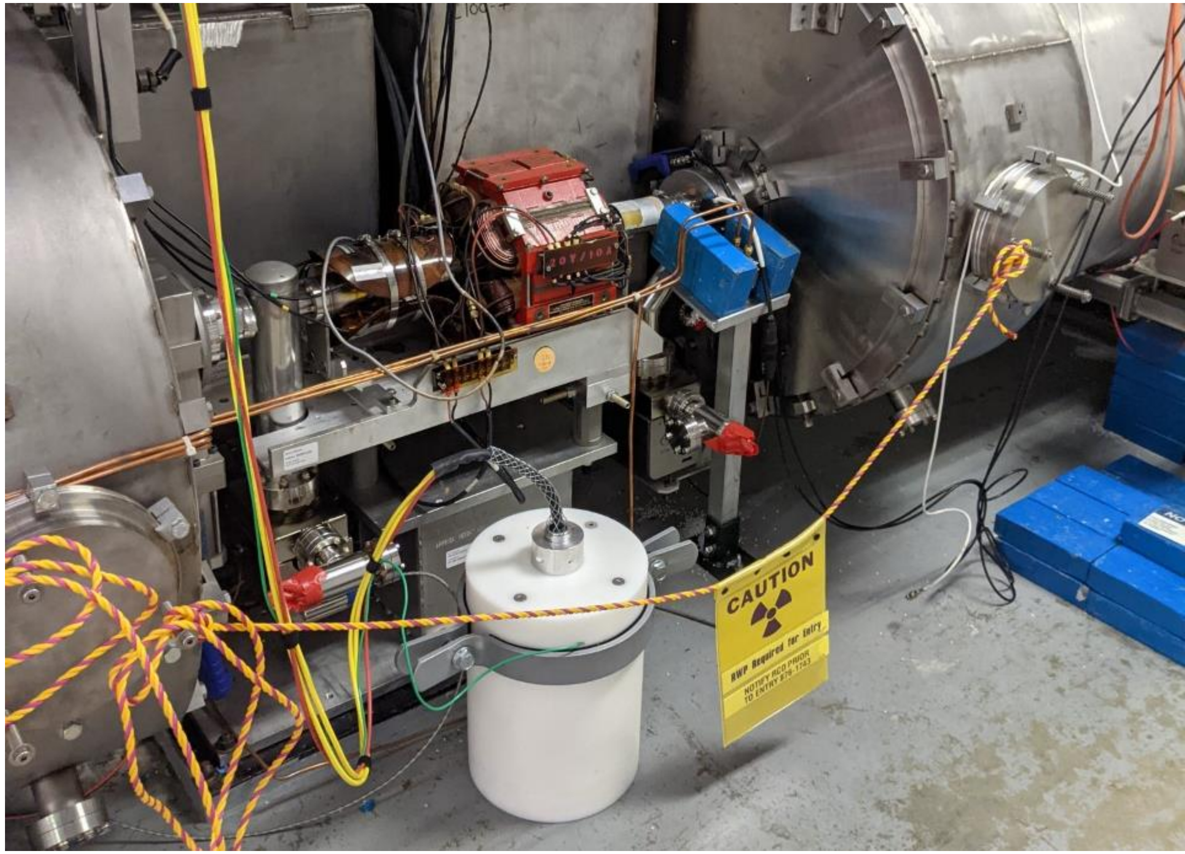
Neutron Dosimetry: Extending the Capabilities

Applications of the NDX Neutron Dose Rate Meters at Accelerators and Irradiation Facilities



Pavel Degtiarenko, JLab

2023 DOE/NIH Meeting

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Neutron Detection and Dosimetry

- Neutron sources:
  - High energy Accelerators – proton, electron, heavy ion beams
  - Medical Accelerators – proton, heavy ion, and neutron therapy
  - Higher energy (E > ~20-30 MeV) X-ray sources / photon irradiators
  - Medical isotope production facilities
  - Neutron generators, and neutron sources in general
- Multiple neutron detection techniques
  - Active Detectors vs. Passive Dosimeters
  - Detectors: Single Event vs. Integrating
  - More complex detection systems, including neutron Imaging
- Universal need in reliable dosimetry and neutron monitoring

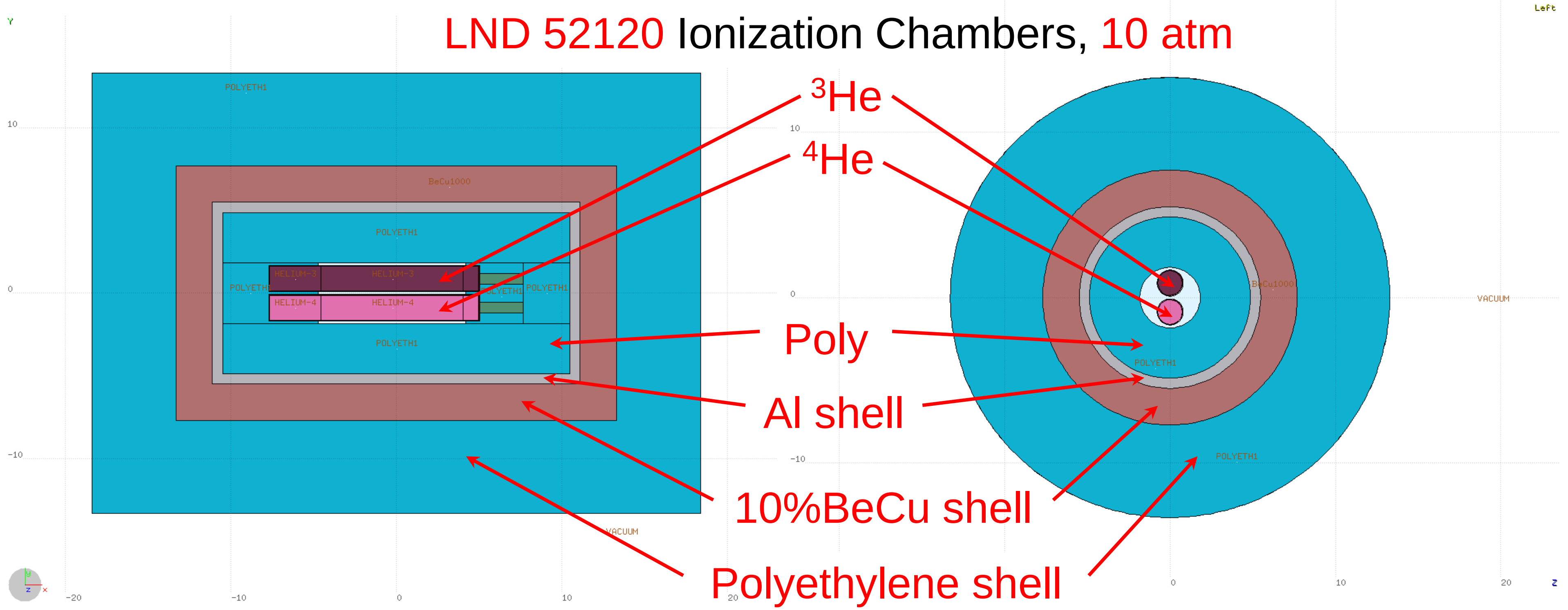
Neutron Detection at Accelerators: Challenges

