SURGE PROTECTION FOR LIQUID ARGON TPC DETECTORS

Ben Jones, MIT

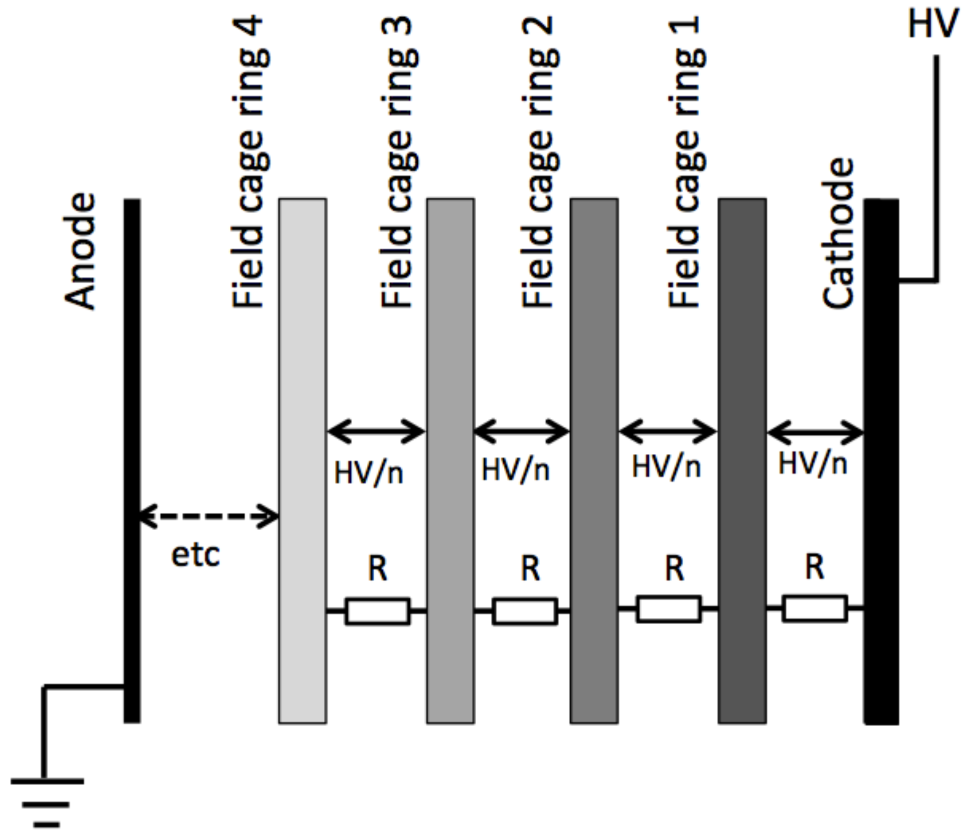
This Talk

- **1. Introduction to the HV transient problem**
  - **HV transients on the field cage**
  - **Possible solutions**
  - **Surge protection : GDTs and varistors**
  - **Devices installed in MicroBooNE**

- 2. Testing of HV surge protectors
  - Behavior in cryogenic conditions
  - Cryogenic robustness under high energy and voltage
  - Purity impacts
  - Testing on the MicroBooNE TPC

MicroBooNE field cage rings

Voltage distribution in the MicroBooNE field cage



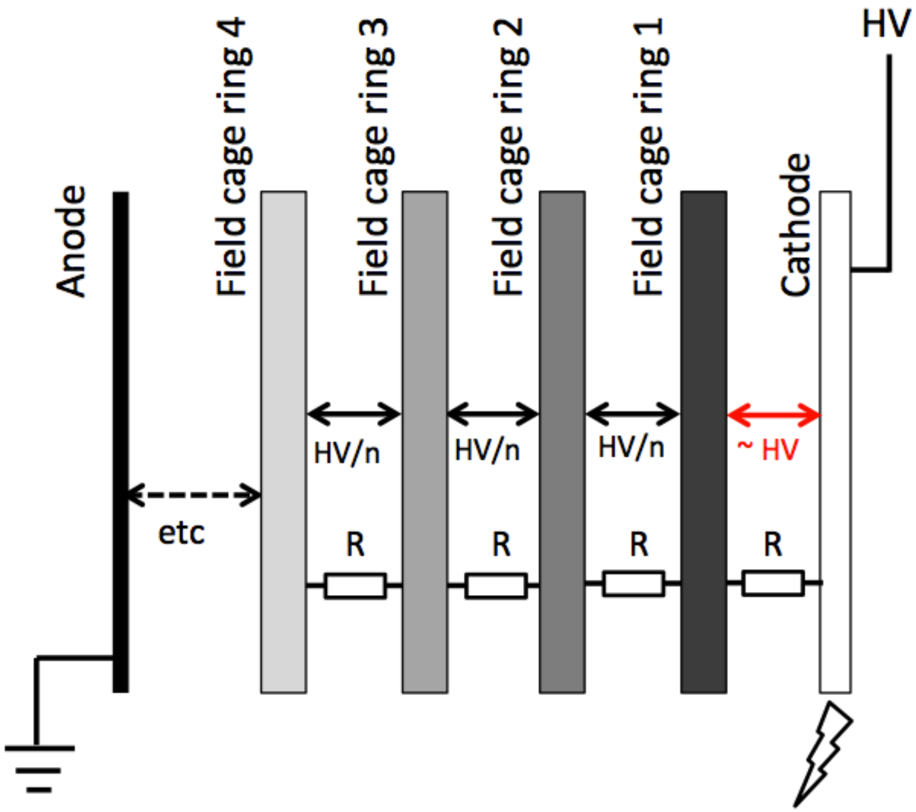
Field cage distributes high voltage and provides a uniform E field

MicroBooNE design:

4 x 1 GΩ SlimMox resistors
-> R = 250 MΩ ring-to-ring

What can happen in a breakdown?

- Consider cathode discharge to ground.
- Field cage tubes have a capacitance so remain charged.
- Large resistances prevent charge redistributing in the field cage.
- Capacitances O(1 nF) and resistances O(100 MΩ) lead to relaxation times O(0.1 s)
- Similar (sometimes worse) behavior if a field cage tube discharges.

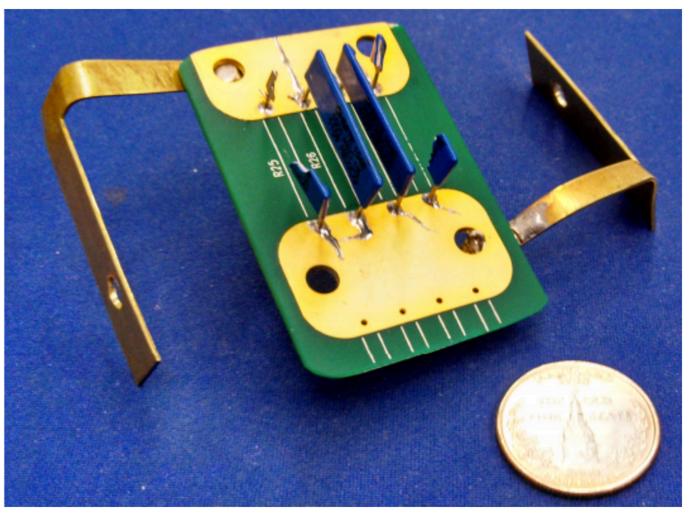


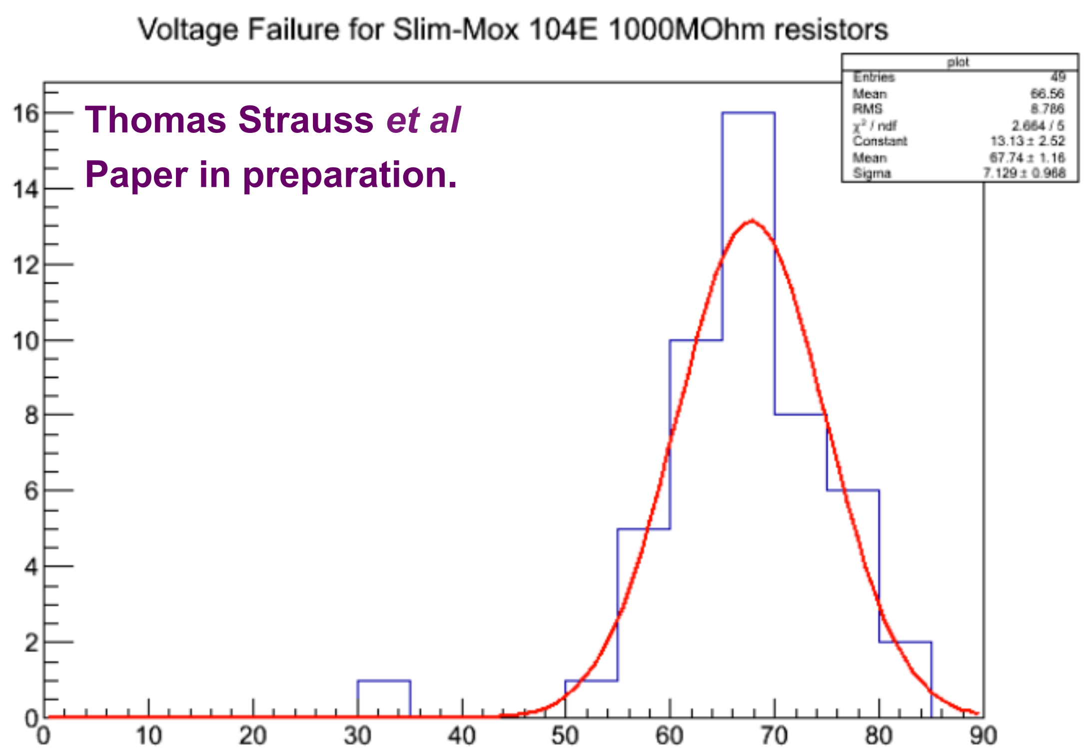
*The exact voltages evolved depend on **all** the capacitances in the TPC-Cathode-Cryostat system*

Uh Oh…

- Stress tests of installed SlimMox resistors for MicroBooNE show that they fail at voltages as low as 30 kV
- Simulations of the TPC in a spark condition show that we expect up to 90 kV held for ~0.5 s in a breakdown event.

Typical failure mode:





What can we do???

If you don’t want to get hurt by lightning…

What can we do???

Option 1 – if you have to go out in the lightning, be heavily armored.

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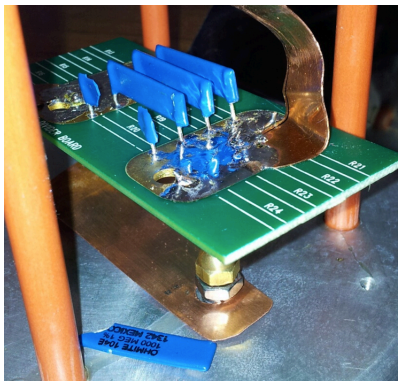


MicroBooNE SlimMox resistors

10 kV rating (air)
Failures from 30kV (LAr) experimentally.

Metallux “zebra” resistors

48 kV rating (air)
No failures up to 130 kV (LAr) experimentally

Paper on resistor testing in preparation

What can we do???

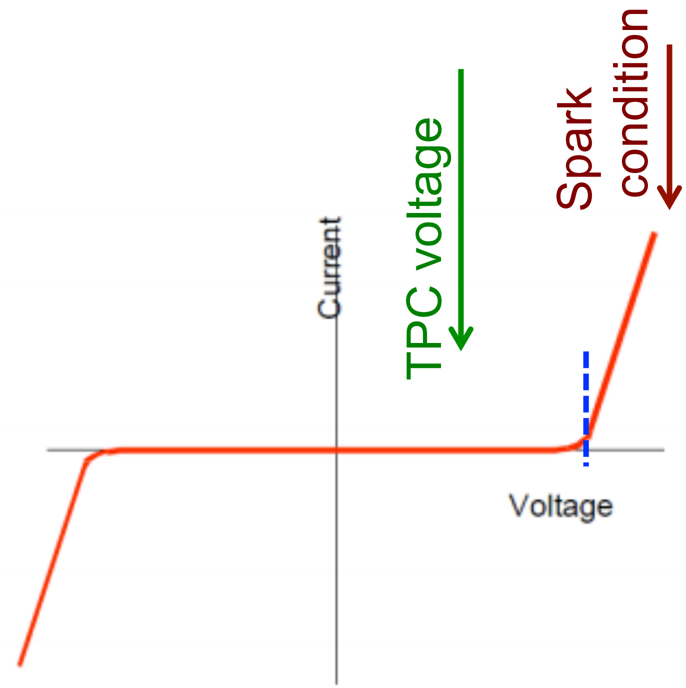
Option 2 – don't go out in the lightning

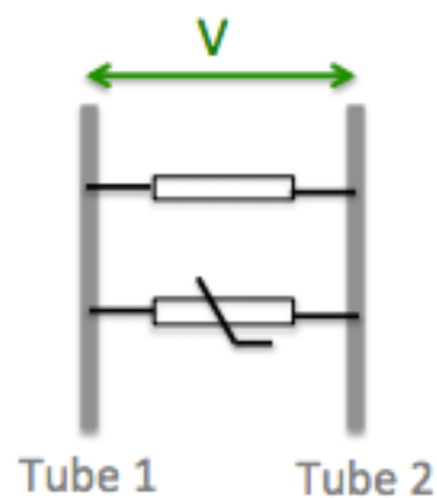
Surge arrestors

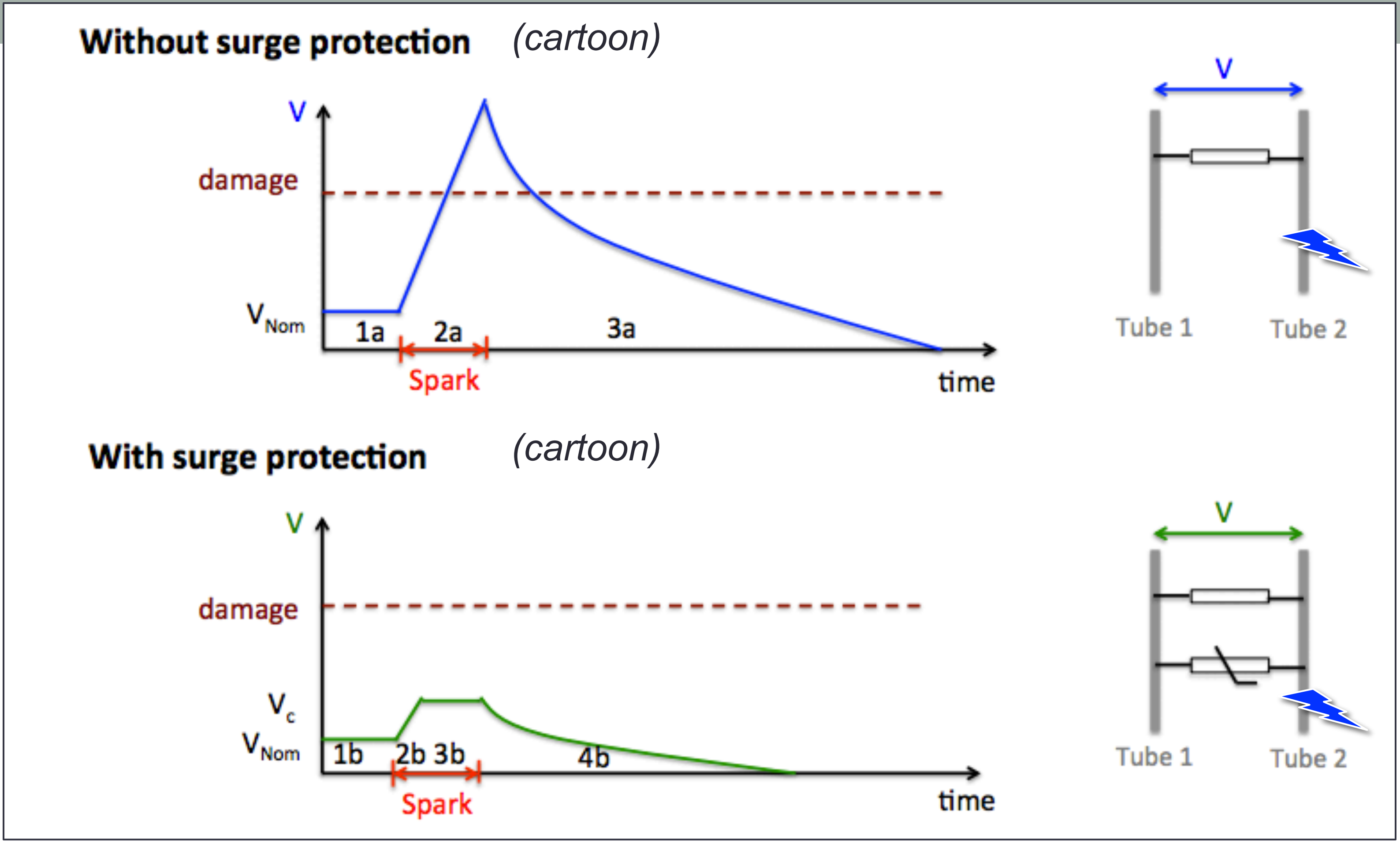
- Very nonlinear V-I characteristic
- ~ open at low voltages
- ~ short at high voltages

- The transition voltage is called (roughly) the clamping point

- We look for devices which clamp above TPC nominal voltage (2kV) but below resistor tolerance (10kV)





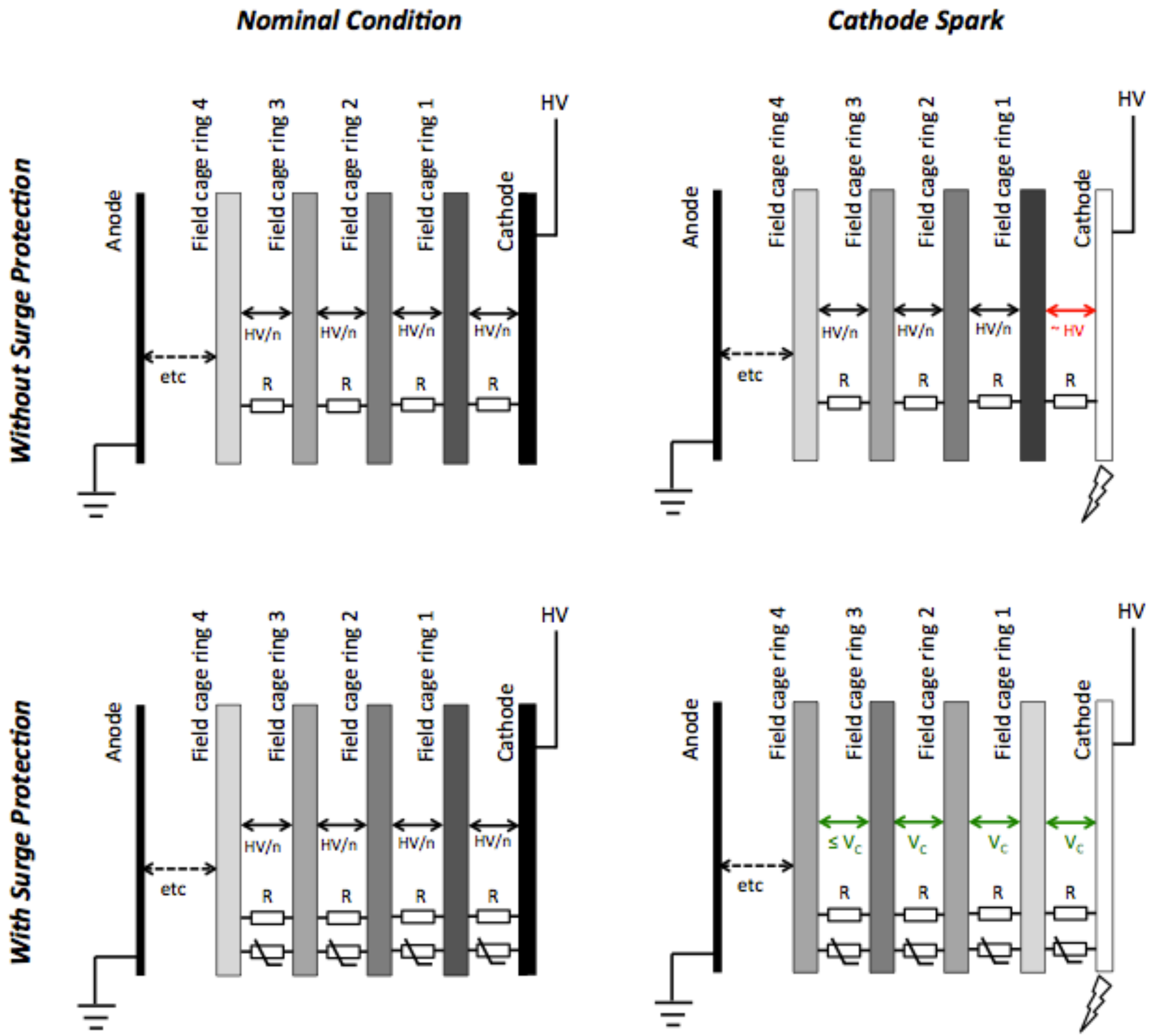


With surge protection, the potential difference does not rise above the clamping voltage.

