Calibration and Readiness of the ISS-RAD Charged Particle Detector

R. Rios on behalf of the ISS-RAD Science Team

Contact: ryan.r.rios@nasa.gov

The International Space Station (ISS) Radiation Assessment Detector (RAD) is an intra-vehicular energetic particle detector designed to measure a broad spectrum of charged particle and neutron radiation unique to the ISS radiation environment. In this presentation, a summary of calibration and readiness of the RAD Sensor Head (RSH) – also referred to as the Charged Particle Detector (CPD) – for ISS will be presented. Calibration for the RSH consists of p, He, C, O, Si, and Fe ion data collected at the NASA Space Radiation Laboratory (NSRL) and Indiana University Cyclotron Facility (IUCF). The RSH consists of four detectors used in measuring the spectroscopy of charged particles – A, B, C, and D; high-energy neutral particles and charged particles are measured in E; and the last detector – F – is an anti-coincidence detector. A, B, and C are made from Si; D is made from BGO; E and F are made from EJ260XL plastic scintillator.

ISS-RAD: Charged Particle Detector

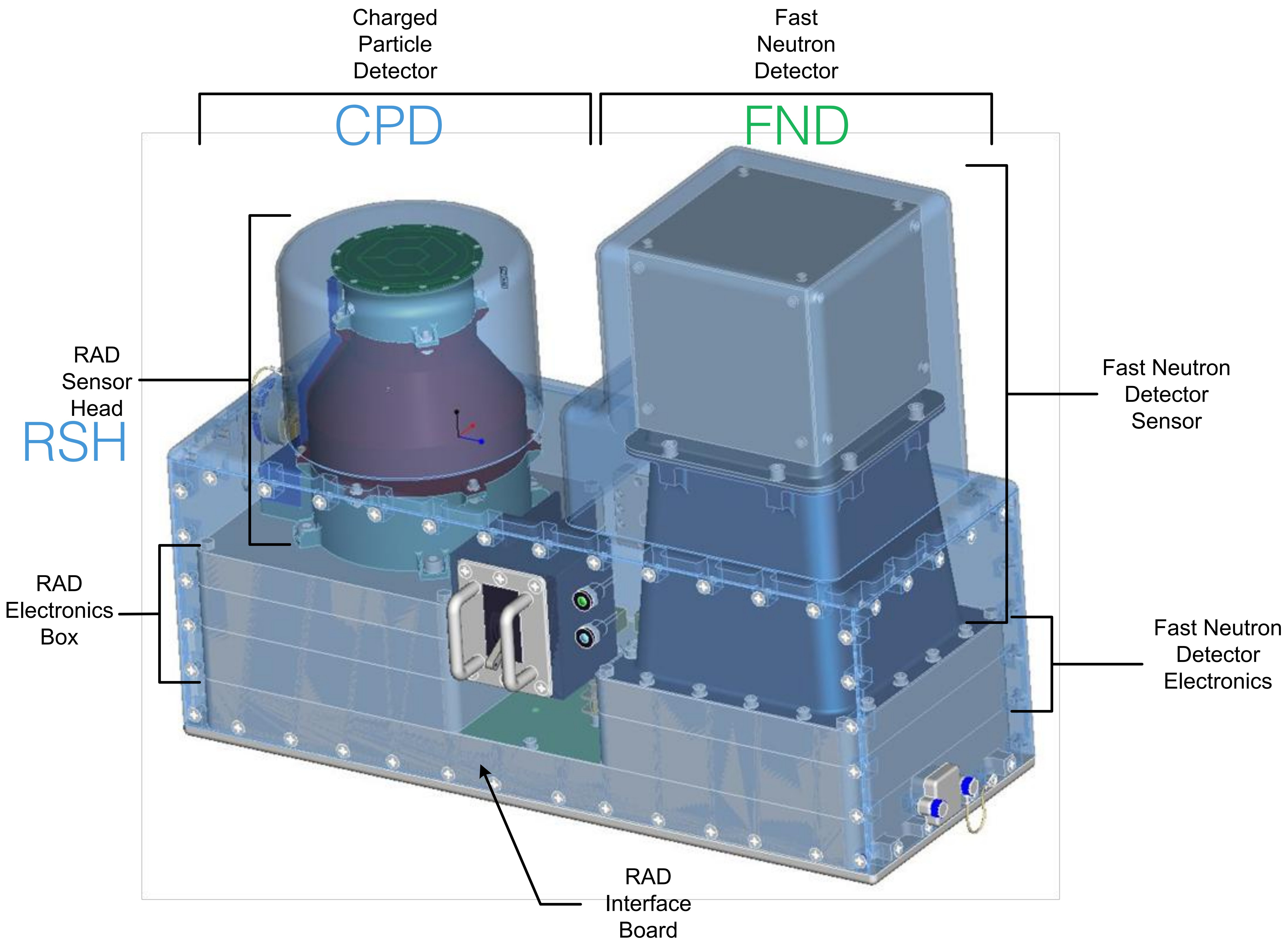
Calibration and Readiness

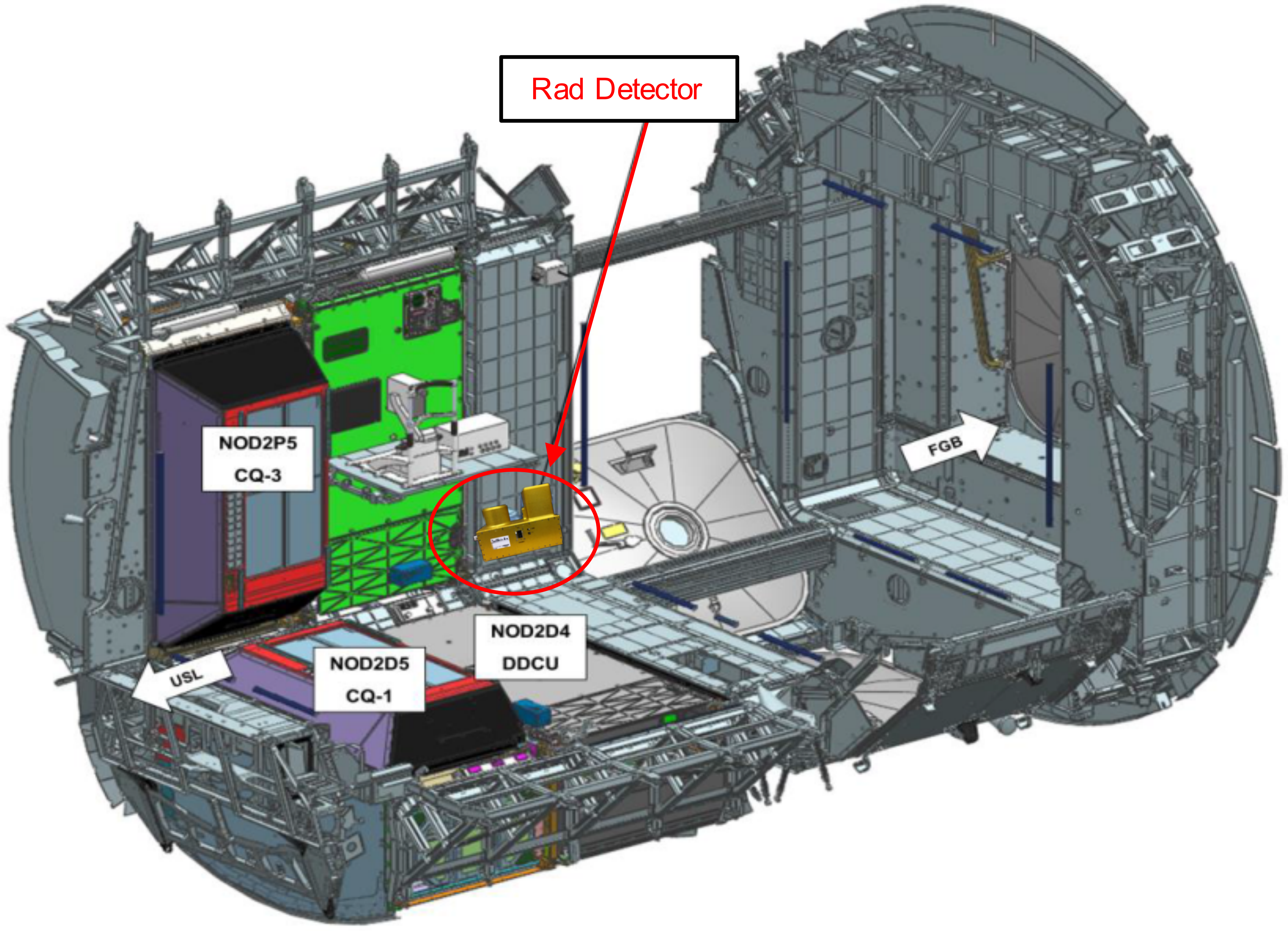
R. Rios, Ph.D. on behalf of the RAD Science Team
Space Radiation
Analysis Group **NASA**

At a Glance

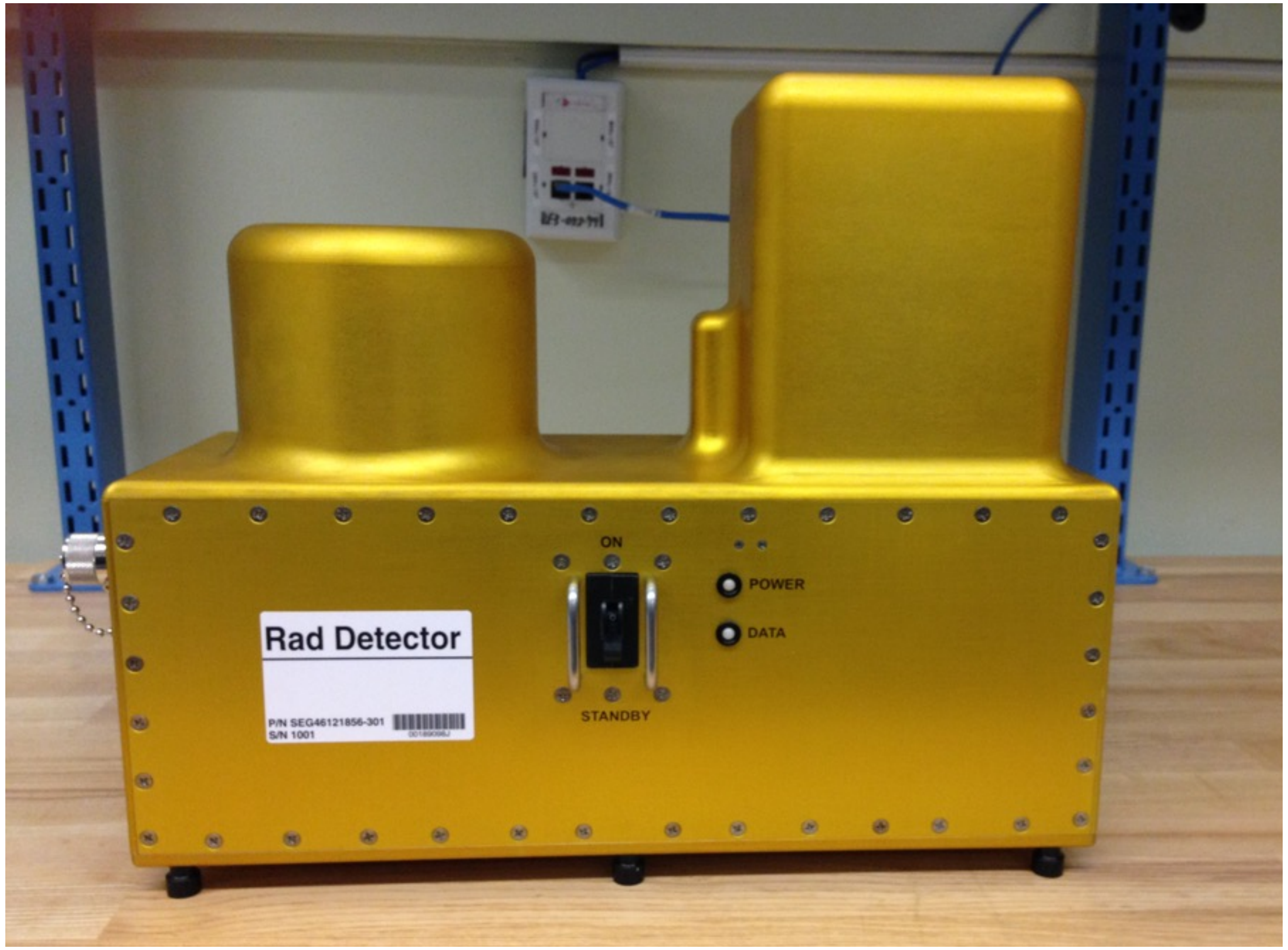
- Instrument Overview
  - Hardware Design
  - Data Analysis
- Detector Calibration
  - Calibration Campaigns
  - Sub-detector Highlights
- Charge Resolution
- Calibration Results from Ground Analysis Software
- Summary

