Impact of high deposited energy on Single Event Burnout in LGAD sensors

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on behalf of:

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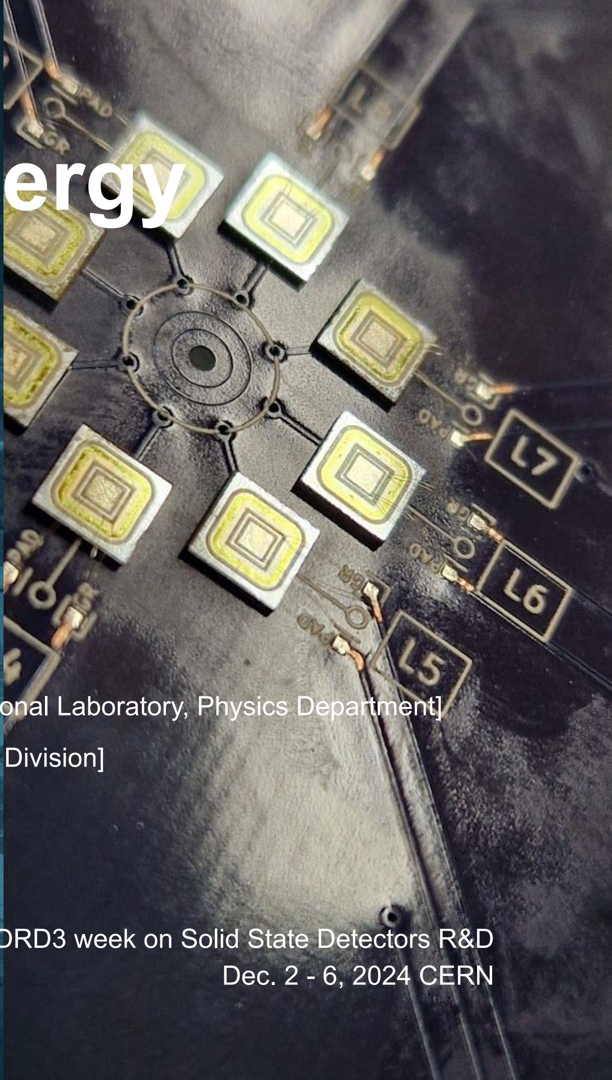


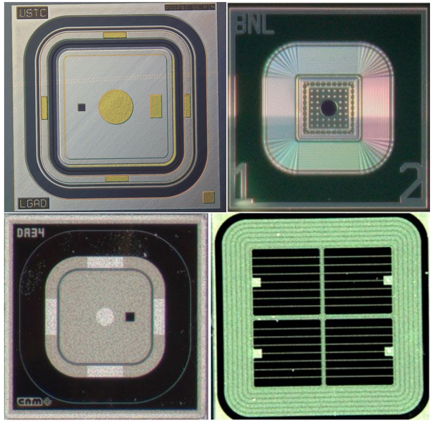
2nd DRD3 week on Solid State Detectors R&D
Dec. 2 - 6, 2024 CERN

Single Event Burnout

Low Gain Avalanche Diodes (LGADs)…

- …can achieve 20-30 ps timing thanks to **internal gain**
- …are being extensively used in **HEP, NP, space applications**, etc.
- …will be central in future HEP (HL-LHC, FCC) and NP (EIC) experiments
- …can withstand **fluences** up to ~ 10^{15} n_{eq}/cm^2

LGAD sensors produced by various manufacturers



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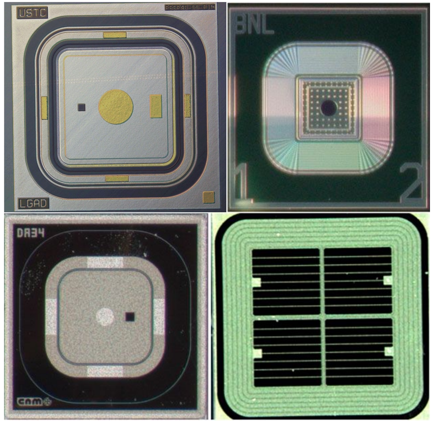
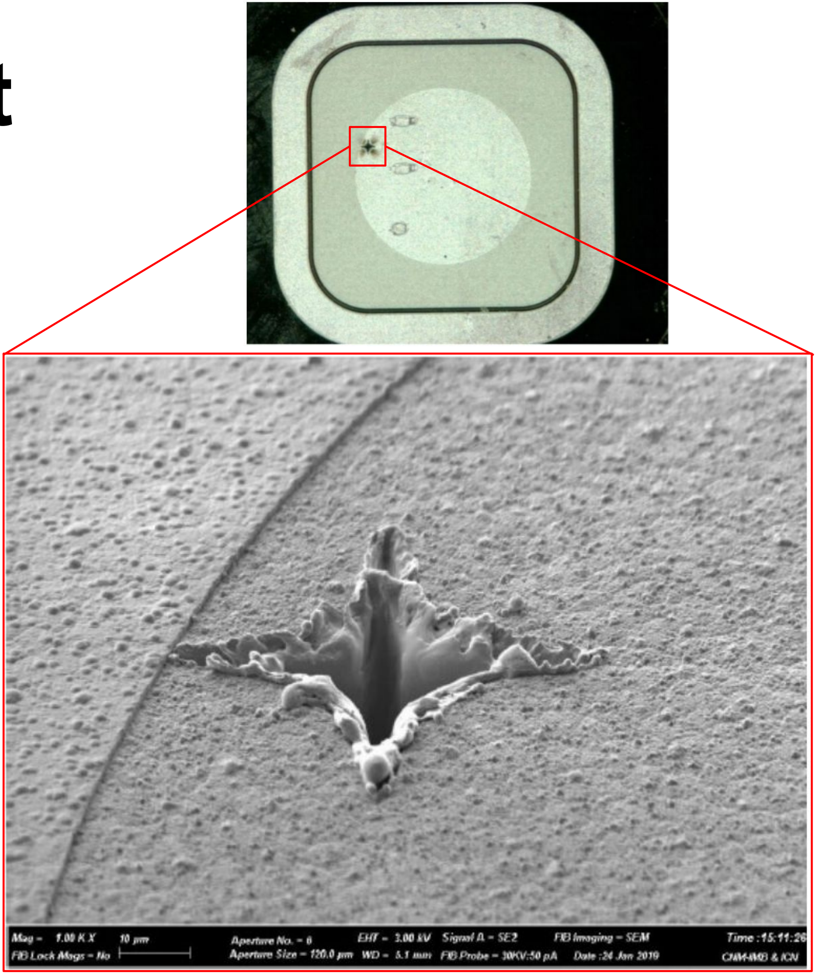


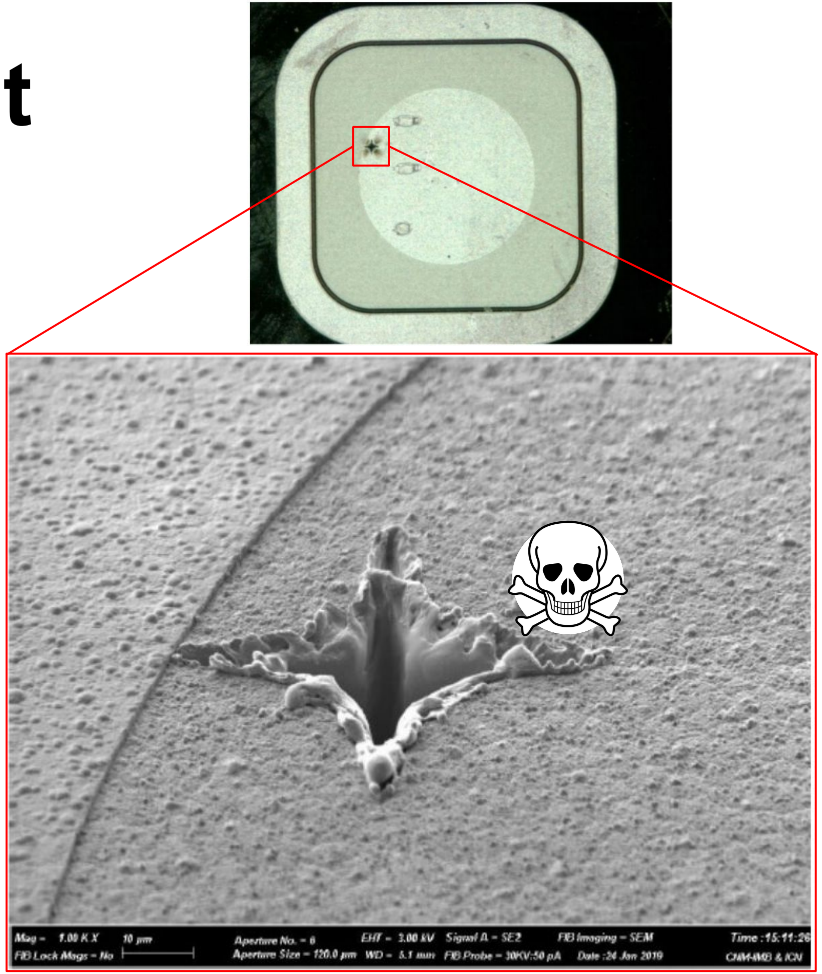


V. Gkougkousis, "LGAD Safety and Stability Concerns " – HGTD Sensor Meeting April 2018, CERN-OPEN-2023-017

Single Event Burnout

Ionizing radiation can create temporary damage (Gain Suppression) or permanent fatalities (**Single Event Burnout, SEB**)

- In high E^{dep} interactions, high local charge density is created in silicon
- **Collapse of the local field** and avalanche breakdown
- Enough to **melt silicon** and destroy the entire sensor



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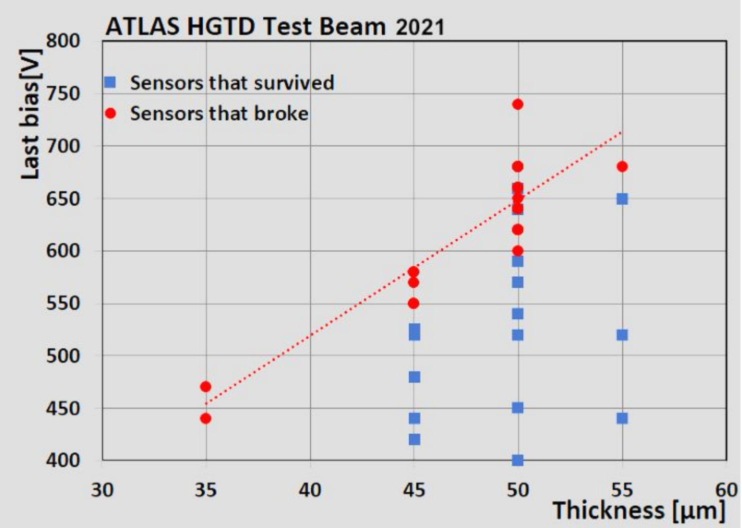
SEB Threshold

