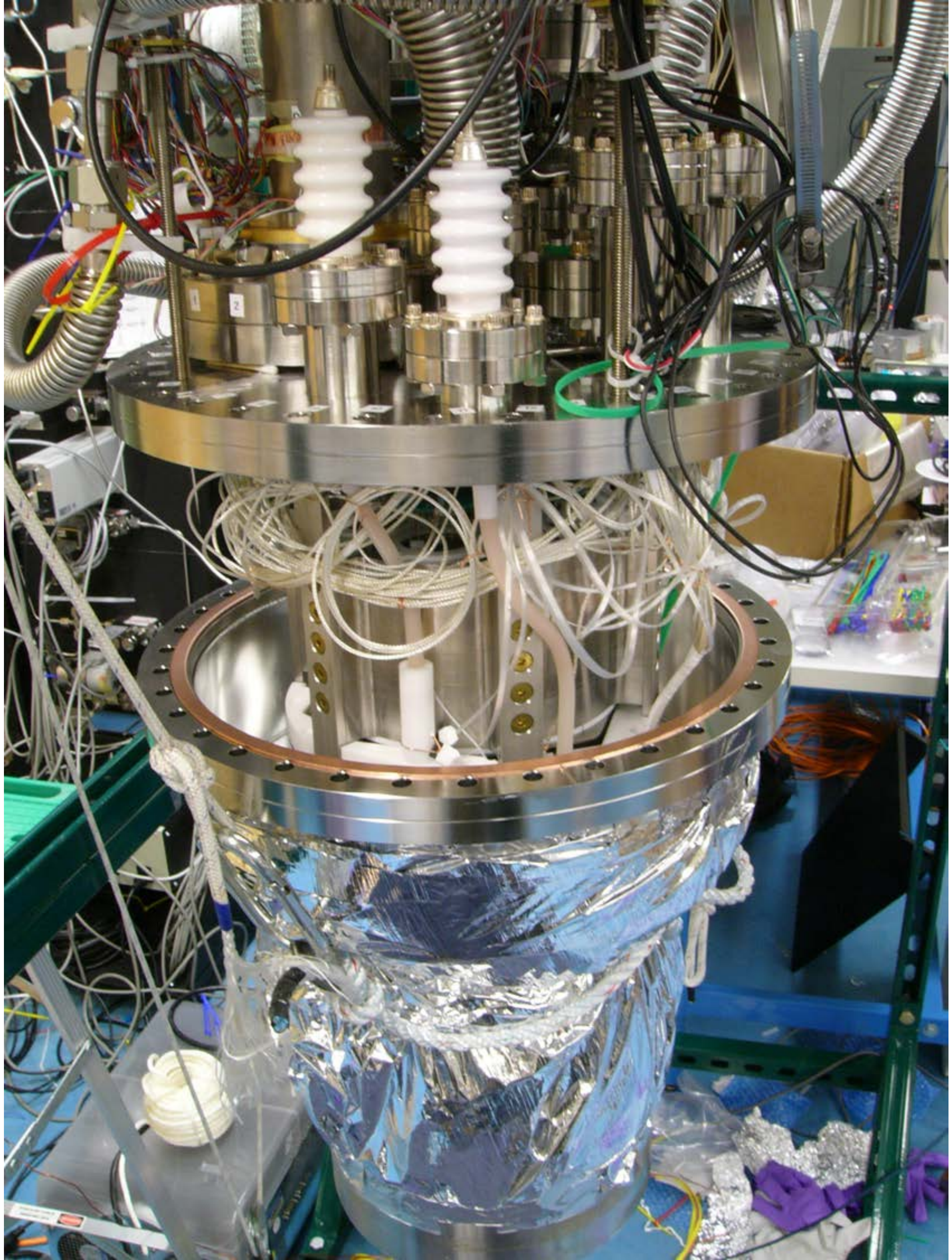


PIXeY in cross section

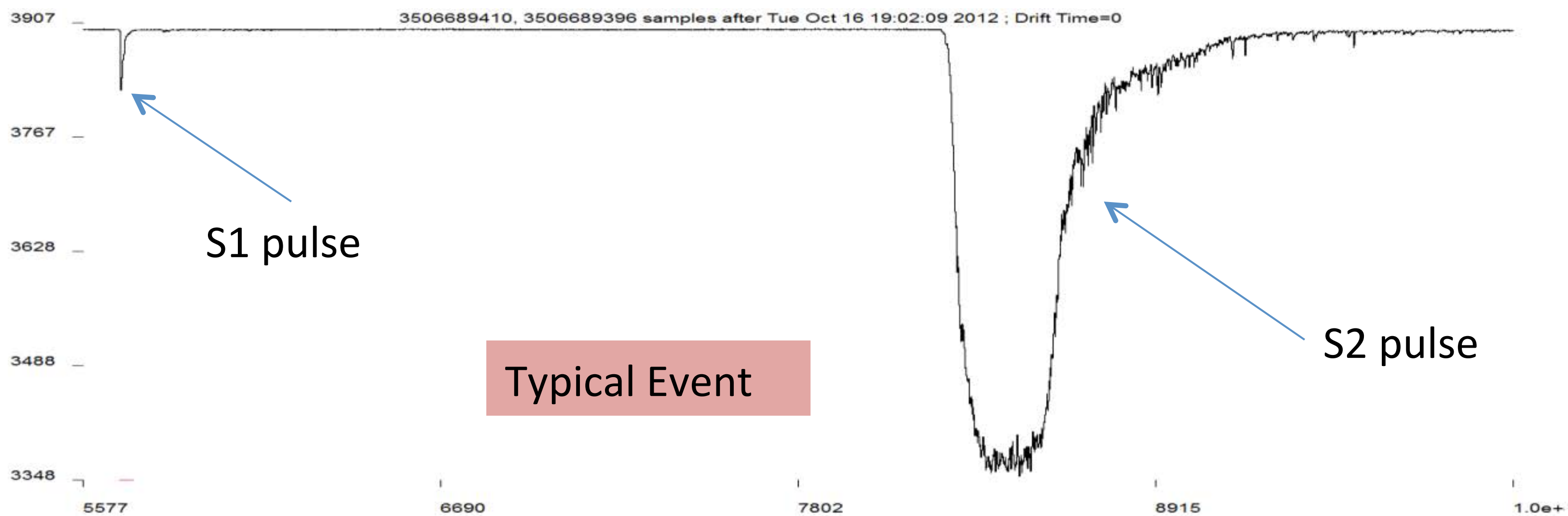


TPC With Grids

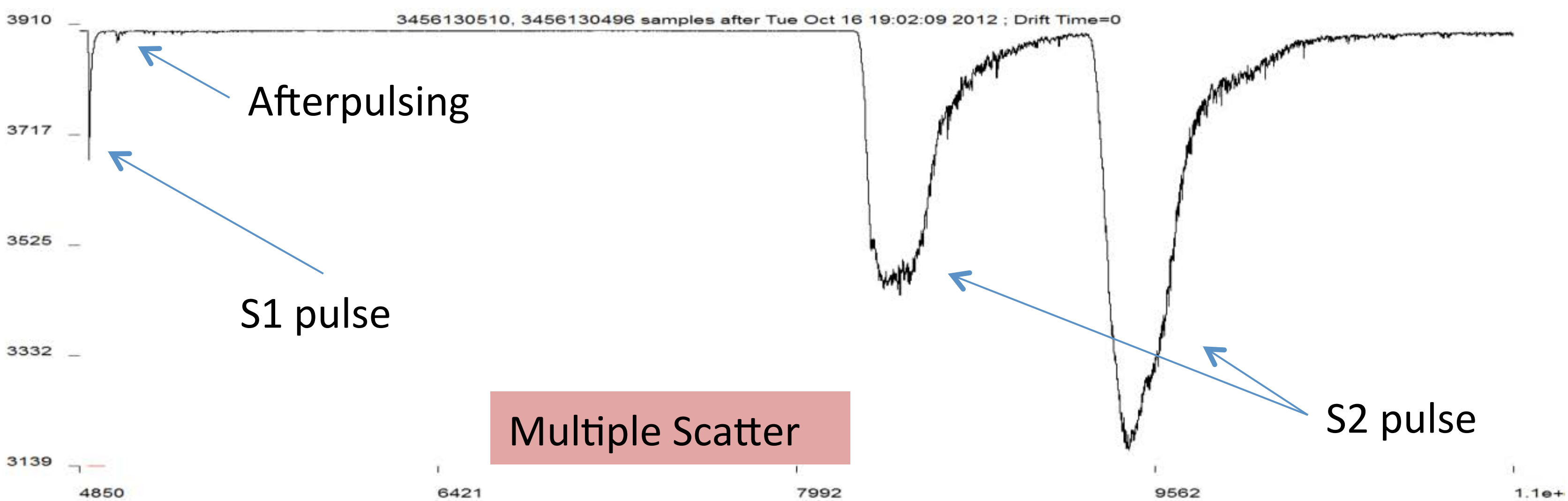




Waveforms

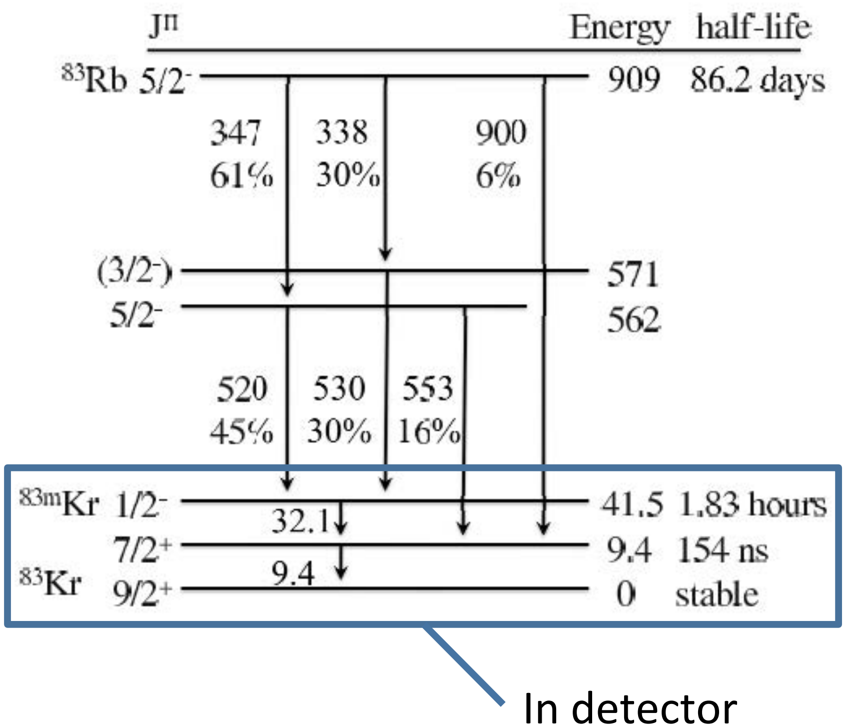


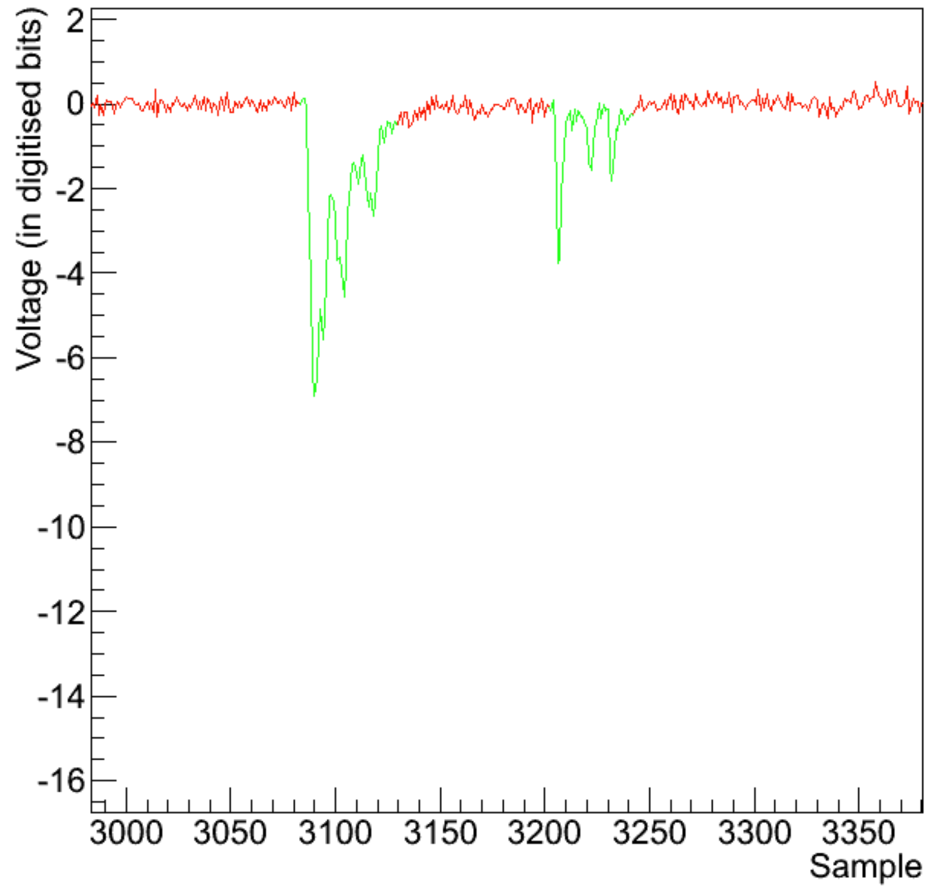
3506689410, 3506689396 samples after Tue Oct 16 19:02:09 2012 ; Drift Time=0
3907
3767
3628
3488
3348
5577
6690
7802
8915
1.0e+
S1 pulse
S2 pulse
Typical Event



3456130510, 3456130496 samples after Tue Oct 16 19:02:09 2012 ; Drift Time=0
