

# Charge collection physics in very large diameter germanium crystals

DE-SC0013268

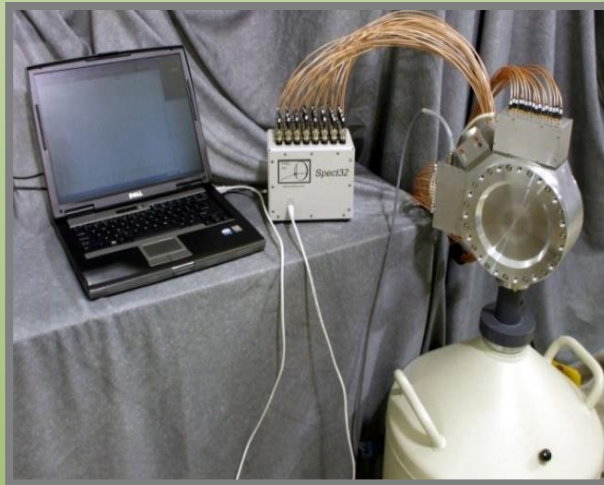
4/11/2016 – 8/7/2018

Ethan Hull PI , PHDS Co.

A collaboration with C.J. (Kim) Lister at U. Mass Lowell

- **PHDS Co. Introduction**
- **Very large diameter crystal properties (140 mm)**
- **New products from *very* large-diameter HPGe crystals**

- Est. Fall 2004 – Nuclear and Solid State Physics Origin
  - History: Custom Nuclear-Physics Detectors
  - Recently: Modular HPGe Systems
- Complete Germanium Detector Manufacturing and R&D
  - Concept
  - Design
  - Crystal Growth
  - Detector Fabrication
  - System Integration
  - Software application
  - Sales & Service



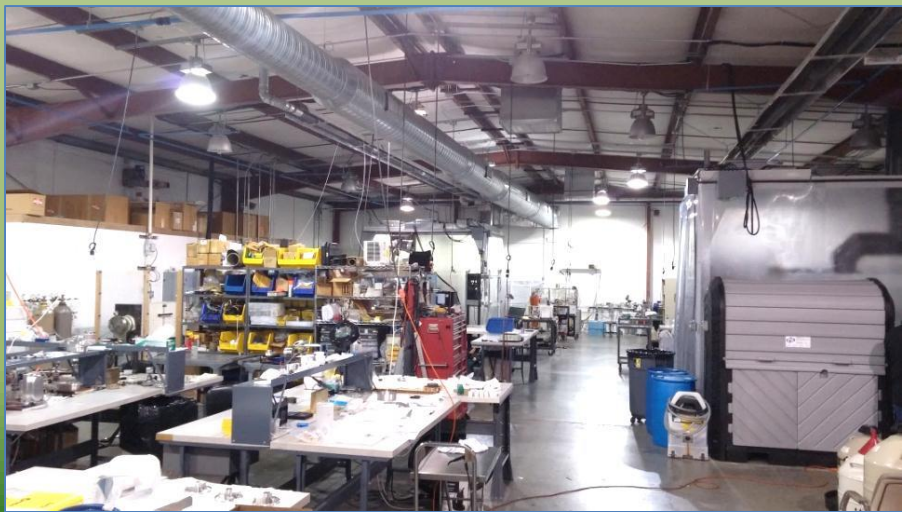
**NPX (150 lbs.)**



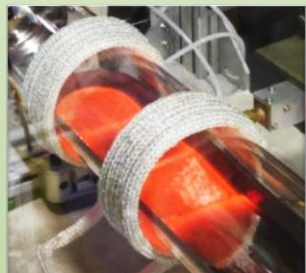
**GeGI-5 (15 lbs.)**

**A nuclear physics lab in one hand  
Scientist OR Soldier**

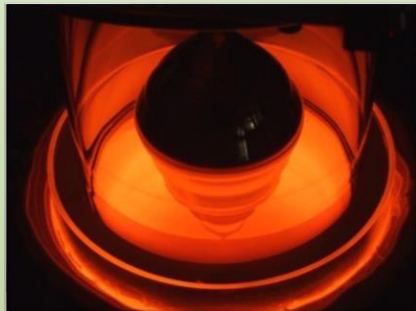
**10,000 ft<sup>2</sup> Manufacturing  
and R&D Facility in  
Knoxville, TN**



# Vertical manufacturing of GeGI Imaging Spectrometers



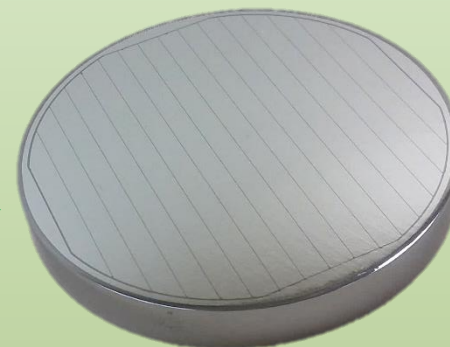
Ge Zone Refine



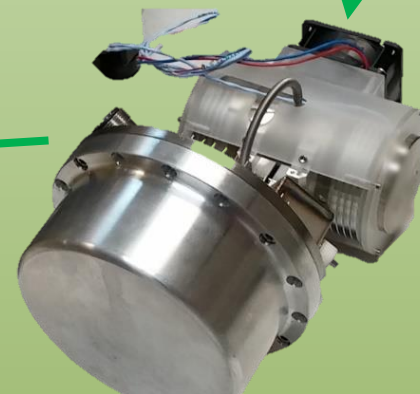
HPGe Crystal Growth



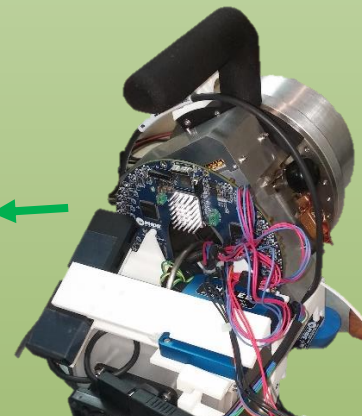
Analysis



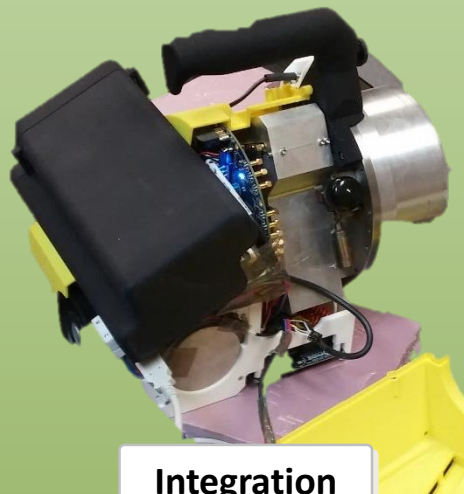
Fabrication



Cryogenics



Electronics



Integration



GeGI 5

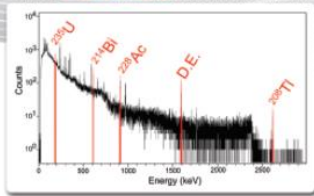
# GeGI<sup>®</sup>

**RAD NUC STANDOFF DETECTOR**  
Fast & Accurate Location, Identification & Quantification



Wide-angle optical camera combined with gamma-ray imaging spectrometer capture the nuclear environment quickly and accurately.

## High Resolution Spectroscopy and *Automatic* Identification



## Applications

- Military and Civilian CBRNE Operations
- Nuclear Safeguards
- Nuclear Security
- Special Nuclear Materials Analysis
- Decommissioning & Decontamination

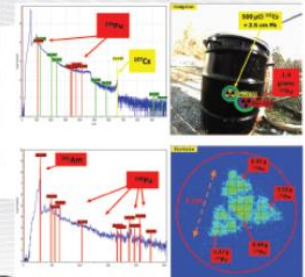


## Specifications

Dimensions:	10.5 in x 8 in x 5.5 in (26 cm x 20 cm x 14 cm)
Weight:	1.5 lbs (6.8 kg)
Battery life:	3 hours internal, 5 hours external, all hot swappable
Power supply:	100-240 VAC, 50-60 Hz
User maintenance:	None
Energy resolution:	FWHM < 2.1 keV (0.3 %) at 662 keV
Gamma-ray Compton imaging field of view:	4π (360°)
Optical (camera) field of view:	2π (185°)
Pinhole imaging field of view:	60° cone
Sensitivity: 10 <sup>4</sup> Ci <sup>137</sup> Cs at 1 meter (3.3 μR/hr, 33 nSv/hr)	
Detection and ID time (662 keV) (Be):	3.7 sec ± 1.0 sec
Location (Compton image) time:	30 sec ± 13 sec
Exposure/rate capacity:	200 kcps (10% Dead time) in 1.5 mR/hr <sup>60</sup> Co
Energy range:	30 keV – 3 MeV
Imaging energy range:	
Pinhole (2.54-cm thick Pb 60°):	30 keV – 662 keV
Compton:	140 keV – 3 MeV
Isotope library (400 isotopes):	Auto detect and/or user selected/specified
Isotope Identification:	37 frequently encountered isotopes
Detector (Ge crystal) dimensions:	90-mm diameter, 11-mm thick
Active detector volume:	60 cm <sup>3</sup>
Active detector area:	55 cm <sup>2</sup>
Cool-down time:	2.5 hours
Start-up time (cold):	2 minutes
Included:	Rugged daylight-readable glove-touch tablet, pelican case, power supply, battery charger

## Features

- Standoff Location Detection Identification
- Distance Range (10 cm - 50+ meters)
- Automatically specifies SNM, NORM, IND, MED
- Germanium gamma-ray spectroscopy (16k ch)
- Full 360° Standoff Visualization (Compton)
- <sup>235</sup>U (186 keV) <sup>239</sup>Pu (375 keV, 414 keV)
- User-friendly single-button glove-touch operation
- Hot swappable battery operation
- Full session save and reload capability
- Full data-stream availability
- Wireless capable/wireless option can be disabled
- Twist-lock mil-spec power connector
- Long-lived internal cooler (5 years +)
- Reachback file: ANSI N42.42 format
- Remote operation



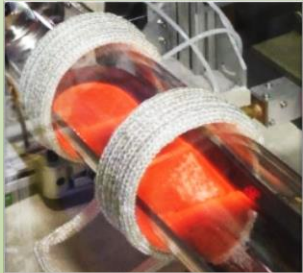
Lead (Pb) Pinhole Imaging Aperture  
60-degree Field of View



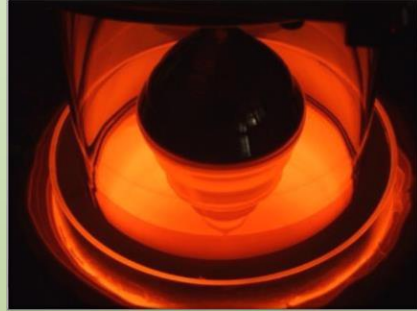
3/18

**A product with global impact**  
**9 countries, 4 continents**

# Fulcrum: The newest PHDS Co. commercial detector



Ge Zone Refine



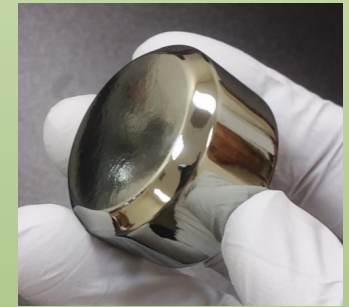
HPGe Crystal Growth



Analysis



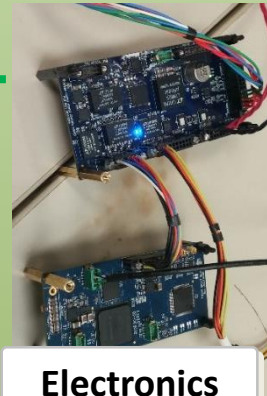
Fabrication



Detector



Cryogenics



Electronics



Integration



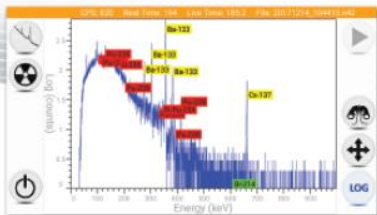
Fulcrum

# Fulcrum™

Hand Held HPGe Detector



High Resolution Spectroscopy and *Automatic* Identification



## Applications

- Military and Civilian CBRNE Operations
- Nuclear Safeguards
- Nuclear Security
- Special Nuclear Materials Analysis
- Decommissioning & Decontamination

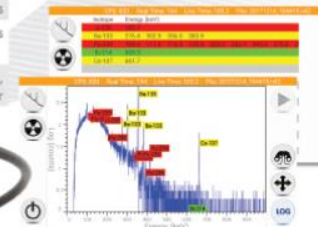


## Specifications

Weight:	7.0 lbs.
Battery Life:	4 hours internal, 12 hours external, hot swappable
Power supply:	100-240 VAC, 50-60 Hz
User Maintenance:	None
Energy Resolution:	FWHM ~ 1.0 keV at 122 keV FWHM ~ 2.2 keV at 1332 keV
Sensitivity:	10- $\mu$ Ci 137Cs at 1 meter (3.3 $\mu$ R/hr, 33 nSv/hr) (662 keV) $6\sigma$ : 12.9 seconds +/- 1.9 seconds
Rate capacity:	~ 100 kcps ~ 50% dead time
Detector (Ge Crystal) dimensions:	40-mm diameter, 20-mm thick
Cool-down time:	60 minutes
Start-up time (cold):	2 minutes
Included:	Android mobile phone i/o device, pelican case, power supply, battery charger

## Features

- Most compact HPGe detector system
- Lowest weight HPGe detector system
- Integrated Stirling-cycle cooler
- Automatically specifies: SNM, NORM, IND, MED
- Germanium gamma-ray spectroscopy: 32 kch
- User friendly OMNI Android app
- Wireless or hardwired data transmission available
- TwistLock mil-spec power connector
- Long-lived internal cooler (10+ years run time)
- Single button Reachback (ANSI N42.42)

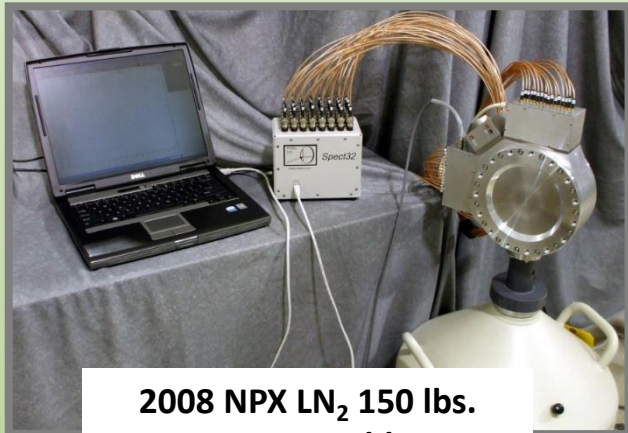


Optional External Lithium Battery Pack



The most compact HPGe detector in the world (7-8 lbs.)

