# NDX dose rate meters with extended capabilities: high dynamic range neutron dosimetry in the presence of strong photon radiation fields

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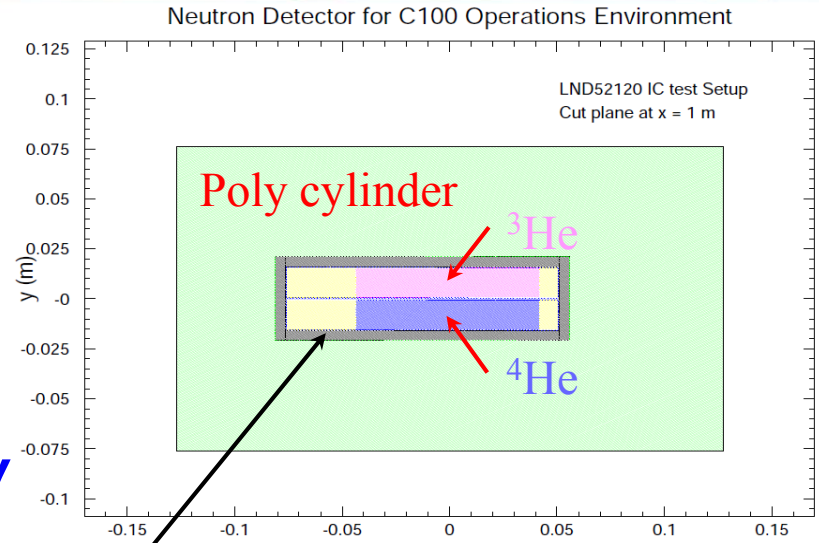
# Outline

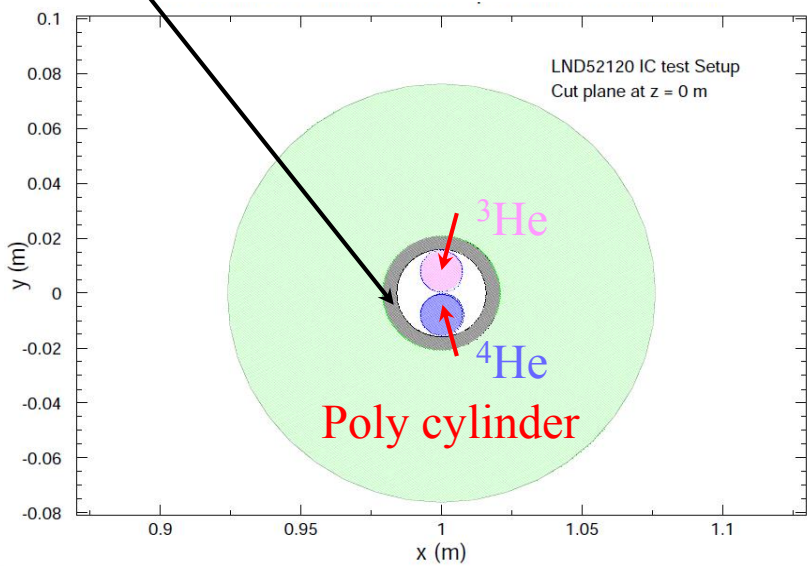
- Neutron dose rates inside High Energy electron accelerators:
  - Important for radiation safety, radiation damage, activation
  - Needed to evaluate and benchmark the simulation models
  - Difficult to measure due to overwhelming photon radiation
  - Monitors fail: radiation damage, high photon background
  - Passive dosimetry: lack of online monitoring capability, generally small dynamic range
- Need in the new neutron dosimetry techniques:
  - Online monitoring
  - Insensitive to photon background
  - Large dynamic range
- NDX: novel neutron dose rate meter with extended capabilities
  - High pressure ionization chambers filled with $^{3}He$ and $^{4}He$
  - Neutron moderator with Beryllium-loaded reflector / multiplier

# Original Idea (2016)

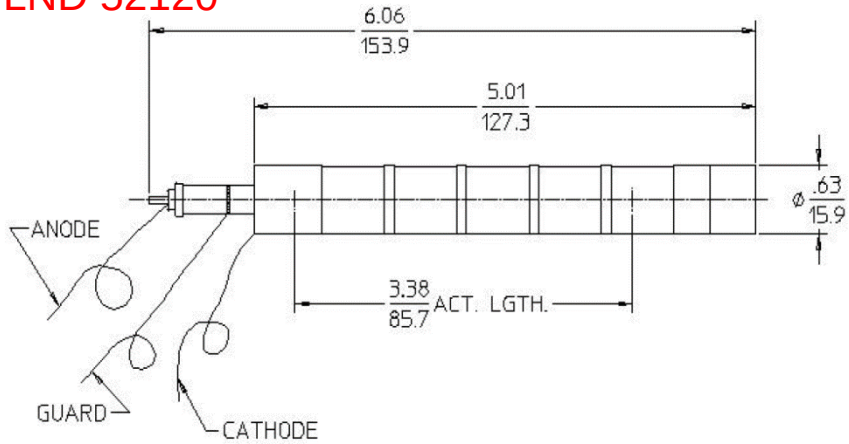
- Propose to use two small LND ICs, filled with $^3$He and $^4$He (1 atm gas pressure) placed together in a poly moderator, with lead or tungsten shield
- $^4$He and $^3$He: ~0.1 pA in 1 rad/h $\gamma$
- $^3$He: ~10 pA in 1 rem/h neutrons




Lead shield / neutron multiplier




LND 52120

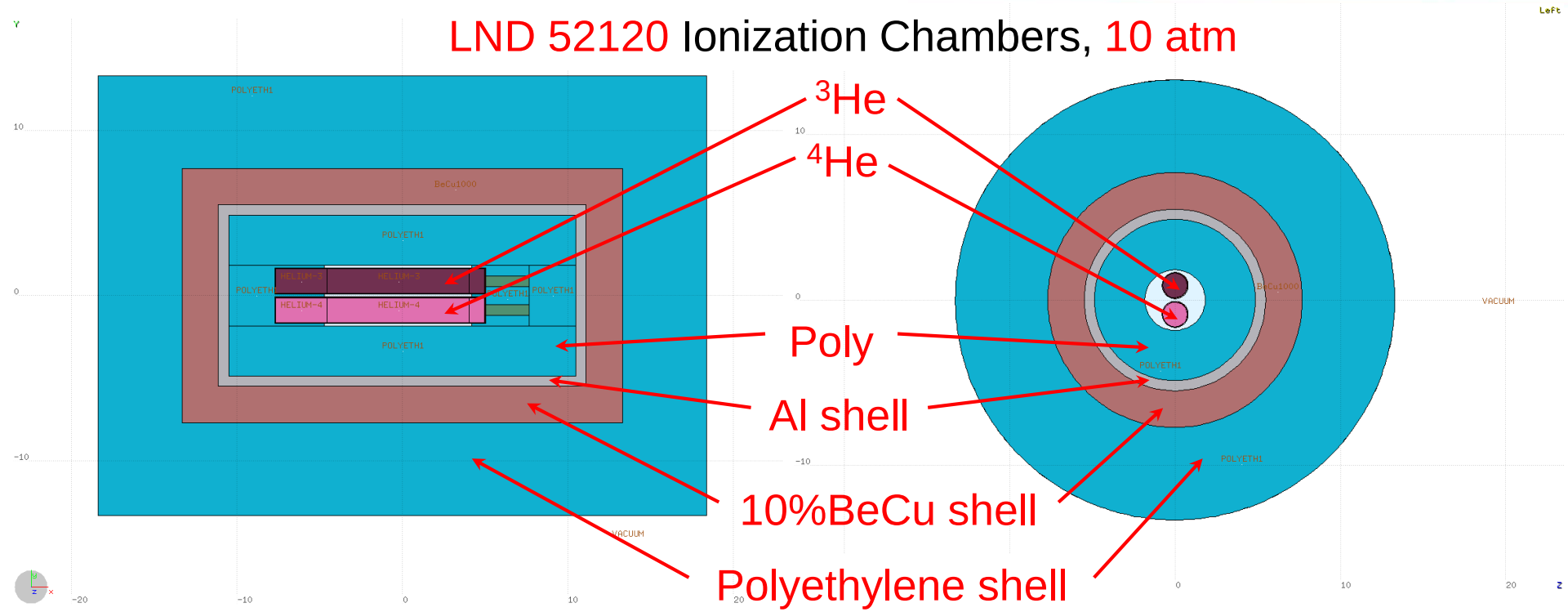


# Principle of Operation

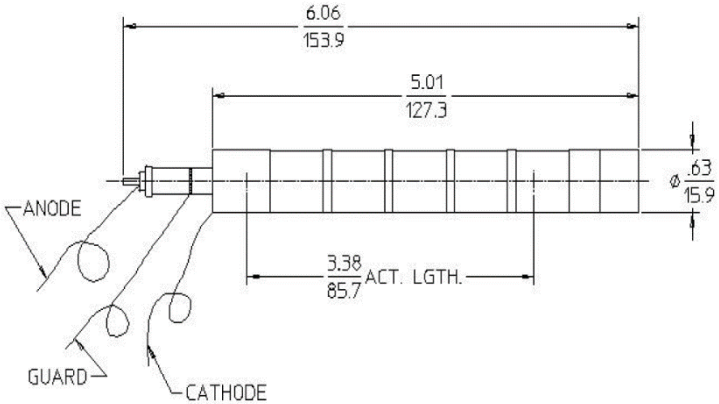
- Captured moderated thermal neutrons produce measurable current in the $^{3}$He-filled ion chamber, and photons produce small symmetrical response in both $^{3}$He- and $^{4}$He-filled ion chambers.
- A sensitive electrometer-type current readout needed, with a long-term stability in pA range.
- Using Beryllium-Copper alloy layer inside the moderator improves the linearity of the neutron energy response function. Beryllium acts as a "neutron multiplier" in the energy range of 10-50 MeV, where other neutron detectors lack response. At higher energies (~0.5-10 GeV) neutrons interact with Copper and improve the response due to the spallation reactions.