Prevents not only large resistor overvoltage, but also G10, argon breakdowns...

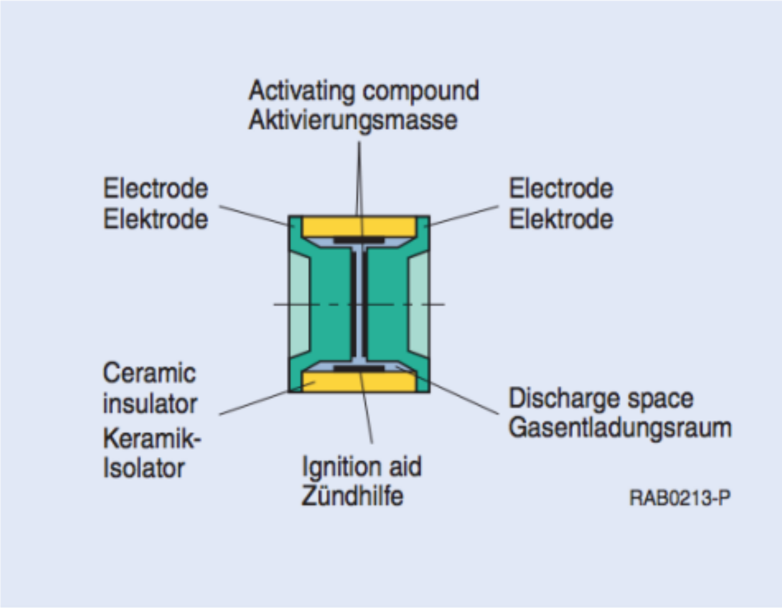
Independent of details of higher order capacitances, spark location, etc.

** Except for possible very short timescales (light travel time) due to inductive effects*


Nominal Condition
Cathode Spark
Without Surge Protection
With Surge Protection
Anode
Field cage ring 4
Field cage ring 3
Field cage ring 2
Field cage ring 1
Cathode
HV
HV/n
~ HV
etc
R
≤ V_C
V_C

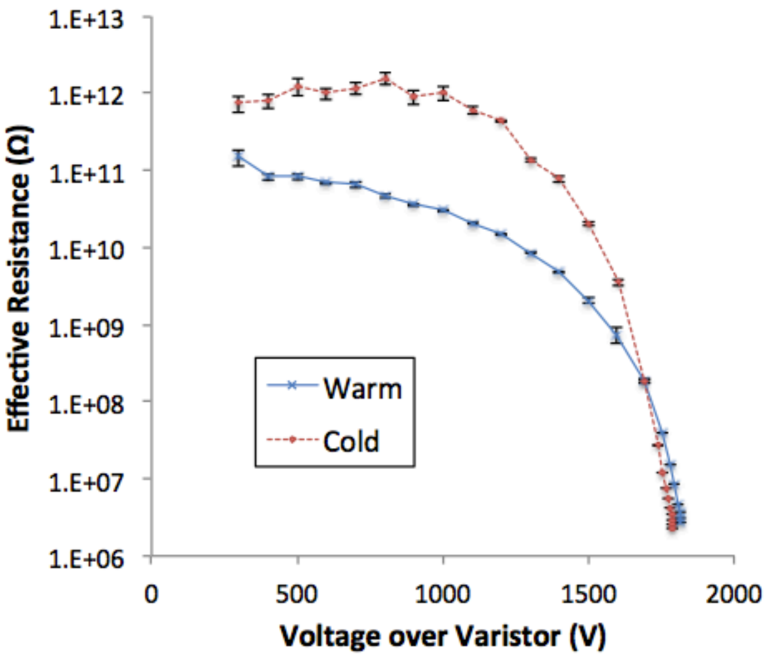
Gas Discharge Tubes

- Two electrodes 1-2 mm apart in a gas
- About $1.50 each
- Very insulating below clamping point
  - Our measurements :
    10TΩ warm, 40TΩ in LAr
- At clamping point, spark develops within the gas
- Single device provides adequate clamping (4500V and 7500V models available)
- Very rapid transition from open to conducting with overvoltage, giving a crowbar action
  - Our measurements :
    <50 ns warm and Lar



Varistors

- Pressed zinc oxide ceramic grains act as a matrix of p-n junctions, giving a highly nonlinear I-V curve
- Continuously varying nonlinear resistance from >1TΩ to Ω, giving a clamping action.
- About $1.30 each
- Clamping voltage can be controlled by varying grain size and dopant composition
- Highest voltage device available for TPC mounting has 1800V clamp – need 2 or 3 in series.



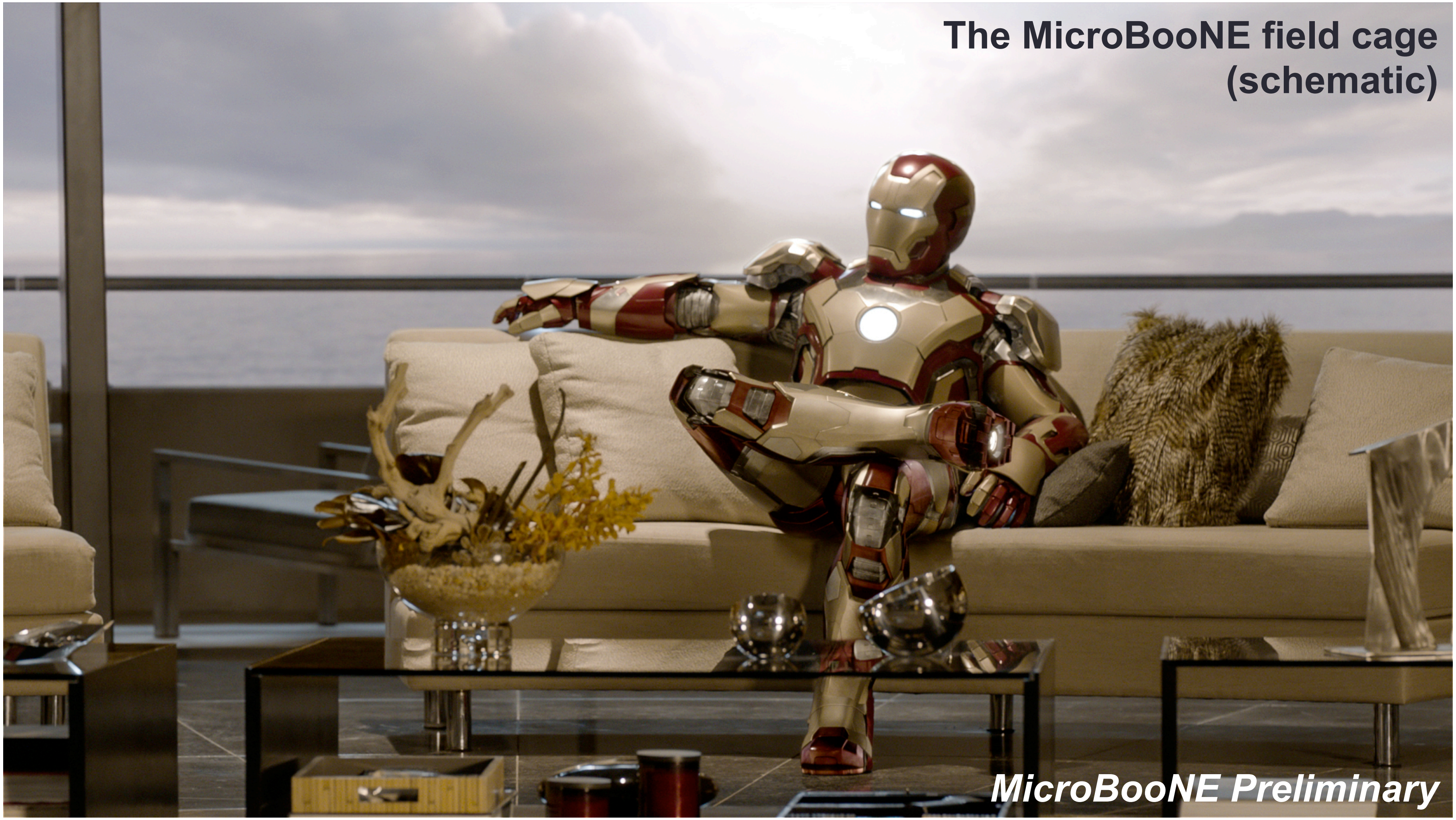
What can we do???

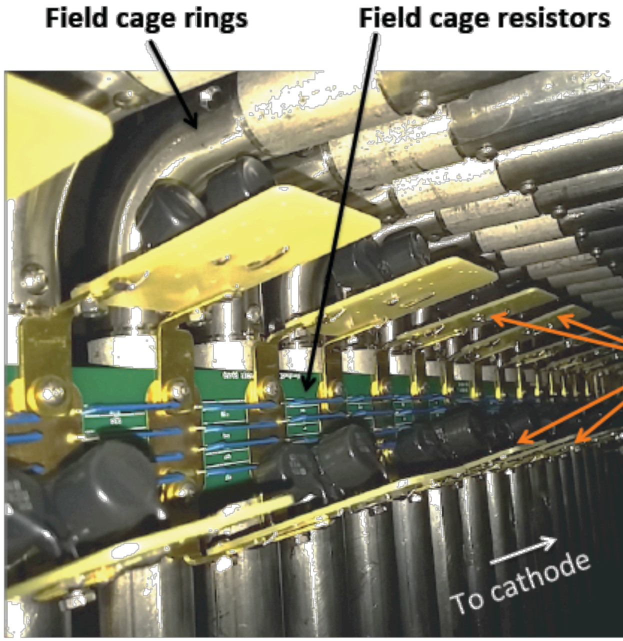
Option 1

Option 2

(note – there was also option 3, tune the field cage capacitances to adjust the dynamics of the discharge - this was hobbled by the non-availability of suitably rated capacitors)

What we actually decided to do:





Surge protection boards
(3 series varistors)

“Chill on the couch” on first 32 of 64 field cage rings

Panasonic ERZ-V14D182 varistors

Rated for 50 J, 5000A surges -55 to 175 C

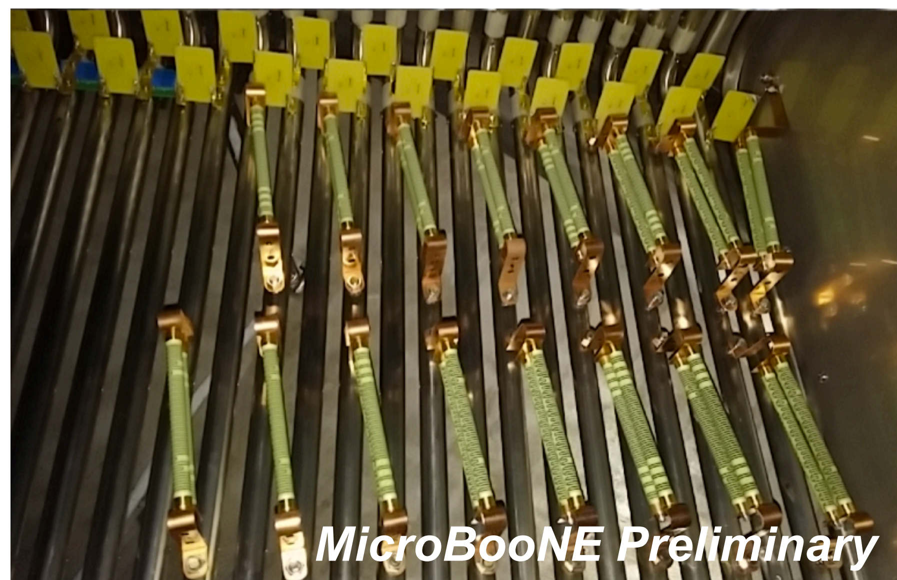
163 units tested in expected surge condition in LAr

“Wear heavy armor” on first 16 of 64 field cage rings

Metallux 969.23 0.5 GΩ

Rated 48 kV in air -55 to 175 C

8 units tested to full experiment HV (130 kV) in LAr



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    - Possible solutions
    - Surge protection : GDTs and varistors
    - Devices installed in MicroBooNE

- **2. Testing of HV surge protectors**
    - **Behavior in cryogenic conditions**
    - **Cryogenic robustness under high energy and voltage**
    - **Purity impacts**
    - **Testing on the MicroBooNE TPC**

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- **2. Testing of HV surge protectors**

arxiv 1406.5216
submitted to JINST

Testing of High Voltage Surge Protection Devices for Use in Liquid Argon TPC Detectors

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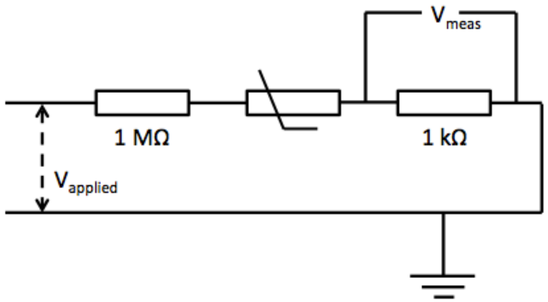
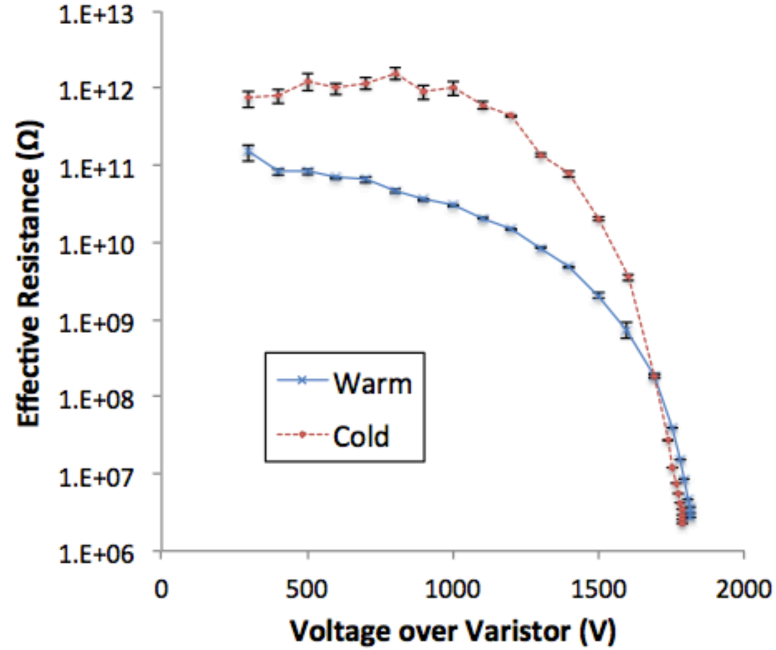
Jonathan Asaadi[a], Janet Conrad[b], Sowjanya Gollapini[c], Ben Jones[b]*, Hans Jostlein[d], Jason St John[e], Thomas Strauss[f], Steve Wolbers[d], Joseph Zennamo[g].

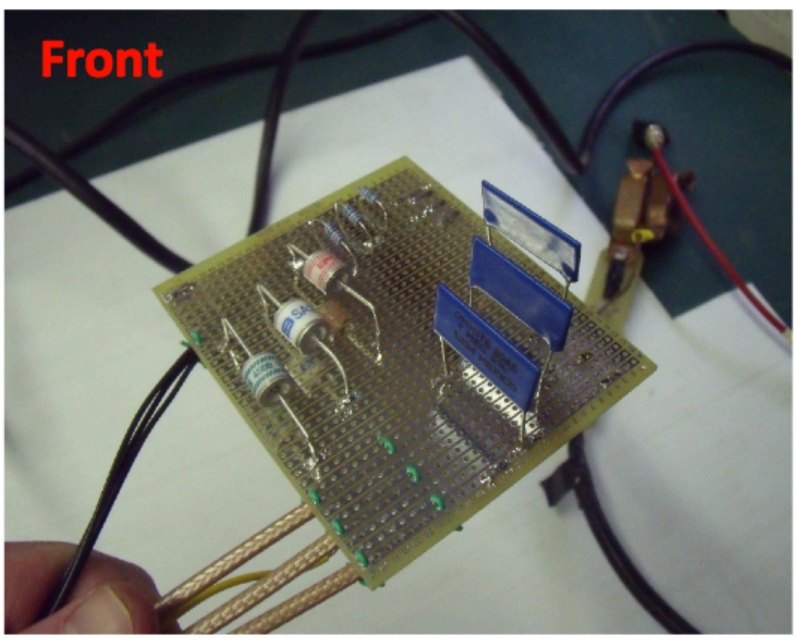
Testing individual units

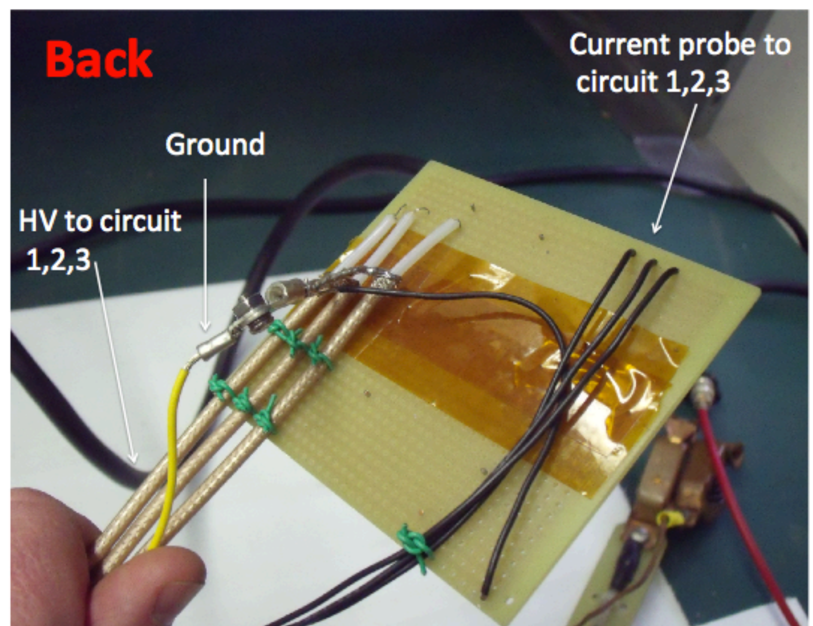
Measure the numbers + curves I already showed you in the introduction with this circuit →