# Germanium System Evolution at PHDS Co.



**2008 NPX LN<sub>2</sub> 150 lbs.  
Non-portable**



**2009 NPX-M 75 lbs.  
Non-portable**



**2010 GeGI-1 55 lbs.  
Movable**

**2017 !!**



**2017 GeGI-5 15 lbs.  
Hand Portable**



**2014 GeGI-4 28 lbs.  
Personnel Portable**



**2013 GeGI-3 33 lbs.  
Transportable**



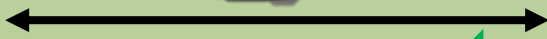
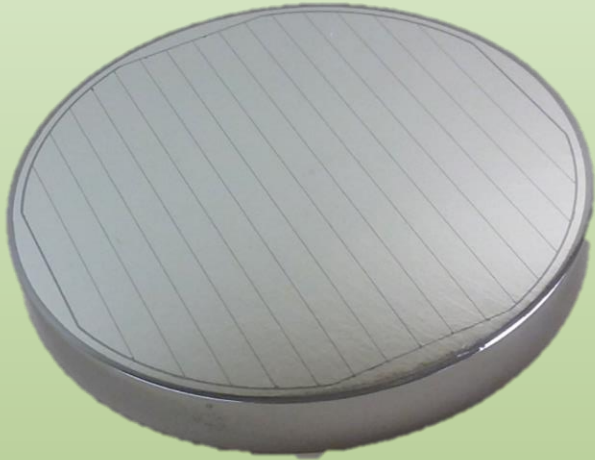
**2017 Fulcrum 7-8 lbs.  
Hand Portable**





This program: Make larger diameter detectors commercially viable

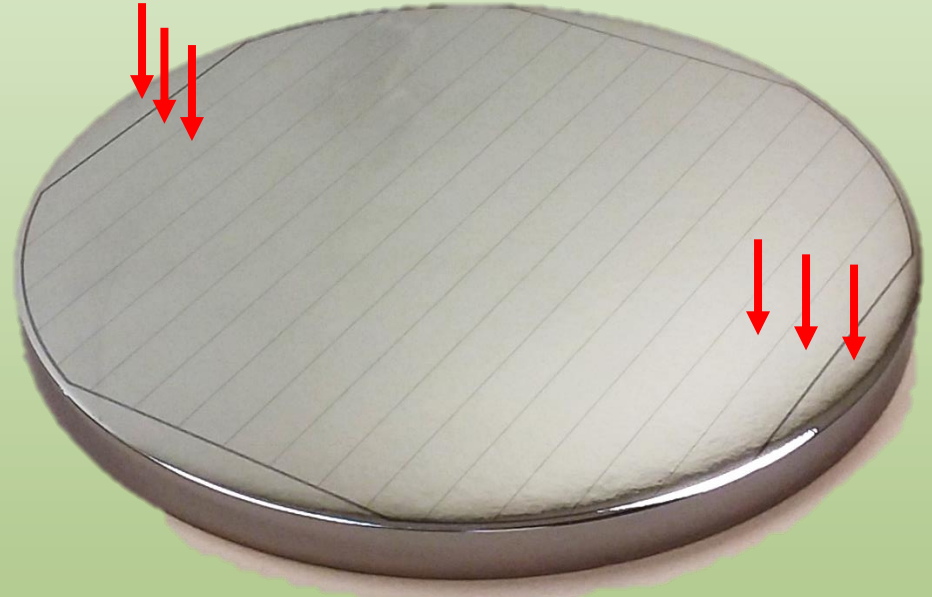
Excessive Leakage  
Current (and Trapping)



90 mm dia



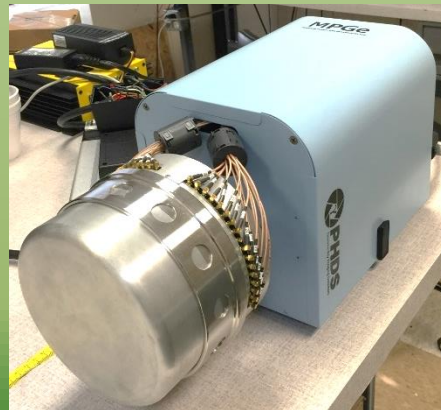
GeGI



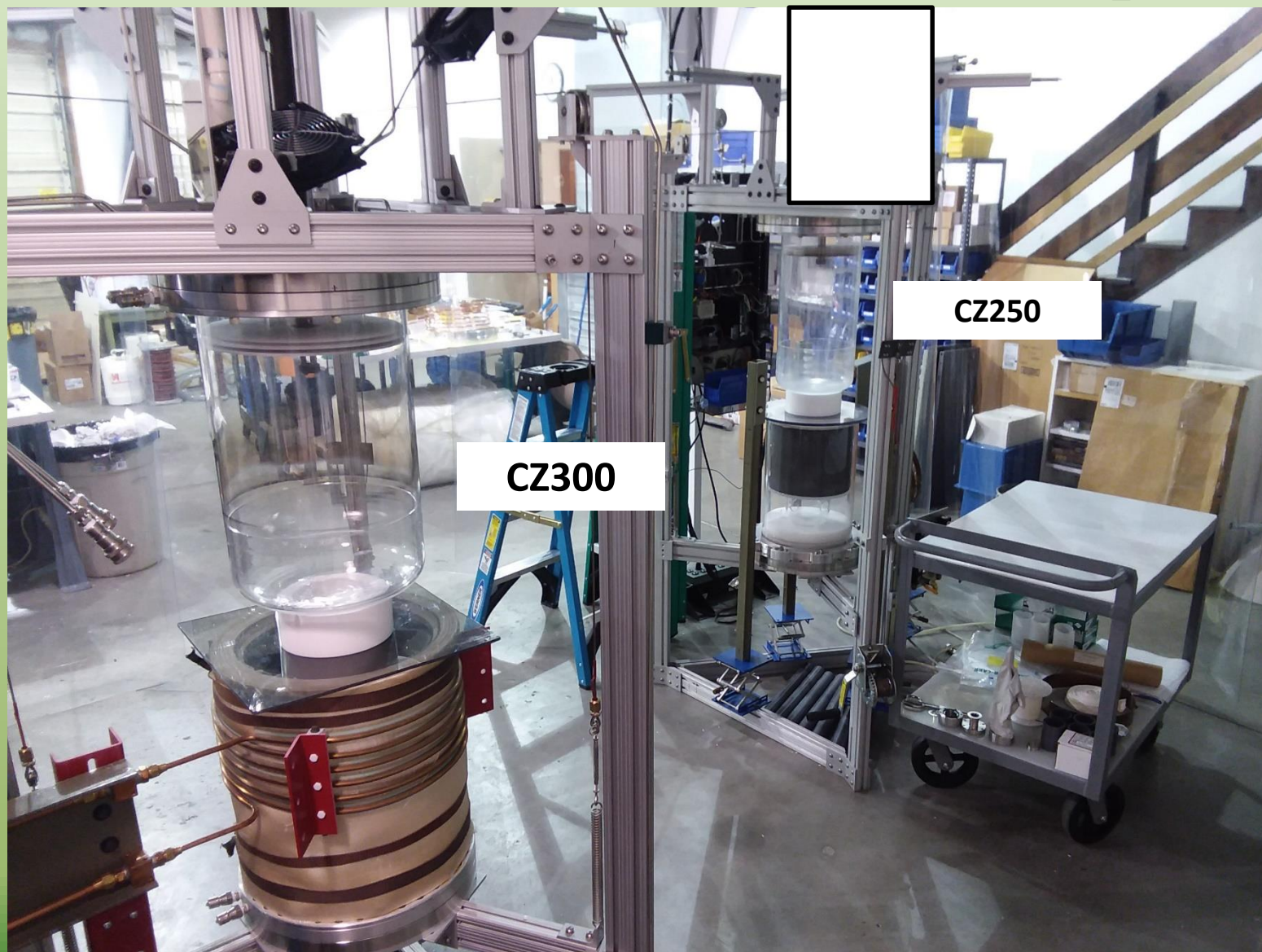
140 mm



Most of the time they do not work....



Increase the hot zone from 240 to 310 mm  
Keep away from the outside of the puller

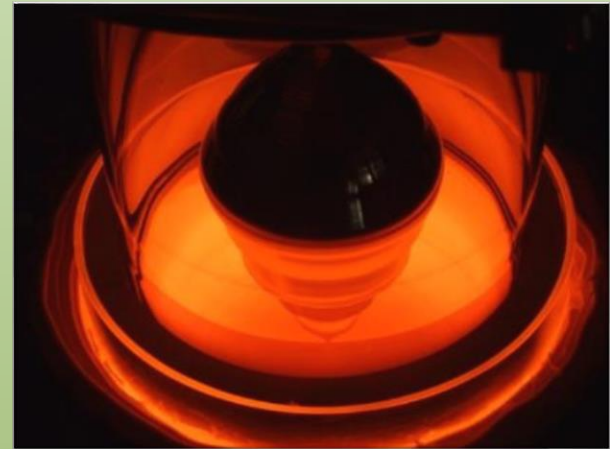


**CZ300**

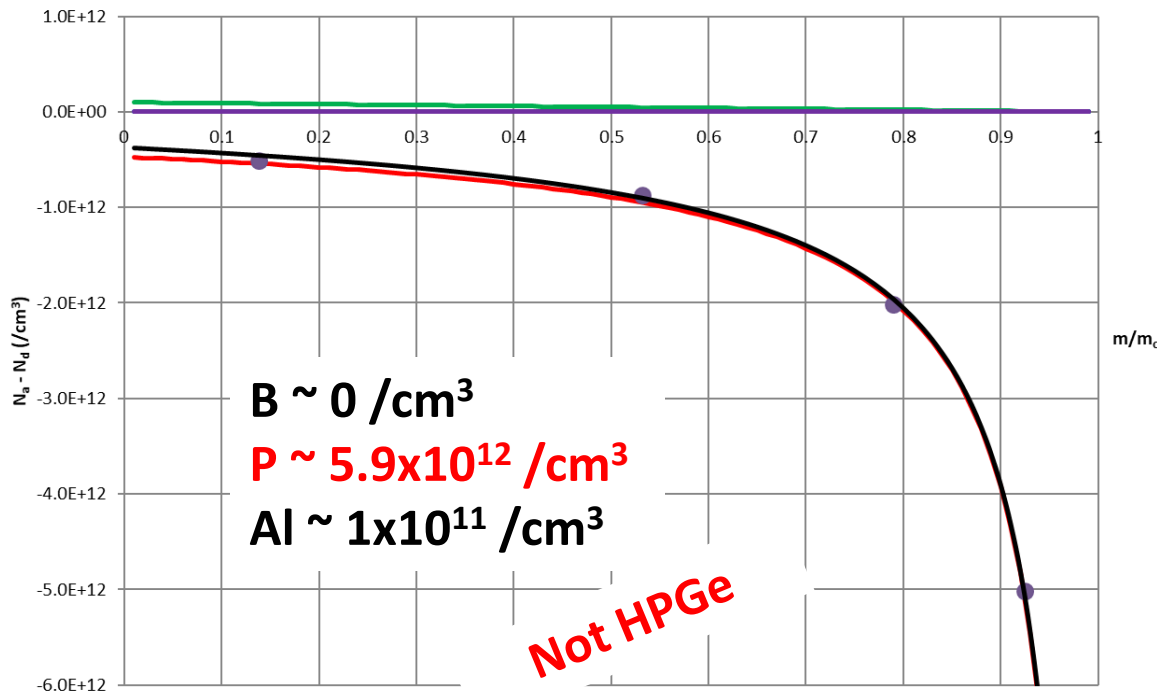


**The first crystal from  
CZ300 10.1 kg**

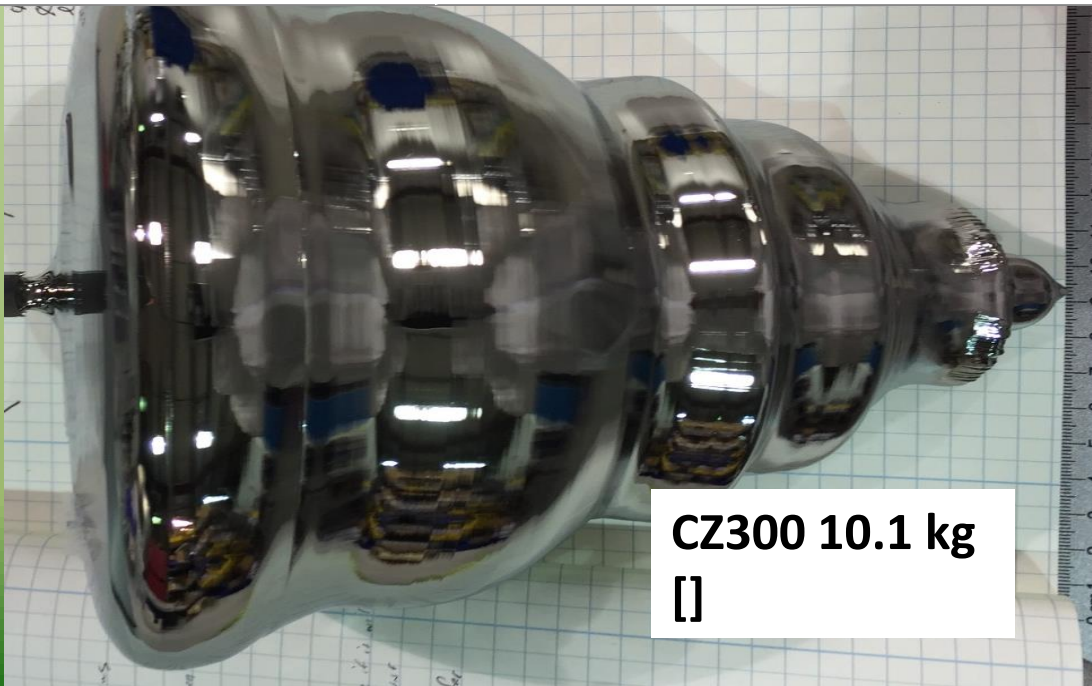
**CZ250**



$$C(m) = C_0 k (1 - m/m_0)^{(k-1)}$$



Boron  $k = 20$   
 Phosphorus  $k = 0.08$   
 Aluminum  $k = 1$   
 Indium  $k = 0.001$