3910
3717
3525
3332
3139
4850
6421
7992
9562
1.1e+
Afterpulsing
S1 pulse
S2 pulse
Multiple Scatter

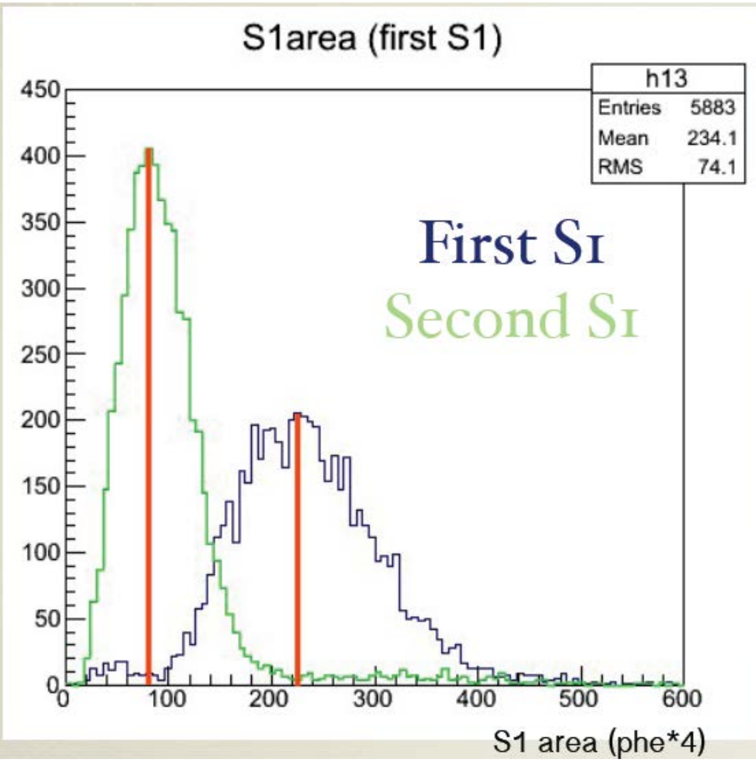
Kr-83m

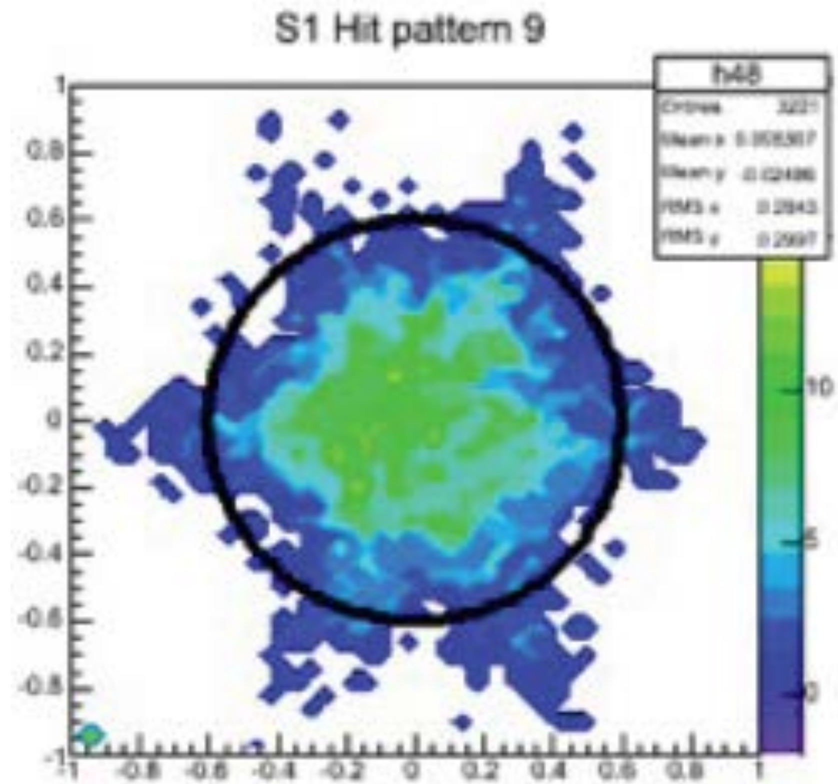




- Inject Kr-83m directly into liquid xenon
- Increased rate noted 5-10 min. after injection
- Spectral and other datasets taken 2-4 hrs. later

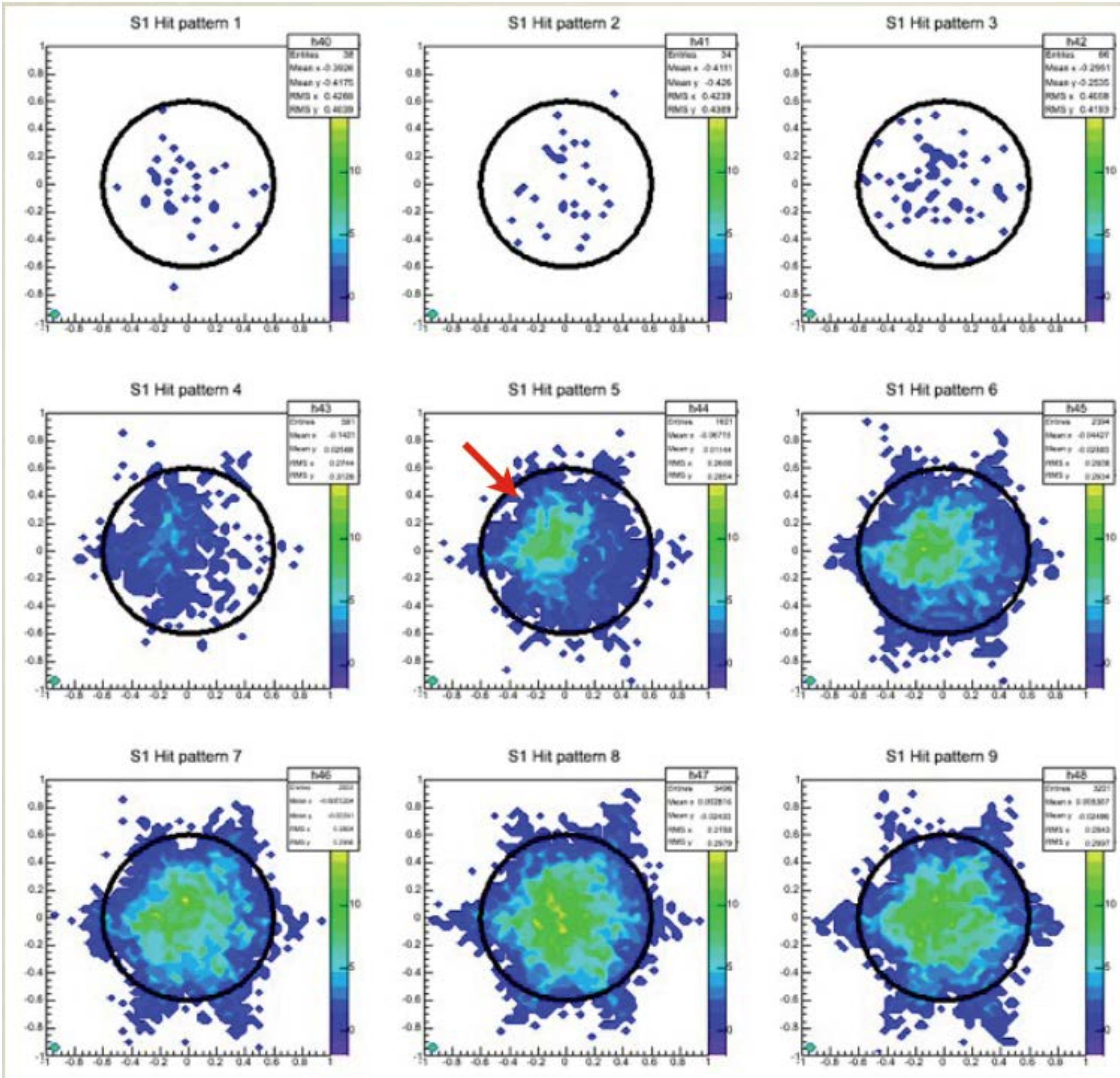
Kr-83m





Kr-83m appears in the top left and spreads over the whole volume in 5-10 min.