- Operations in high radiation fields up to hundreds of rem/h
  - Detector front-end electronics damaged if placed close by
- High dynamic range needs
  - Typical pulse mode readout limited due to pile-up
- Good response in a wide neutron energy range up to few GeV
  - Typical moderator designs limited at 10-15 MeV
- Real time operations necessary, reaction times order of seconds
  - Use of passive dosimetry limited
- Operations in overwhelming photon backgrounds from:
  - Field emission radiation around accelerating cryomodules
  - Beam losses at electron accelerators

Problems and the Proposed Solution at CEBAF

- Beam line activation became visible after 12 GeV upgrade in 2012
  - Standard radiation monitoring showed significant FE dose rates
  - Hundreds of R/h photons, tens of rem/h neutrons
  - Real-time detectors saturated and get damaged
  - Passive dosimetry wouldn’t allow monitoring and control
- The novel idea to monitor neutron production in such conditions, circa 2015:
  - Use small high pressure Ionization Chambers inside a moderator to achieve high dynamic range of the measurements
  - Symmetric ^{3}He- and ^{4}He-filled ICs to evaluate and subtract photons
  - Electrometer to read small pA-range currents over long triaxial cables
  - Use of Be-loaded moderator for uniform energy response

NDX Prototype FLUKA Model



- ❑ Small high pressure ionization chambers filled with ^{3}He and ^{4}He
- ❑ Cylindrical neutron moderator with Beryllium-loaded layer

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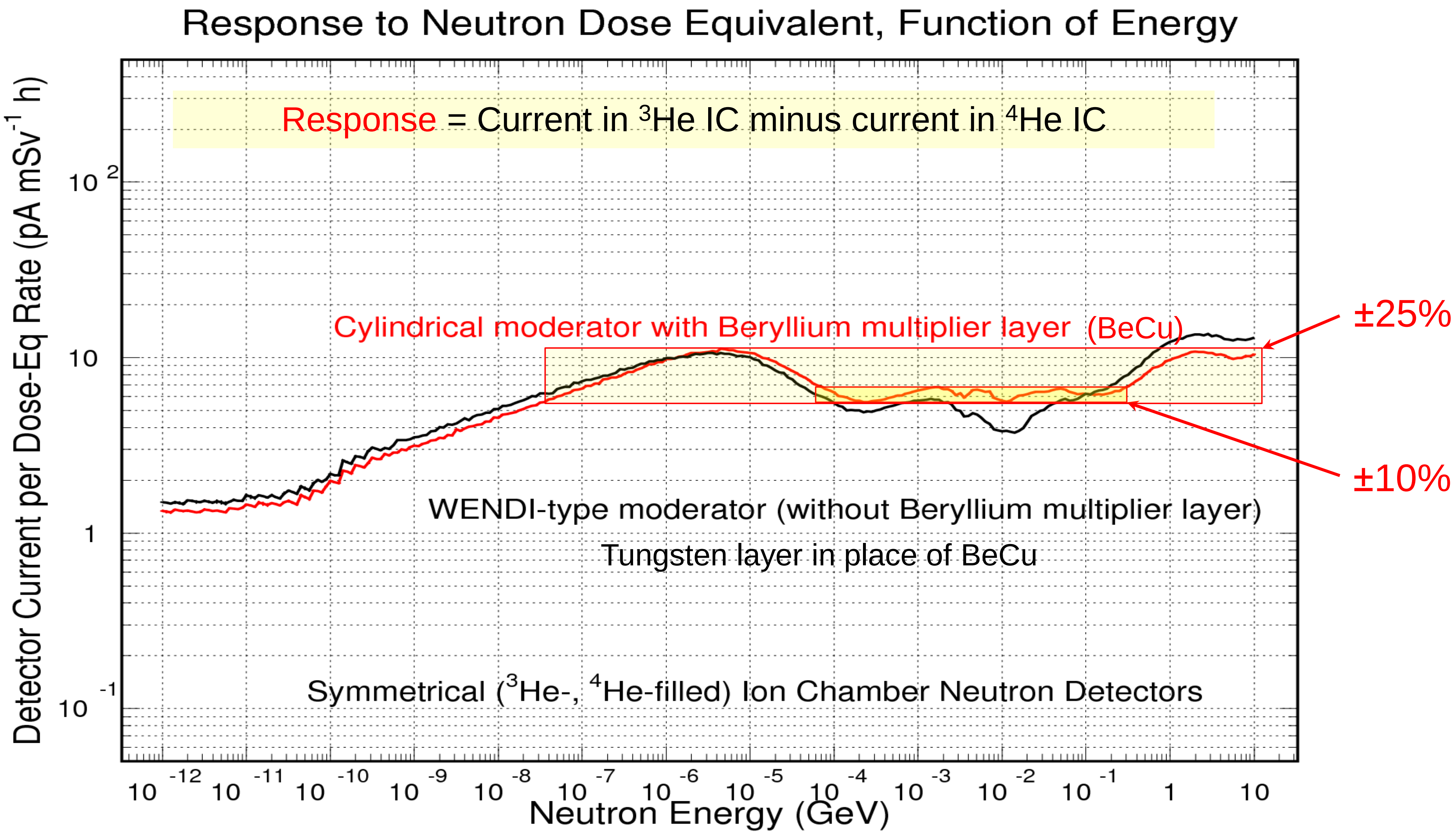
Principle of Operation

- Captured moderated thermal neutrons produce measurable current in the ^{3}He-filled ion chamber and photons produce small and symmetrical response in both ^{3}He- and ^{4}He-filled ion chambers
- A sensitive electrometer-type current readout, with a long-term stability in 0.1 pA range (I400 electrometer from PTC). The readout is possible using long (up to 100-150 feet) triaxial cables
- 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 (~0.05-10 GeV) neutrons interact with Copper and improve the spectral response due to the spallation reactions