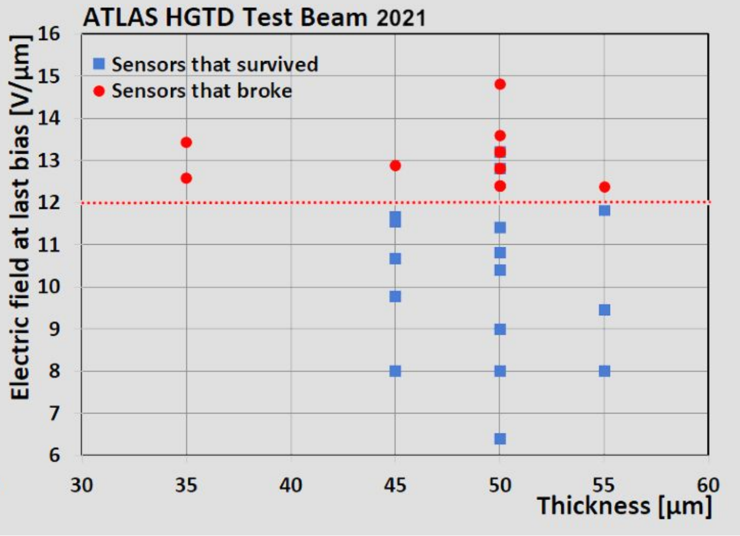
Most important thing you should remember from this presentation:

SEB is a Threshold effect

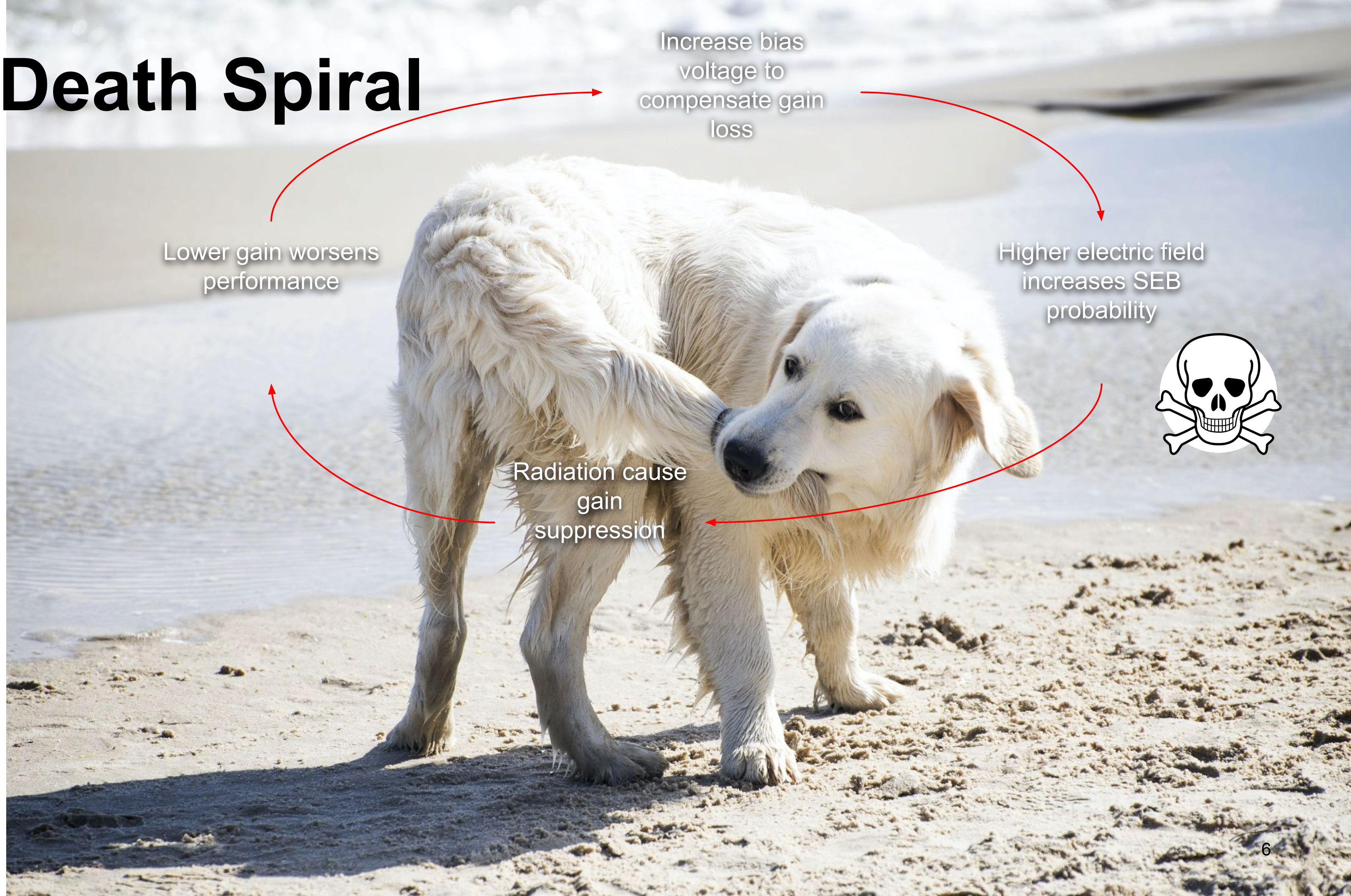
- SEB threshold depends on **electric field**
- Previous studies (ATLAS, CMS et al.) observed that $\mathbf{E_{SEB}}$ **~12 V/µm** are required to trigger SEB

L.A. Beresford "Destructive breakdown studies of irradiated LGADs at beam tests for the ATLAS HGTD





The Death Spiral

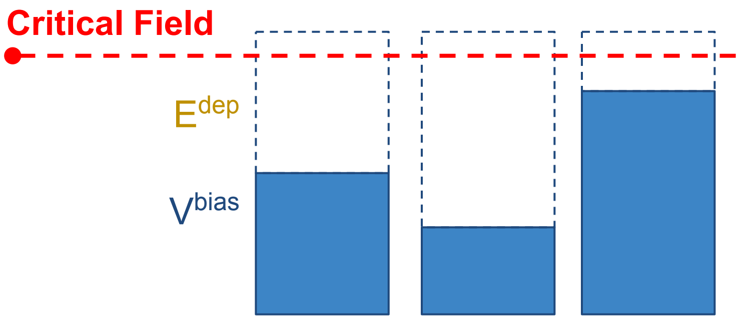


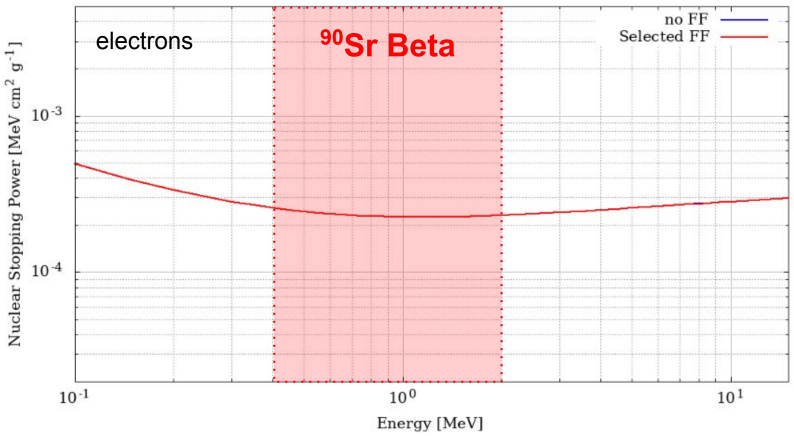
SEB vs E_{dep}

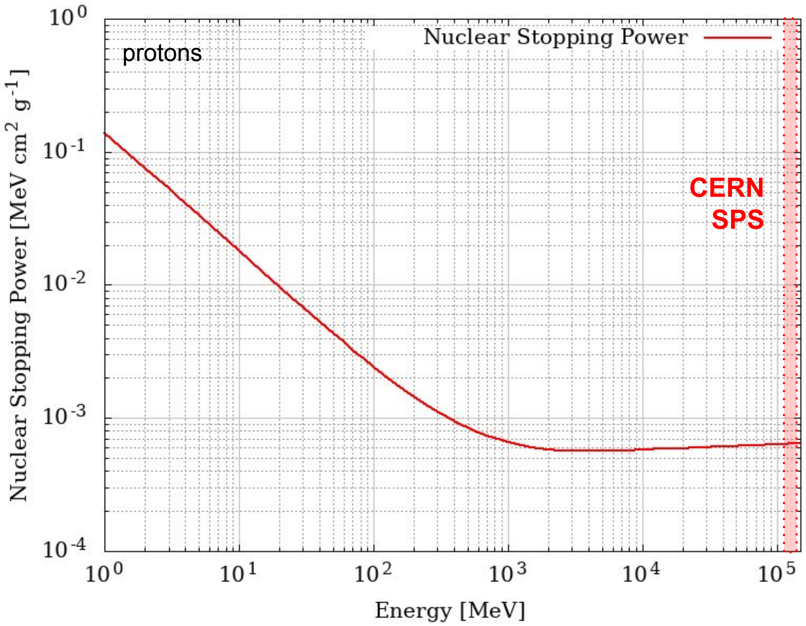
Studies of SEB performed so far using…

- Betas from **^{90}Sr**
- **CERN SPS** (120 GeV pions) / **FNAL FTBF** (120 GeV protons)
- DESY high-energy electrons

All studies use minimum ionizing particles…
but SEB triggered by **deposited energy!**



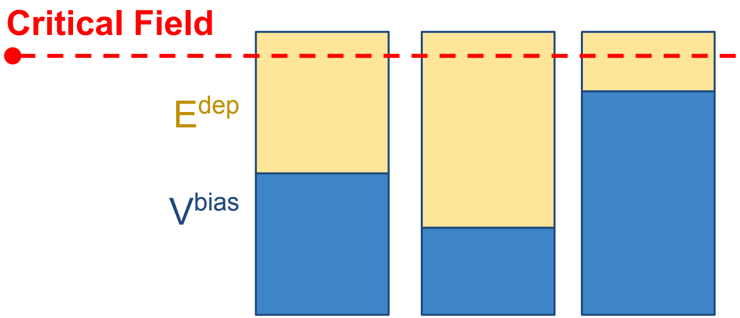


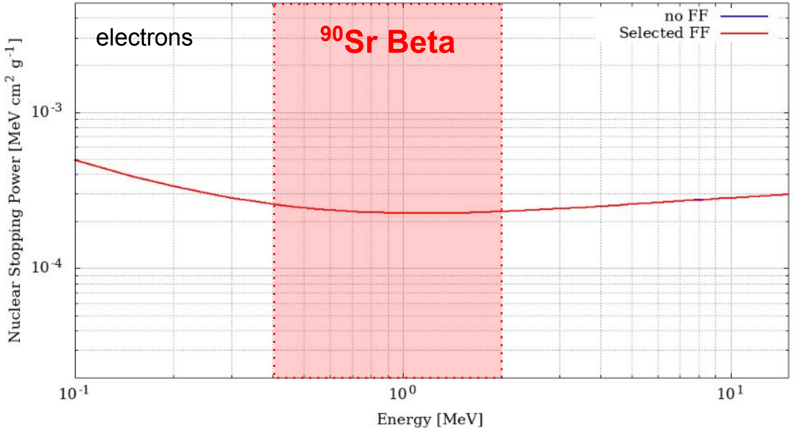


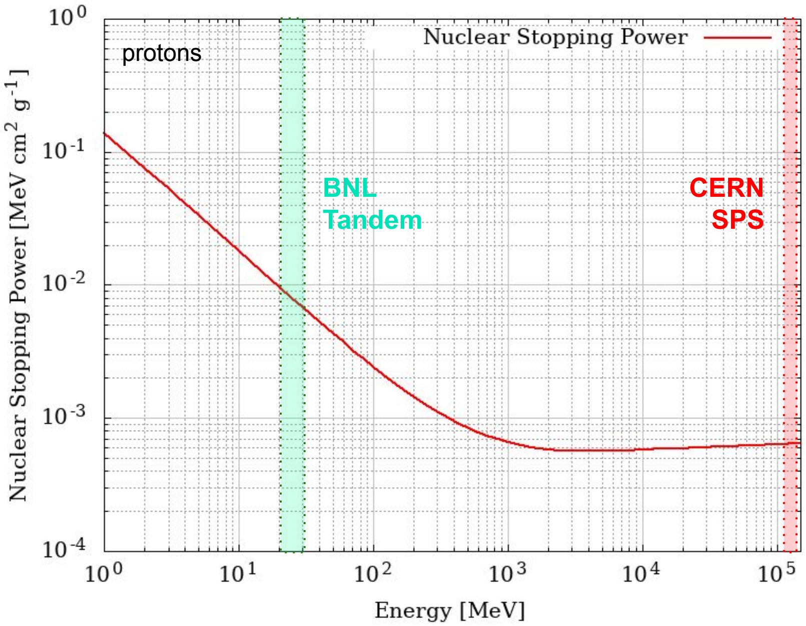
SEB vs E_{dep}

Does SEB Threshold depends on deposited energy as well?

