How to kick 200,000 muons per second into a storage ring

Chris Stoughton
Fermilab, 13 August 2019

using slides of

Dr. Jessica Esquivel
"Kicker Wars: Episode II"
Muon g-2 Elba Collaboration Meeting
27 May 2019

KICKER WARS: EPISODE II

Dr Jessica Esquivel

g-2 Elba Collaboration Meeting

05-27-19

TODAY'S DISCUSSION

OUR KEY POINTS

Overview of the Kicker System

Kicker Upgrades & Hurdles

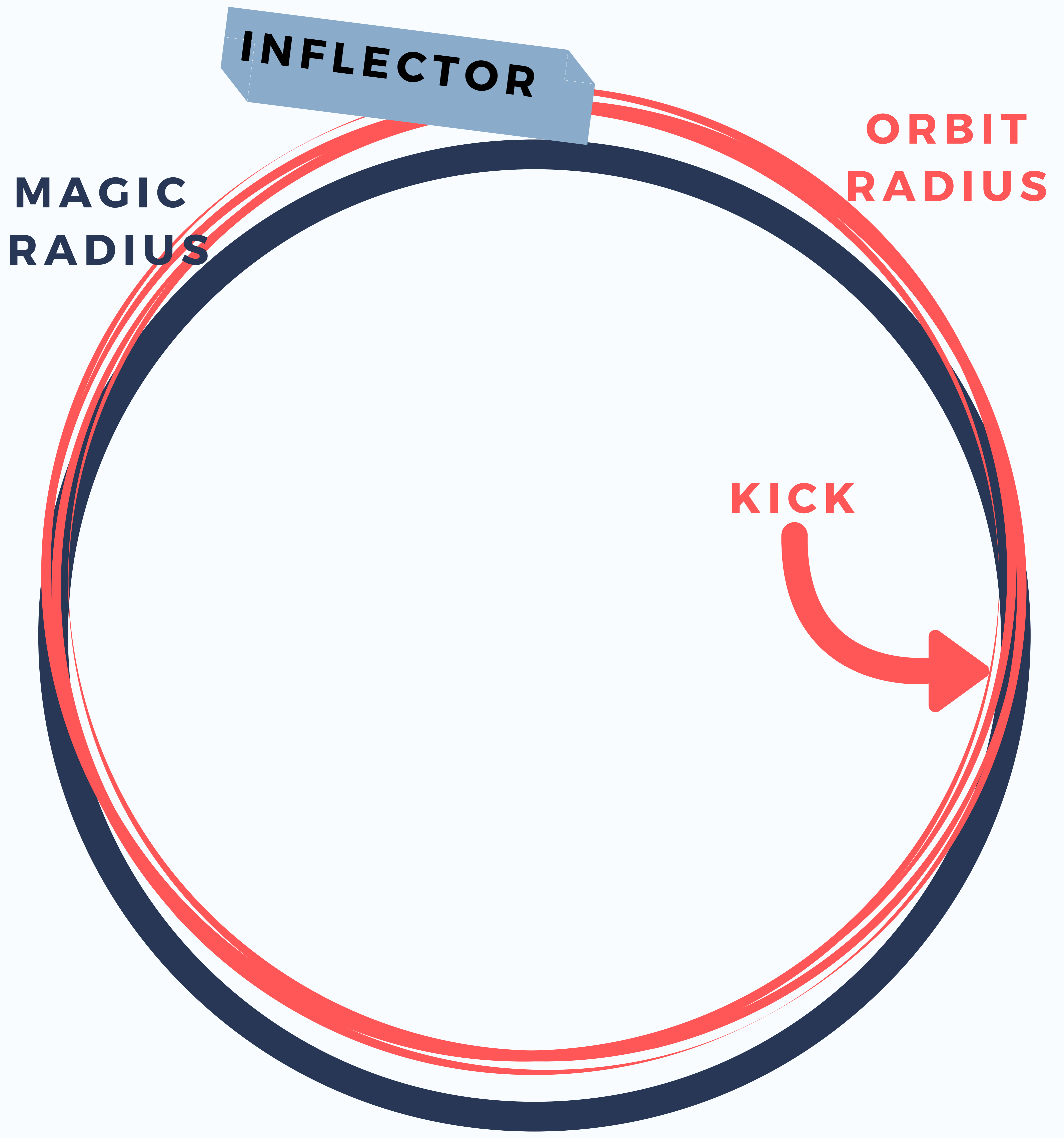
Kicker Characterization, Calibration & Conditioning

Summary

We want to thank the many engineers, technicians, and collaborators who helped rebuild and upgrade the kicker system. We could not have done it w/o you!

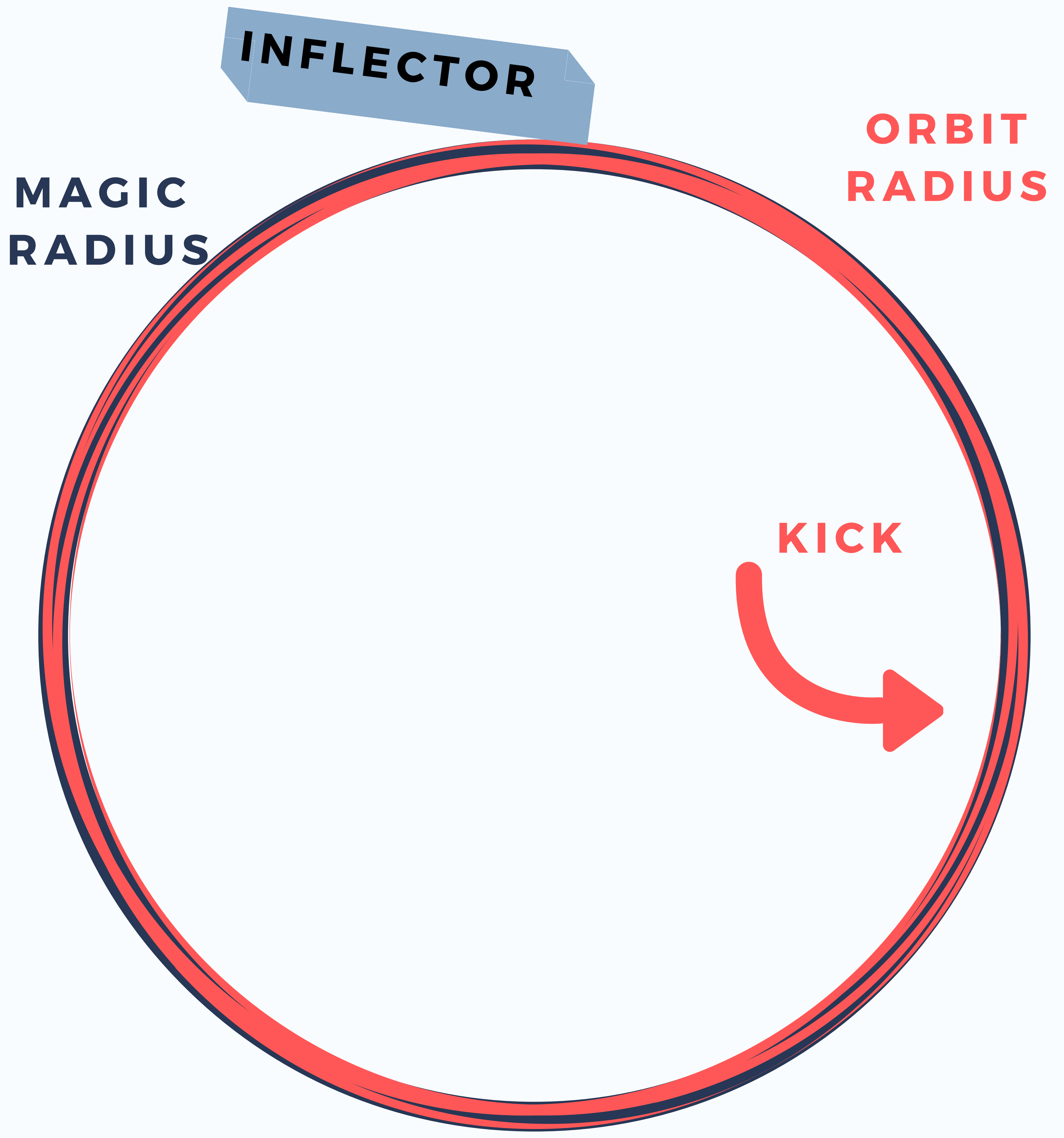
OVERVIEW OF THE KICKER SYSTEM

- MUONS INJECTED INTO STORAGE RING OFF MAGIC ORBIT
- LARGE TANGENTIAL FORCE NEEDED TO "KICK" MUONS ONTO CORRECT ORBIT



OVERVIEW OF THE KICKER SYSTEM

- MUONS INJECTED INTO STORAGE RING OFF MAGIC ORBIT RADIUS
- LARGE TANGENTIAL FORCE NEEDED TO ”KICK” MUONS ONTO CORRECT ORBIT
- KICK IDEALLY IS NARROWER THAN 149 NS
- TOO WEAK A KICK AND MUONS WILL BE AT TOO HIGH A RADIUS
- TOO LONG A KICK AND MUONS WILL BE KICKED MULTIPLE TIMES



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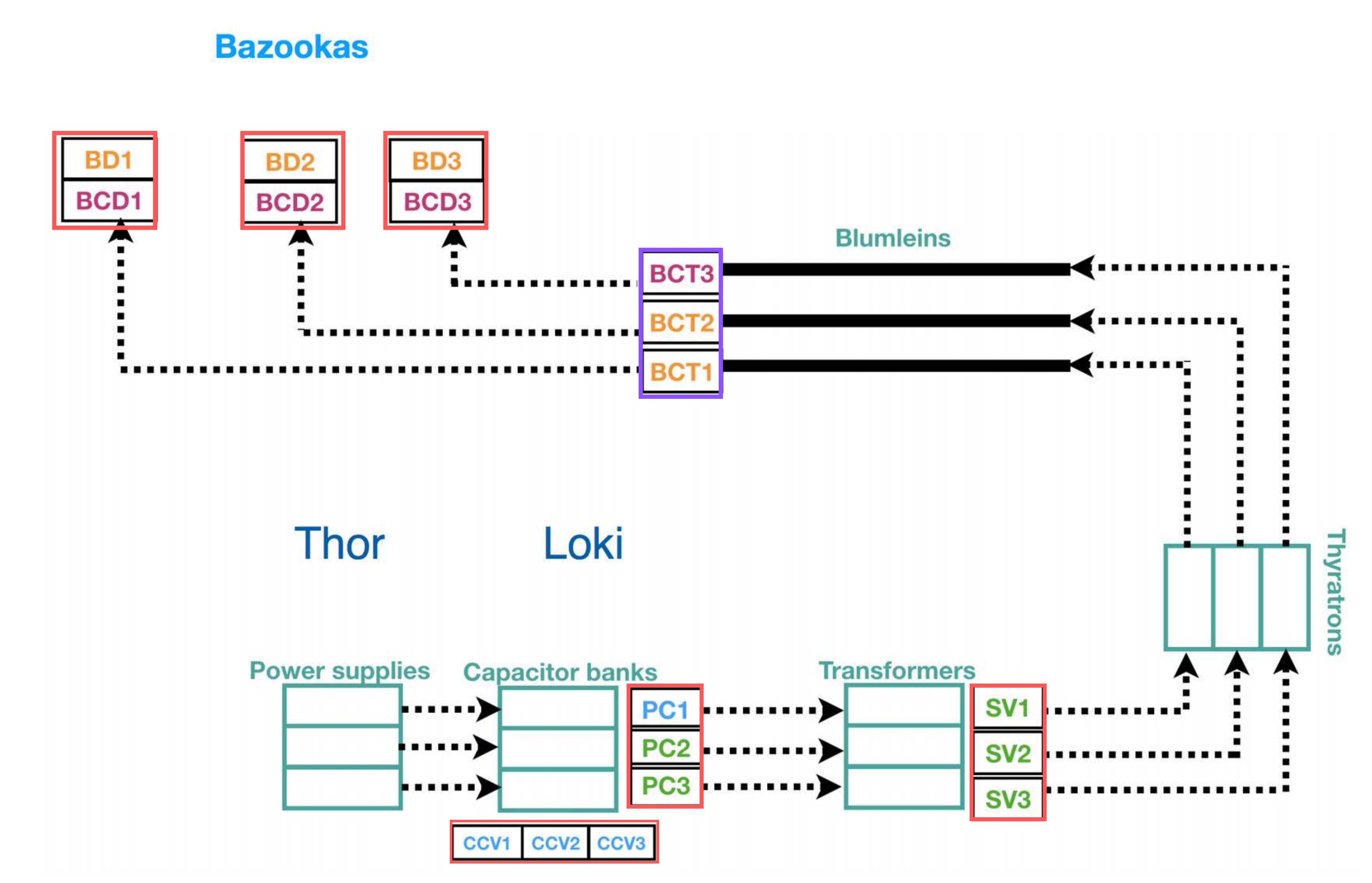

Credit: Saskia

- Power supplies provide 700 V to charge capacitor banks
- Transformers perform a nominal step-up of 85:1 going from 700V to 60kV and transfer this to blumleins
- Blumleins act as a Pulse Forming Network with the thyratron acting as the switch
- Bazooka transfers current to kicker magnets via the vacuum feedthrough

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STEP 1: POWER SUPPLIES AND CAPACITOR BANKS

Power supplies provide 700V to charge capacitor banks

In run 1, power supplies could not provide enough charge in required time

New power supplies installed (2 per capacitor bank) and capacitor bank upgraded to accommodate more power

STEP 2: TRANSFORMERS

Transfer charge from capacitor banks to blumleins

Nominal step-up of 85:1 to go from 700V to 60kV

STEP 3: THYRATRON & BLUMLEINS

Blumleins act as Pulse Forming Network (PFN) with 3 concentric conductors separated by insulating standoffs and filled with castor oil

Thyratrons are the switch to tell blumleins to send current to kickers

STEP 4: BAZOOKAS AND VACUUM FEEDTHROUGHS

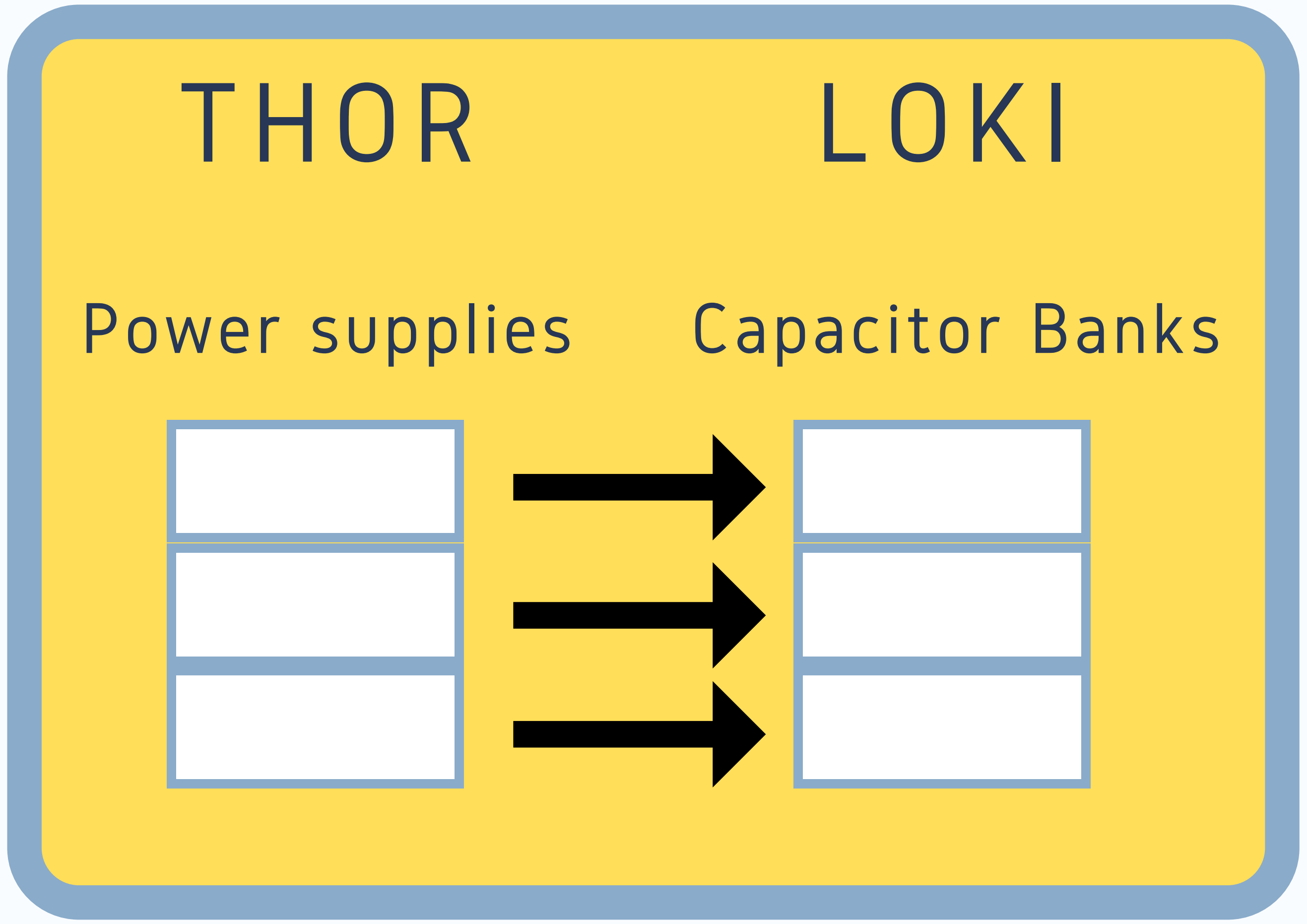
More progress since November Collaboration Meeting:

Complete Bazooka redesign and New Vacuum Feedthroughs

STEP 5: DAQ UPGRADES

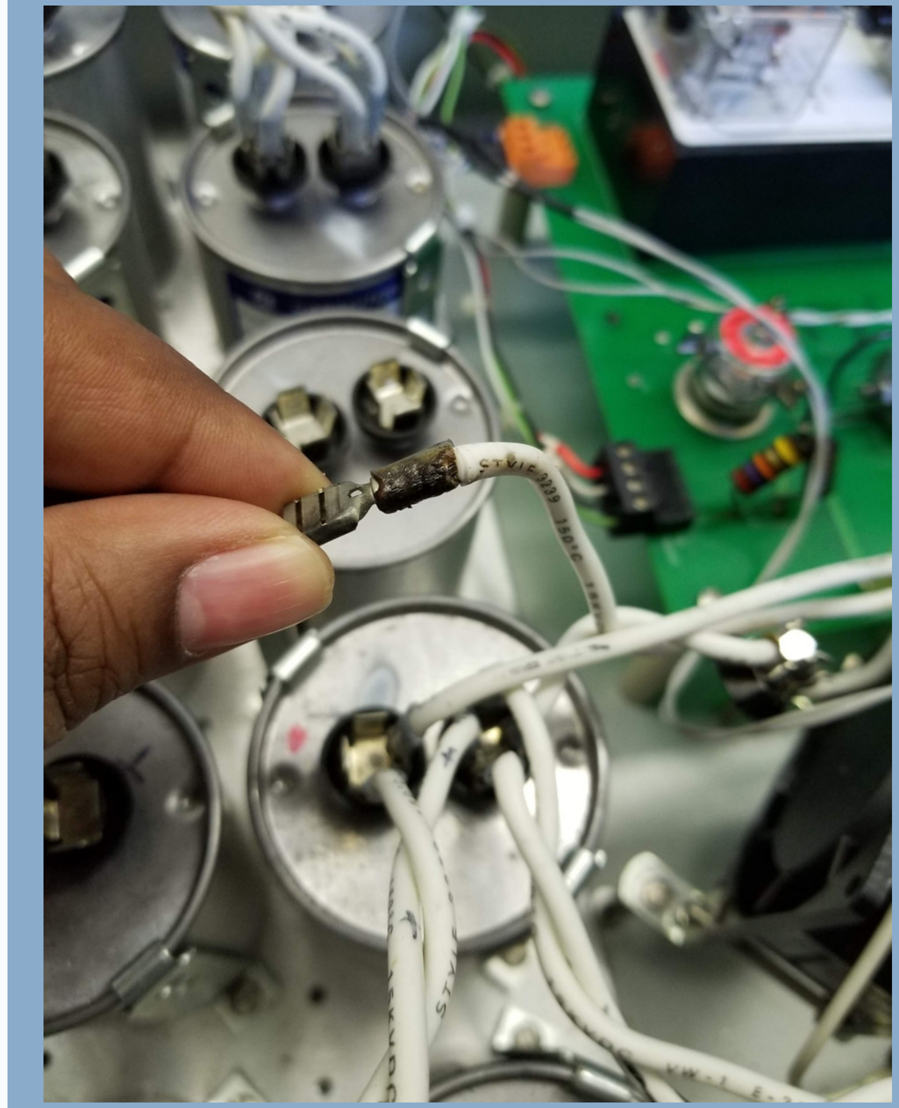
CCC triggers updated, Interlock and automatic spark detection implemented