Energy Dependence of the Detector Response



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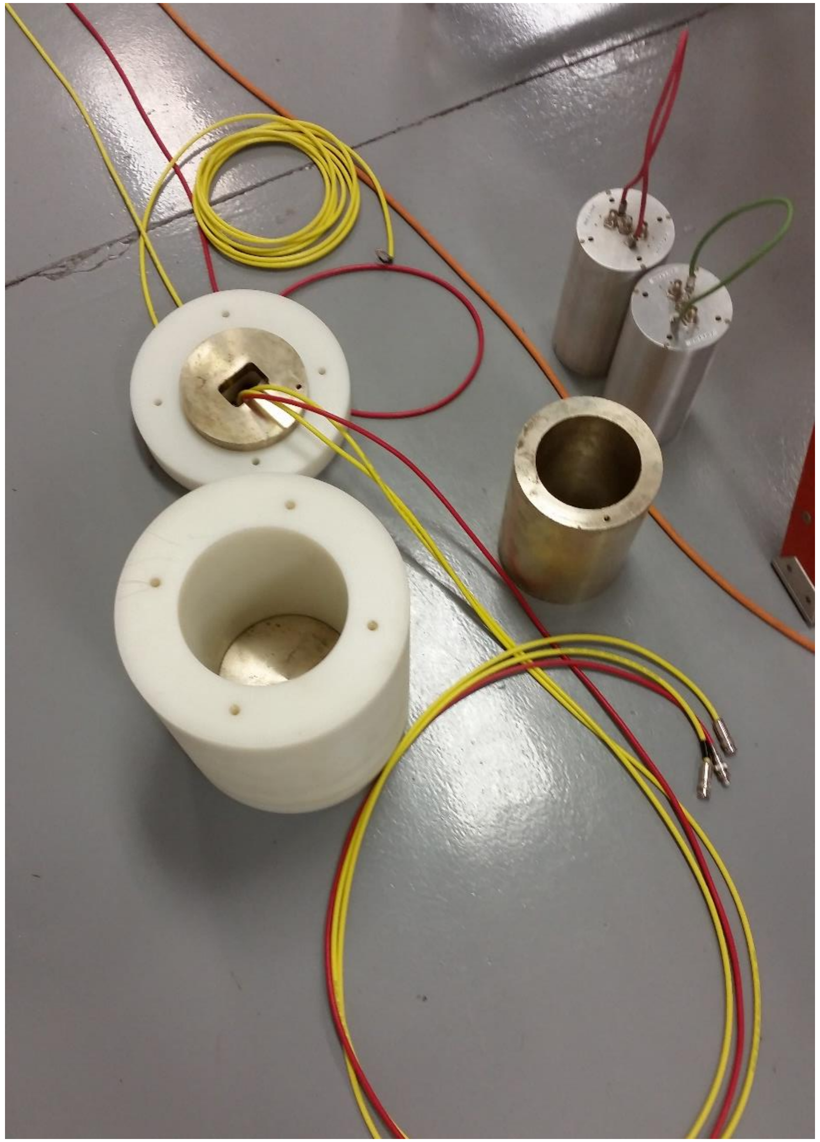
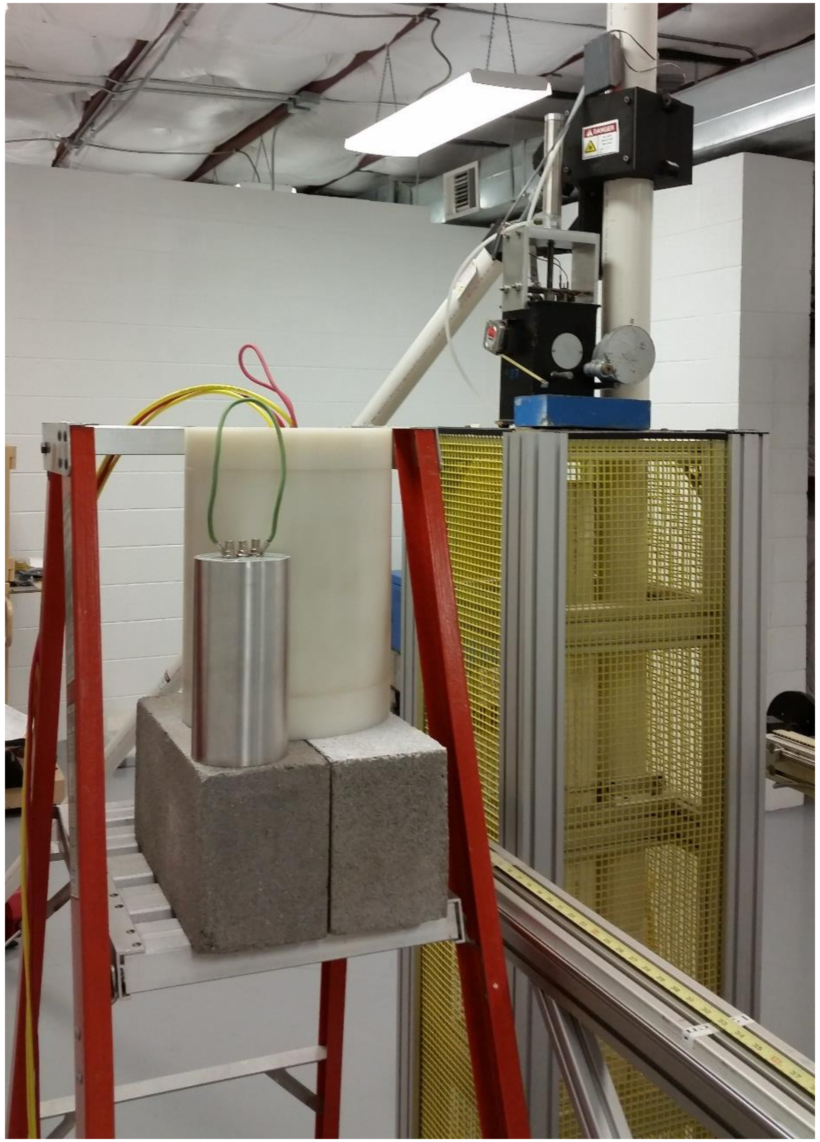
History of NDX detectors at JLab