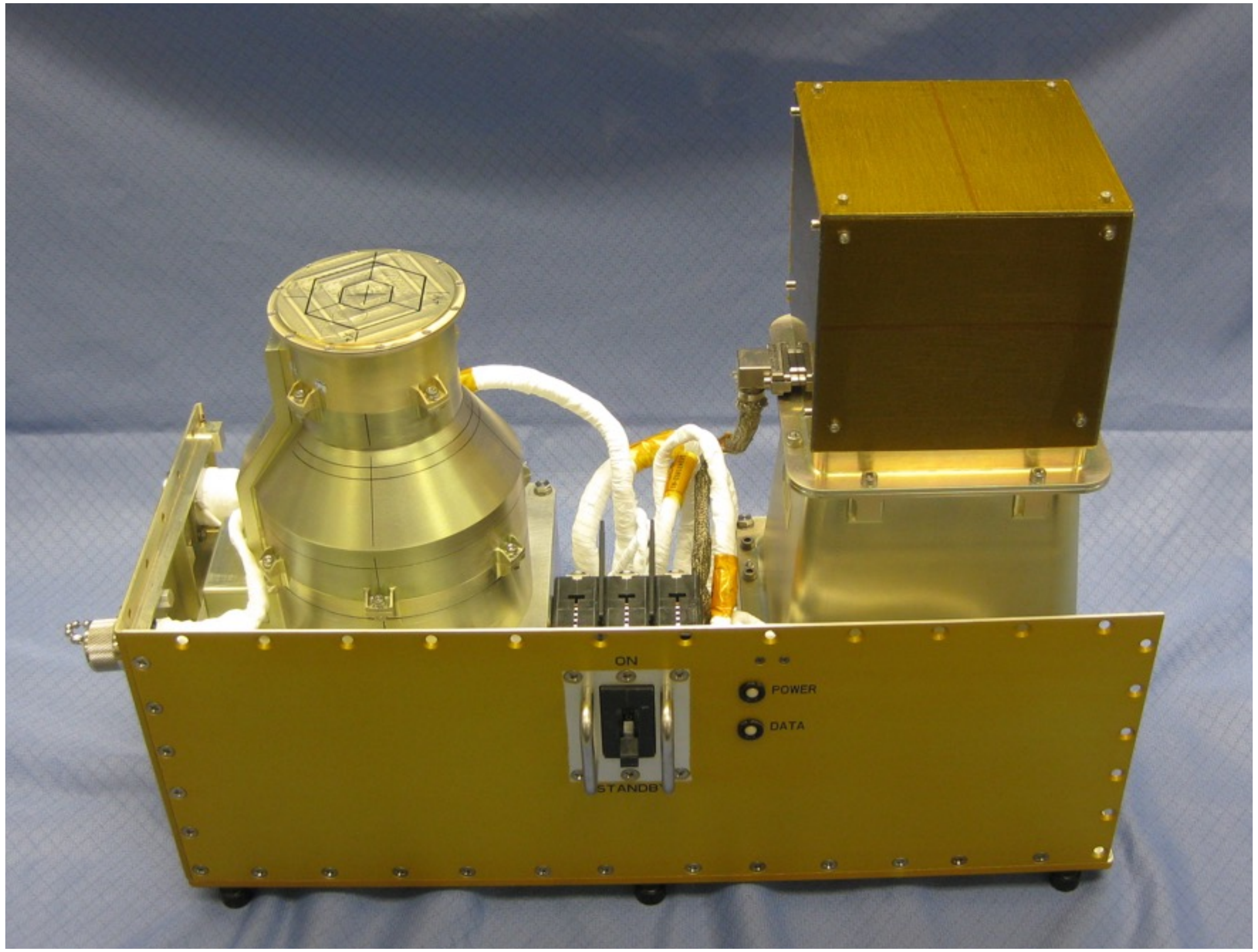
CAD Model


Charged
Particle
Detector
CPD
Fast
Neutron
Detector
FND
RAD
Sensor
Head
RSH
RAD
Electronics
Box
Fast Neutron
Detector
Sensor
Fast Neutron
Detector
Electronics
RAD
Interface
Board


Rad Detector
NOD2P5
CQ-3
NOD2D5
CQ-1
NOD2D4
DDCU
USL
FGB

Flight Model



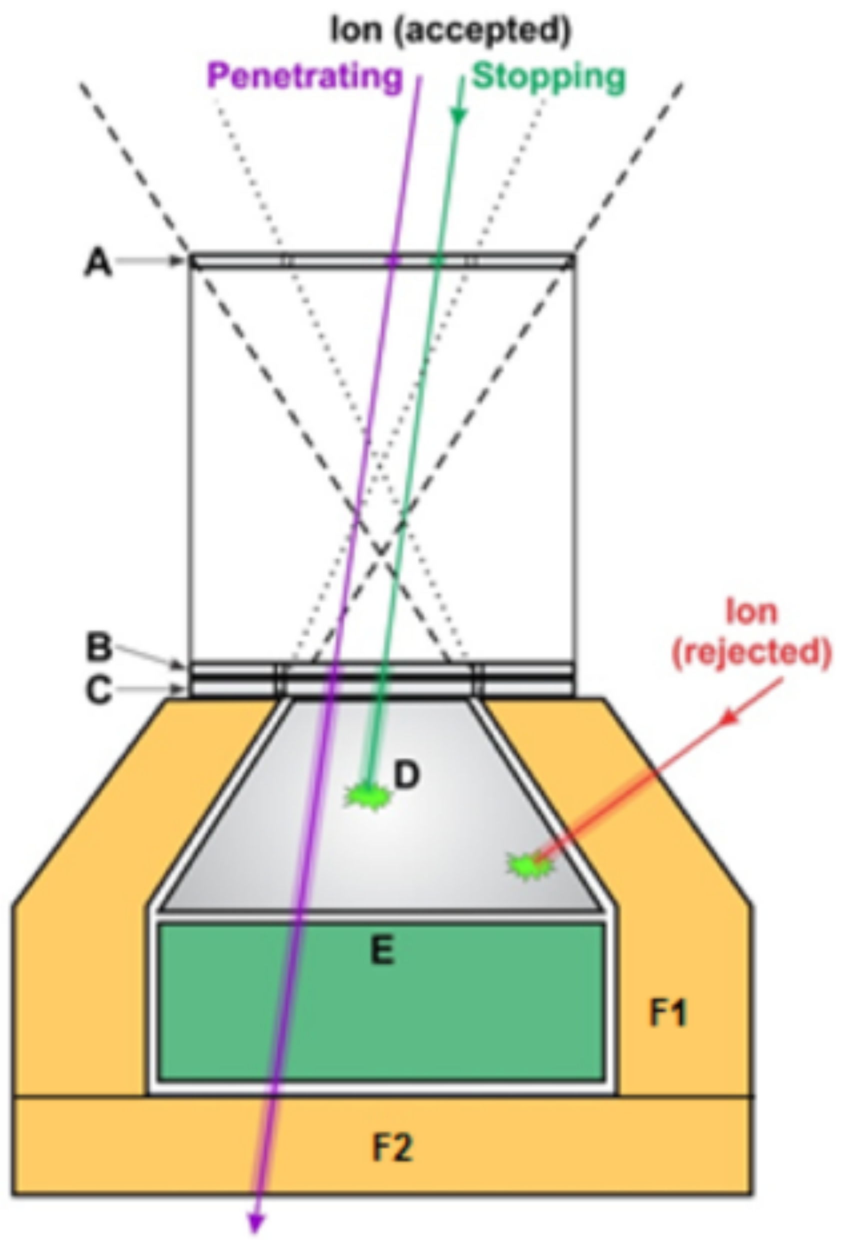


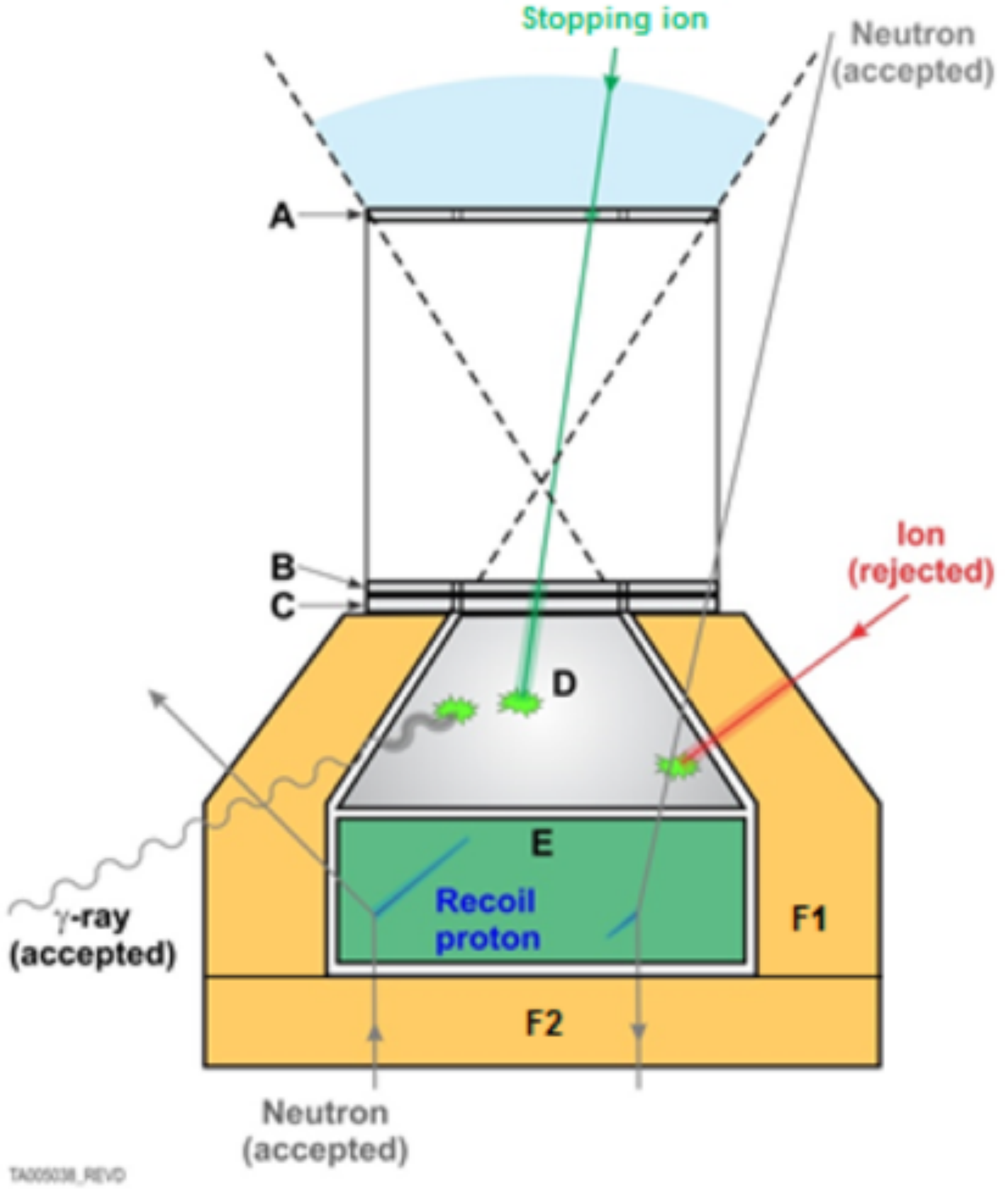
CPD/RSH Design

- The RAD Sensor Head (RSH)/Charged Particle Detector (CPD) is a legacy MSL design and consists of several sub-detectors which are used for charged and neutral particle dosimetry and spectroscopy.

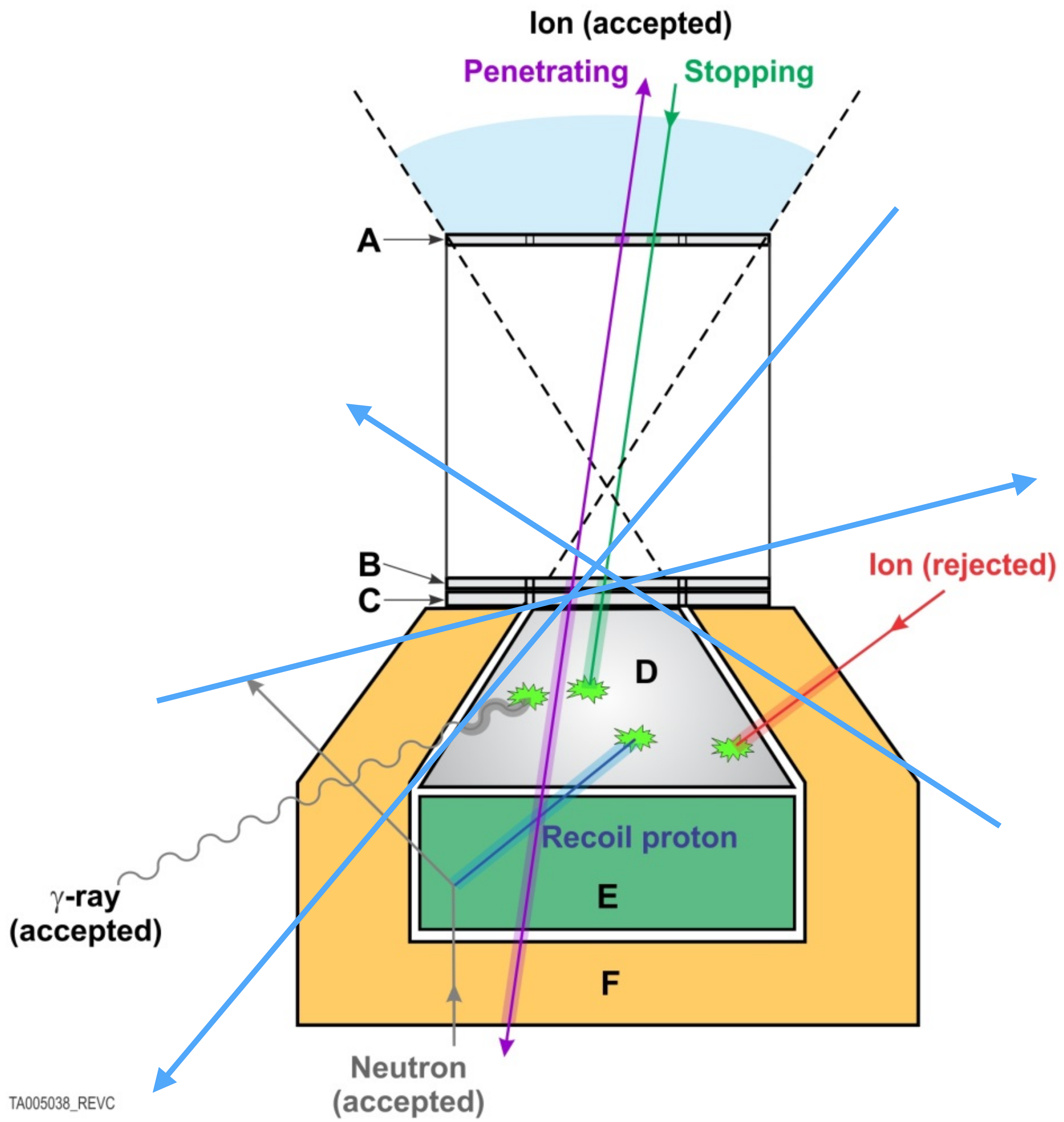
Detector	Material	Type	Purpose
A, B[1], C	Si	SSD	Charged particle spectroscopy
D	BGO[2]	Scintillating Calorimeter	Energy resolving detector
E[1]	EJ260XL[3]	Scintillator	High-energy particle measurements
F	EJ260XL[3]	Scintillating Anti-coincidence	Anti-coincidence counter