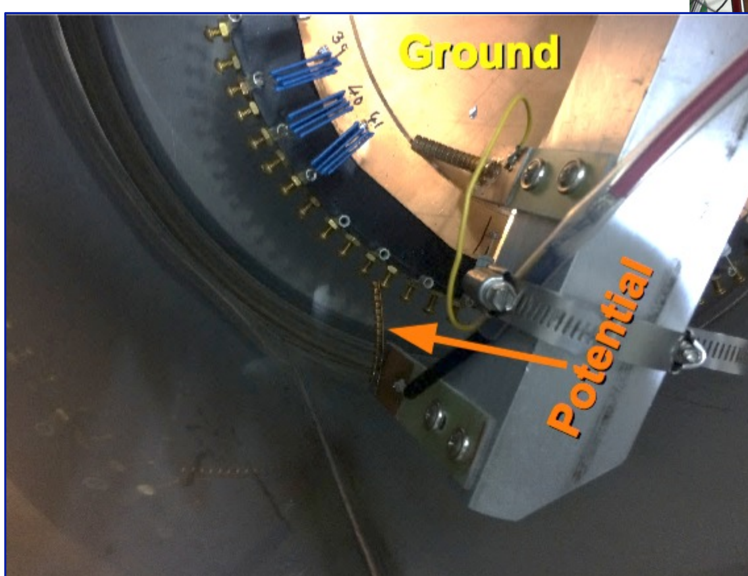
3 interleaved circuits on a bread board:

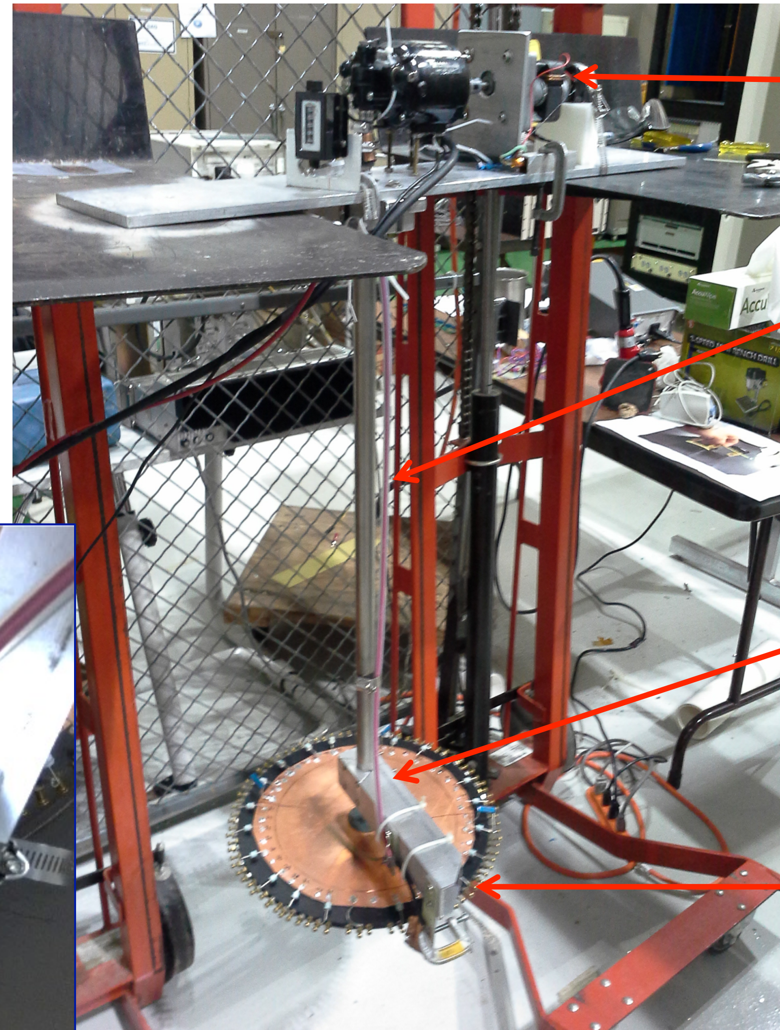




Characterizing large sample of devices

After detailed characterization of a few, 168 varistors and 60 GDTs were tested warm and cold





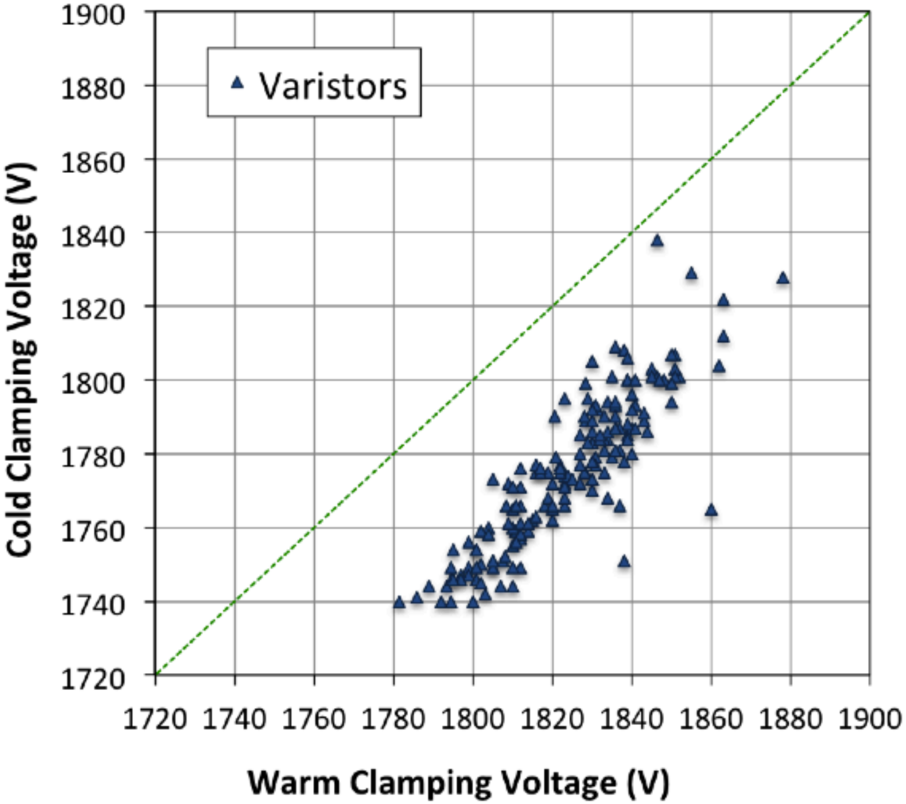
Motor to turn wheel

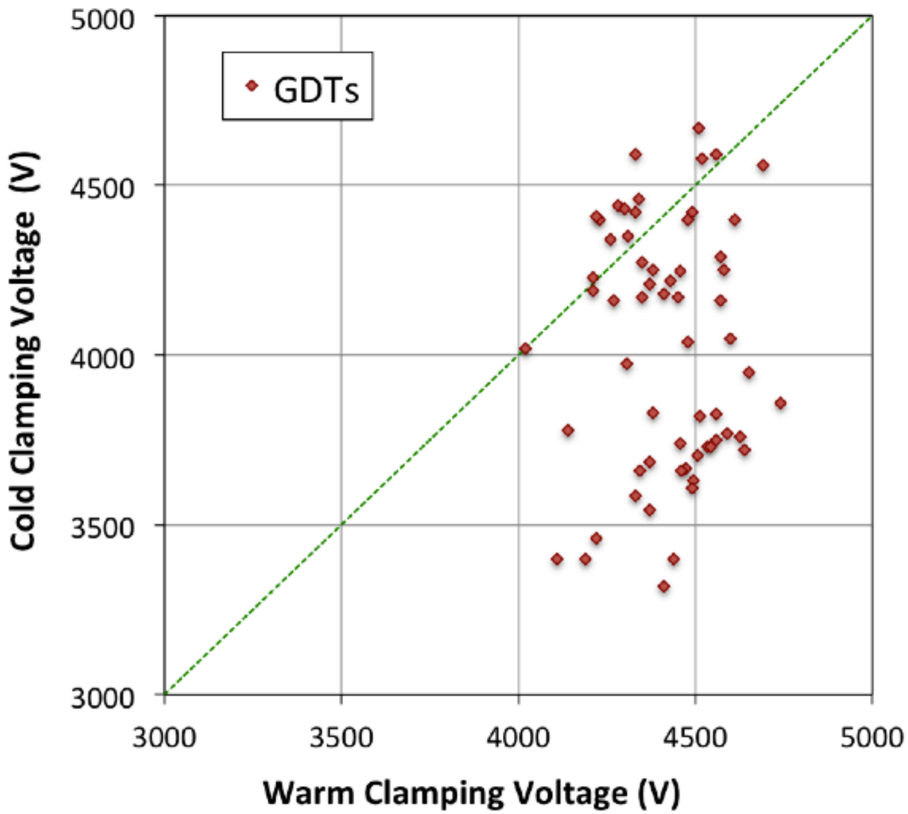
Shaft

Ground contact (to center of wheel)

HV contact

Warm vs Cold Clamping Behaviour





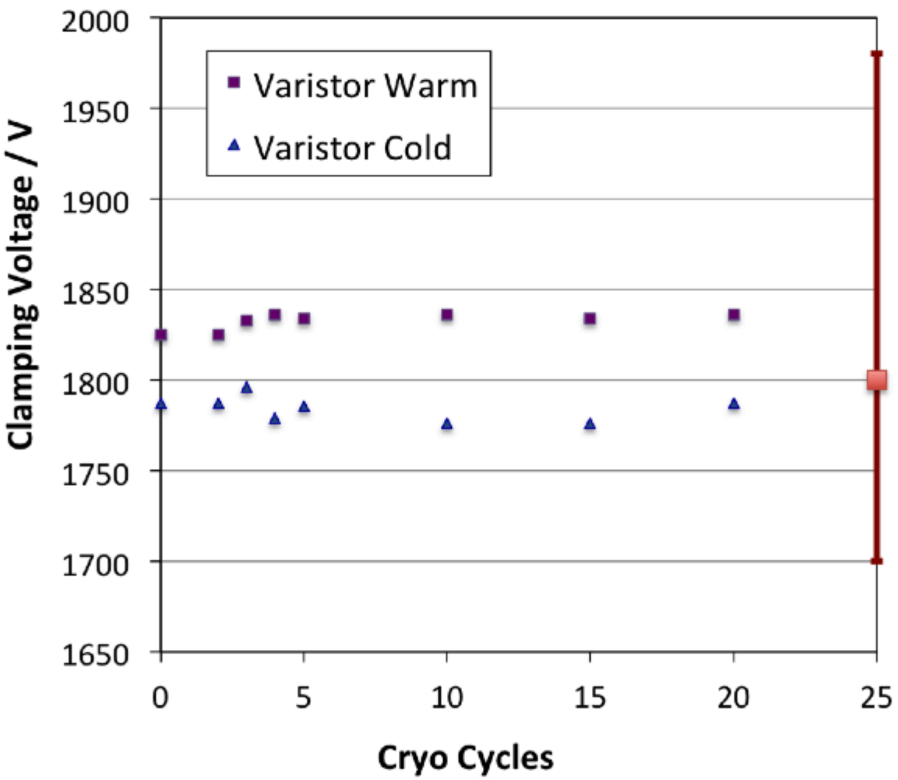
Clamping voltage defined as V applied for 0.5 mA current draw

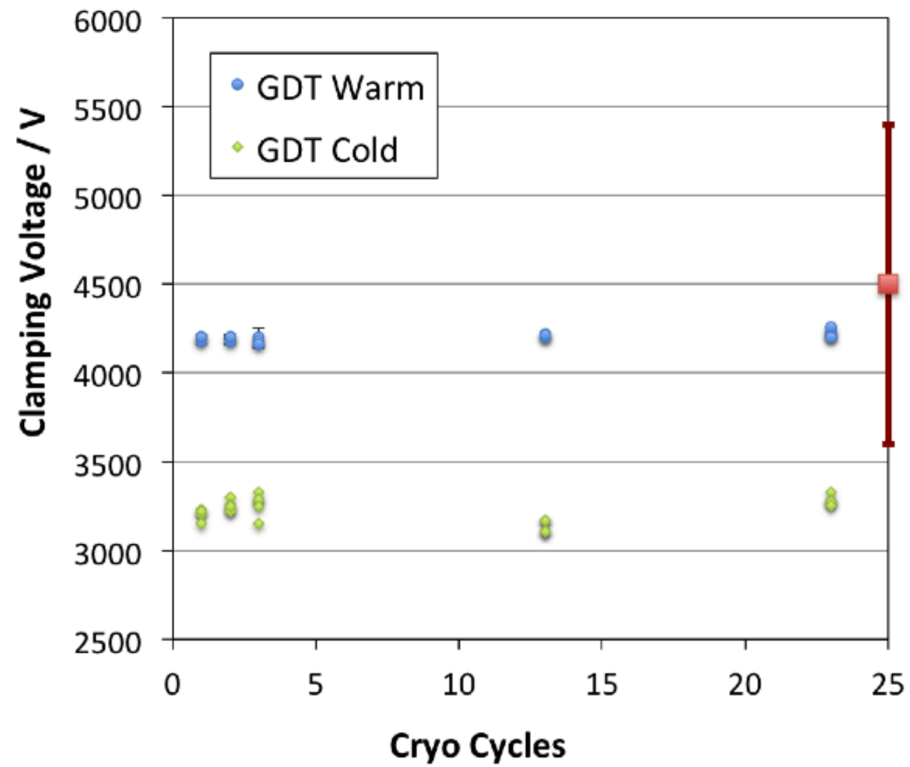
Clamping voltage defined as V applied for device sparkover and power supply trip

Stress by repeated cryo cycling

Check mechanical robustness under repeated cryo cycles

No deviation from initial properties observed.

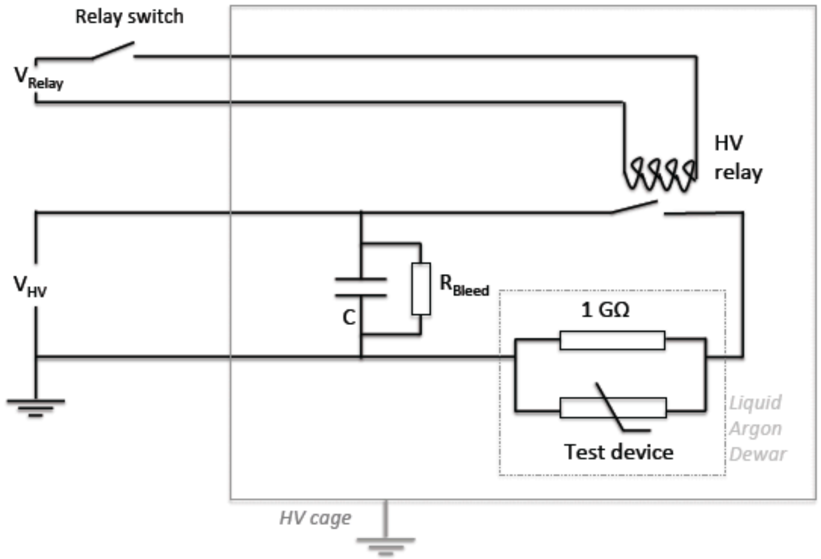


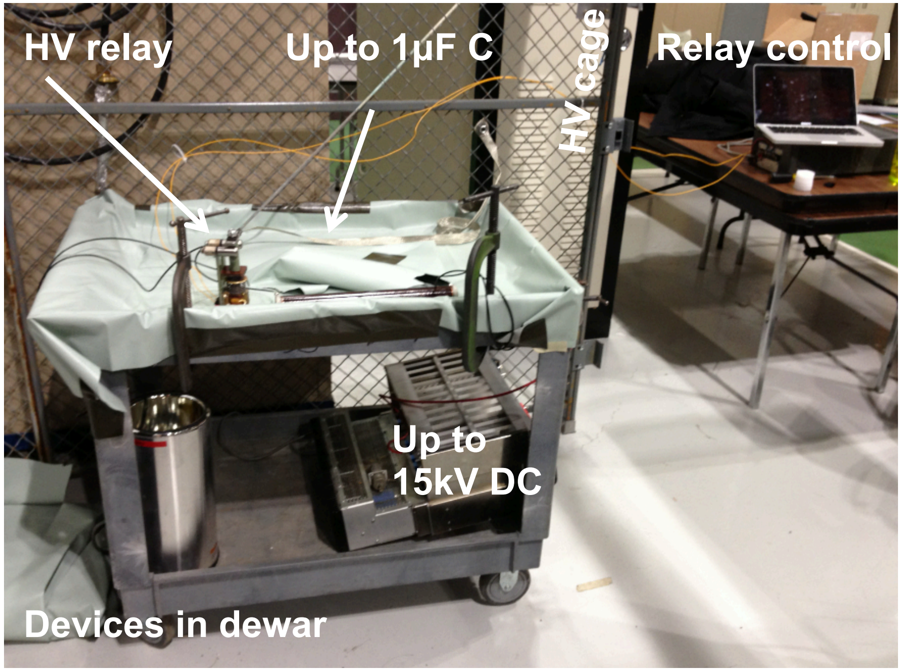


Both devices function similarly in both LN2 and LAr.