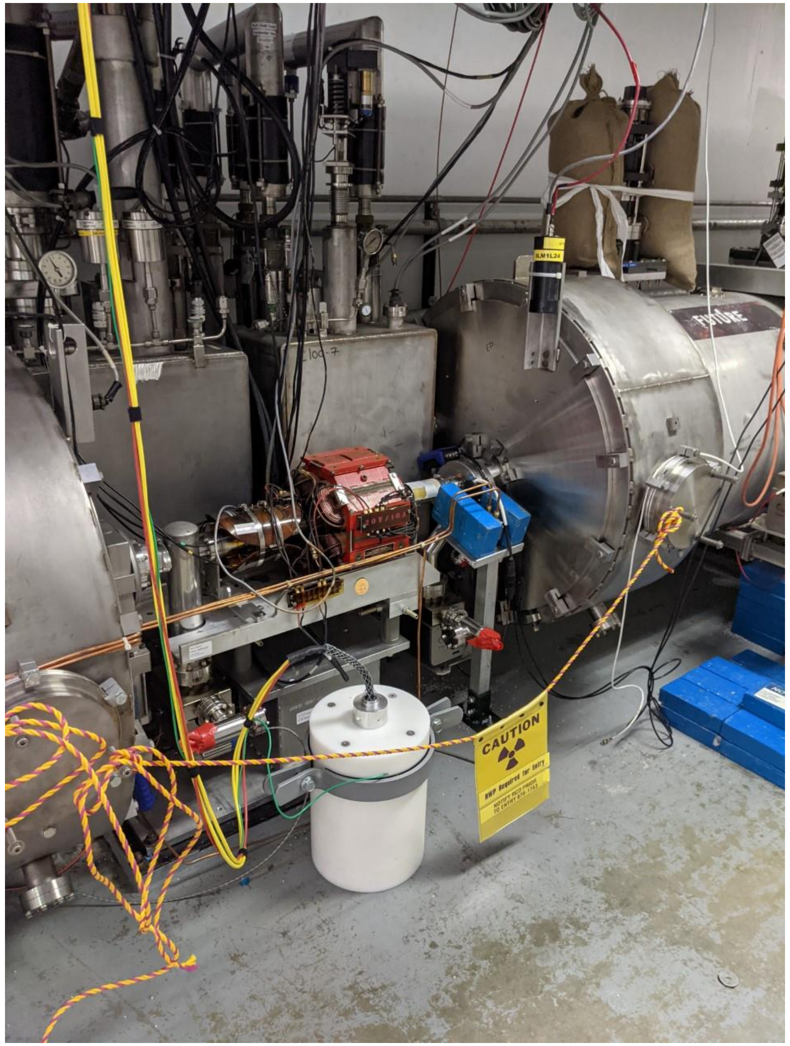
- 2016-2018: simulations, design optimization, prototyping, tests
- 2018-2020: various deployments of the prototype detectors
  - Around experimental targets and beamlines at the Experimental Halls
  - In the accelerator tunnel at one of the C100 cryomodules
  - Demonstrated reliable and stable operation in wide-range dose rates
  - Rates of up to 10-30 rem/h neutrons in 0.3-1 kR/h photon field
  - First use in the field emission optimization
- July 2021: 22 new detectors with updated design in the tunnel
  - Main task to optimize the field emission radiation around C100s
  - Successful use in the FE optimization during 2021-2023 operations
  - Successful use in the beam transport optimization (steering, halos,…)
- Summer 2023: 10 more units to be deployed in the tunnel