1. B/E - cyclic, omnidirectional charged particle dosimetry
2. Bismuth Germanium Oxide.
3. Plastic scintillator.



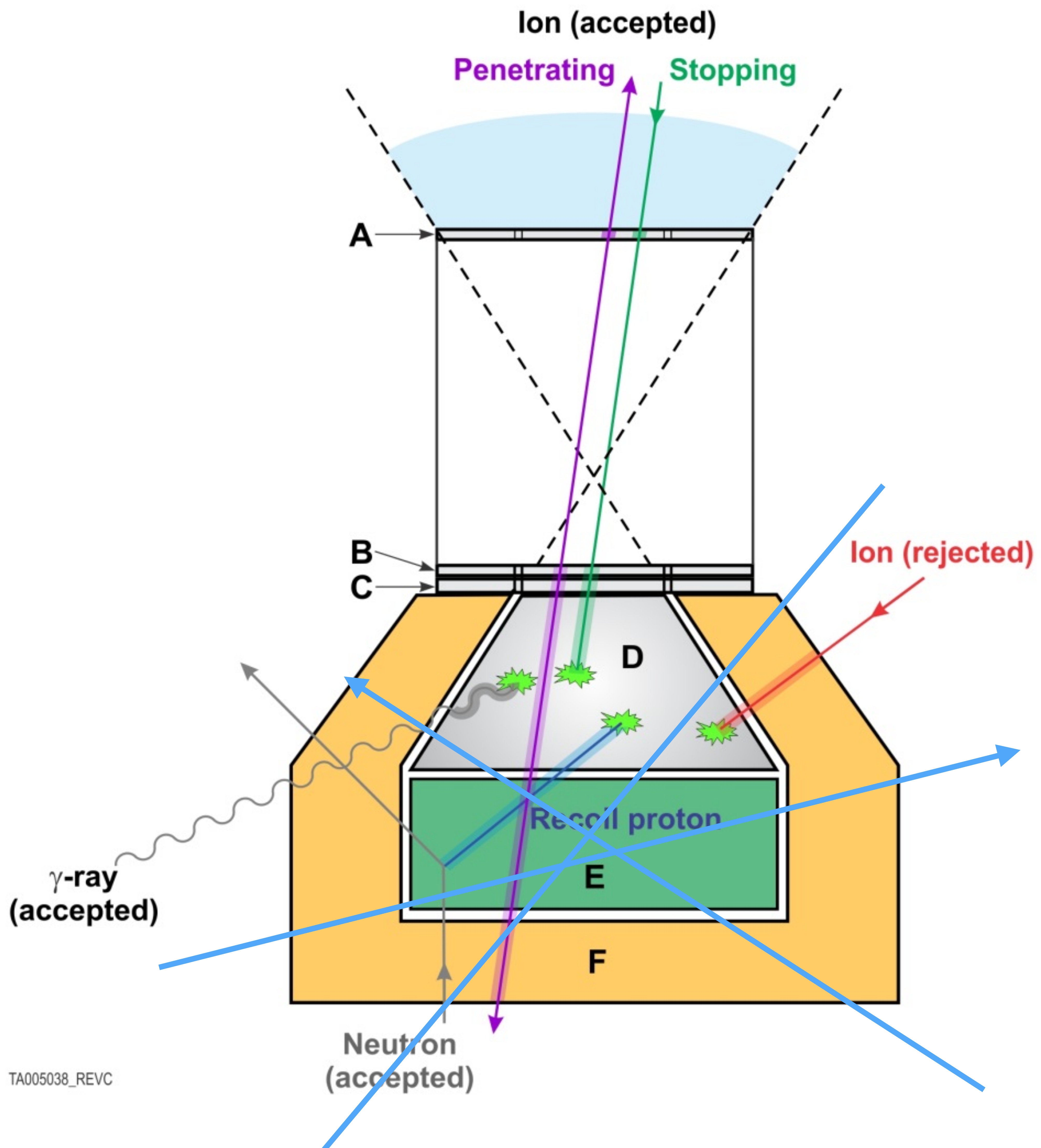


B Dosimetry



- B dosimetry trigger doesn't require any particular geometry, just any hit above noise.
- Dosimetry picks up charged particles from all directions, as well as γ-rays and neutrons with limited efficiency.

E Dosimetry



- RAD reads out all E channels whenever there's a hit above threshold in EH and EL in coincidence.
  - EH and EL refer to high and low gains.
  - This coincidence criterion avoids spurious triggers when a γ-ray hits a single diode (rather than hitting the scintillator) and gives an apparent large energy deposit.
- Like B, the E dosimetry trigger doesn't require any particular geometry, just any hit above noise.
- Again, the dosimetry trigger picks up charged particles from all directions, as well as γ-rays and neutrons.
- E is more efficient for neutrons than B and less efficient for γ's.

Data Products

- RAD has two modes of operation:
  - **calibration** - all raw detector data are streamed out over USB.
  - **science (flight)** - all raw detector data are processed and/or analyzed online; results are stored in non-volatile memory (NVM).
    - Raw data is stored in the NVM at a prescaled rate of 2Hz.
    - Online analysis results are telemetered once per minute (i.e., cyclic), including the caution and warning alarm bit.
- Additionally stores/telemeters event rates and housekeeping information.
- Data packets and the stored data from the NVM are processed/analyzed by the Ground Analysis Software (GAS).

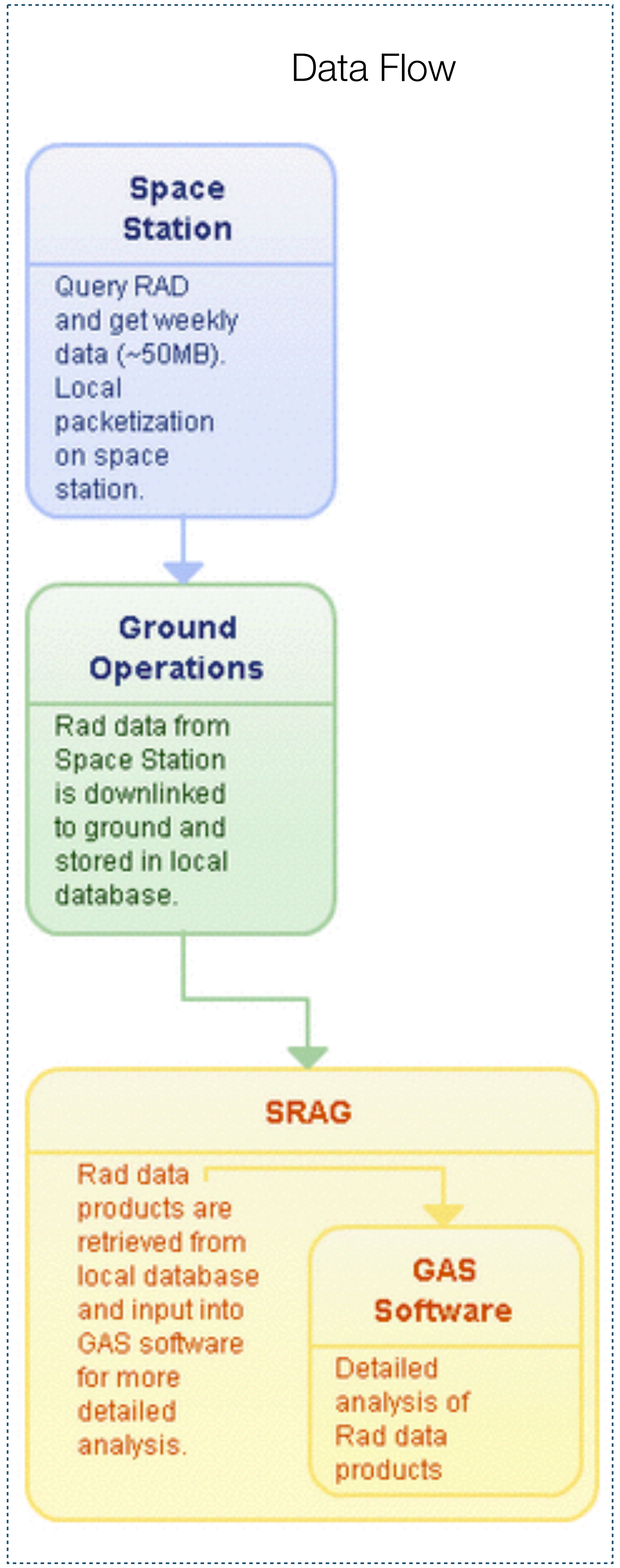
Item	Energy Range	Detector	Analysis
Proton Flux	20 - 34; 35 - 72; 72 - 122 MeV	CPD	Online (cyclic)
Charged Dosimetry	0.2 - 850 keV/μm		
Neutral Dosimetry and Spectroscopy	0.5 - 8 MeV (n^0)	FND	Both
	5 - 80 MeV (γ, n^0)		
Helium Differential Flux ($Z<3$)	30-200 MeV/n	CPD	Offline (GAS)
Heavy Ion Flux ($Z\geq3$)	100-200 MeV/n		
LET_{Water}	0.2 - 850 keV/μm		

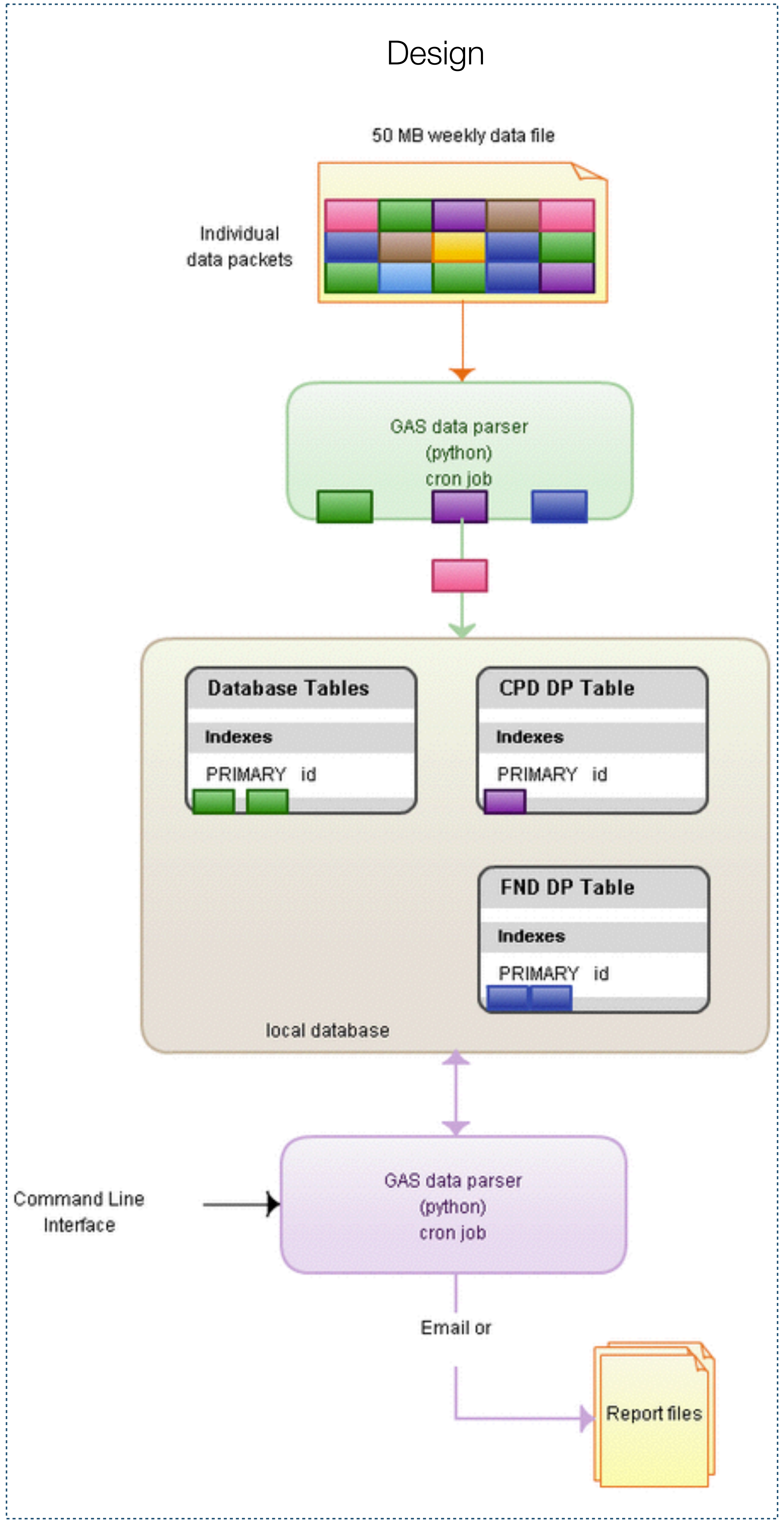
Data Acquisition

- The concept of operations for ISS-RAD onboard ISS is that it will *only* operate in science mode, where data is partially analyzed on-board the detector.
    - The data structure is highly complex but is well-documented & described.
    - There are 45 data packets in this mode; mostly used for data analysis.
    - We anticipate ~50MB/week of science mode data; RAD is capable of storing ~4GB of data in non-volatile memory.
- We have two independently developed codes that can read the data; in operations we'll use the Ground Analysis Software (GAS) developed by Big Head Endian, which is used to both process and analyze data.