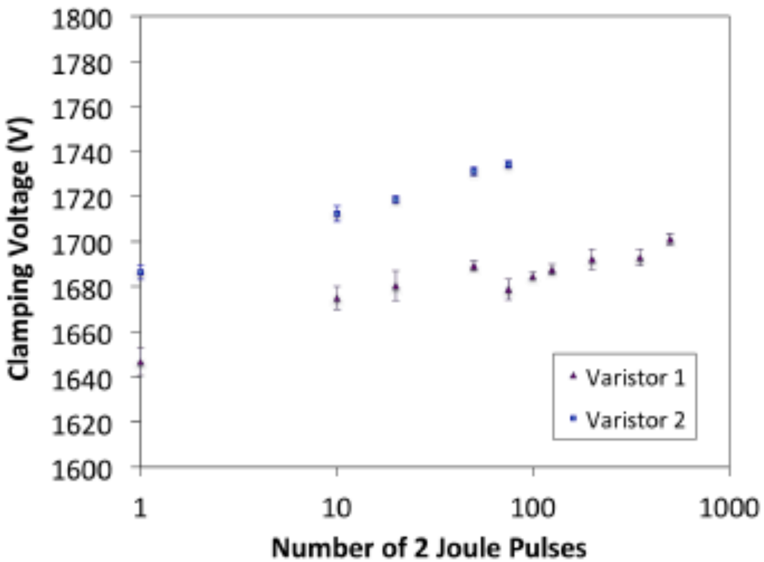
Energy Dissipation Test

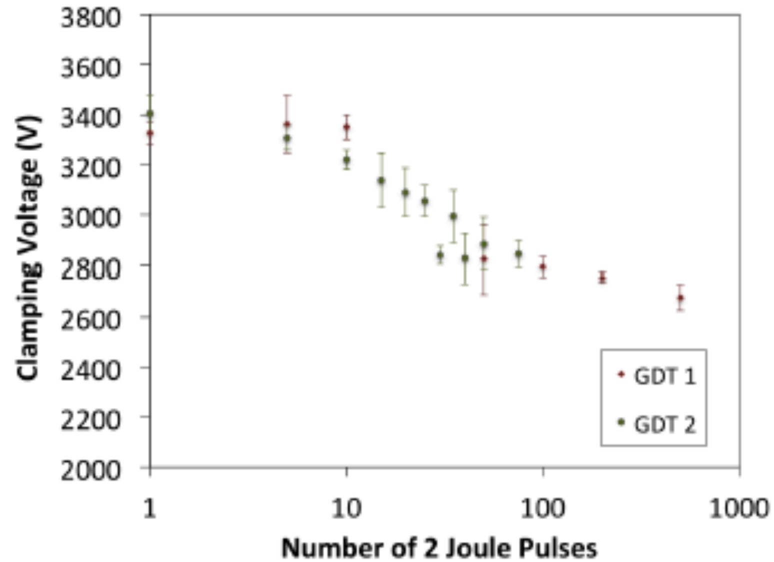
- Energy which would have been dissipated into resistors has to be dissipated into surge arrestors
- We calculate expected energy based on prediction of spice model.
- We find nominal MicroBooNE dissipation requirement is at most 2J per device.
- **We tested energy dissipation using a large capacitor discharged thru a HV relay ->**

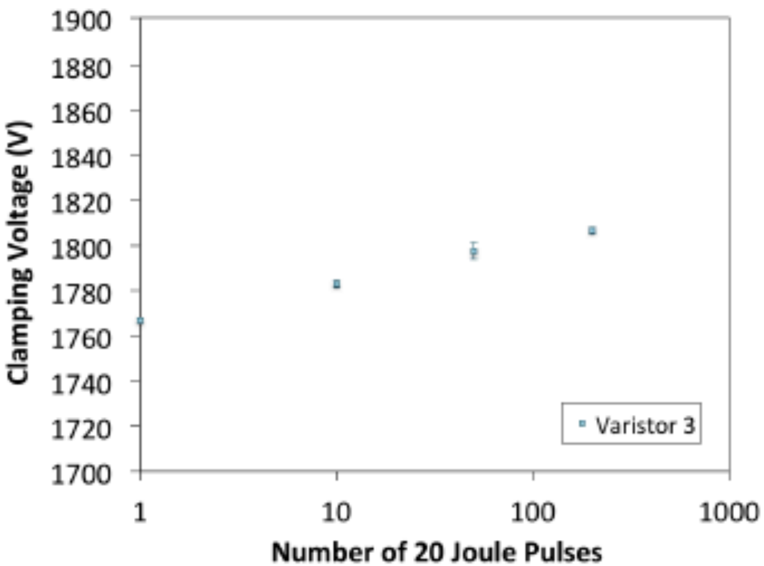


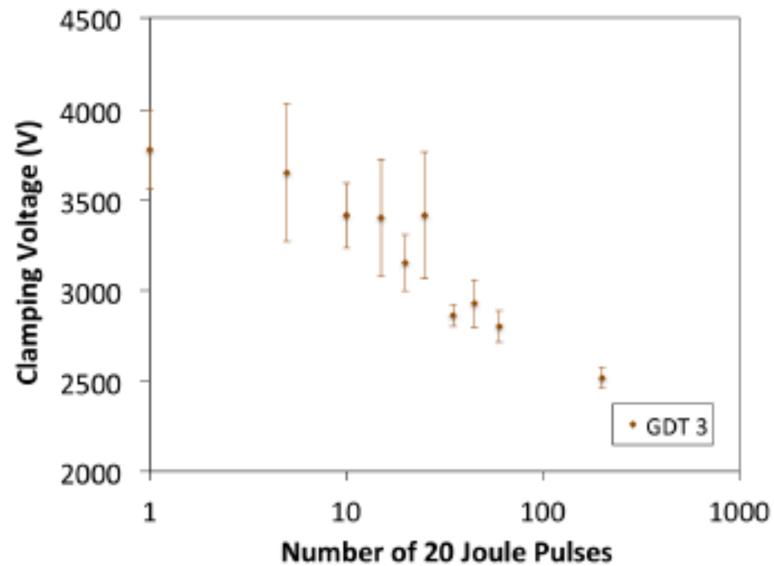


Multi-surge robustness (up to 500 surges)

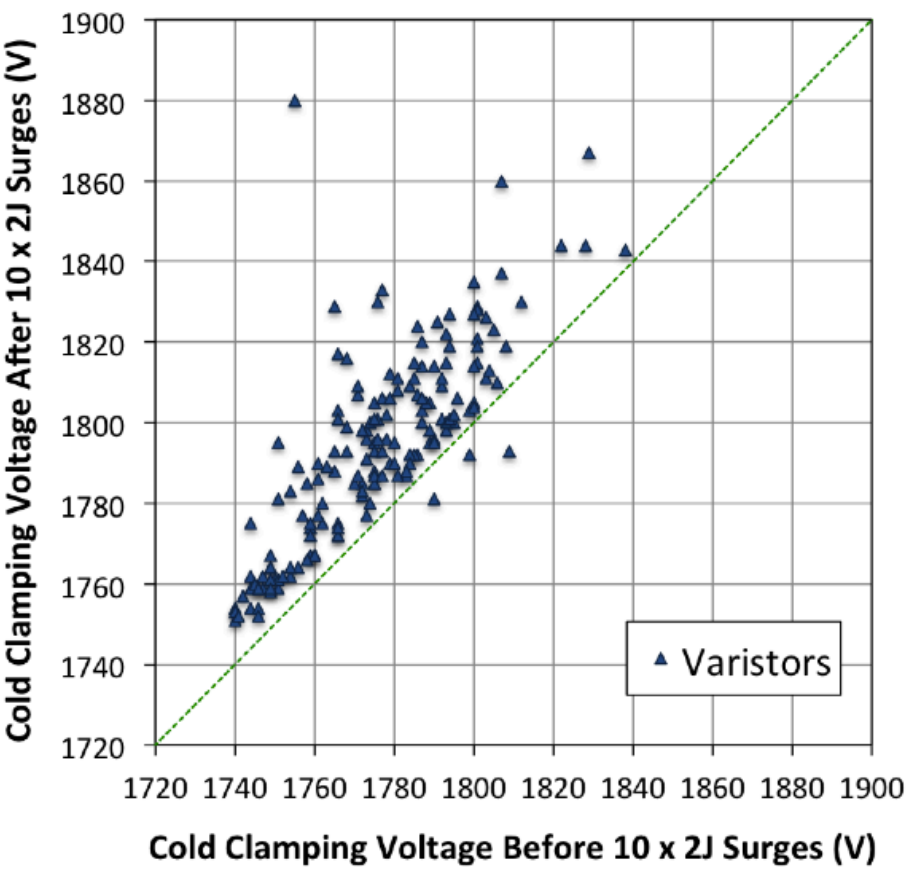


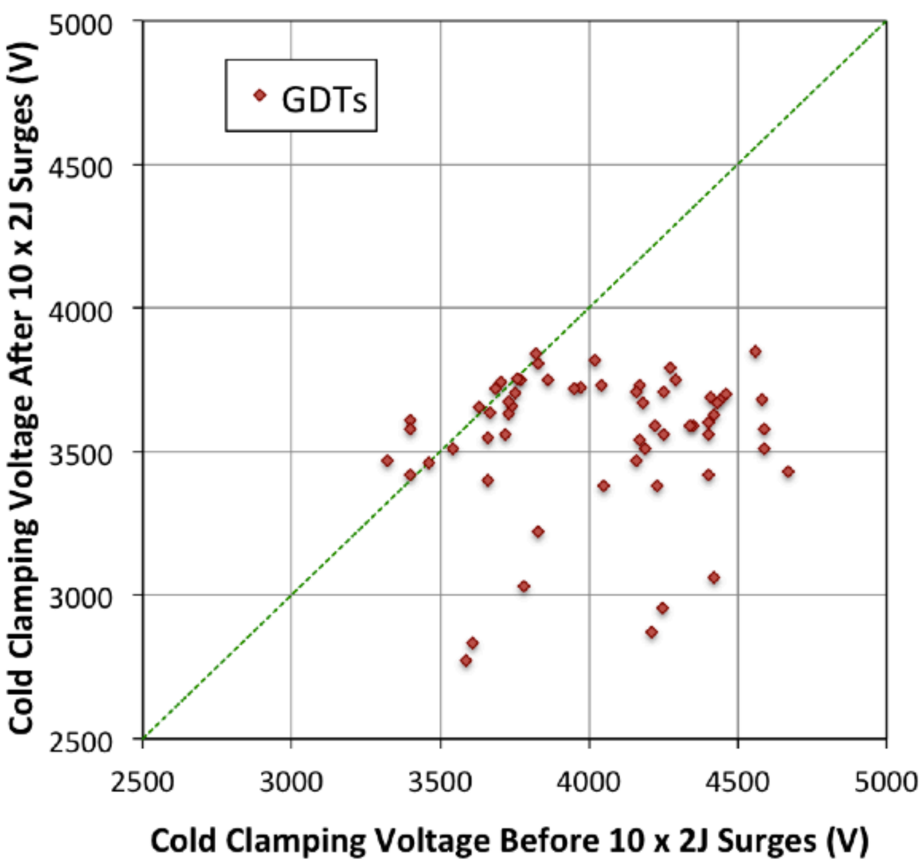






High stats 10 surge test (168 varistors, 60 GDTs)





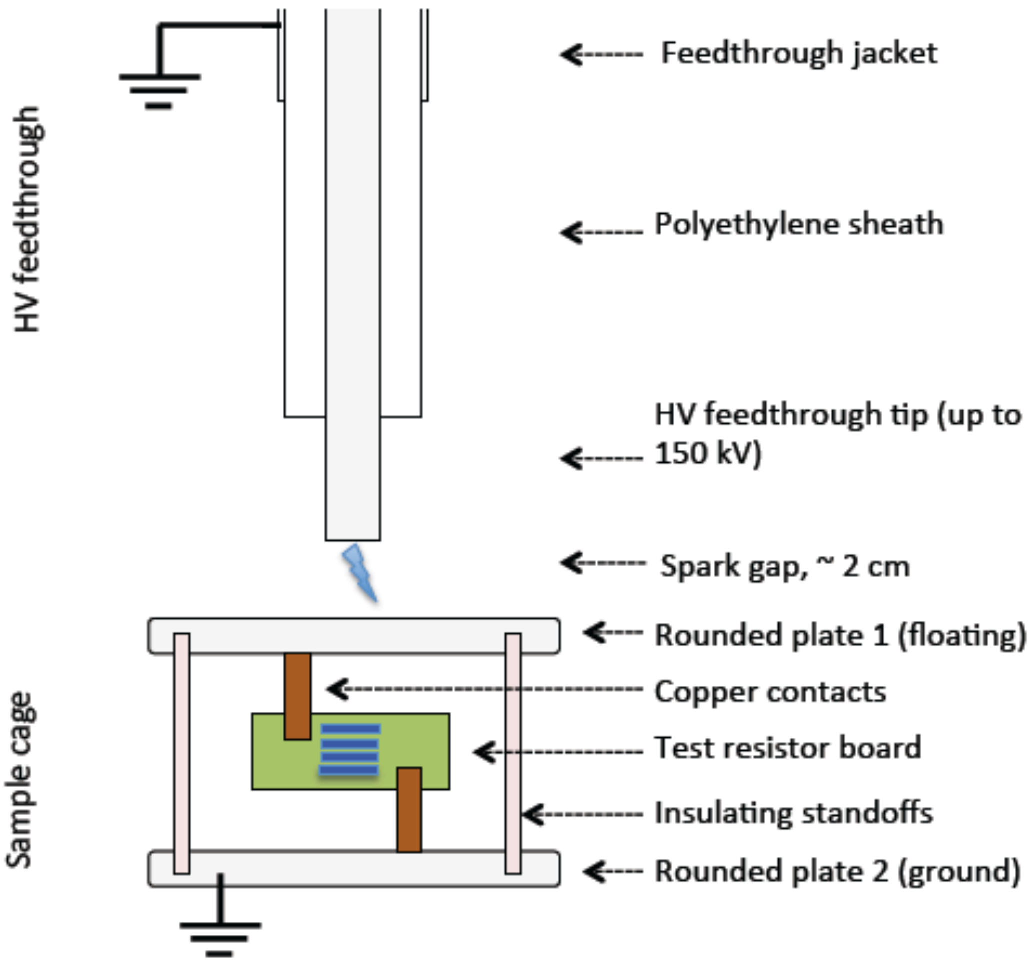
HV transient test

In a non-inductive system, surge arrestor prevents over voltages from being developed

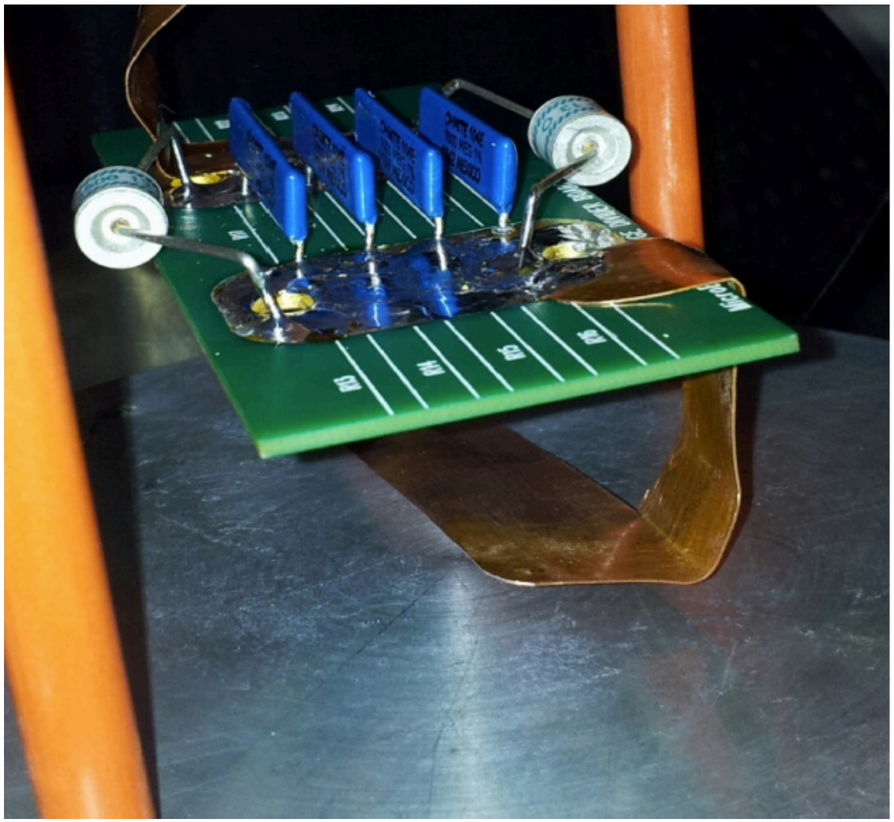
Inductances may cause HV pulses to occur on timescales O(light travel time), tens of ns

We used the MicroBooNE Glassman HV supply and prototype feedthrough to generate a short, full HV transient

A spark provides a conducting path to bring the top plate to full HV and discharge the feedthrough (C ~ 500pF).



Transient Overvoltage Test



~20 sparks delivered at:
50kV, 60kV, 70kV…. 150kV.

At upper limit of power supply:
20 x 150 kV

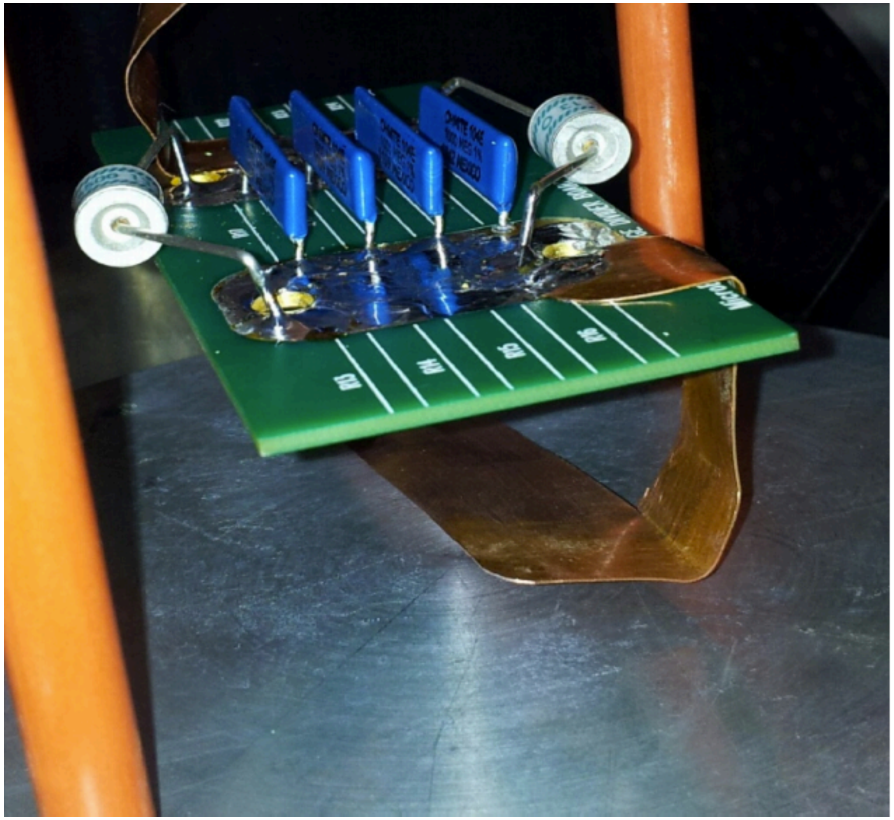
GDTs and resistors all survived.

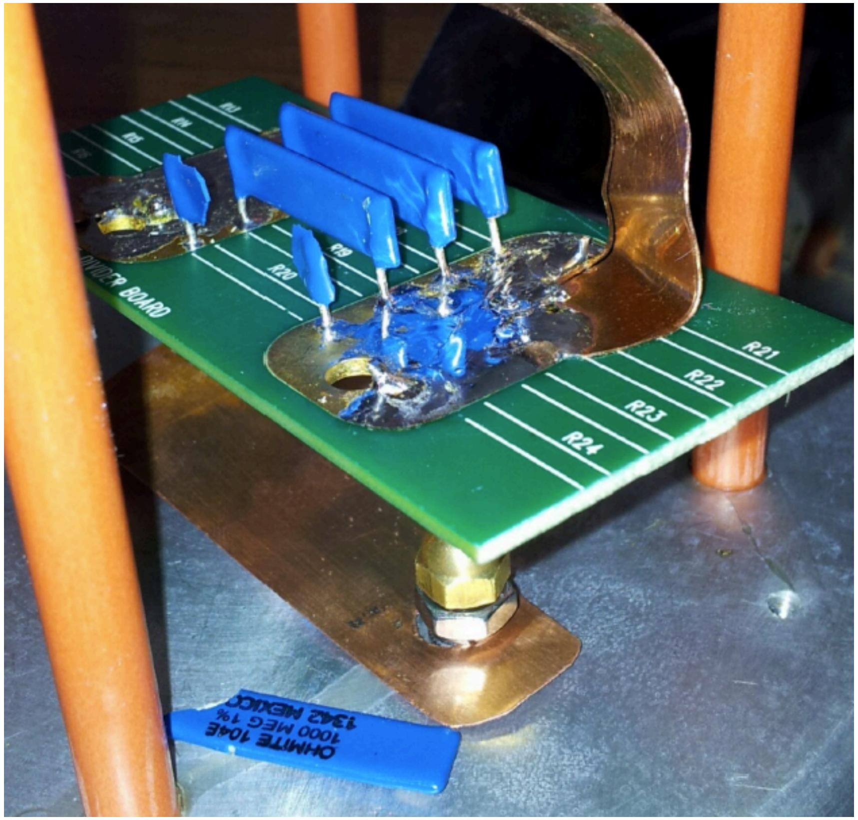
GDTs removed and tested – fully functional with expected clamping voltage.