Two Prototype Detectors and the New NDX Set

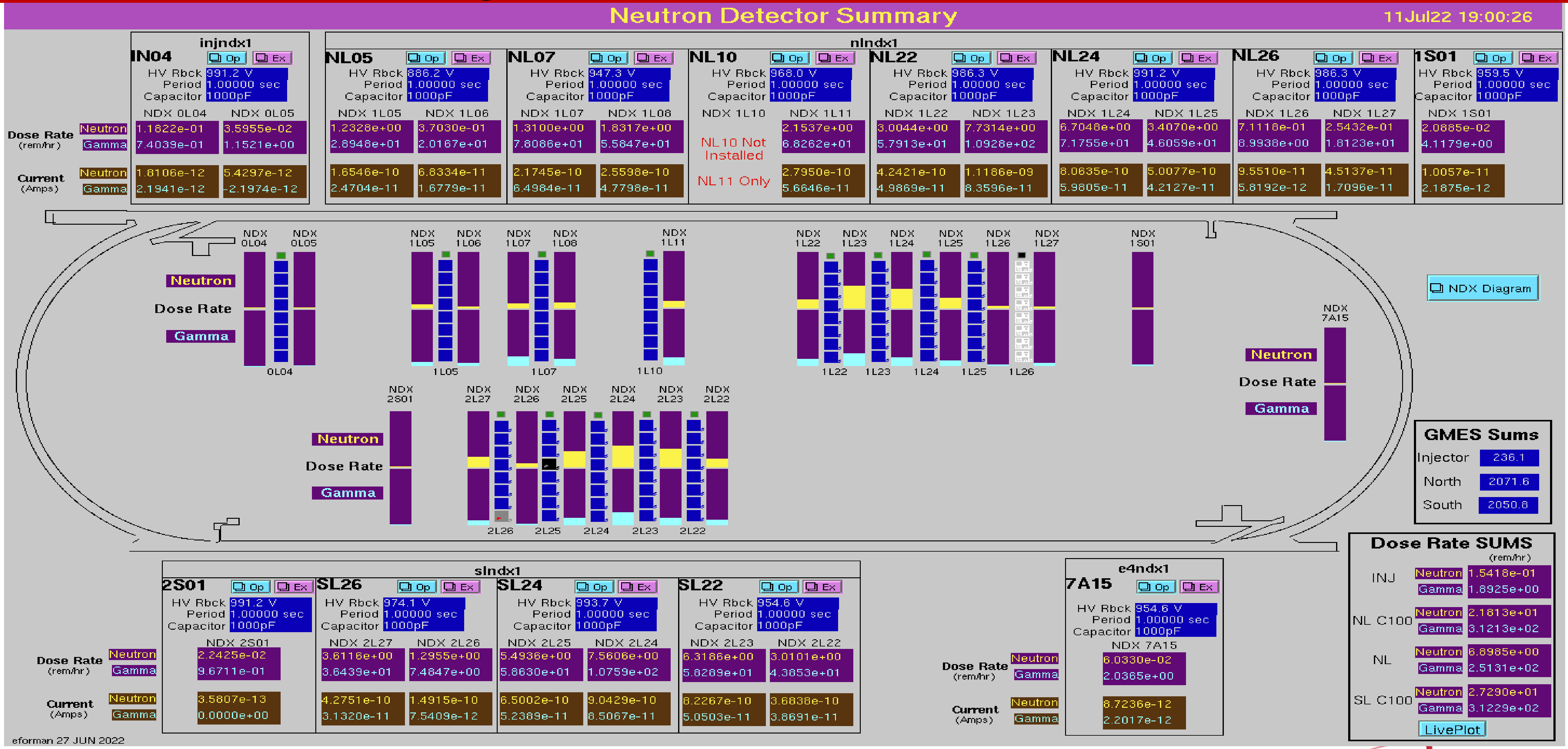




New Detectors at the Range and in the Tunnel



NDX Summary EPICS Screen at CEBAF



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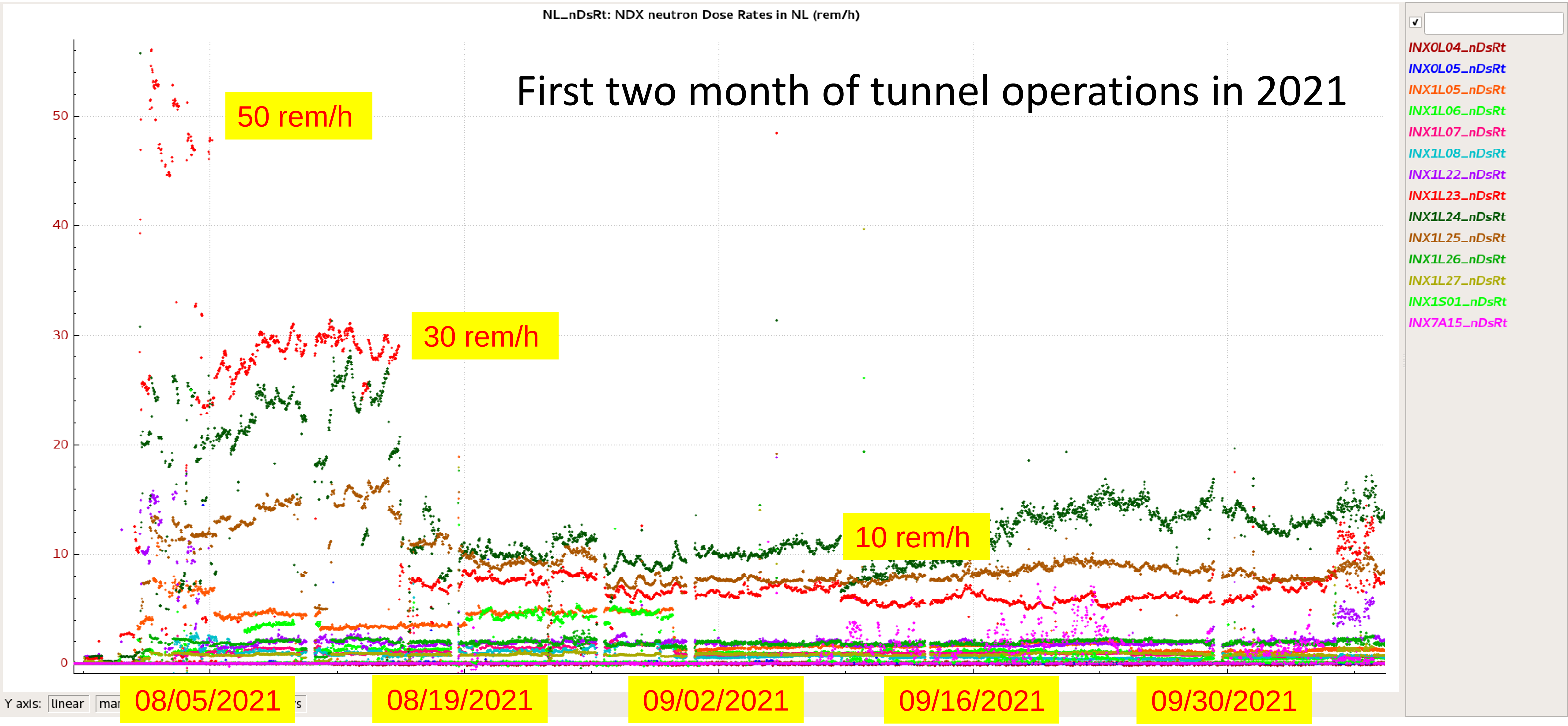
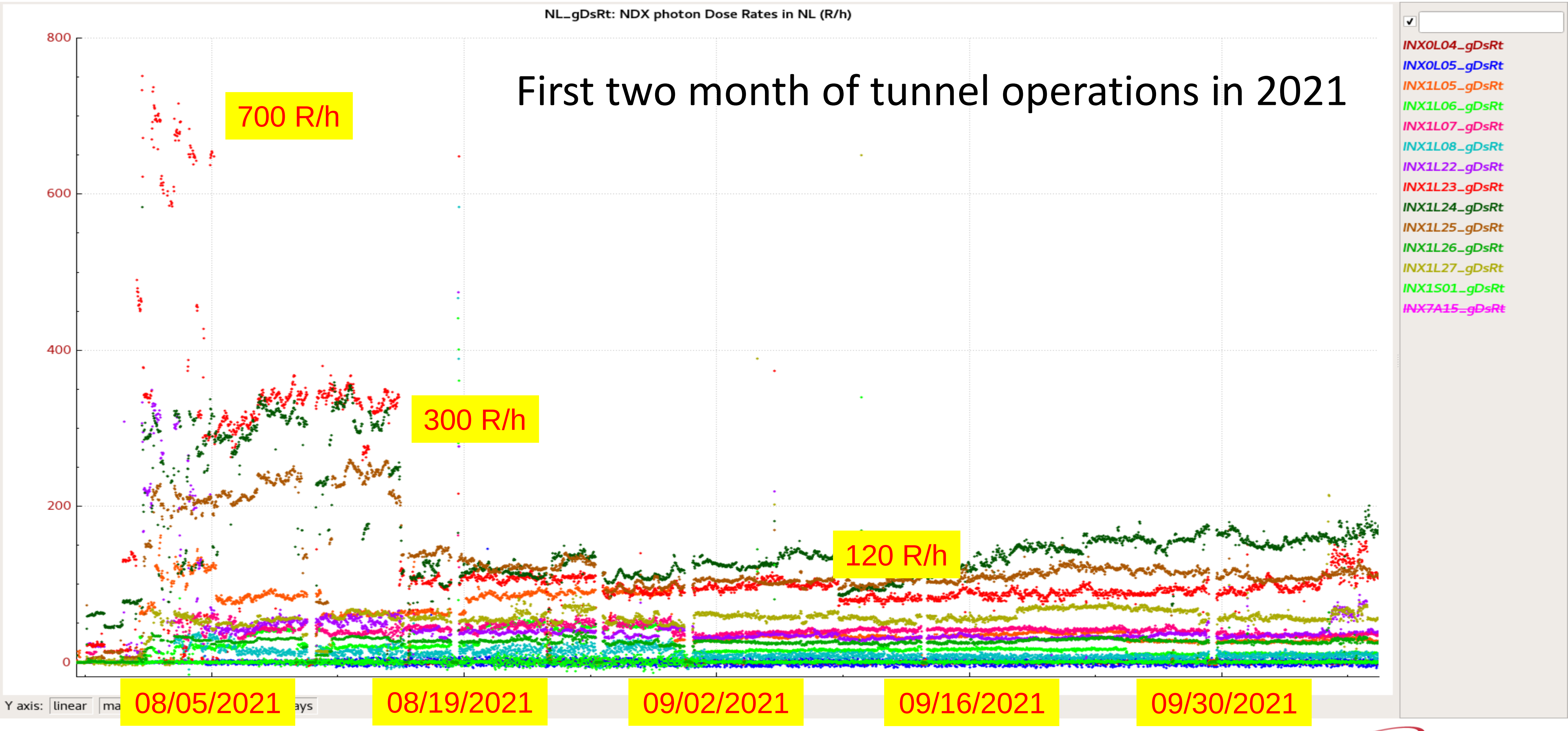
Two-Month History of Neutron Dose Rates at NL