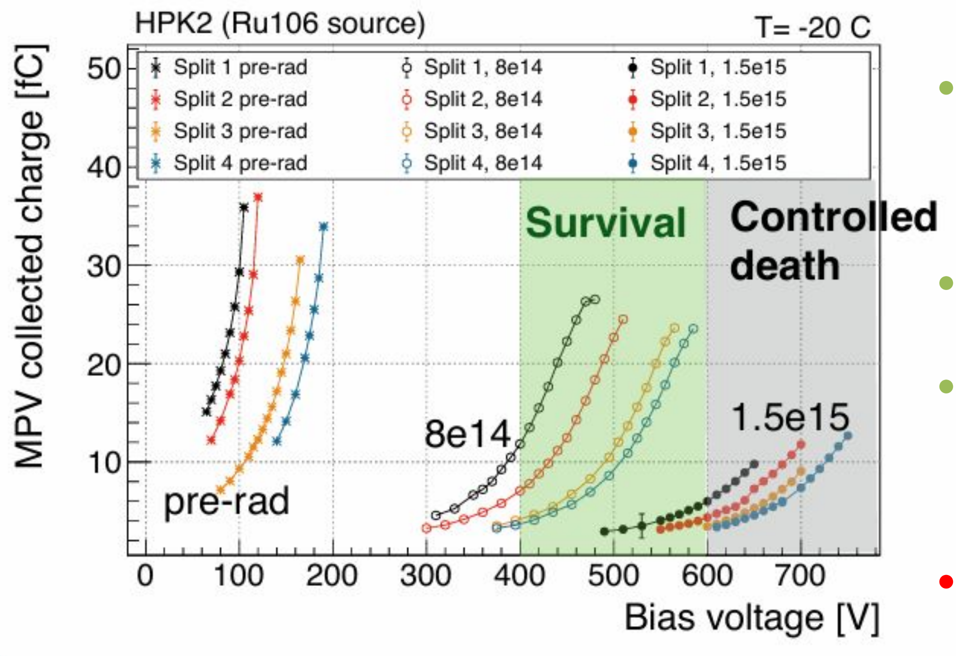
- Exploit BNL **Tandem Van De Graaff**
- Inject more charge in interactions with lower energy protons and heavy ions
- Phase space unreachable with electrons or higher energy accelerators (SPS, FNAL, etc.)







Critical



Plot courtesy of R. Heller [LBNL], *"Studies of LGAD mortality using the Fermilab Test Beam"*

- Electric field only defined by:
  - **Silicon thickness**
  - **Bias Voltage**
- Testing BNL fabricated-LGADs & diodes with **different thicknesses (20, 30, 50 um)**
- Threshold field for SEB: **E_{SEB}~12V/μm**
  - **V_{SEB} = 600 V for 50um thick sensor**
  - …non-irradiated LGADs break down at **V_{BD}<200 V**
- **Extensive irradiation of LGADs** ($1.5x10^{15}$ n_{eq}/cm^2) is required to achieve such electric field

RINSC neutron flux

LGADs irradiated to 1.5x10^{15} n_{eq}/cm^2 at RINSC

(Rhode Island Nuclear Science Center)

- Neutrons up to 1-10 MeV
- 2 MW, light water cooled, pool type reactor
- Pneumatic system for samples with flux of 2x10^{12} n/cm^2s
- Post irradiation, kept at -20 C, shipped to BNL, and "baked" at 60°C for 80 min for uniform annealing

SEB at BNL Tandem Van de Graaff

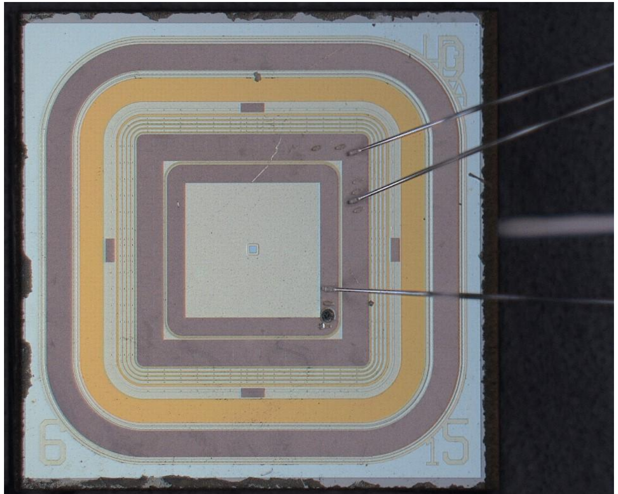
Beam parameters

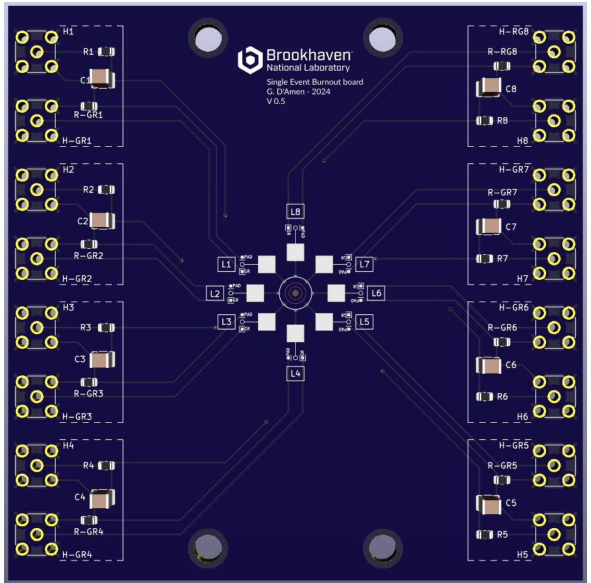
Species	Energy	E_{dep}	Target Rate	Target fluence (per voltage point)
Proton	28 MeV	O(10) MIPS	1-2 x 10^7 p/s*cm^2	10^9 p/cm^2
Gold	330 MeV	O(10^4-10^5) MIPS	2 x 10^4 ions/s*cm^2	10^6 ions/cm^2

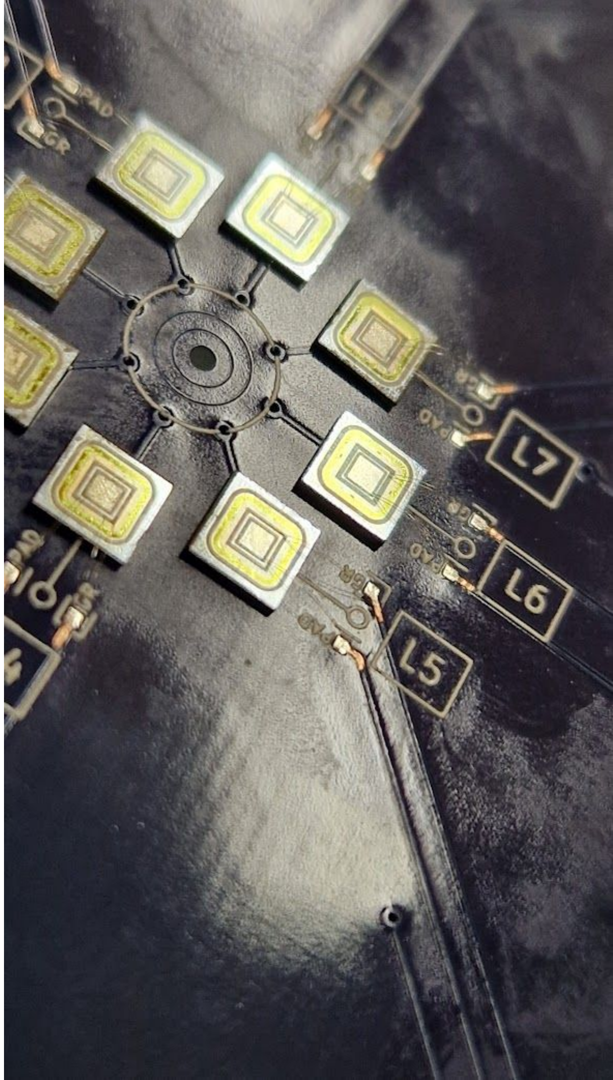
Experimental Setup

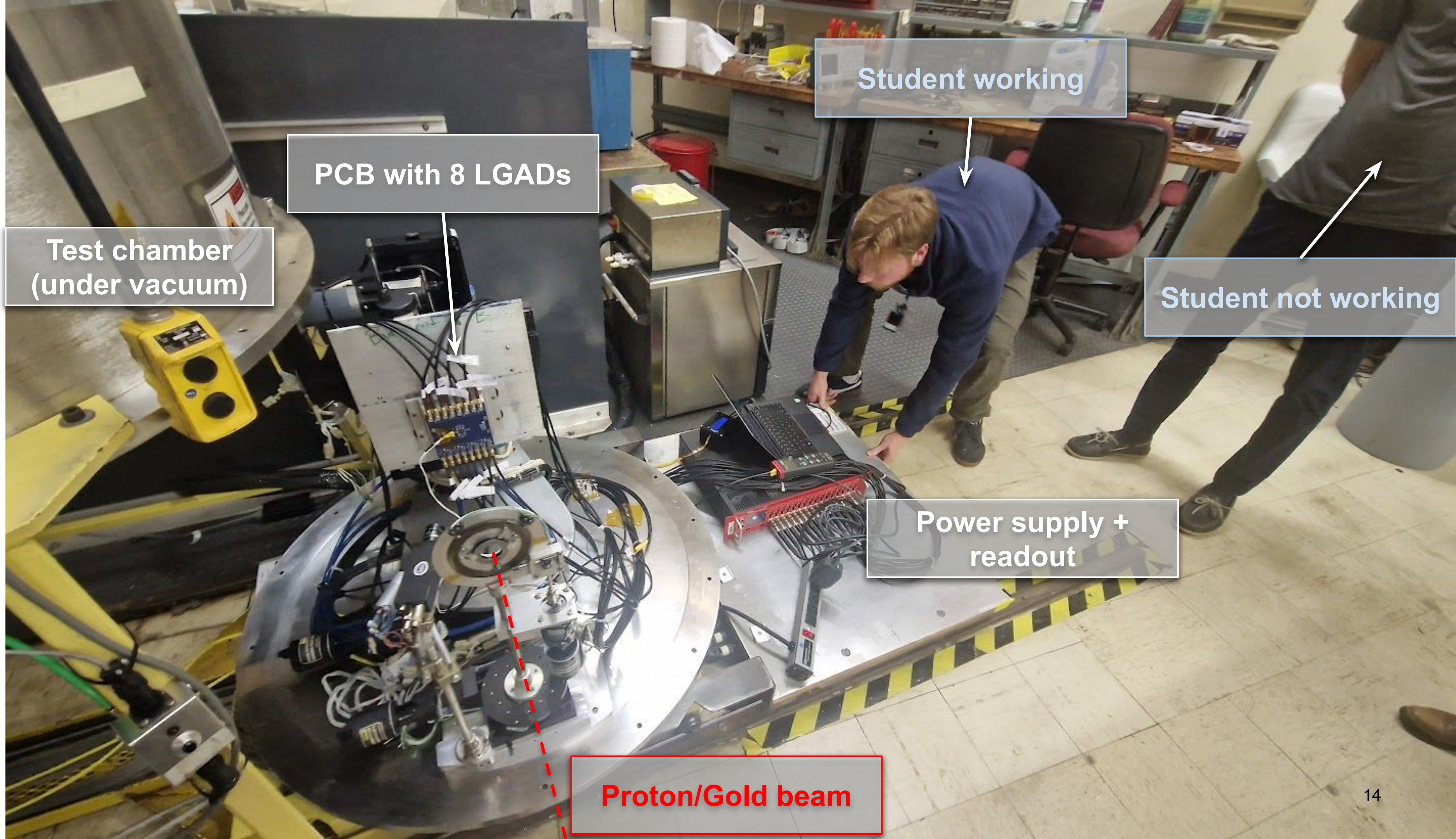
Custom readout PCB

- 8 BNL LGADs tested at once
- **Independent Bias** for each sensor
  - Bias increased in fixed steps from 0 V to Breakdown
- Independent readout of each LGAD **Pad** and **Guard Ring** currents