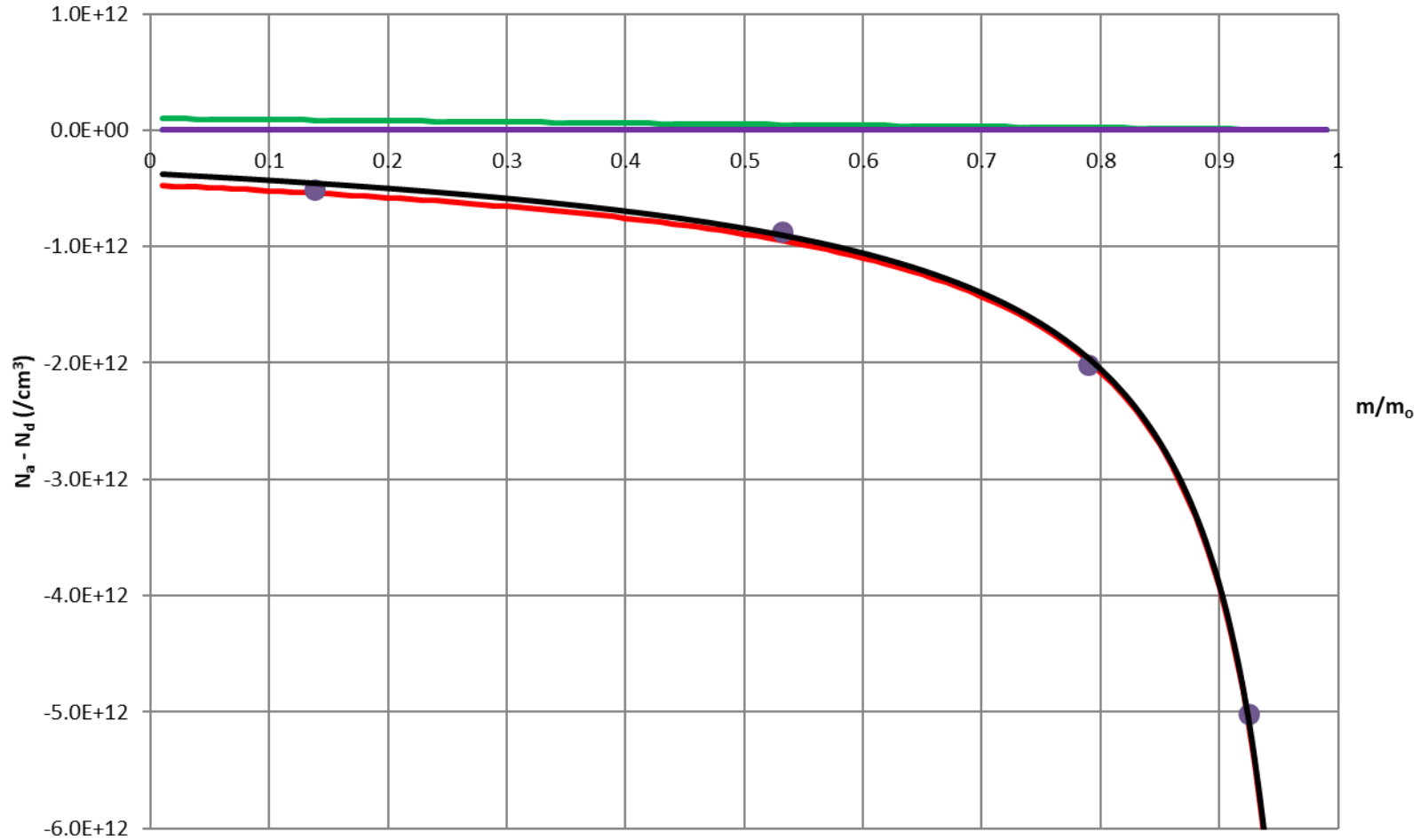
**CZ300 10.1 kg**  
 []