Two-Month History of Photon Dose Rates at NL



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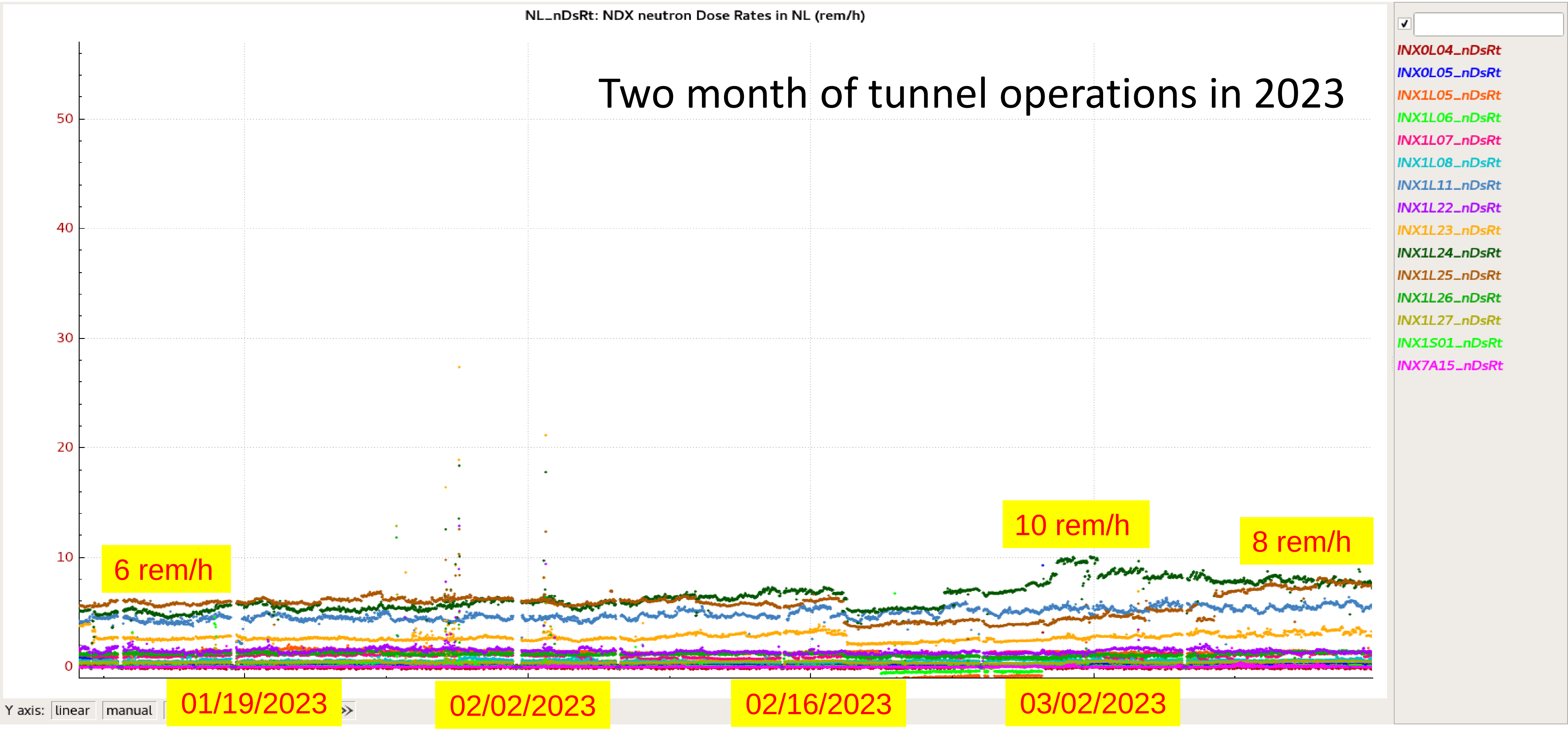
History of Neutron Dose Rates at NL in 2023



Neutron Dosimetry at CEBAF and beyond

- Neutron dose rate monitoring in the accelerator tunnel is used for
  - Field emission optimization in cryomodules
  - Beam loss control, beam steering optimization
- Real-time neutron monitoring helps to optimize running conditions
  - Minimize radioactive isotope production
  - Minimize personnel exposure during service accesses
  - Limit radiation damage to equipment
- Real-time neutron and photon monitoring in the experimental halls helps in the optimization of the running conditions during Physics experiments
- Very linear dose rate response and great stability makes it a good candidate for the dose rate measurement standard detector

Summary

- NDX neutron dose rate meters may characterize high energy beam losses and activation at high energy particle accelerators
- In the case of C100 cryomodules at CEBAF NDX detectors monitor multi-cavity and multi-module amplified field emission, the source of radiation damage and site activation
- In addition, NDX may also characterize local high energy beam losses in the vicinity of their location
- Neutron monitoring provides better coverage of the monitoring site than typical photon radiation detectors, due to better neutron propagation through typical materials, and more isotropic production source terms. Beam loss location/triangulation possible
- NDX detectors serve well the needs of performance optimization at C100 cryomodules and at other locations at CEBAF

Summary (continued)

- NDX detectors, PTC electrometers and data acquisition in combination with EPICS data readout show stable and reliable operation, with expected performance parameters
- Work is in progress to use the NDX data in the Artificial Intelligence program for automated machine control and optimization. Expansion of the system is scheduled at CEBAF
- NDX technology is suitable for real time neutron measurements essentially in any high dose rate radiation fields; will work in pulsed fields, or in fields dominated by photons
- Publication: NDX: Neutron Dose Rate Meters with Extended Capabilities, 2019 IEEE Nuclear Science Symposium and Medical Imaging, Conference Paper, Publisher: IEEE
- Patent No.: US 10,281,600 B2, May 7,2019