# FLUKA Model, Be Loaded Moderator

LND 52120 Ionization Chambers, 10 atm

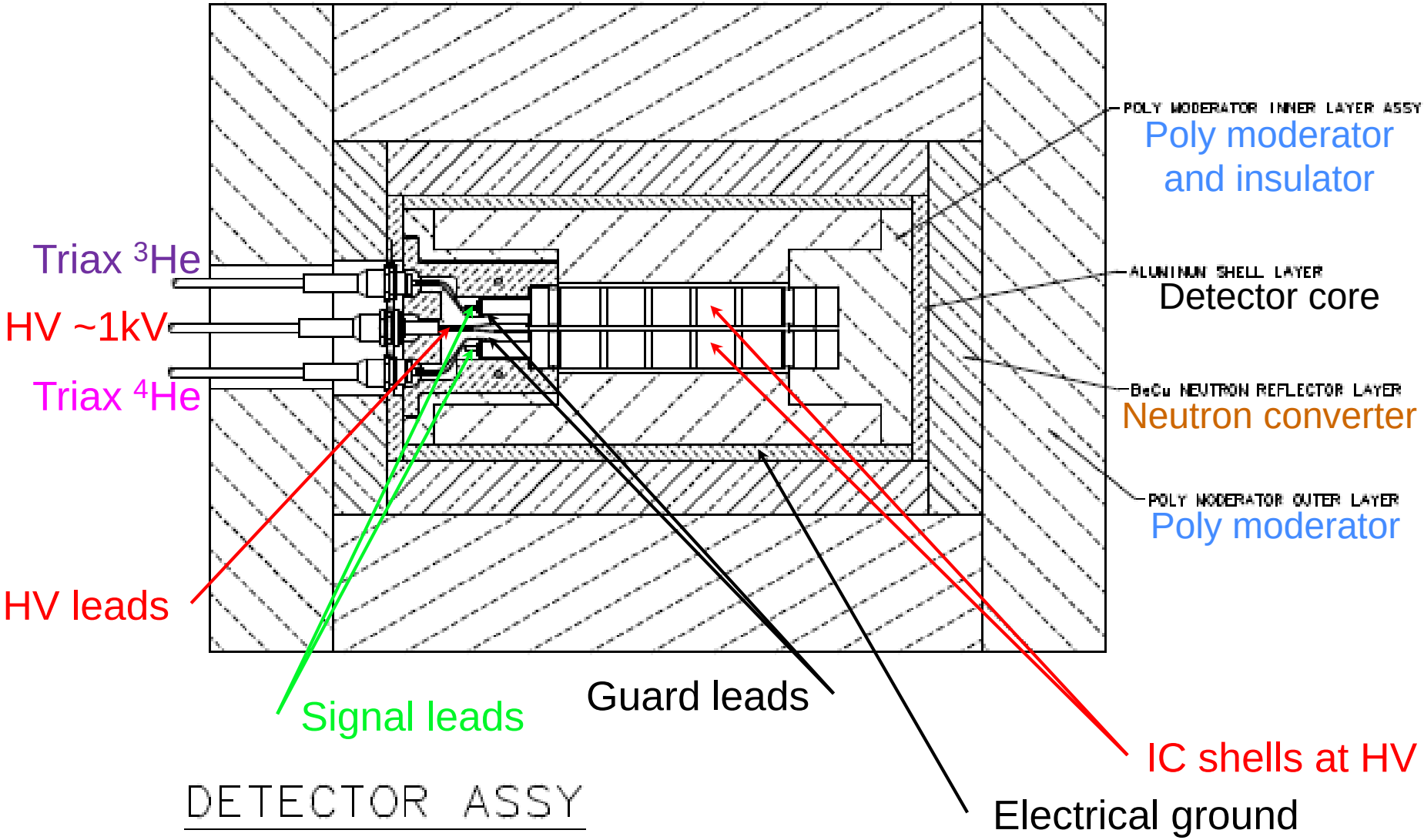



Cylindrical moderator assembly

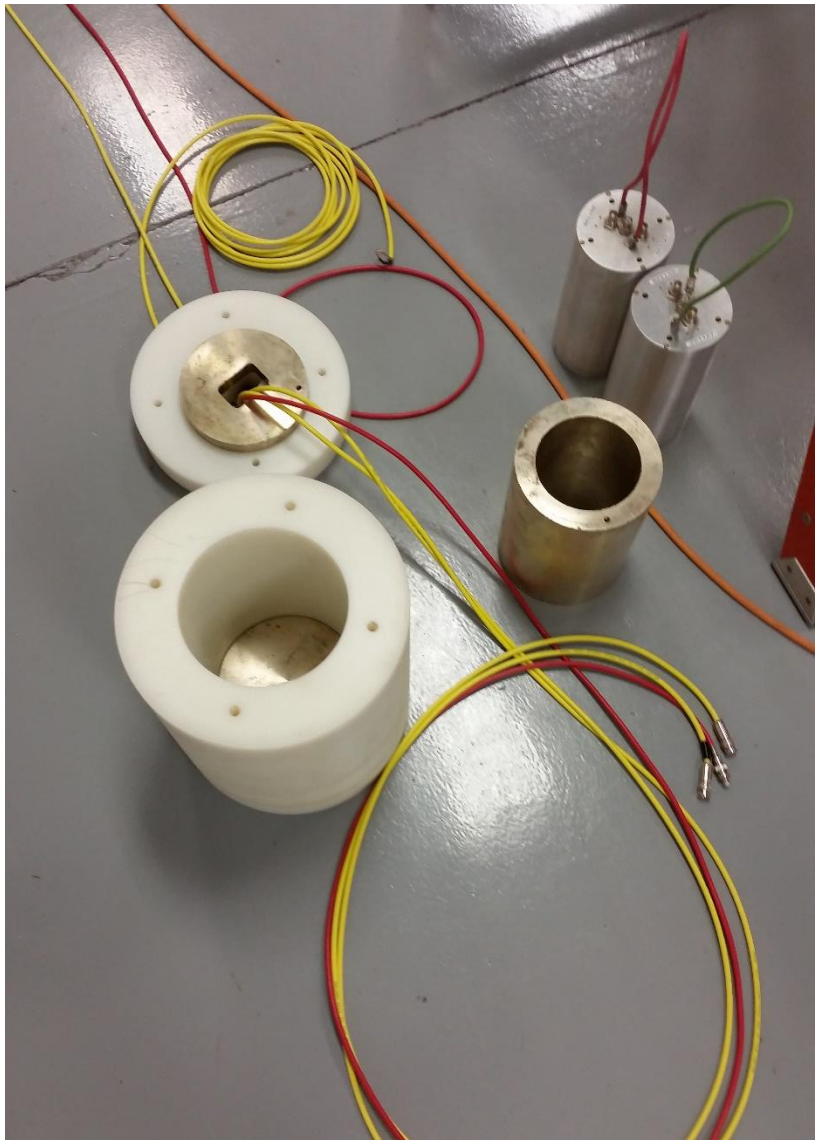


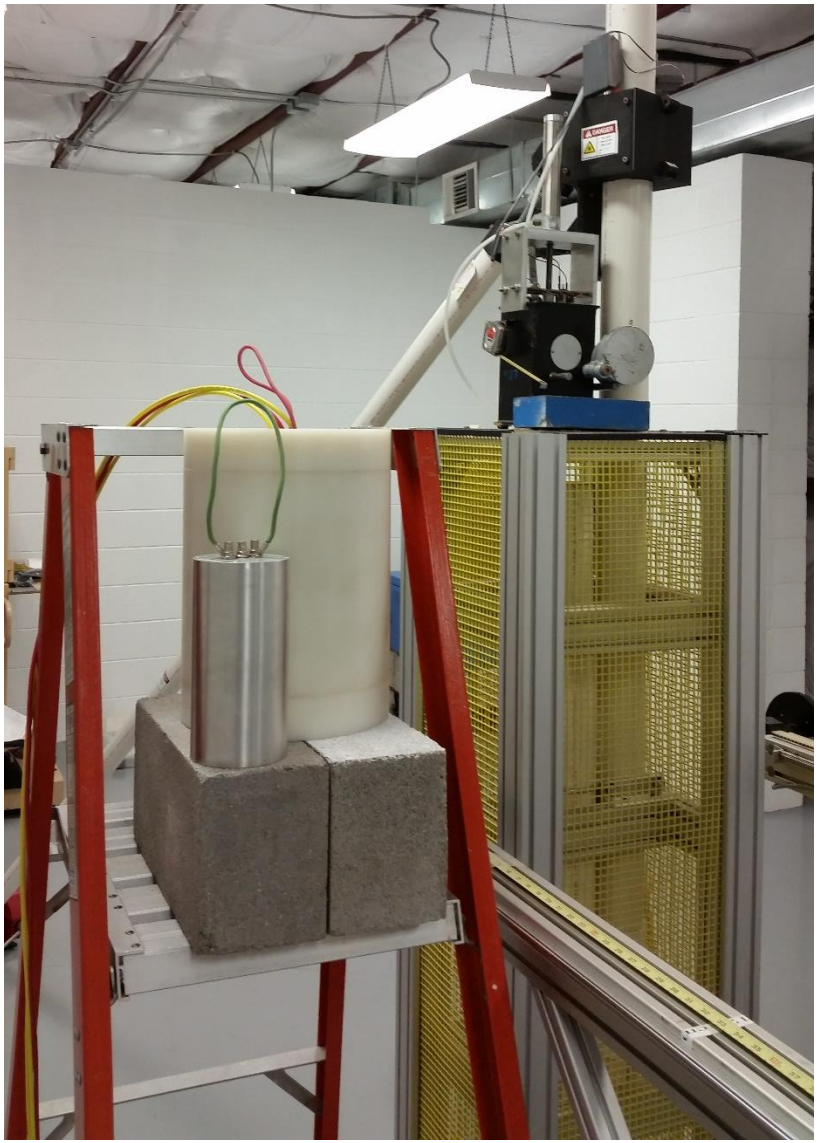

Ion Chamber Quote: $(1350+750)

# Prototype Assembly Drawings



# Prototype Detectors





# Calibration

- The calibration of the detectors in the test neutron fields at RadCon range (AmBe neutron source, max calibration field about 75 mrem/h) resulted in the values of the calibration coefficients of about $C_n$ = 12 mrem/h per pA.
- The symmetric response of the $^3$He and $^4$He ion chambers to high photon dose rates (~100 Rad/h) was tested in the gamma irradiator at RadCon, and the difference was found to be under 10%. This factor is used in the current subtraction procedure.
- The formulas for neutron and photon dose rates:

$$nDsRt = C_n*[(nCur-B_n) - F_g*(gCur-B_g)]$$

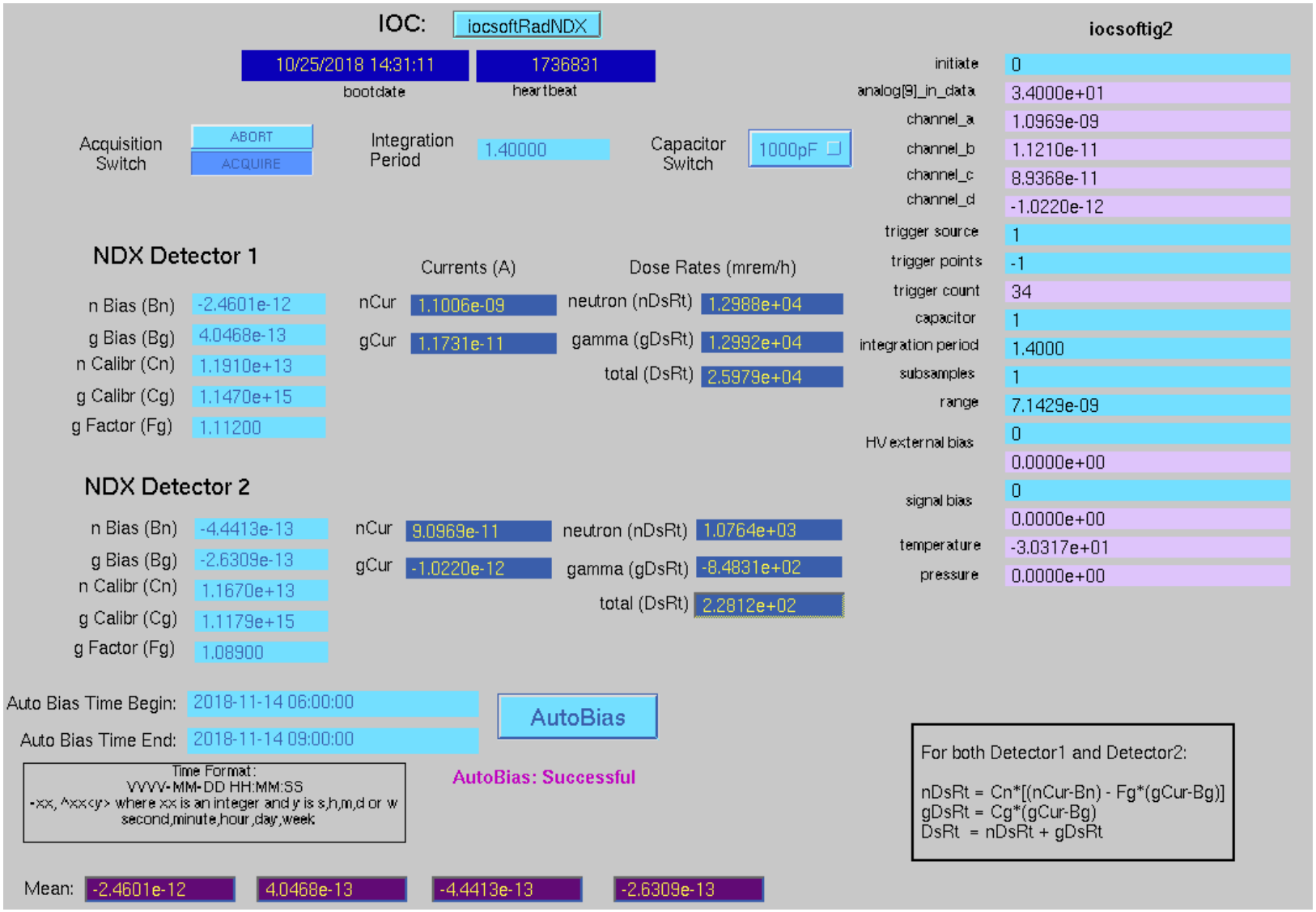
$$gDsRt = C_g*(gCur-B_g)$$

- Long-term bias current stability within ~1 pA (~10 mrem/h)