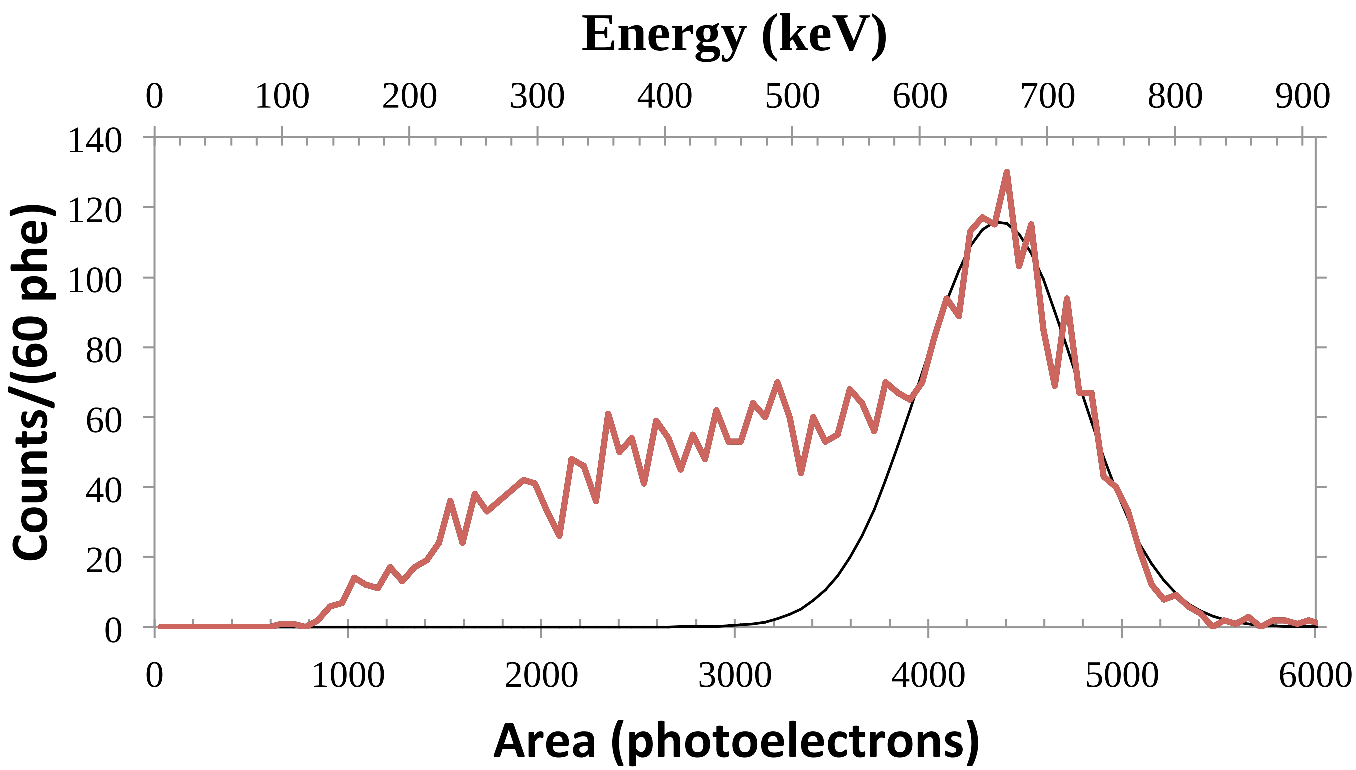
Kr-83m


S1 Hit pattern 1
S1 Hit pattern 2
S1 Hit pattern 3
S1 Hit pattern 4
S1 Hit pattern 5
S1 Hit pattern 6
S1 Hit pattern 7
S1 Hit pattern 8
S1 Hit pattern 9

PIXeY – Zero Field Light Collection

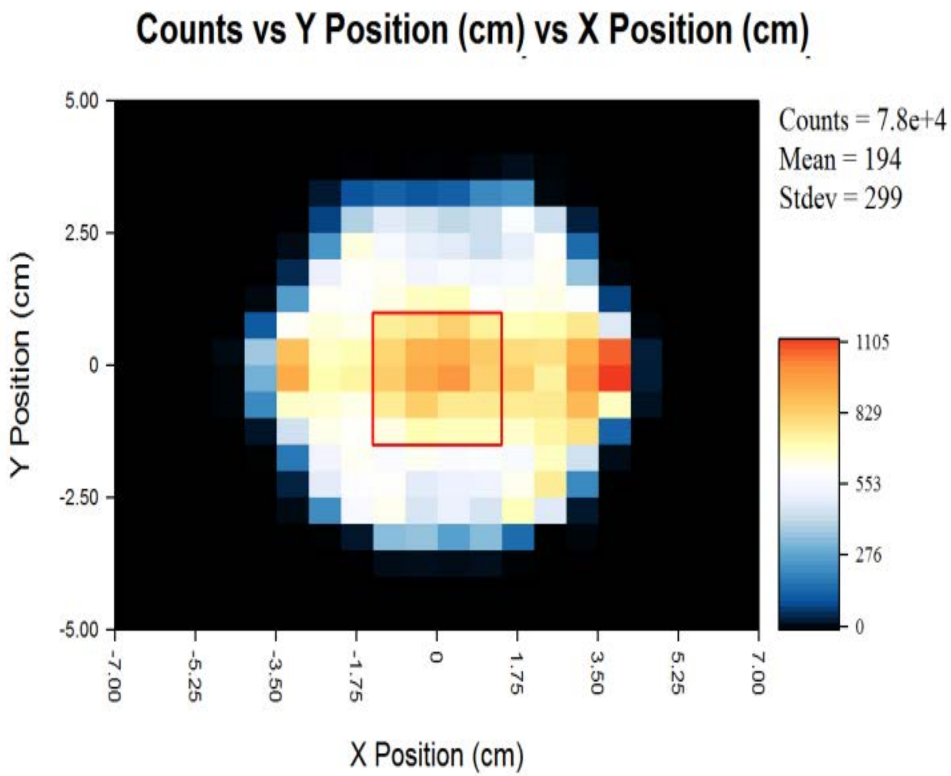
3721 Counts from Cs-137

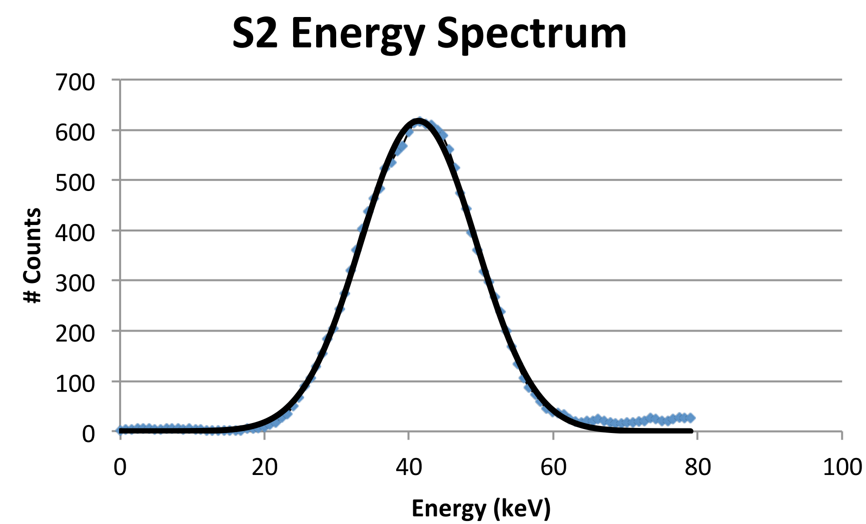
Cuts: Depths in top third of detector, east quadrant of detector



Zero field light collection:
6.7 Phe/keV

Kr-83m – Energy Spectra





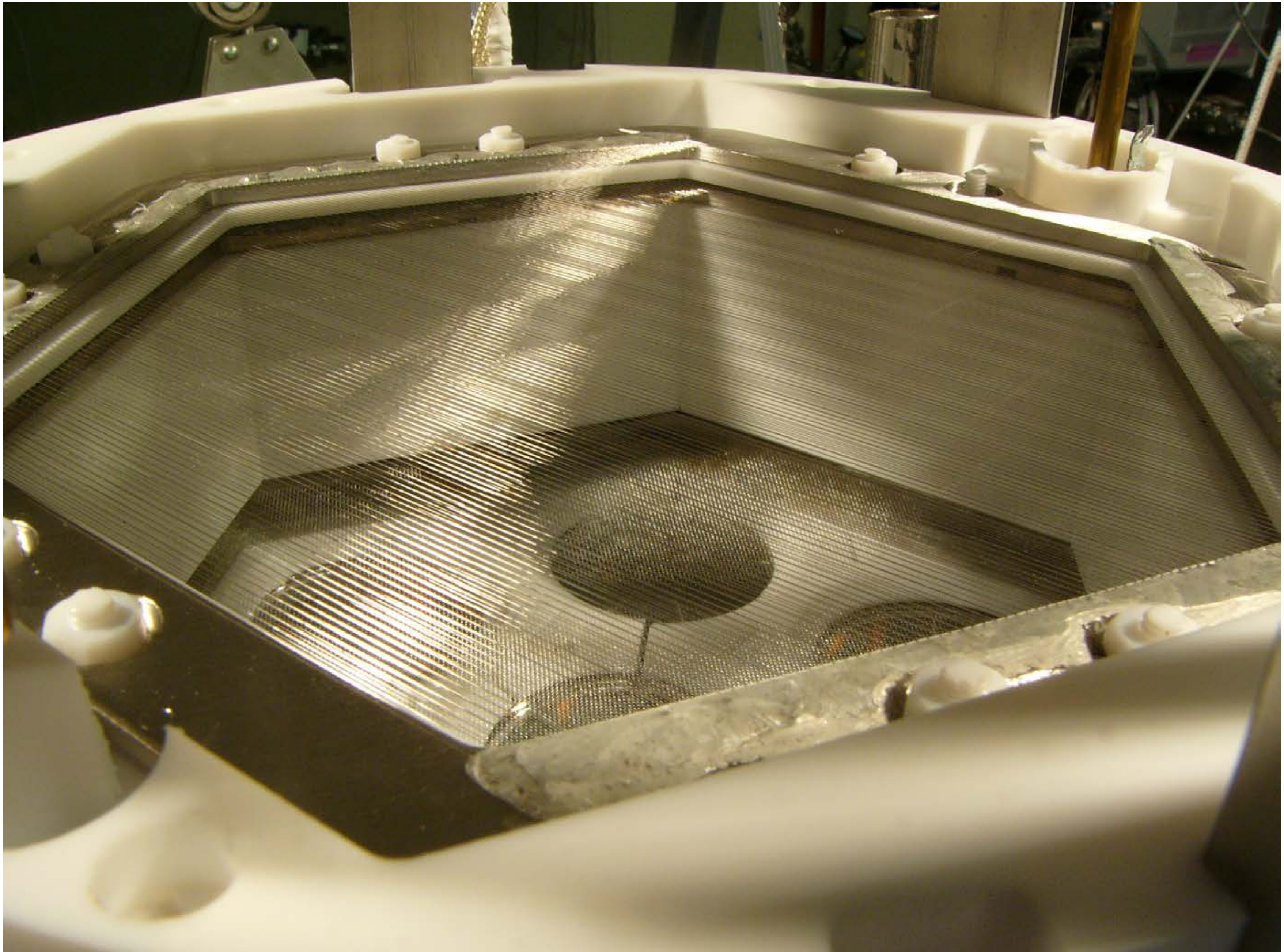
- Position cuts
- Lifetime correction

Yet to be done:

- Gain optimization/flat fielding
- Drift time cuts
- Background modeling

- 19% σ at the combined energy peak
- Agrees with extrapolated xenon10 energy resolution.
- Optimization of resolution currently ongoing

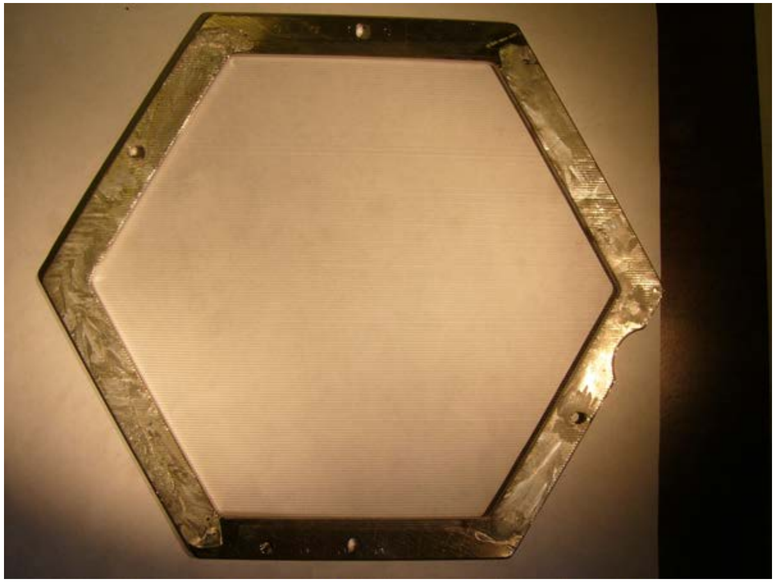
Glorious Hardware!