Ground Analysis Software (GAS)

- GAS is a robust processing and analysis framework written in Python that uses MySQL (or Maria) for its database storage backend.
  - ROOT is also mixed into the code and was used for validation and verification.
- Apart from ISS-RAD data, we have the ability to incorporate ISS position into many of RAD's data packets.
- GAS has a simple and scriptable command-line interface and a simple API.
  - Easy to automate.
  - Fairly easy to extend.

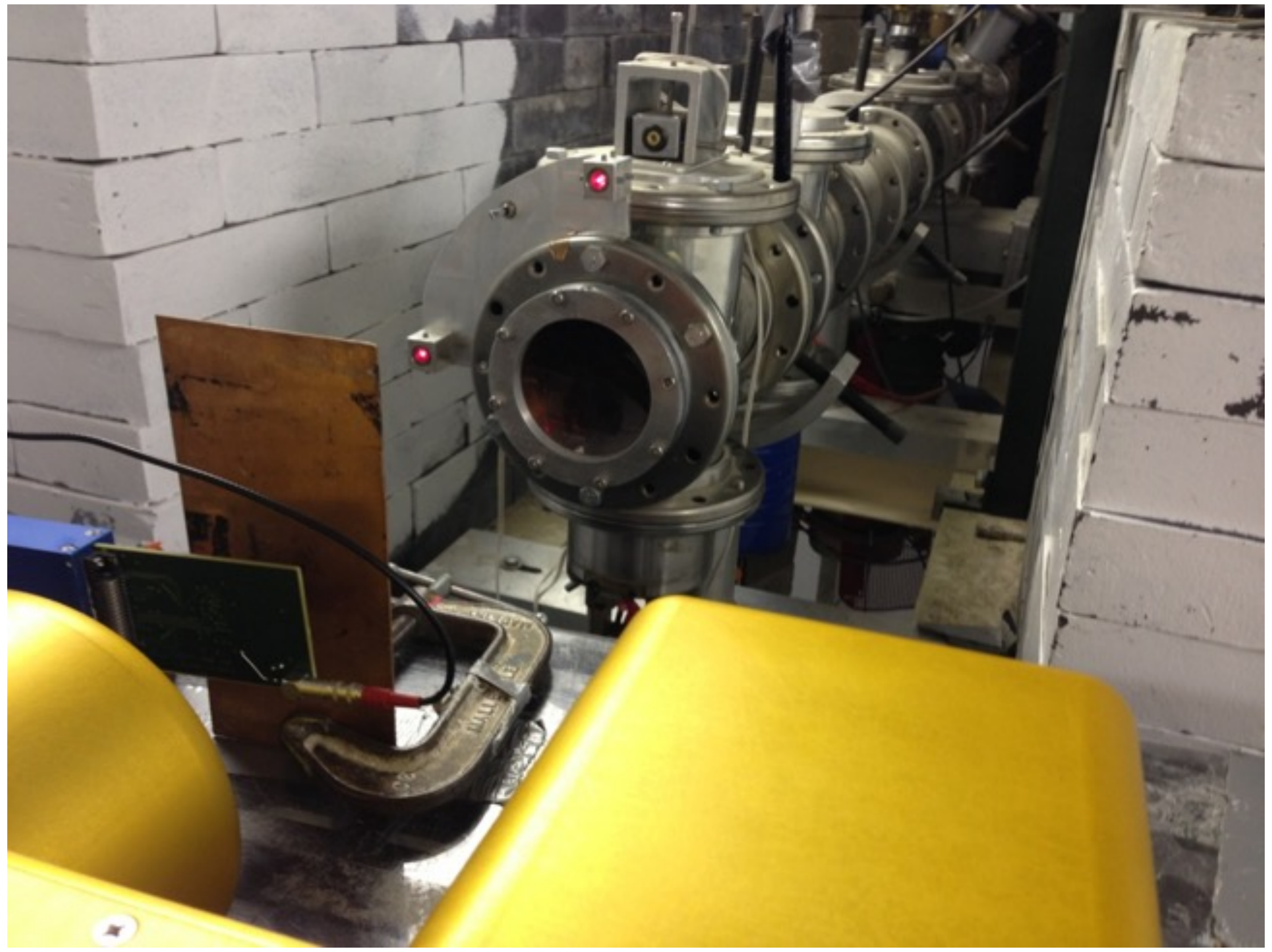




Detector Calibration

RSH Calibration

- Flight model sent to NASA Space Radiation Laboratory (NSRL) and Indiana University Cyclotron Facility (IUCF) for multiple calibration campaigns in 2014.
- Hardware responsiveness tested using ^{137}Cs (JSC) and O at ~10^5 ions/spill.
  - Surpassed expectations when in science mode.
- AmBe for neutral particle measurements.



RSH Calibration Campaigns

Beam Type	Month	Facility	Purpose
p, C, Si, Fe	April x 2	NSRL	Calibration and requirements testing
p, He, Fe	June		
p	August	IUCF	Proton calibration and verification
p, O	October	NSRL	Extra calibration

RSH Sub-detectors

A1, A2, B, and C:

- Standard SSDs with one electron/hole pair correlation to each 3.6 eV of energy deposited - ΔE.
- Each one is 300μm thick.
    - In the resulting Landau/Vavilov distributions, ΔE of a MIP:
        - 118 keV (mean)
        - 77 keV (peak)
- B is used to report dosimetry cyclically.

D, E, F1, and F2:

- Scintillators with non-linear light output with respect to the energy deposited.
- Scintillation light is shared between two readout diodes in D and E; results in position dependence of the signals.
- E is also used to report dosimetry cyclically.

Si SSDs: A1, A2, B, C

- Each detector is read out by four VIRENA (Voltage-Input Readout for Nuclear Applications) channels - Low, Medium, High, and Ultra-high.

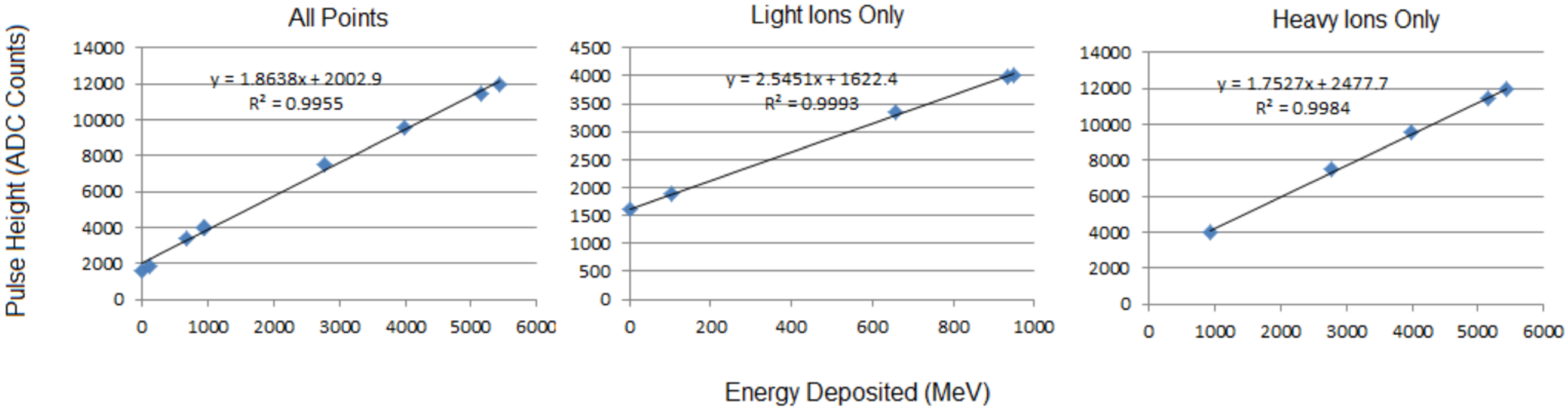
Detector	Low Gain	Medium Gain	High Gain	Ultra-High Gain
A1, A2, B	x1	x8	x1	x8
C	x1	x4	x1	x8

  - Note: The VIRENA has 36 readout channels; only 32 are used.
- The CPD uses unconventional units for ΔE - 2 keV units; e.g., the firmware would report a ΔE of 100 keV as 50 units.

Scintillating Calorimeter: D

- MSL-RAD used MIPs for calibrating the scintillator readout, for which the quenching of light is minimal.
  - Same philosophy was applied to ISS-RAD.
- Calibration was primarily focused on calibrating DH first, high-energy data was used in the resulting analyses.
  - Motivation: more beam runs in which its signal stayed on-scale, while DU saturated.
  - D-penetrating data spanned multiple energies between $2 \leq Z \leq 14$.
  - Gain studies between DH and the other 3 gains yield good relationship results within a few percent; typical of the VIRENA.

D - Penetrating v. Stopping



- Slope of the calibration depends on the choice of ions; an effect of quenching.
- We end up with two possible calibration curves, one for light and stopping ions and the other for heavier and penetrating ions.
  - MSL is primarily interested in penetrating ions and uses a fit with heavy ions.
  - ISS-RAD will use the light ion calibration curve for our data products.
    - This essentially covers stopping protons and ^{4}He with ΔE up to 500 MeV.

D for Protons

- NSRL has a beam structure which is generally throws off the dead time calculations used when RAD is in science mode.
- We went to IUCF and recalibrated D for stopping protons.
    - C. Zeitlin analyzed the data overnight and in realtime, producing new EVIL tables for us on the fly.
        - In the end we suffered from very wide energy distributions at low energies.
            - Solution - increase the number of bins in the histogram and the width of the energy flux bins.
    - D is very dense, around 20 g/cm^2, and will stop protons with energies between between 18 and 120 MeV.

Scintillating Detector: E

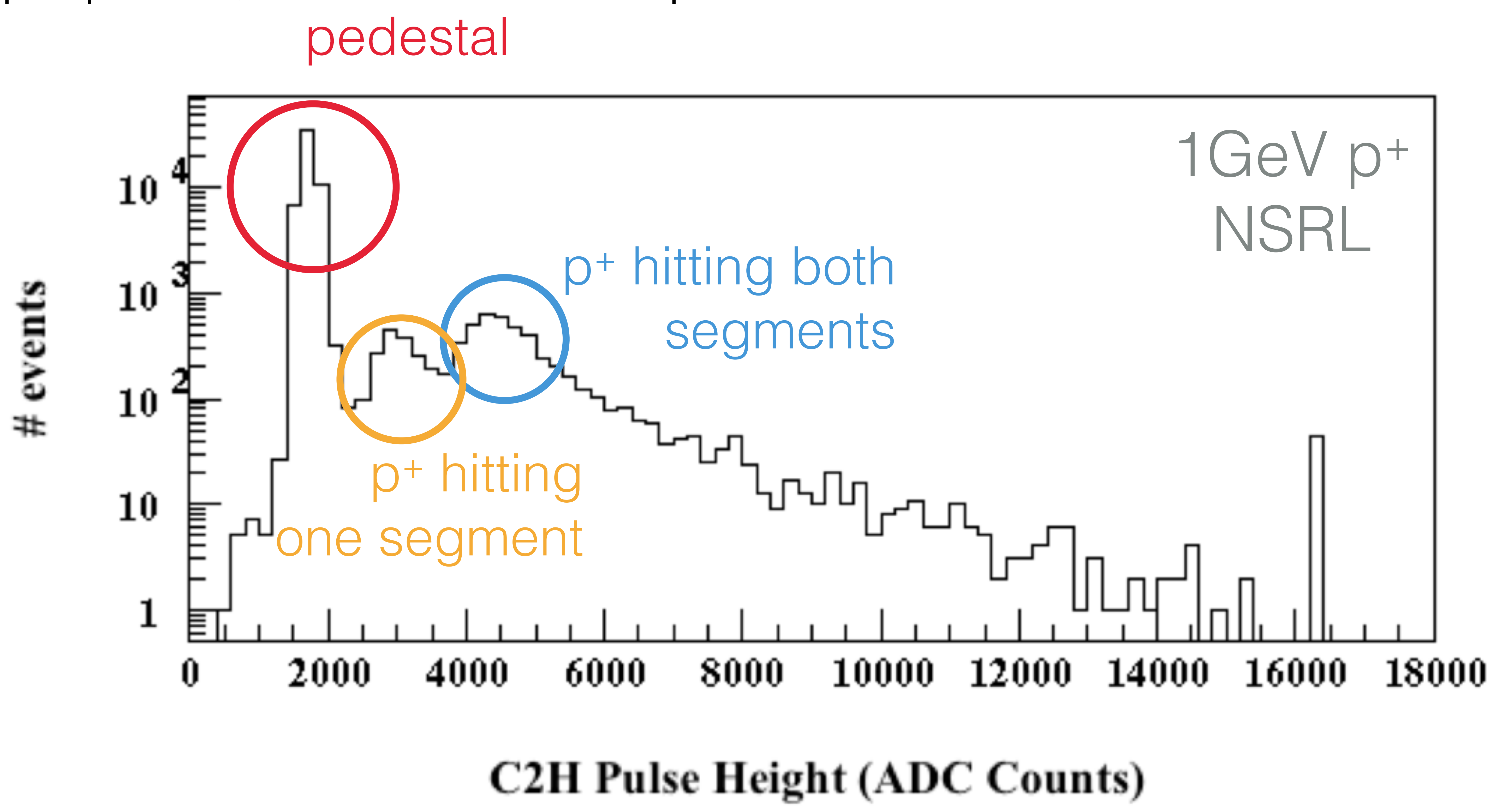
- The E detector only presents only 1.8 g/cm^2 and will stop protons with energies between 123 and 134 MeV.
  - The large majority of particles that traverse E will therefore be penetrating particles, and so (unlike D) there is little or no question about which set of calibration parameters should be used.
- Calibration techniques are similar to D.
  - Gain factors were calculated using a mix of high-energy ions similar to that used for the DH penetrating particle calibration.