STEP 6: MONITORING AND CALIBRATION



CAPACITOR BANK & THYRATRON CHASSIS UPGRADES

- Capacitor bank chassis upgraded for 2 power supply input
- Rewired capacitor bank chassis to repair damage
- 12 ohm resistors in capacitor banks replaced with a lower dissipation protection network
- Heater current monitor readout added
- Thyratron Chassis fuse protection & improved grounding



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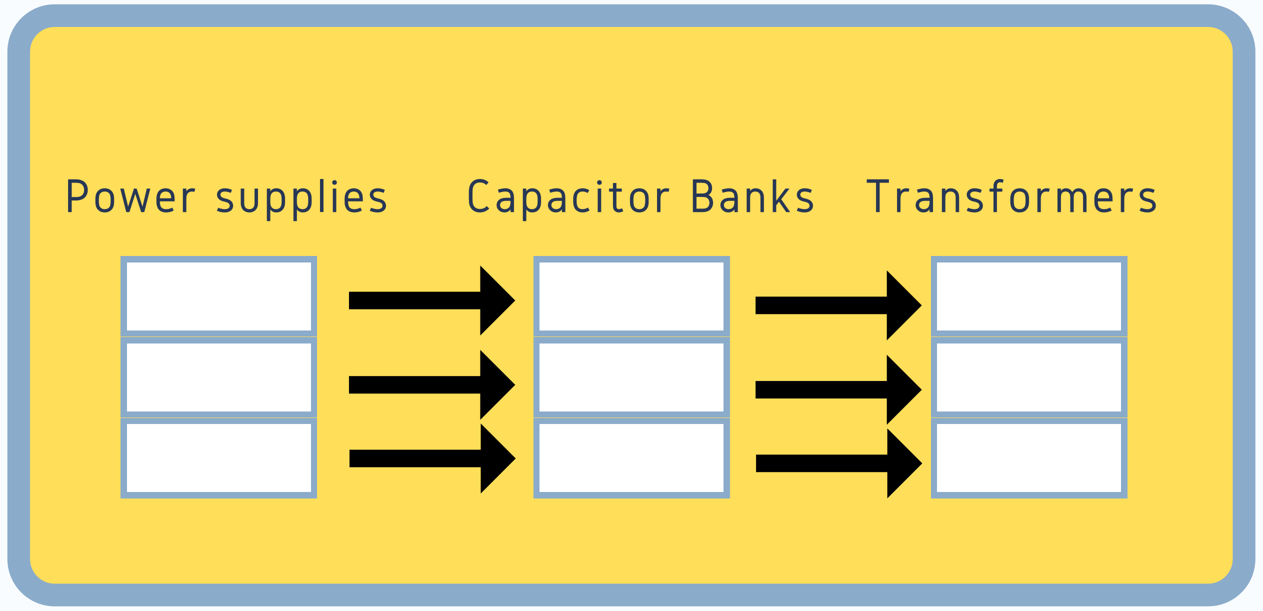

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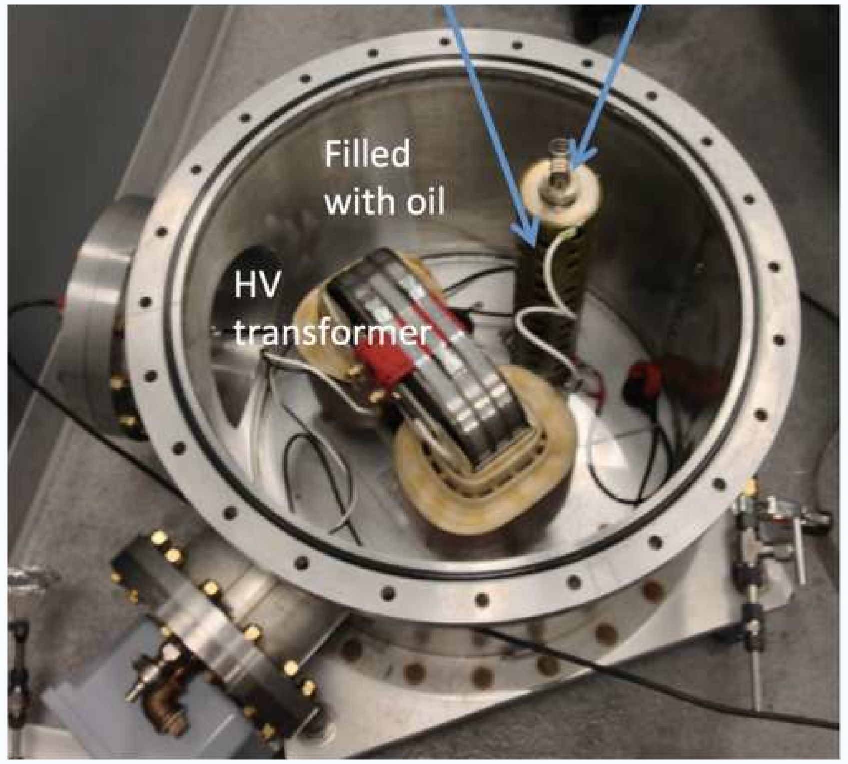
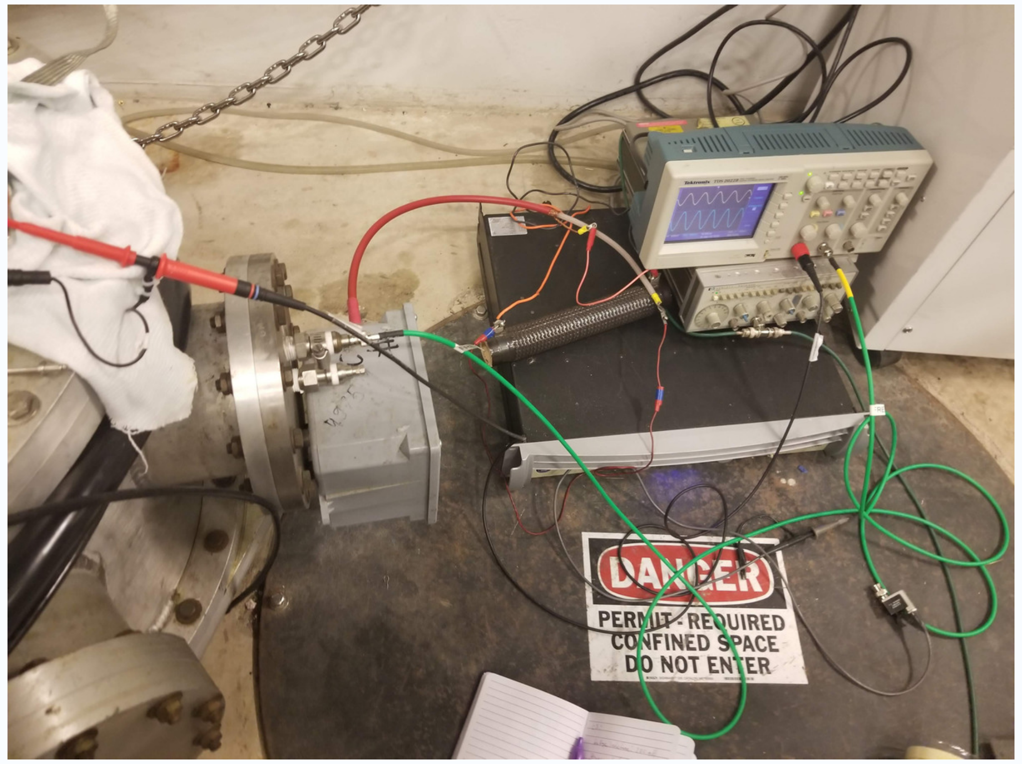
TRANSFORMERS





Diagnostic	K2 Test 1	K2 Test 2	K3 Test 1
Leakage inductance	183μH	180μH	230μH
Primary inductance	100mH	100mH	100mH
Input voltage	11.3V_{pp}	23.4V_{pp}	22.2V_{pp}
Output voltage	0.99kV_{pp}	2.12kV_{pp}	2.08kV_{pp}
Ratio	1:87.8	1:90.6	1:93.7
Secondary input voltage	0.99kV_{pp}	2.20kV_{pp}	2.02kV_{pp}
Secondary output voltage	0.35V_{pp}	0.74V_{pp}	0.58V_{pp}
Capacitive divider ratio	2834.3:1	2973.0:1	3458.9:1

VOLTAGE AND INDUCTANCE MEASUREMENTS

Were performed on K2 and K3 blumlein charging transformers to confirm the calibration that what was seen in run 1.

STEP UP RATIOS

Were directly obtained by measuring the Input and Output Voltages

CAPACITIVE DIVIDER RATIOS

Were directly obtained by measuring Input and Output Secondary Voltages

These ratios were in contrast to the originally expected 5000:1

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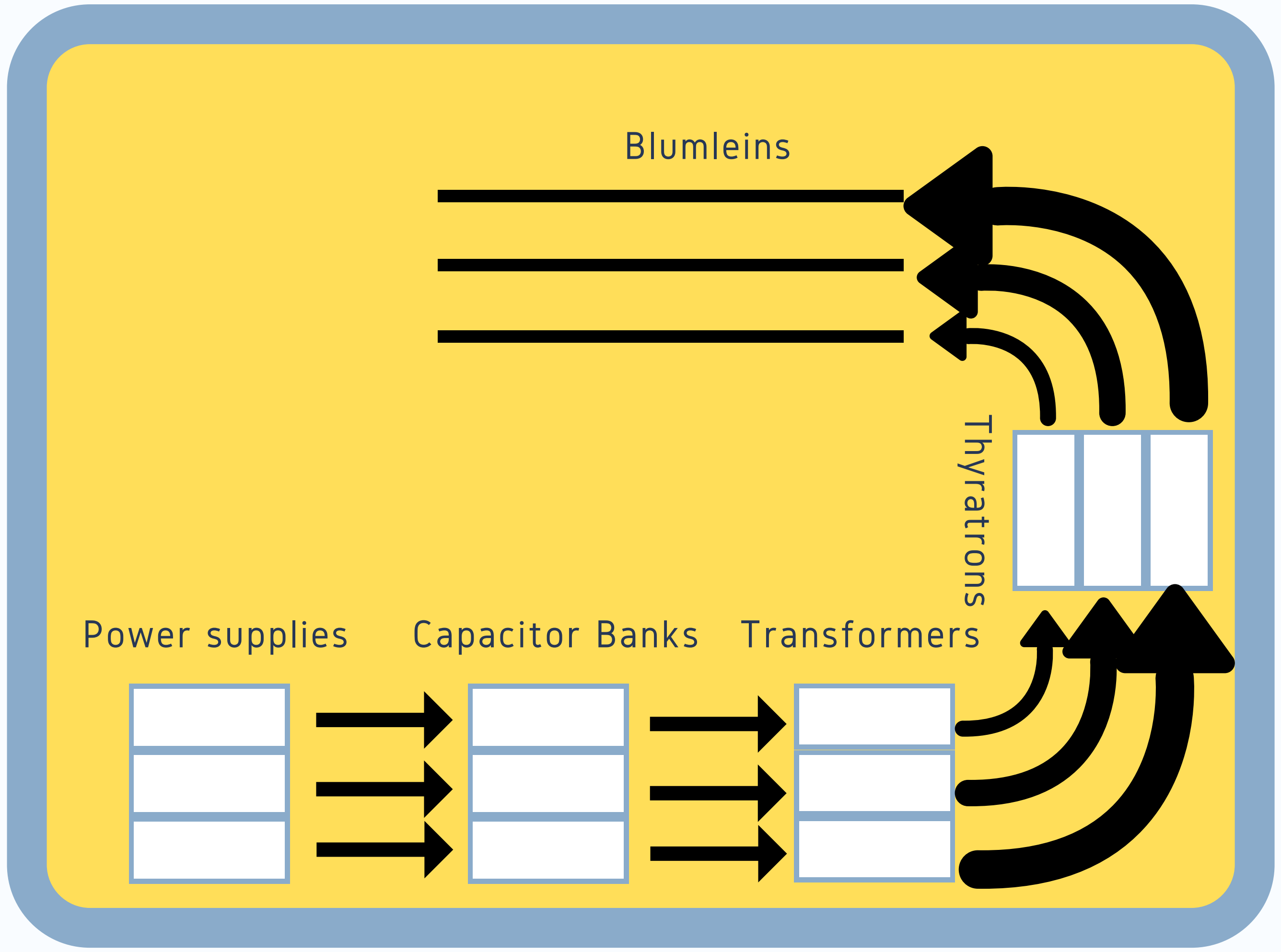

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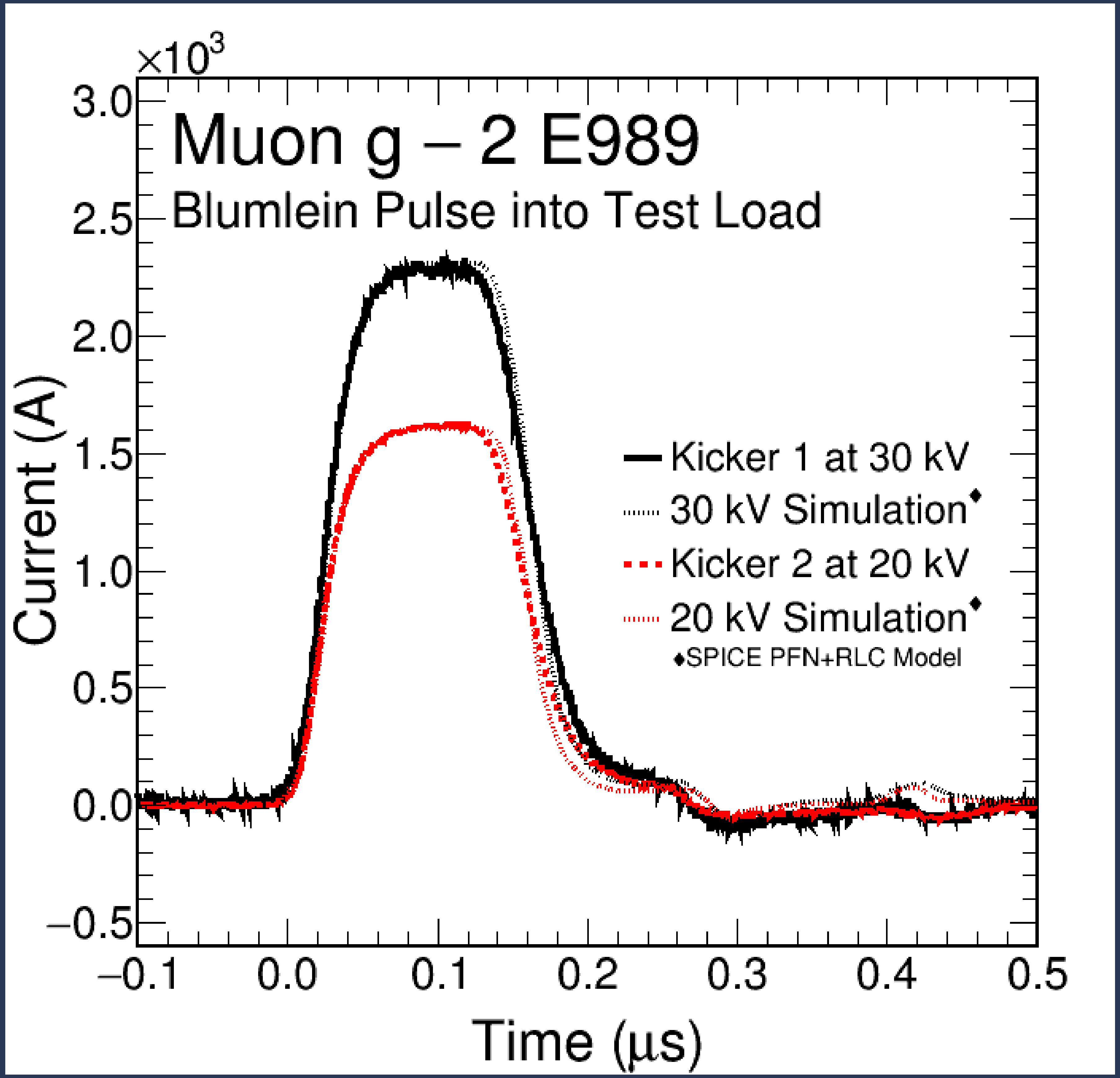
THYRATRON & BLUMLEINS

Blumleins were taken to Lab F:

Pitting on conductors were polished down, broken macor insulating standoffs were removed and replaced with torlon ones and resistance was measured on all 3 blumleins.

Thyratron heater cables upgraded

New thyratron installed (2 spares that need work)



Blumlein Qualification

Pulse into 12.5 ohm resistive load

Test showed refurbishments were successful

Quantifies performance and demonstrates reasonable comparison to SPICE simulation

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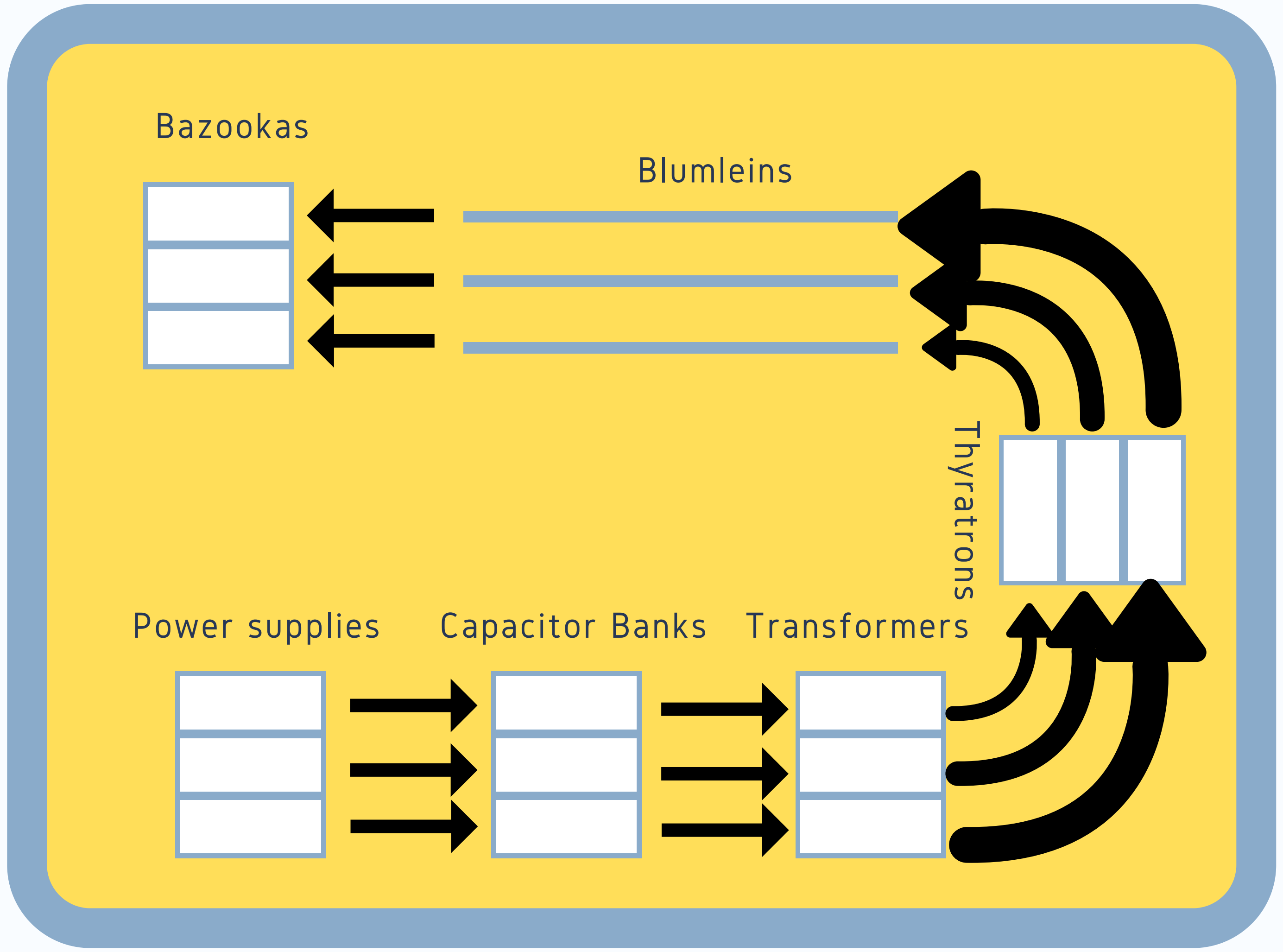