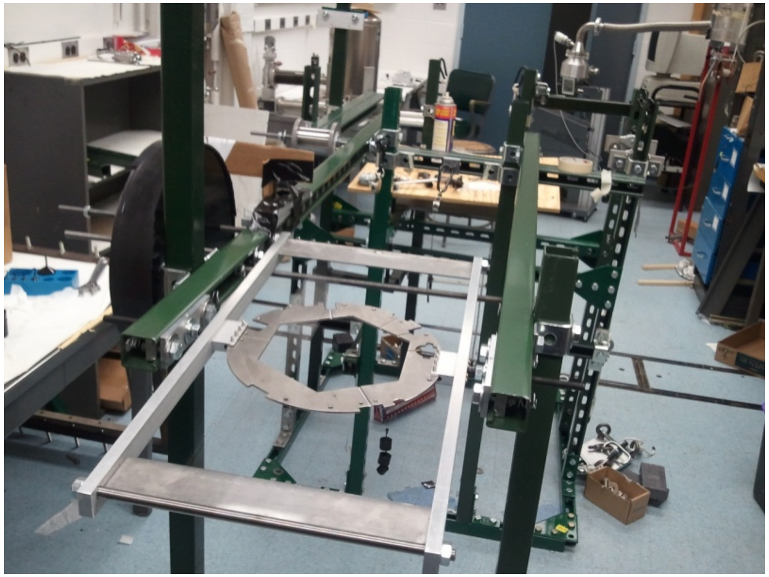


Parallel Wire Grids

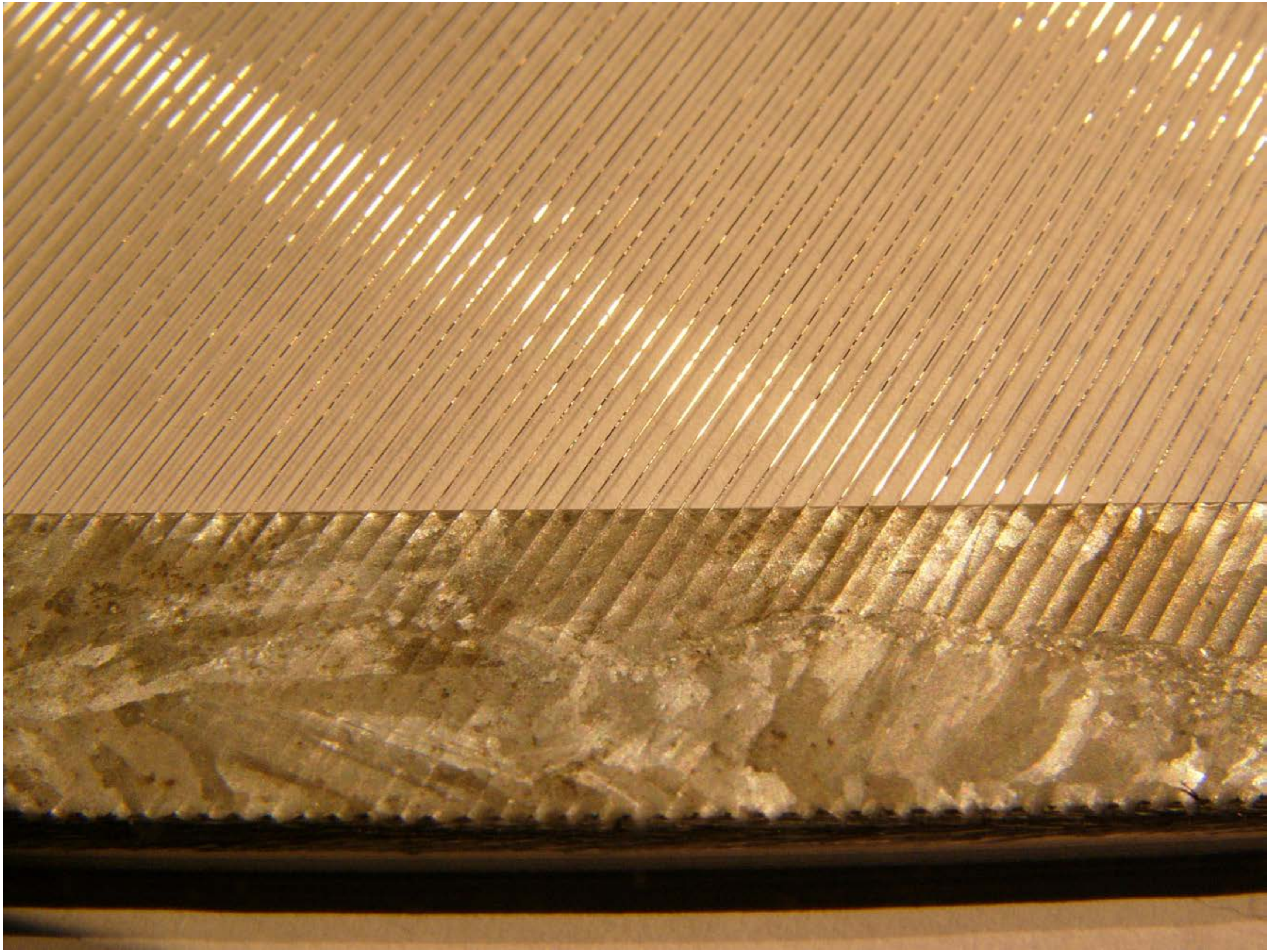
- Specifications
  - Wire and frame are monel alloy 400
  - 92% transparent field establishing grids
  - 80 µm wire, 1 mm pitch
  - 250 g/wire tension
  - Can be made to arbitrary pitch
- Maintain uniform tension while cold