**Need:**

1. High purity
2. Mass  $\sim 20$  kg

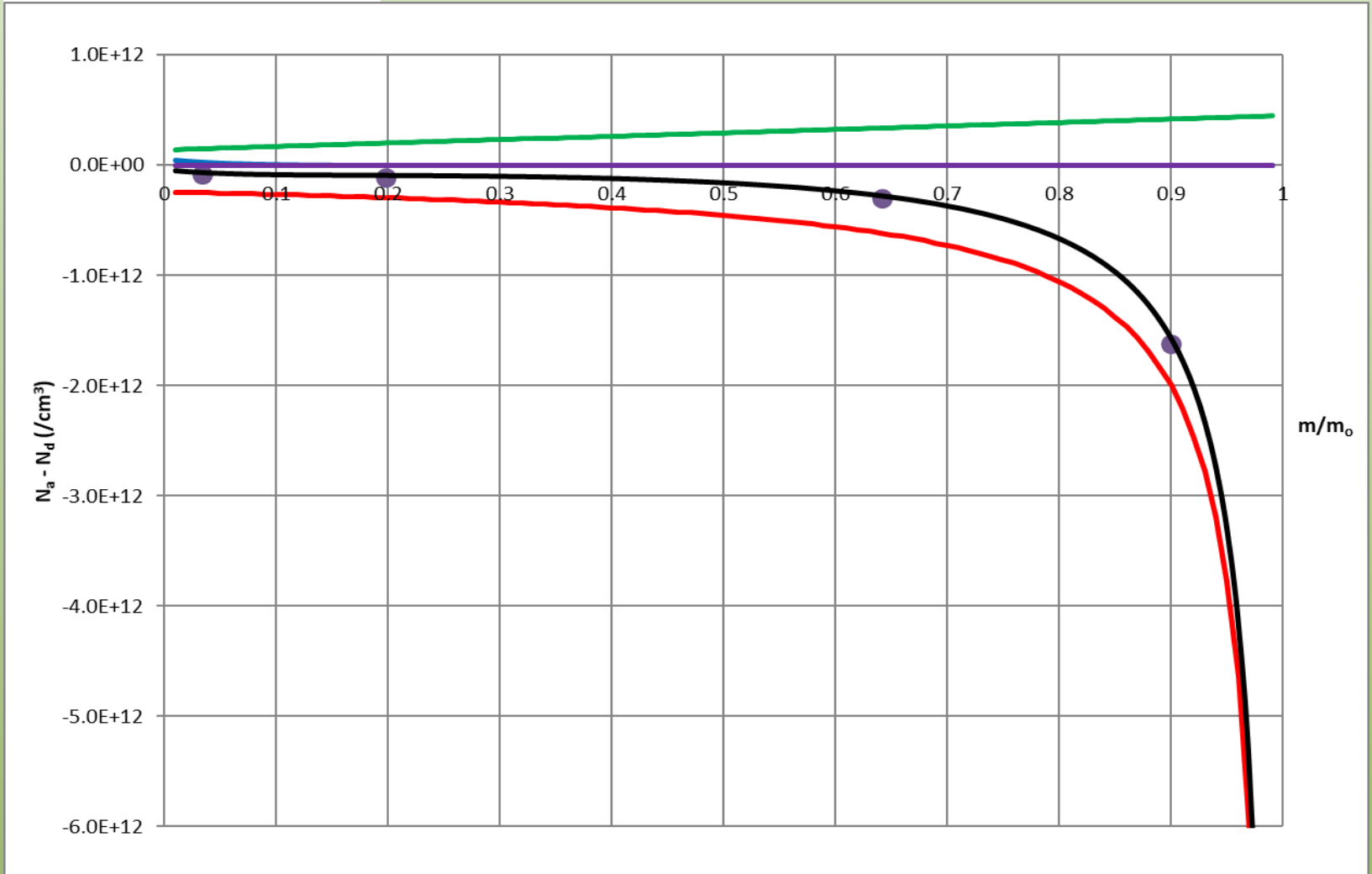
10140 g

$P = 5.9 \times 10^{12} / \text{cm}^3$



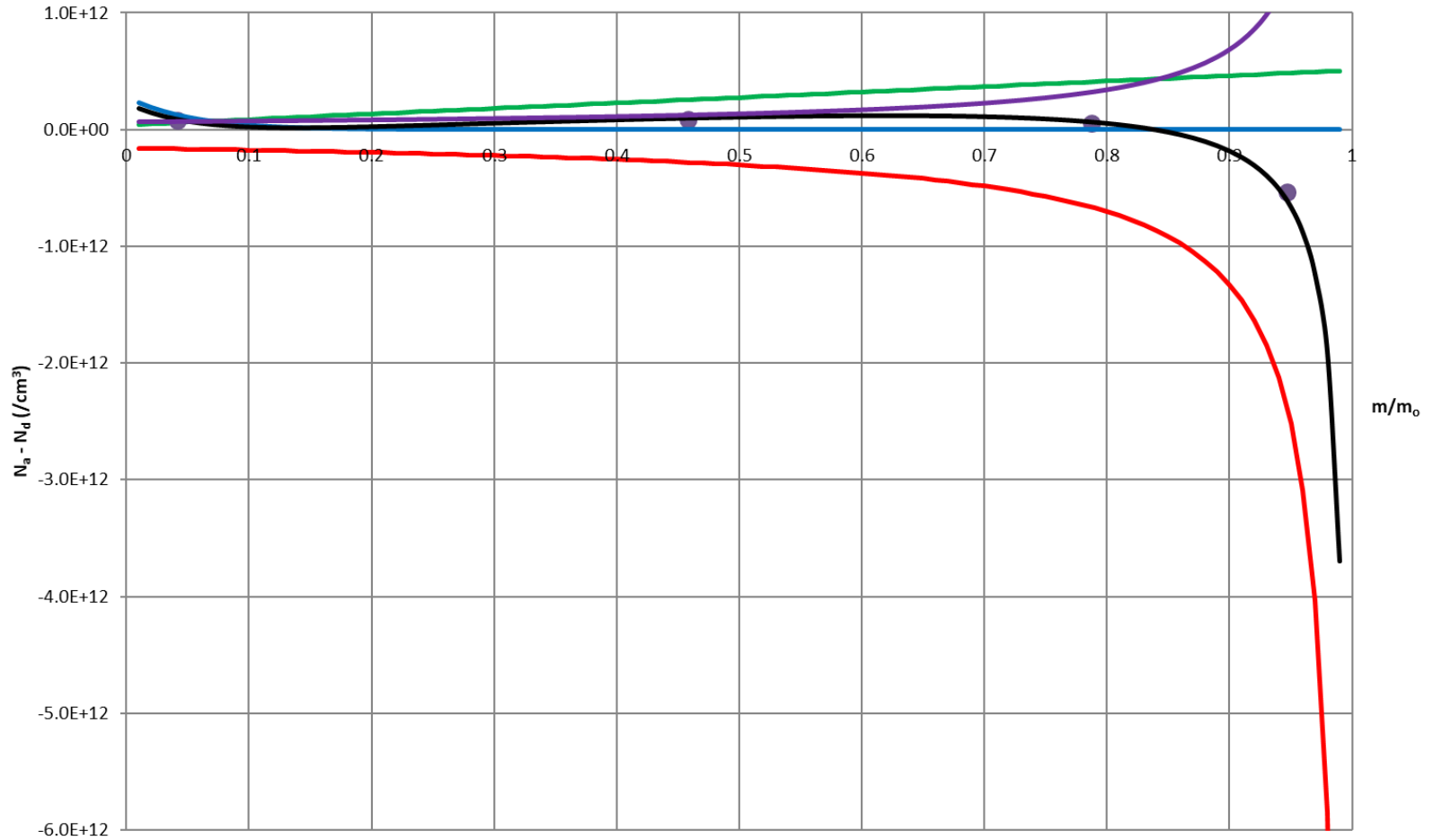
9470 g

$P = 3.0 \times 10^{12} / \text{cm}^3$



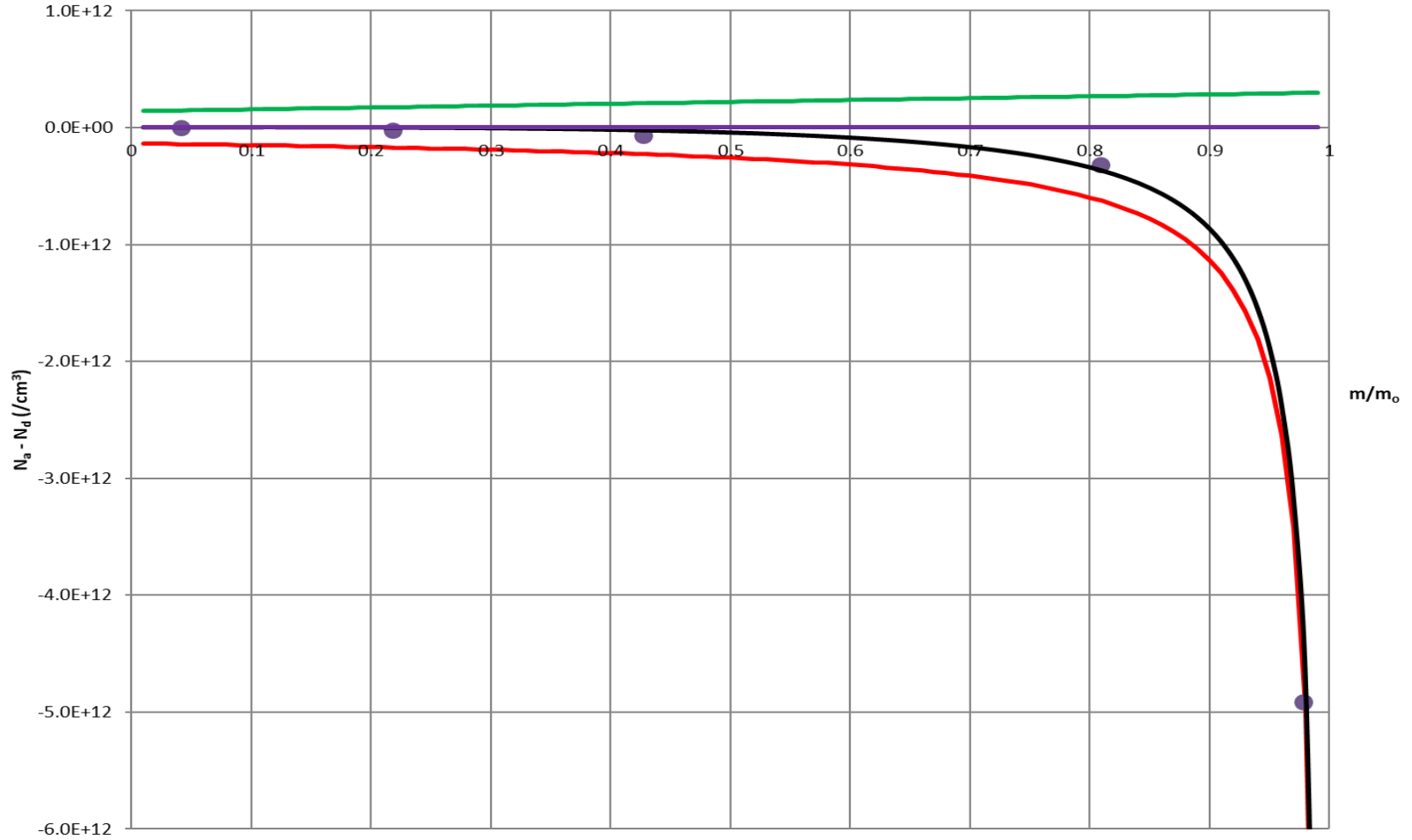
12229 g

$P = 2.0 \times 10^{12} / \text{cm}^3$



14516 g

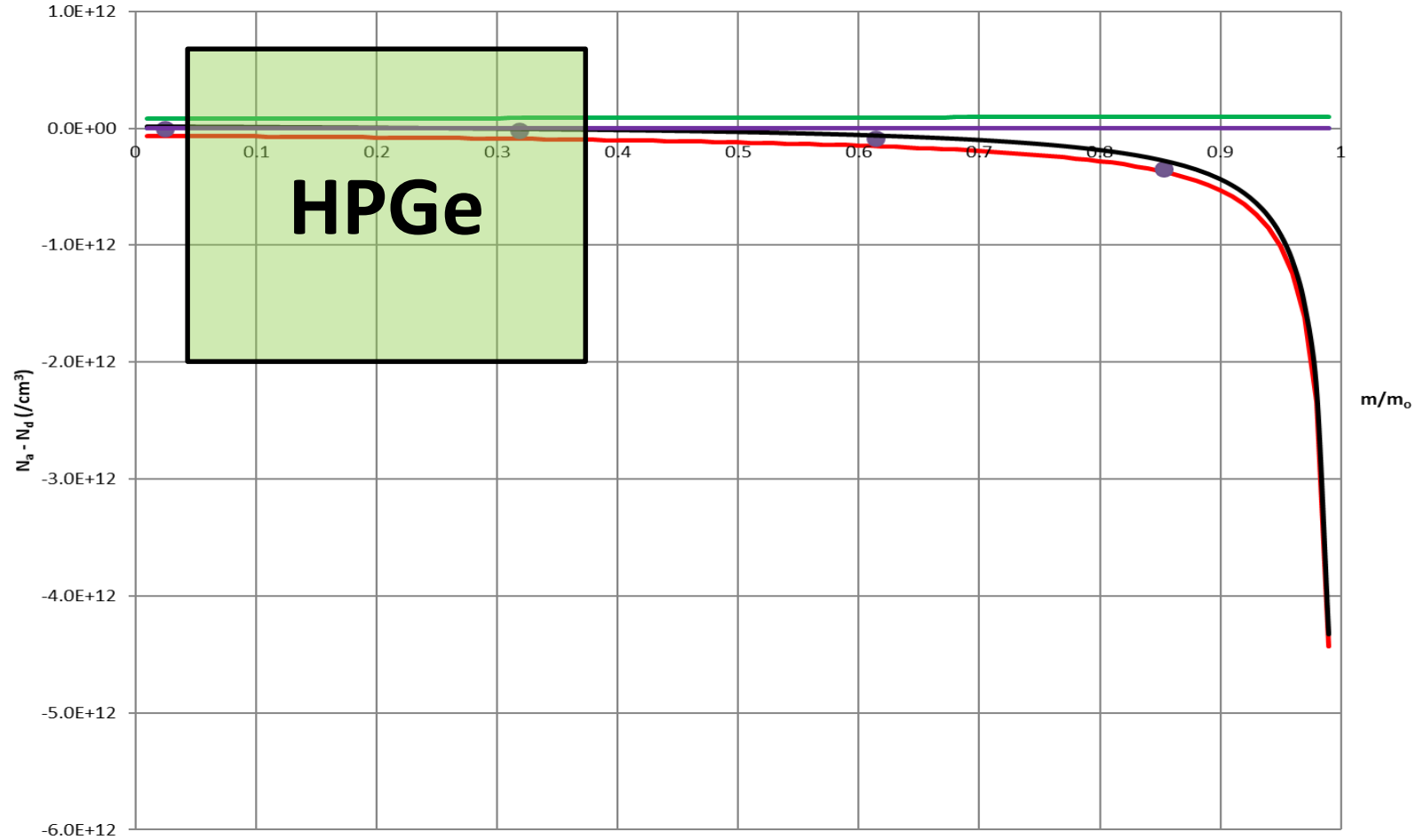
$P = 1.7 \times 10^{12} / \text{cm}^3$



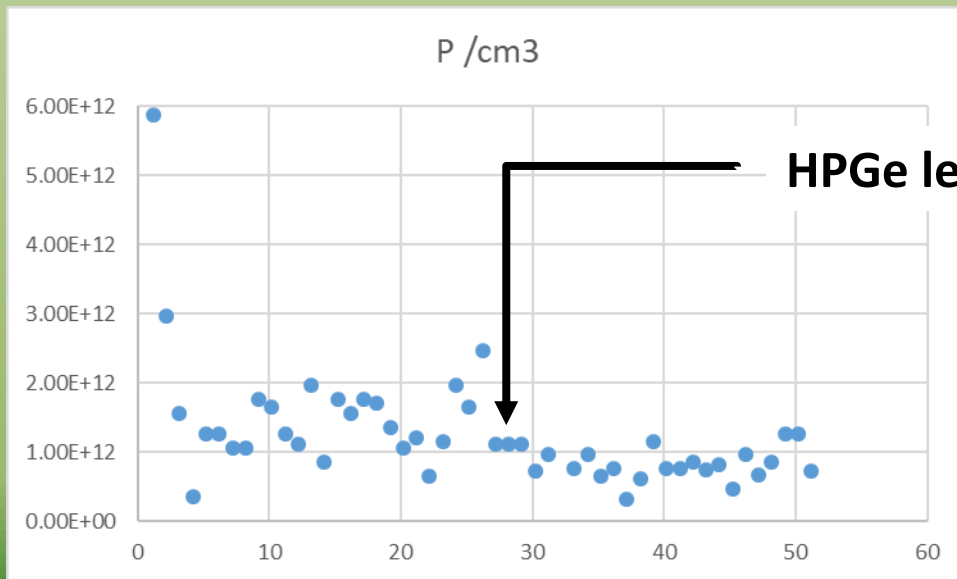
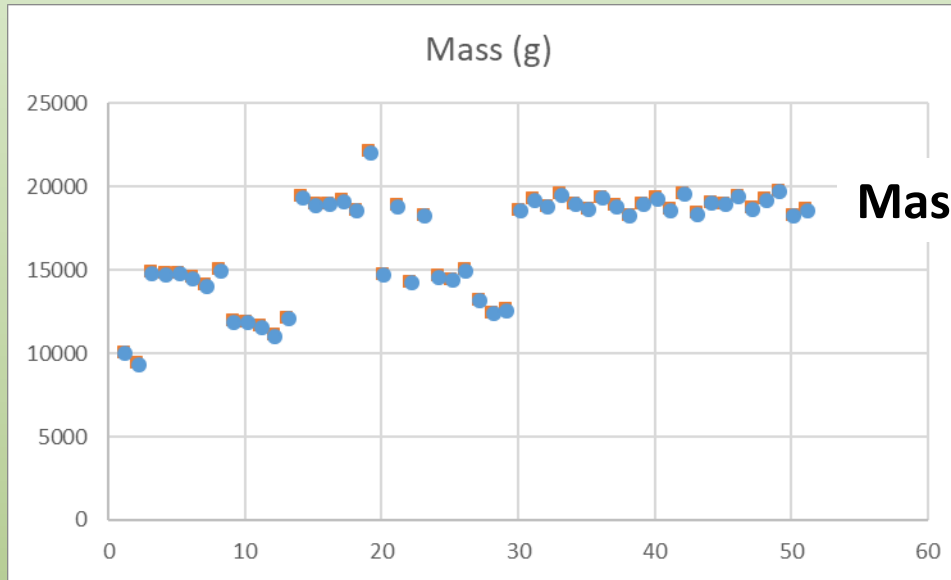


19696 g

$P = 0.9 \times 10^{12} / \text{cm}^3$

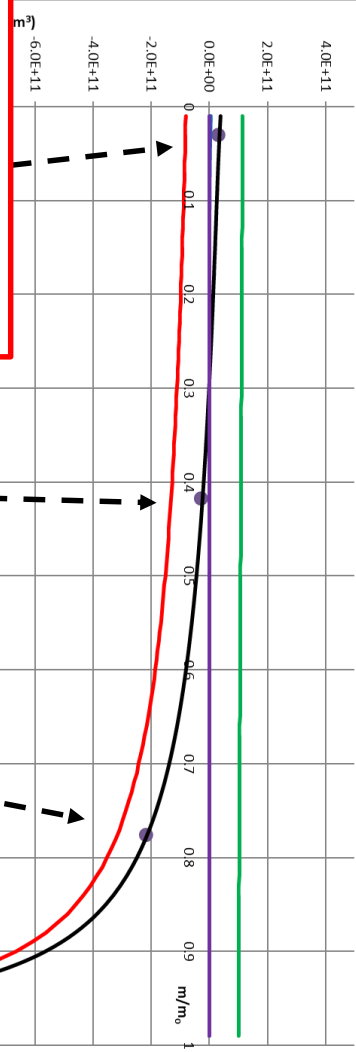
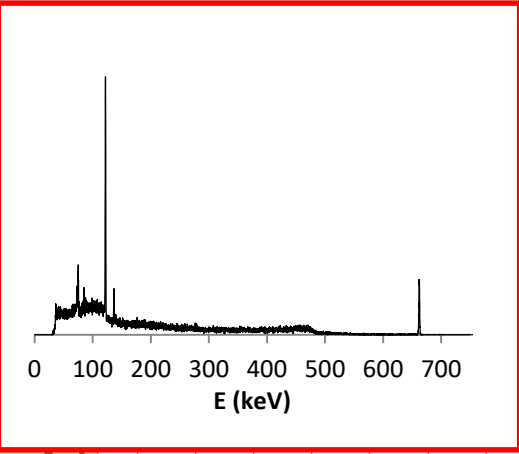
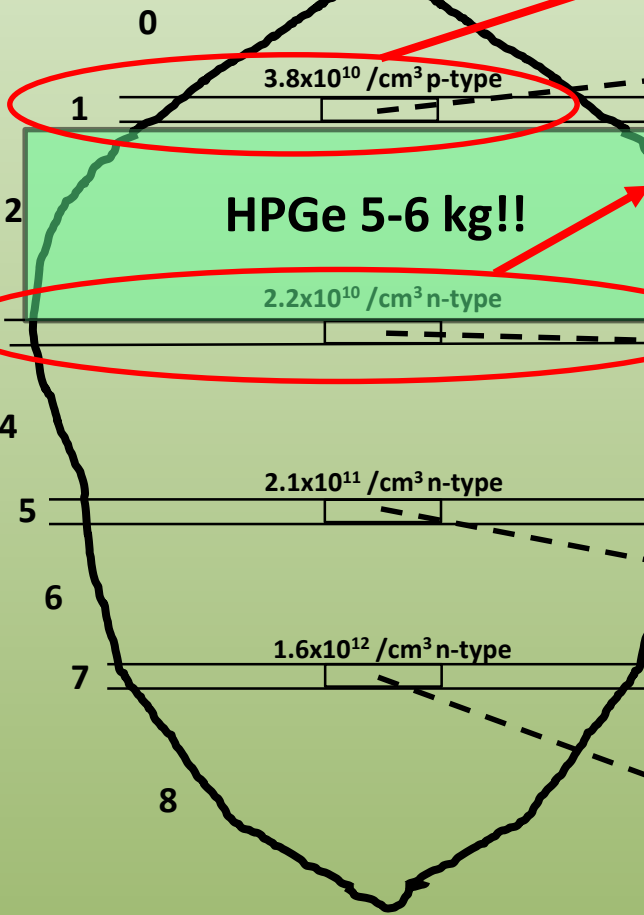