Repeat with varistors – same behavior

GDTs + varistors are robust against overvoltages of up to 150kV in liquid argon.

Resistor Protection



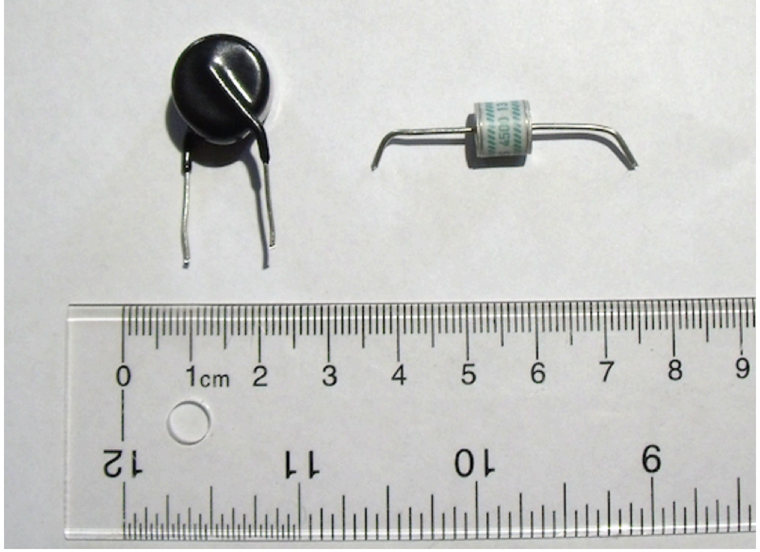


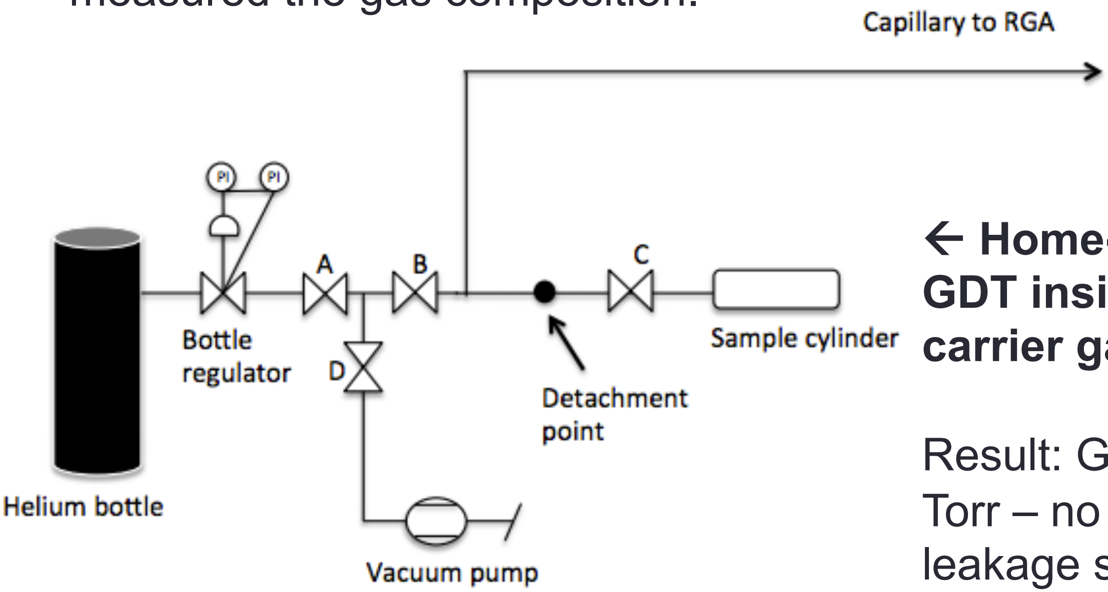
Resistors w / surge protection
After > 20 x 150 kV sparks

Resistors only (same set)
after one 70kV spark

Purity Effects

- **The device must not damage argon purity**
- In MTS test, free electron lifetime remained >9ms for 55 hours with filters off.
- GDTs contained an unknown gas, which was a potential worry.
- We reverse engineered the device and measured the gas composition.

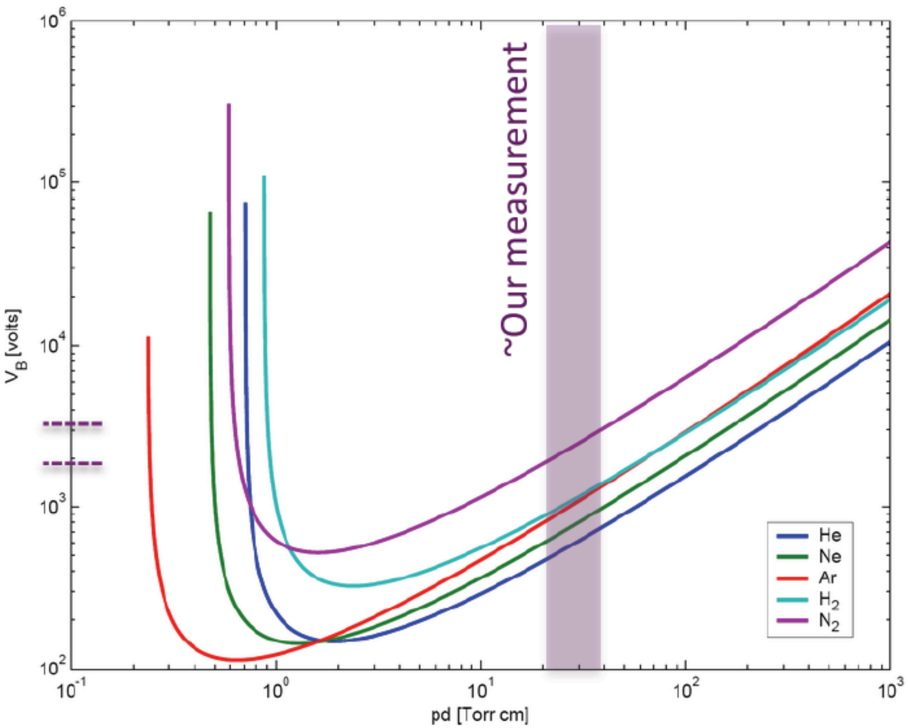


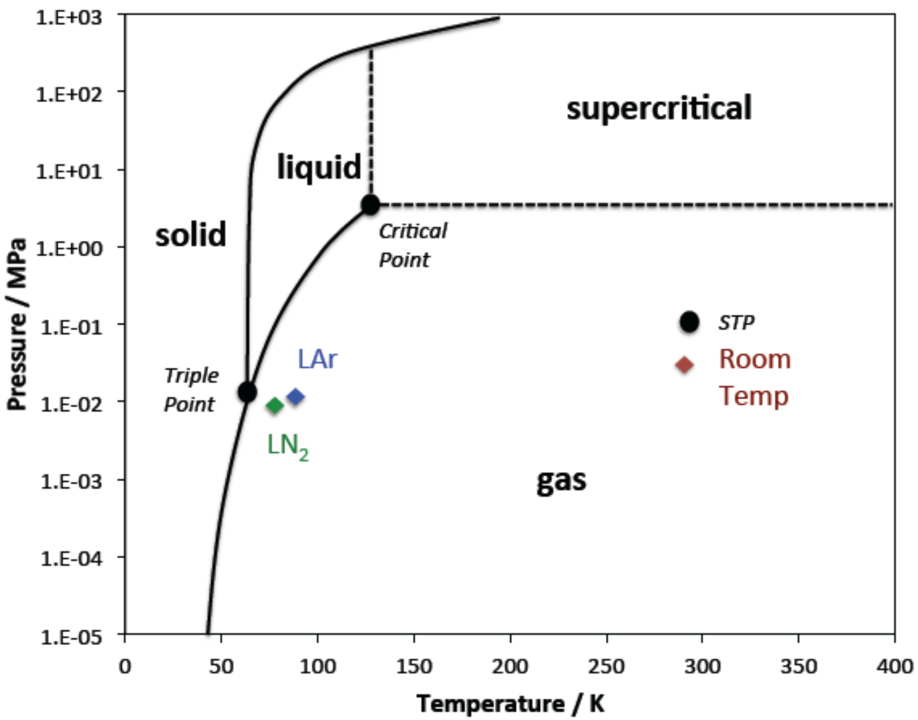


← Home-made setup for breaking open a GDT inside a pre-characterized helium carrier gas

Result: GDT contains only nitrogen at 250 Torr – no problem for purity even in complete leakage situation (10^{-12} contamination/GDT).

As interesting aside : physics works.





1. Comparison with Paschen curve shows for this N2 pressure and electrode spacing, ~3kV breakdown.

2 Comparison with phase diagram for N2 shows that GDT contents remain vapor at LAr and LN2 temperatures, so GDT continues to function.

Direct test on field cage

We applied lower clamping varistors to the field cage to demonstrate the clamping effect in the real capacitive network using a lower voltage pulse.

Direct test on field cage

We switch off HV and send a specific tube to ground simultaneously to simulate a HV discharge. We measure voltage on a pair of adjacent tubes.

Simulations show that tube 1 to ground is worst case, so we focus on this first

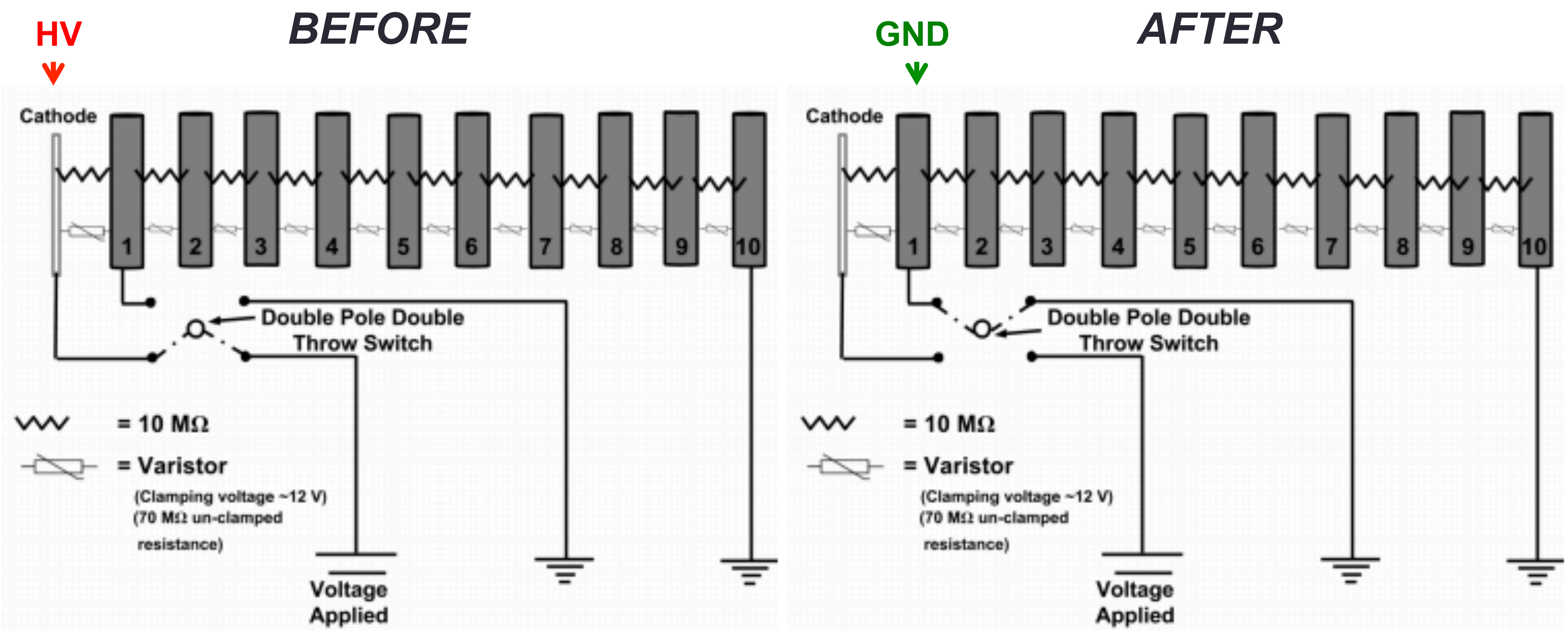
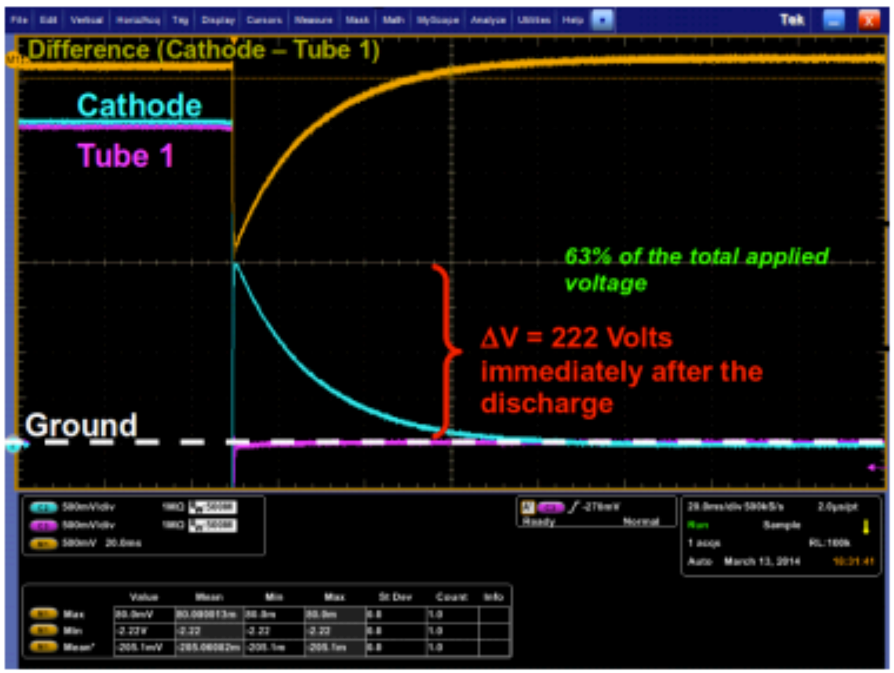


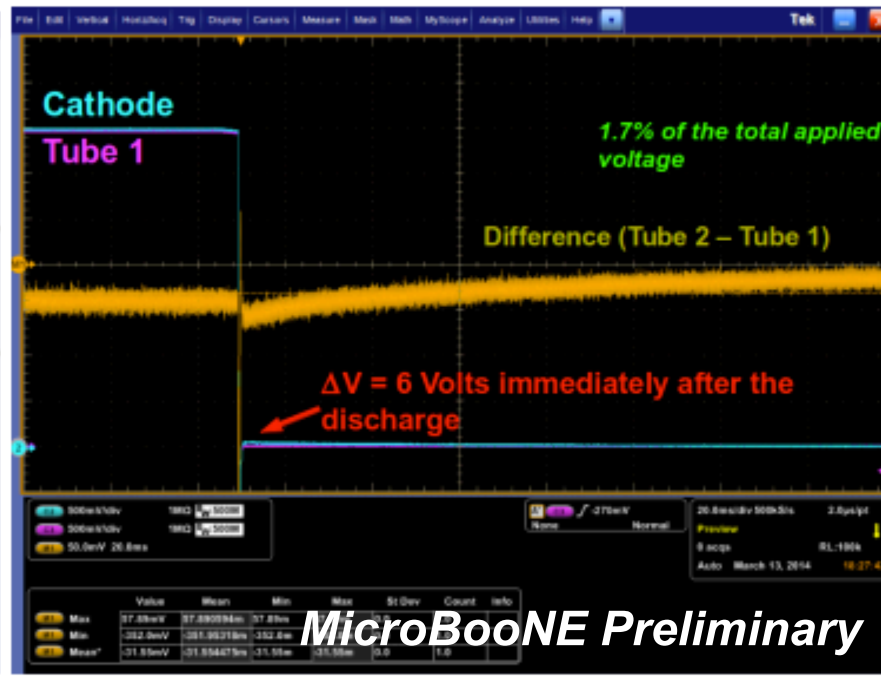
Figure 1: Schematic for our testing setup with the switch (a) charging the cathode and (b) simultaneously removing the voltage supplied to the cathode and grounding tube 1 (T1).

Demonstration of clamping on the TPC

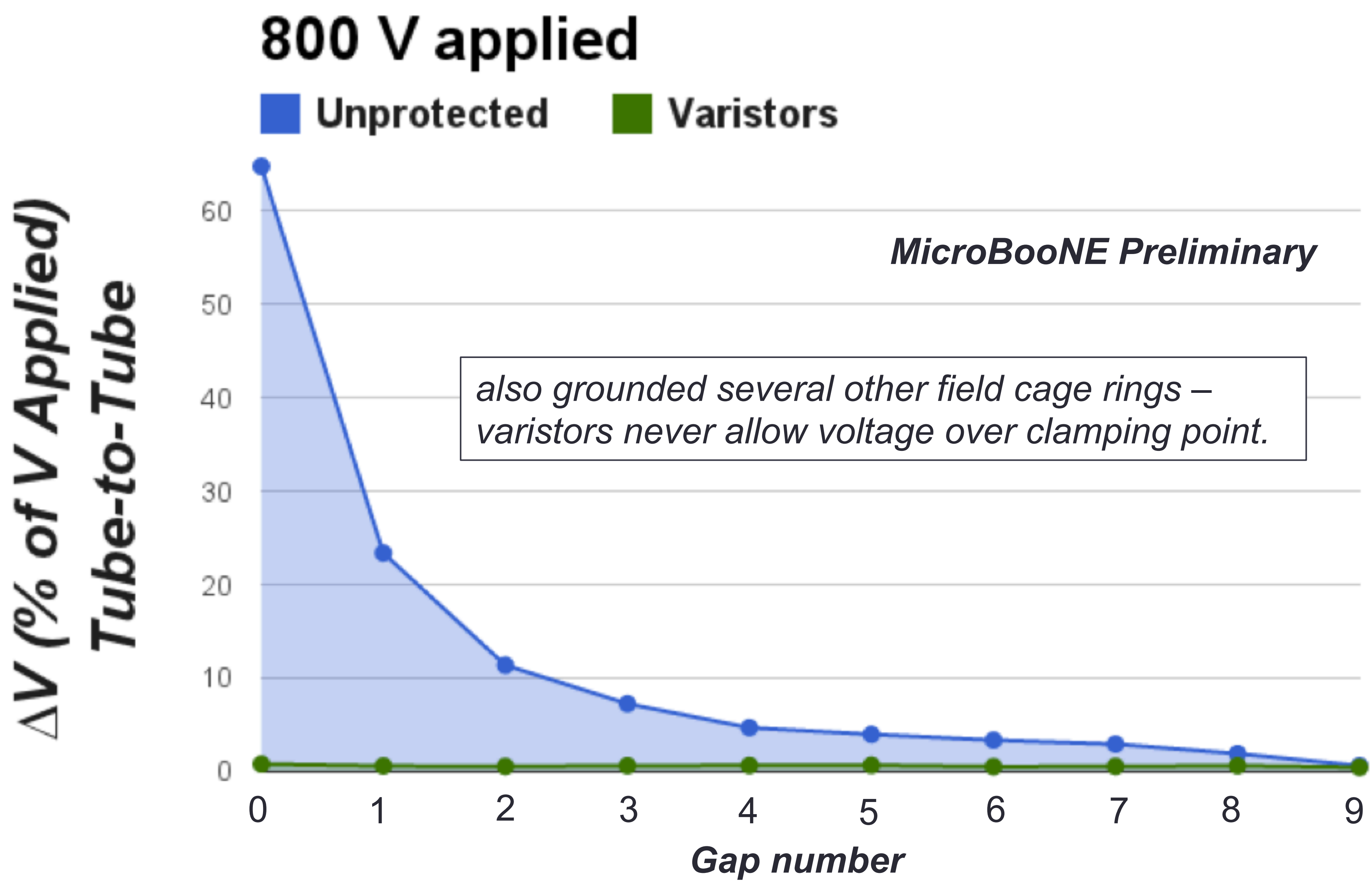
Unprotected



Protected



Varistors act to clamp potential difference during discharge event


800 V applied
Unprotected
Varistors
ΔV (% of V Applied)
Tube-to-Tube
MicroBooNE Preliminary
also grounded several other field cage rings – varistors never allow voltage over clamping point.
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
Gap number