Anti-coincidence: C2, F1, F2

- Primarily used for veto logic for neutral particle analysis; for that purpose the most important aspect of each is the slow token threshold setting.
- The Level 2 trigger defines a neutral particle event in E as being an energy deposit above threshold in E with no corresponding hits in B, C, C2, F1, or F2, based on the slow token mask.
  - Thus the slow threshold setting affects the results at the hardware level.
    - An incorrect (too high) setting could allow in contamination from charged-particle events, or could (if it is too low) cause valid neutral particle events to be rejected.
  - Though the emphasis for these channels is on their thresholds, the Level 3 logic does make use of calibrated energy deposits in these detectors for analysis of neutral-particle candidate events.

C2 Calibration

- C2 consists of two segments of the B diode wired together with one segment of the C diode (Si); calibration is straightforward, the relation between pulse height and deposited energy can be accurately calculated from first principles.
- For calibration purposes, we use the 2-hit peak in beam data.



F1, F2

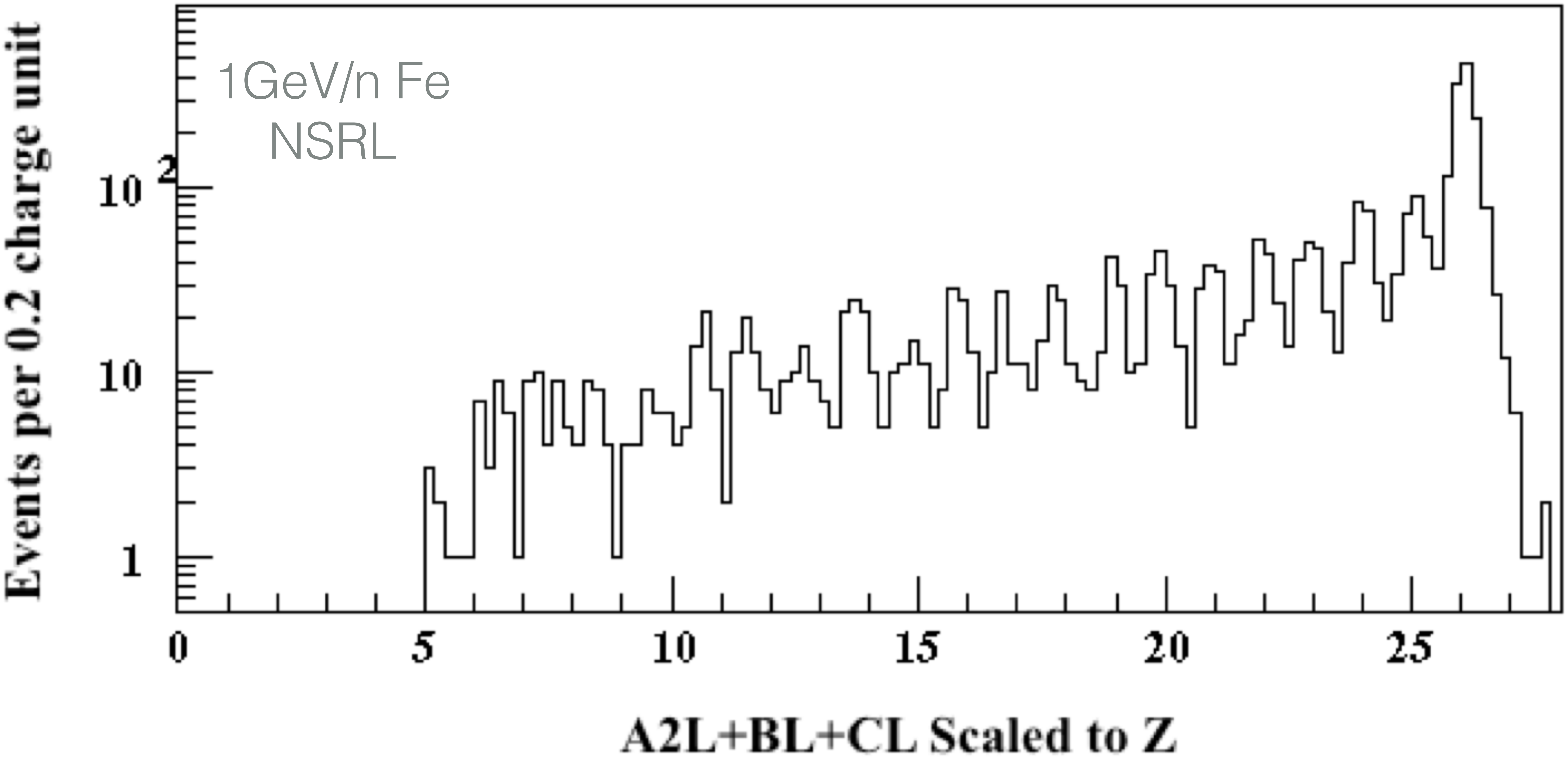
- In the plastic anti-coincidence system, F1 is the upper, barrel-shaped part; F2 is bottom part.
- F2 is expected to have calibration nearly identical to that of the E high-gain channels.
- The gain of F2L is about equal to that of EH, and that of F2H should be about the same as EU.
    - Both detectors are made of the same material and are 1.8 cm thick; both have 1 pF feedback capacitors in their preamplifiers and both have a first-stage shaping amplifier with x16 gain.
    - Beam data can be used to check the gains because high-energy charged particles deposit nearly equal energies in the two detectors as they pass through.
- F1's readout channels are not as easy to calibrate in the usual beam configuration, since most particles do not hit F1 and even those that do have unknown paths through the plastic.
    - However, the F1 channels are expected to have the same calibration as the corresponding F2 channels, because the detectors are composed of the same material in the same thickness, with identical nominal gains in the electronics.
    - Therefore, the table entries for the F1L and F1H gains have been set equal to those for F2L and F2H, respectively.

Charge Resolution

Requirements

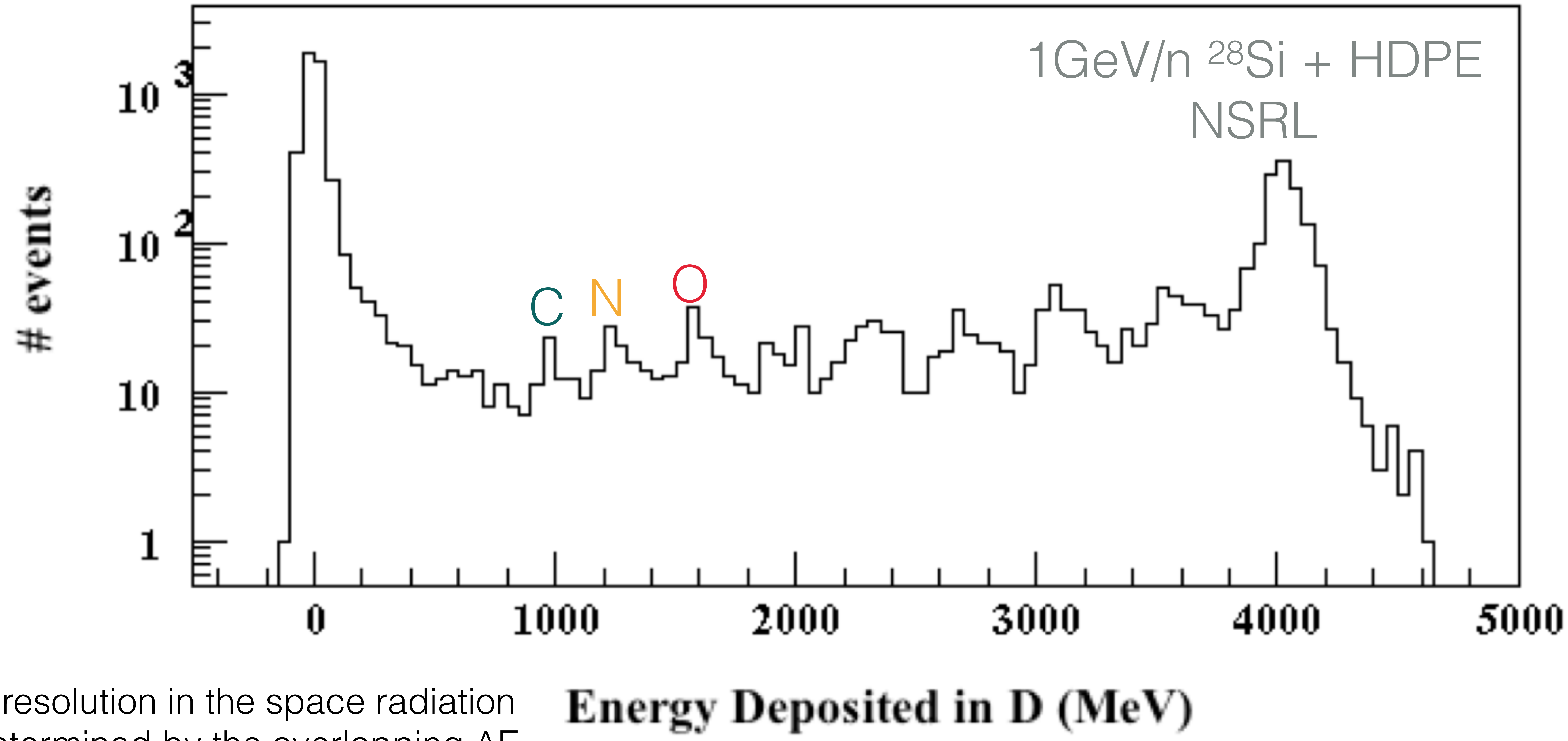
- The CPD is required to provide data with charge resolution of ±2 charge units for particles with energies above 500 MeV/n.
- Beam data taken at the NSRL demonstrate that the inherent resolution of the CPD exceeds this requirement for monoenergetic particles.
- In flight, there is a fundamental, unavoidable limitation on charge resolution of about ±2 charge units that has nothing to do with intrinsic resolution.

Intrinsic Resolution



Intrinsic resolution of the system for monoenergetic ions can be seen to be well under 1 charge unit.