# 51 crystals grown and analyzed



<20171220>

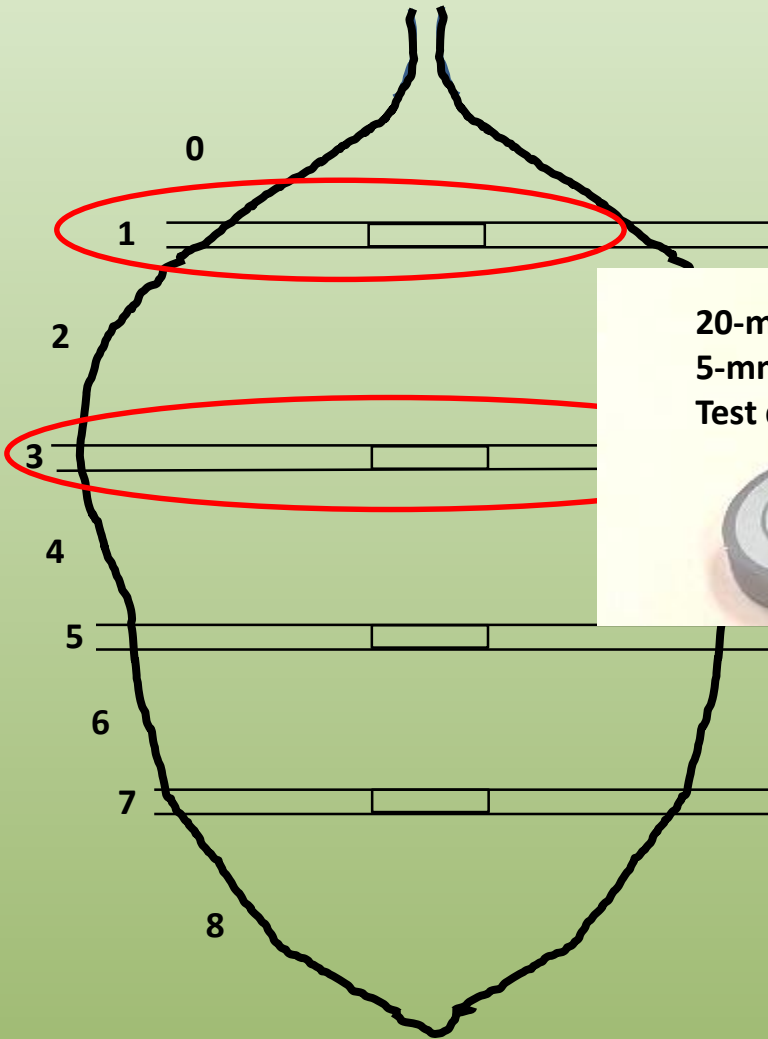
18.9 kg



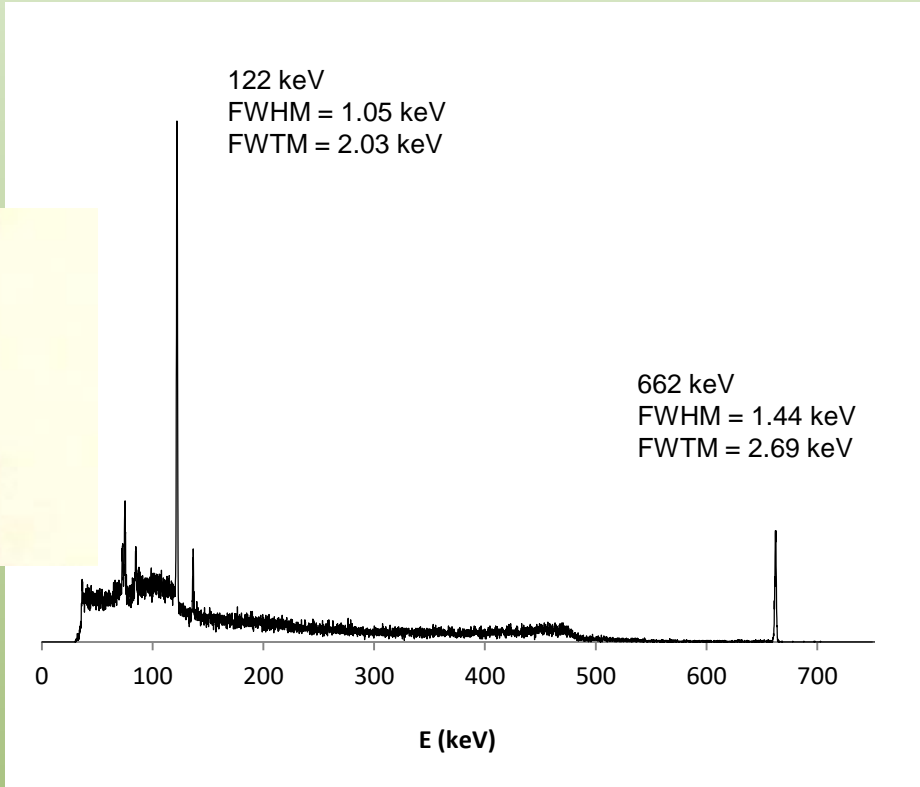
**B** =  $3.0 \times 10^8 / \text{cm}^3$  p-type  
**P** =  $1.0 \times 10^{12} / \text{cm}^3$  n-type  
**Al<sub>0</sub>** =  $1.1 \times 10^{11} / \text{cm}^3$  p-type  
**Al<sub>1</sub>** =  $1.0 \times 10^{11} / \text{cm}^3$  p-type

30 analyzed crystals

Test detector results

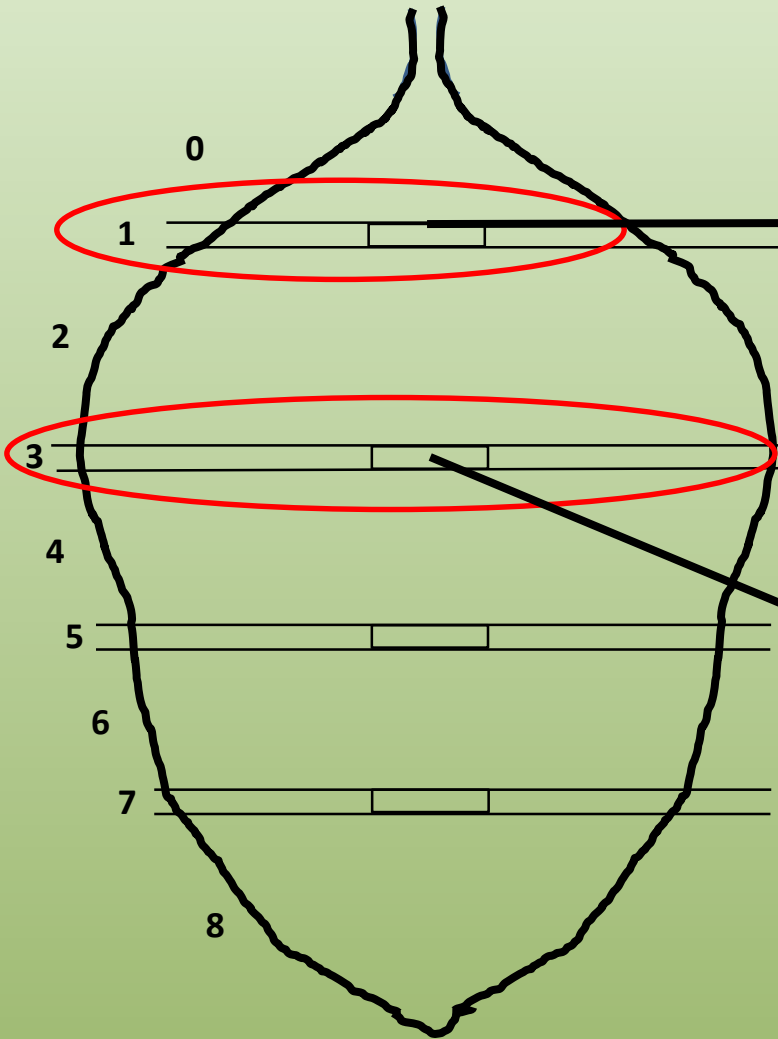


20-mm diameter  
5-mm thick  
Test detectors

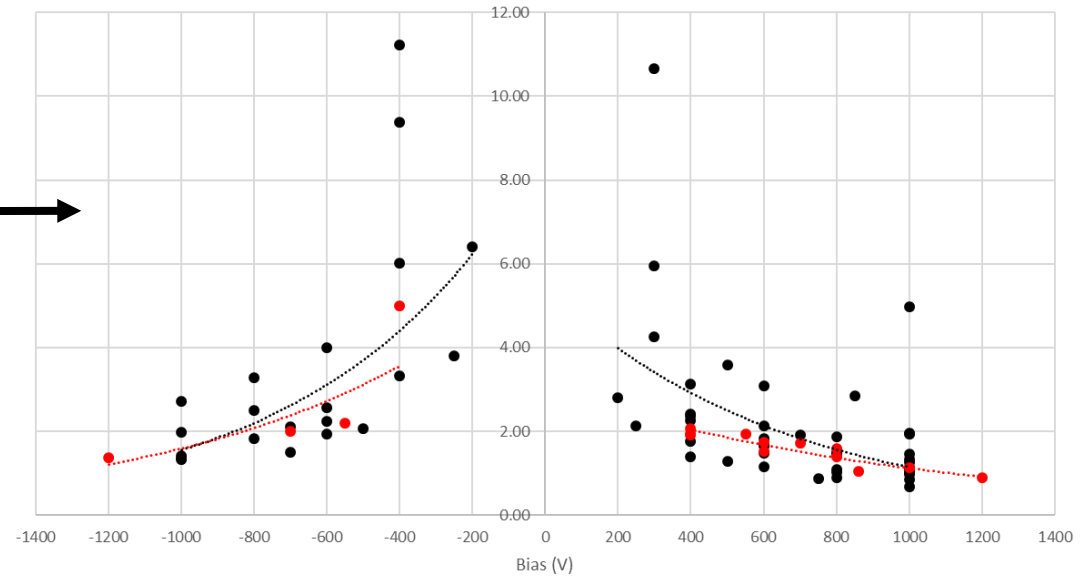


$$FWHM_{det} \cong \{FWHM_{662}^2 - FWHM_{122}^2\}^{\frac{1}{2}}$$

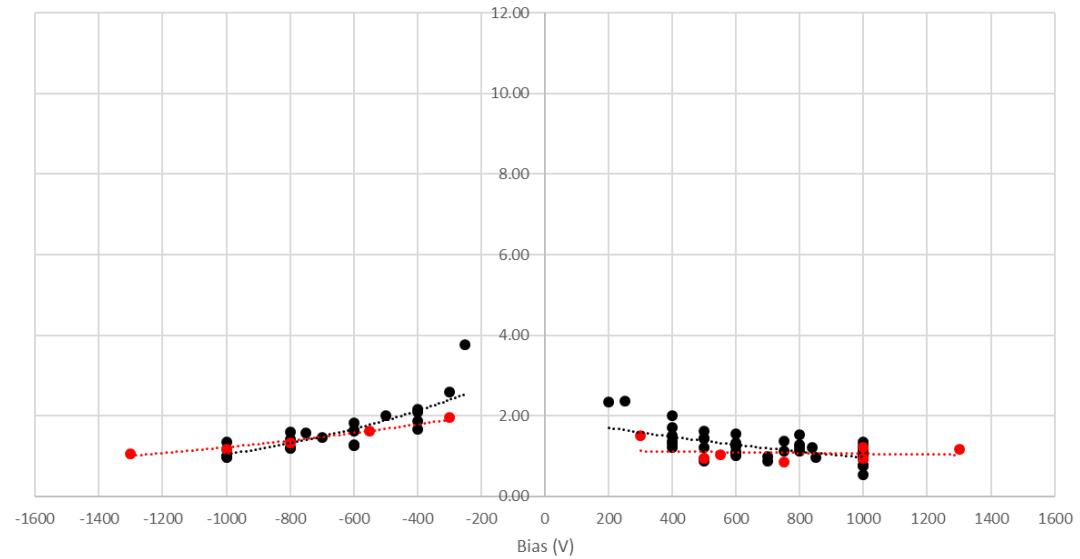
# Spectroscopy



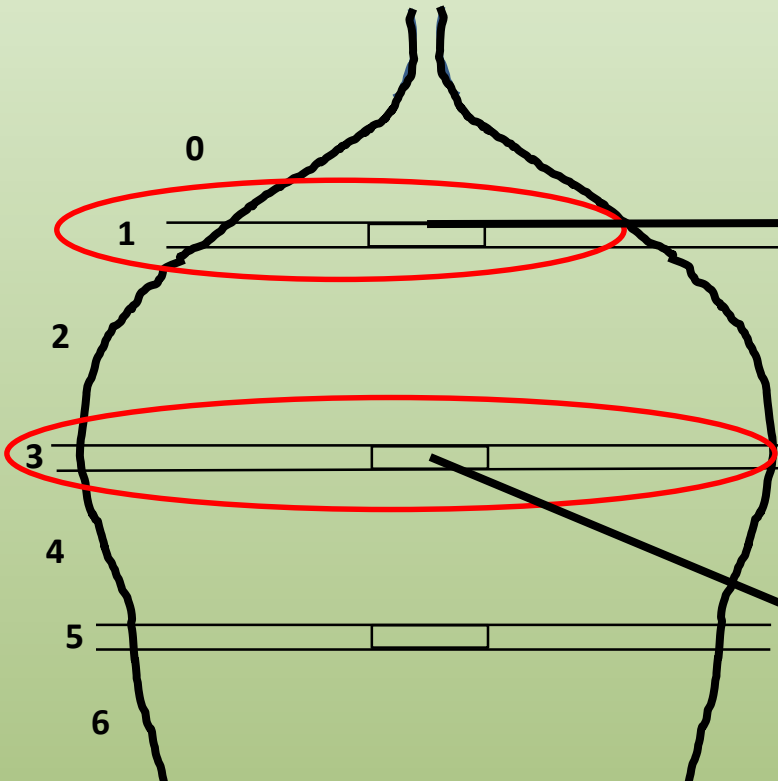
Slice 1 FWHM<sub>det</sub>



Slice 3 FWHM<sub>det</sub>

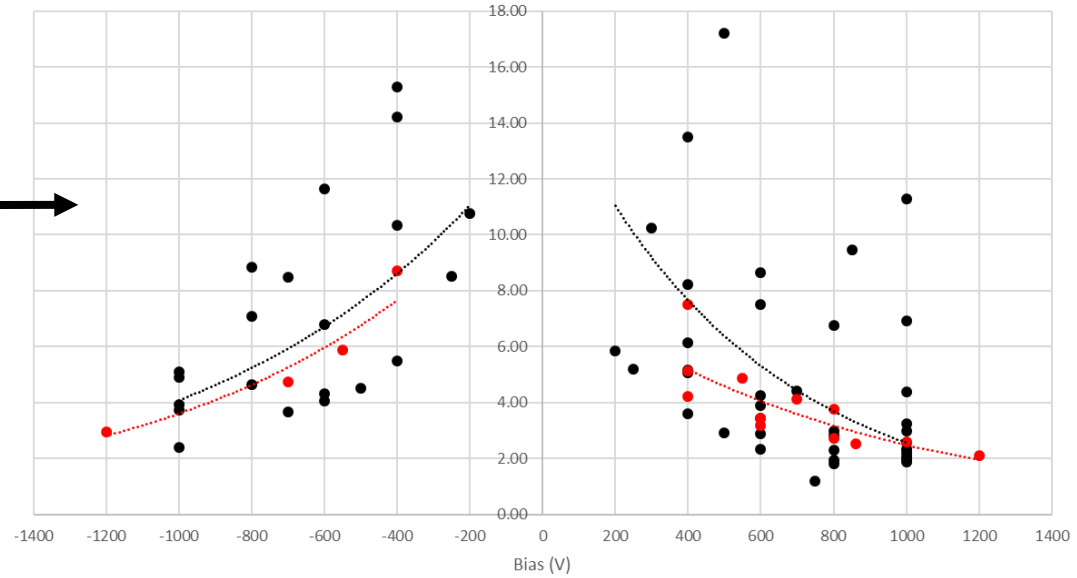


# Spectroscopy

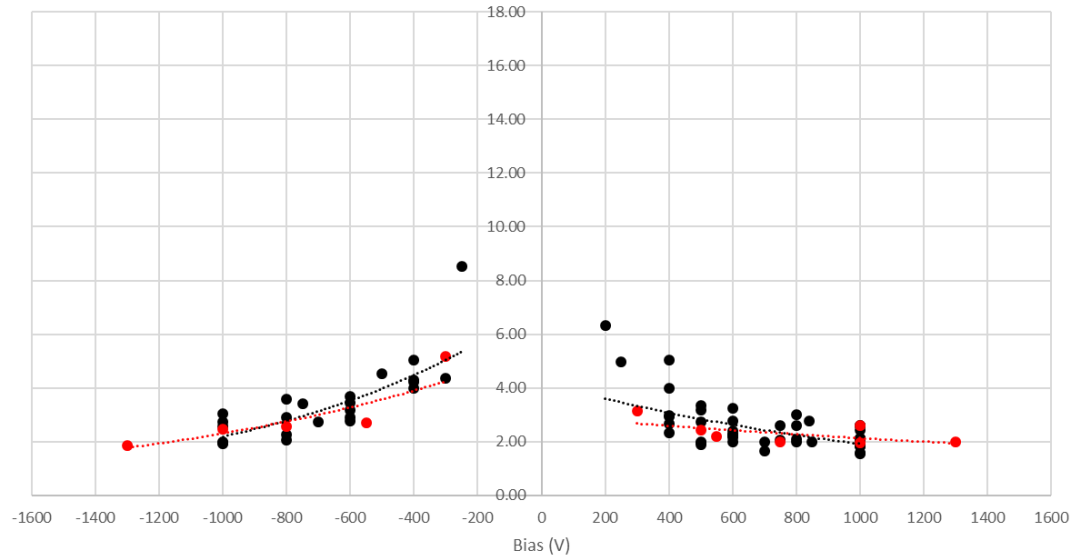


**For large mass (19 kg) crystals  
strain regions  
lower E fields  
where it matters the most  
(center detector data)**