Other bench-top tests (see paper)

- Test for light emission alongside LBNE paddle tests in TallBo
- Insulation resistances measured warm and cold
- Measurements of clamping and insulation of series combinations
- Long term test performed in LAr (1000 device hours) to check for no spontaneous breakdowns
- Run in high purity argon test performed to check functionality in appropriate dielectric environment

Other field cage tests:

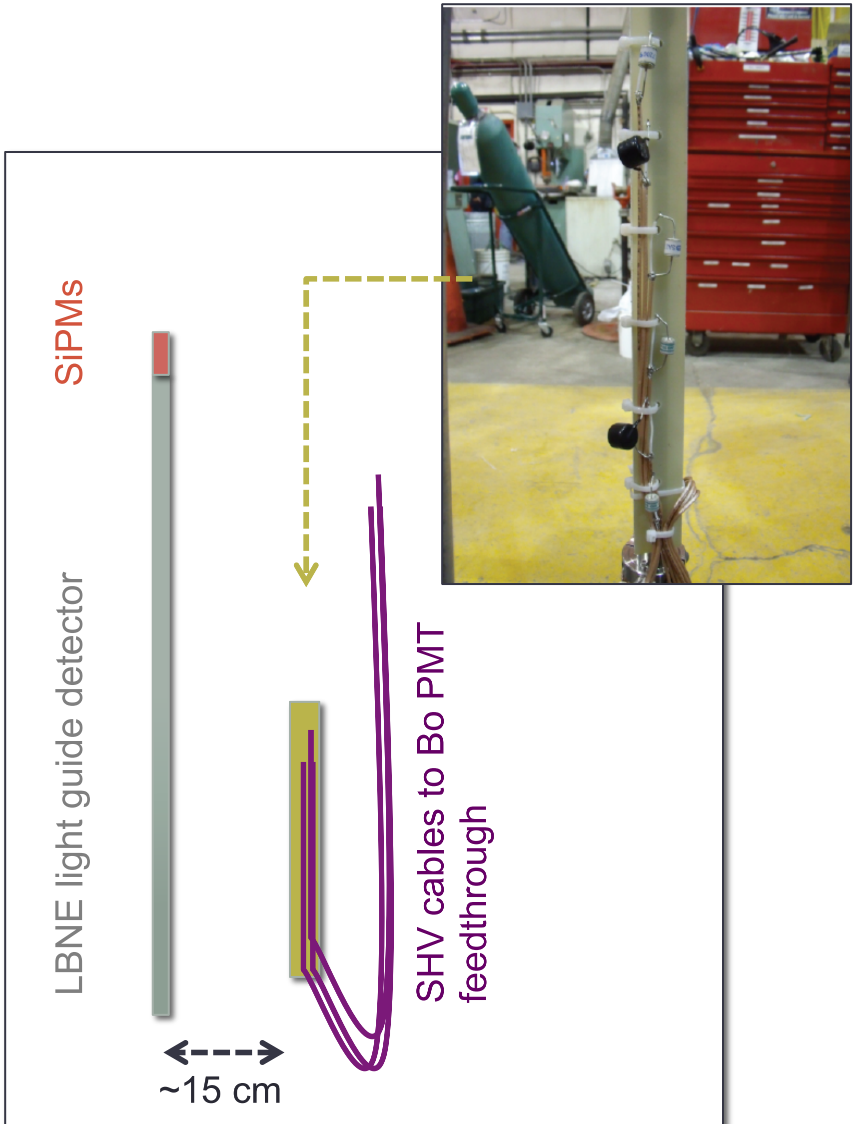
- Varistor observed to give clamping in all tested situations, including:
  - Spark at cathode
  - Spark at tube 1
  - Spark at tube 8
  - Incomplete grounding
  - Delayed HV supply trip

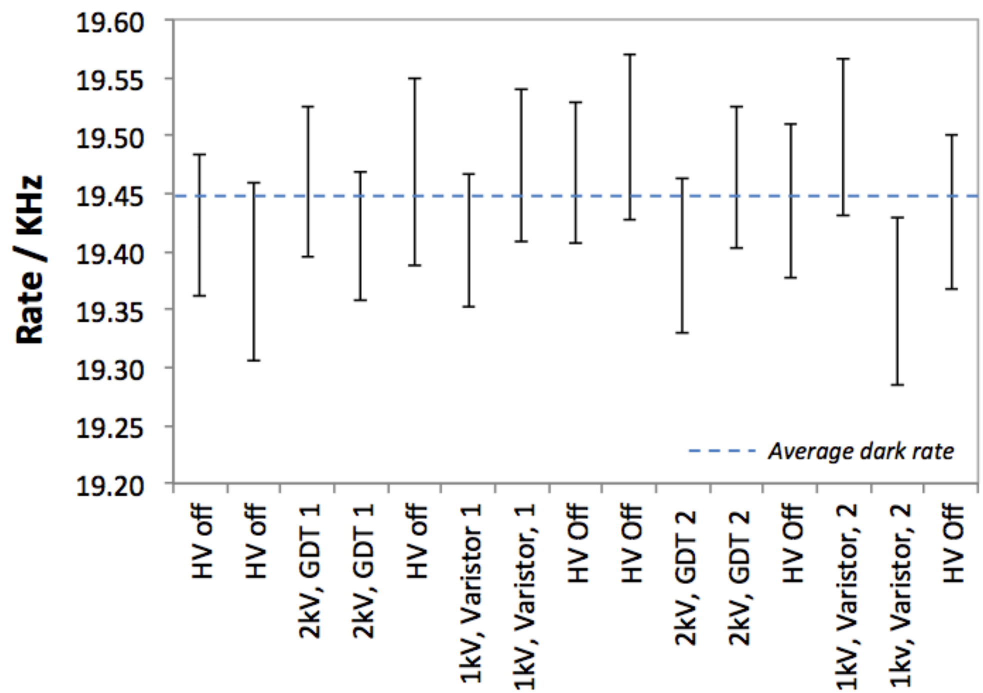
Thank you for your attention.

Backups

Light Emission

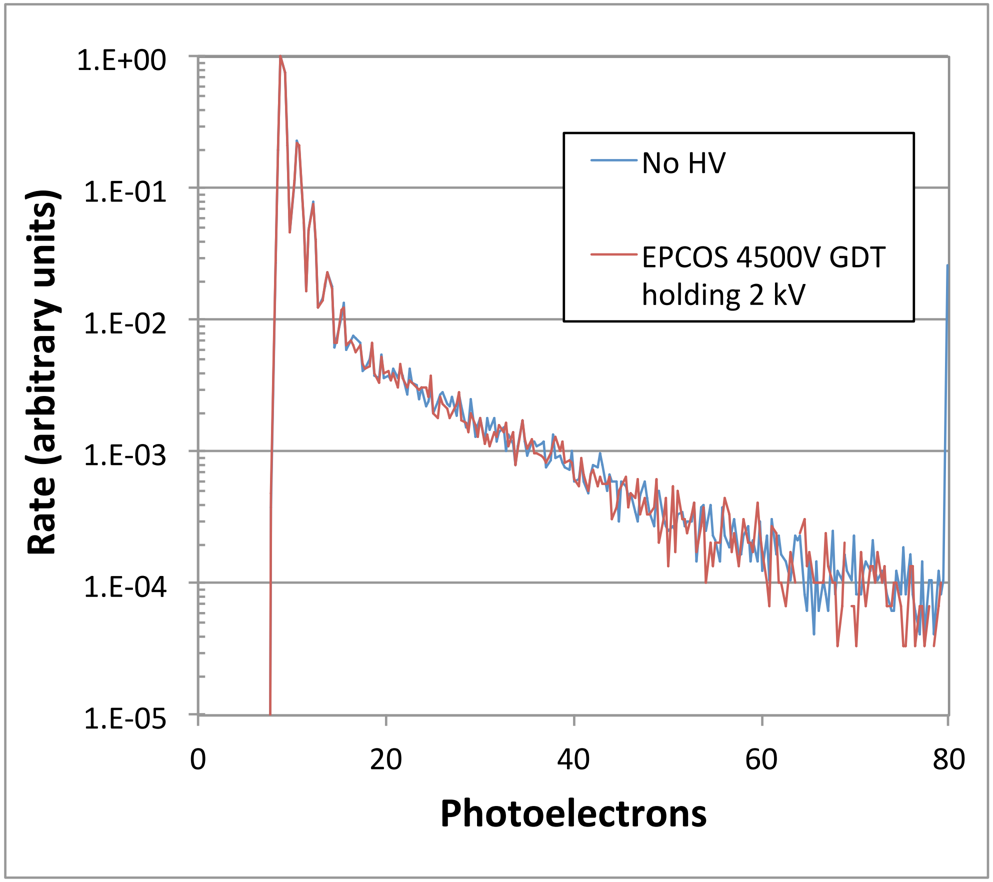
- Tested for light emission alongside LBNE light-guide tests in Tall Bo
- **No emission seen under nominal applied voltage**
- GDTs were observed to emit light during discharge events





Flash Emission

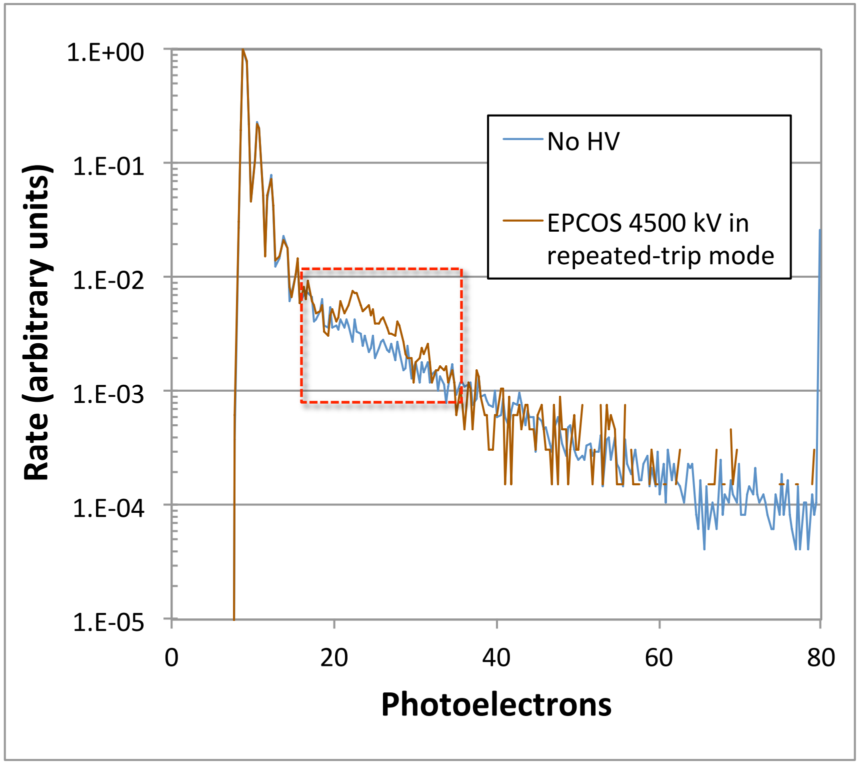
- A lower rate of larger pulses would also be a problem. We compare pulse size distribution with and without GDT to check for flashes.

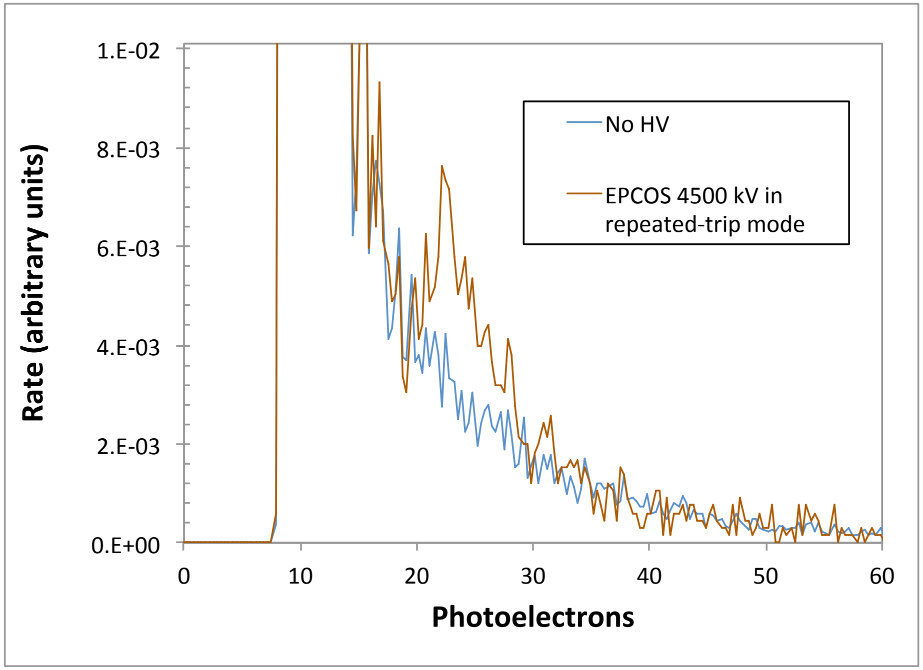


No difference from HV-off cosmic spectrum, including in overflow bin.

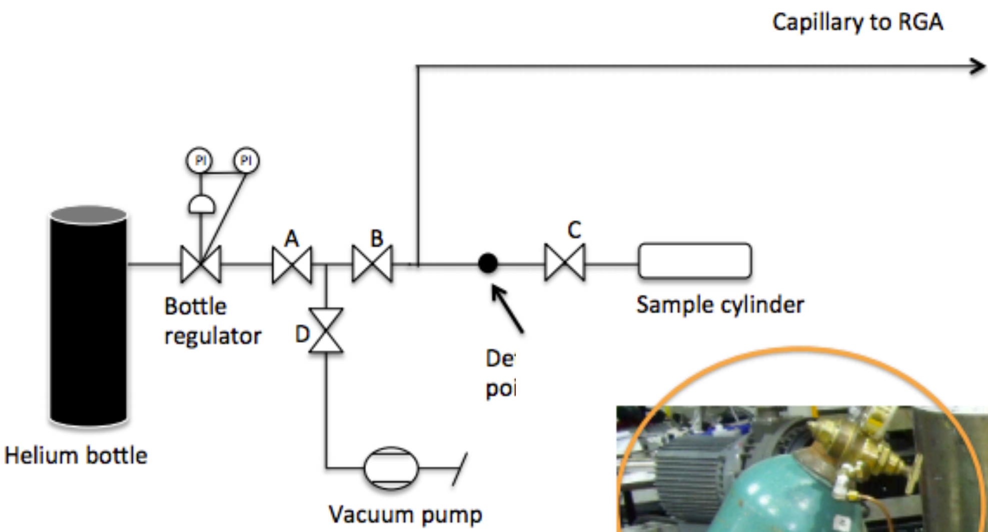
Discharge Light

- We do see the light in the discharge condition – but we don't care about that (spark will be much brighter)





Gas Composition



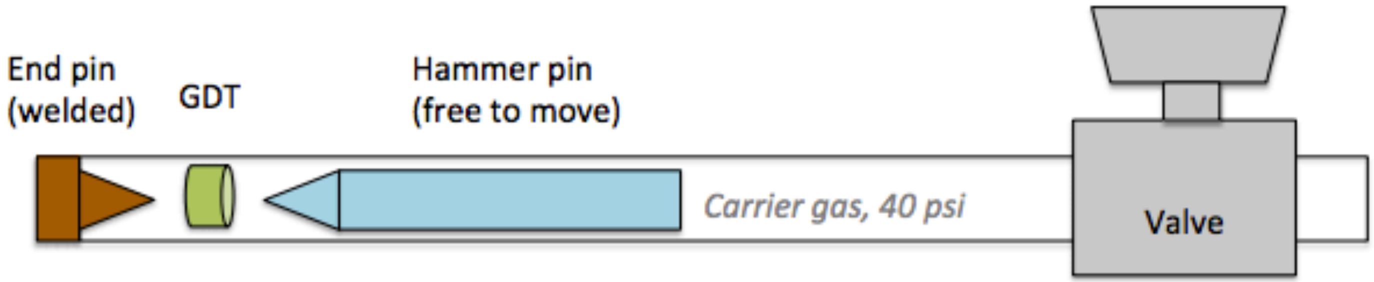
Built a setup at PAB to supply GDT contents in helium carrier gas to UGA

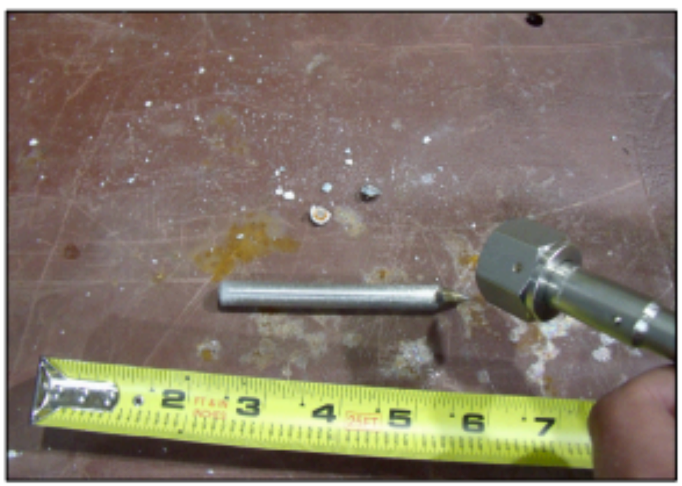
Helium bottle Vacuum Sample cylinder

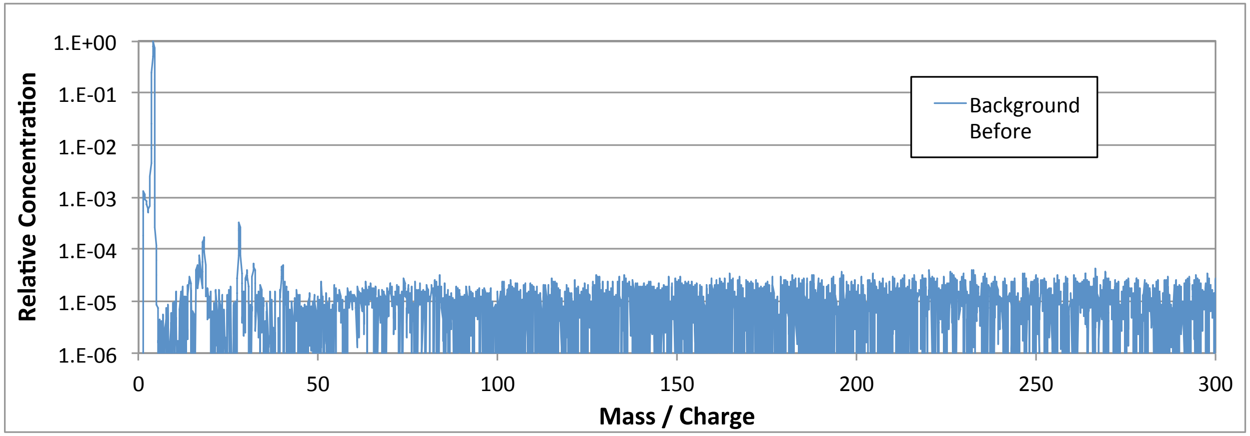
Sample chamber filled carrier gas and this gas is characterized.   Then chamber closed and device ruptured.