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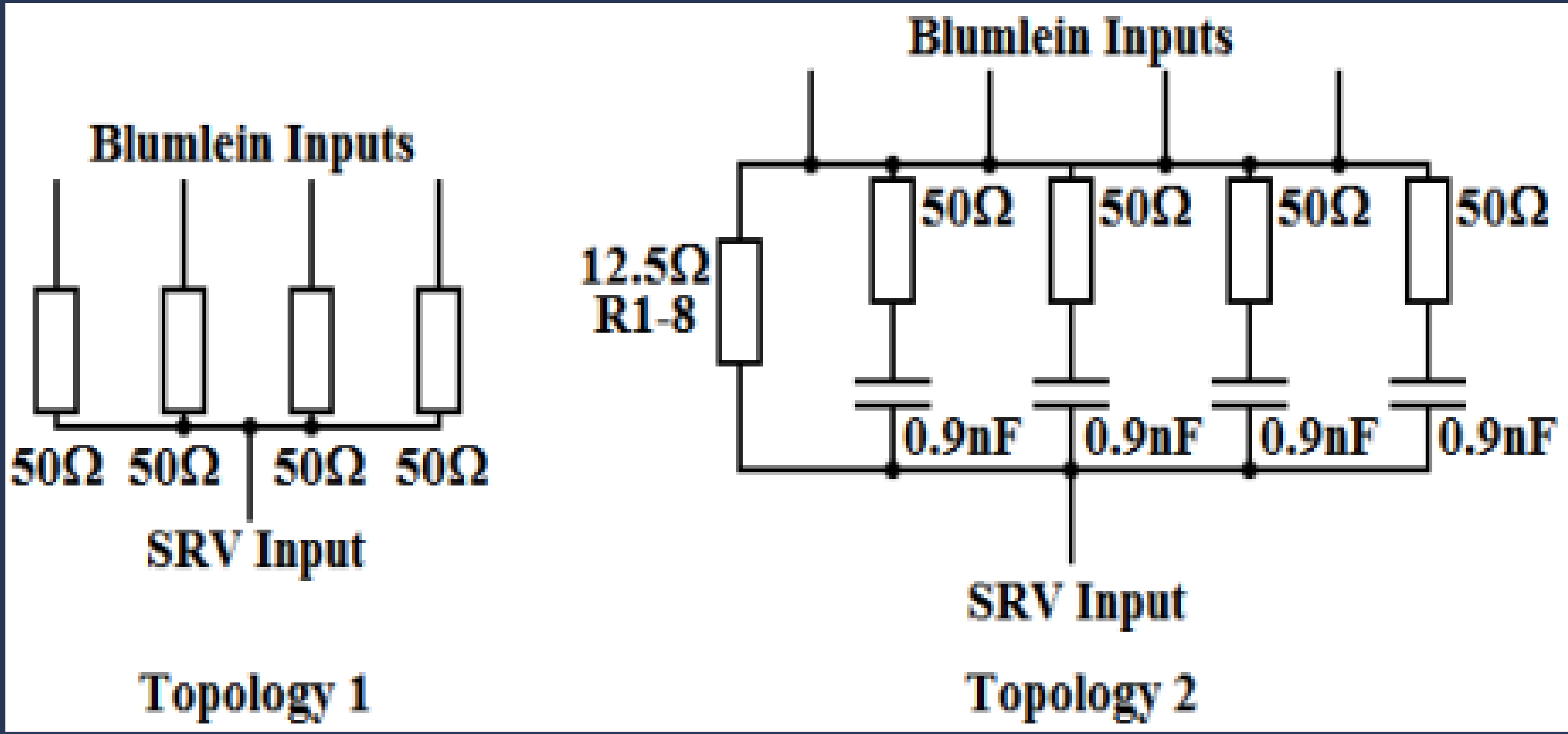
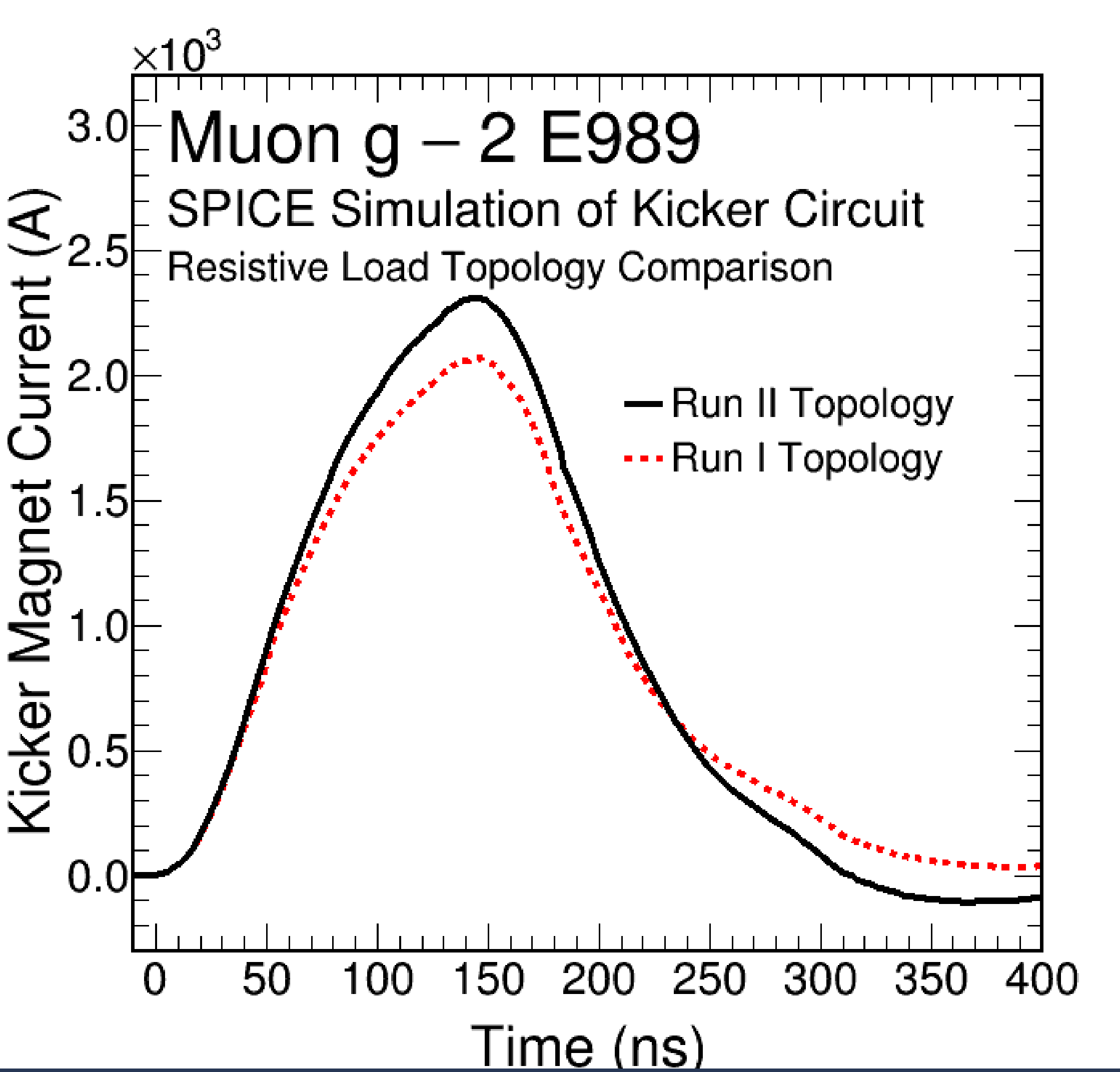
New GUI monitoring system

STEP 6: MONITORING AND CALIBRATION



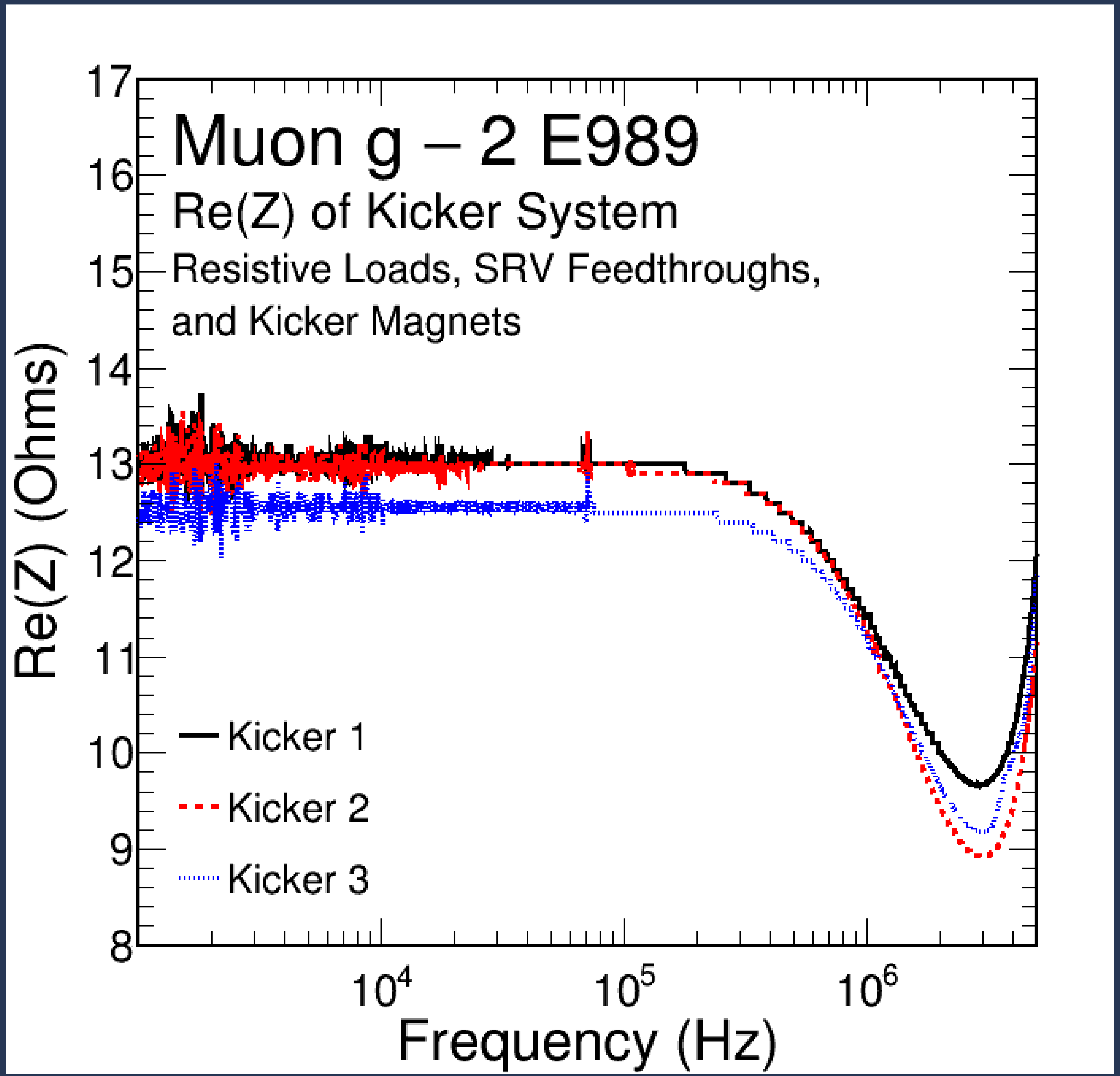


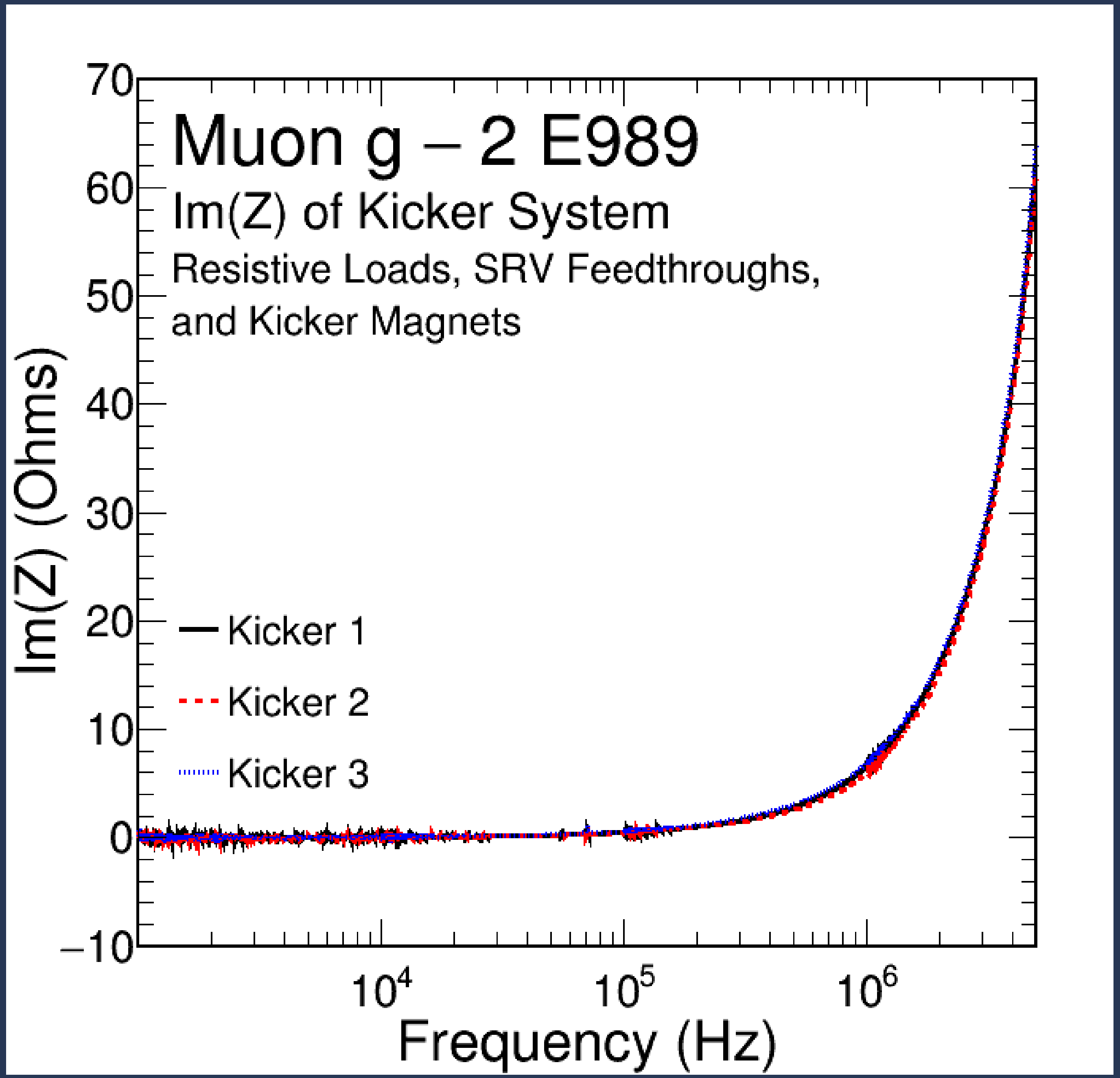
BAZOOKA UPGRADE

- Moved from Topology 1 to Topology 2 over shutdown
- More robust components and construction
- Higher peak current (11.6%) due to capacitive speed-up network
- SPICE simulation of kicker circuit with upgraded bazooka design

PROGRESS SINCE NOVEMBER'S COLLABORATION MEETING

BAZOOKA UPGRADE





BAZOOKA UPGRADE

Impedance measurements of bazooka, feedthrough, and kicker magnet

Real component shows bazooka upgrade behaves as expected

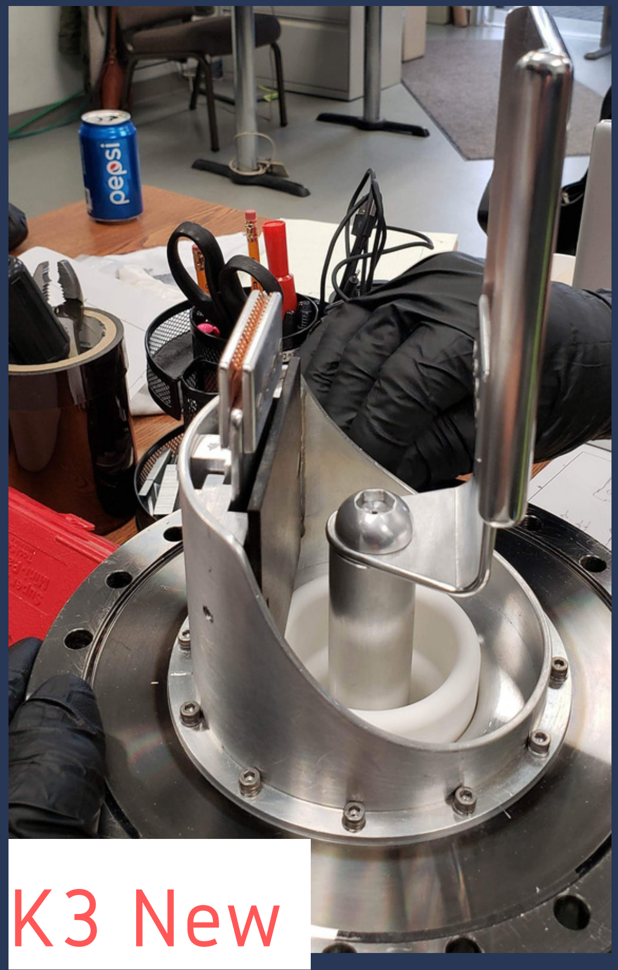
Imaginary component shows effects of the 1.4 uH inductance from kicker magnet

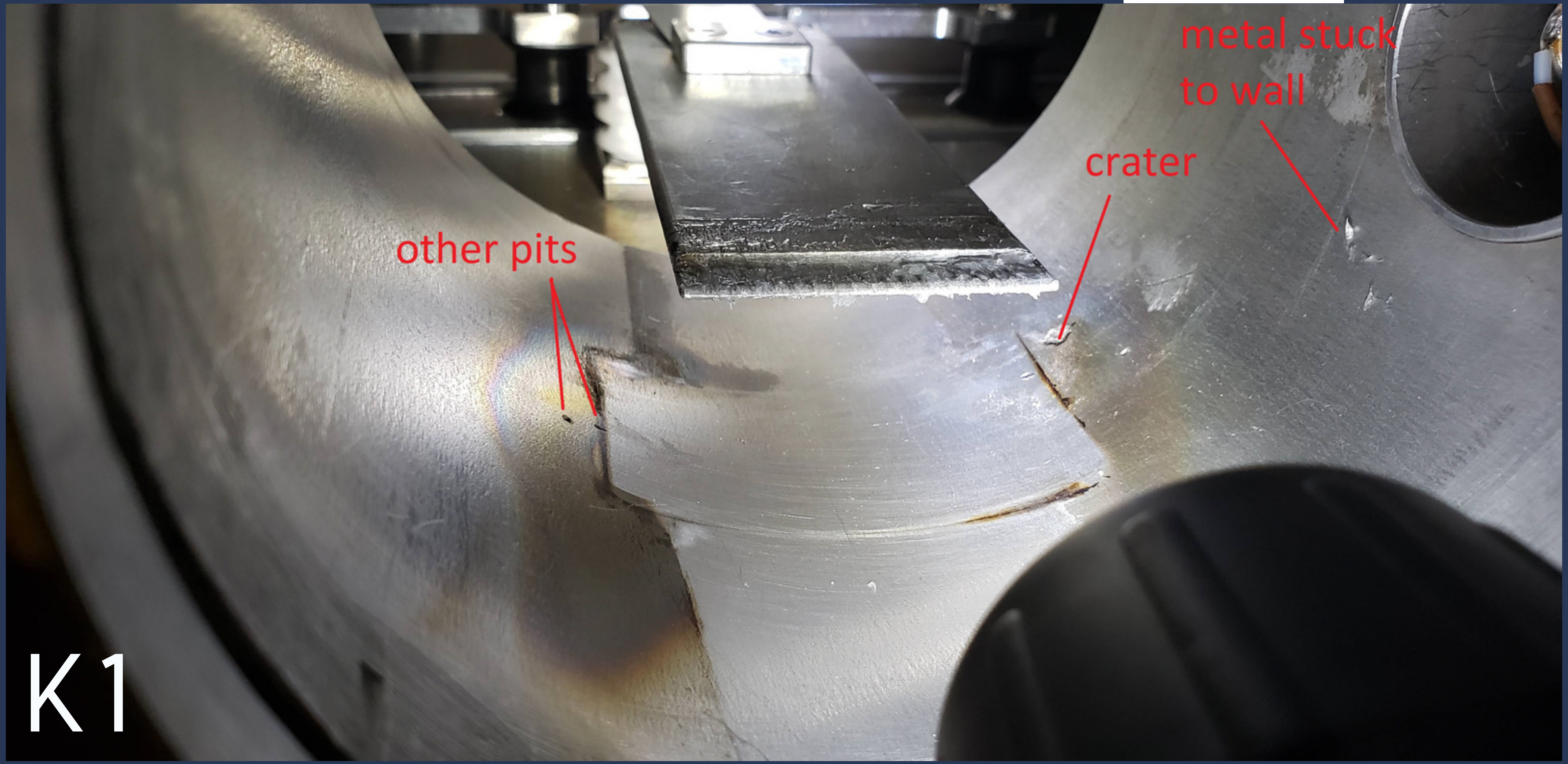
INITIAL VACUUM FEEDTHROUGH UPGRADE

Improvements to couple with new Bazooka.