Expected Resolution

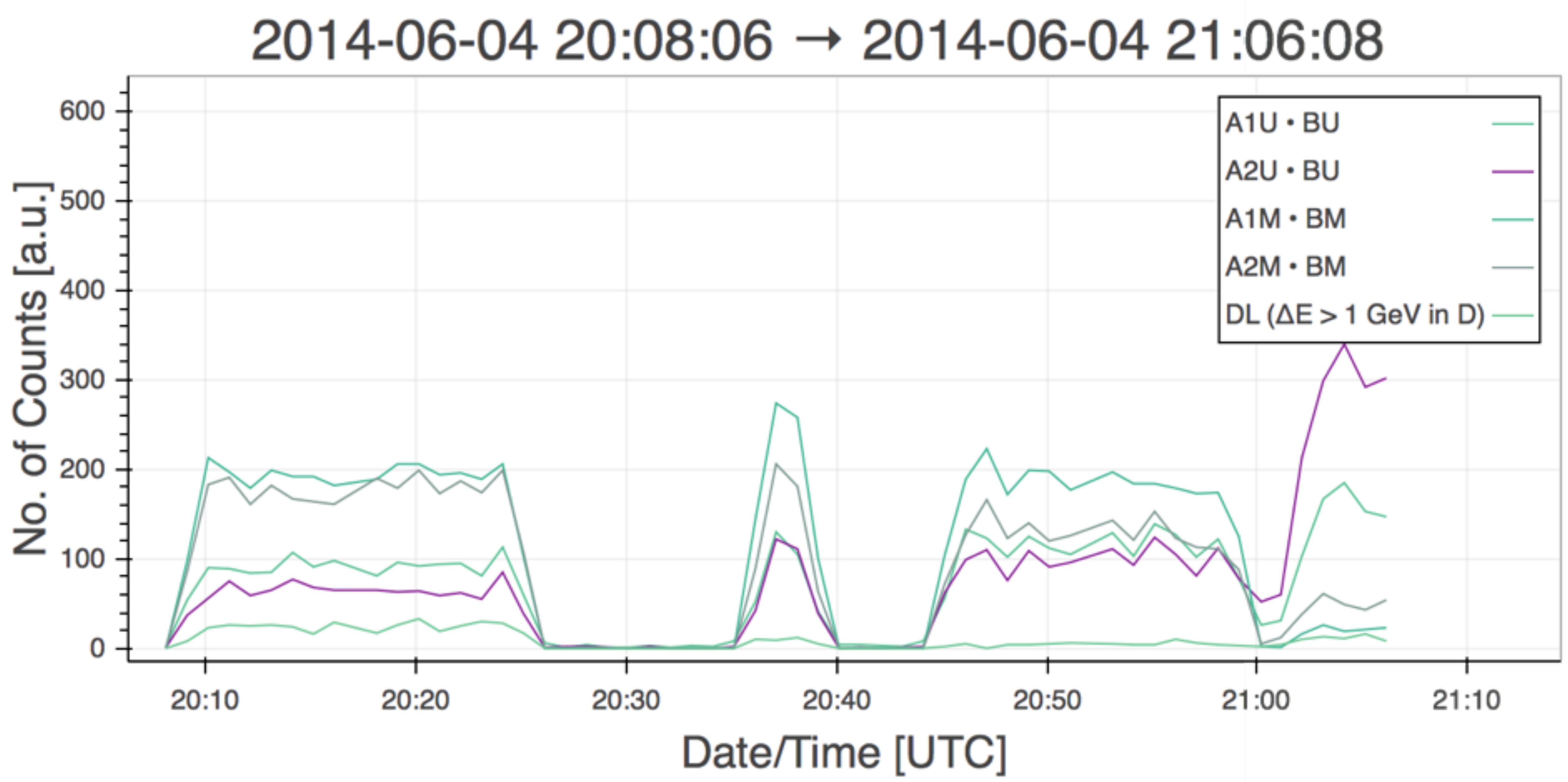


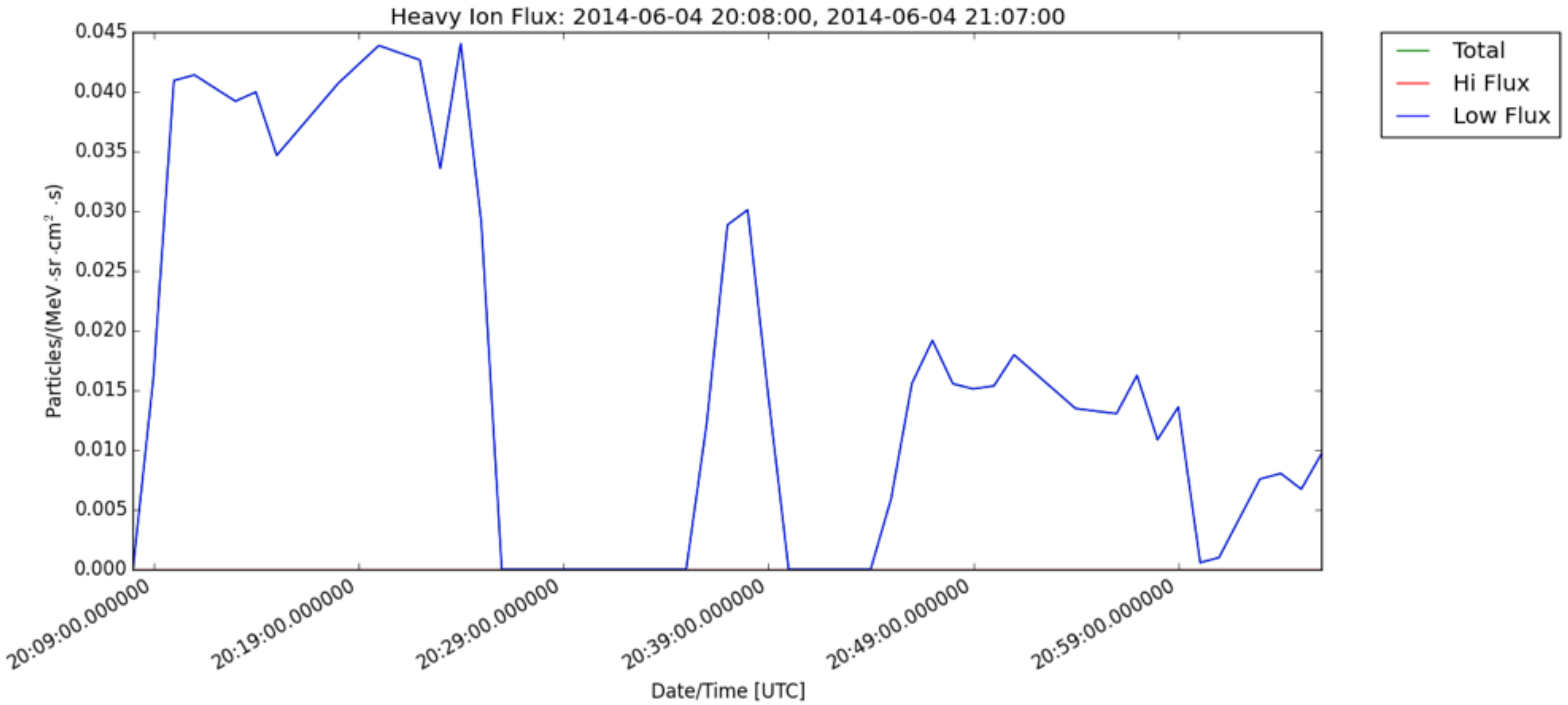
- Limited charge resolution in the space radiation environment; determined by the overlapping ΔE distributions of different ions at different energies, but we are within the allotted 2e units.

Results from Ground Analysis Software

Heavy ion flux: Fe, 200 Mev/n

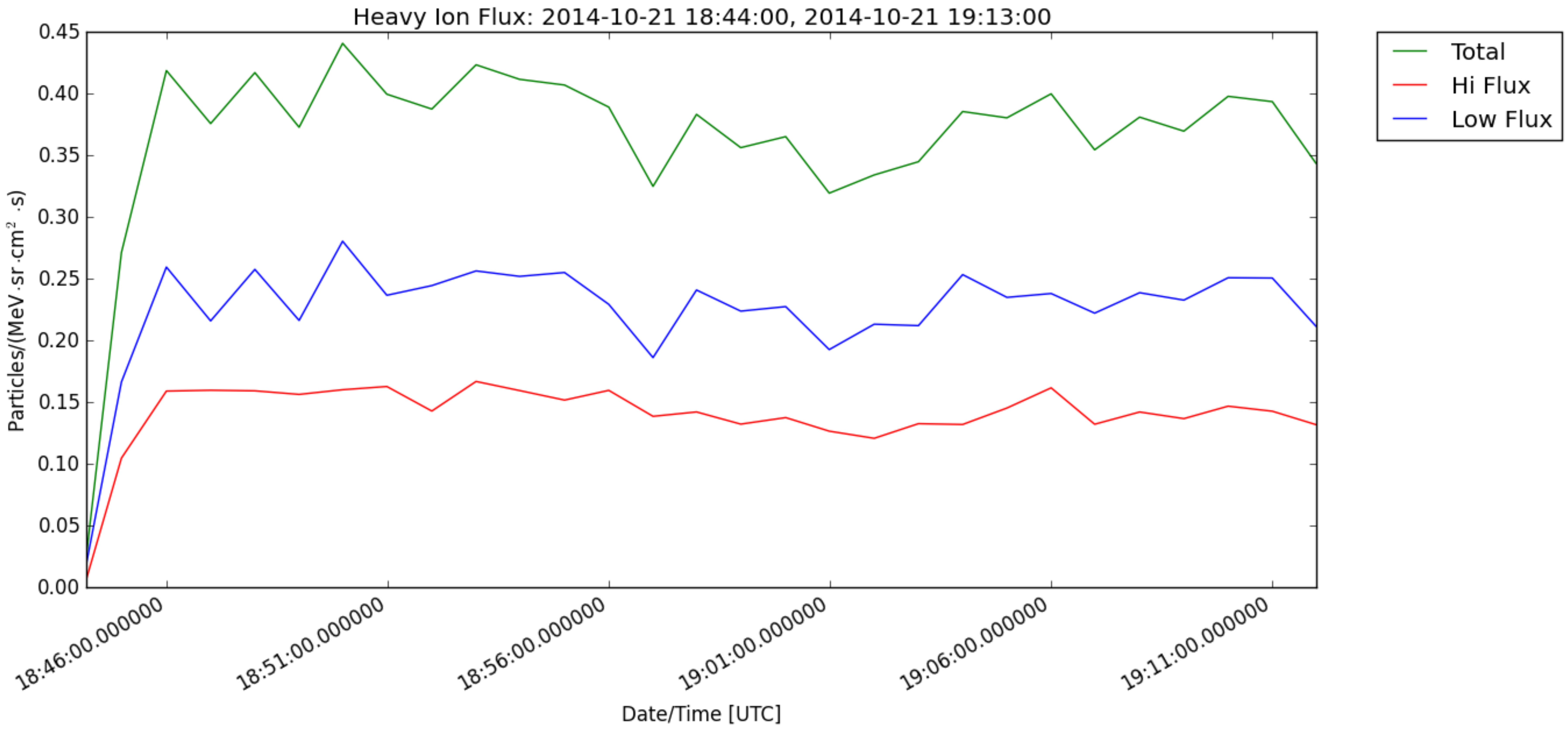
- Above - Level 2 trigger matches from a run at NSRL in June 2014.
  - The drop in rates around 20:24 and 20:38 are due to beam-accesses.
  - Note that after each access, the beam intensity dropped.
- Below - heavy ion flux (from CPD).
  - Accurately reflects the environment and the ions recorded by the CPD.





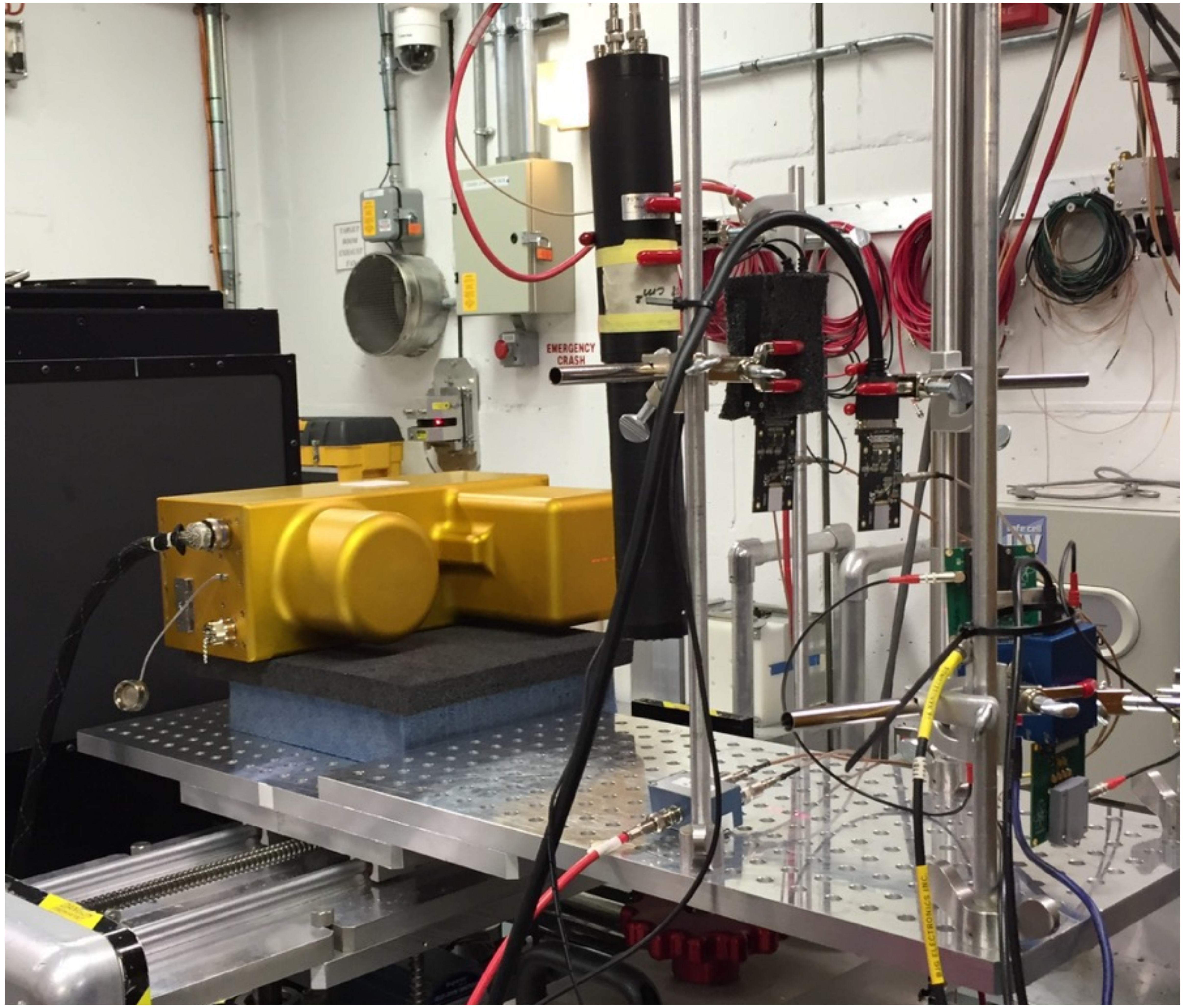
Heavy ion flux: O, 200 Mev/n

- Another heavy ion run taken at NSRL in Oct. 2014, much more stable environment; results are good.