Slice 1 FWTM<sub>det</sub>

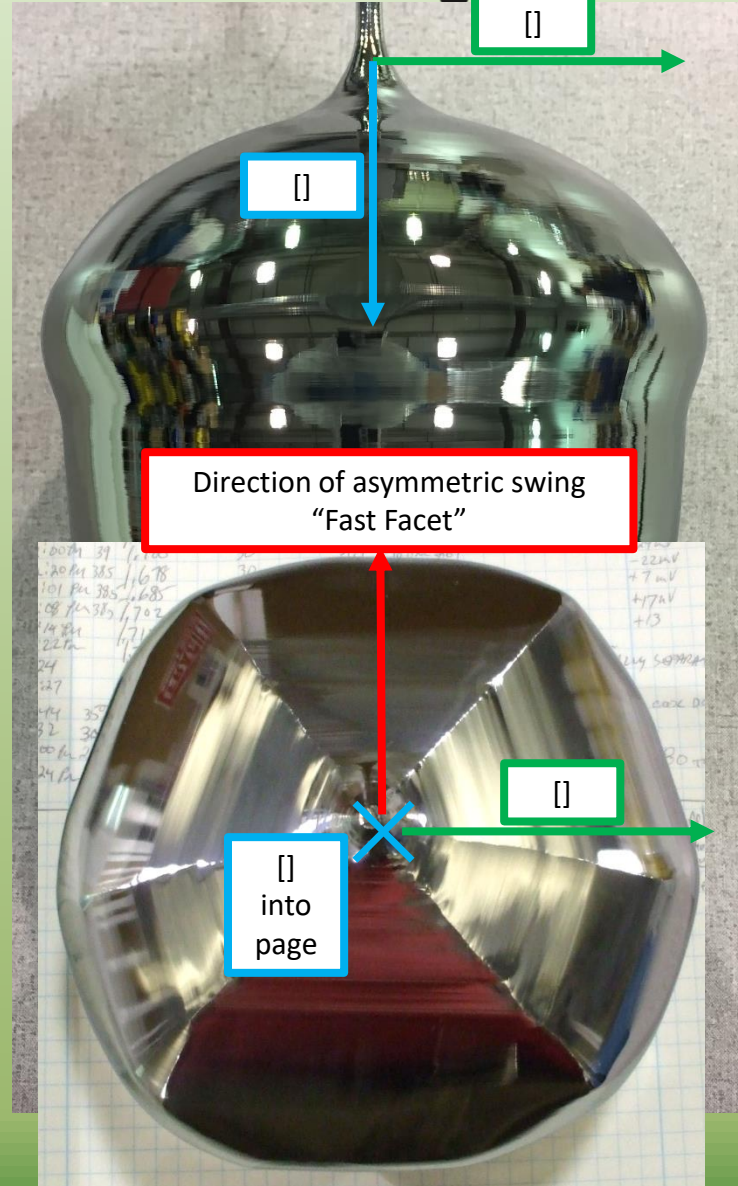
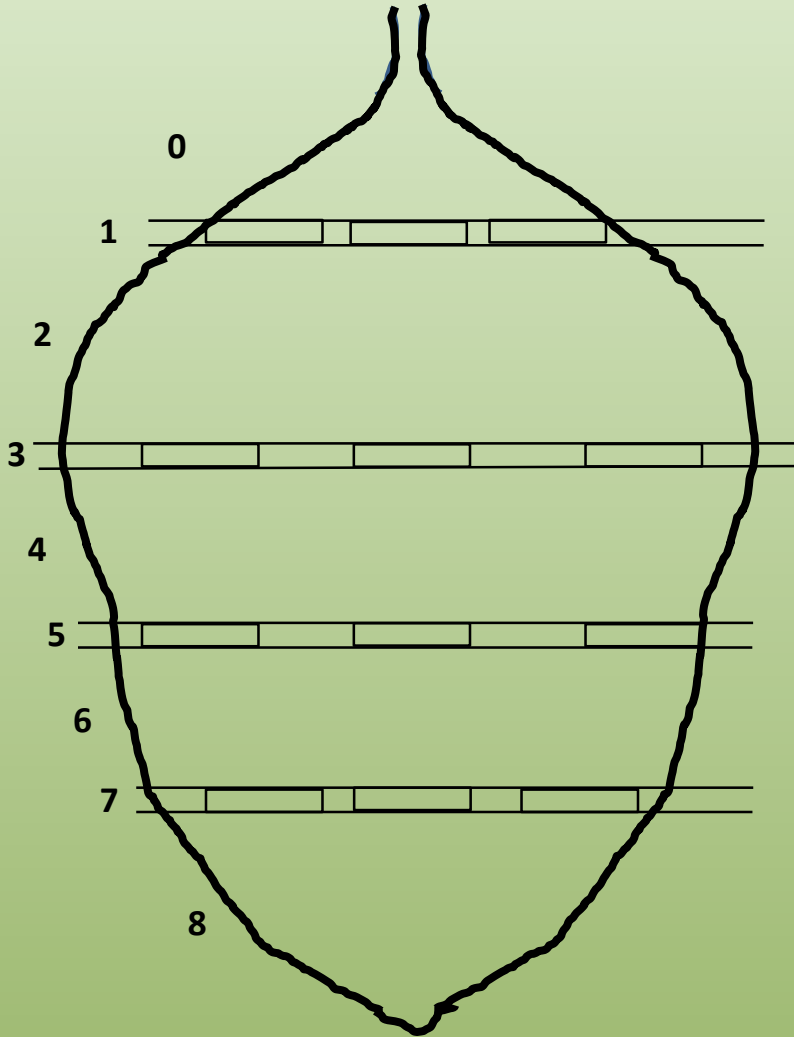


Slice 3 FWTM<sub>det</sub>

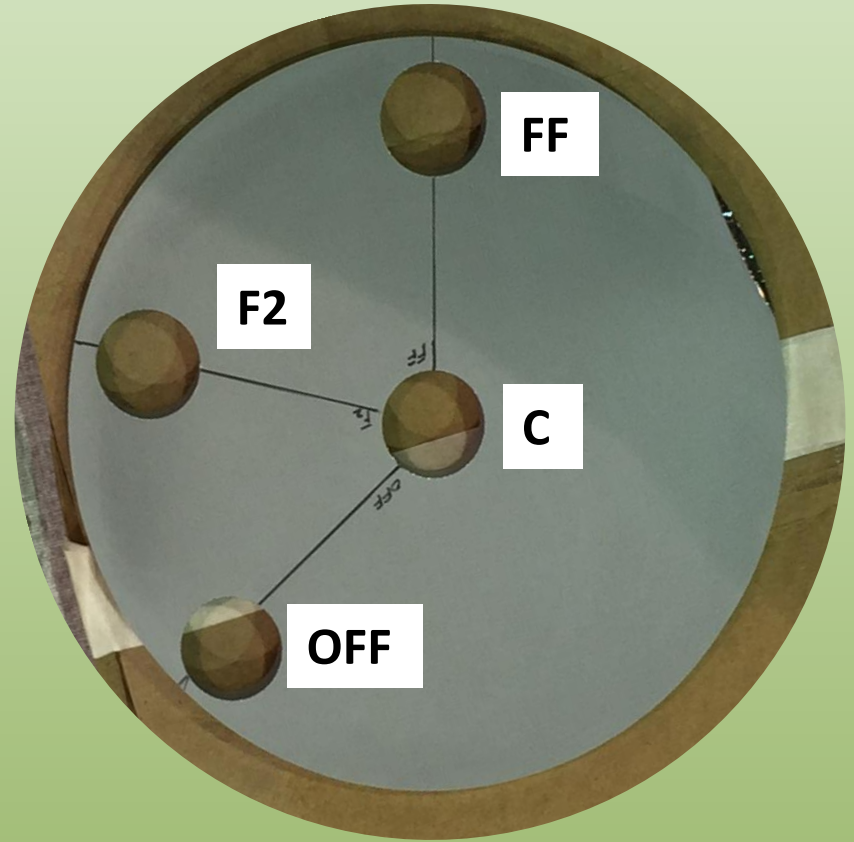
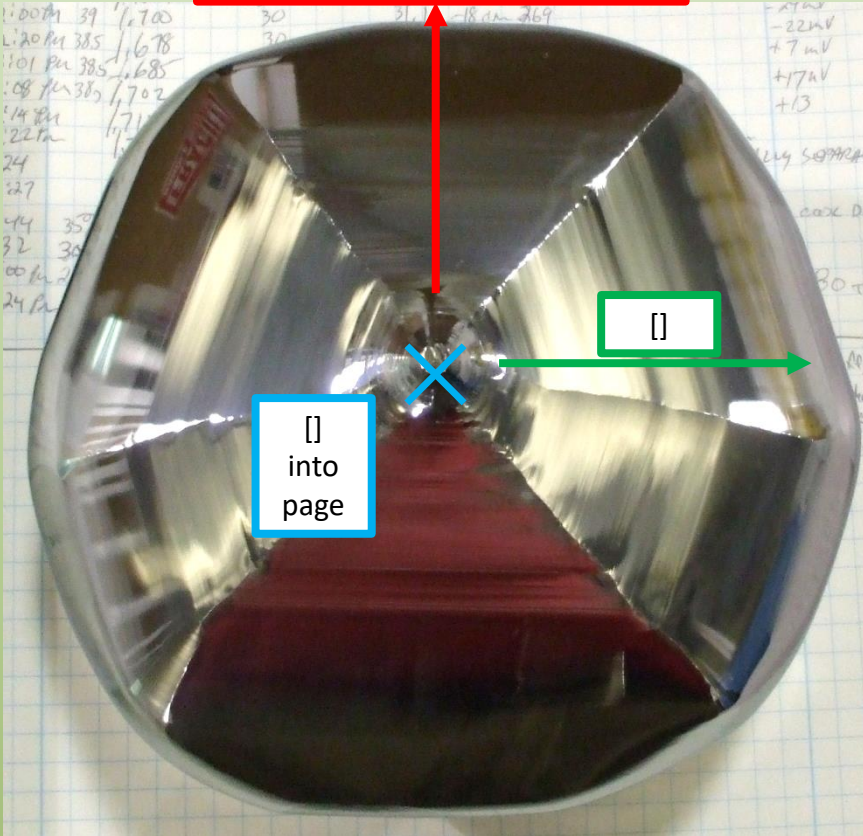


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# Multiple samples – axis properties