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Extras

Notice

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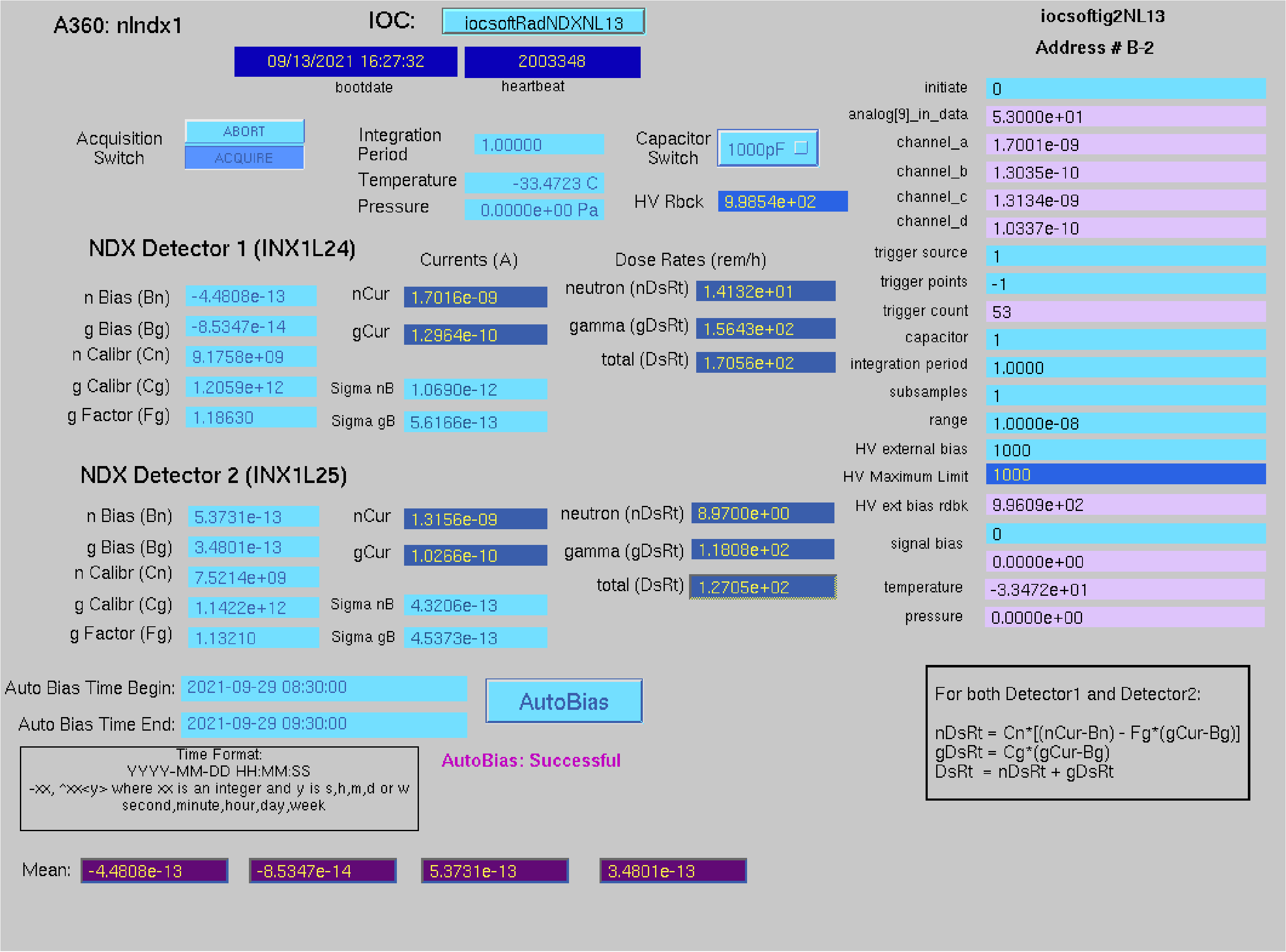
NDX Expert EPICS Screen

- Two NDX detectors per one I400 electrometer from PTC
- Input: HV, integration time, integrating capacitor to set the dynamic range
- Calibration parameters from the CED database
- Tool to measure and apply current biases
- Output: Neutron and gamma Ion Chamber currents
- Dose rates in rem/h calculated



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Calibration

- The calibration of the detectors in the test neutron fields at Jlab's Radiation Control range (AmBe neutron source, max dose rate field about 75 mrem/h) resulted in the values of the calibration coefficients of about C_n = 0.12 mSv/h per pA
- The symmetric response of the ^{3}He and ^{4}He ion chambers to high photon dose rates (~1 Sv/h) was tested in our ^{137}Cs gamma irradiator, and the asymmetry was found to be under 10%. This factor is used in the subtraction procedure to obtain correct values of ionization current caused specifically by neutron captures
- The formulas for neutron and photon dose rates:

$$nDsRt = C_n*[(nCur\text{-}B_n) - F_g*(gCur\text{-}B_g)],\quad gDsRt = C_g*(gCur\text{-}B_g)$$

- Long-term bias stability within ~0.5-1pA (~0.05-0.1 mSv/h)