- Only slightly magnetic, even when cold



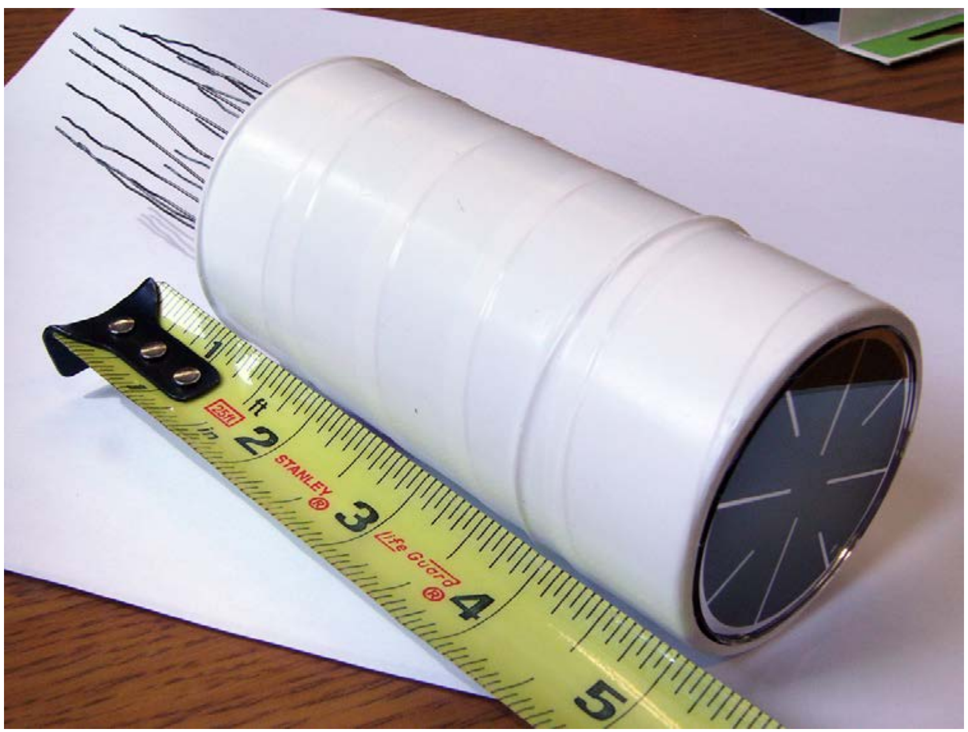


Anode Grid – 1 mm wire spacing

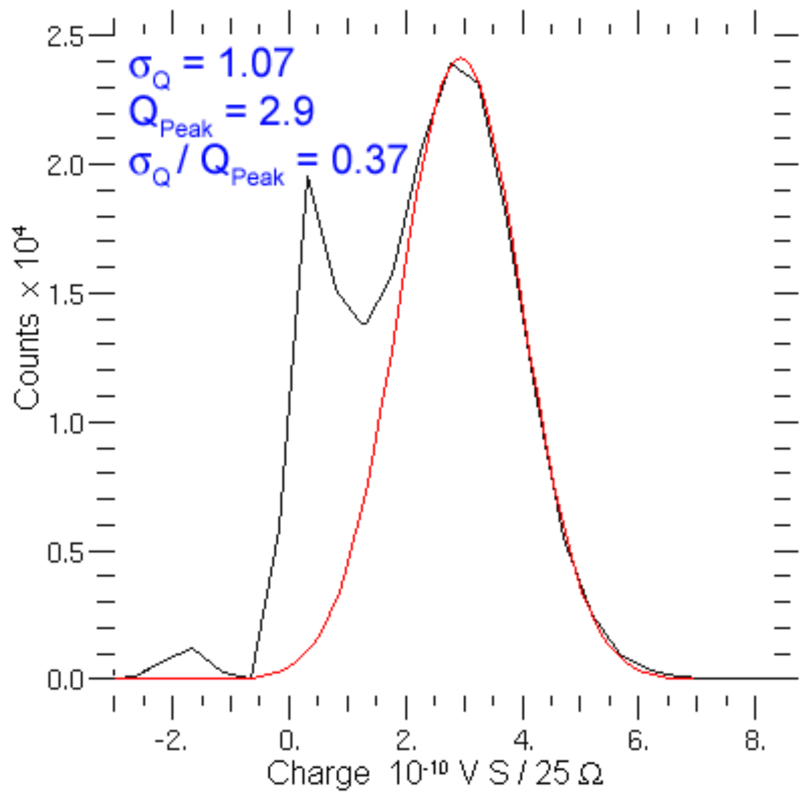


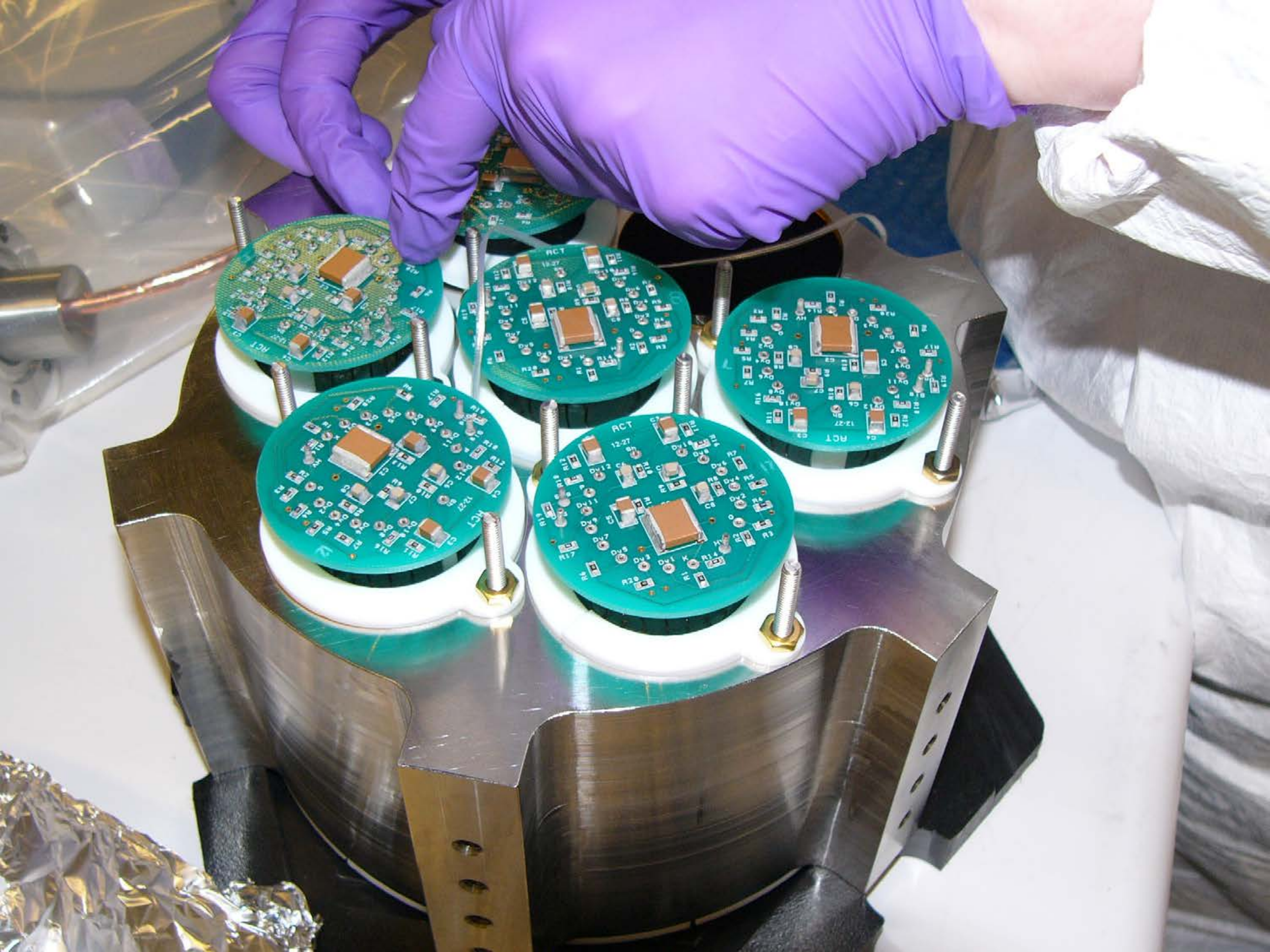
Photomultiplier Tubes – Hamamatsu 8778

- Direct collection of 175 nm Xe scintillation light through quartz window.
- Bialkali Photocathode; 35% quantum efficiency; gain $10^5 – 10^7$
- Operate immersed in liquid xenon.
- Used in the LUX and XMASS LXe dark matter experiments.