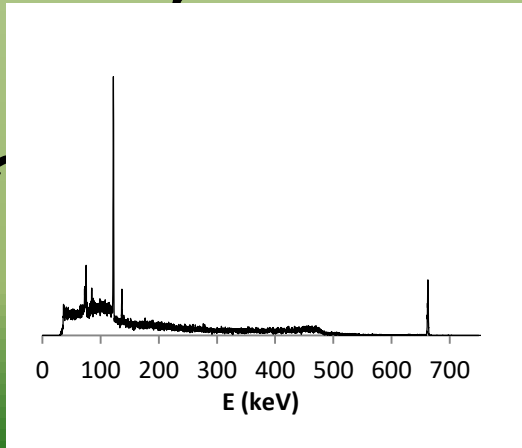
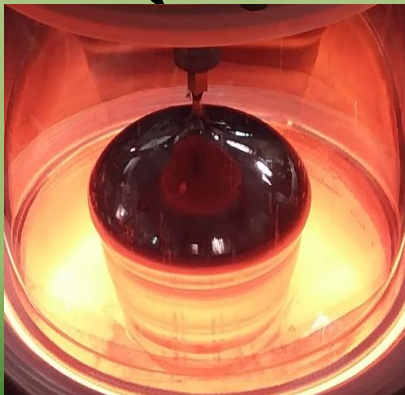
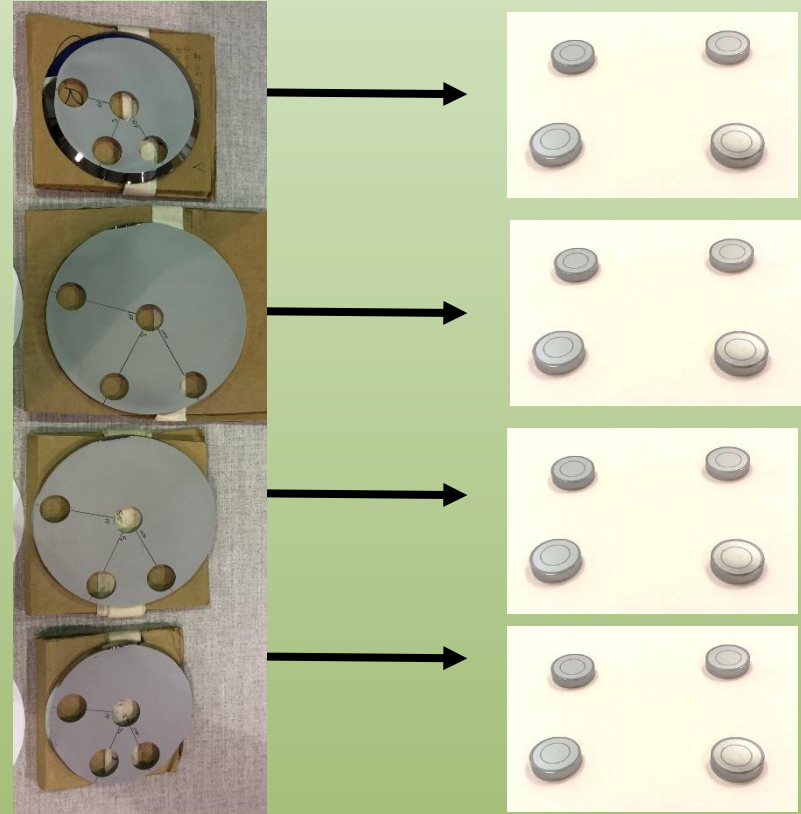
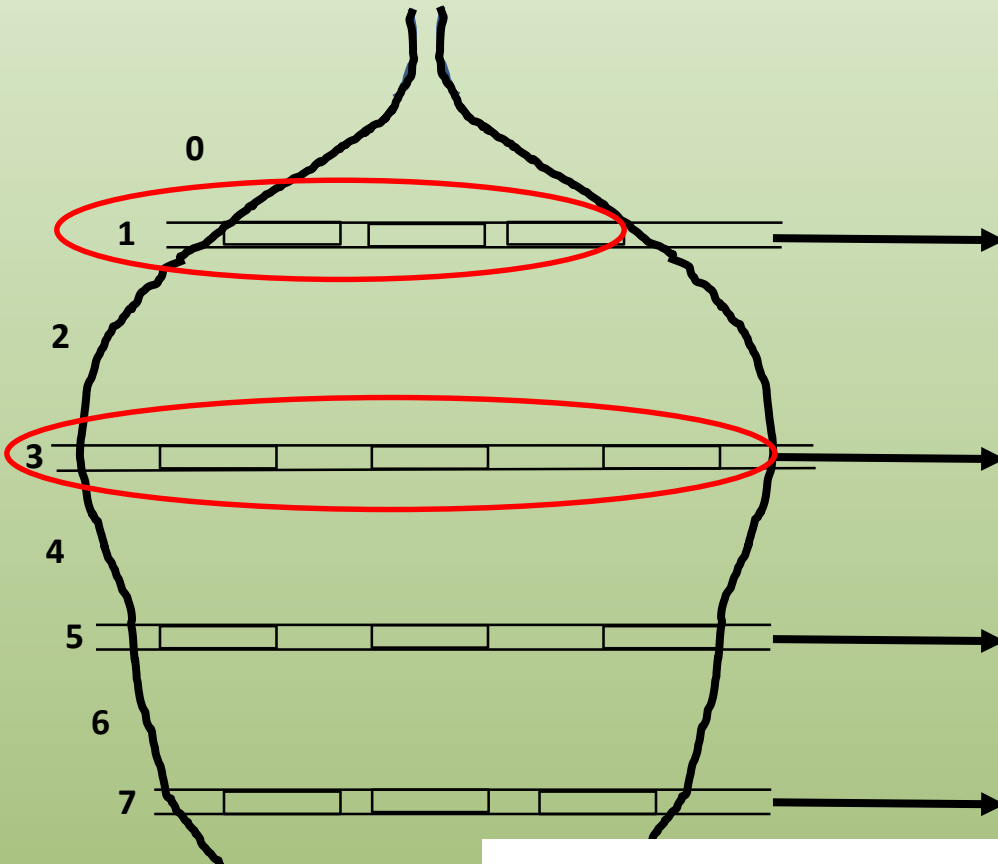
Direction of asymmetric swing  
"Fast Facet"





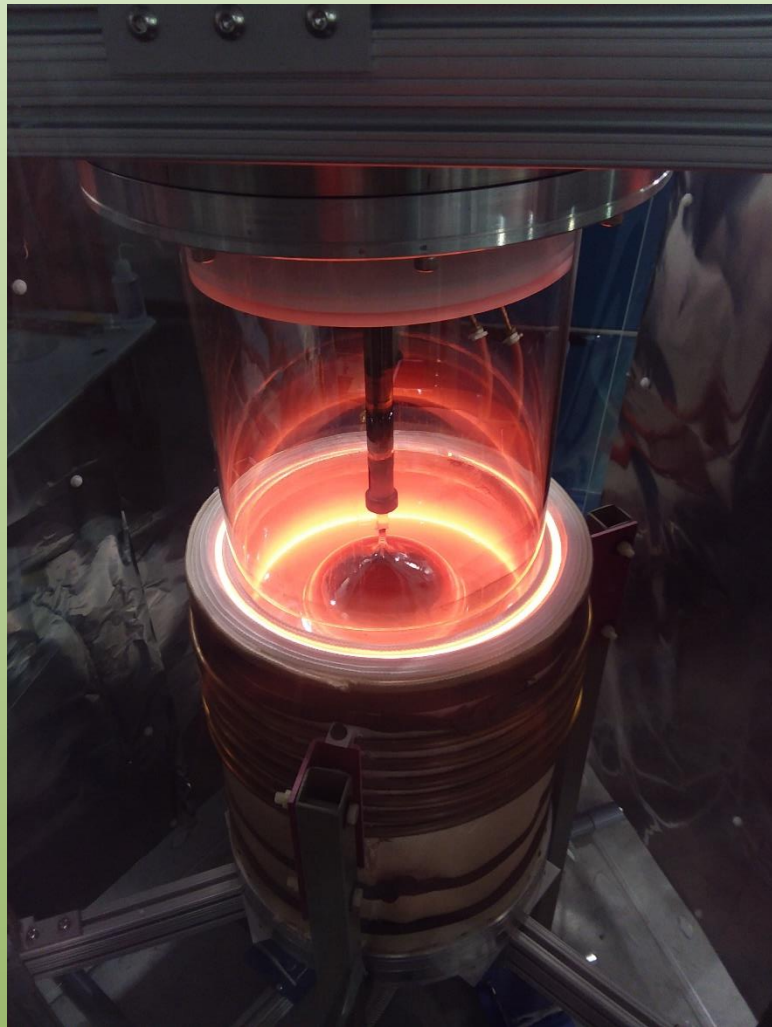
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# Multiple samples – axis properties



$$FWHM_{det} \cong \{FWHM_{662}^2 - FWHM_{122}^2\}^{\frac{1}{2}}$$

<20180501> []



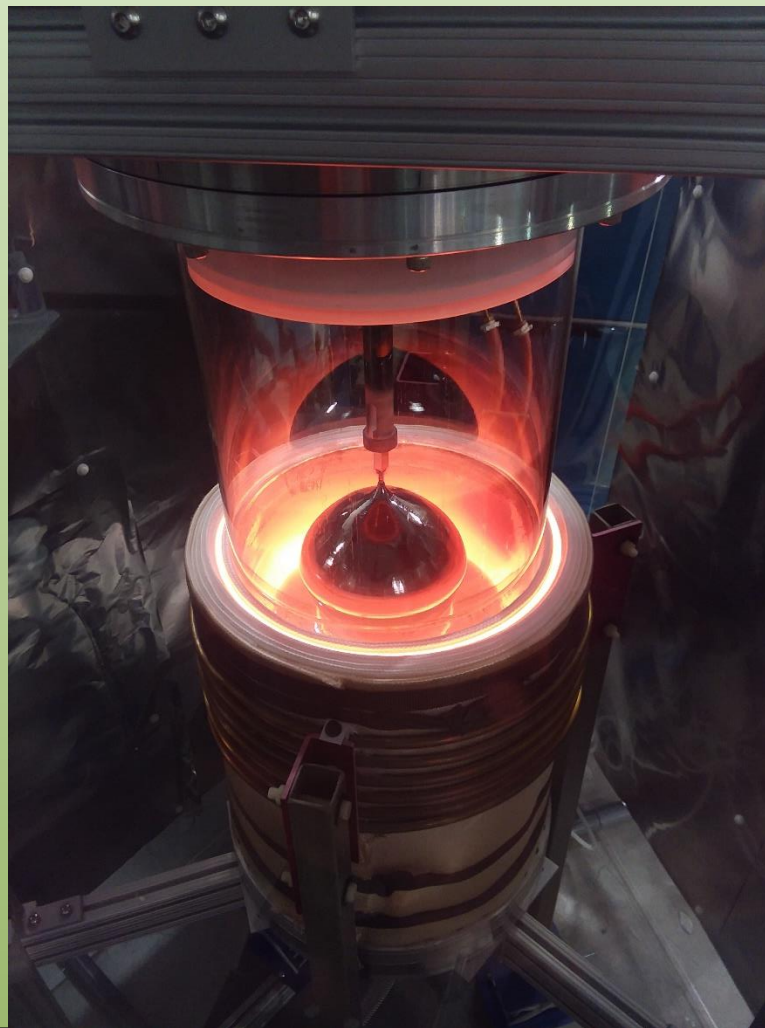
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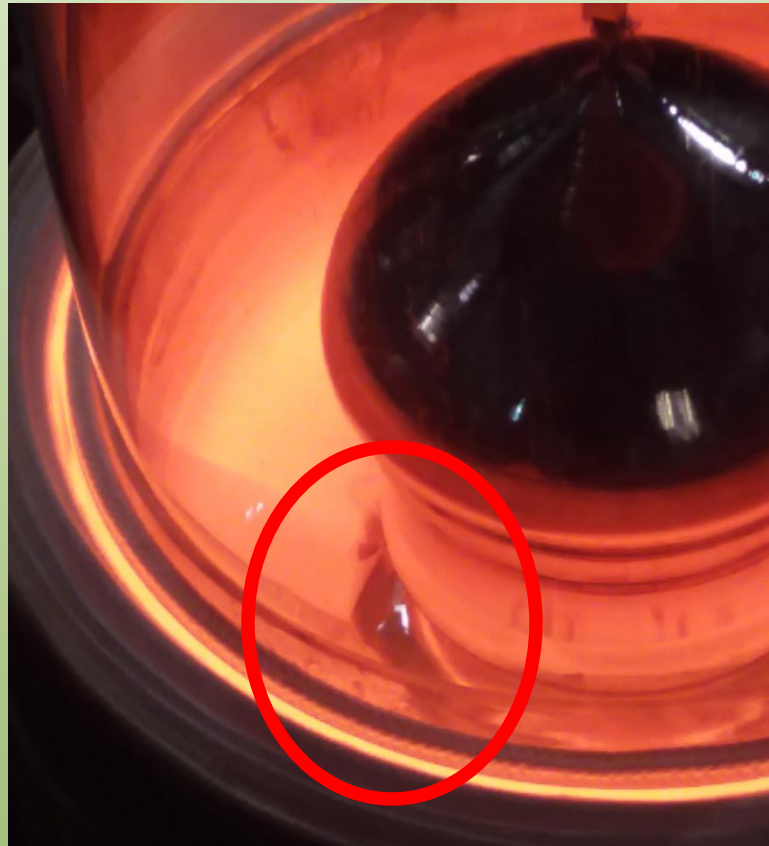
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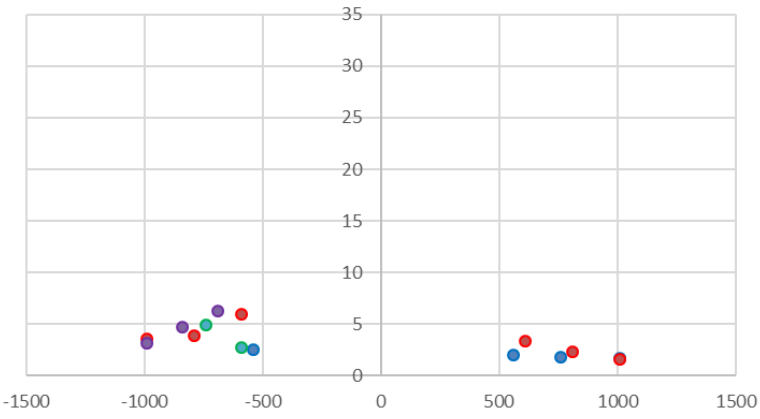
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**Freeze**

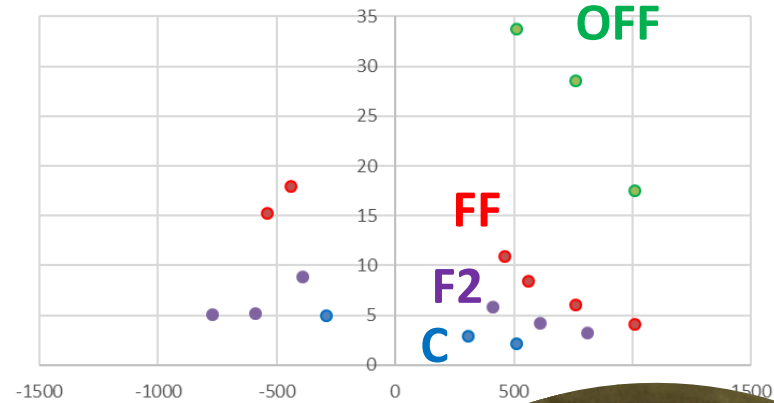
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Slice 3 FWTM<sub>det</sub>



<20180425> []