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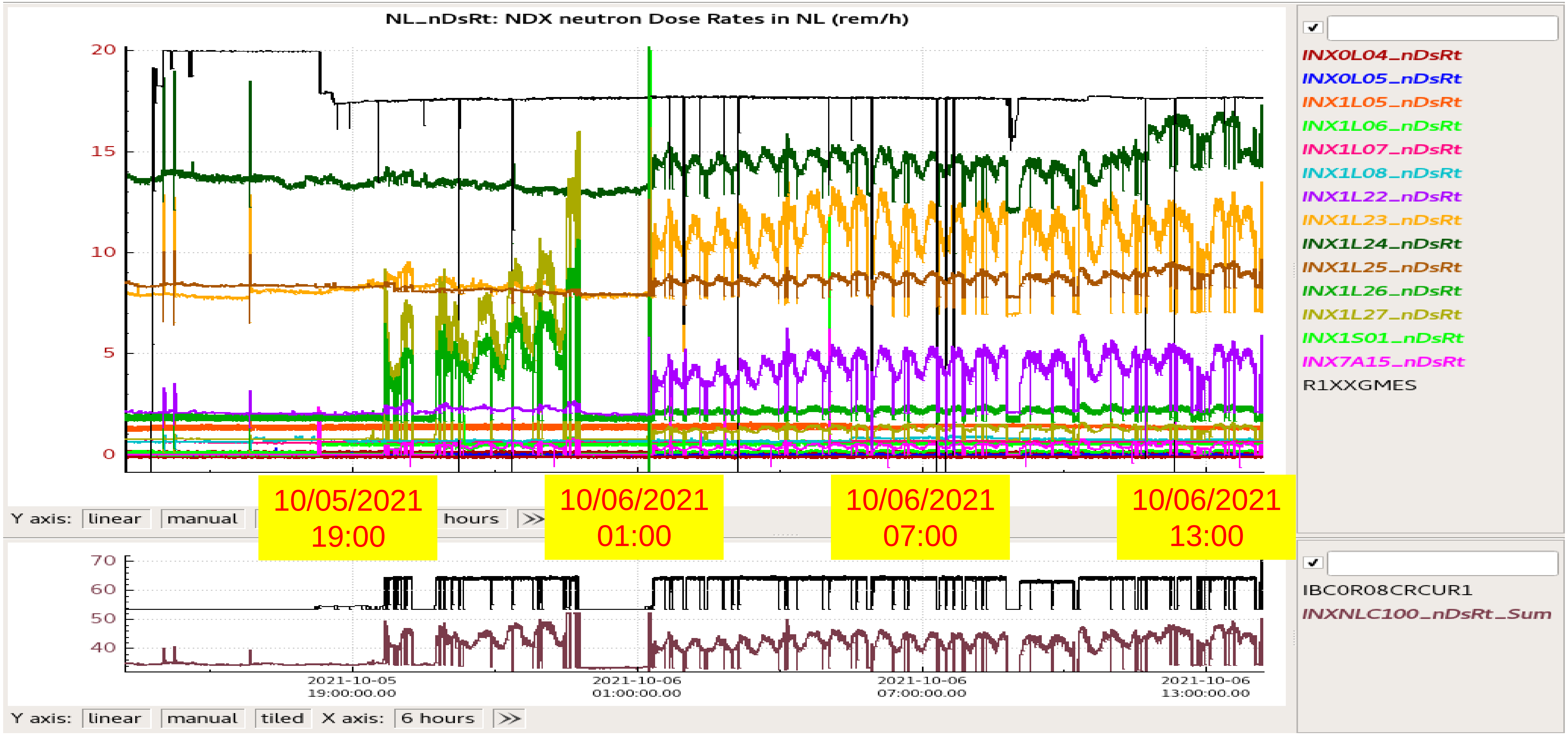
Chronic Beam Loss Pattern, October 2021



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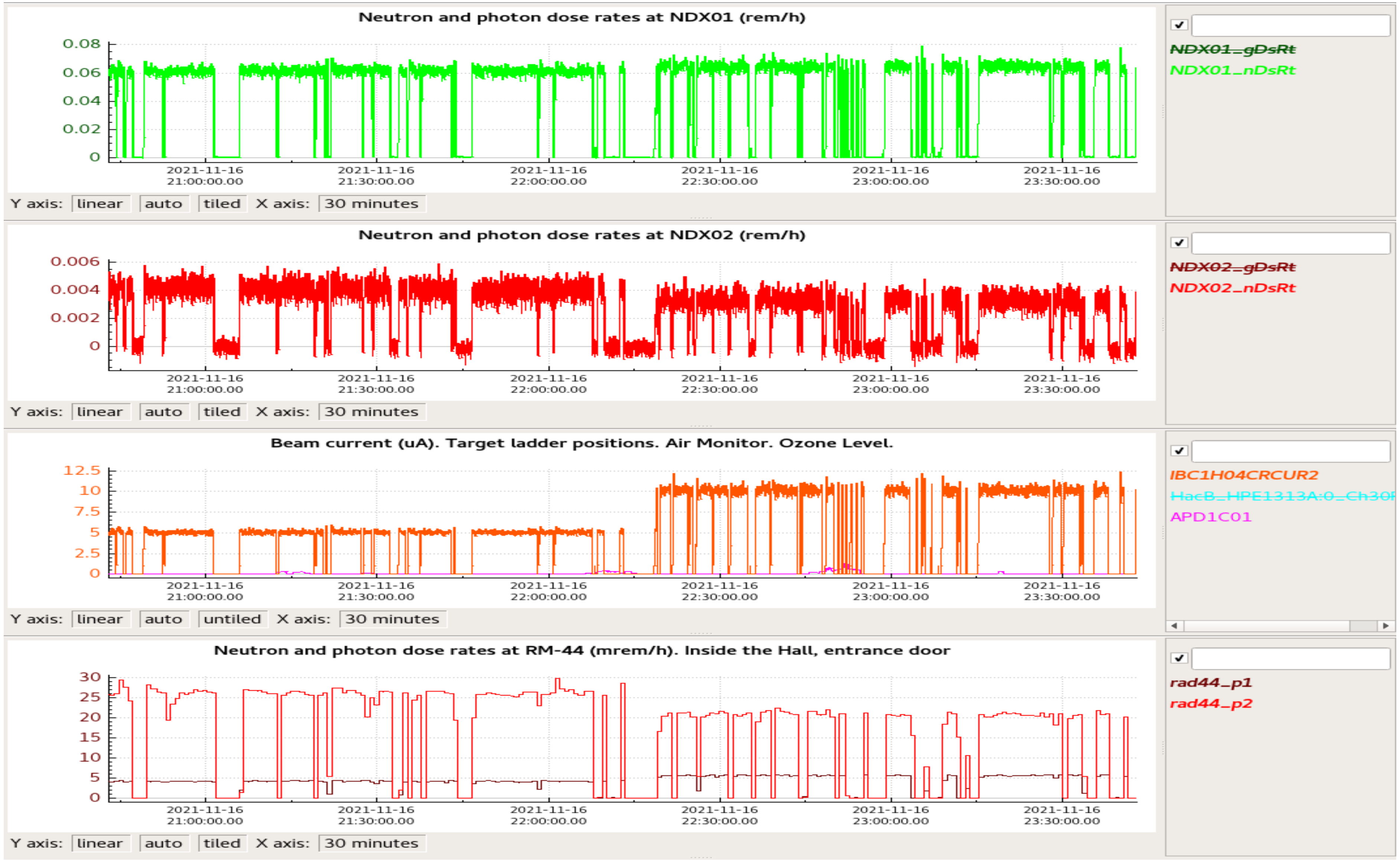
Low Level Neutron Dose Rate Measurements

- ❑ Two NDX detectors currently installed in Hall A inside the shielding enclosures for electronics
- ❑ NDX01 in the bunker close to the target. Observed neutron dose rates at about 60 mrem/h
- ❑ NDX02 in the shielded electronics hut at the back of the Hall. Readings are close to the sensitivity level of a few mrem/h



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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

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