Different scheme for fluorinert seal to stop leaks into vacuum

All new parts on bazooka side





FURTHER NECESSARY VACUUM FEEDTHROUGH UPGRADE

After initial installation of feedthrough, started to see sparking in kickers

K3 could not hold voltage

Modified HV connector (Sled) to reduce E field

Removed all teflon, both tape and blocks

Offset HV lead 1/4” farther from bottom of port

Replacement done on K1 & K3, K2 pending

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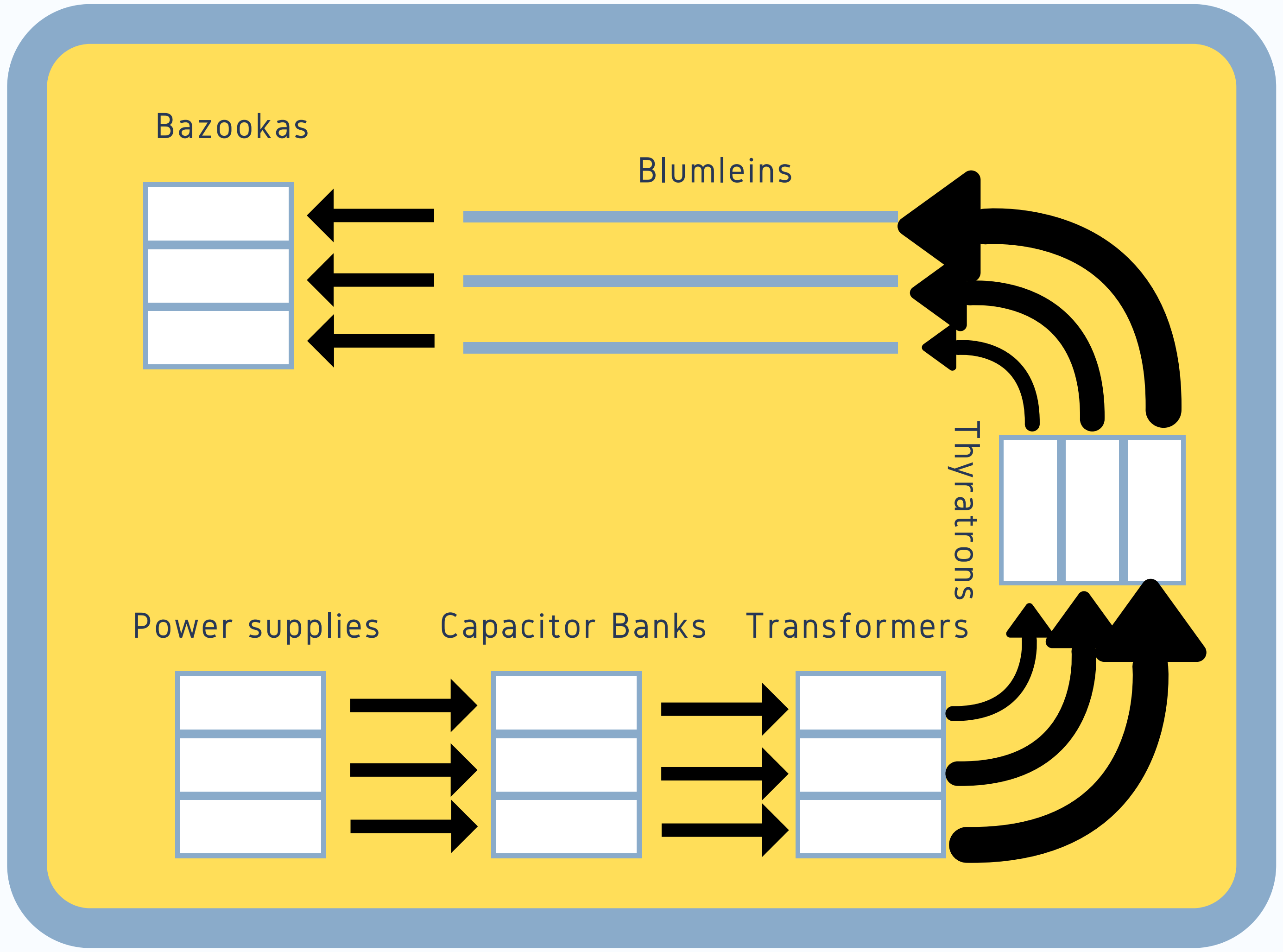
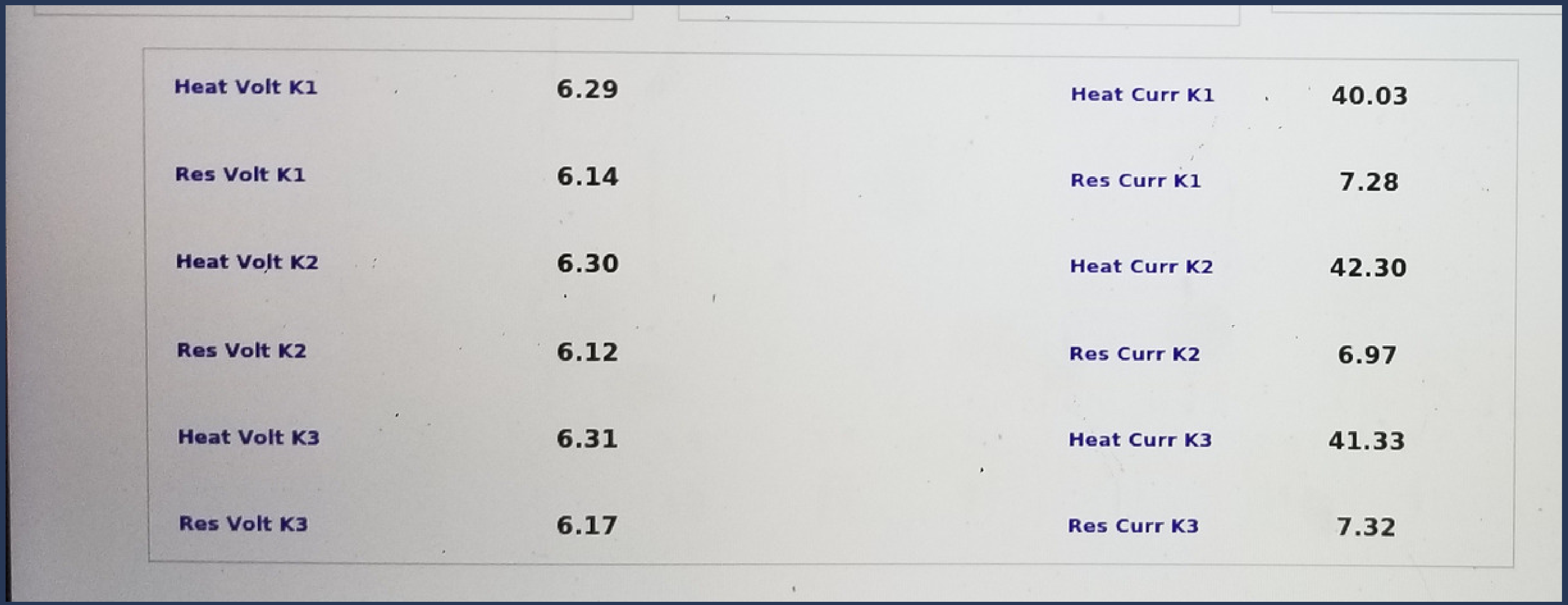
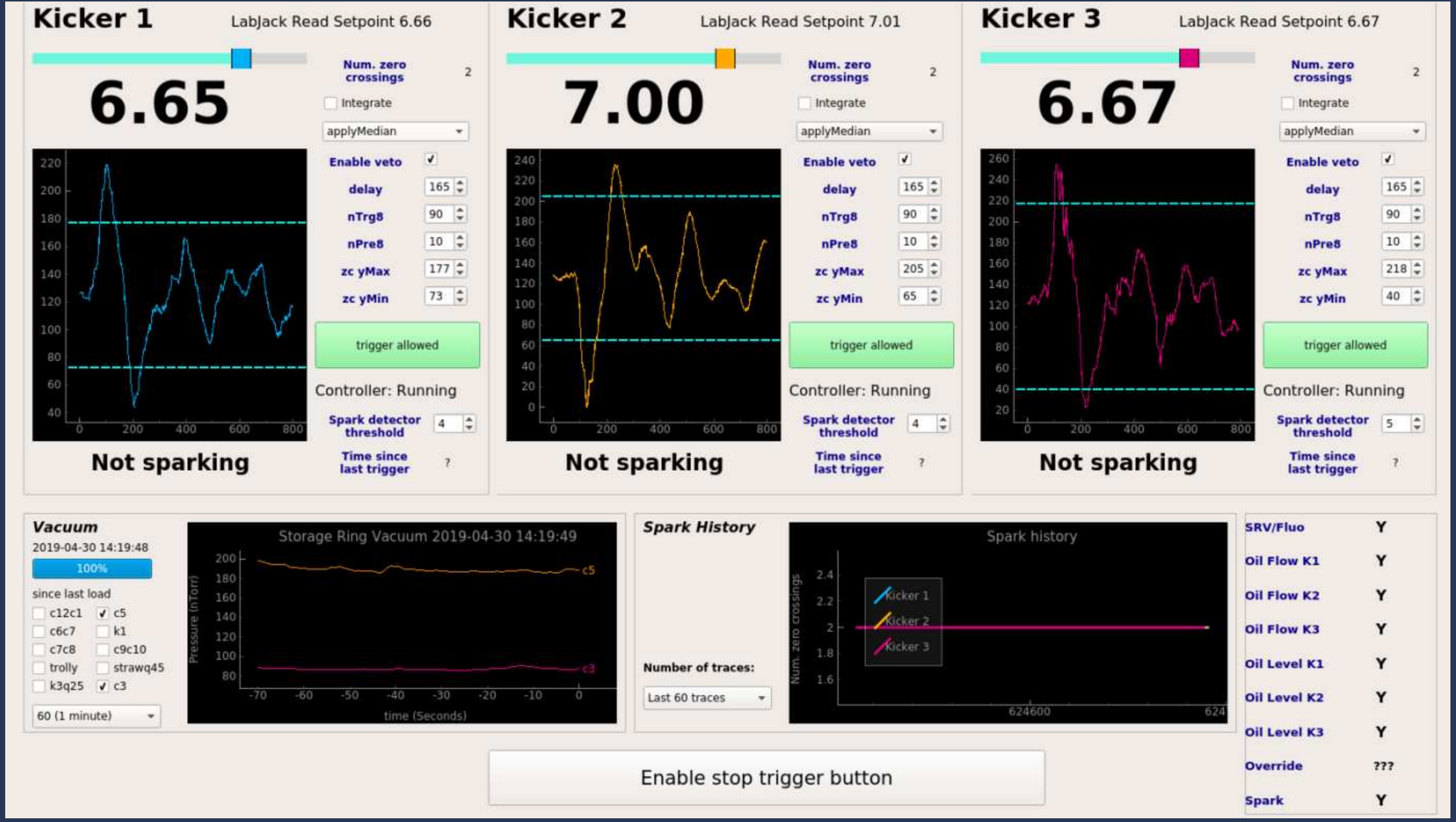
Presentations are communication tools that can be demonstrations.

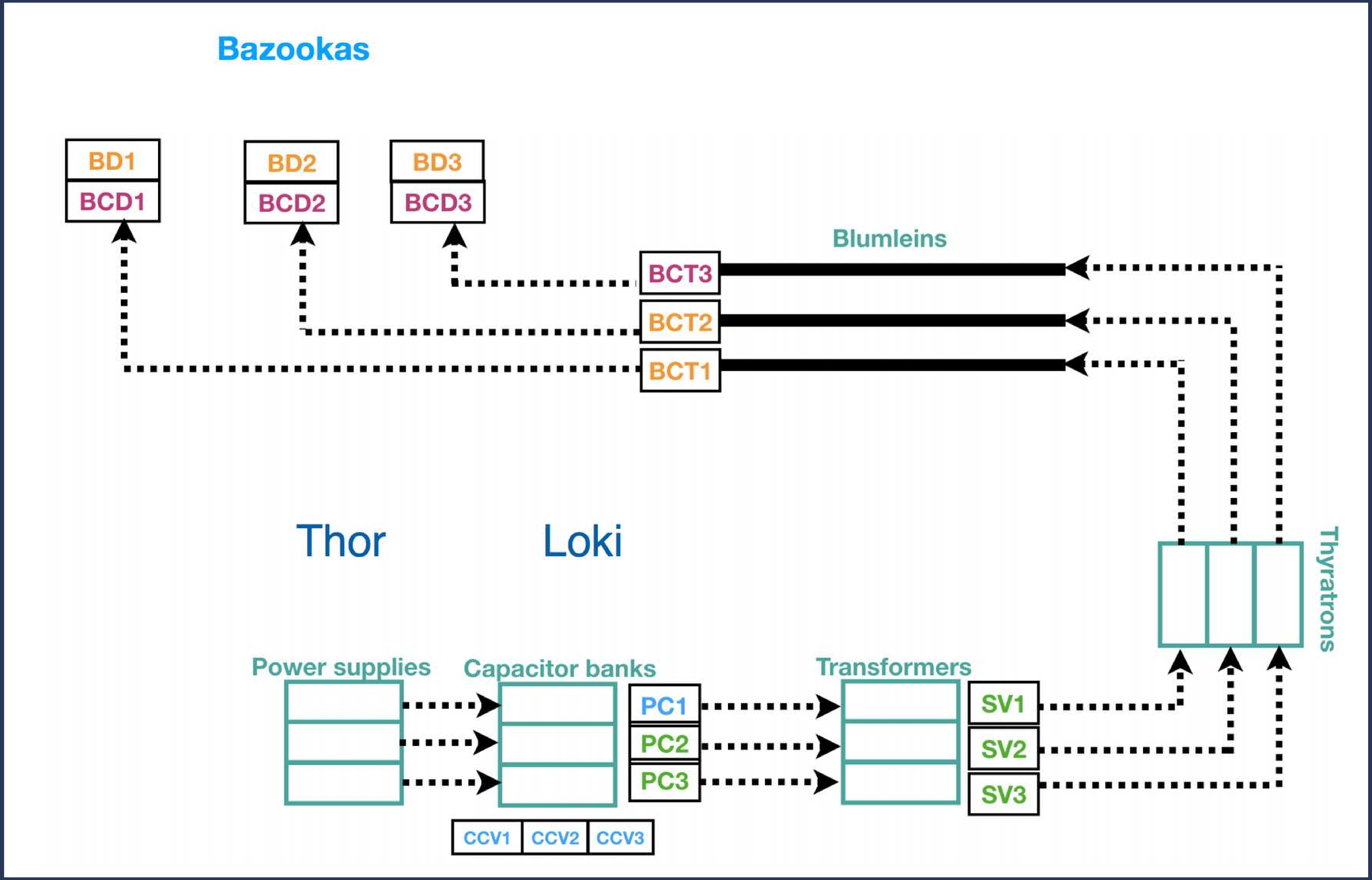






DAQ UPGRADES

- GUI controls Kicker strength
- Spark detection integrated with GUI
- Additional monitors for vacuum activity, oil level/flow, thyratron heater/reservoir voltages and currents, and fluorinert status



DAQ UPGRADES

- Capacitor Charge Voltage
- Primary Current from Capacitor Banks
- Secondary Voltage from step-up transformers (SV)
- Pick-up coil and Bazooka (BD)
- Capacitive Dividers on Bazooka (BCD)