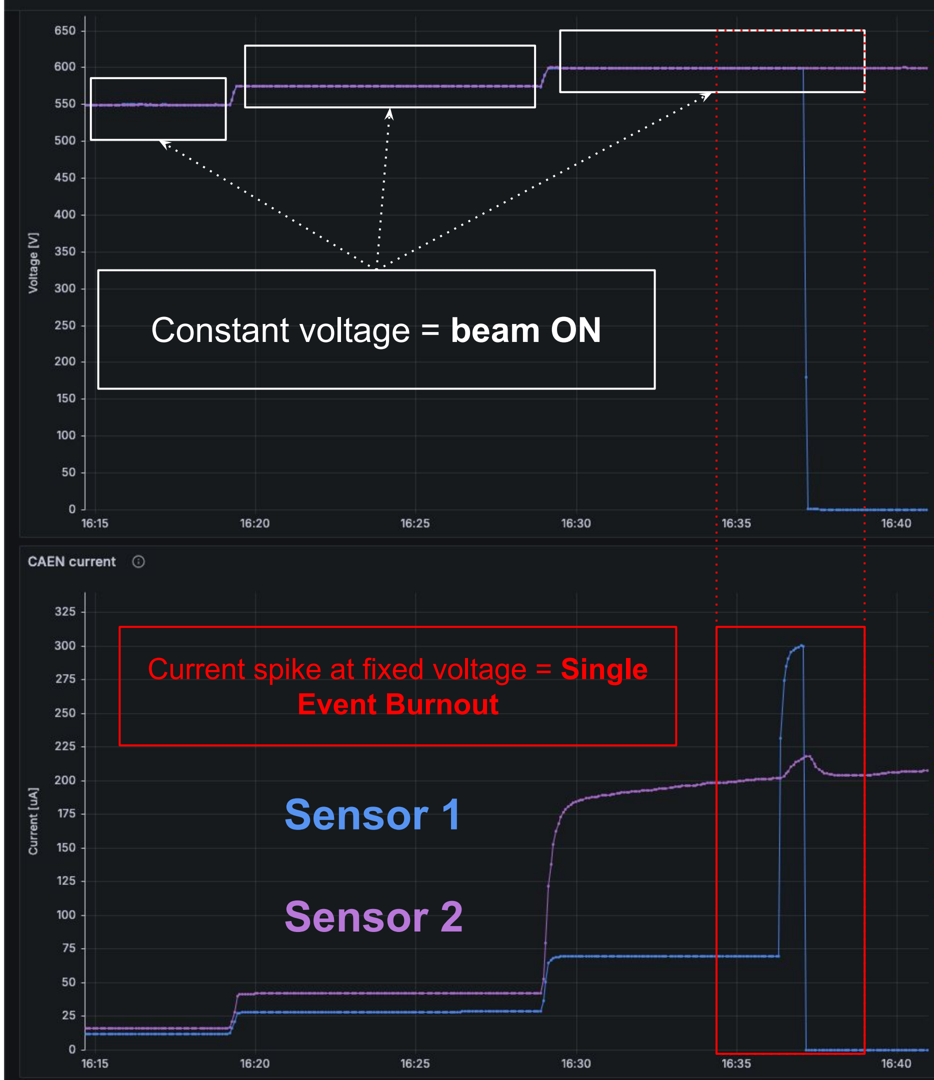



Test chamber (under vacuum)
PCB with 8 LGADs
Student working
Student not working
Power supply + readout
Proton/Gold beam

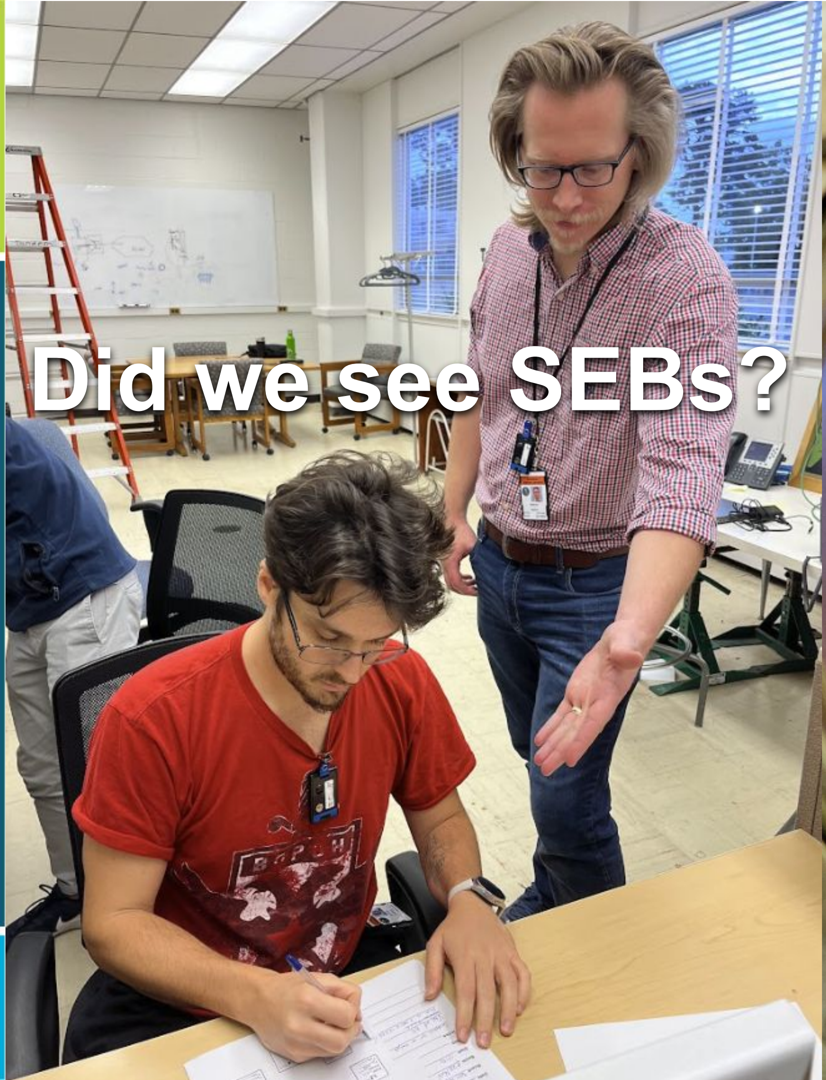
Identifying SEB

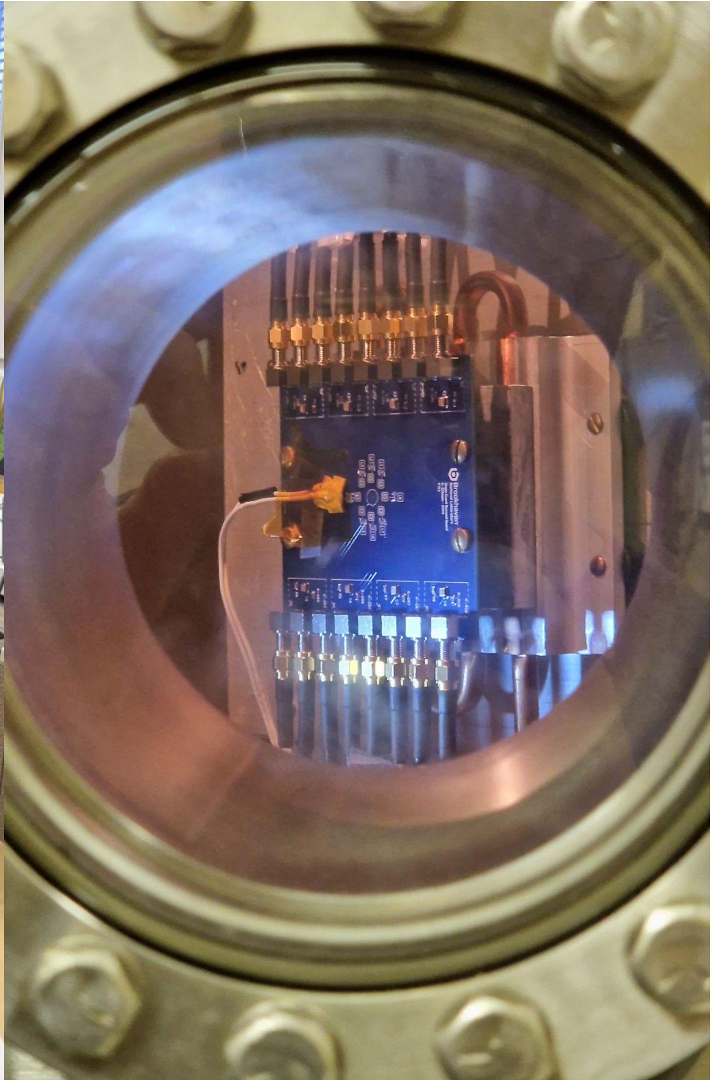
LGADs can die for a variety of reasons…

1. Monitoring V^{BIAS}, I^{PAD}, I^{GR} data using Grafana to **identify SEB candidates**
2. While beam is off, **increase voltage in fixed steps**
3. When at a **constant voltage**, fire beam, check current
4. If **current spikes** (>300 uA) at **fixed voltage with beam on**, we have a **candidate SEB**



Did we see SEBs?