Slice 3 FWTM<sub>det</sub>



Free

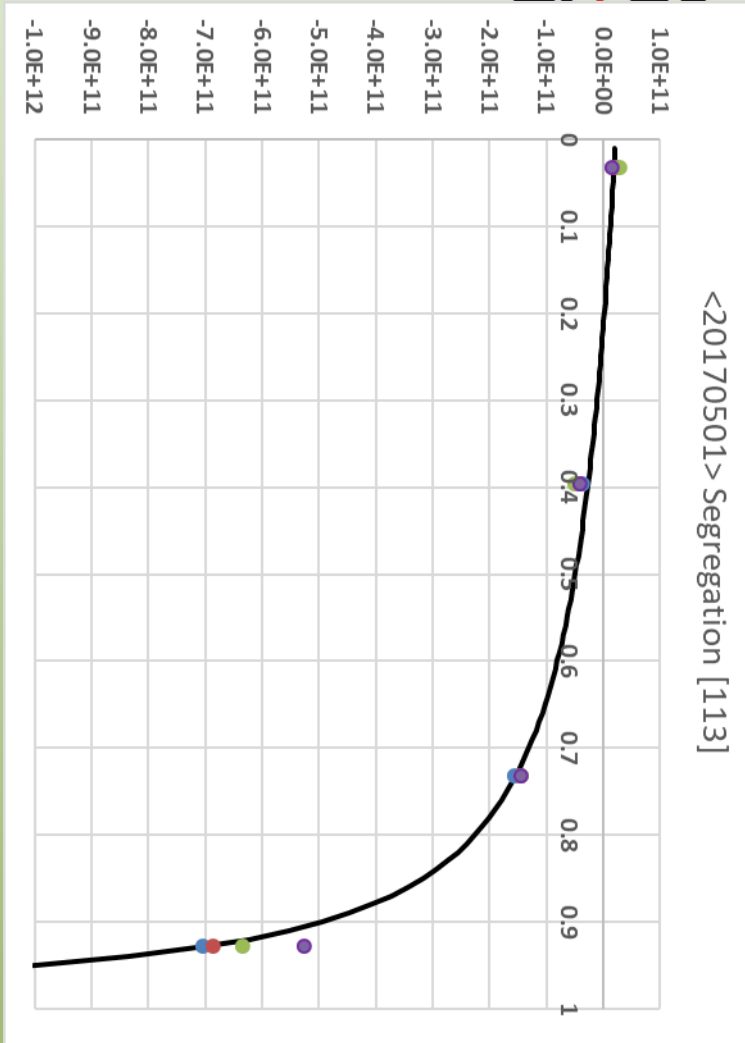
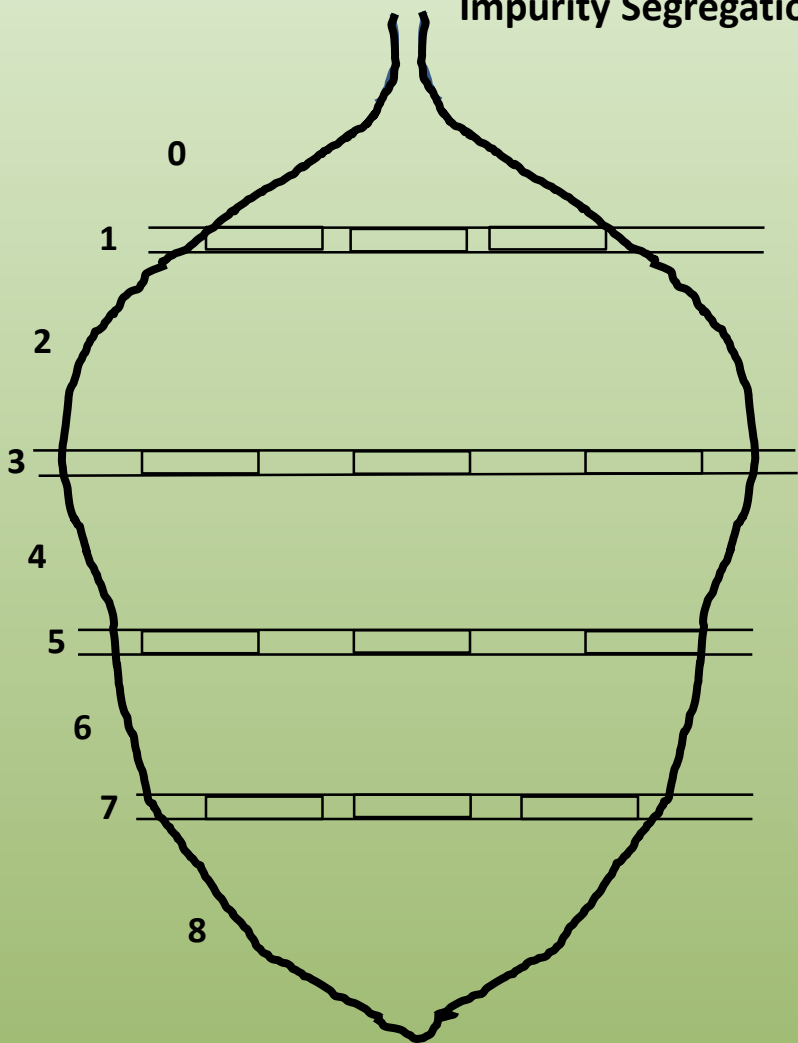
<20180501> []

Multiple samples – axis properties

Impurity Segregation



Ray Imaging Detectors



Impurity Segregation is as radially uniform in [] crystals ✓



# 1. New Commercial Detector – Fulcrum



**Fulcrum™**  
Hand Held HPGe Detector

**PHDS**  
Gamma Ray Imaging Detectors

Pu-239  
U-235  
Cs-137  
Kp-237  
Ba-133

High Resolution Spectroscopy and *Automatic* Identification



**Applications**

- Military and Civilian CBRNE Operations
- Nuclear Safeguards
- Nuclear Security
- Special Nuclear Materials Analysis
- Decommissioning & Decontamination

**Specifications**

Weight:	7.0 lbs.
Battery Life:	4 hours internal, 12 hours external, hot swappable
Power supply:	100-240 VAC, 50-60 Hz
User Maintenance:	None
Energy Resolution:	FWHM – 1.0 keV at 122 keV FWHM – 2.2 keV at 1332 keV
Sensitivity:	10 <sup>4</sup> Ci 137Cs at 1 meter (3.3 µR/hr, 33 nSv/hr) (662 keV) 6σ: 12.9 seconds +/- 1.9 seconds
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Detector (Ge Crystal) dimension:	40-mm diameter, 20-mm thick
Cool-down time:	60 minutes
Startup time (cold):	2 minutes
Included:	Android mobile phone I/O device, pelican case, power supply, battery charger

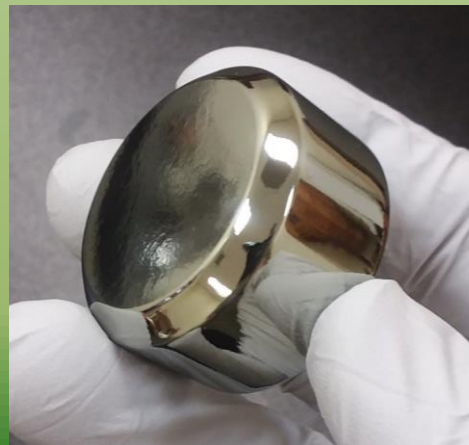
**Features**

- Most compact HPGe detector system
- Lowest weight HPGe detector system
- Integrated Stirling-cycle cooler
- Automatically specifies: SNM, NORM, IND, MED
- Germanium gamma-ray spectroscopy: 32 kch
- User-friendly CMNI Android app
- Wireless or hard-wired data transmission available
- Twistlock mispec. power connector
- Long-lived internal cooler (10+ years run time)
- Single button Reachback (ANSI N42.42)

Optional External Lithium Battery Pack



PHDS Co. 3011 Amherst Road, Knoxville, TN 37921 | (865) 202 6253 | www.phdsco.com, sales@phdsco.com



# Commercial Impact

## 1. New Commercial Detector – Fulcrum



**25 cm<sup>3</sup>**

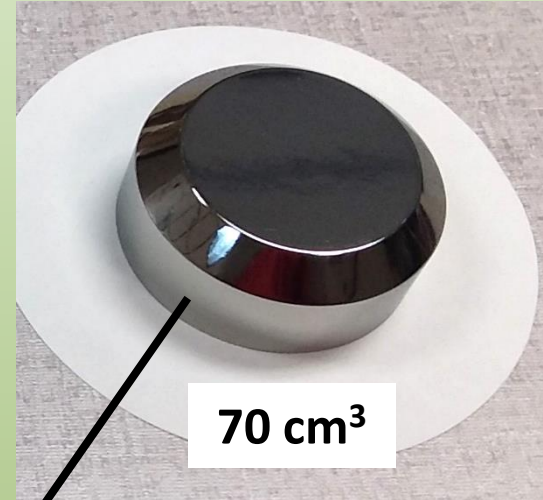
**70 cm<sup>3</sup>**

# Commercial Impact

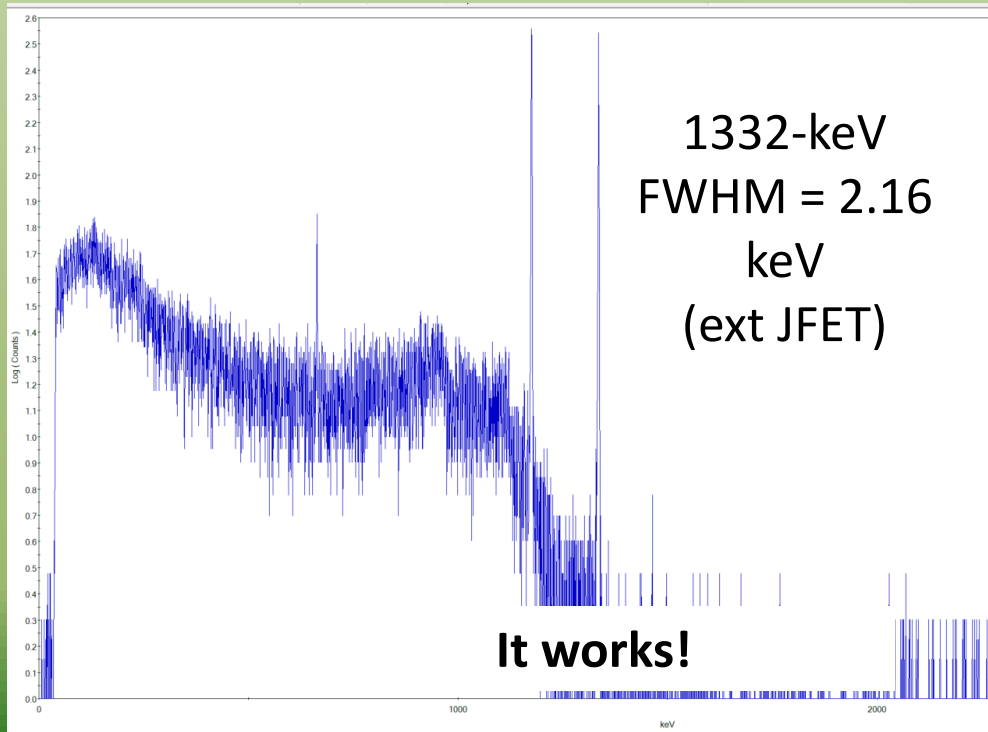
## 1. New Commercial Detector – Fulcrum



Fulcrum

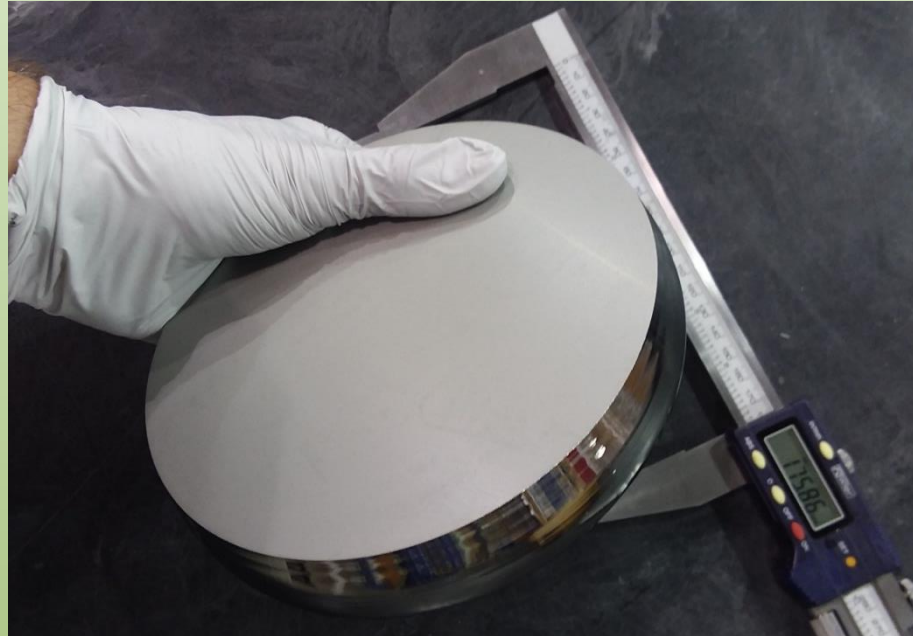


70 cm<sup>3</sup>



## Commercial Impact

### 2. New very-large rare-particle DOE Nuclear Physics research detector



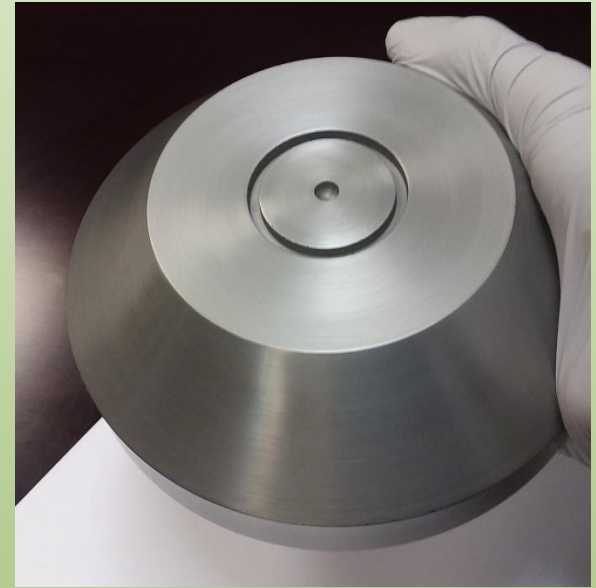
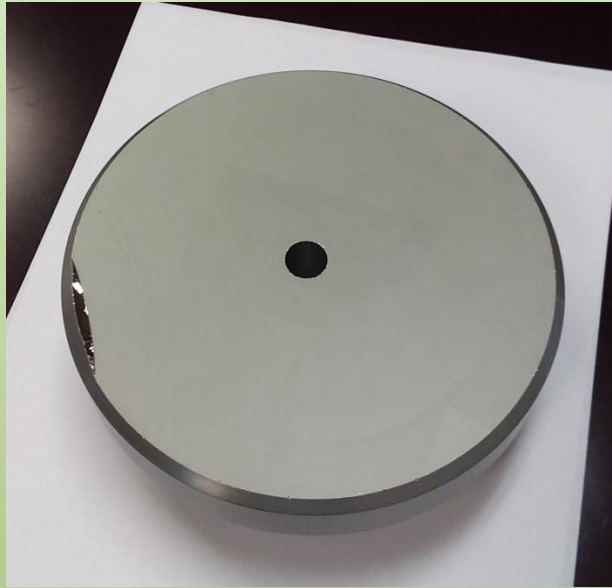
60 mm

Very large (6.7 kg) HPGe Slab  
Being made into a novel  
(customer specified)  
detector design  
Enabled by this program

170 mm

# Commercial Impact

## 2. Practice grinding and polish etch



Thank you