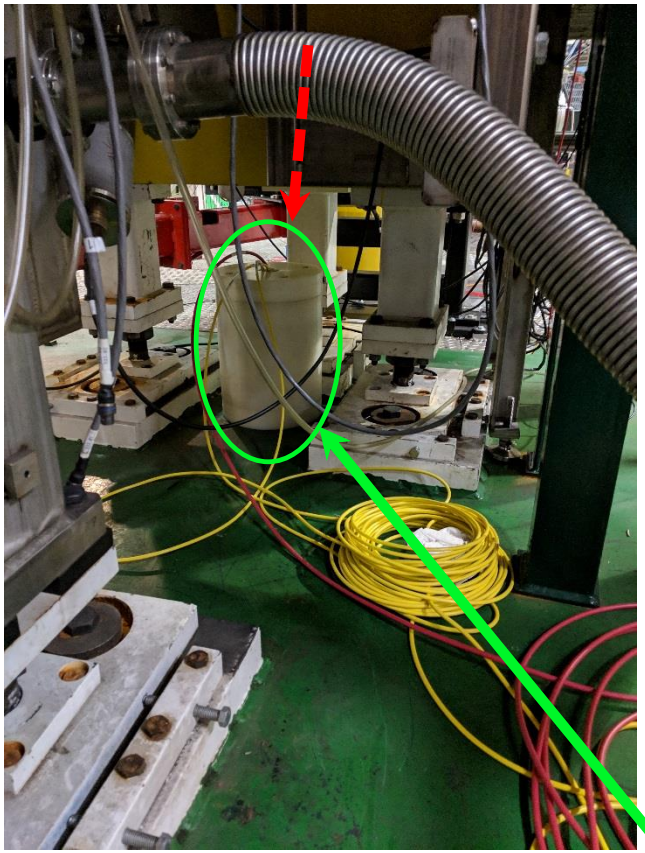
# Pyramid Front End Electronics

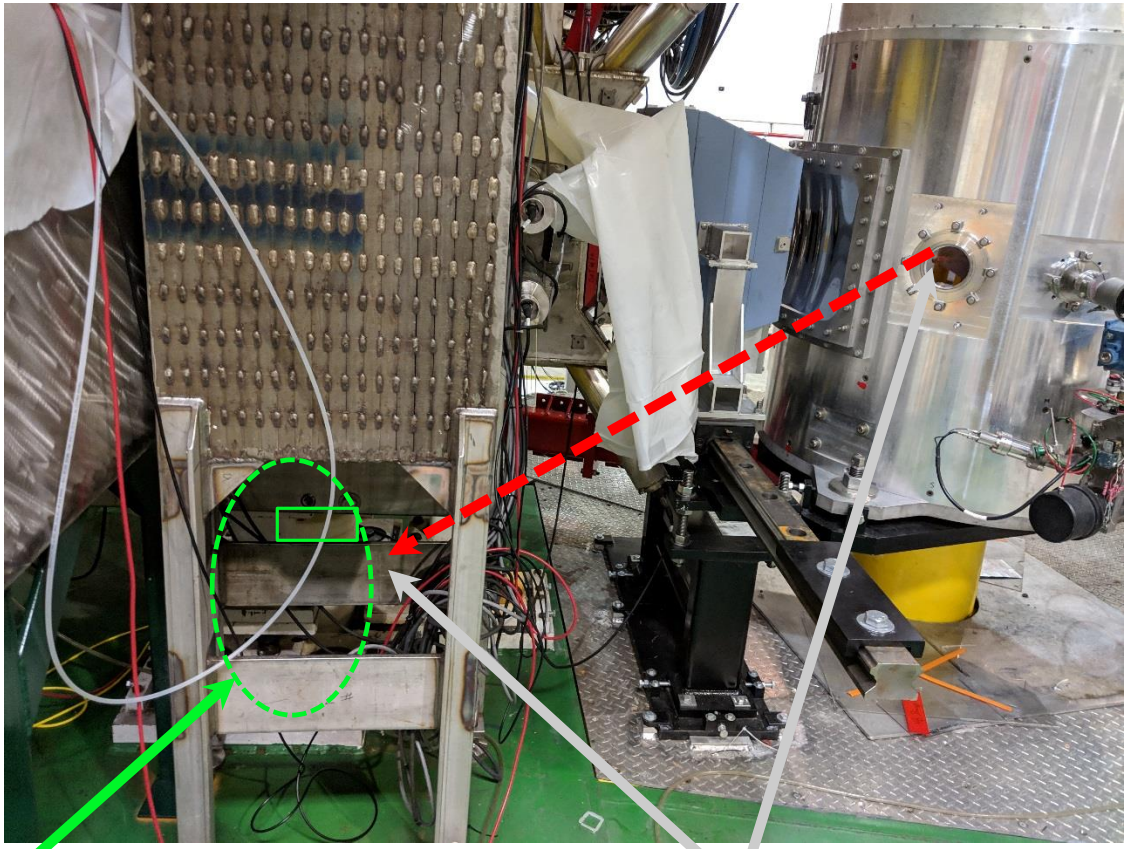
- Pyramid Technical Consultants, Inc.
  - Four channels
  - Sensitivity and stability down to 0.1 pA
  - Network connectivity for the data readout
  - "EPICS ready"
  - Cost at about $6k