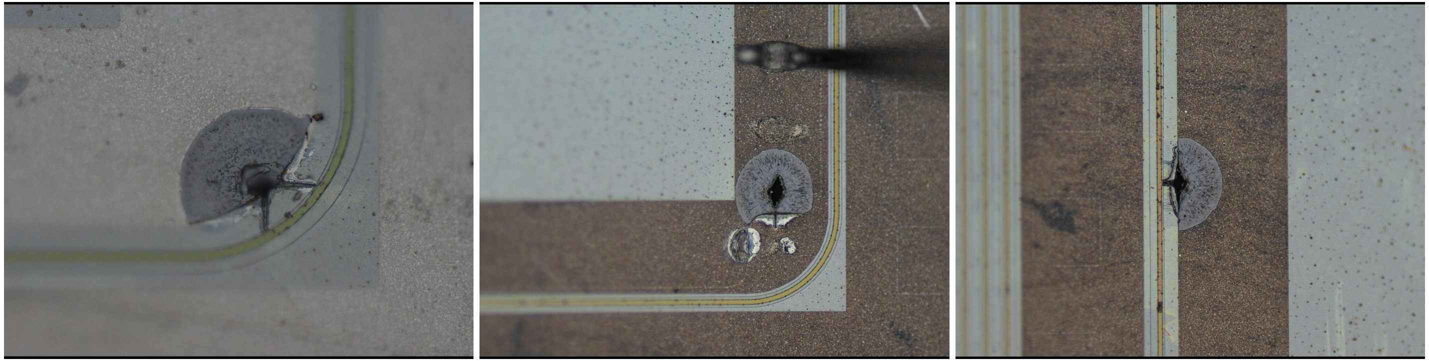




Microscopy & Death categorization

Class I Deaths
SEB candidates

- High current spike
- **Fixed** Voltage
- Beam **ON**



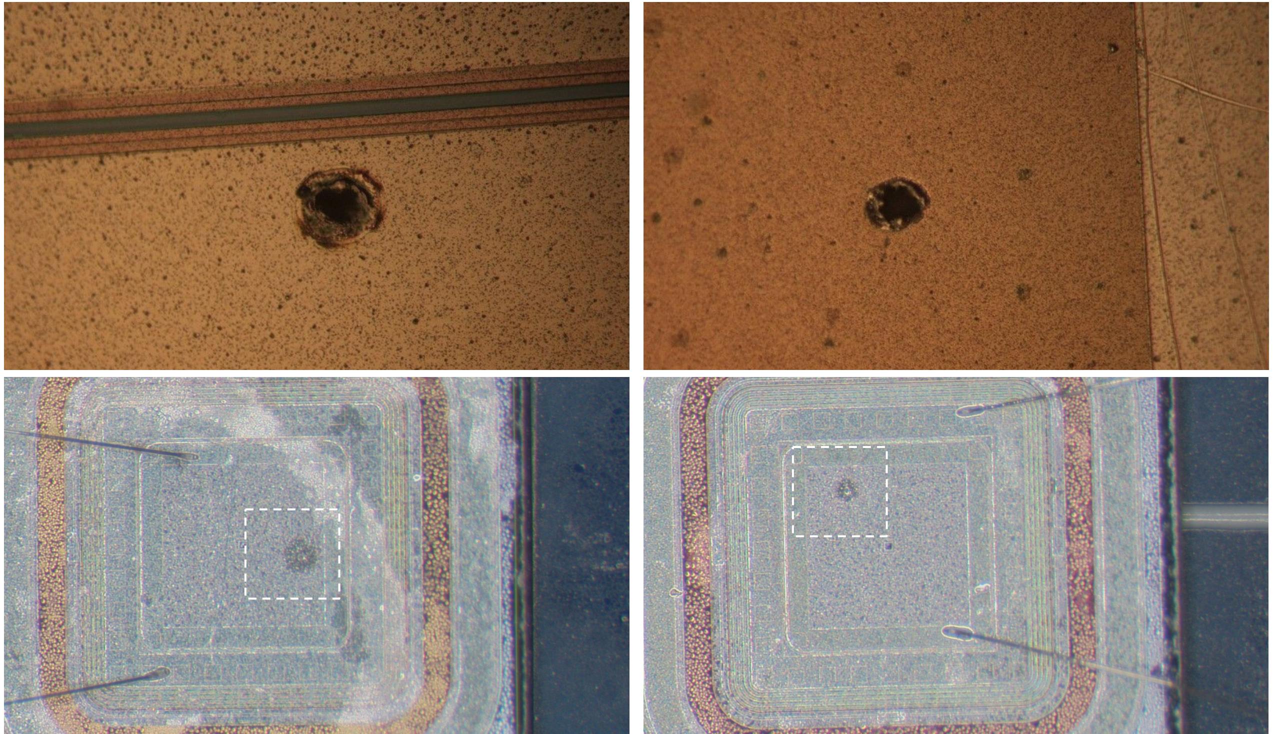
Class II Deaths
Electrical failure

- High current spike
- **Ramping** Voltage
- Beam **OFF**

Microscopy & Death categorization

SEB Death mark

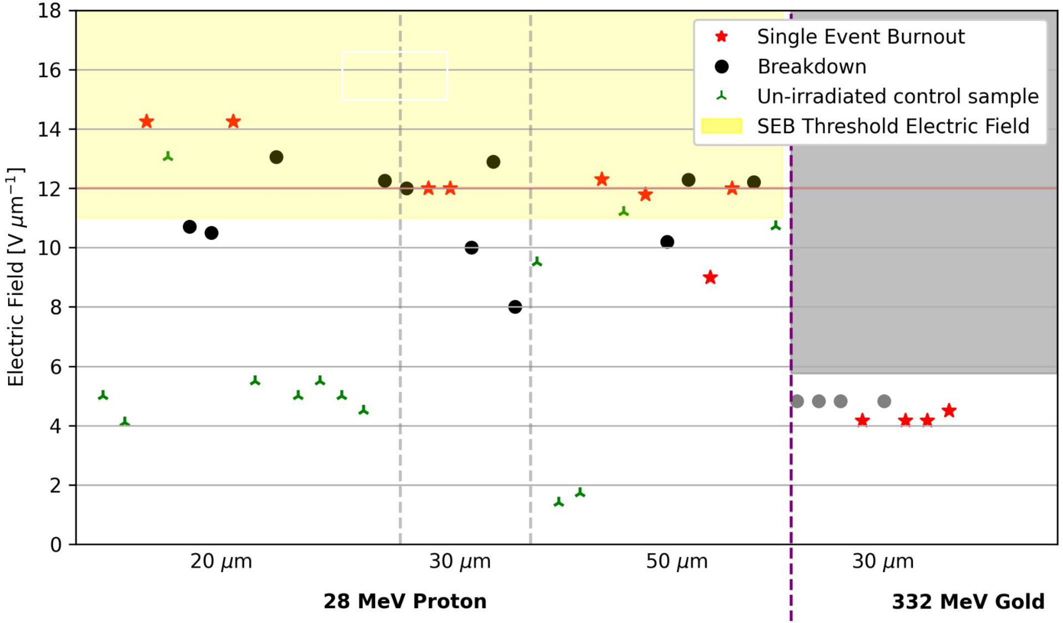
- Current spike (always)
- Non-recoverable short (often)/increased leakage current (always)
- ~10 um wide “*bullet hole*” and burnt mark (often for protons, not observed for gold)



Observed deaths

SEBs with 28 MeV protons

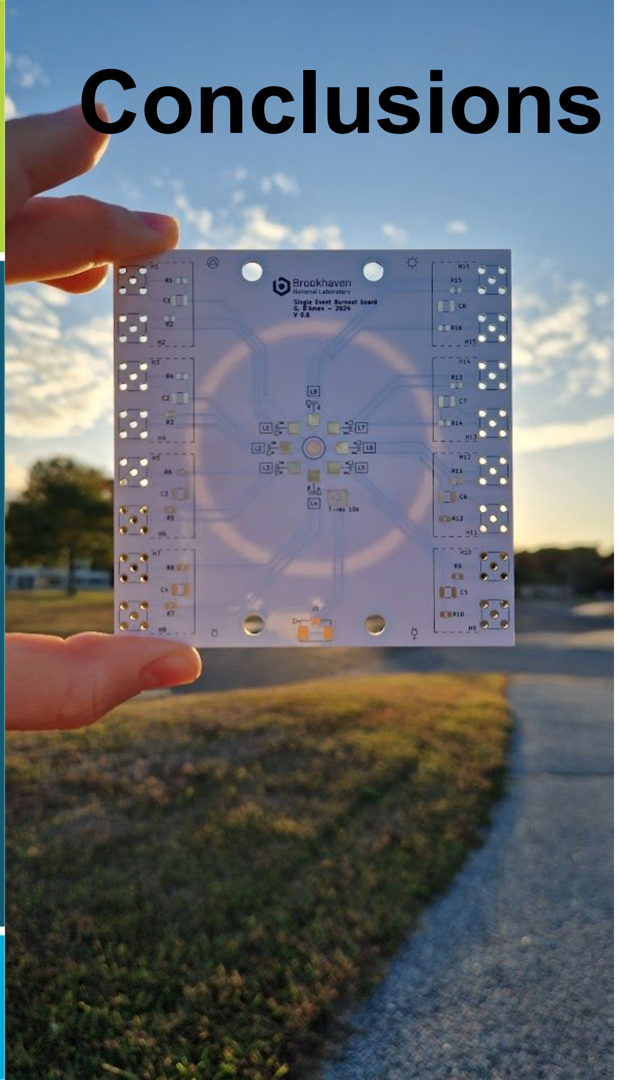
- E_{dep} = ~10-20 MIPS
- **E_{SEB} ~<u>9-14 V/µm</u>**
- *Compatible with 120 GeV protons*
- Craters and burn marks observed on surface



SEBs with 330 MeV gold

- E_{dep} = ~10^4-10^5 MIPS
- **E_{SEB} ~<u>4 V/µm</u>** (limited statistics, potentially lower distribution tail)
- Craters and burn marks <u>not</u> observed on surface (Gold ion Bragg peak?)
- Incomplete run (stopped at 145 V) due to accelerator failure

Conclusions & Future outlook



- SEB threshold for BNL LGADs using 28 MeV protons **compatible with value observed** for 120 GeV hadrons
- SEB threshold for BNL LGADs using 330 MeV Gold ions **~3x times lower**, suggesting role of high deposited energy in SEB
  - …but with **different phenomenology for heavy ions**
  - Will require more studies targeting Nuclear applications
- Will soon follow up with dedicated **AC-LGAD run** (sensors have already been irradiated & mounted)
- Plan to extend study to 14 MeV protons and other ion species to map **E_{dep} vs V_{SEB} characteristic**

Acknowledgments

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Artur Apresyan	[FNAL]
Chris Madrid	[TTU]
Ron Lipton	[FNAL]
Tom Kubley	[BNL] and the Tandem Van de Graaff team at BNL
Don Pinelli	[BNL]
Wei Chen	[BNL]
Chris Musso	[BNL]

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Links

New insight into gain suppression and single event Burnout effects in LGAD

Destructive breakdown studies of irradiated LGADs at beam tests for the ATLAS HGTD