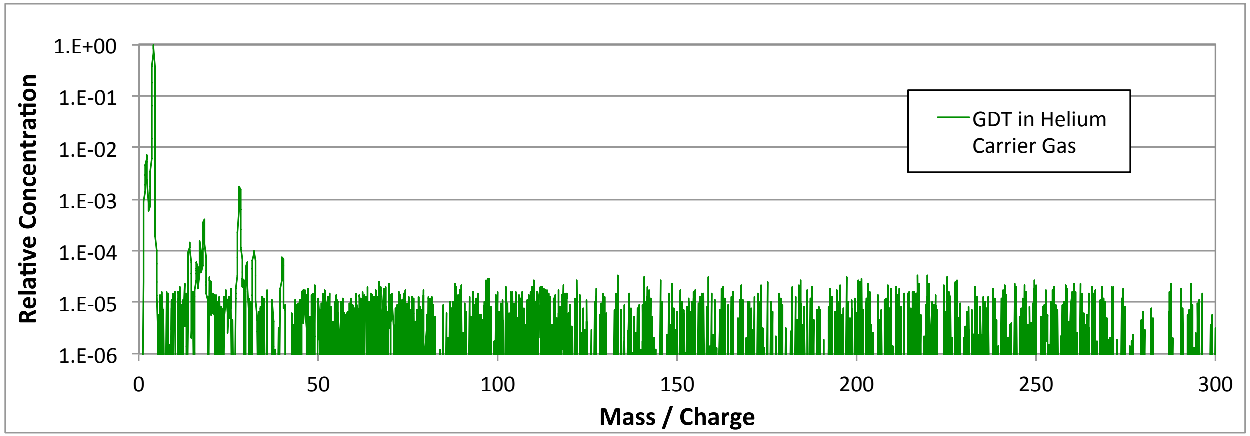
Measure resulting gas mixture with UGA. Subtract background.

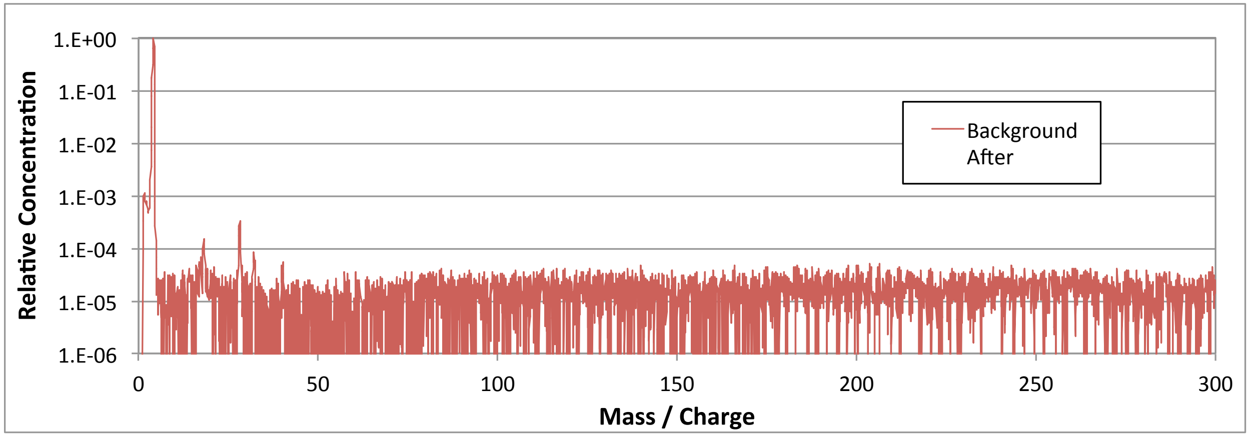
Flush with fresh gas after device broken. Re-characterize to check background stability.





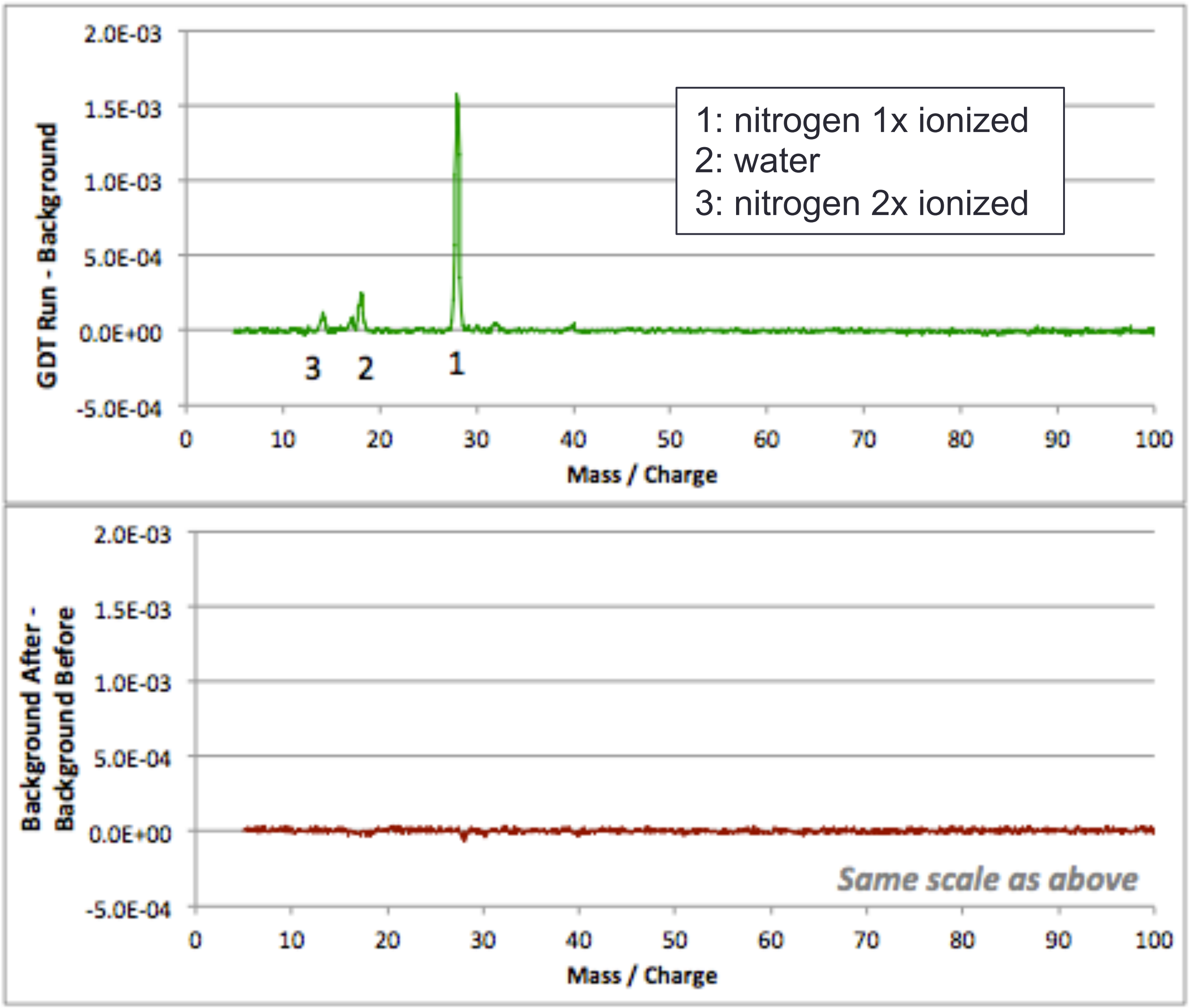






Important :

Nothing above atmospheric gasses region



GDT contains only nitrogen at ~99% level

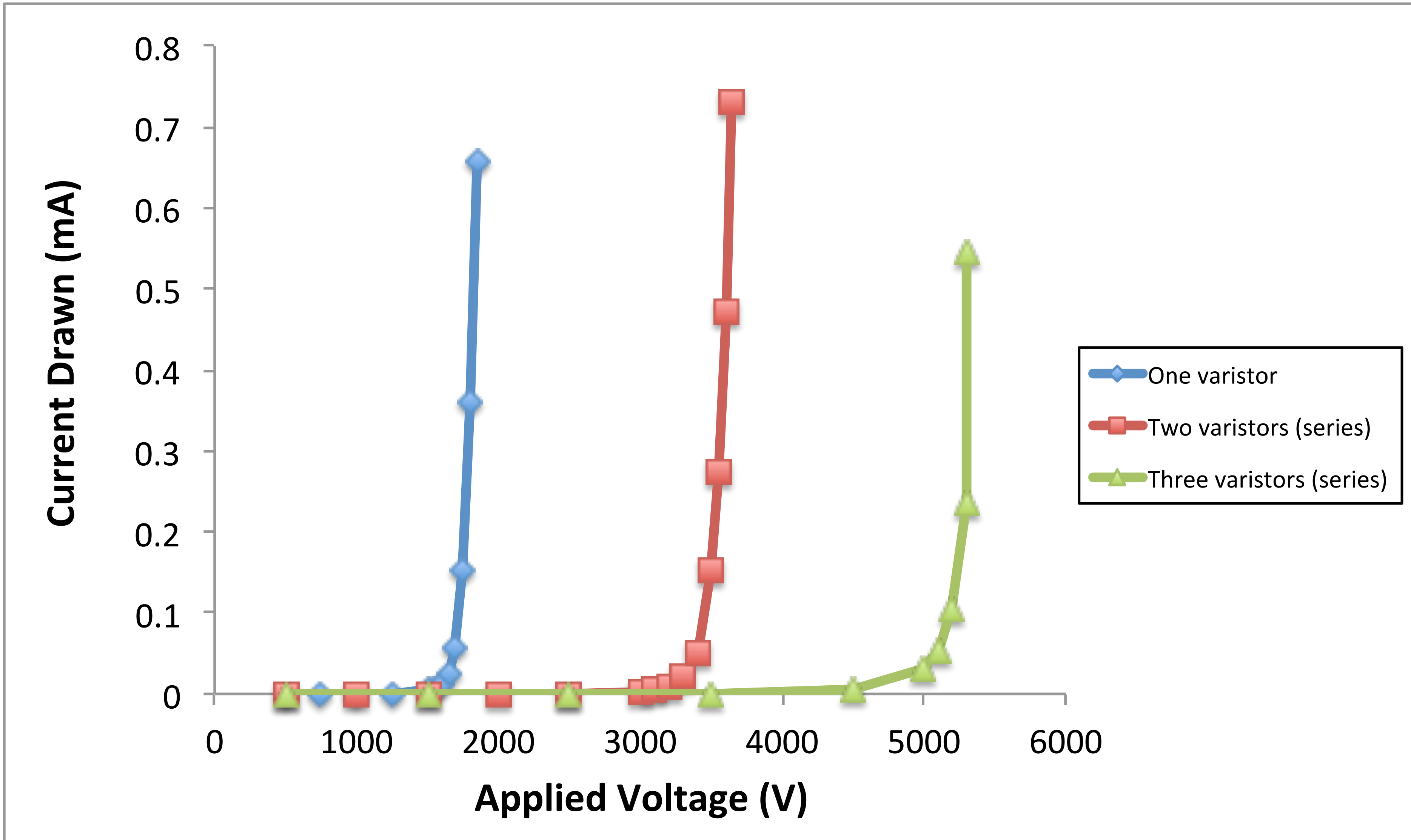
We also characterize the amount of N2 per device

We find that N2 is at 250 Torr in the GDT.

If all nitrogen from all devices leaked into MicroBooNE, 1 part in 10^{10} contamination.

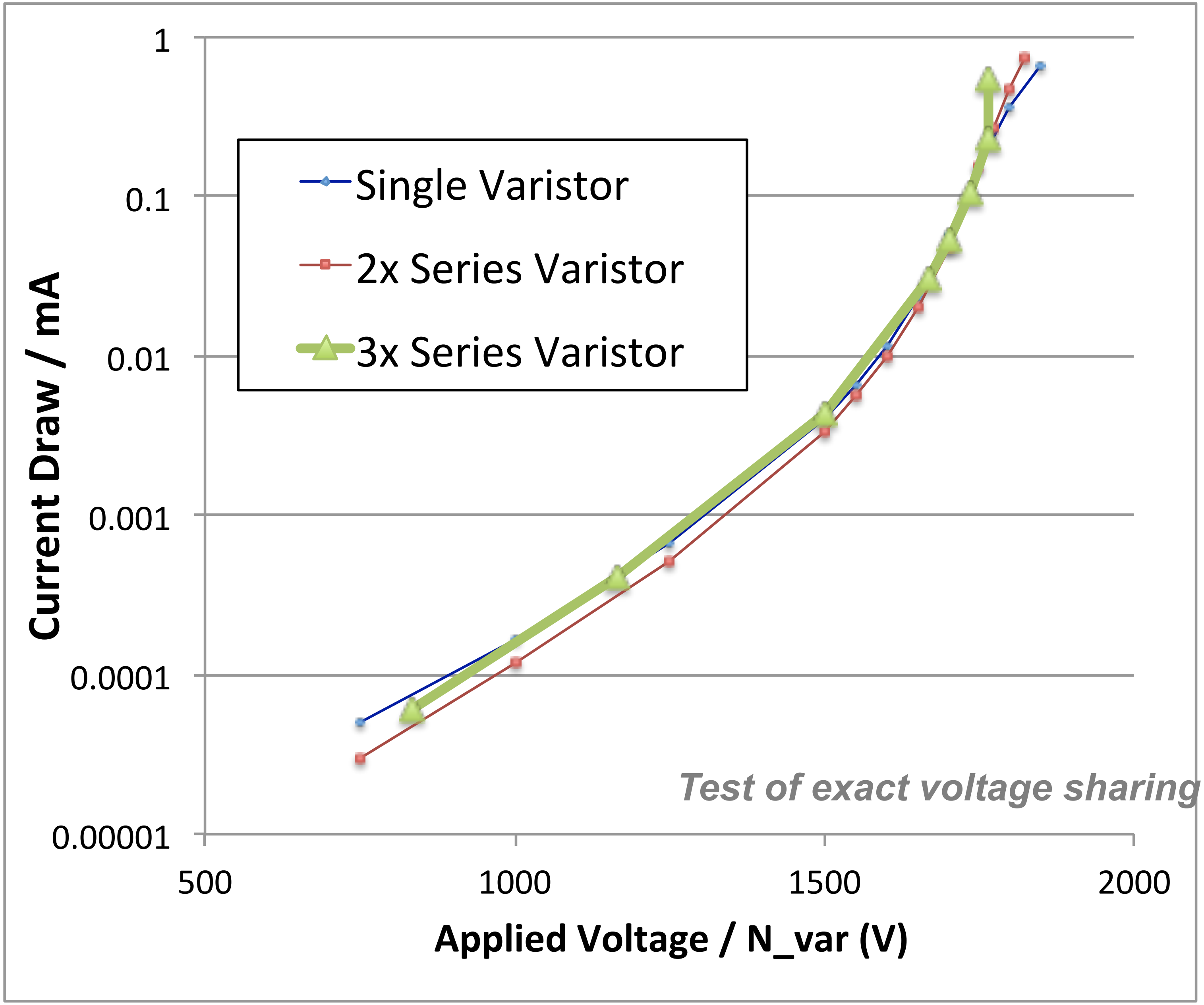
-> No purity risk.

DC clamping

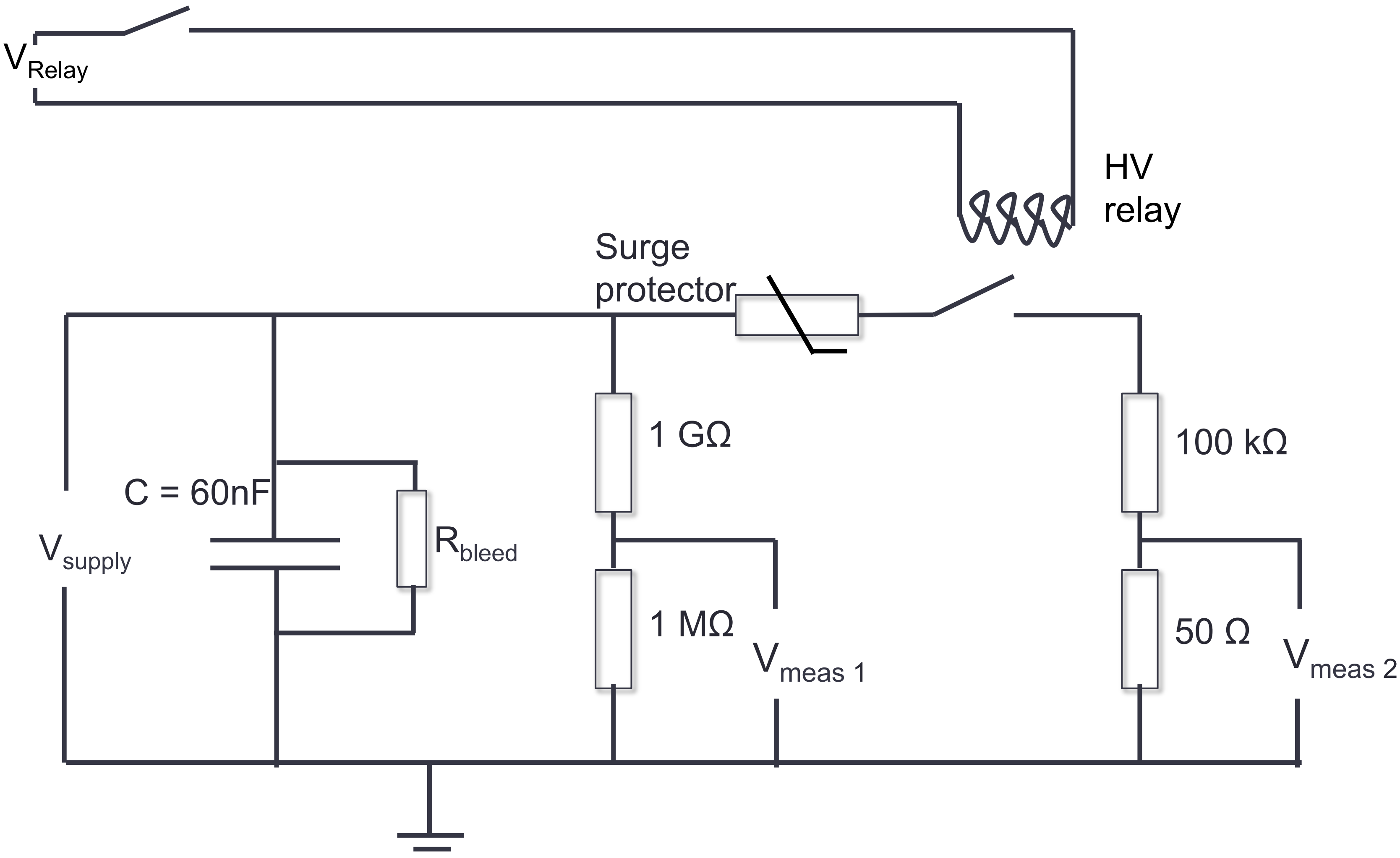


Current Drawn (mA)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1000
2000
3000
4000
5000
6000
Applied Voltage (V)
One varistor
Two varistors (series)
Three varistors (series)