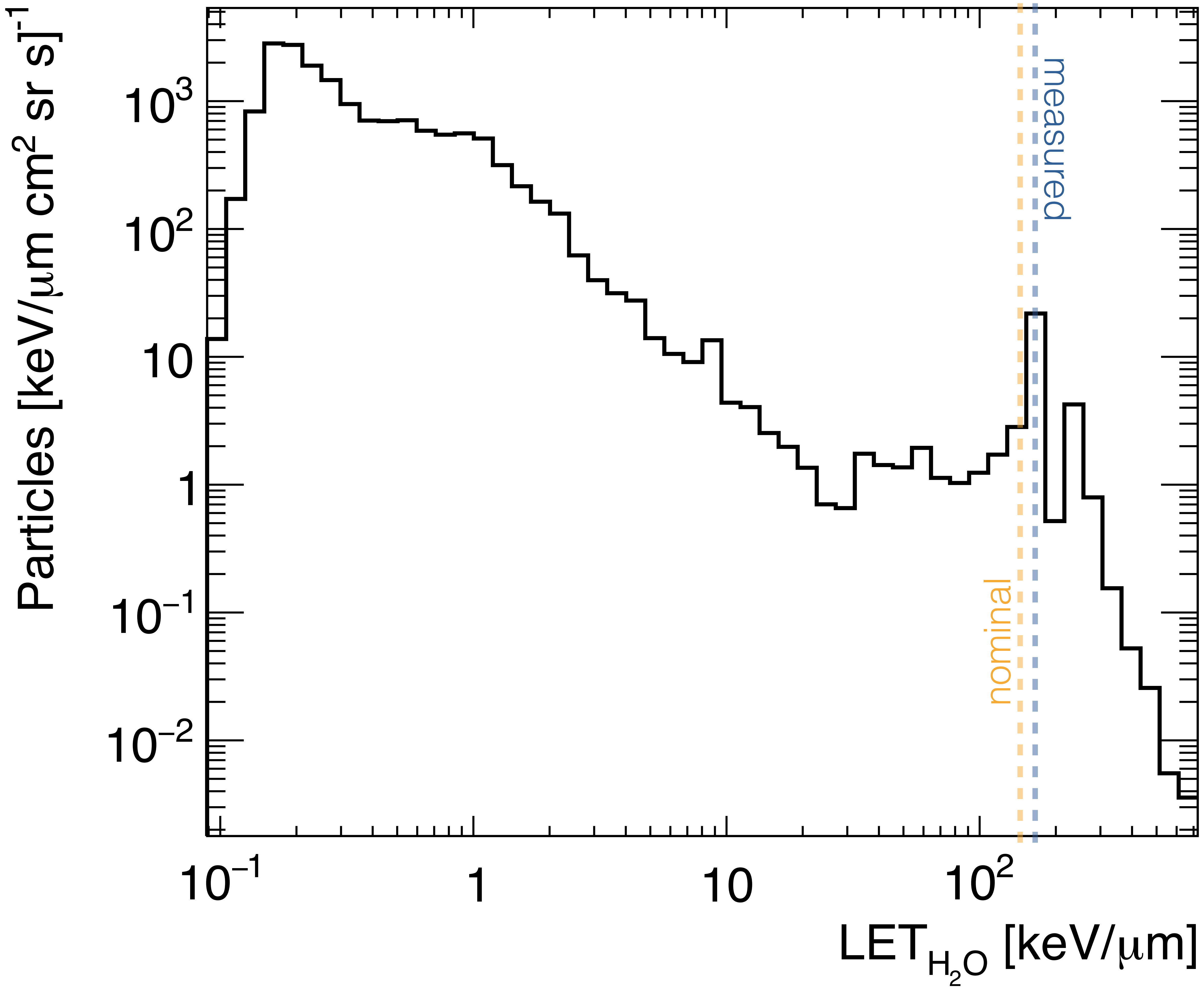
LET$_{Water}$ Spectra

- During a calibration run, RAD usually has one or several Timepix units in front of the CPD (not necessarily directly in front).
    - We run parasitically off each other to share beam time at various facilities.
    - There are four Timepix units in the picture to the right.
- The direct effect is that ISS-RAD measures a dE/dx larger than the nominal LET for an incident beam.
    - In some cases, the beam was not-clean and the “conversion” to differential spectra makes the distribution appear dirtier than it actually is.

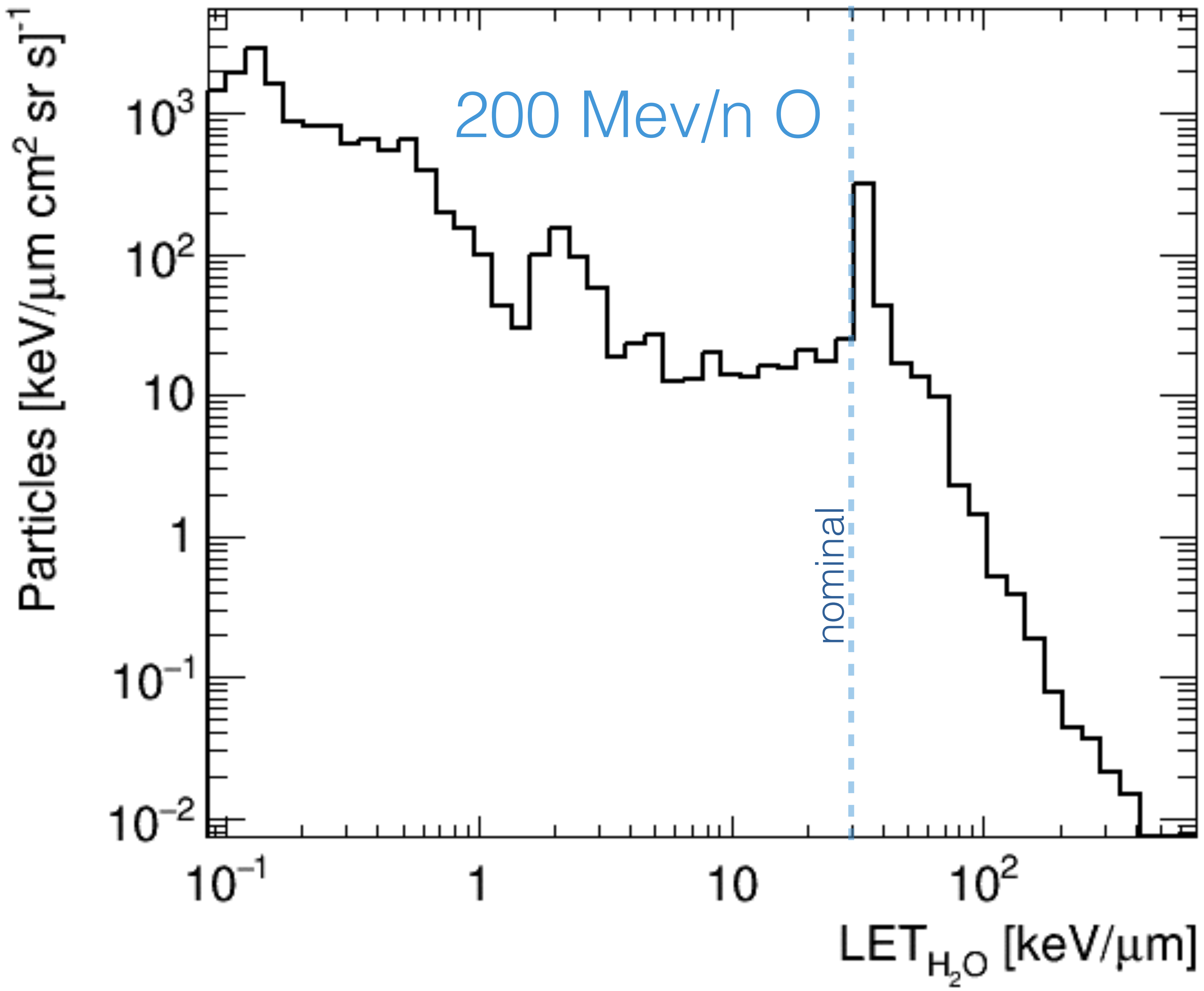


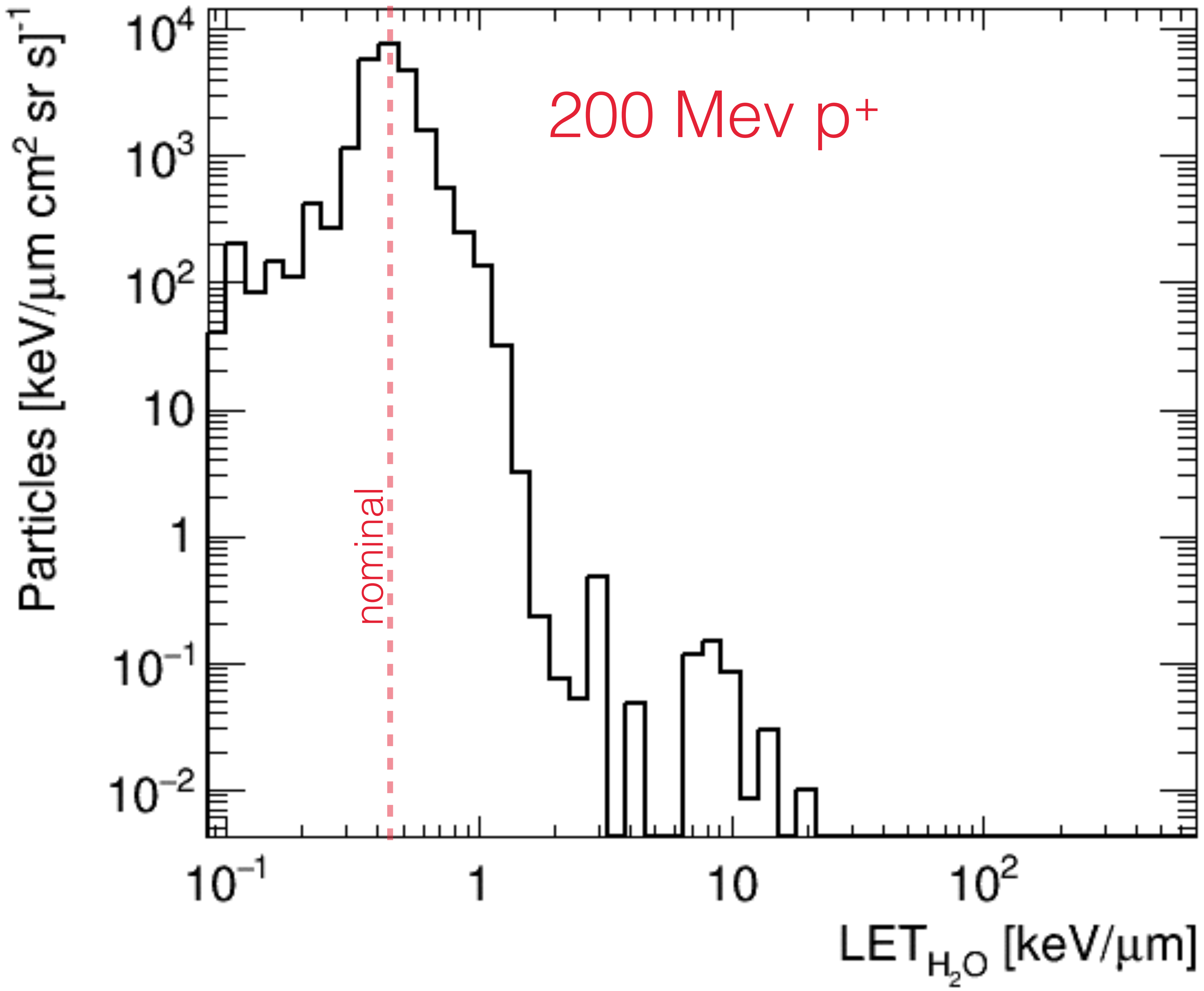
LET_{Water} Spectrum: Fe, 1 GeV/n

- For 963 MeV/n Fe at NSRL:
  - Nominal LET_{Water} ~ 151.6 keV/μm.
- We measured LET_{Water} ~167.3 keV/μm.
  - Bin is [152.8, 181.7) keV/μm.