# NDX I-400 EPICS Expert Screen



# NDX01 Detector, SHMS Platform under HB Magnet



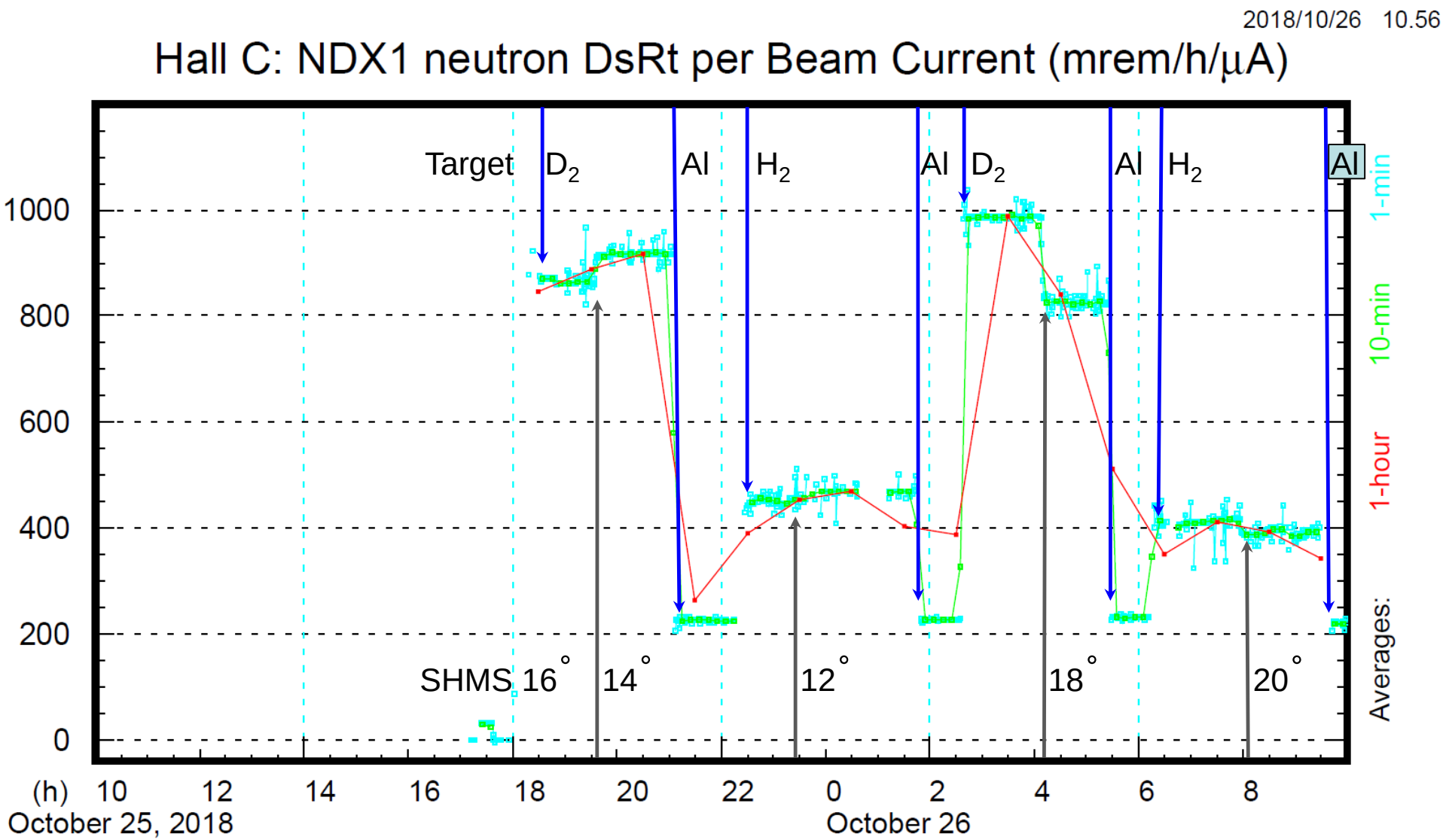


NDX01 Detector under HB magnet

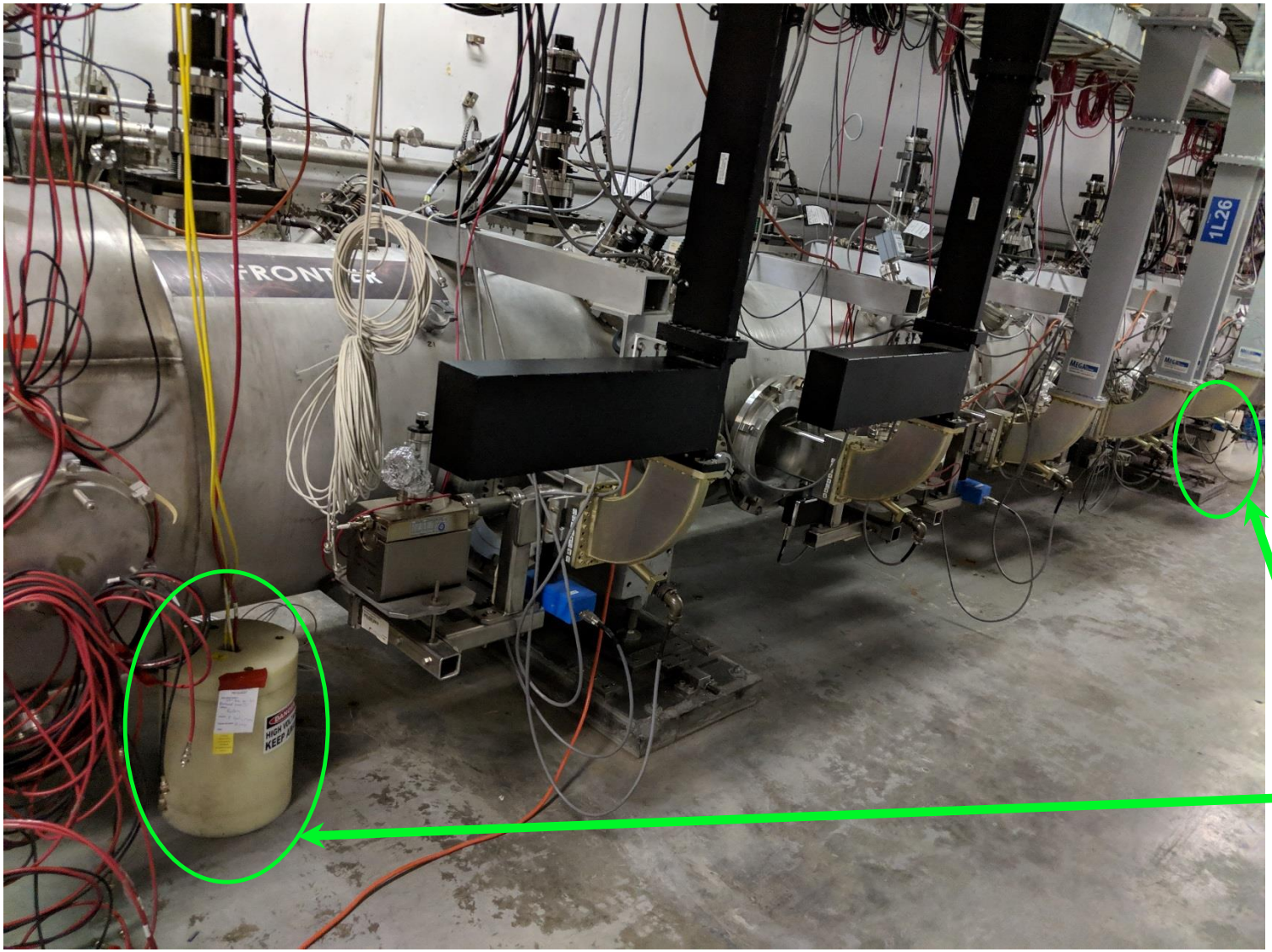
Approx. 3 m from target

# NDX02 on SHMS Platform Downstream

# NDX01 Dose Rates per Beam Current



# NDX01 and NDX02 under NL26

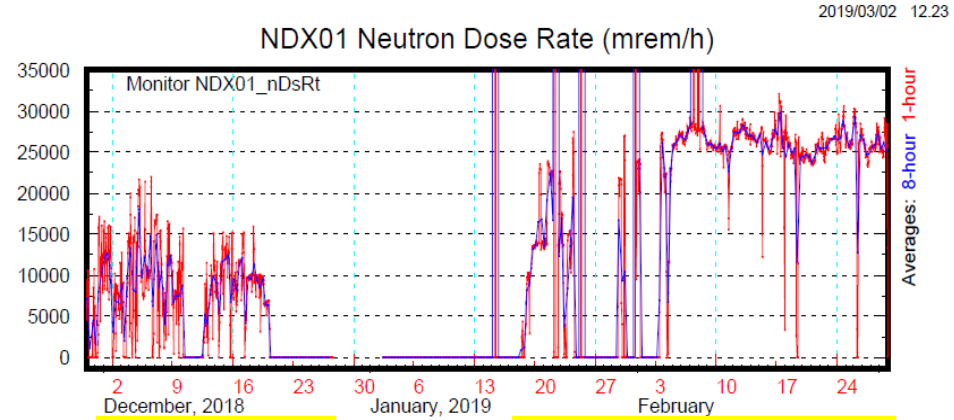



NDX02

NDX01

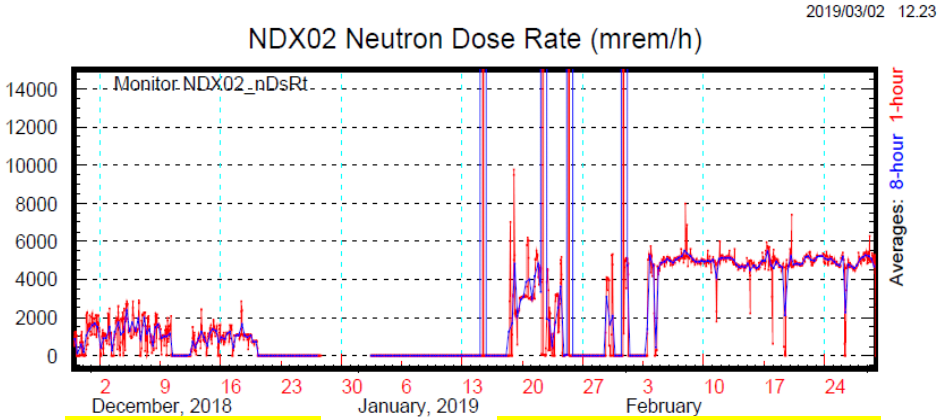
# NDX Detectors: Last Three Months

Neutron and photon dose rates measured by the NDX detectors during the last weeks in Hall C, and in the beginning of operations in the North Linac at NL26