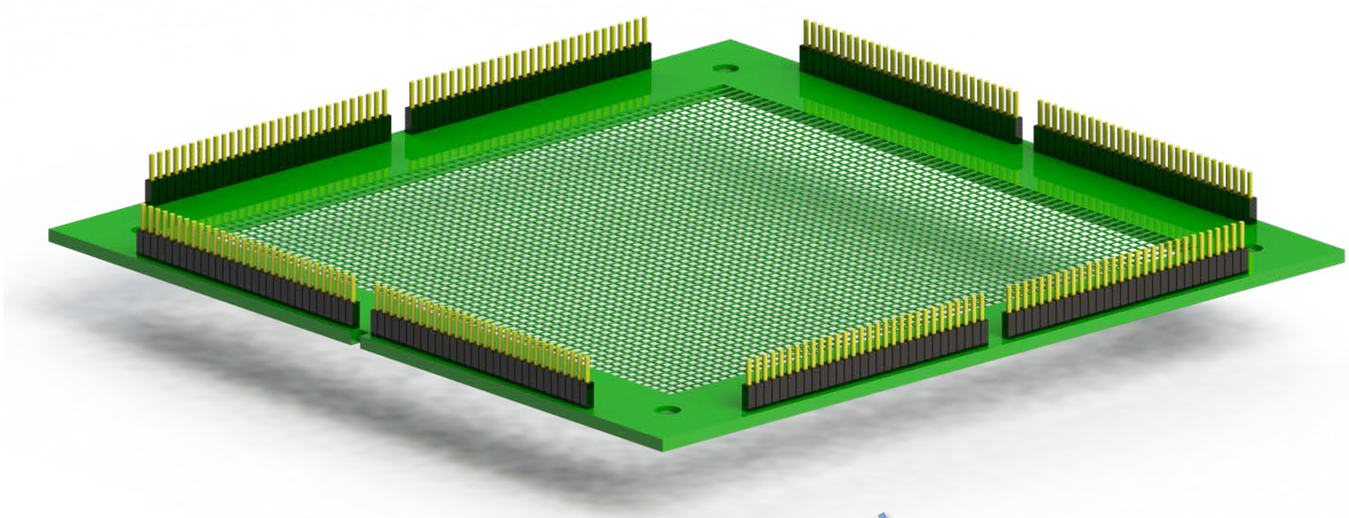


Single Photoelectron spectra




ACT
12-27

Crossed Wire Grid Readout



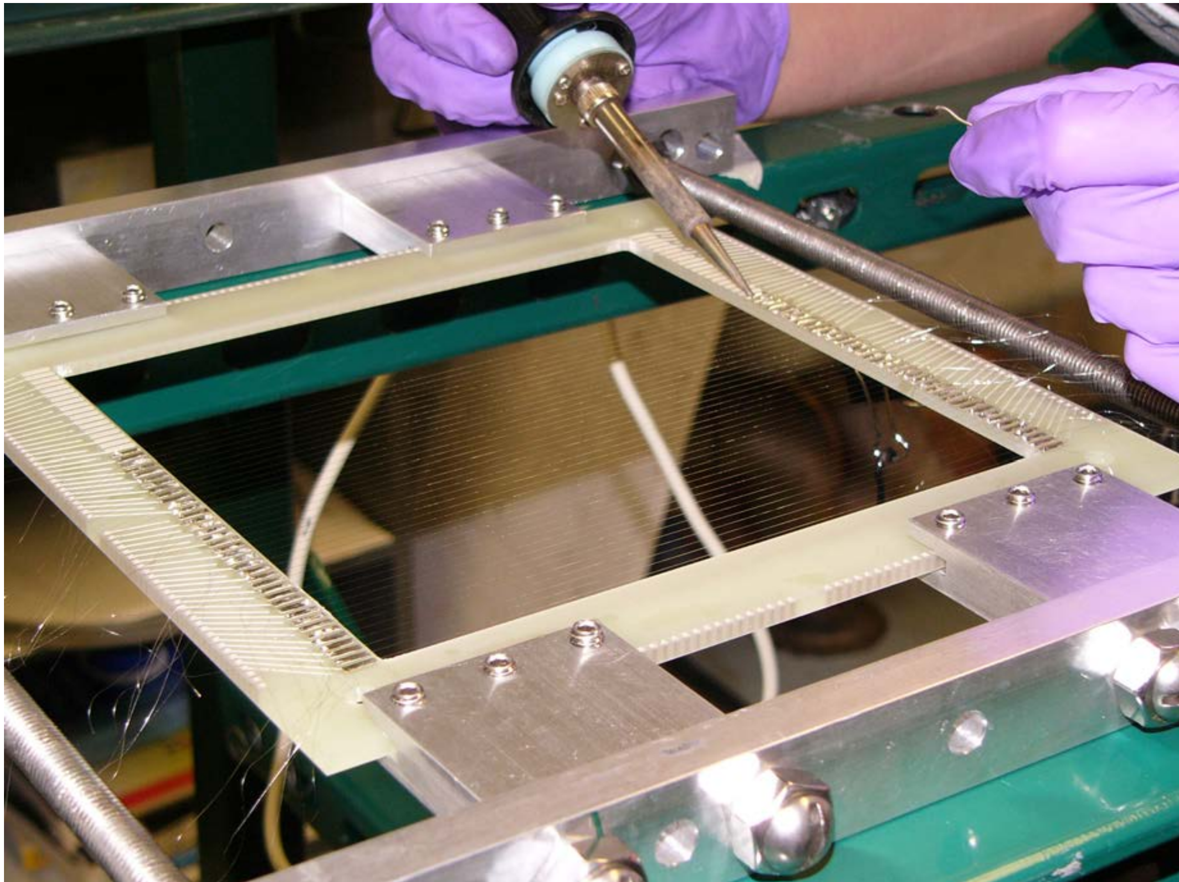
60 X-wires and 60 Y-wires

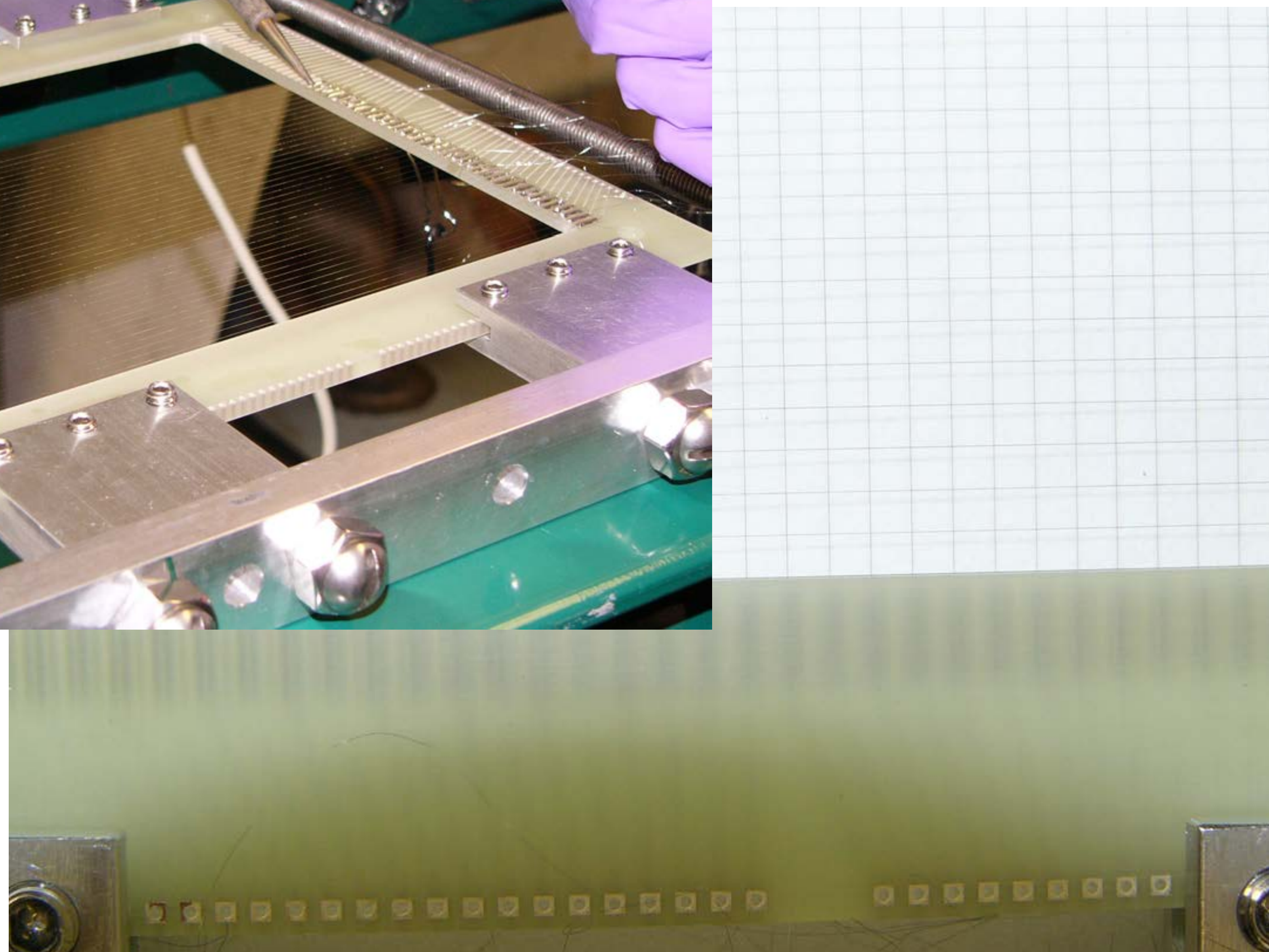
3 mm spacing between wires
45 micron wire diameter

Upward electron velocity 1.5 mm / µs

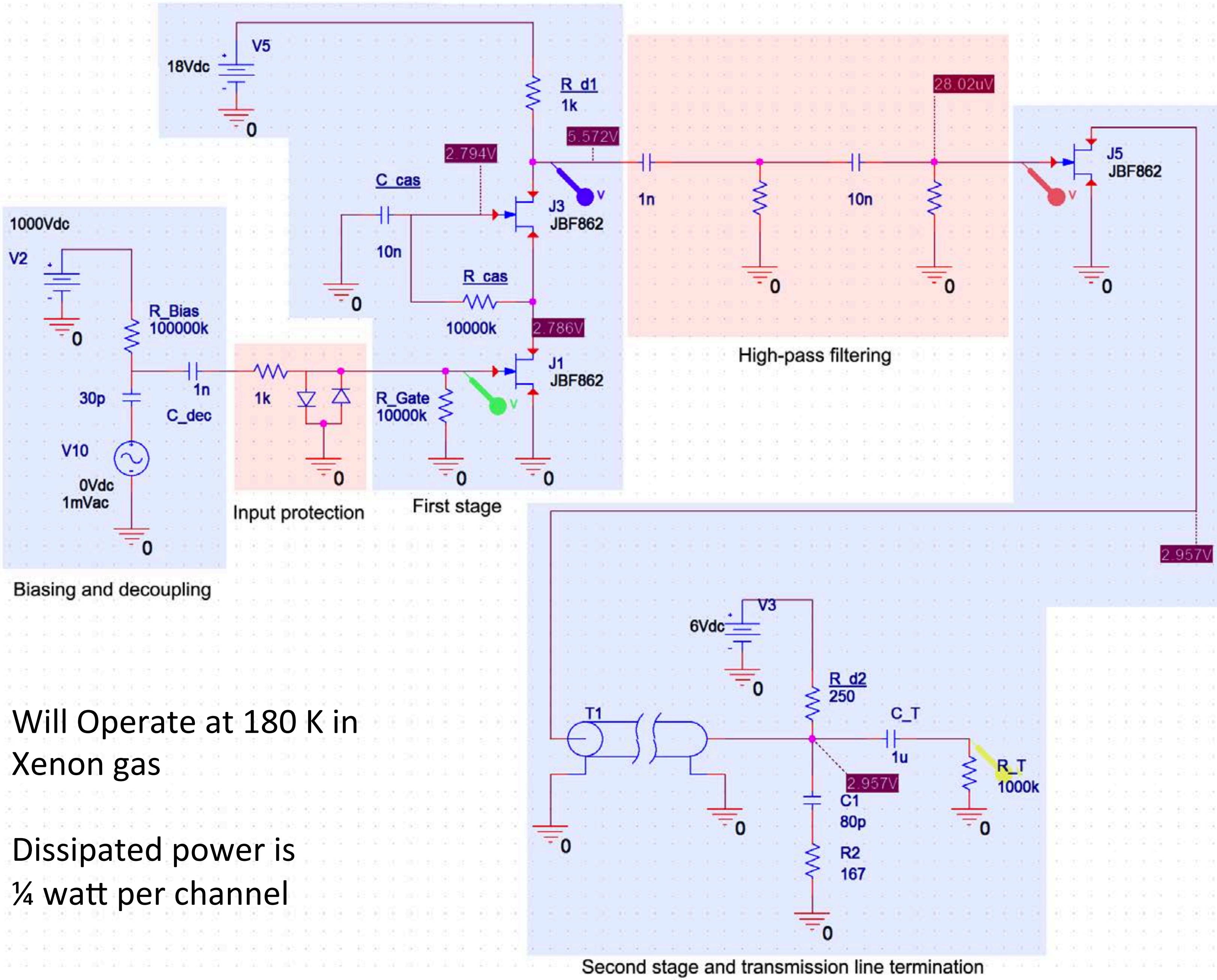
CAEN liquid argon TPC readout
128 channels, 12 bit, 2.5 MS /sec