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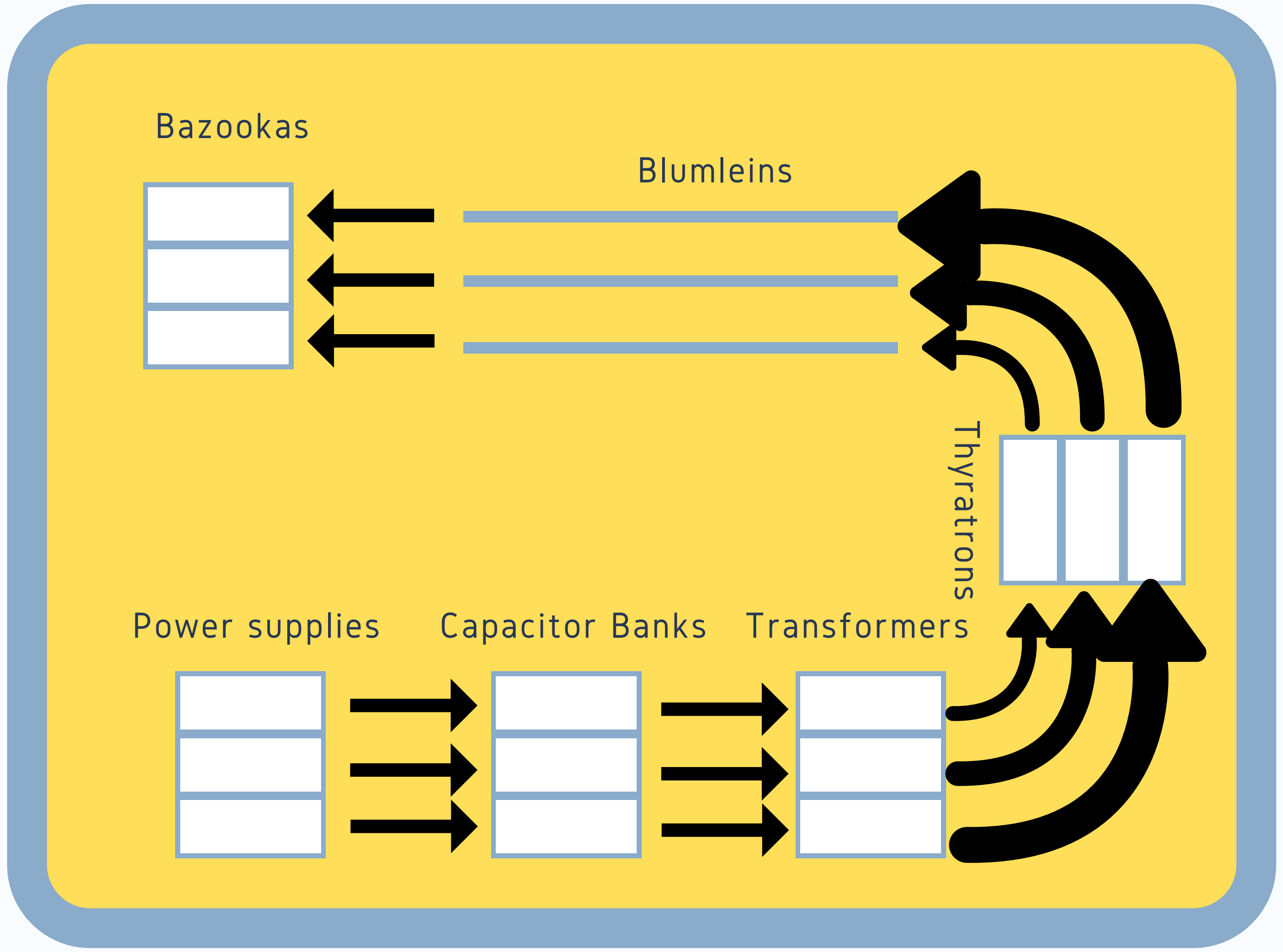
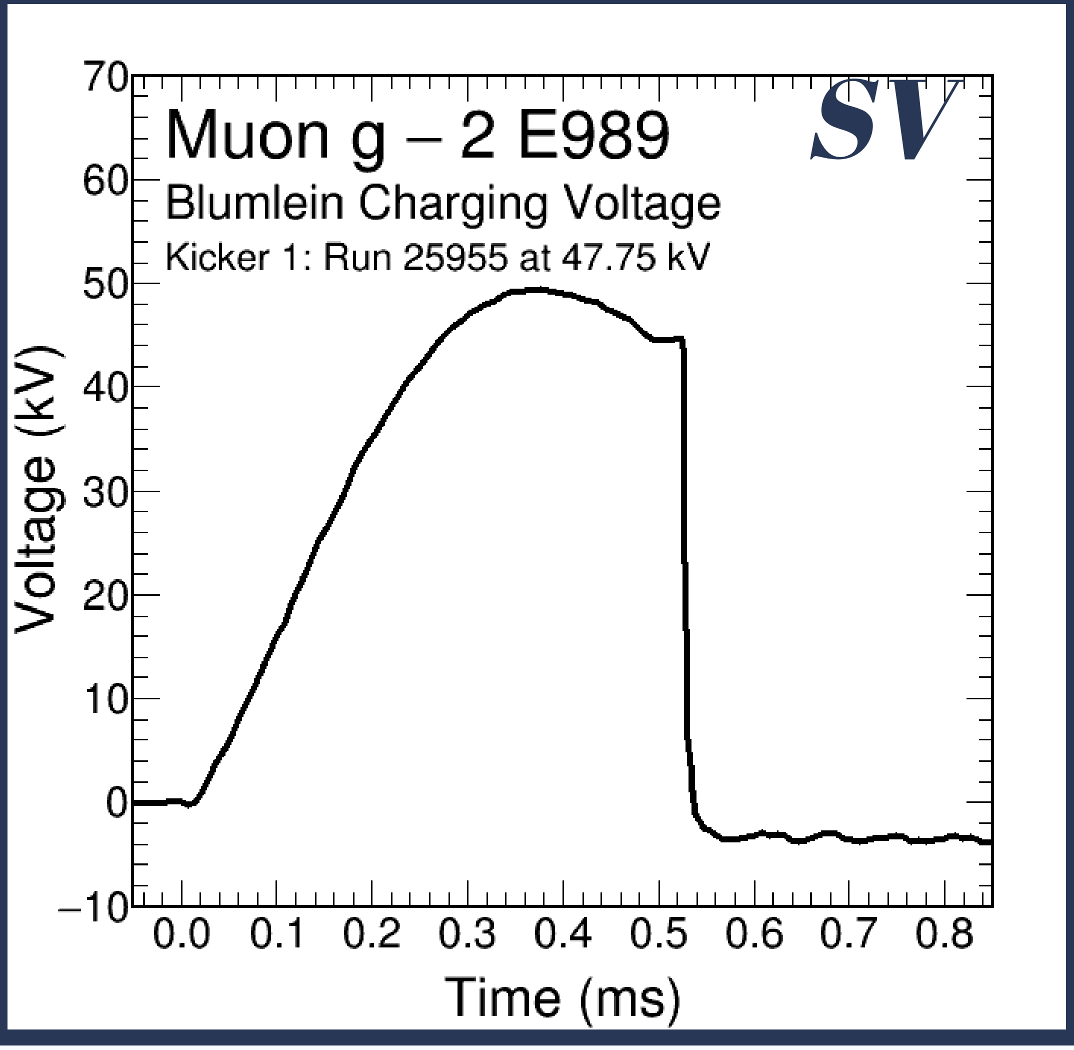
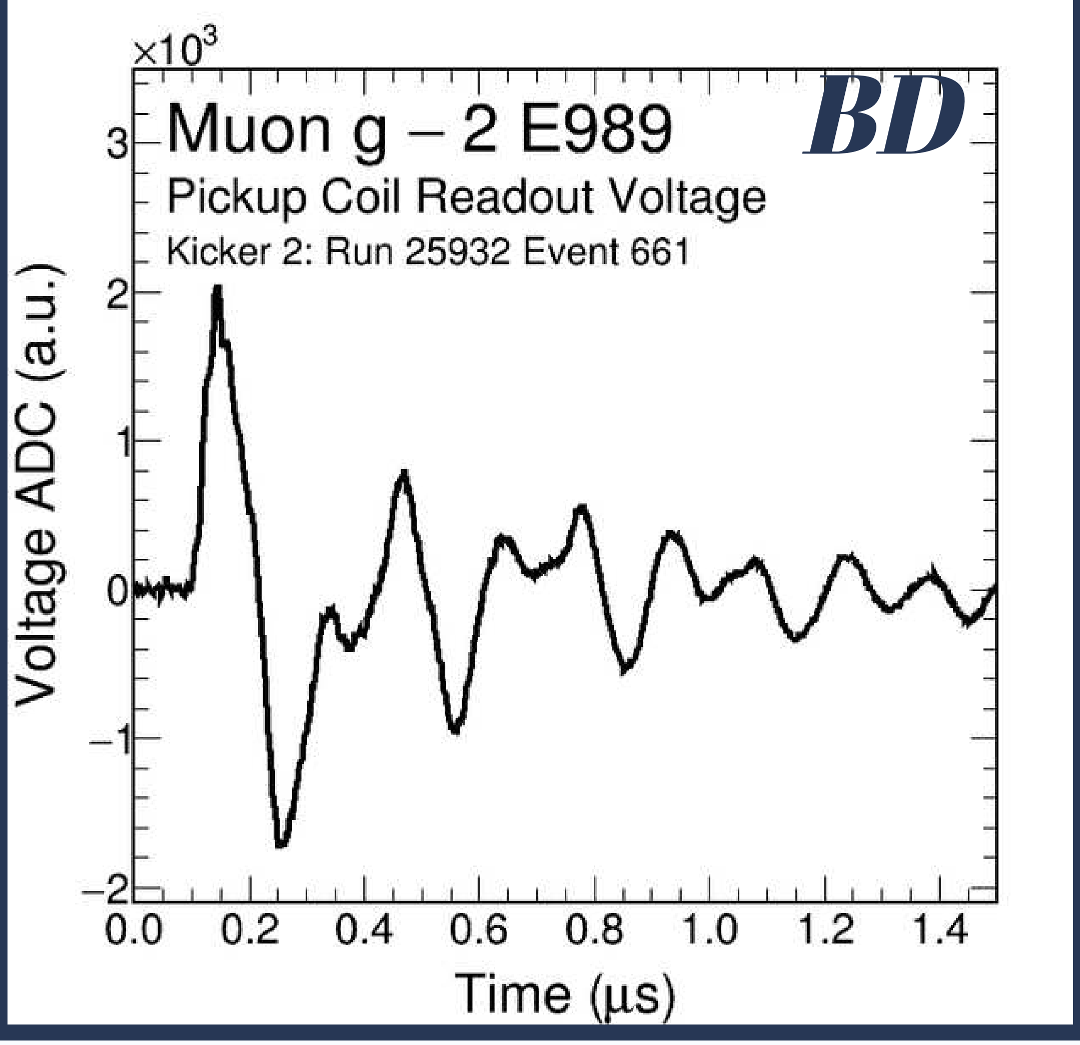
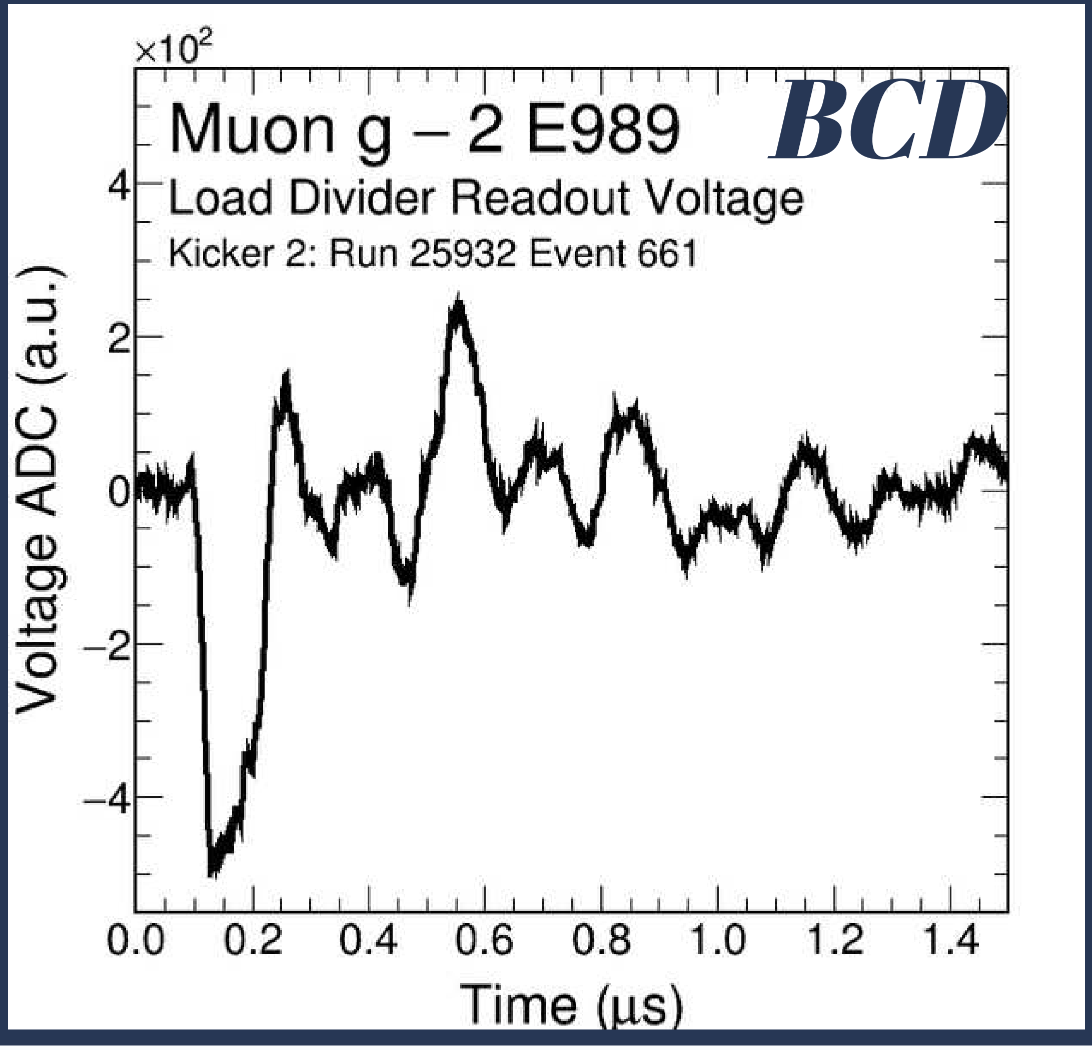


MAIN MONITORS IN PLACE



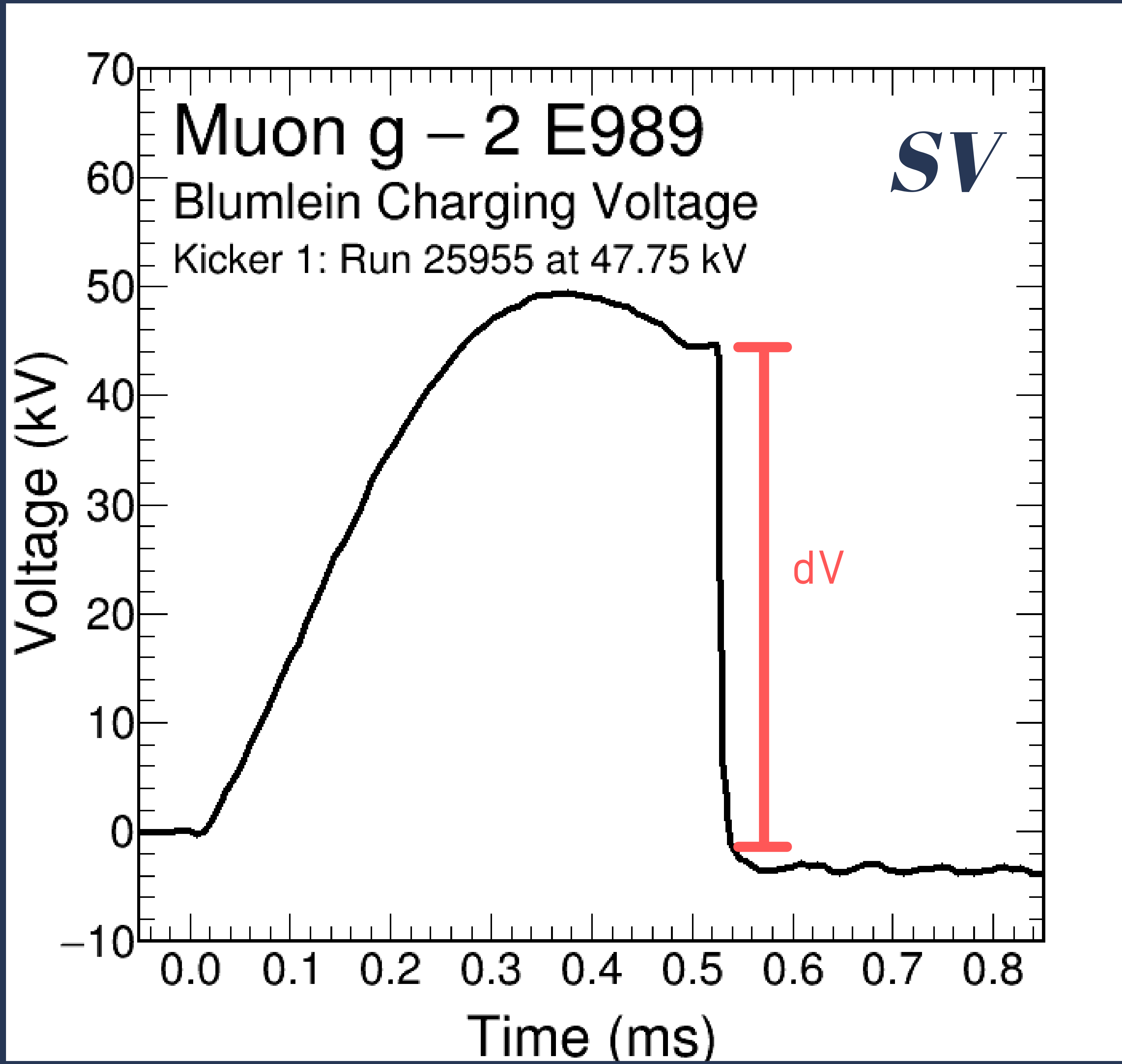




- SV from transformers
- Key for voltage calibration
- Monitors blumlein health

- Used to monitor for and trip on sparks
- Important for timing kicker pulse to muon beam

- New readout from bazooka
- Proportional to bazooka voltage
- Distortion in shape points to problems



Calibration

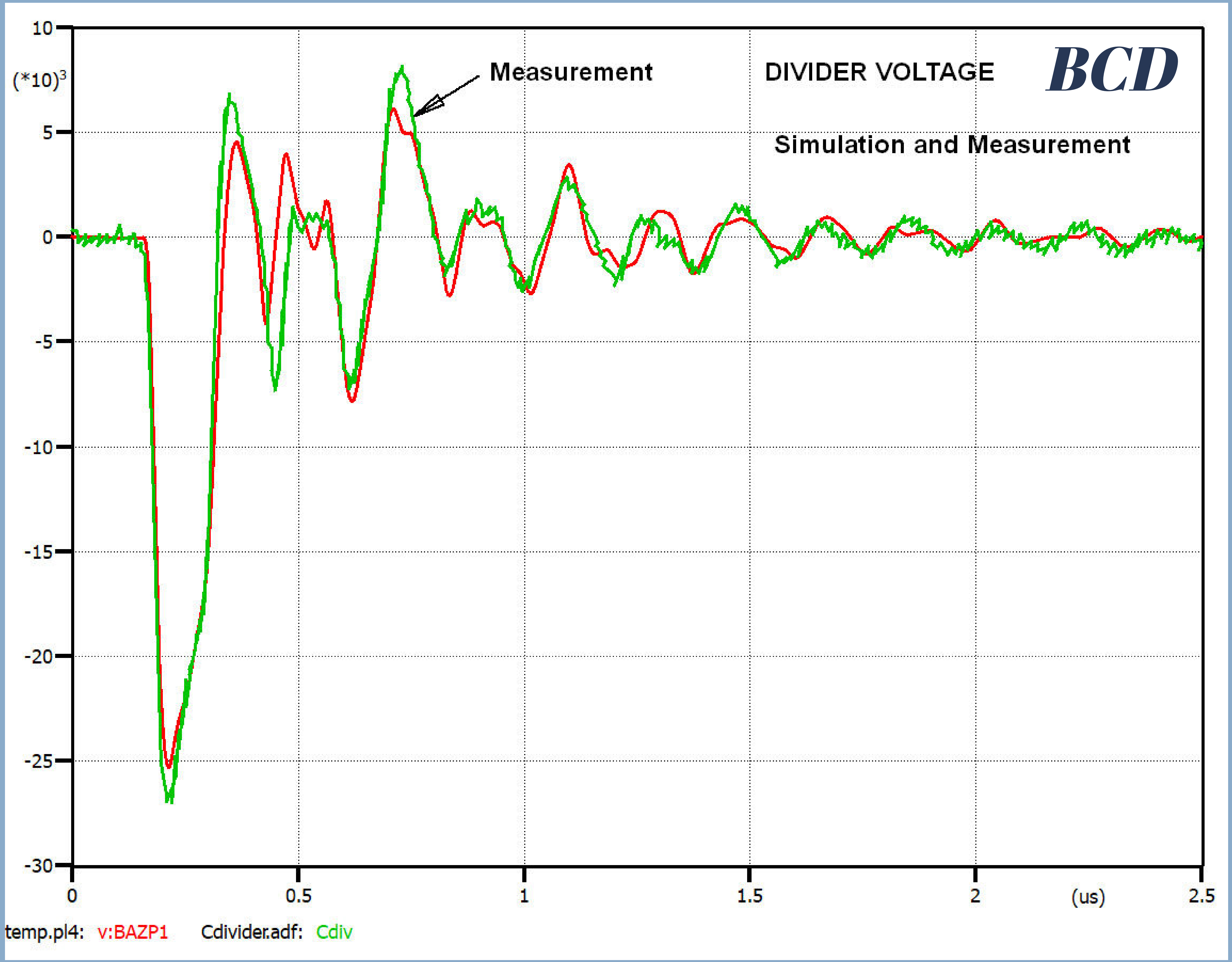
Linear fits of dV as a function of reference voltage

$$
\begin{aligned}
V_{K1}^{II}(V_{ref}^{K1}) &= 7.26[kV/V] \times V_{ref}^{K1} - 0.59[kV], \\
V_{K2}^{II}(V_{ref}^{K2}) &= 6.78[kV/V] \times V_{ref}^{K2} - 0.38[kV], \\
V_{K3}^{II}(V_{ref}^{K3}) &= 7.18[kV/V] \times V_{ref}^{K3} - 0.81[kV].
\end{aligned}
$$

$$
\begin{aligned}
V_{K1}^{I}(V_{ref}^{K1}) &= 20.56[kV/V] \times V_{ref}^{K1} + 0.84[kV], \\
V_{K2}^{I}(V_{ref}^{K2}) &= 19.59[kV/V] \times V_{ref}^{K2} - 0.59[kV], \\
V_{K3}^{I}(V_{ref}^{K3}) &= 18.51[kV/V] \times V_{ref}^{K3} + 1.59[kV].
\end{aligned}
$$