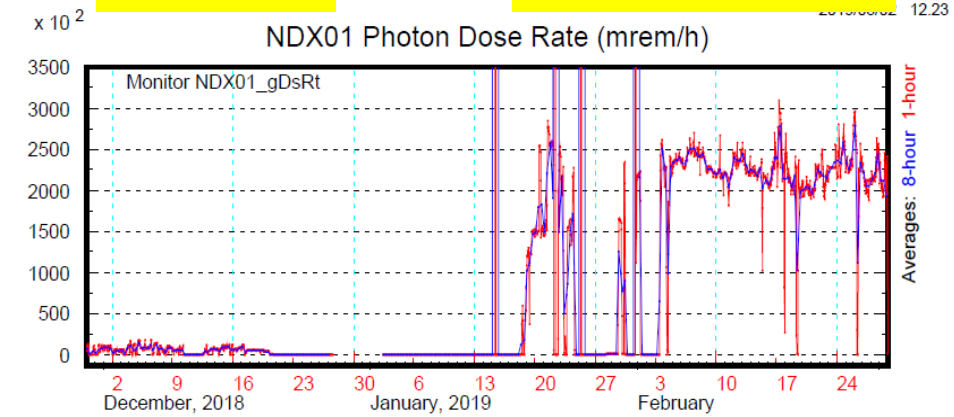

Hall C

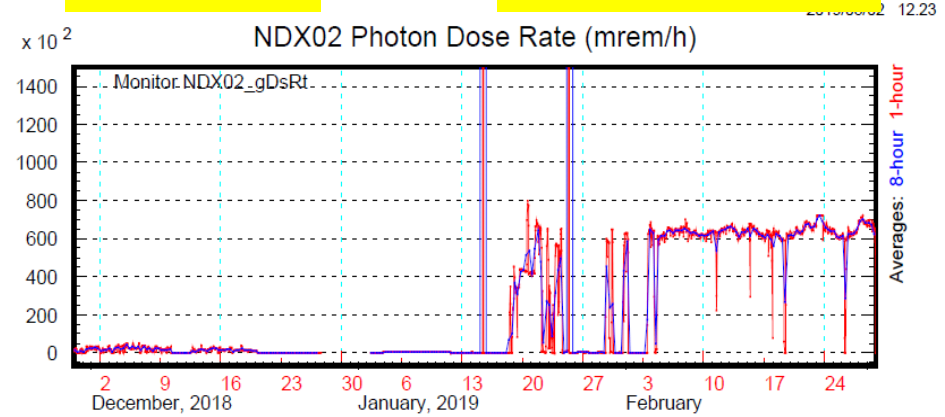
NL26



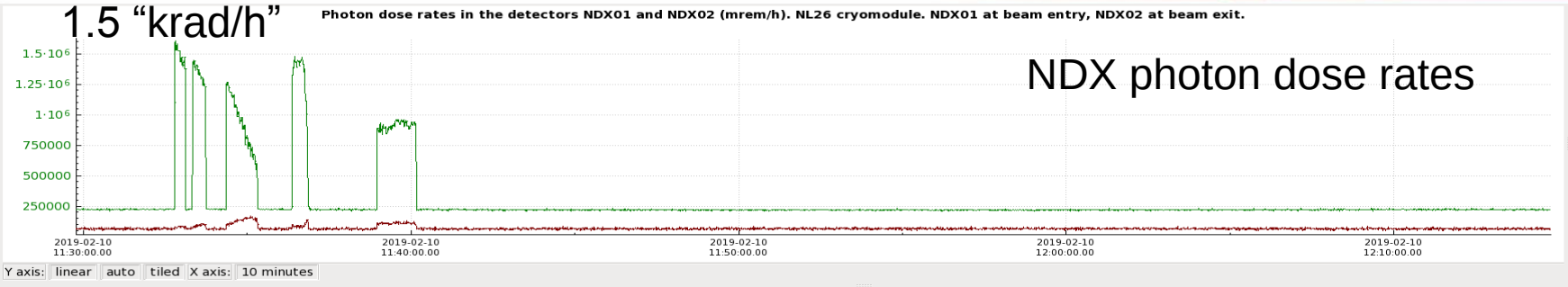

Hall C

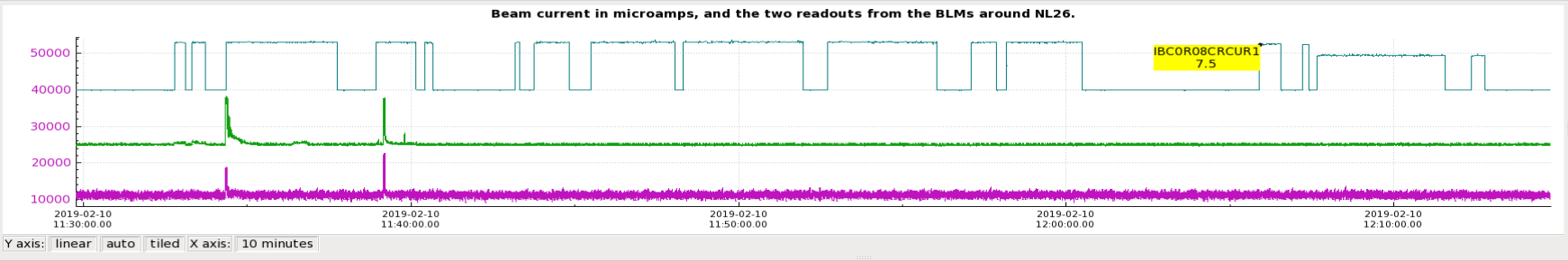
NL26

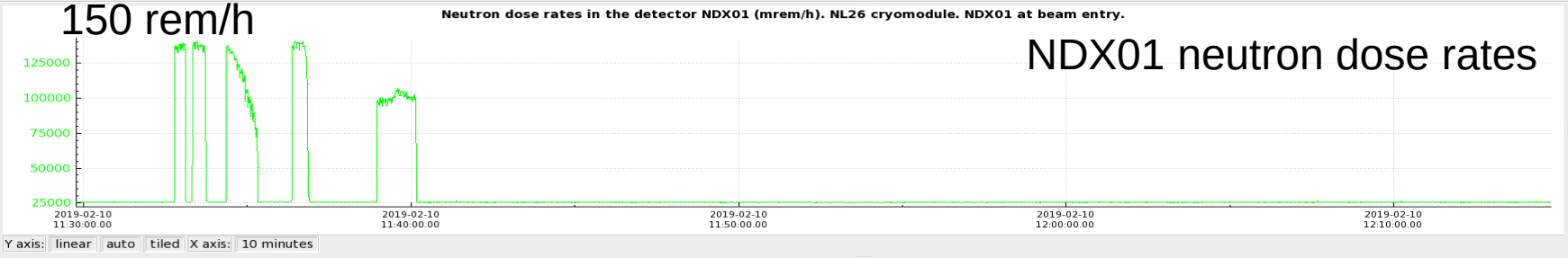


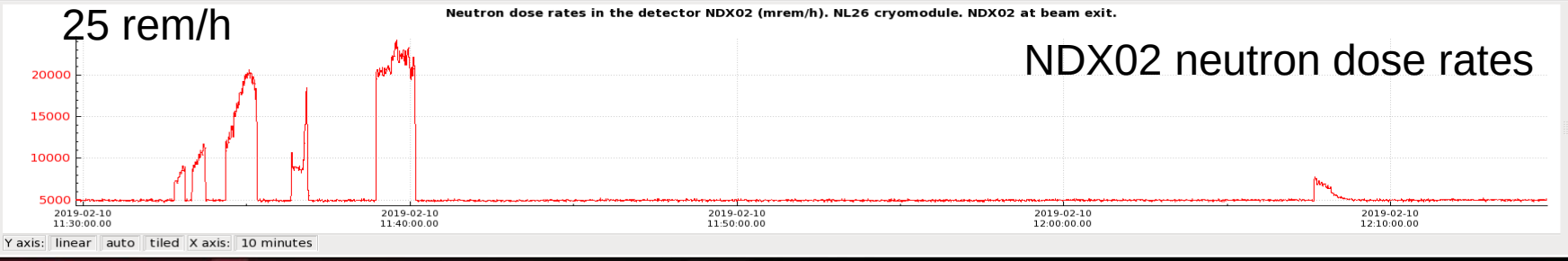



# Beam Loss Events around NL26



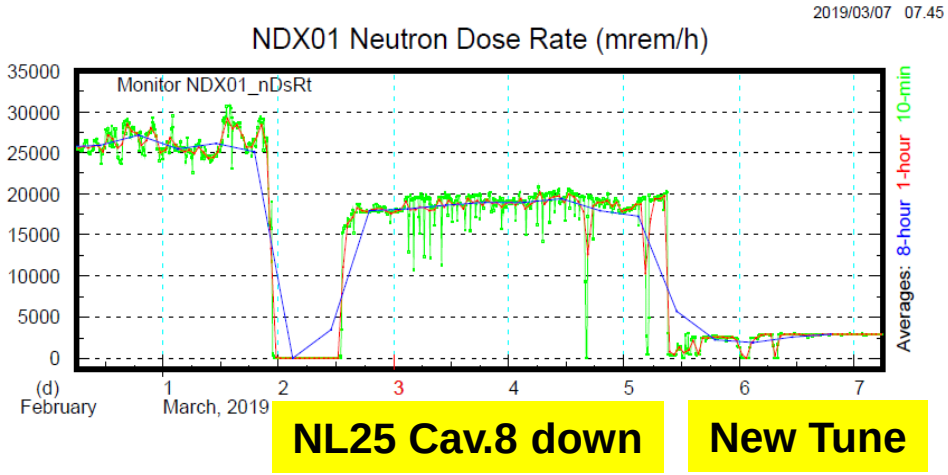



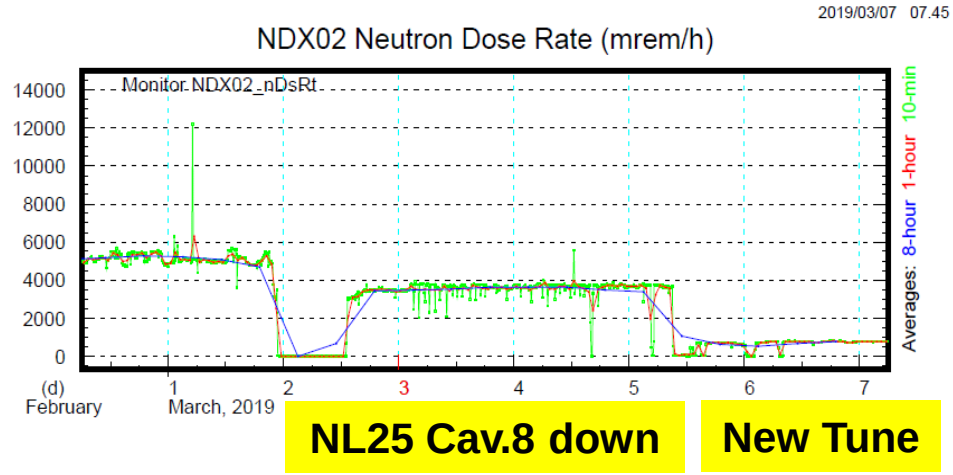



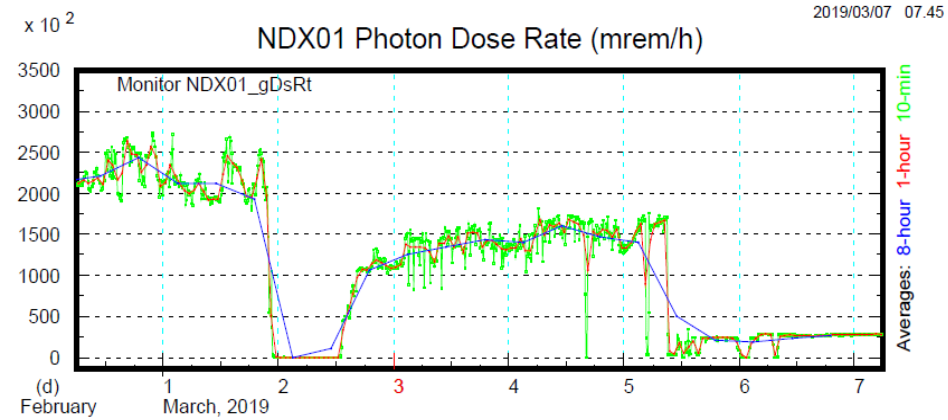
# C100 Gradients Optimization

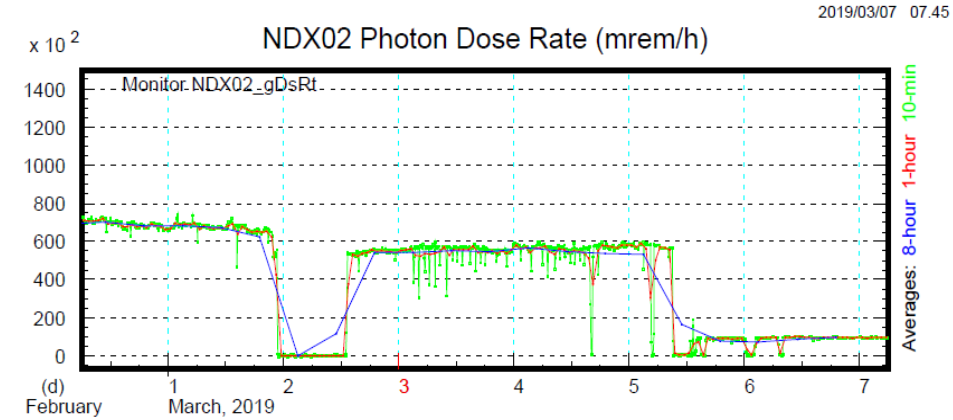
Last week of operations in the North Linac at NL26:

After a month of high field emission dose rates, a couple of days with NL25 Cavity 8 down, then tune to the new $E_{beam}$



# Summary

- Stable and reliable operation of the two prototype NDX detectors has been demonstrated during the two-month run in Hall C, and a month at the NL26 cryomodule, addressing the problems:
  - Neutron detection in the presence of overwhelming photon radiation fields at JLab:
    - at the experimental halls
    - around the SRF cryomodules
    - possible beam loss monitoring
  - Improving quality of the neutron ambient dose equivalent measurements at high neutron energies up to 10 GeV
  - Features: radiation hardness, large dynamic range, stability of the neutron detection, characteristic for Ion Chamber operation
- JLab patent submitted, with possible applications in accelerators, photon irradiation facilities, nuclear power plants
- List of "Lessons learned" is compiled to take into account in the future development

# Lessons Learned and Future Development

- Lessons Learned:
  - Picoamp-level readouts demand respect: properly electrically shielded connections, clean assembly, no water and electrolytes, no excessive bending of the triaxial cables.
  - Changes in the design are suggested to satisfy radiation hardness requirements and make assembly simpler: do not use electrical connectors on the body, use instead direct soldering of the radiation-hard triax cables to the Ionization Chambers, and make a separate connector box at a distance (15-20 ft).
  - Do not use the Aluminum inner shell: Al and 10%BeCu react chemically in high radiation fields (humidity contributes). Suggest using 10%BeCu as one grounded shell, embedded in Poly.
- There is a possibility of less bulkier design, using four smaller ICs and a spherical moderator assembly. “Should work” but needs testing.
- For the serial implementation, the regular maintenance and calibration issues must be considered.

# Acknowledgements

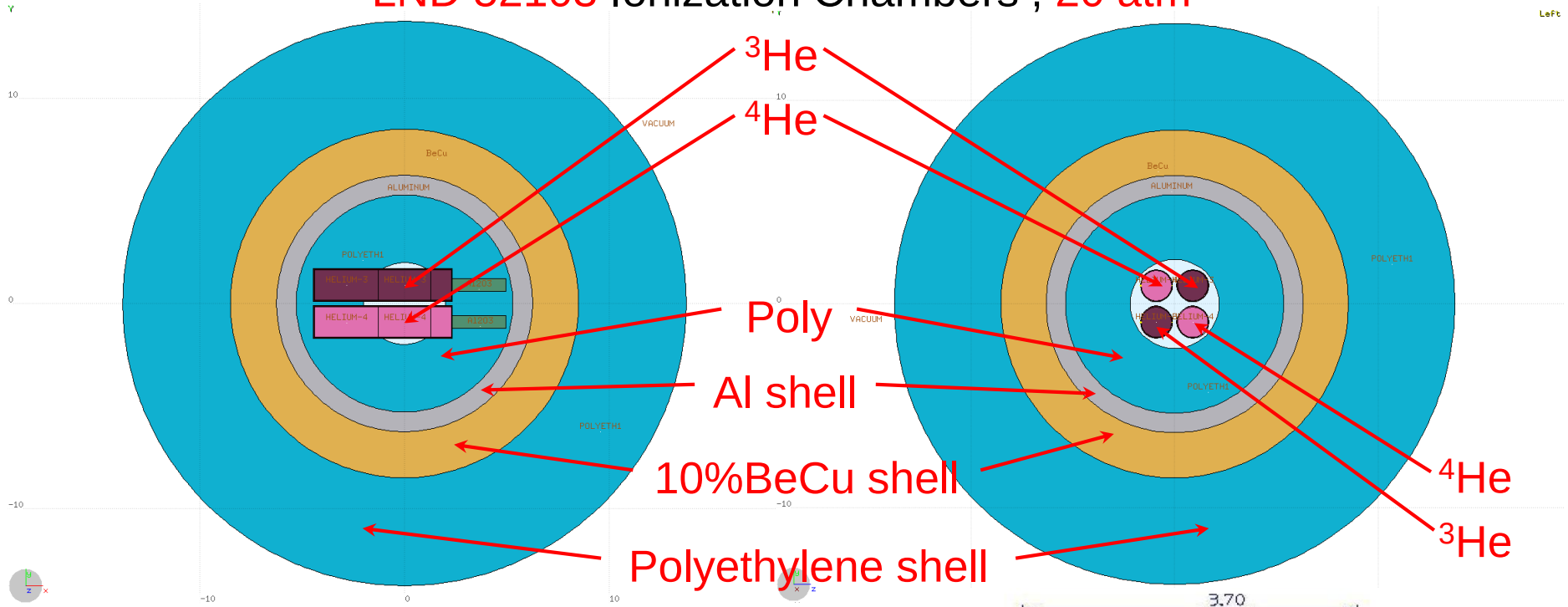

## Thanks to:

- Rolf Ent, Cynthia Keppel, Paulo Medeiros, Bogdan Wojtsekhowski, Brad Sawatzky
- Vashek Vylet, George Kharashvili, David Hamlette, Melvin Washington, John Jefferson
- Chris Cuevas, Armen Stepanyan
- Arne Freyberger, Matt Poelker, Sue Witherspoon
- William Lehnert (LND, Inc.)