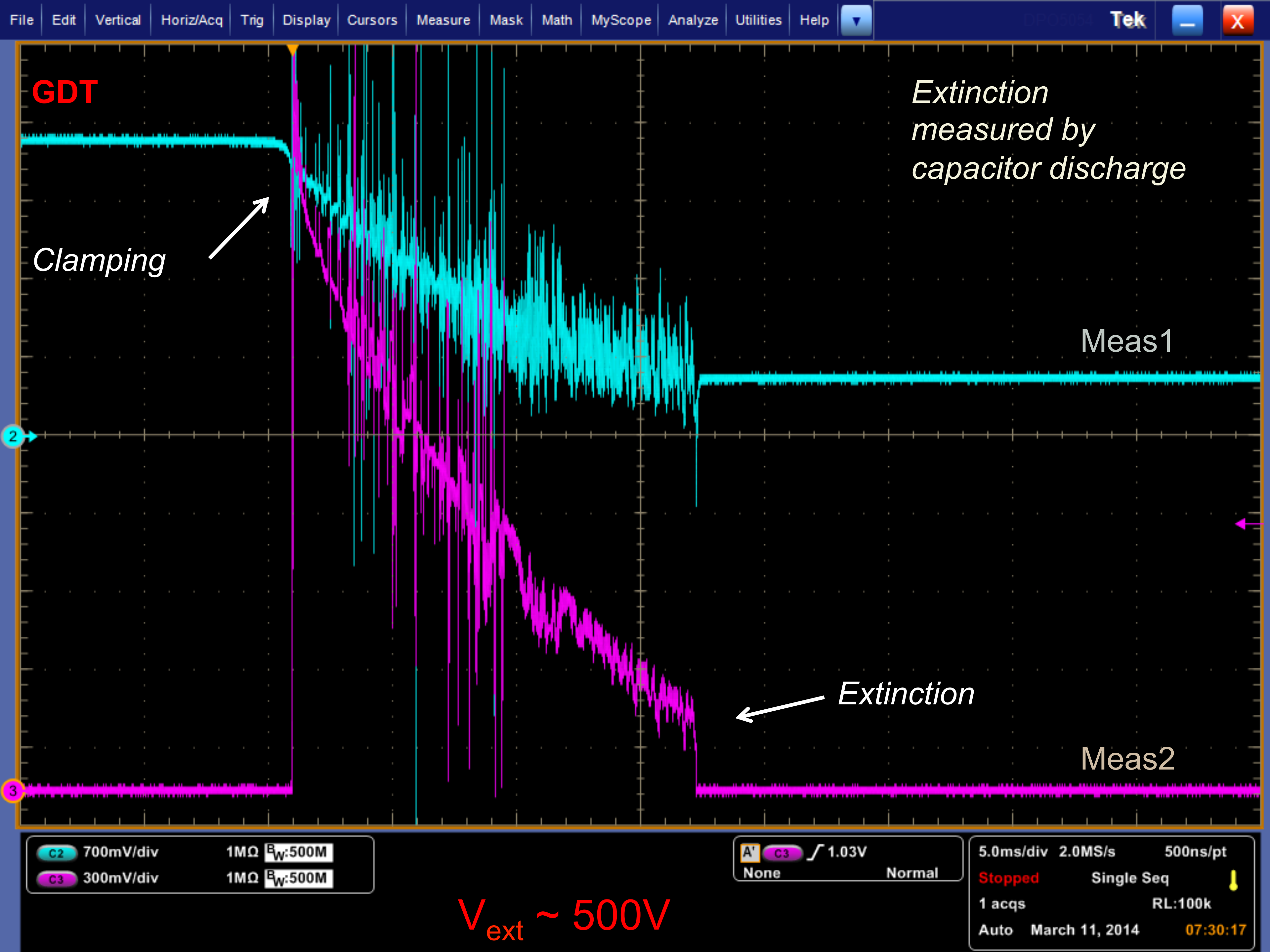
DC clamping



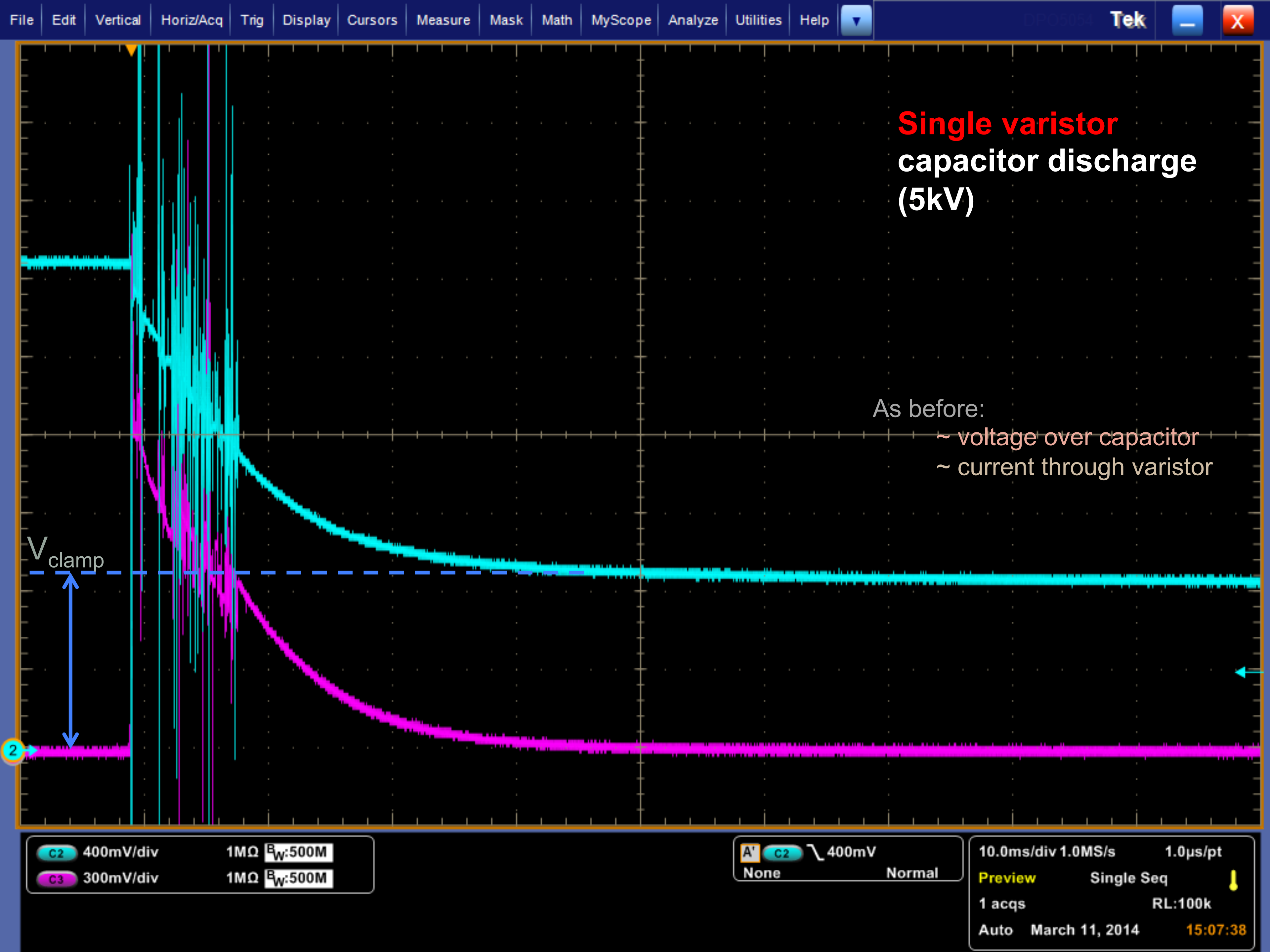
1
0.1
0.01
0.001
0.0001
0.00001
Current Draw / mA
Single Varistor
2x Series Varistor
3x Series Varistor
Test of exact voltage sharing
500
1000
1500
2000
Applied Voltage / N_var (V)



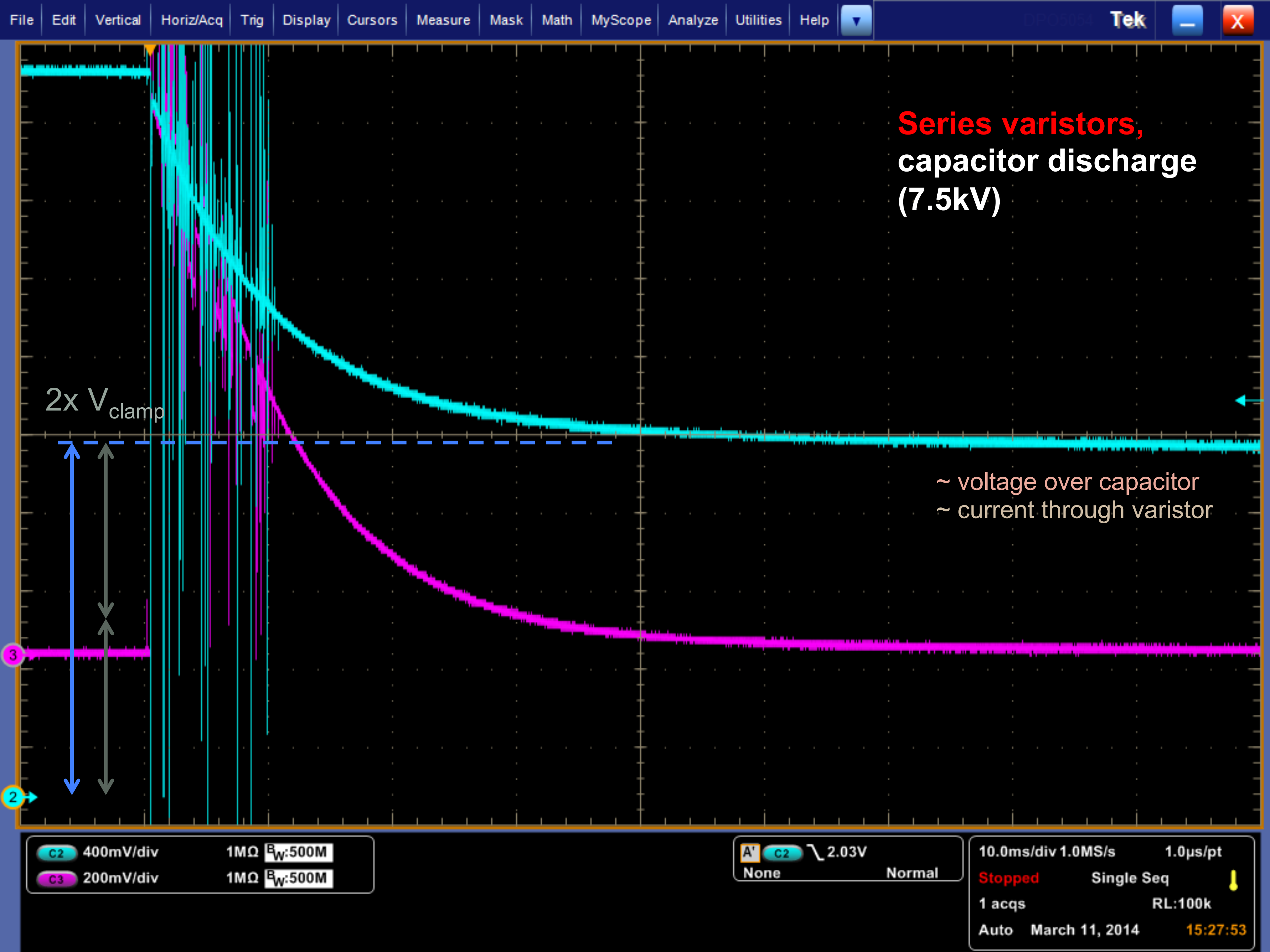
V_{Relay}
HV relay
Surge protector
1 GΩ
100 kΩ
C = 60nF
V_{supply}
R_{bleed}
1 MΩ
$V_{meas\ 1}$
50 Ω
$V_{meas\ 2}$



File Edit Vertical Horiz/Acq Trig Display Cursors Measure Mask Math MyScope Analyze Utilities Help
Tek
GDT
Extinction measured by capacitor discharge
Clamping
Meas1
Extinction
Meas2
C2 700mV/div 1MΩ BW:500M
C3 300mV/div 1MΩ BW:500M
A' C3 1.03V
None Normal
5.0ms/div 2.0MS/s 500ns/pt
Stopped Single Seq
1 acqs RL:100k
Auto March 11, 2014 07:30:17
V_{ext} ~ 500V

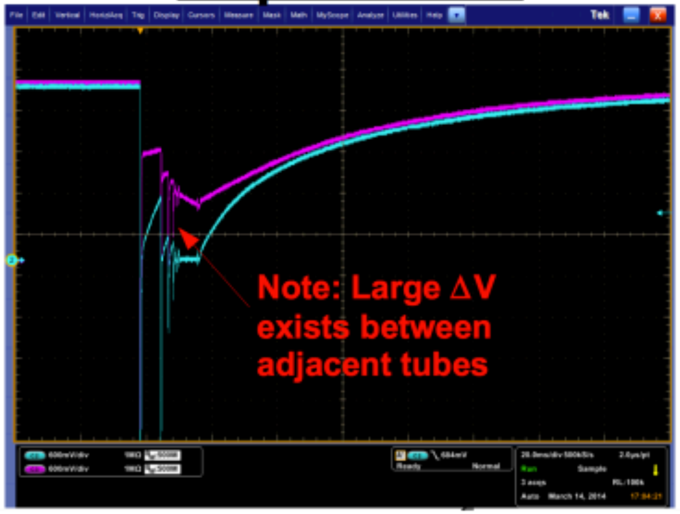


File Edit Vertical Horiz/Acq Trig Display Cursors Measure Mask Math MyScope Analyze Utilities Help
Tek
Single varistor
capacitor discharge
(5kV)
As before:
~ voltage over capacitor
~ current through varistor
V_{clamp}
C2 400mV/div 1MΩ BW:500M
C3 300mV/div 1MΩ BW:500M
A' C2 400mV
None Normal
10.0ms/div 1.0MS/s 1.0μs/pt
Preview Single Seq
1 acqs RL:100k
Auto March 11, 2014 15:07:38

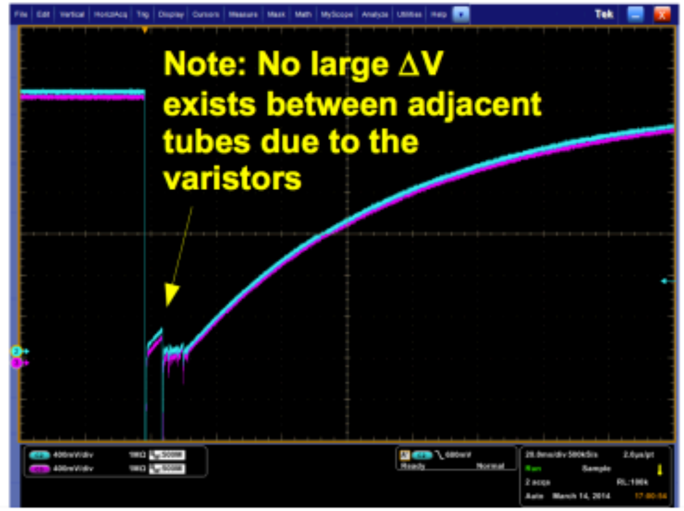


File Edit Vertical Horiz/Acq Trig Display Cursors Measure Mask Math MyScope Analyze Utilities Help
Tek
Series varistors,
capacitor discharge
(7.5kV)
2x V_{clamp}
~ voltage over capacitor
~ current through varistor
C2 400mV/div 1MΩ BW:500M
C3 200mV/div 1MΩ BW:500M
A' C2 2.03V
None Normal
10.0ms/div 1.0MS/s 1.0µs/pt
Stopped Single Seq
1 acqs RL:100k
Auto March 11, 2014 15:27:53

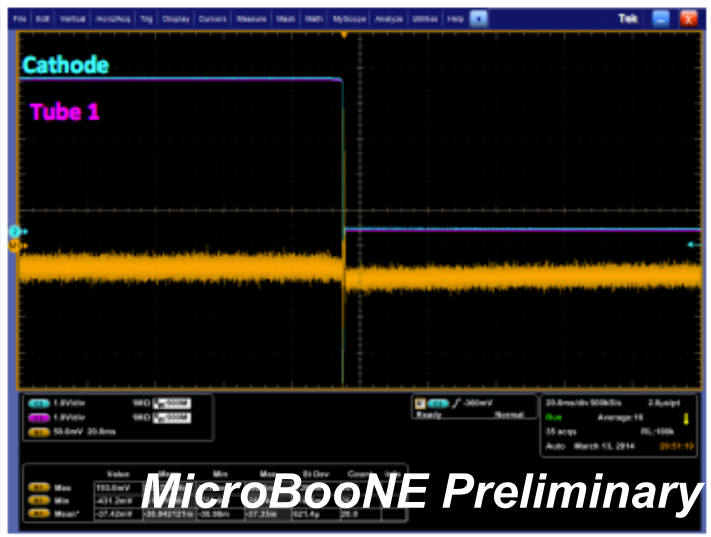
Unprotected



Protected



Brush to ground (rather than hard connection)

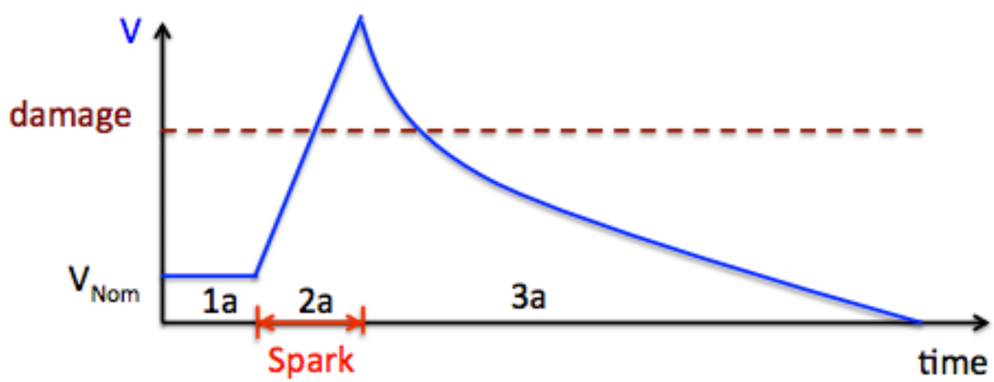


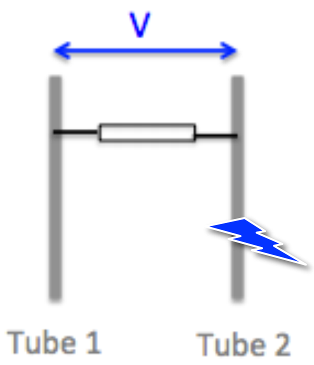
Delayed power supply trip

Varistors clamp field cage voltages successfully in all tested situations.

Role of surge protectors in a spark condition:

Without surge protection *(cartoon)*





1a: nominal field cage voltage held

2a: spark starts, charge flows, large potential developed

3a: spark ends, field cage discharges with some time constant given by RC network