Capacitive Divider

- MODELING VOLTAGE FROM CAPACITIVE DIVIDER USING ATP
- MODEL UPDATED TO MATCH DATA BY SIMULATING BLUMLEIN CYLINDERS, ADDING LOSSES TO CASTER OIL, SLOWING RISE, CHANGING CHARACTERISTICS OF THYRATRON



CREDIT: DAN WOLFF

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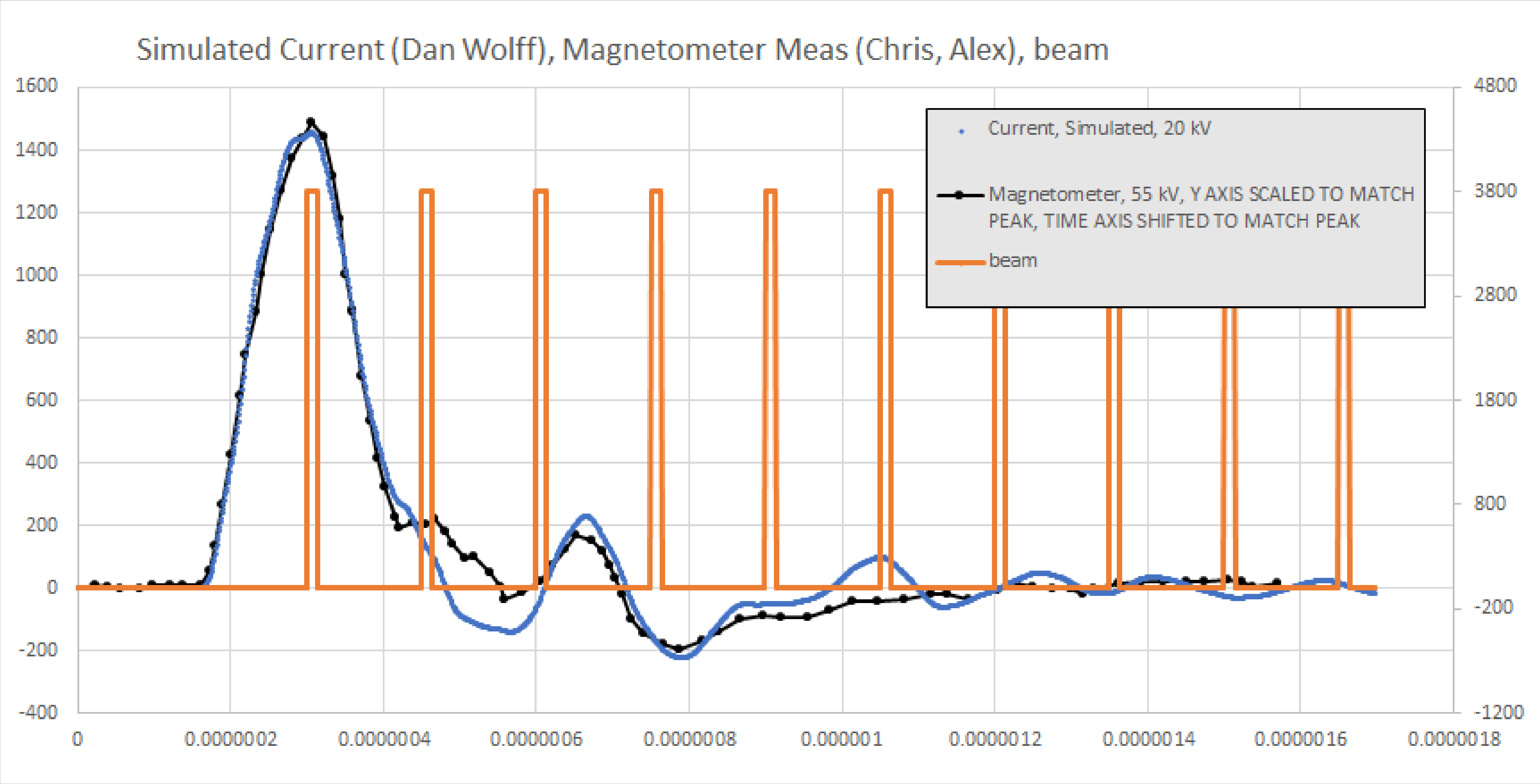
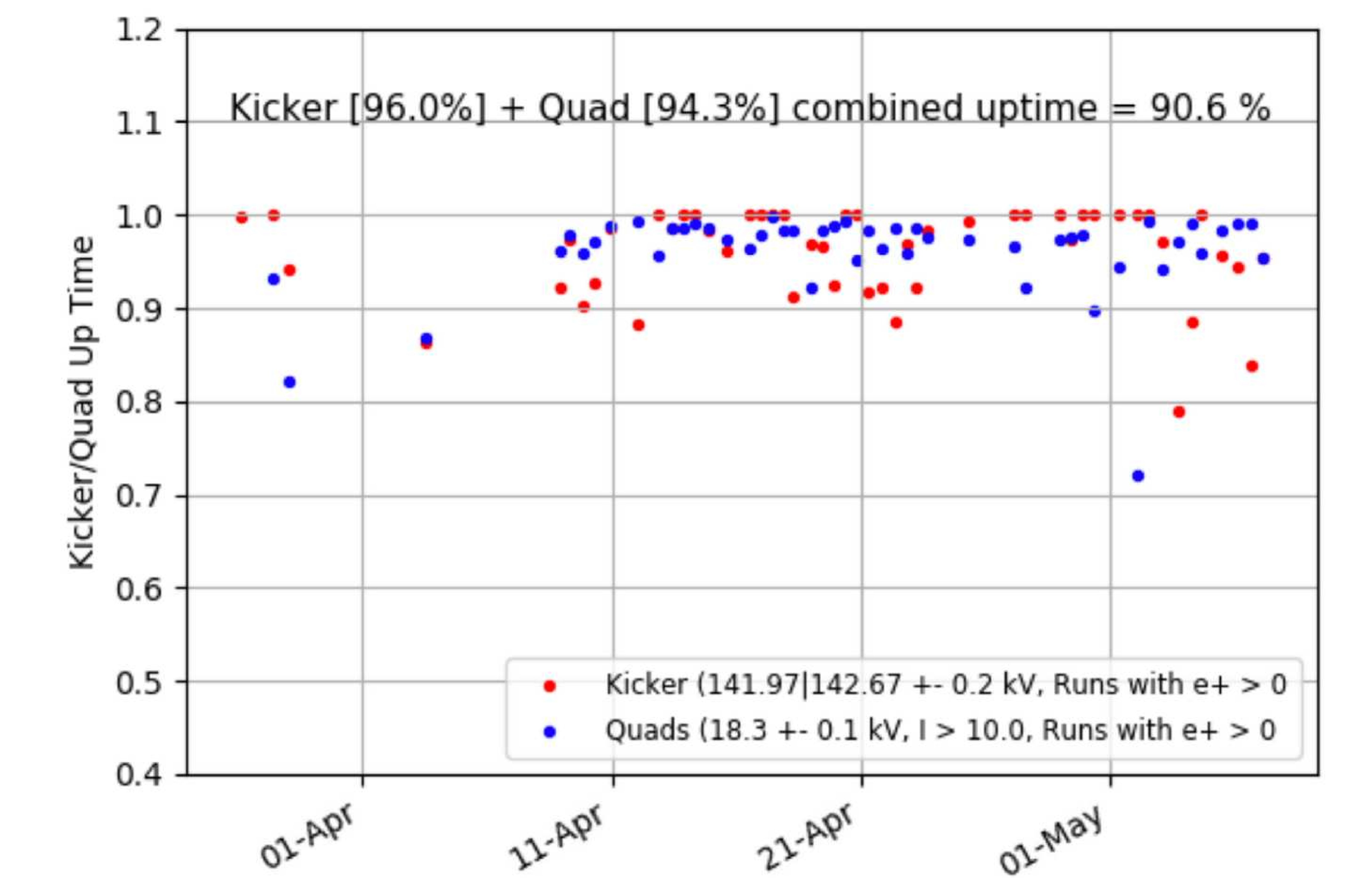
Simulated Current vs Magnetometer measurement



Preliminary simulation to data comparrison

Credit: Mark

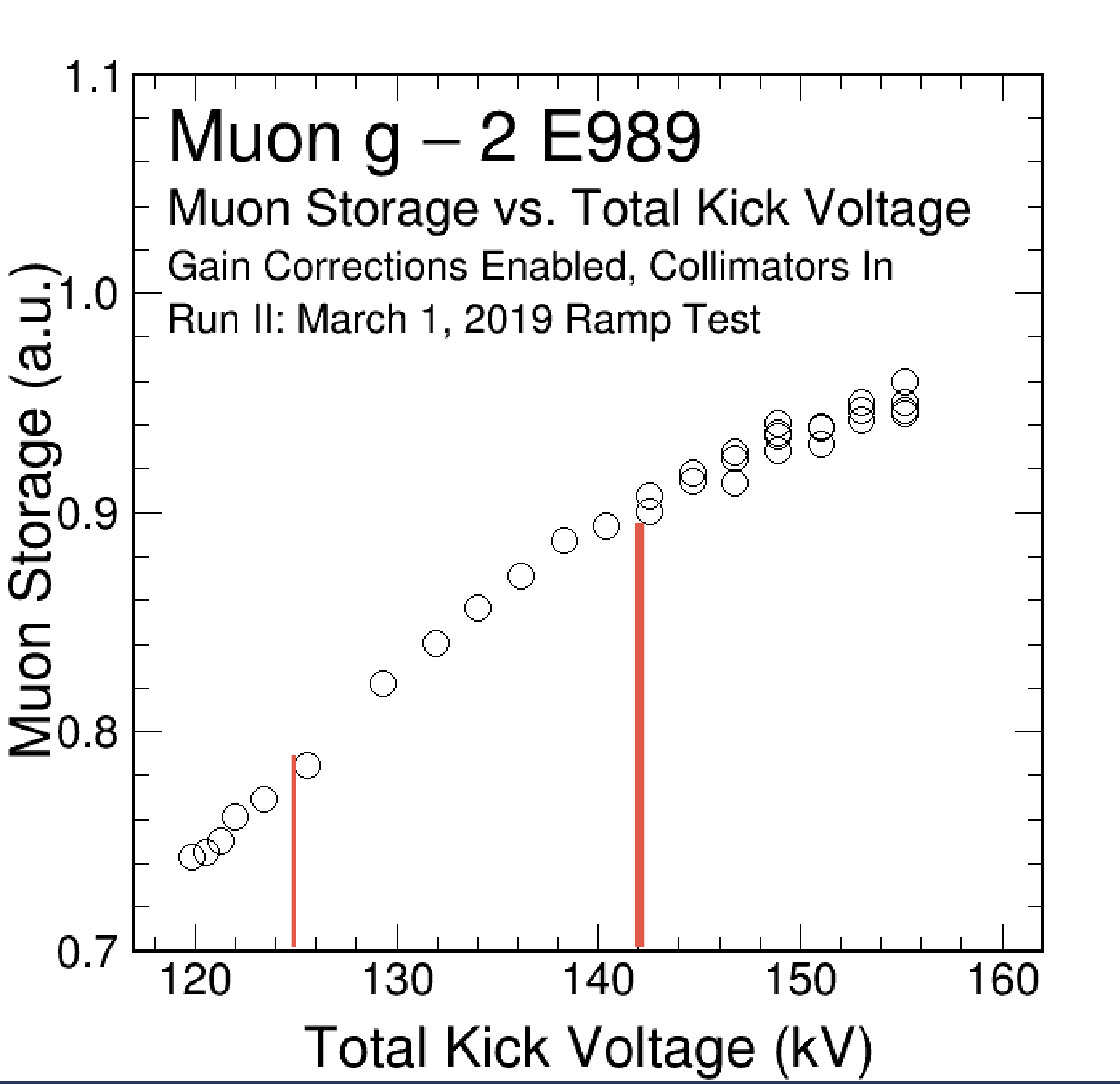


KICKER STABLE @ 142KV

INCREASED MUON STORAGE

Shows stability of kicker system over long periods of time=> 96% uptime

Muon storage in run 1 @ 124kV compared to run 2 @ 142kV



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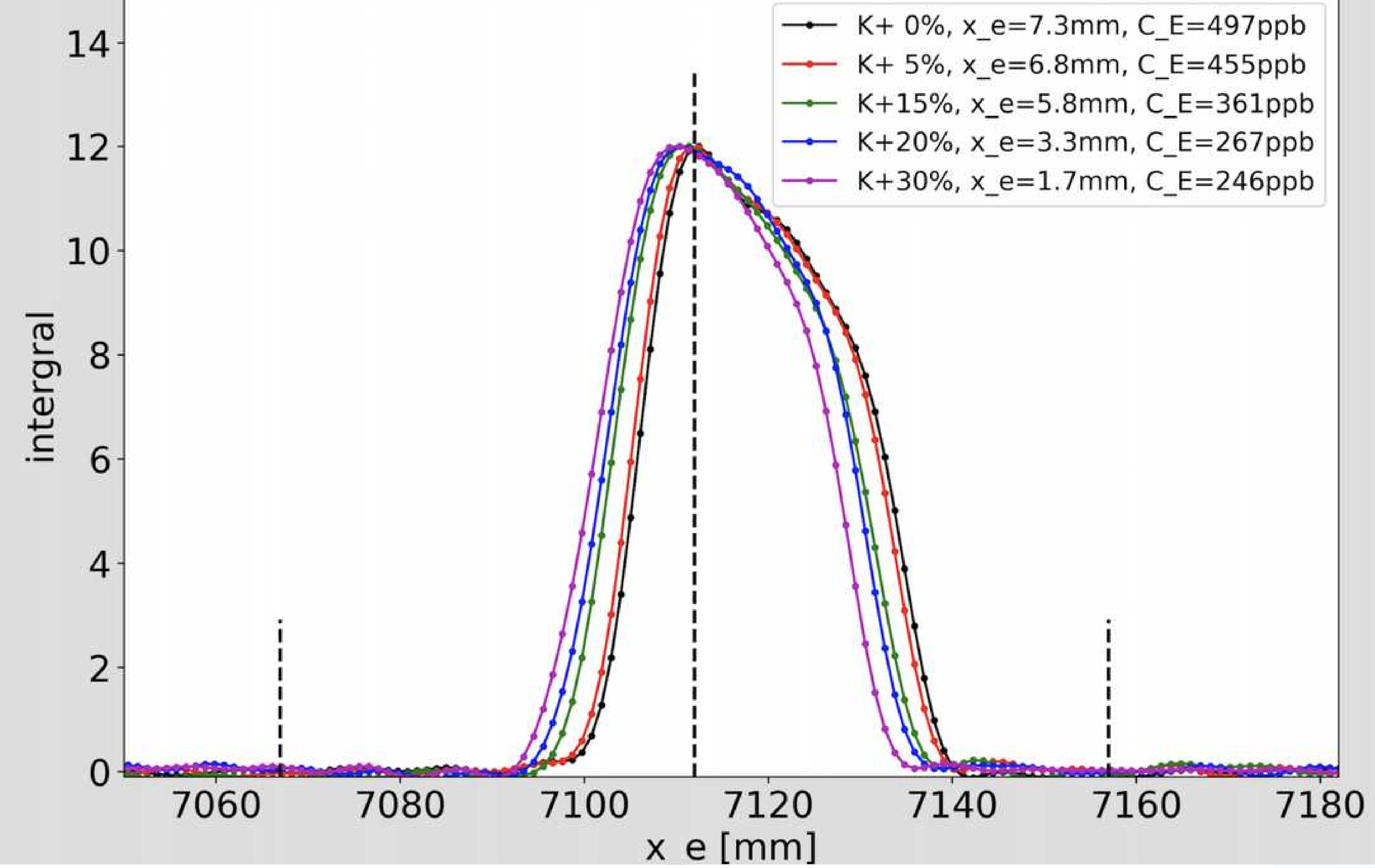
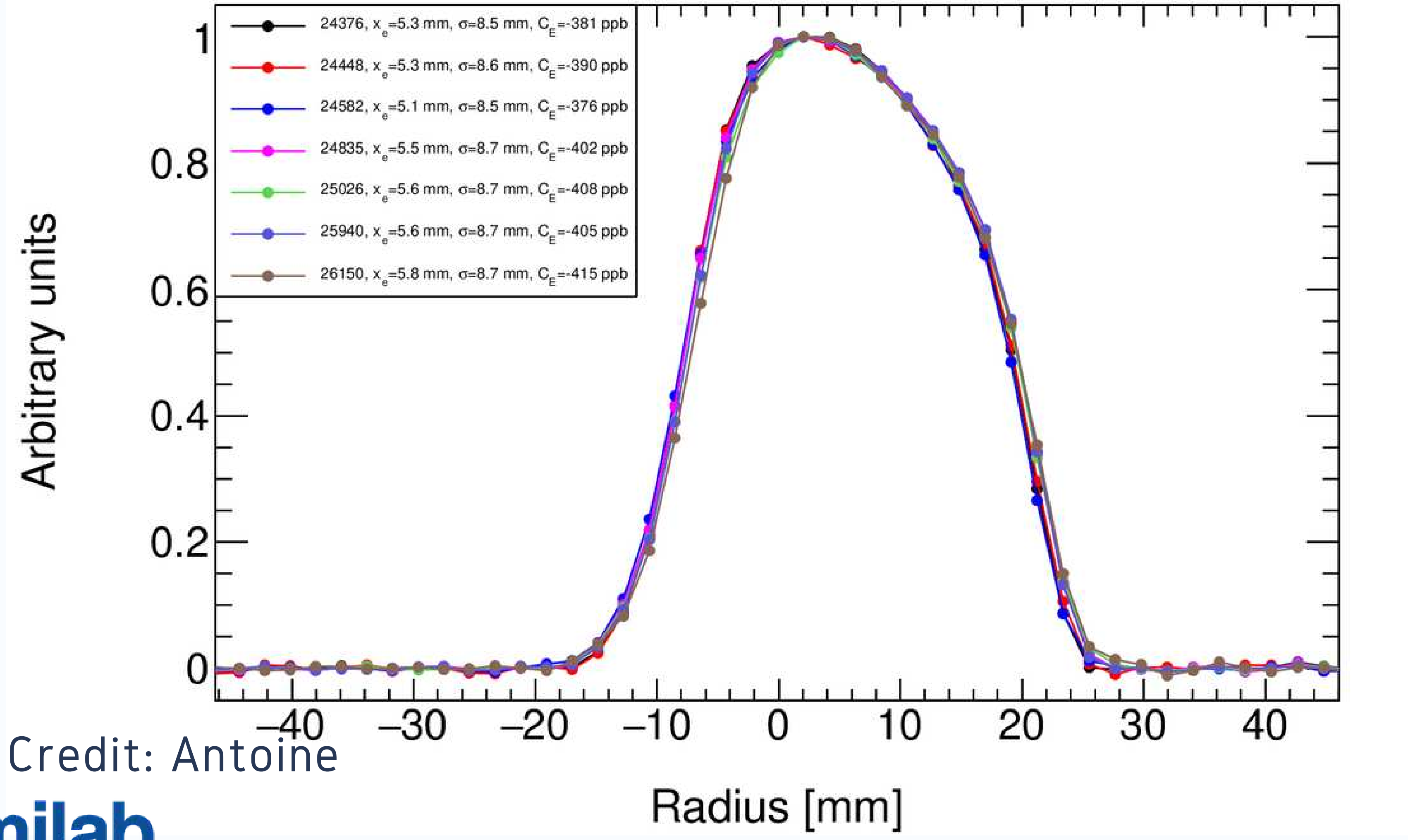
KICKER STABLE @ 142KV

FAST ROTATION ANALYSIS

- Shows stability of kickers from run to run.
- Preliminary results showing reduced CBO
- Stronger Kick results in muons closer to correct orbit