LGAD Single Event Burnout Studies (Technical Report) | OSTI.GOV

BACKUP

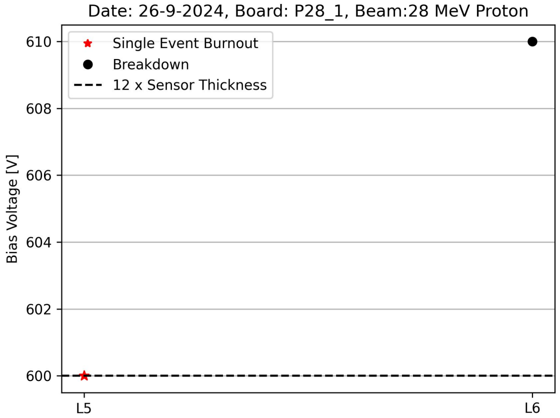
The BNL Tandem Van de Graaff

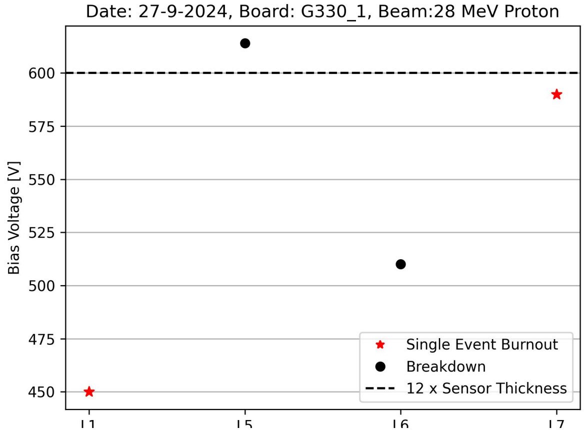
Brookhaven National Laboratory's large **Tandem Van de Graaff** facility consists of two 15-Megavolt electrostatic accelerators

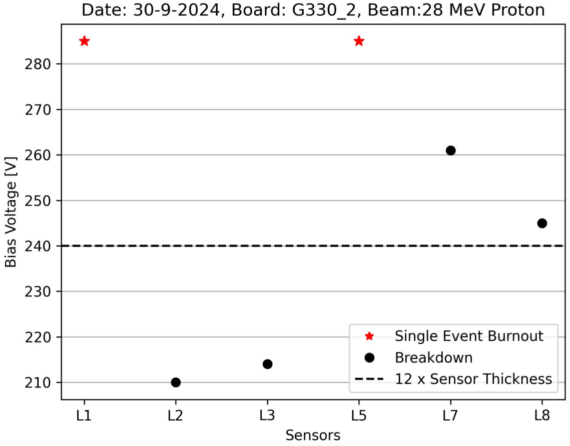
Can produce ion beams of most chemical elements (from protons accelerated to 29 MeV to gold ions accelerated to 337 MeV

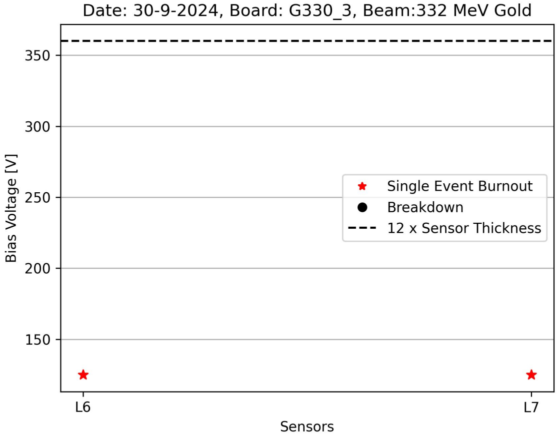
The facility delivers these beams to various irradiation chambers available to users from academia, industry, and other research institutions

Observed Mortality (per sensor type)

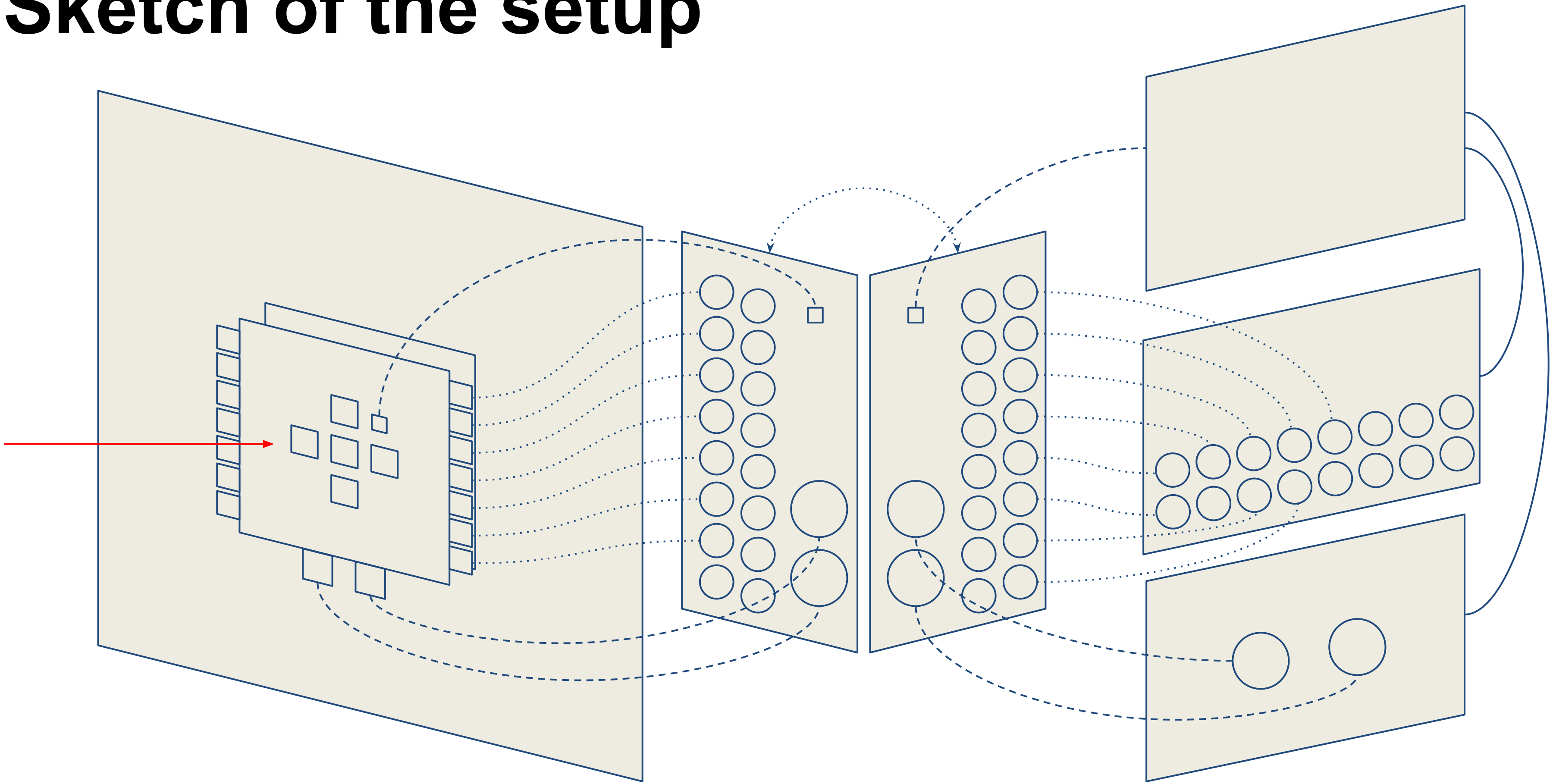








Sketch of the setup



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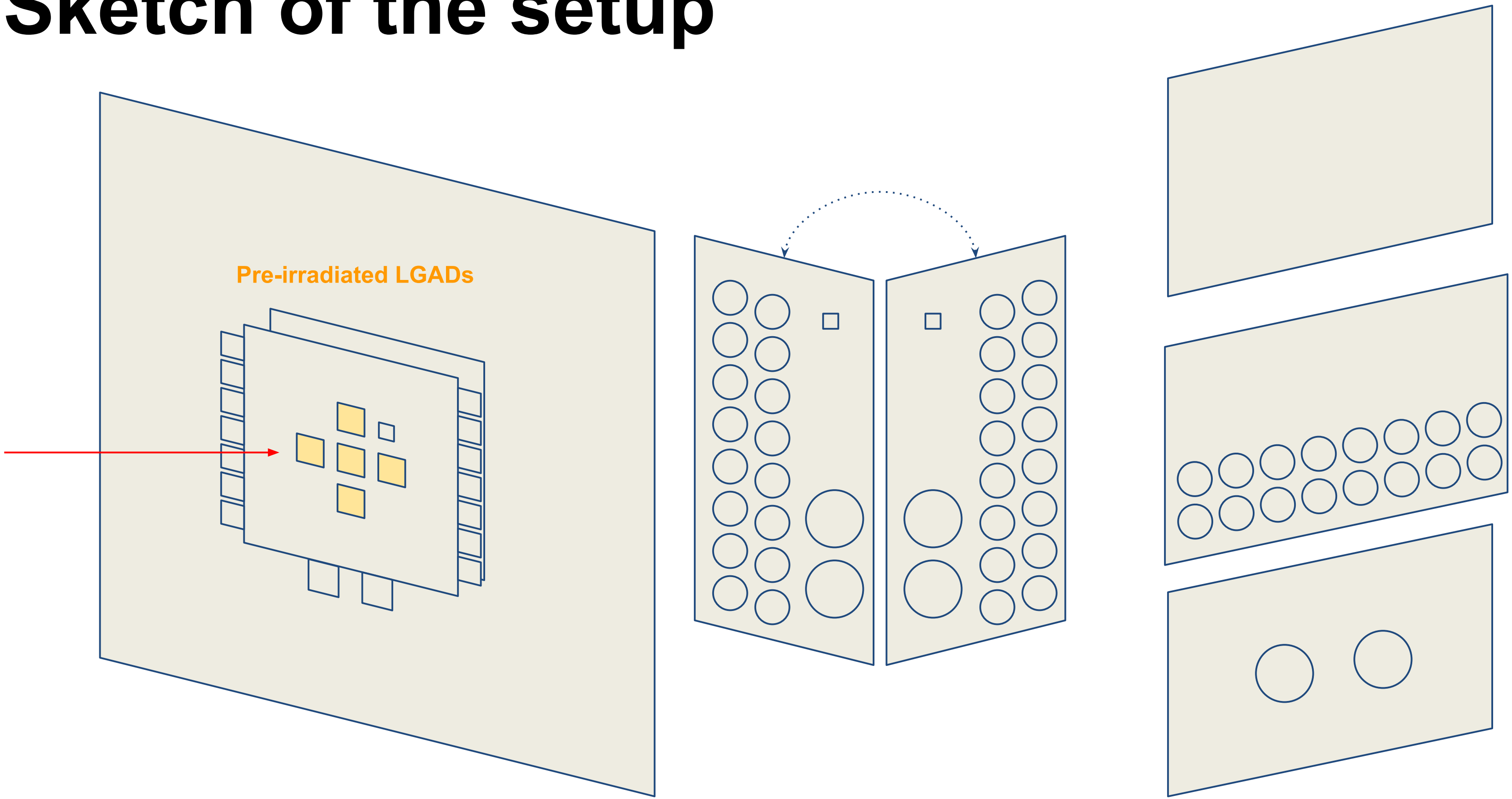