# Extras

# Spherical Moderator Design

LND 52103 Ionization Chambers , 20 atm

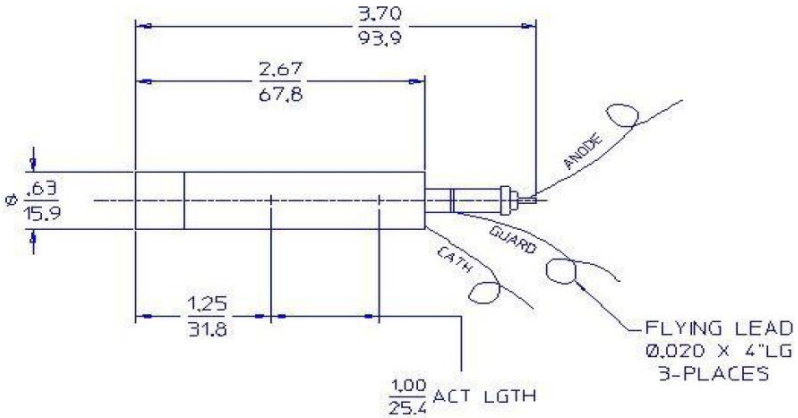



Spherical moderator assembly

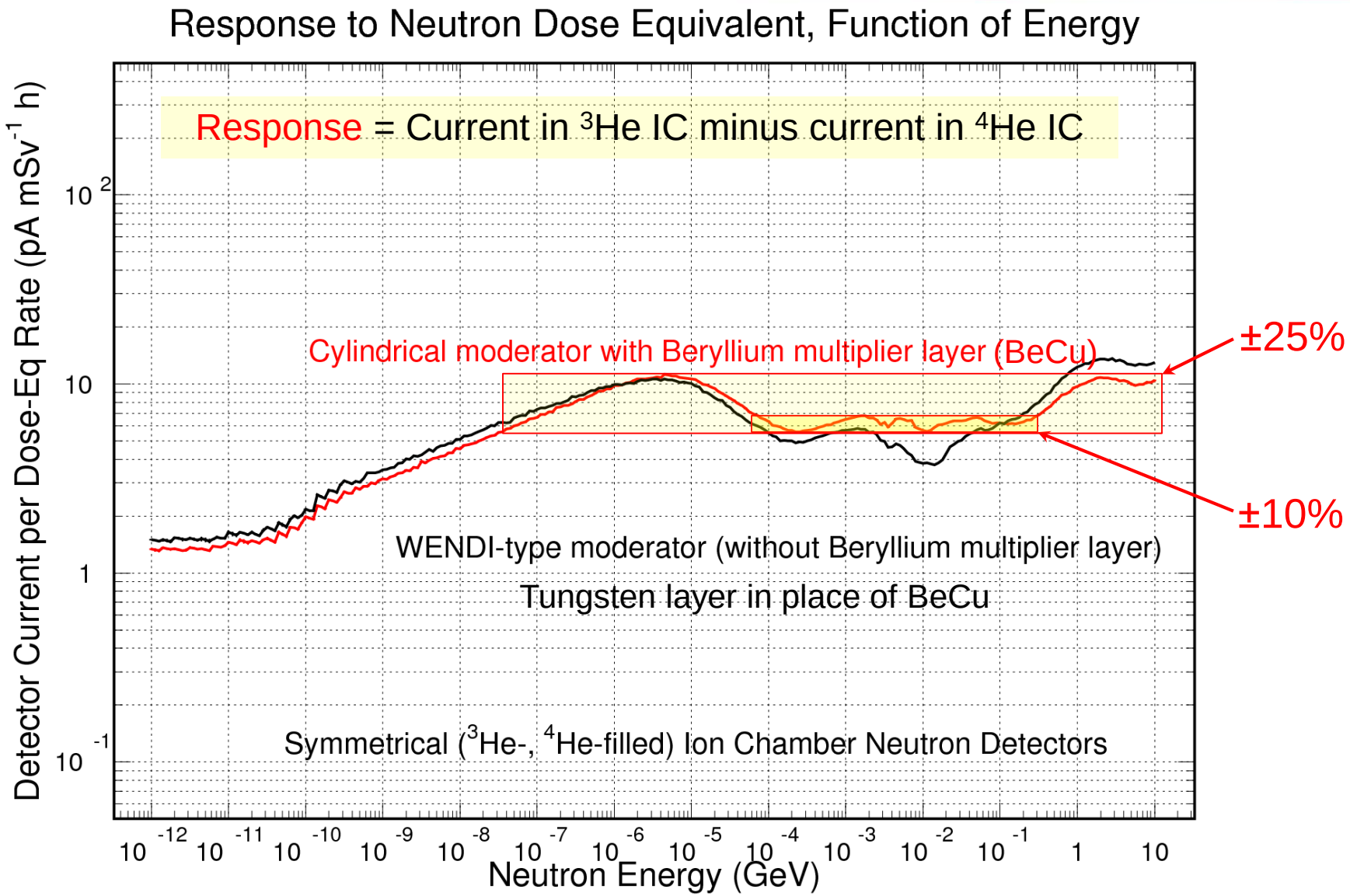
Same sensitivity

Better directional uniformity

Optimal weight of the moderator

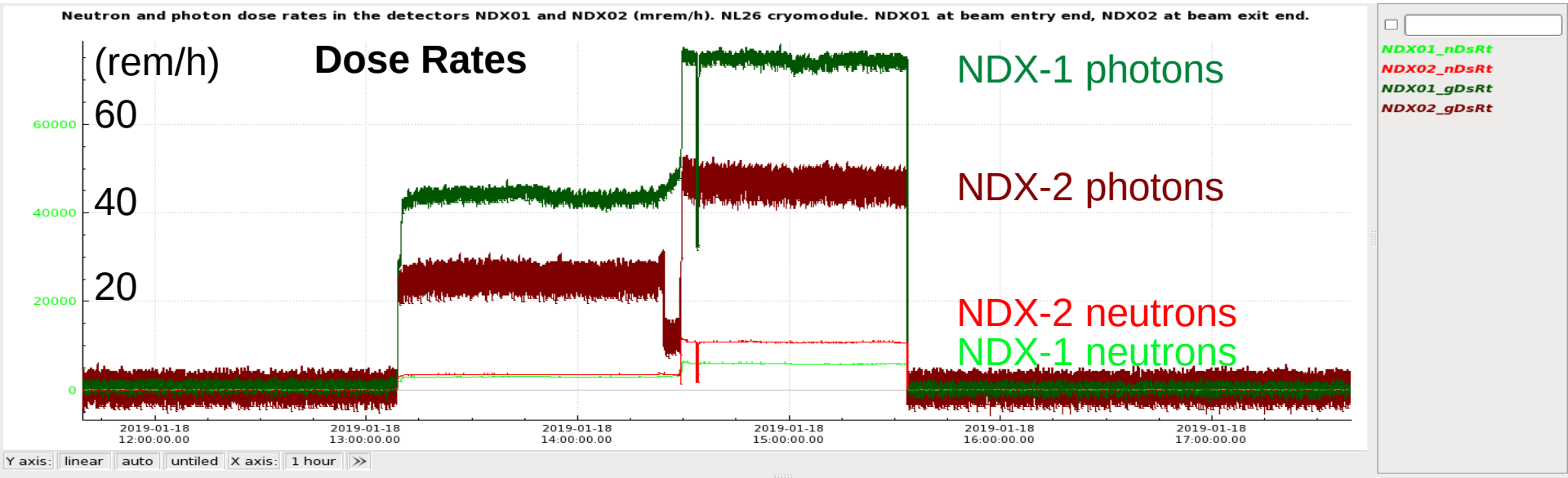


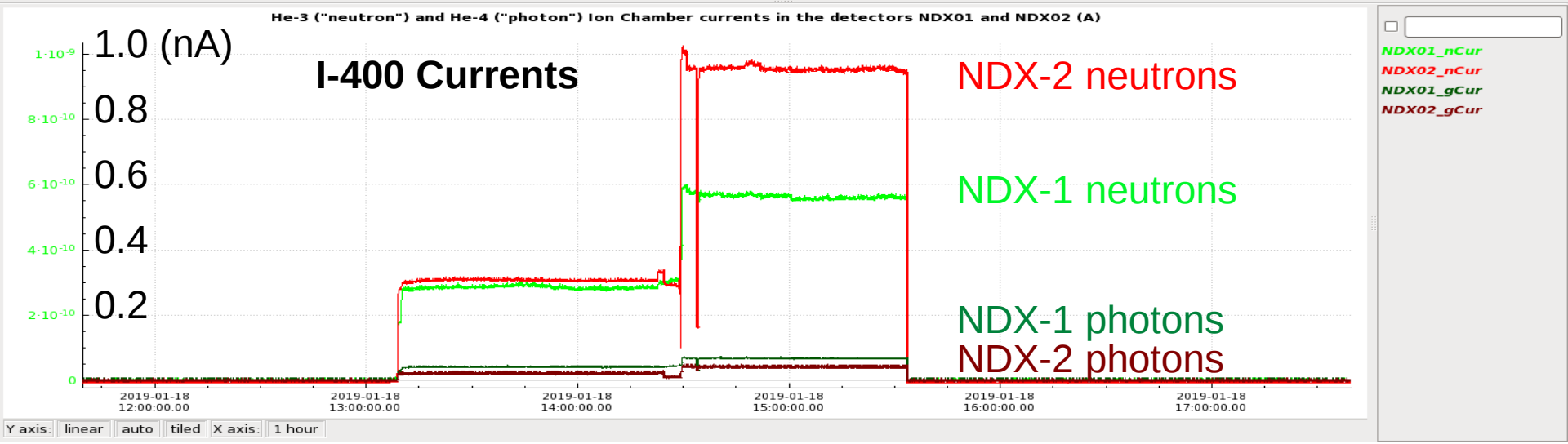
# Energy Dependence of Detector Response



# Beam Loss in Transport Tunnel on 12/14/18

# NDX Operation in North Linac, Example

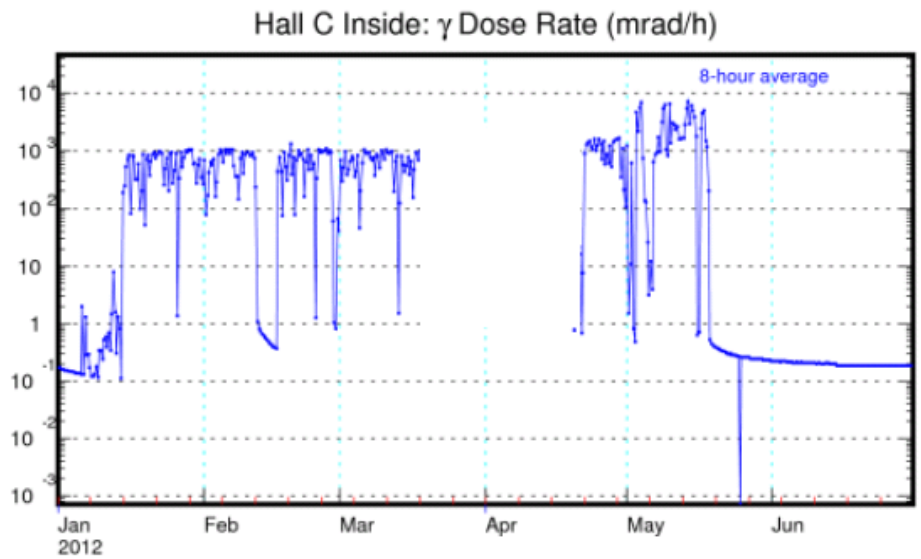


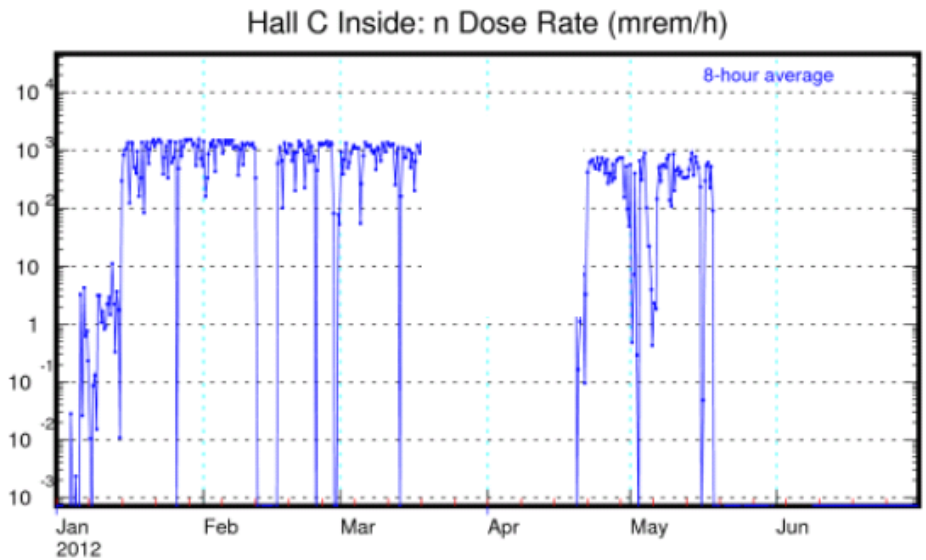



# Gamma Irradiator Tests

# Radiation Environment at Jlab (1)

- Radiation monitoring in the Experimental Halls: γ, n
- Prompt dose rates observed at the back of the Halls: up to ~10 rad/h photons, ~1 rem/h neutrons:



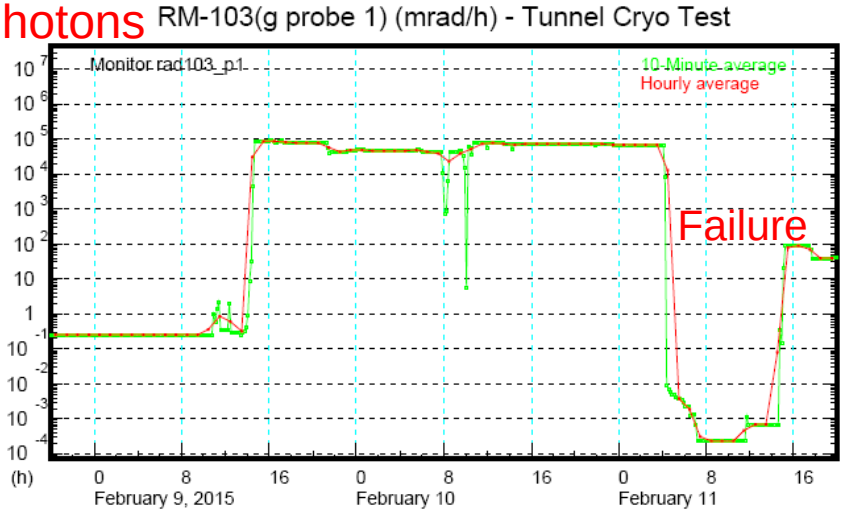




- Prompt dose rates downstream from the targets:
  - many kilorad/h photons (measured with Ion Chambers)
  - hundreds(?) rem/h neutrons (not measured)