Wire readout grid construction





Low Noise Wire Readout Charge Preamplifiers

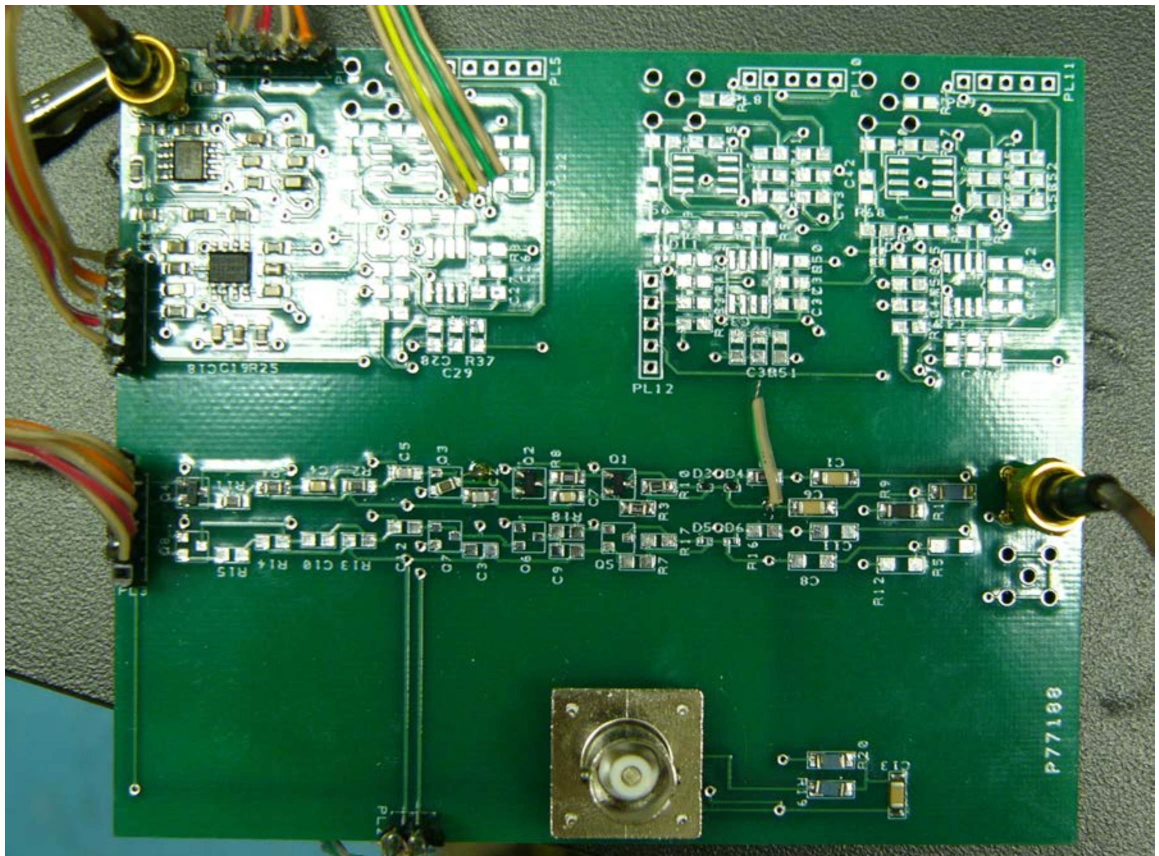


Will Operate at 180 K in Xenon gas

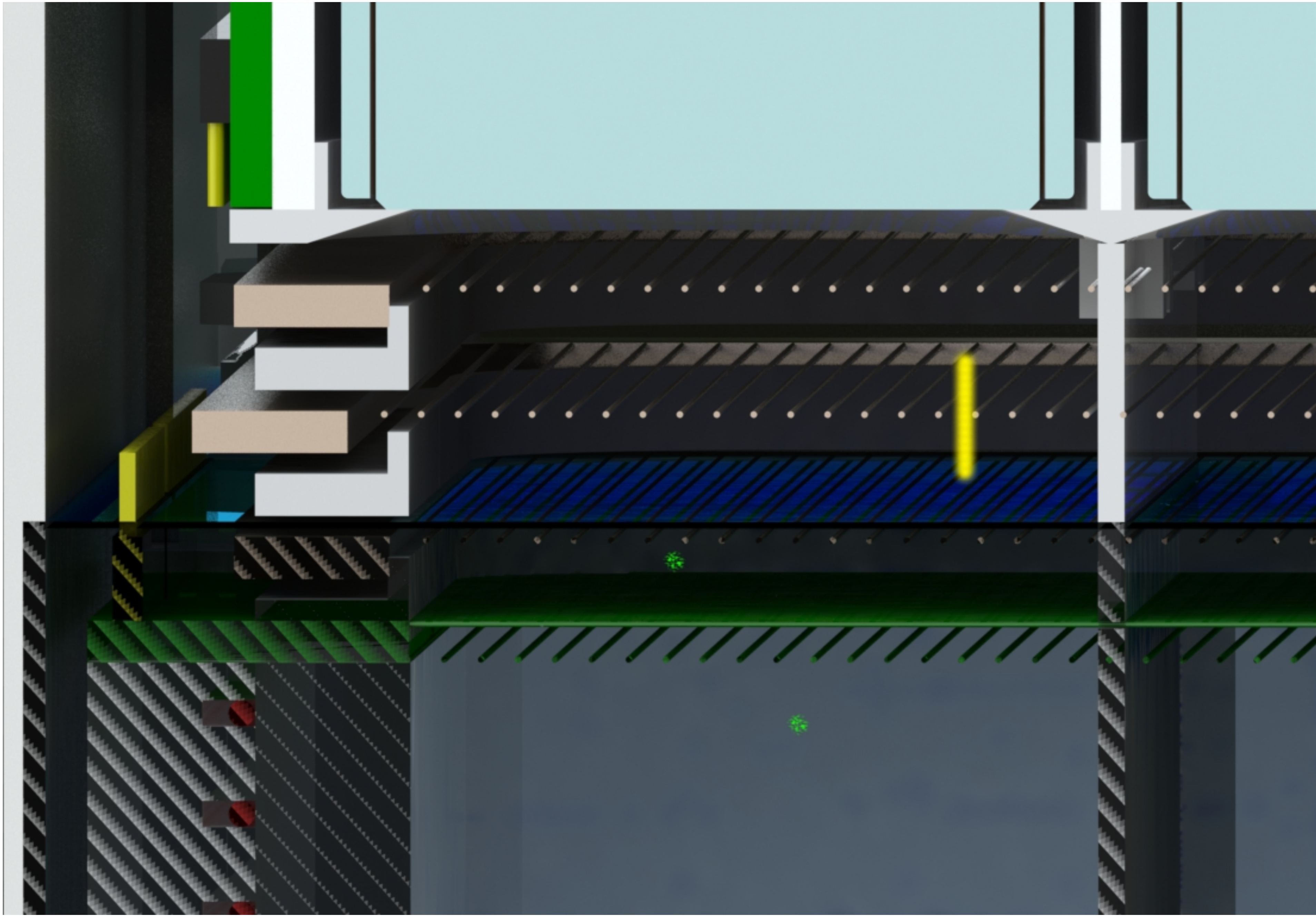
Dissipated power is ¼ watt per channel

Low Noise Wire Readout Charge Preamplifiers

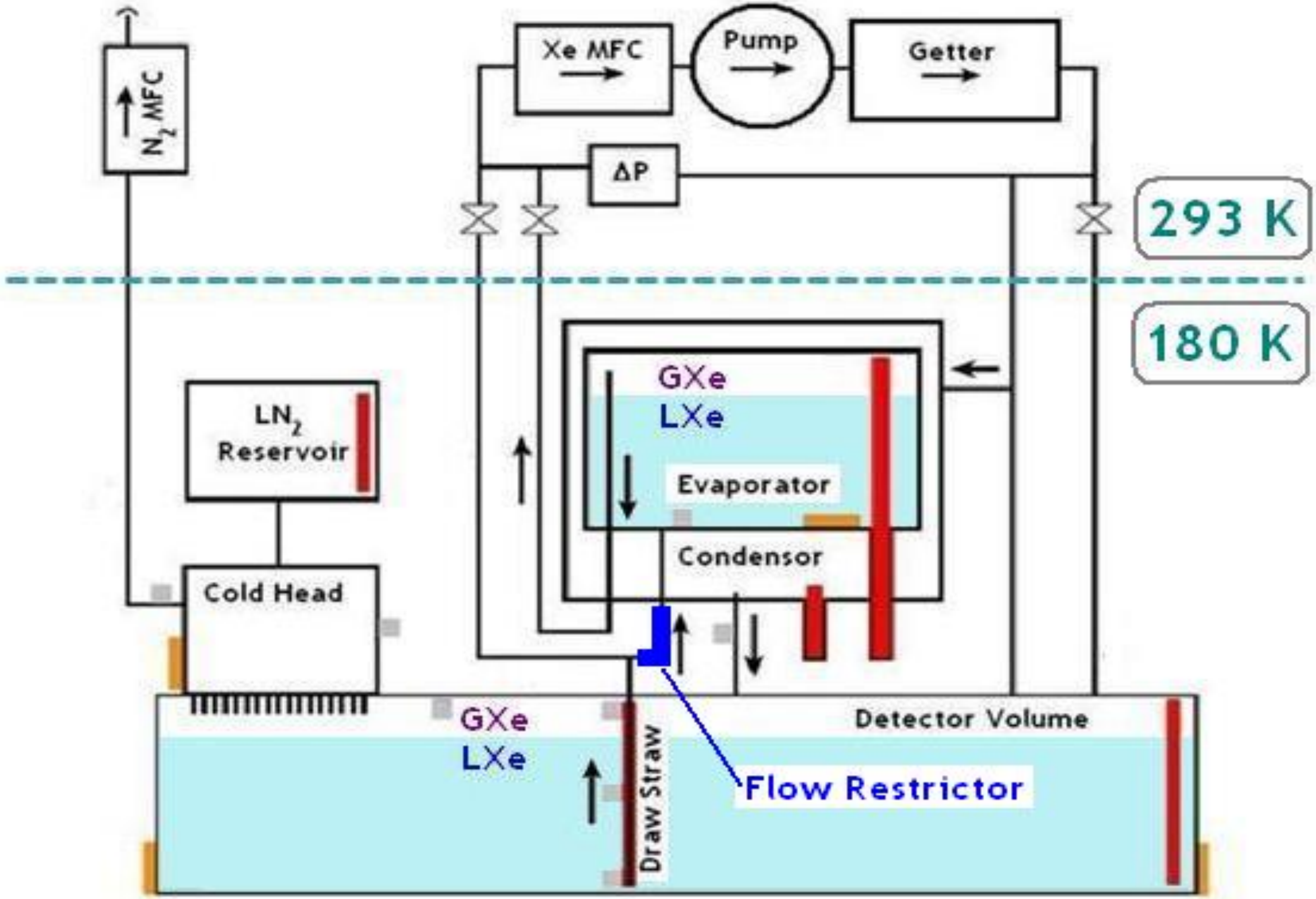
- BF862 FETs for minimal cold first cascode stage.
- Noise modeling suggests SNR of 1 for a 10 keV interaction.
- Design inspired by the GERDA germanium double beta decay experiment.*
- Overall gain of 5 microVolts /electron feeds CAEN 128 channel ADC.
- With 3 mm wire pitch, expect < 1 mm position resolution.



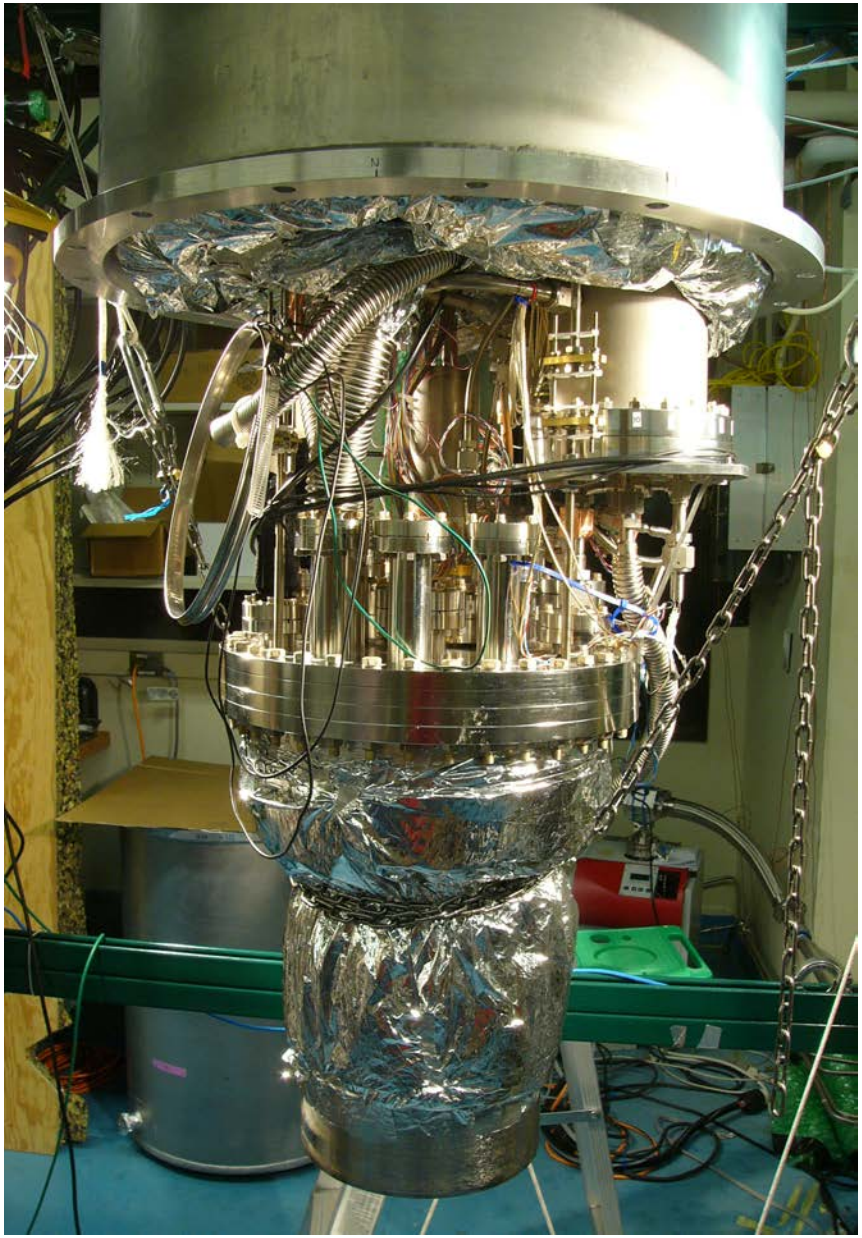
* Cattadori, C. et al. , proceedings of IEEE NSS-MIC , p. 1463 - 1465 (2011)