Credit: Antoine

RUN II UPGRADES SUMMARY

CHARGING SUPPLIES

Two supplies/kicker

Can now charge to any desired voltage in alloted 9 us time

CHARGING CAPACITOR CHASSIS

Lower dissipation of protection network

More reliable operation

THYRATRON CHASSIS

Upgrade thyratron cables,

Fuse protection

Heater/Reservoir voltage/current monitoring

BLUMLEIN REFURBISHMENT

Complete insulating standoff replacement

VACUUM FEEDTHROUGHS

No more fluorinert leaks

Improved vacuum in chamber

BAZOOKA UPGRADE

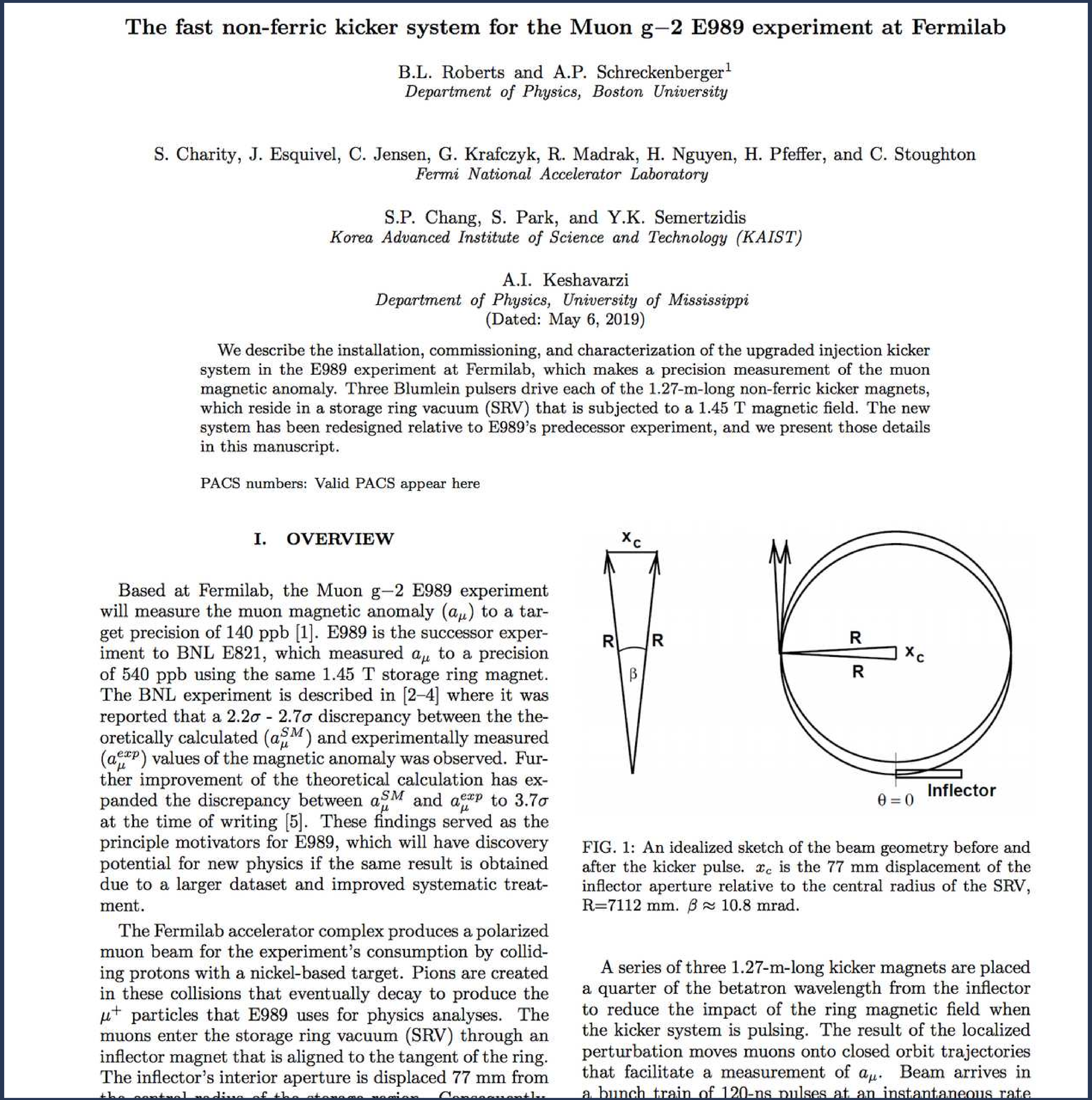
More robust resistors

Capacitive speed-up network => 11.6% more current

New voltage monitor

DAQ UPGRADES

Better remote control and monitoring



The fast non-ferric kicker system for the Muon g−2 E989 experiment at Fermilab

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S. Charity, J. Esquivel, C. Jensen, G. Krafczyk, R. Madrak, H. Nguyen, H. Pfeffer, and C. Stoughton
Fermi National Accelerator Laboratory

S.P. Chang, S. Park, and Y.K. Semertzidis
Korea Advanced Institute of Science and Technology (KAIST)

A.I. Keshavarzi
Department of Physics, University of Mississippi

(Dated: May 6, 2019)

We describe the installation, commissioning, and characterization of the upgraded injection kicker system in the E989 experiment at Fermilab, which makes a precision measurement of the muon magnetic anomaly. Three Blumlein pulsers drive each of the 1.27-m-long non-ferric kicker magnets, which reside in a storage ring vacuum (SRV) that is subjected to a 1.45 T magnetic field. The new system has been redesigned relative to E989's predecessor experiment, and we present those details in this manuscript.

PACS numbers: Valid PACS appear here

I. OVERVIEW

Based at Fermilab, the Muon g−2 E989 experiment will measure the muon magnetic anomaly (a_μ) to a target precision of 140 ppb [1]. E989 is the successor experiment to BNL E821, which measured a_μ to a precision of 540 ppb using the same 1.45 T storage ring magnet. The BNL experiment is described in [2–4] where it was reported that a 2.2σ - 2.7σ discrepancy between the theoretically calculated (a_μ^{SM}) and experimentally measured (a_μ^{exp}) values of the magnetic anomaly was observed. Further improvement of the theoretical calculation has expanded the discrepancy between a_μ^{SM} and a_μ^{exp} to 3.7σ at the time of writing [5]. These findings served as the principle motivators for E989, which will have discovery potential for new physics if the same result is obtained due to a larger dataset and improved systematic treatment.

The Fermilab accelerator complex produces a polarized muon beam for the experiment's consumption by colliding protons with a nickel-based target. Pions are created in these collisions that eventually decay to produce the μ^+ particles that E989 uses for physics analyses. The muons enter the storage ring vacuum (SRV) through an inflector magnet that is aligned to the tangent of the ring. The inflector's interior aperture is displaced 77 mm from

FIG. 1: An idealized sketch of the beam geometry before and after the kicker pulse. x_c is the 77 mm displacement of the inflector aperture relative to the central radius of the SRV, R=7112 mm. $\beta \approx 10.8$ mrad.

A series of three 1.27-m-long kicker magnets are placed a quarter of the betatron wavelength from the inflector to reduce the impact of the ring magnetic field when the kicker system is pulsing. The result of the localized perturbation moves muons onto closed orbit trajectories that facilitate a measurement of a_μ. Beam arrives in a bunch train of 120-ns pulses at an instantaneous rate

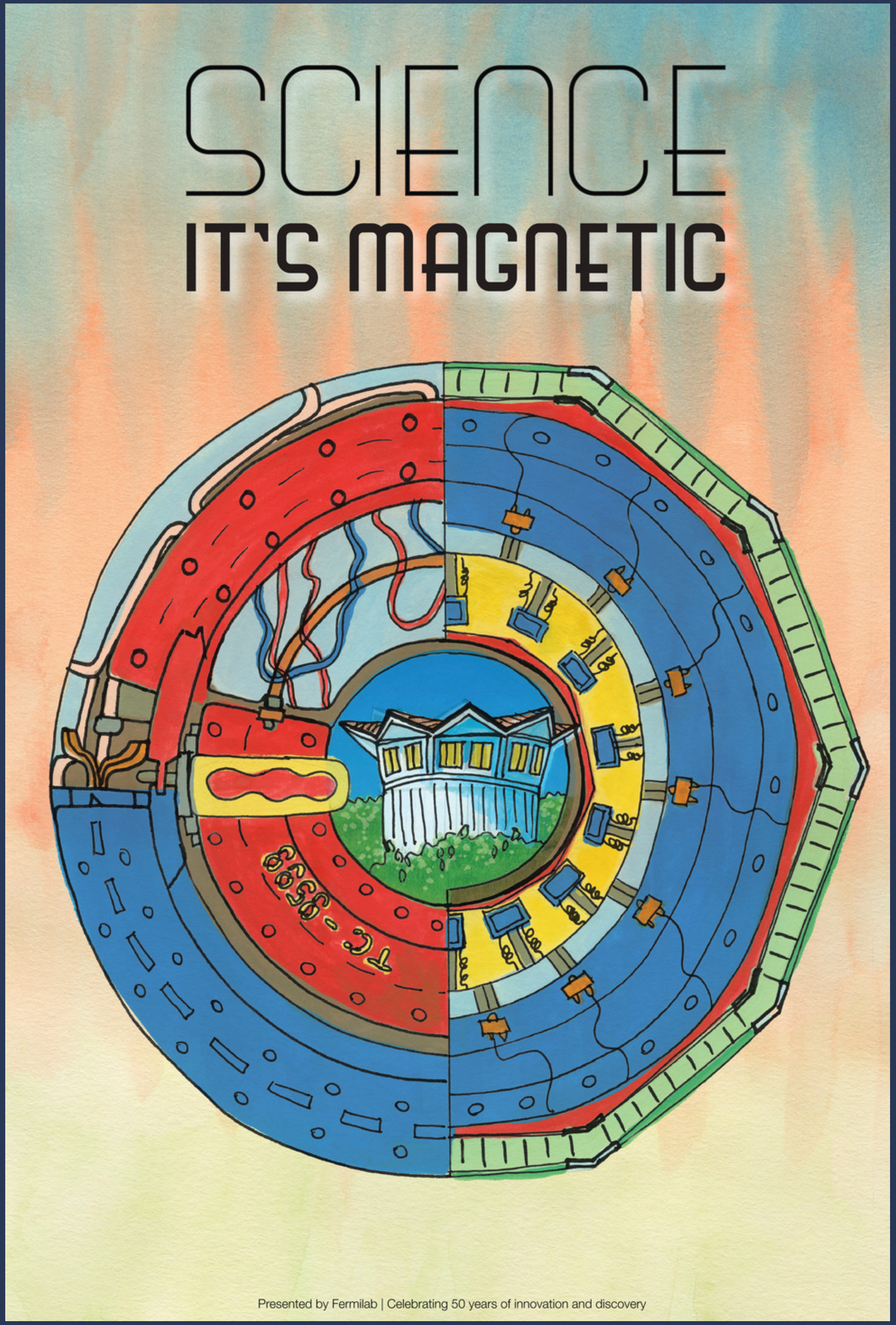
SUMMARY

- 96% average uptime!!
- Stable running at same kick value
- Higher Kick than Run 1
- More characterization than ever before
- Updated simulations
- AND 15-pg In Progress journal paper outlining upgrades, design, monitoring, characterization and calibration being done in Run II

THANK YOU

TO THE ENGINEERS, TECHNICIANS, COLLABORATORS, AND OPERATORS WHO HELPED GET US AND KEEPING US KICKING!

QUESTIONS??



BACKUP

https://docs.google.com/document/d/1rEry7GvgsT4XmYGC64k6fFTIp6PaTX__HfEtRmHDK1U/edit?usp=sharing

LATE FEB

Kicker polarity flip, K3 cable fault most likely due to bad connection

EARLY MARCH

Old standoff removal, kicker spark hunt with mirror and video

MID MARCH

K2 cable fault, kicker/trolley interference, fried capacitor board fixed

LATE MARCH

K3 spark hunt leads to removal of bazooka and teflon block. K3 still sparking heard near feedthrough. K2 cable fault while running at setpoint 7.75

EARLY APRIL

K3 feedthrough replaced with redesign. K2 visual inspection shows browning

MID APRIL

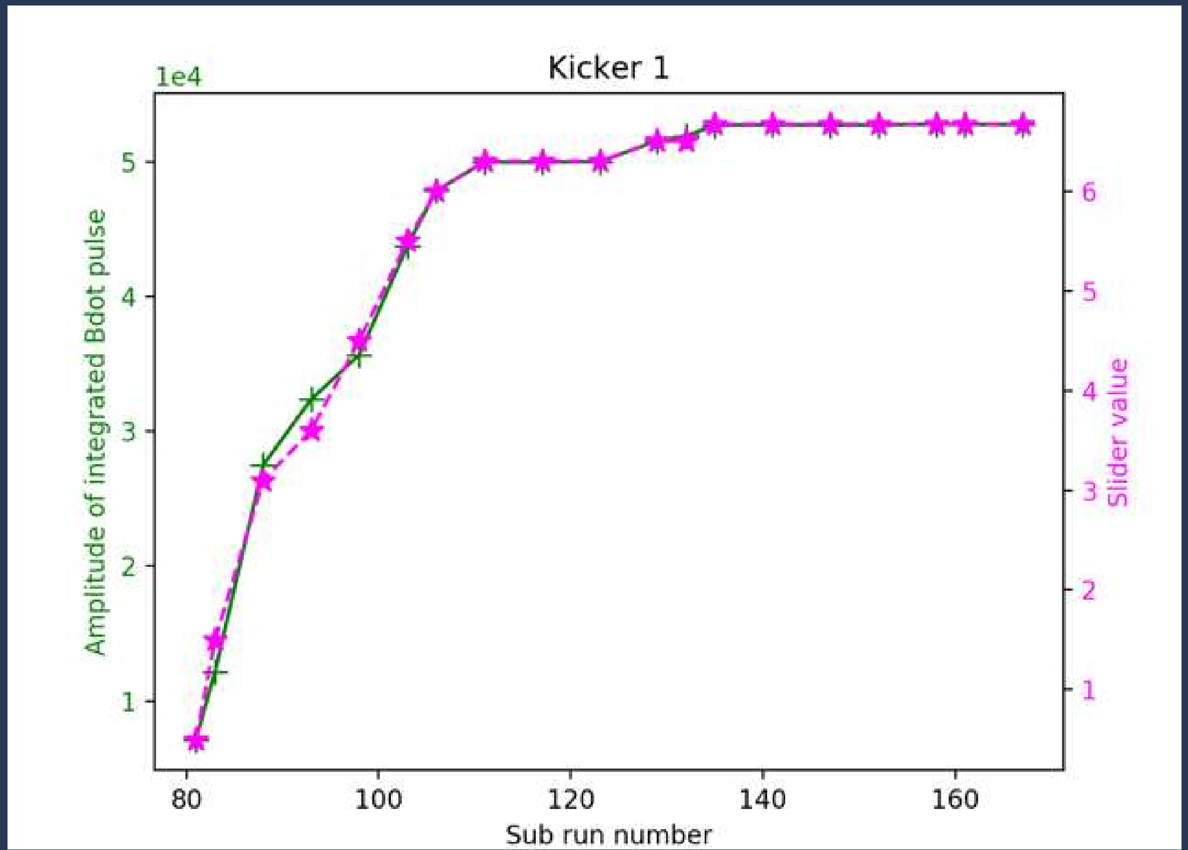
Kickers running stably since K3 feedthrough replacement

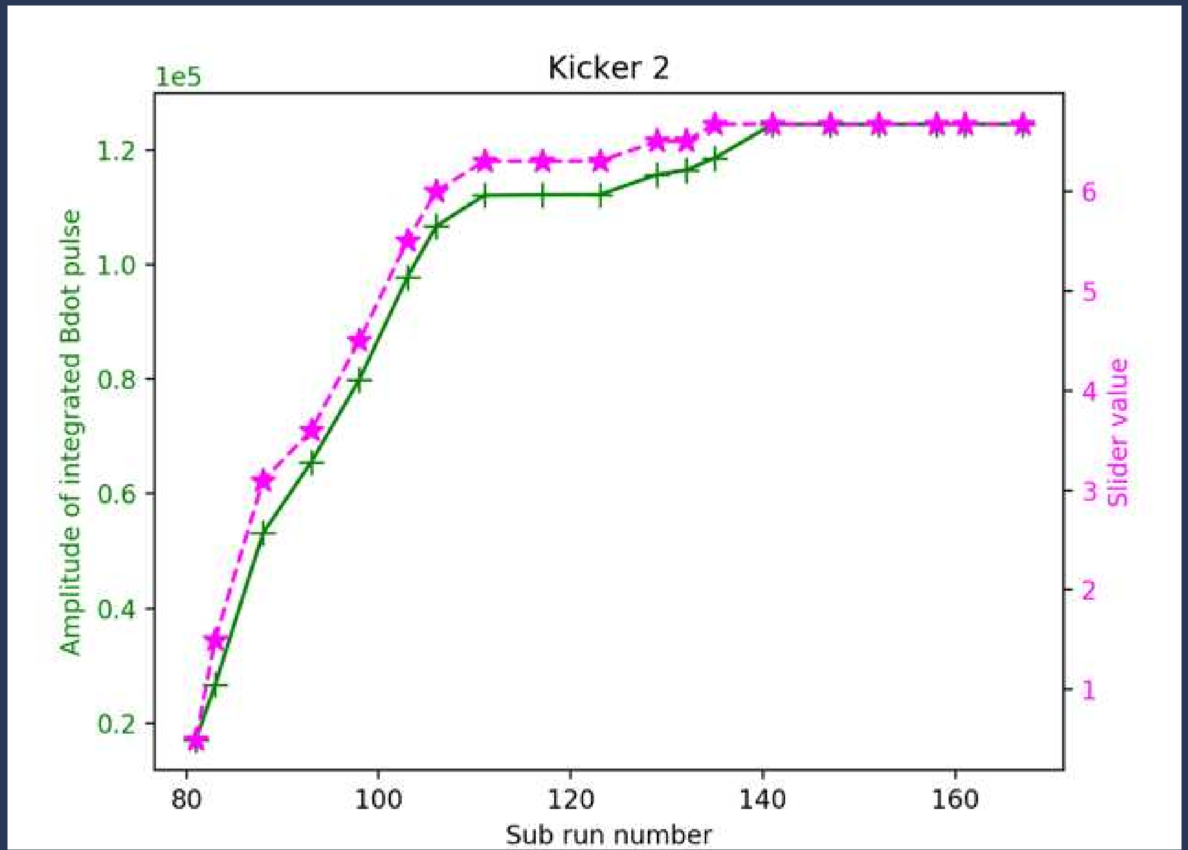
EARLY MAY

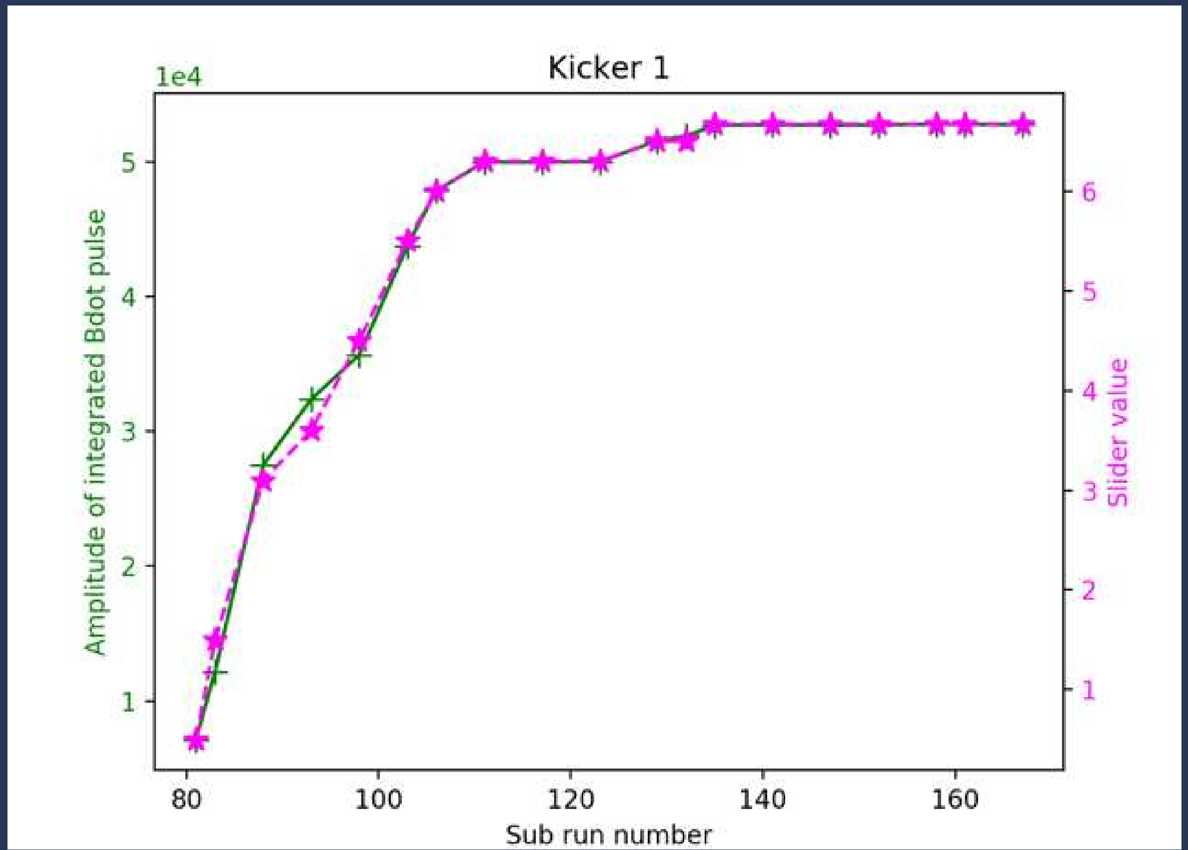
K1 has been sparking more frequently, 9 day shutdown reserved to upgrading K1 with new feedthrough design

