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

MicroBooNE design:

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

Field cage distributes high voltage and provides a uniform E field
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 $O(1 \text{ nF})$ and resistances $O(100 \text{ M}\Omega)$ lead to relaxation times $O(0.1 \text{ s})$.
- 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:*

Thomas Strauss et al
*Paper in preparation.*
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.
What can we do???

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

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
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 $>1\times10^6 \Omega$ to $\Omega$, 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???

(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:

The MicroBooNE field cage
(schematic)
“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

“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
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2. Testing of HV surge protectors

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

Jonathan Asaadi\textsuperscript{a}, Janet Conrad\textsuperscript{b}, Sowjanya Gollapini\textsuperscript{c}, Ben Jones\textsuperscript{b}, Hans Jostlein\textsuperscript{d}, Jason St John\textsuperscript{c}, Thomas Strauss\textsuperscript{f}, Steve Wolbers\textsuperscript{d}, Joseph Zennamo\textsuperscript{g}.

\textsuperscript{a} submitted to JINST
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

Ground
Potential
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)
In a non-inductive system, surge arrestor prevents overvoltages 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 ($C \sim 500\text{pF}$).
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.

\[ \text{Result: GDT contains only nitrogen at 250 Torr – no problem for purity even in complete leakage situation (10^{-12} contamination/GDT)}. \]
As interesting aside: physics works.

1. Comparison with Paschen curve shows for this N2 pressure and electrode spacing, \( \sim 3kV \) 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

Varistors act to clamp potential difference during discharge event
also grounded several other field cage rings – varistors never allow voltage over clamping point.
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

![Diagram showing light guide detector and SiPMs with distances labeled](image)

![Graph showing rate vs. HV settings with average dark rate](image)
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
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 gases 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) vs. Applied Voltage (V)
- Line graph showing current draw for:
  - One varistor
  - Two varistors (series)
  - Three varistors (series)
Current Draw / mA

Applied Voltage / N_var (V)

Single Varistor
2x Series Varistor
3x Series Varistor

DC clamping

Test of exact voltage sharing
Extinction measured by capacitor discharge

\[ V_{\text{ext}} \sim 500\text{V} \]
Single varistor capacitor discharge (5kV)

As before:

\[ V_{\text{clamp}} \]

\[ \sim \text{voltage over capacitor} \]

\[ \sim \text{current through varistor} \]
Series varistors, capacitor discharge (7.5kV)

$2x V_{\text{clamp}}$

~ voltage over capacitor
~ current through varistor
Other field cage tests:

Unprotected

Note: Large $\Delta V$ exists between adjacent tubes

Protected

Note: No large $\Delta V$ exists between adjacent tubes due to the varistors

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:

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