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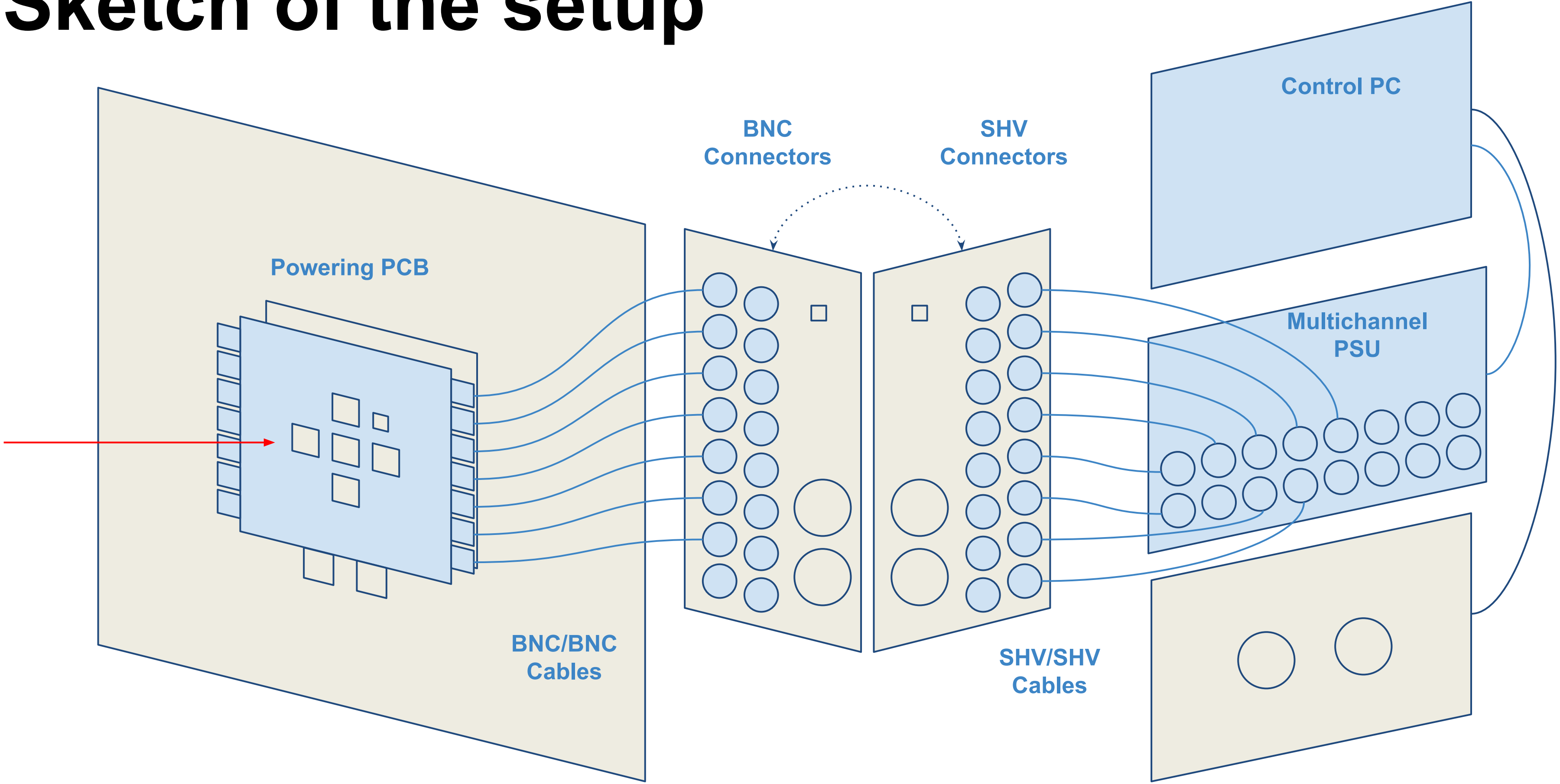

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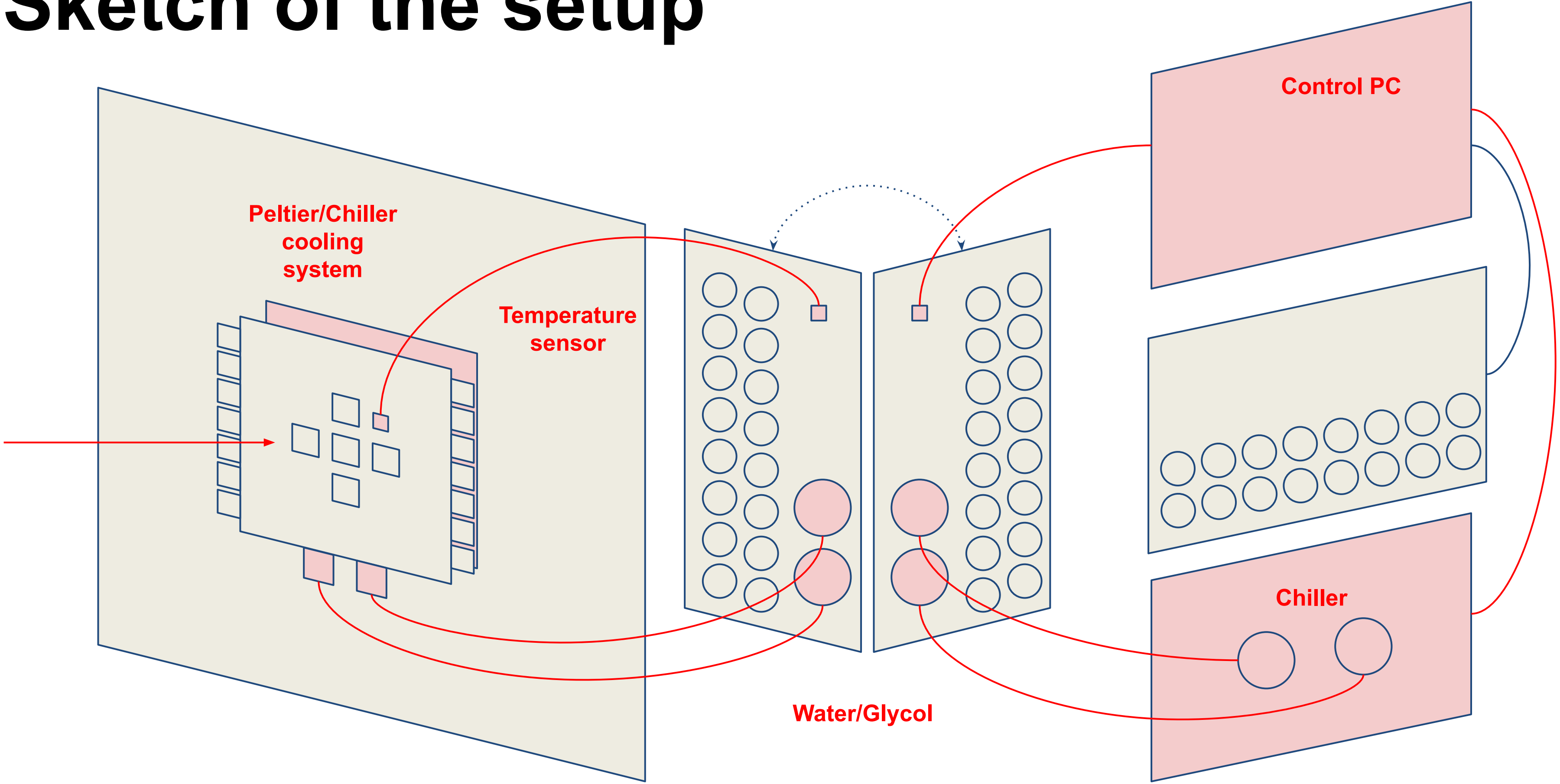
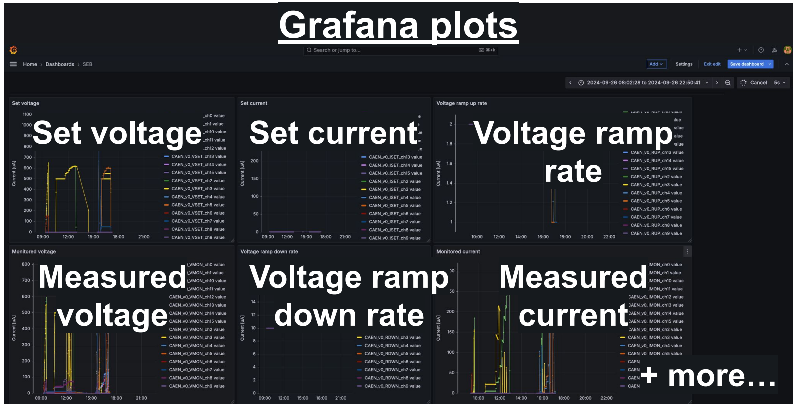
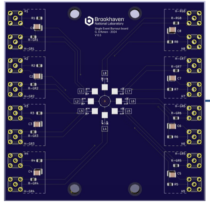


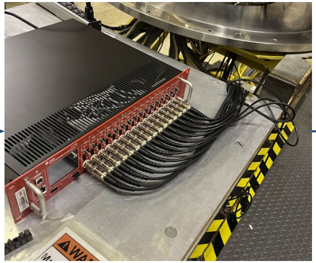
Data taking system

Data path from **sensor** to **monitor**:

- Make full electrical connection from sensors to PC running PSU serial communication s/w and monitoring s/w
- Able to monitor **various parameters** of the 16 CAEN channels (Up to 8 sensors, 8 guard rings)
- Have data and values of all variables saved for entire running period





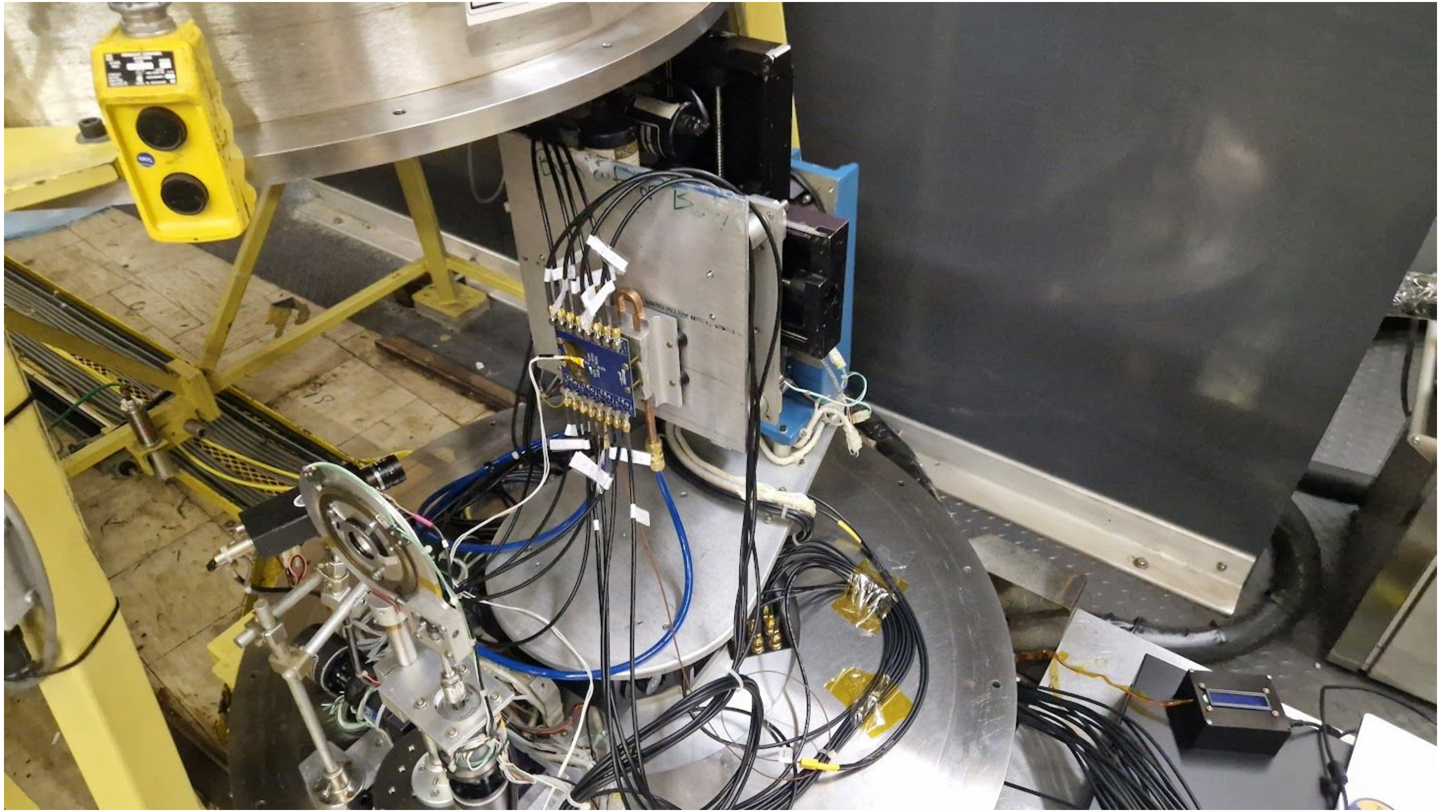


Sensors → CAEN (in target room) → PC (in monitoring room) →

Read/Set CAEN w/ pyserial: [Link] → Upload data to InfluxDB instance [Link] → Visualize data with Grafana: [Link]