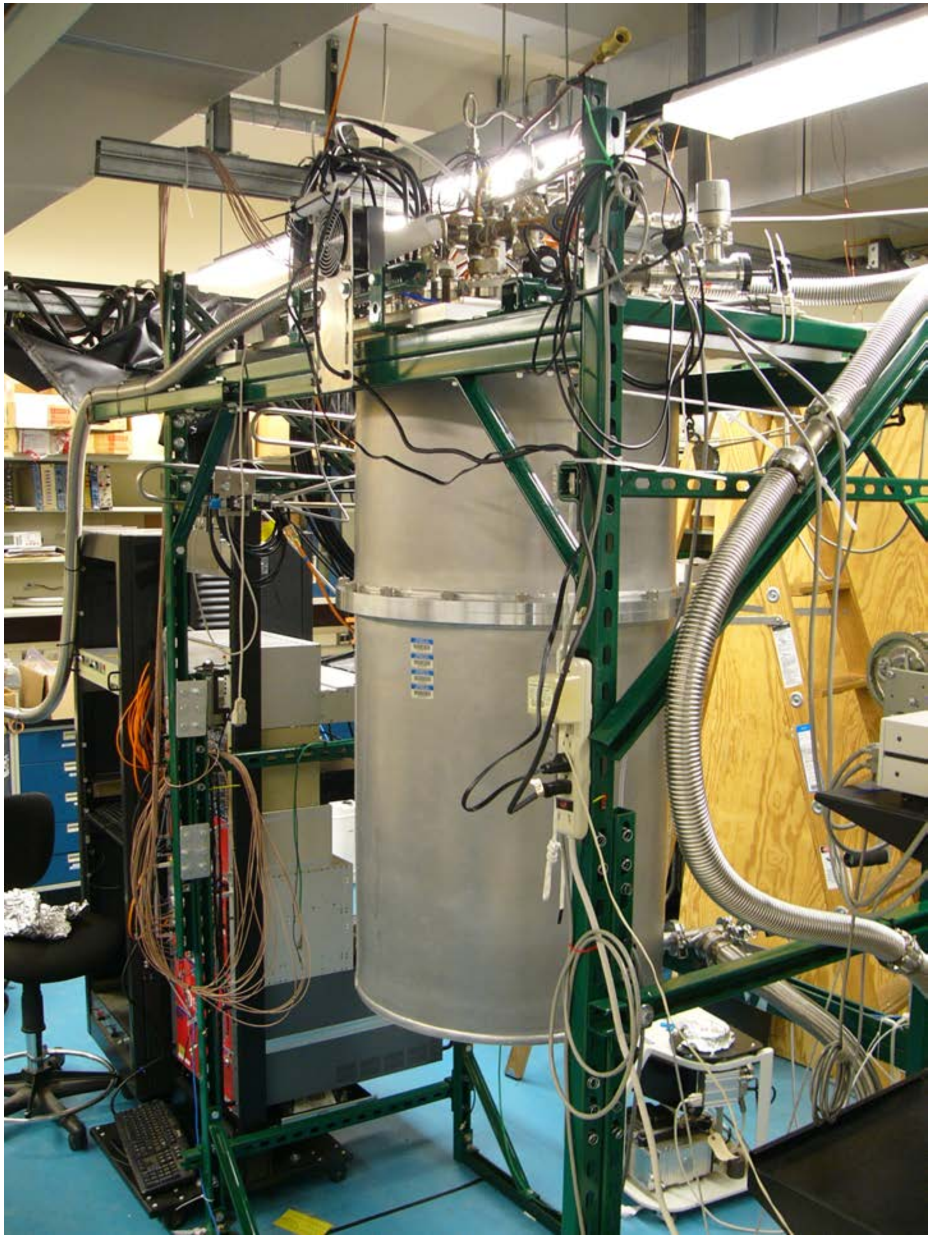


Cryogenics/Circulation Overview

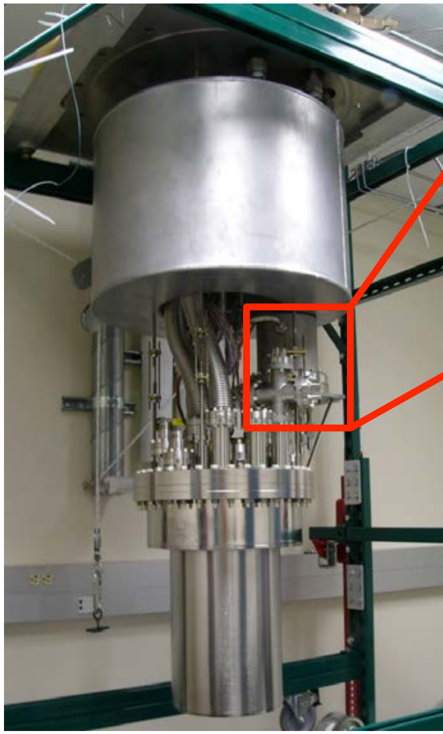


Cryogenics and Circulation



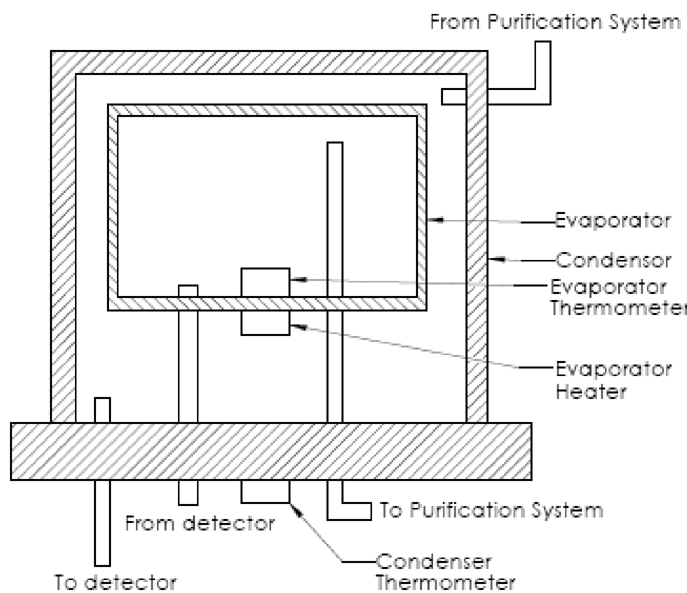


Heat Exchanger Design



Heat exchanger installed above the main volume

Evaporator (left) and outer can (condenser)

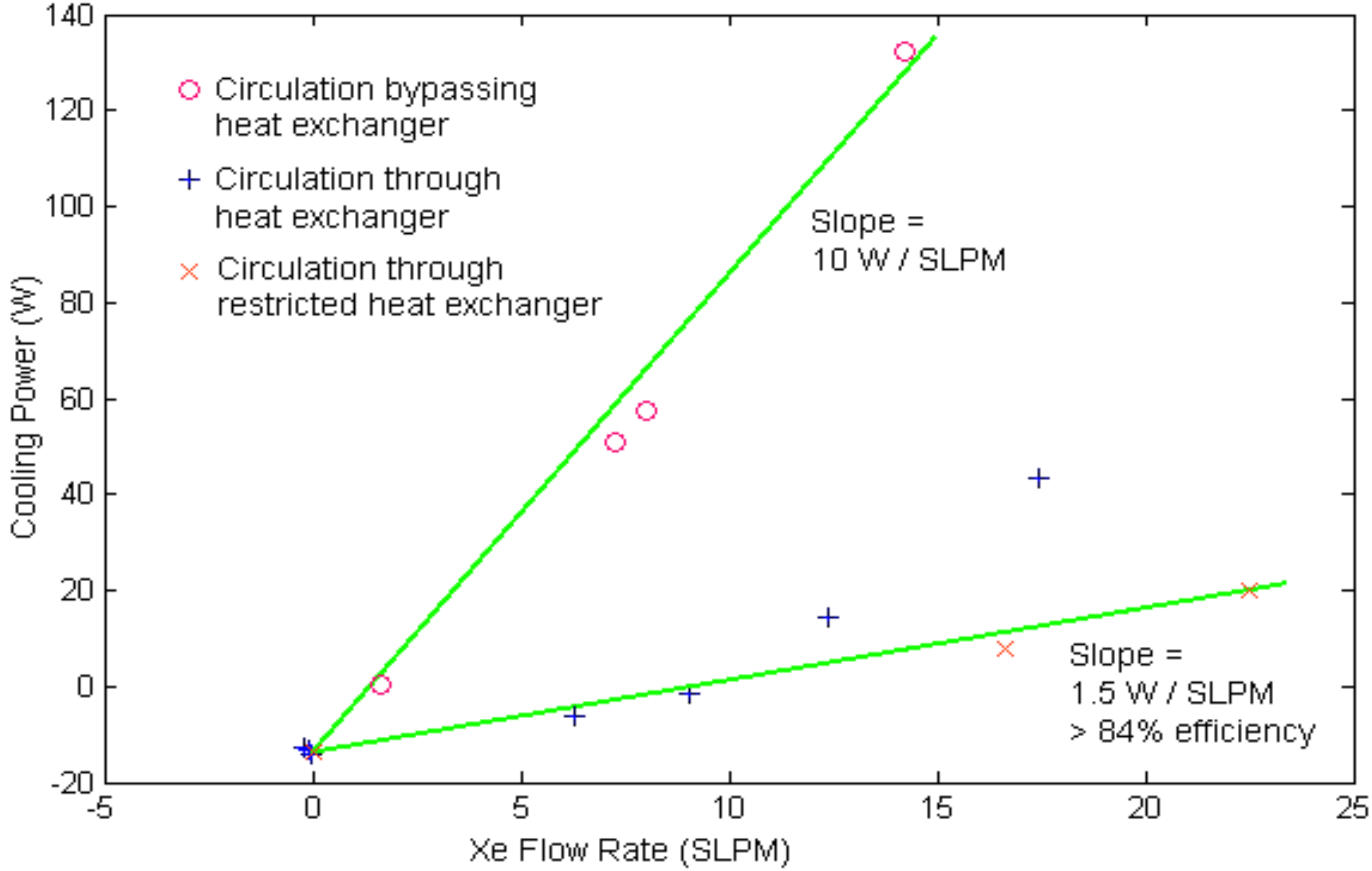


Schematic

Testing the Heat Exchanger

- **Experimental Setup:**
  - **Set a fixed Xe flow rate through the detector.**
  - **Adjust LN_2 flow through the cold head until a steady state temperature and pressure is reached ("Human feedback loop")**
  - **Cooling power needed to maintain this steady state is then calculated from the amount of LN_2 that boils off.**
- **Three plumbing configurations were tested.**
  - **Xe bypasses the heat exchanger (No heat exchange)**
  - **Xe exits the main volume via the evaporator and returns through the condenser. (Normal operation)**
  - **Same as (2), with the addition of a flow restrictor between the main volume and the evaporator.**

Results



Circulation bypassing heat exchanger
Circulation through heat exchanger
Circulation through restricted heat exchanger
Slope = 10 W / SLPM
Slope = 1.5 W / SLPM
> 84% efficiency
Cooling Power (W)
Xe Flow Rate (SLPM)
140
120
100
80
60
40
20
0
-20
-5
0
5
10
15
20
25

Results

- **Bypassed mode: 10 W/SLPM cooling power required to maintain a steady-state environment**
- **Normal operation: 1.5 W/SLPM cooling power required, up to a flow rate of 12 SLPM**
  - **Heat exchange with 84% efficiency!**
  - **At 12 SLPM the evaporator floods with LXe and heat exchange becomes inefficient -> required cooling power increases dramatically for >12 SLPM**
- **Normal operation, restricted flow: 1.5 W/SLPM cooling power required up to 22.5 SLPM**
  - **Prevents flooding; heat exchange occurs with 84% efficiency up to the maximum flow rate!**