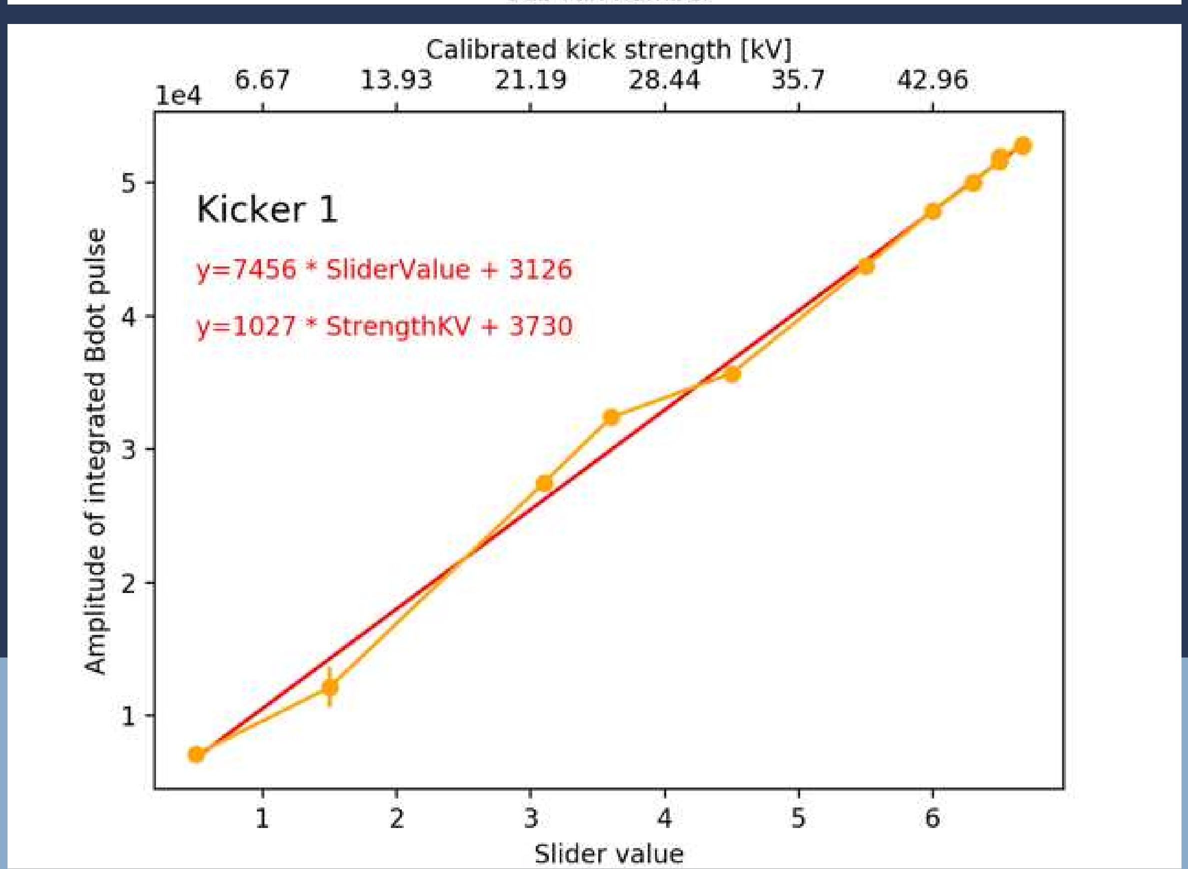
MID MAY

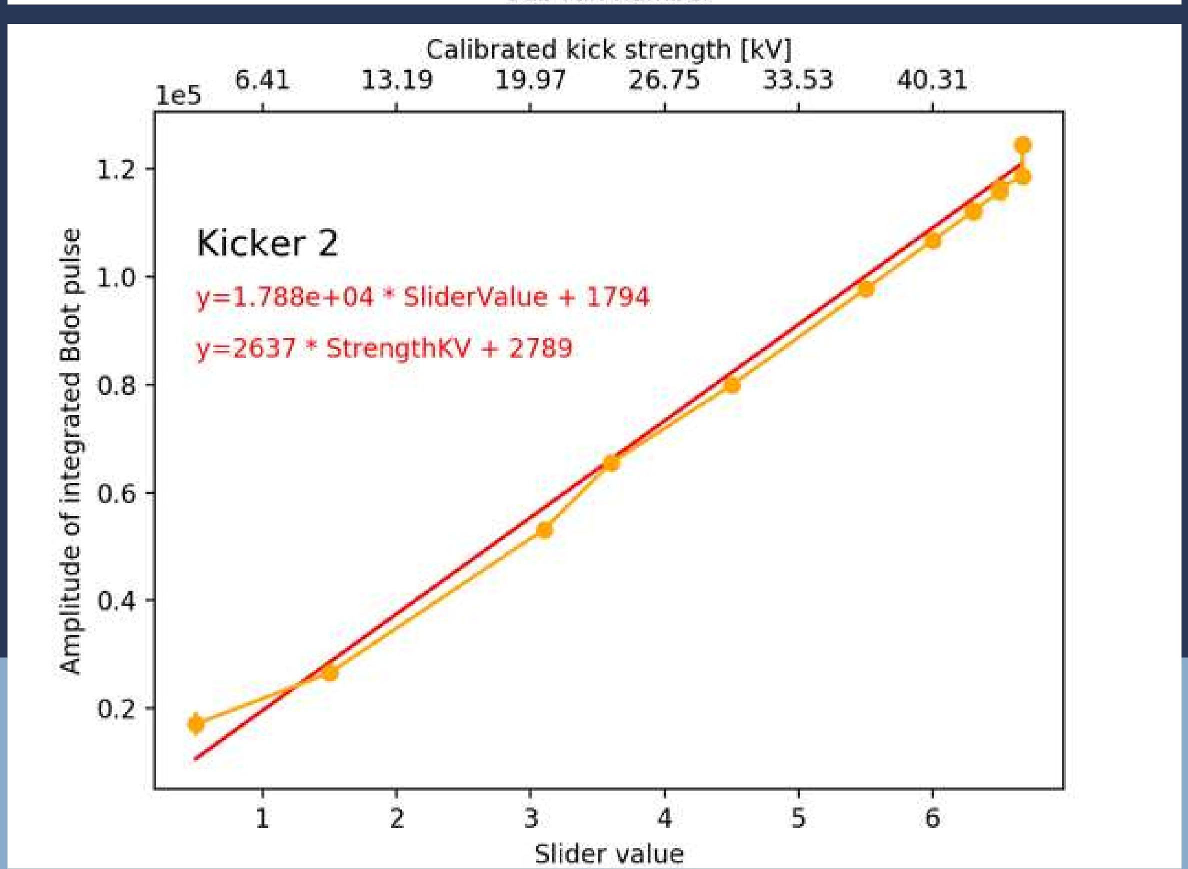
K1 browning on side teflon block, port, and crater from HV on wall of port. Also brown downstream standoffs and pitting on side of wall due to z-bracket

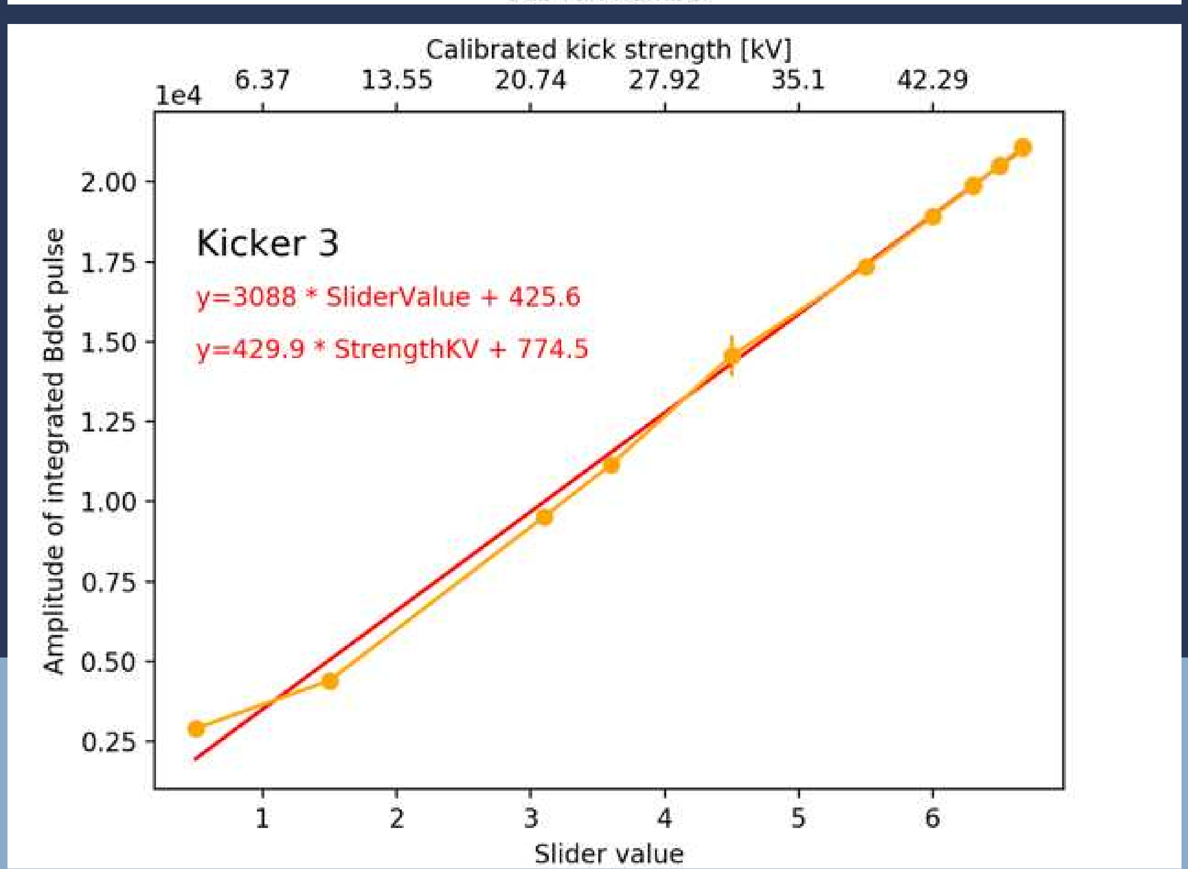




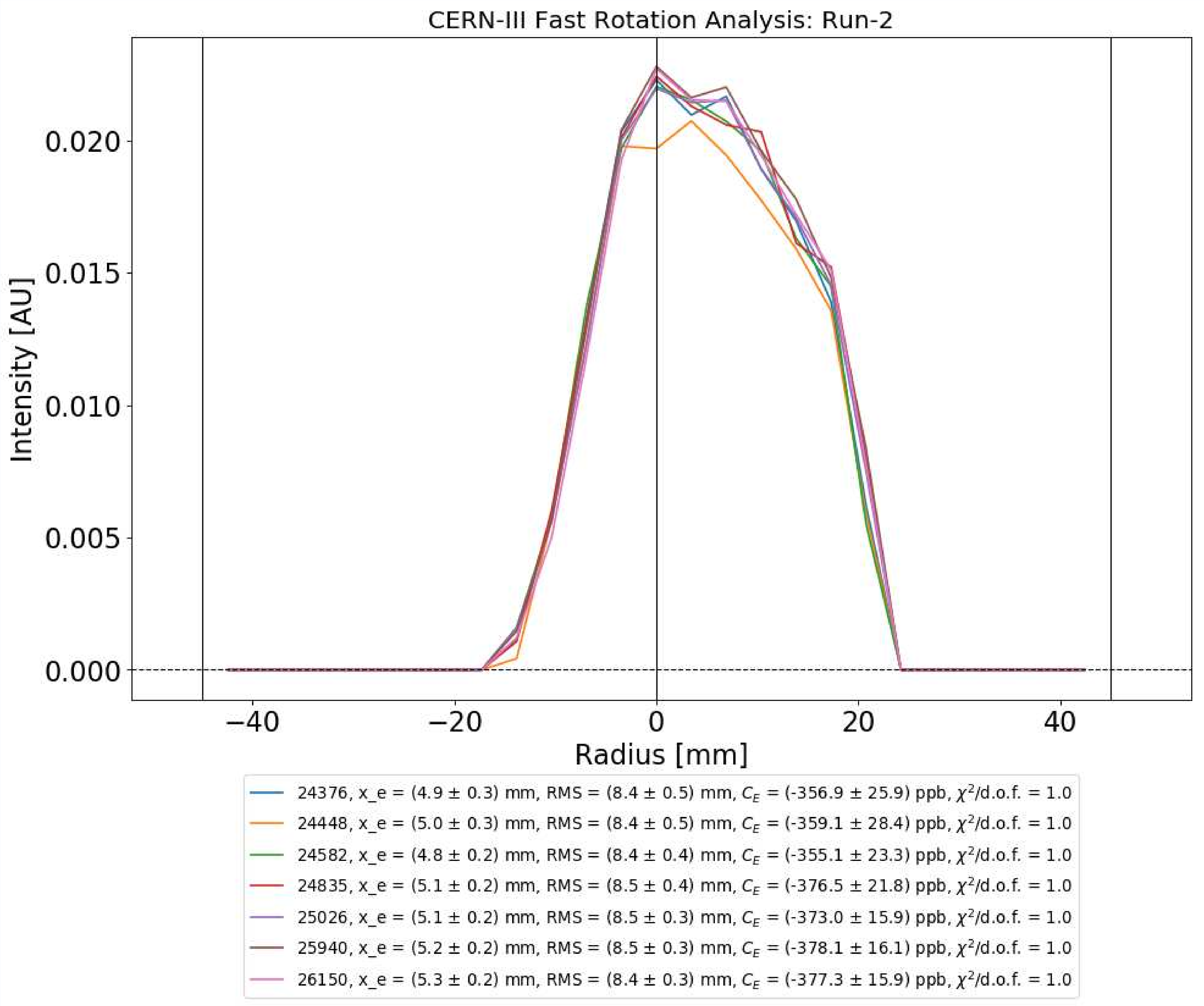








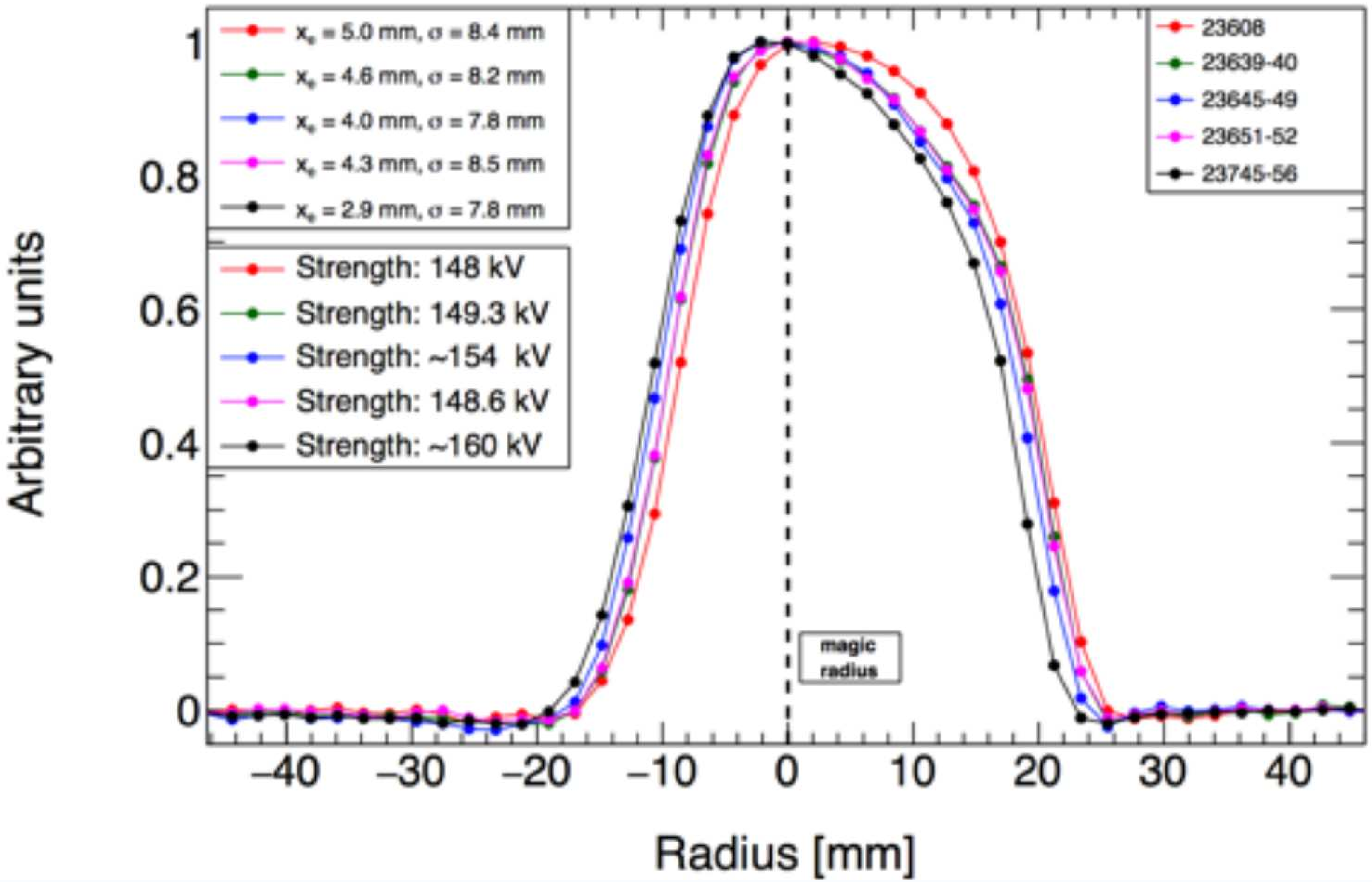
CALIBRATED KICK STRENGTH



FAST ROTATION ANALYSIS

CREDIT: ALEX

CERN-III on Run 2 datasets



x_e = 5.0 mm, σ = 8.4 mm
x_e = 4.6 mm, σ = 8.2 mm
x_e = 4.0 mm, σ = 7.8 mm
x_e = 4.3 mm, σ = 8.5 mm
x_e = 2.9 mm, σ = 7.8 mm
Strength: 148 kV
Strength: 149.3 kV
Strength: ~154 kV
Strength: 148.6 kV
Strength: ~160 kV
23608
23639-40
23645-49
23651-52
23745-56
magic radius
Arbitrary units
Radius [mm]
1
0.8
0.6
0.4
0.2
0
−40
−30
−20
−10
0
10
20
30
40