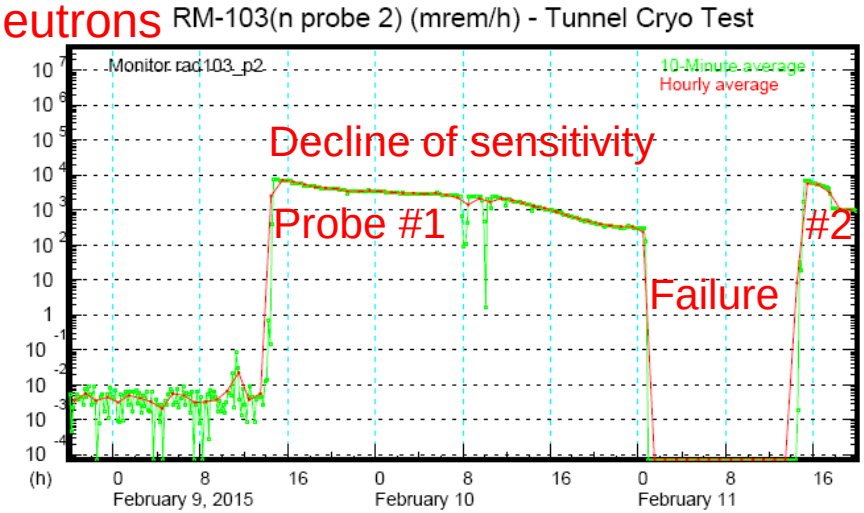
# Radiation Environment at Jlab (2)

- Radiation monitoring around C100 cryomodules: γ, n
- Dose rates observed at 1 foot, ~100 rad/h γ, ~10 rem/h n :

Photons




Neutrons

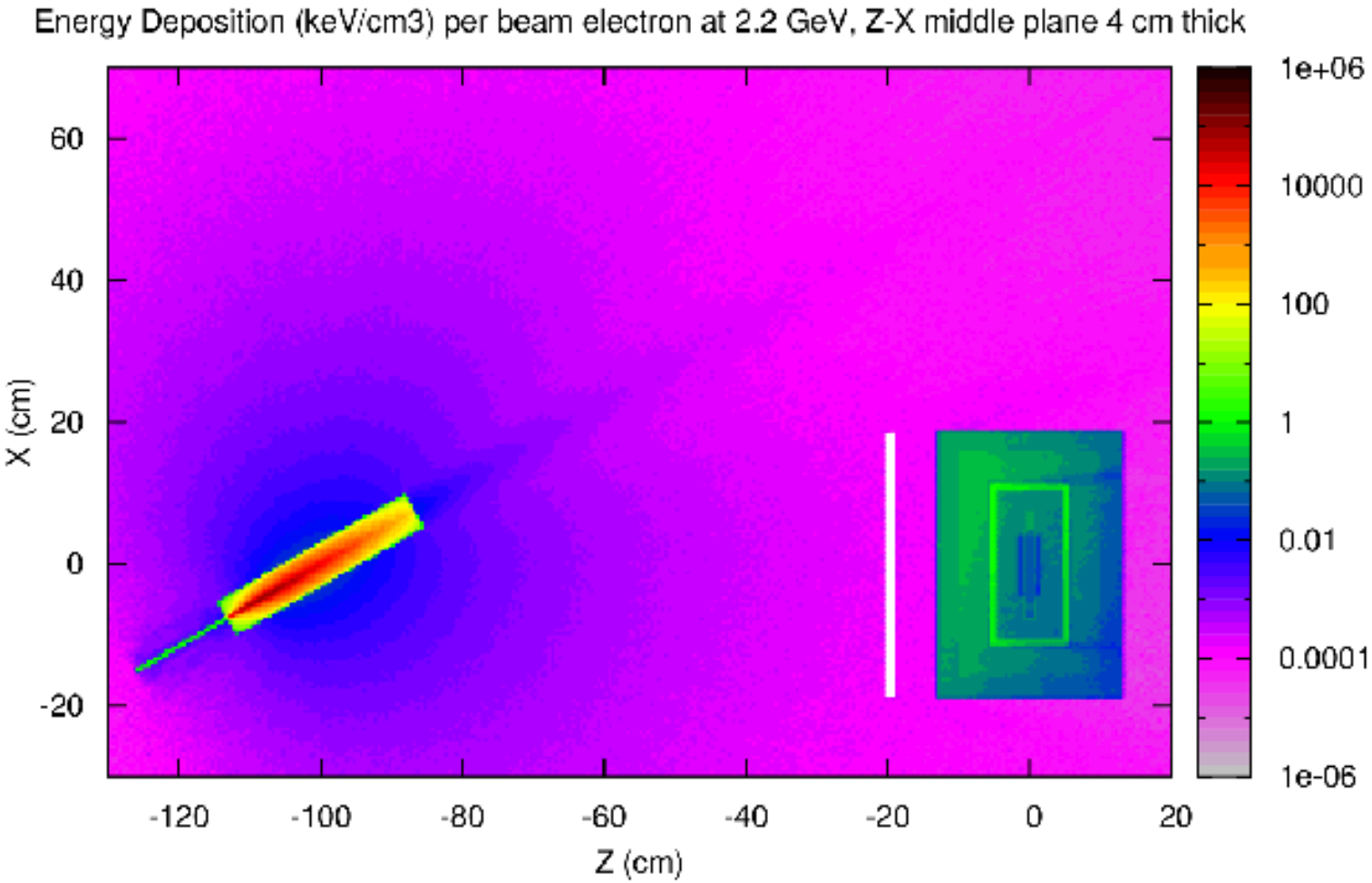



- JLab standard CARM probes do not survive for long
- Typical proportional neutron counters won't work: long cables, high rates, sensitivity to gammas
- Need radiation-hard photon- and neutron-sensitive ICs with remote front-end and DAQ electronics

# Detector next to a thick target at 2.2 GeV

FLUKA: Showing energy density in the target, air around, and the detector

Neutron Dose rate estimate is about 0.036 of the Total Dose rate

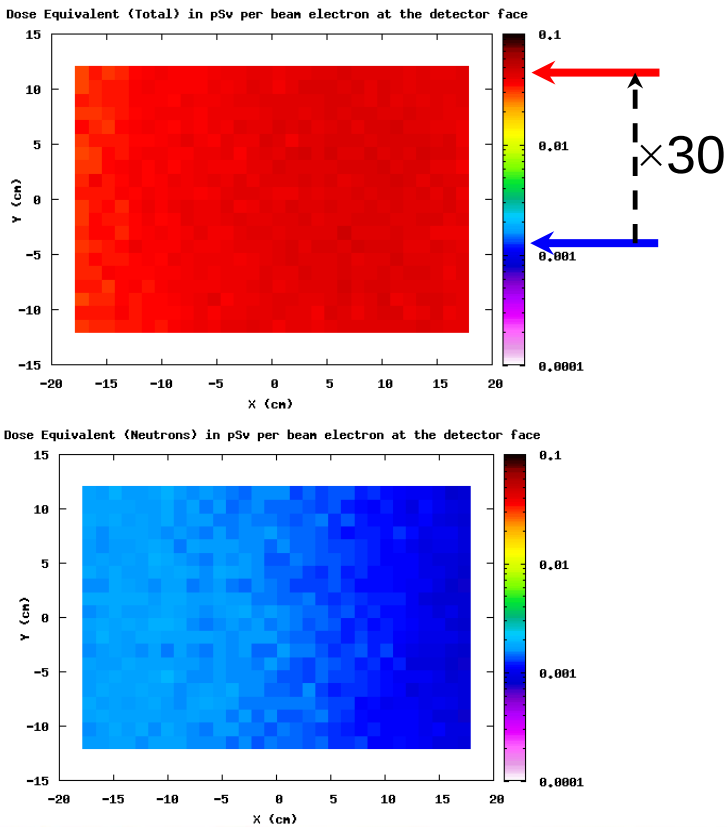


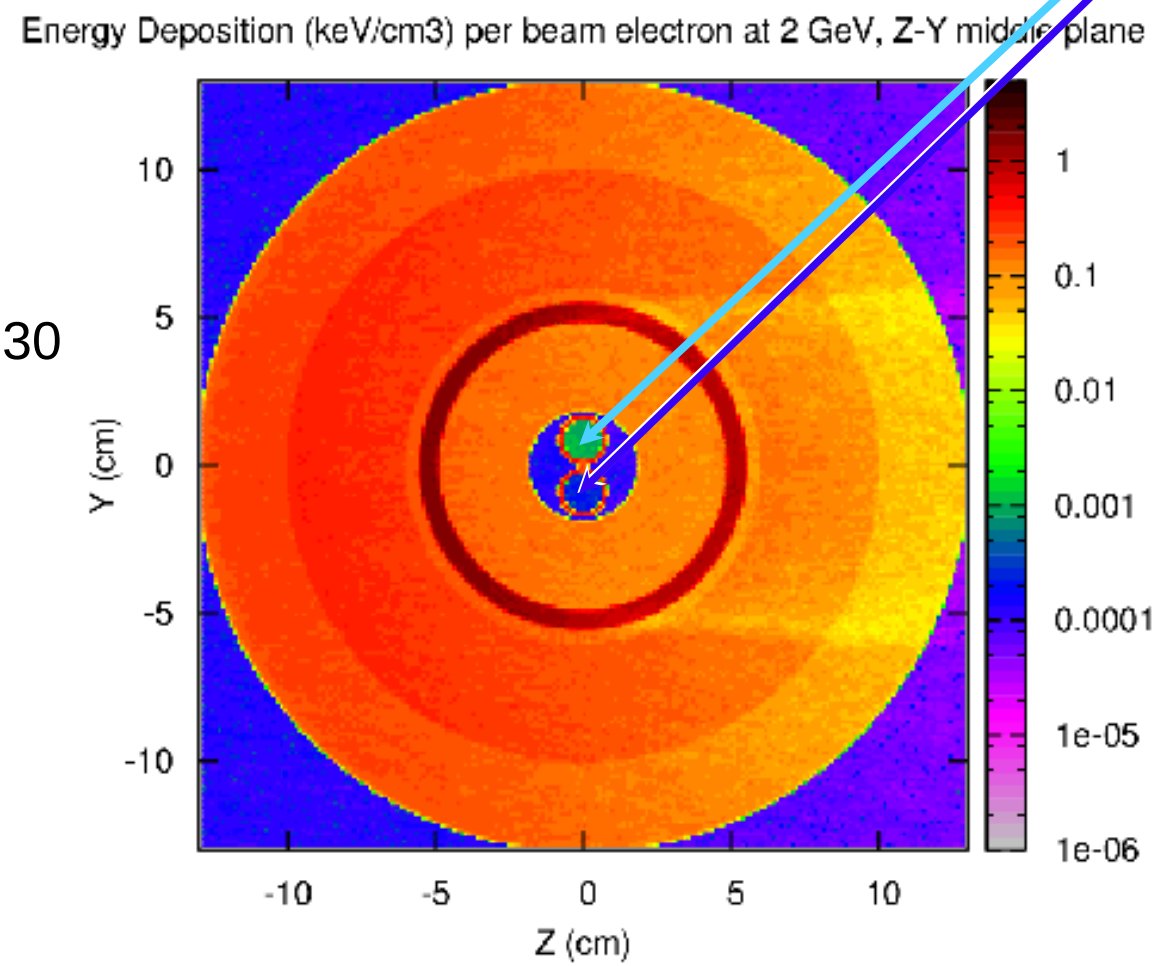
# Detector next to a thick target at 2.2 GeV

FLUKA: Showing energy density in the air around, and in the detector

The ratio of ionization currents from $^{3}$He IC to $^{4}$He IC equals to 4.5

Face Dose Rates (Total and Neutron):