LET_{Water} Spectra



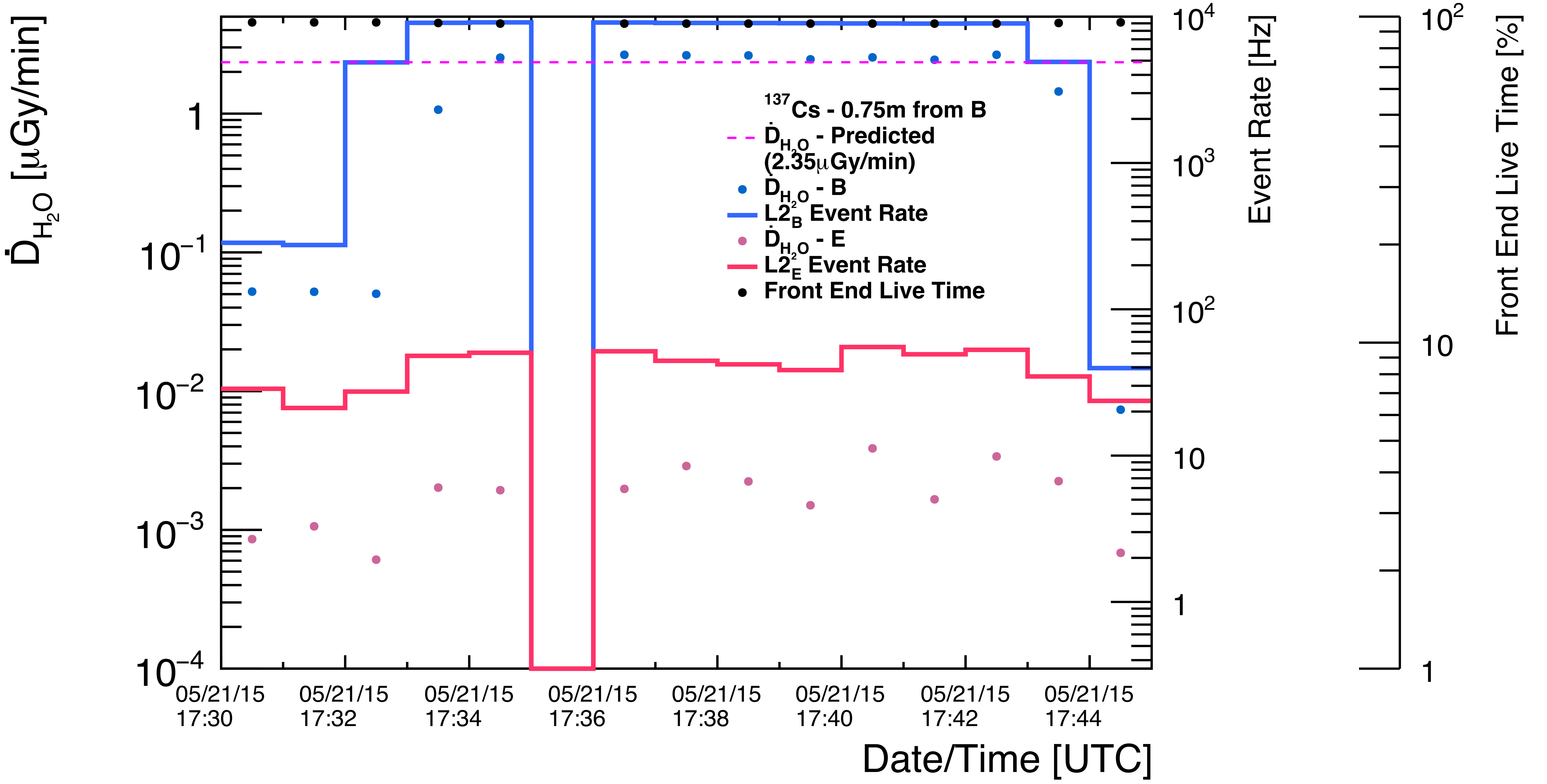


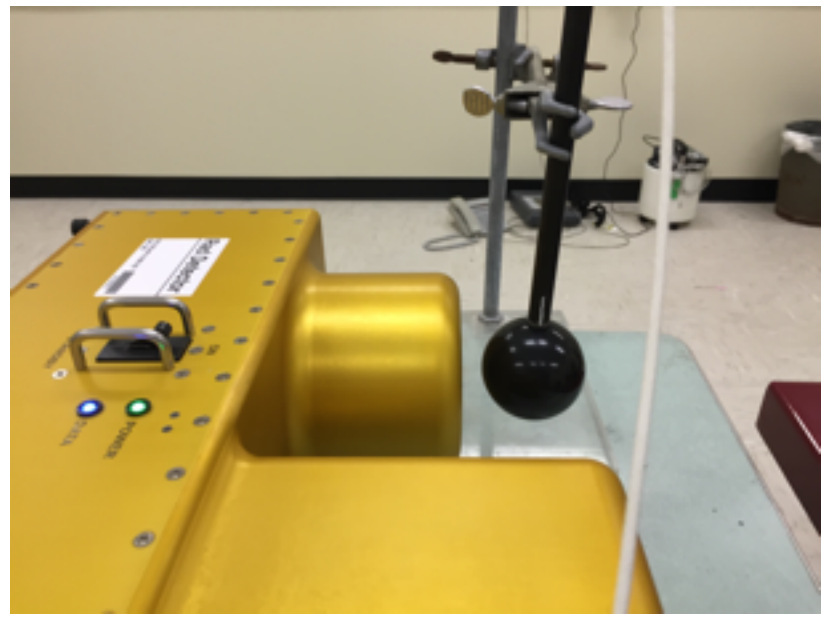
Nominal LET_{Water} ~30 keV/μm.

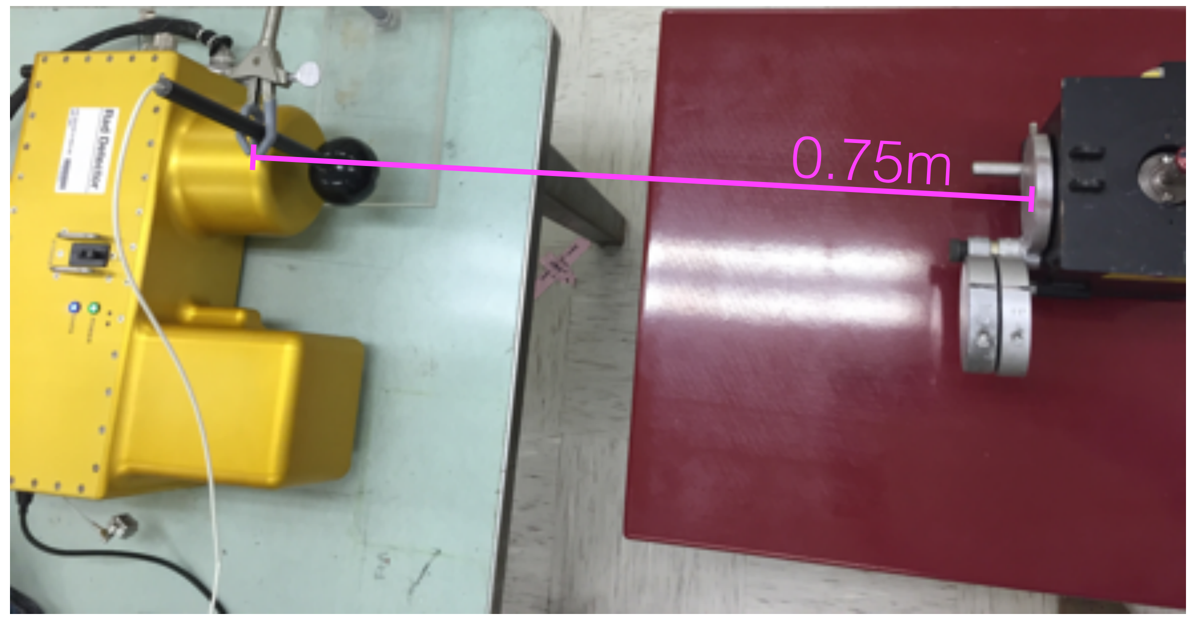
Nominal LET_{Water} ~0.46 keV/μm.

^{137}Cs on CPD Dosimetry

- For our setup, the expected dose rate in B, calculated using measurements from a calibrated ion chamber, should be ~2.35μGy/min.
  - ISS-TEPCs calibrated in identical fashion.
- On average, B measured ~2.5μGy/min; we see excellent performance.
- E performs as expected.
  - ^{137}Cs decays to 662 keV γ's.
  - E has a threshold of ~2MeV; which is above the edge of noise.
  - Many particles stop in BGO.
- Health-wise:
  - Average front-end live rate is 97.7%.
  - L2 dosimetry counters show that measurements are within hardware capabilities.







Summary

- The flight model of ISS-RAD should have gold status on United Airlines from its many calibration campaign trips to NSRL, IUCF, and PTB. Alas, it does not.
- Previous experience with MSL-RAD has been incredibly useful in calibrating the RSH, which was calibrated primarily using beam data and trial and error.
  - Calibration results reflect on our current best estimates; we are able to adjust or refine parameters after flight data have been received and analyzed.
- RAD measures omnidirectional doses in both Si and plastic.
  - They track each other well considering the statistical noise in the silicon measurement.
- We are ready for ISS-RAD!

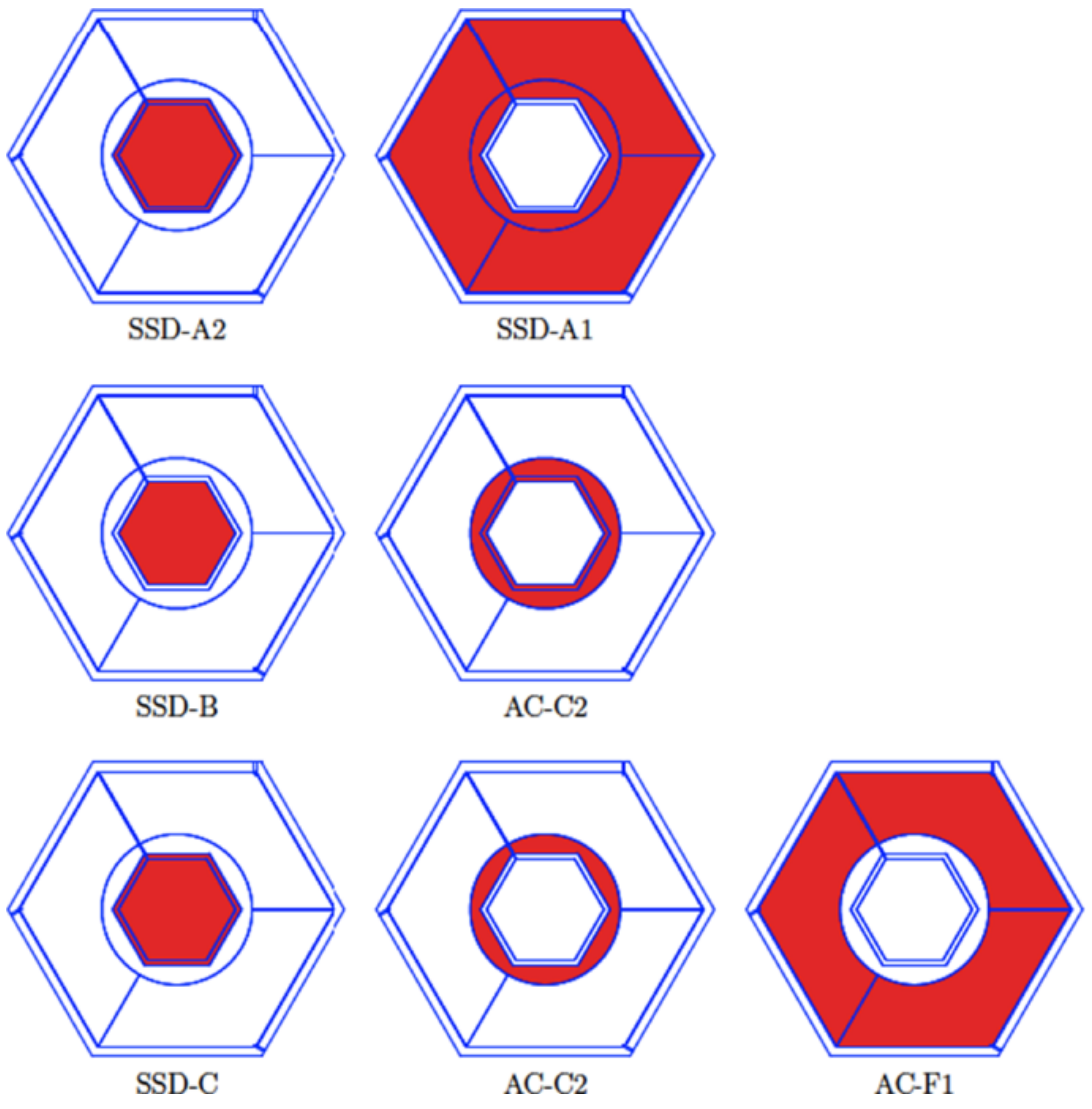
References

1. C. Zeitlin, *Calibration and Configuration of ISS RAD*. 16343 - CC - 0.
2. R. Rios, *Validation and Verification of the Radiation Assessment Detector's Ground Analysis Software*. SRAG-INT-RAD-2015-001.

Additional Material

Position Sensitivity and Triggering

L2 Trigger Matches	Description	Information
0	A1U·BU	A1 histogram
1	A2·BU	A2 histogram
2	A1M·BM	A1 histogram
3	A2M·BM	A2 histogram
4	BU	B dosimetry
5	EU·EN	E dosimetry
6	EU·EN·!AC	E histogram
7	DU·DN·!AC	D histogram
8	EU·EN·DU·DN·!AC	DE histogram
9	DL (ΔE>1 GeV)	Heavy ion
10	Penetrating charged particles.*	
11	Stopping charged particles through A1.*	
12	Stopping charged particles through A2.*	
13	!F1·!F2·!E·!D·B	Stopping particles in B or C; neutral in B.*
14	Event count with fast but not slow triggers.	
15	Catchall	



Signal Processing in the Radiation Assessment Detector for MSL - Stephan Böttcher

* - Counter only no readout.

Proton Flux Bins and Dosimetry Conversion Factors

Proton Flux Band	Energy Range [MeV]	Combined E/G Factor	x-bins
1	20 - 34	12.57	1 - 5
2	35 - 71	32.33	6 - 9
3	72 - 122	44.9	10 -12

Tissue equivalent conversion factor for B dosimetry is 1.23

γ, n^0 Products: AmBe

- Neutral data are analyzed by software written by Jan Köhler; very similar to MSL-RAD's analysis software.
- Here are the results using AmBe collected at PTB Apr. 2015.
  - No high-energy γ's were measured by CPD.

Data Product	Result
n^0 absorbed dose	0.00376451 ∓ 0.000587954 μGy
n^0 dose equivalent	0.0201704 ∓ 0.00482871 μSv