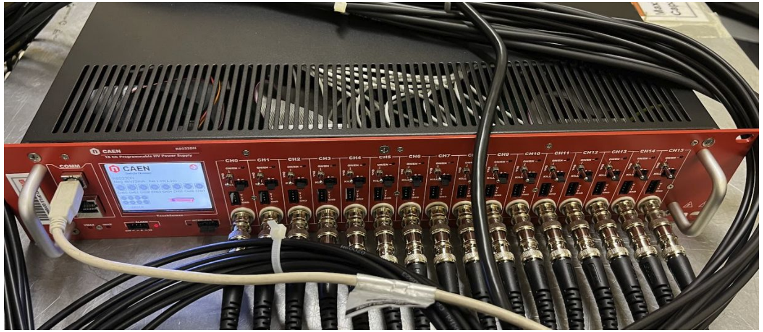
PC software [Link to Git]

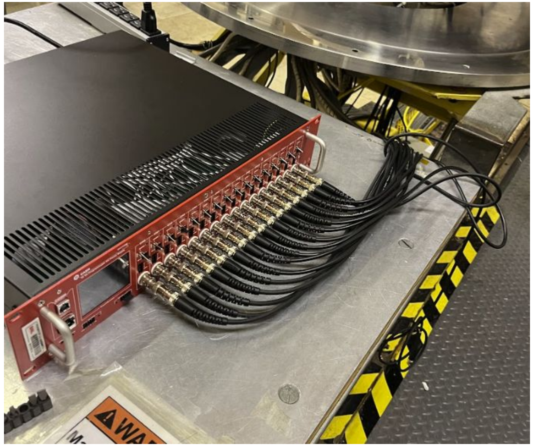
Thermal Control

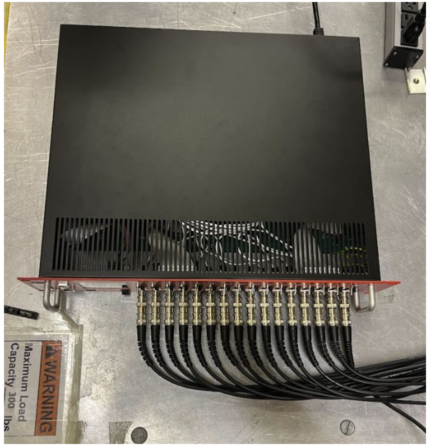


CAEN pictures

- Additional pictures of the CAEN PSU:

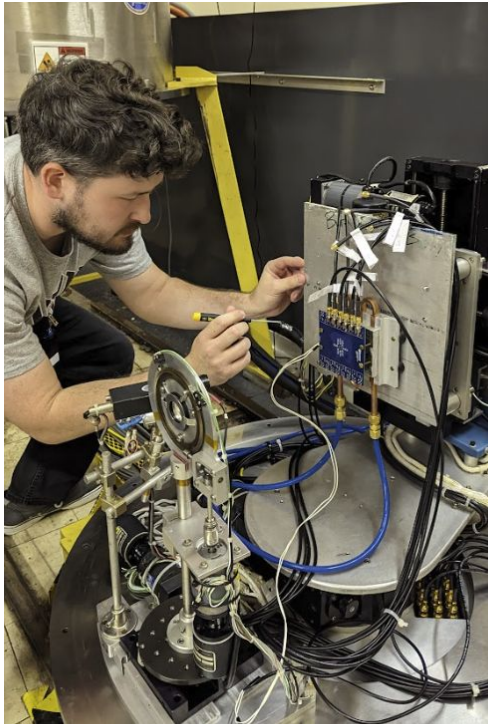






- **Powering - CAEN Multi-channel PSU**
  - 16 channels (up to 4kV)
  - Remote connection and control over custom interface
  - Interact via python drivers: [Software repo]

Team pictures



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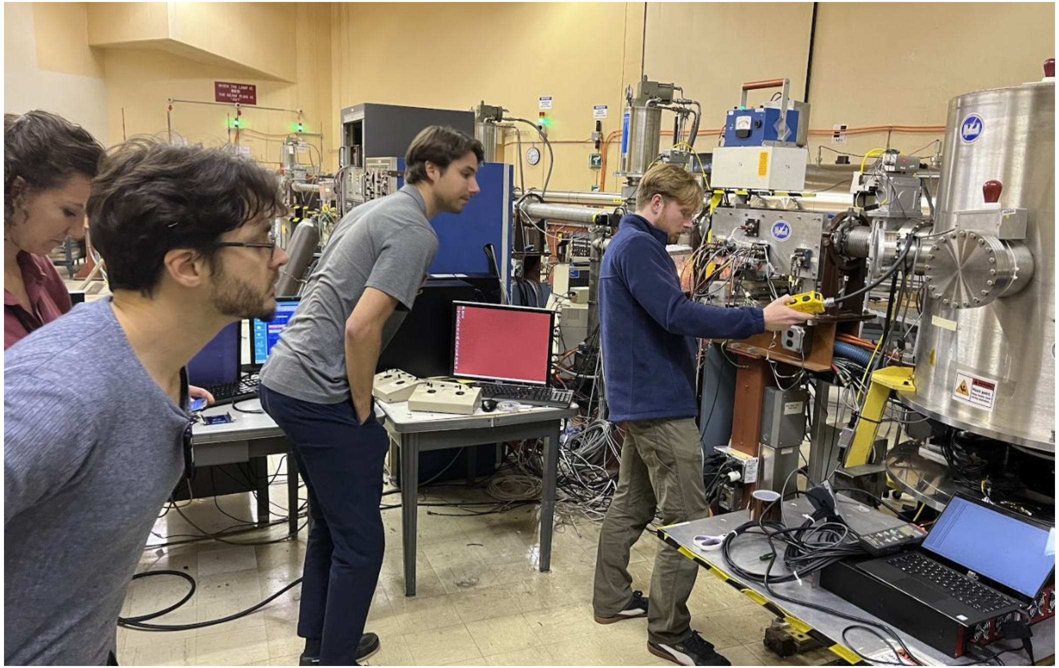

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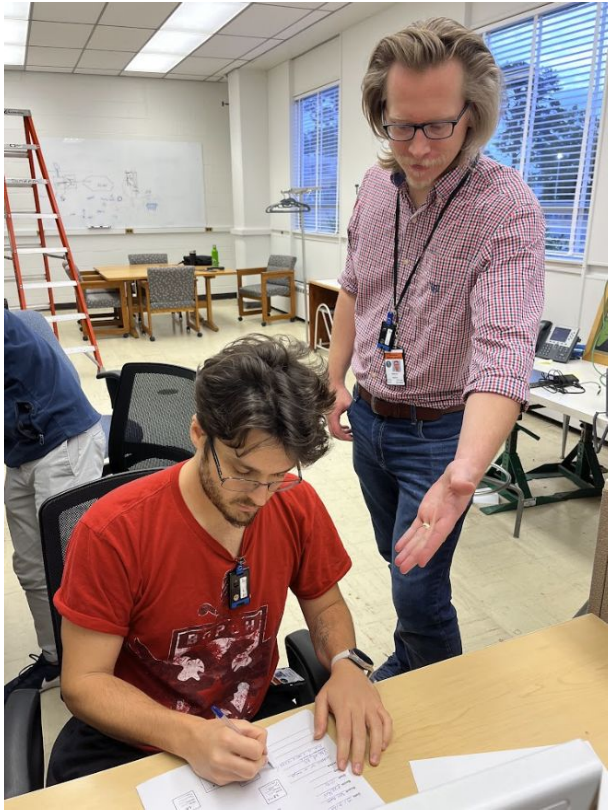

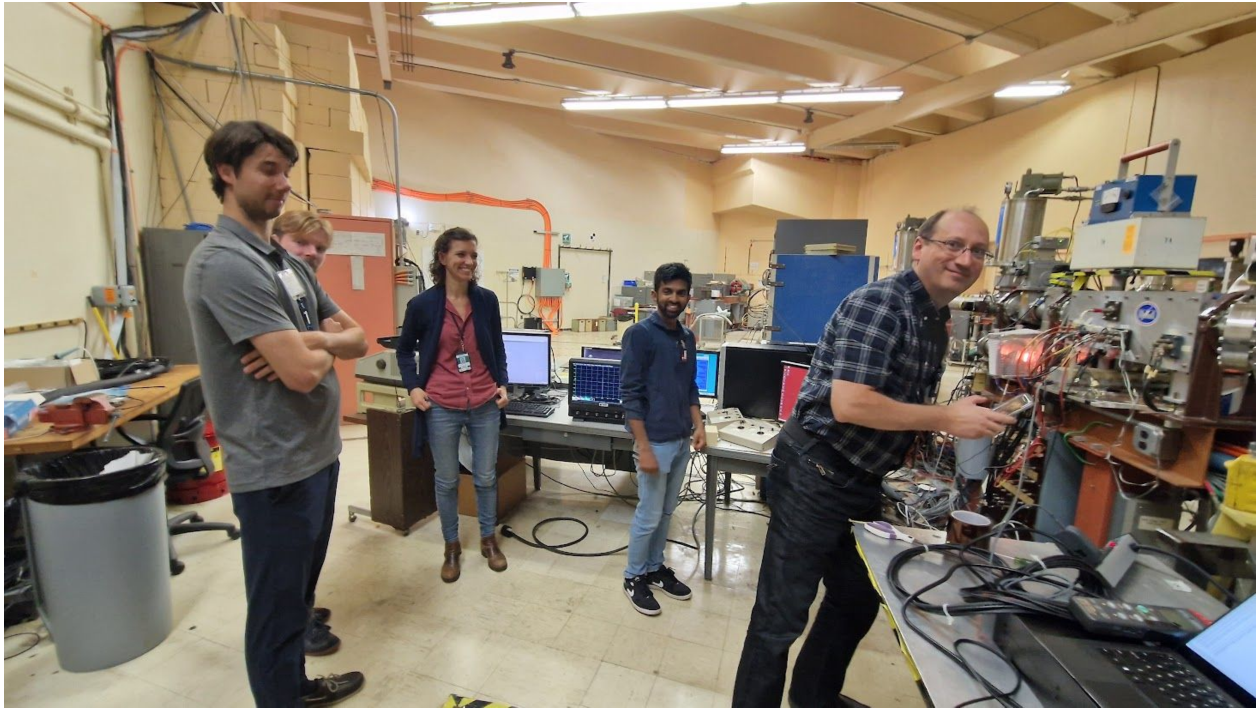

Sensor Irradiation at RINSC