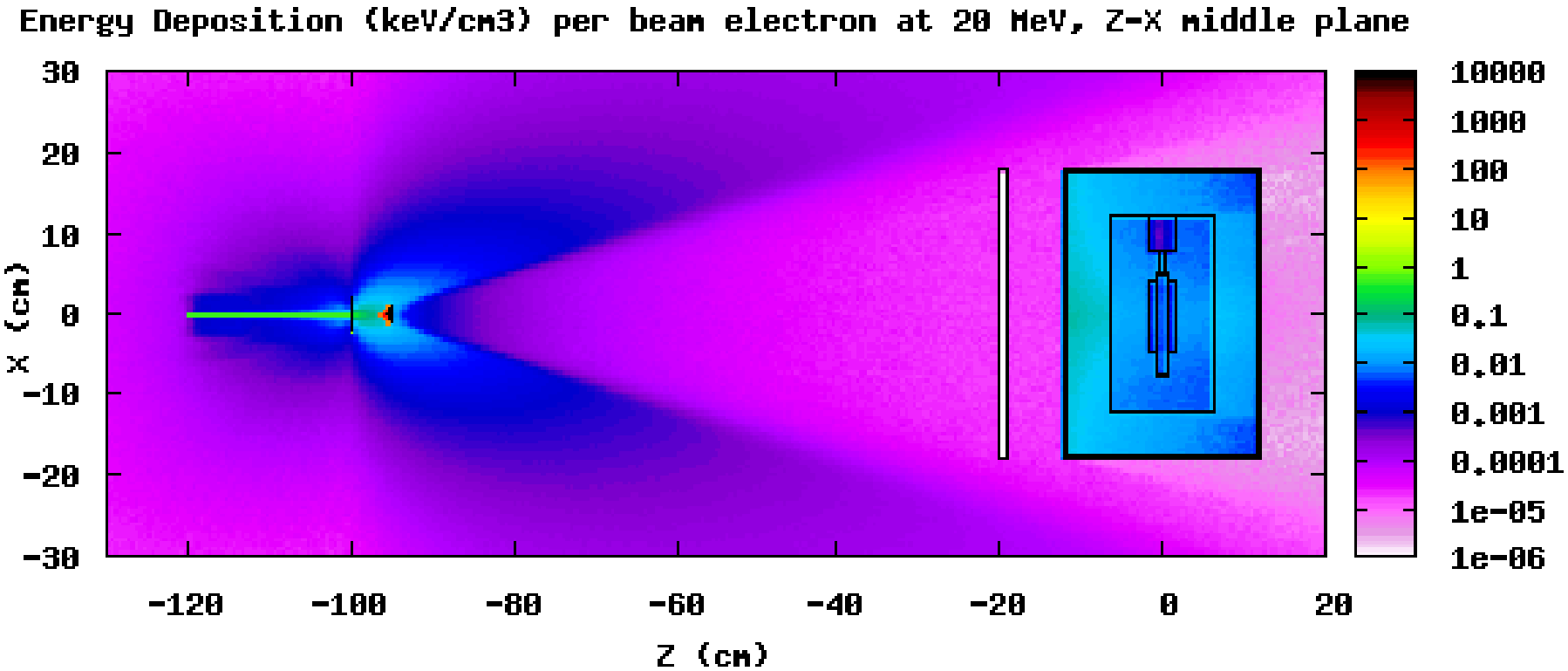


# Detector in the 20 MV photon beam

FLUKA: Showing energy density in the target, air around, and the detector

Neutron Dose rate estimate is about 0.0025 of the Total Dose rate

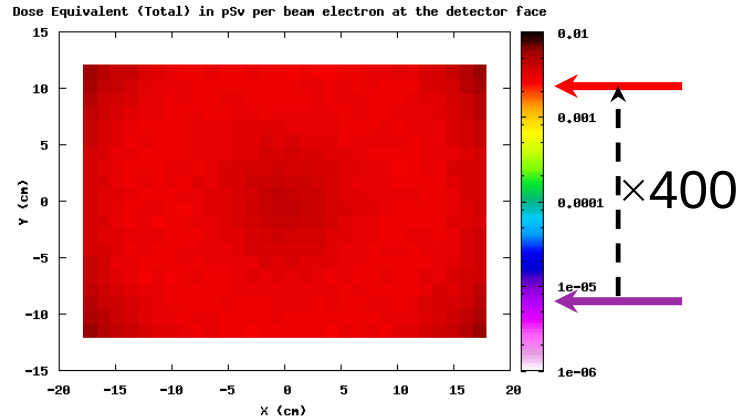


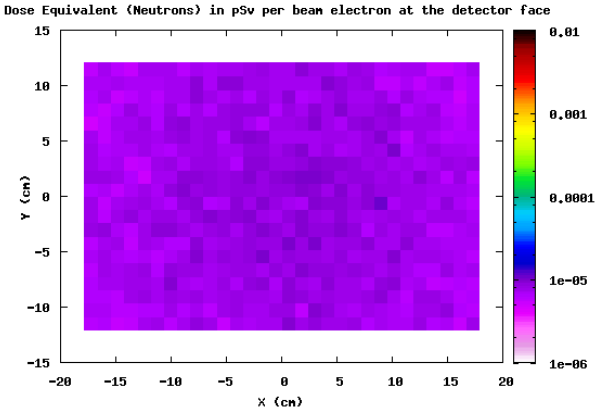
# Detector in the 20 MV photon beam

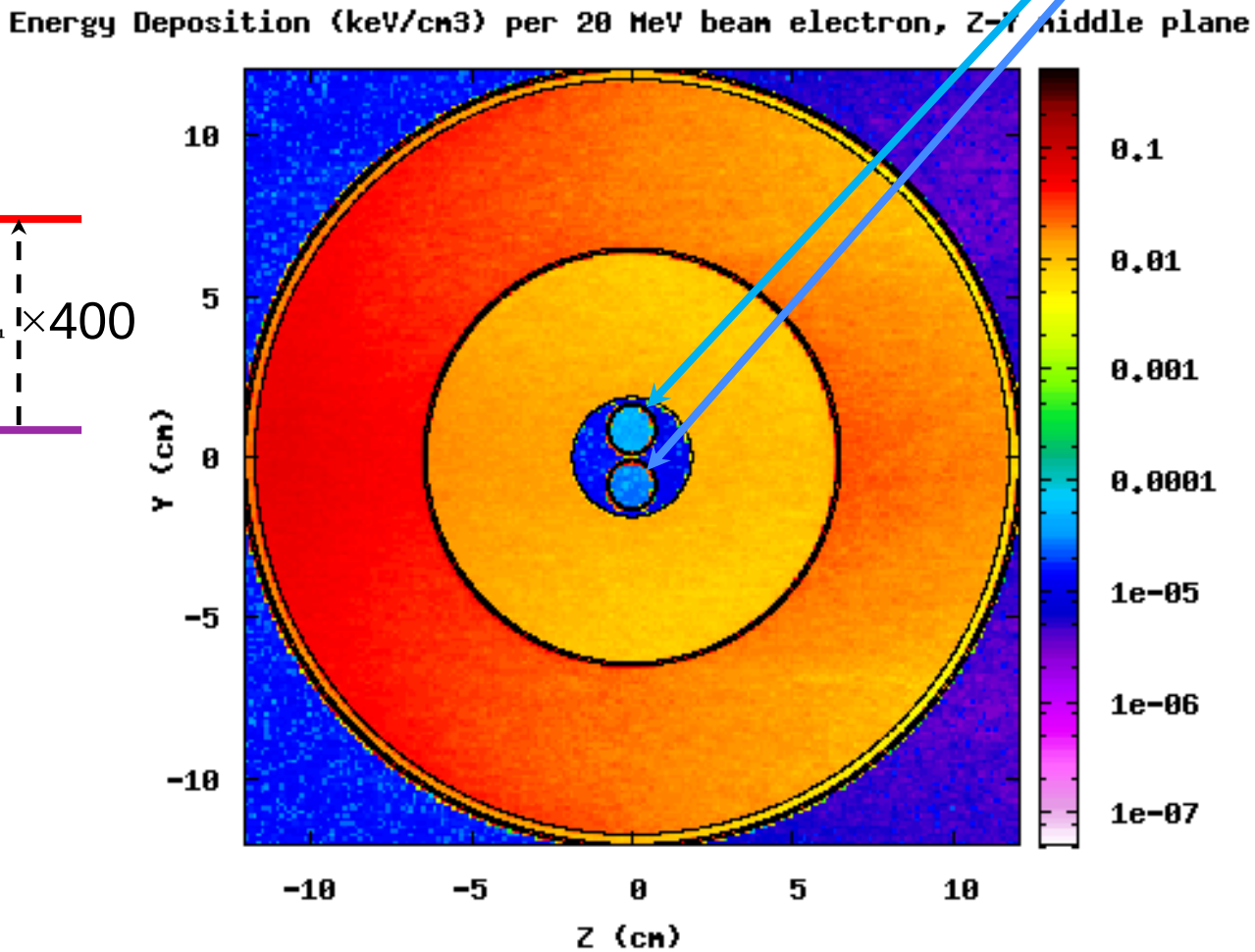
FLUKA: Showing energy density in the air around, and in the detector

The ratio of ionization currents from $^{3}He$ IC to $^{4}He$ IC equals to 1.65

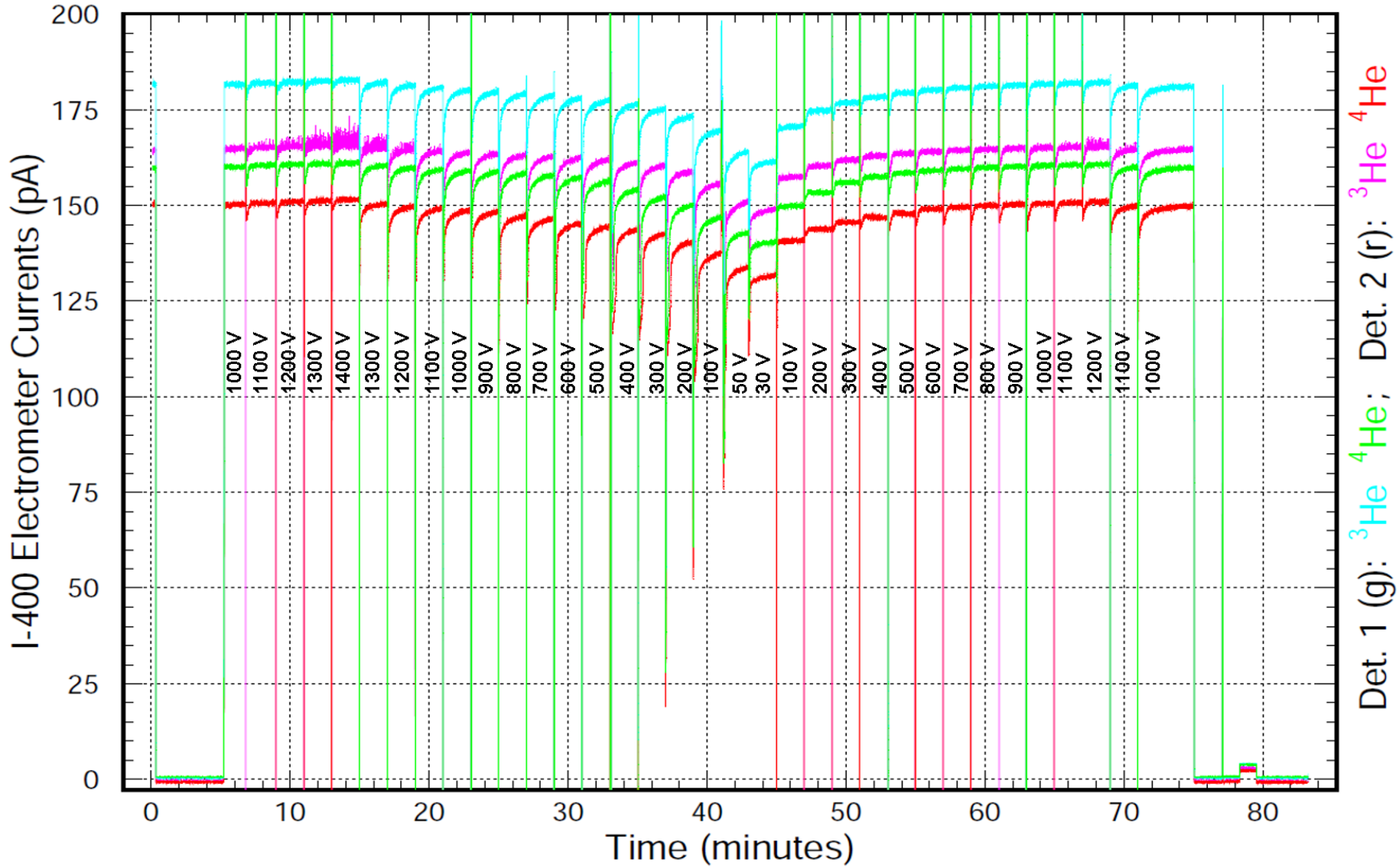
Face Dose Rates (Total and Neutron):



# HV Plateau Studies in Photon Field



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[2] R. H. Olsher, H.-H. Hsu, A. Beverding, J. H. Kleck, W. H. Casson, D. G. Vasilik, and R. T. Devine. “WENDI: An improved neutron rem meter”, Health Physics, 79(2):170ff, 2000.

[3] I. O. Andersson and J. A. Braun. “Neutron rem-counter with uniform sensitivity from 0.025 eV to 10 MeV”, in: Proceedings of the IAEA Symposium on neutron dosimetry, Vienna, 2:87–95, 1963.

[4] C. Birattari, A. Ferrari, C. Nuccetelli, M. Pelliccioni M., and M. Silari. “An Extended Range Neutron Rem Counter”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 297:250–257, 1990.