Glass Dielectrics for DC Bus Capacitors

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APE010

Objectives

- The overall objective is to build glass capacitors with high temperature reliability. Glass capacitors are capable of operating at 140°C and 650V (Power Electronics and Electric Motors - PEEM Goal*).
- The research directly addresses the DOE PEEM requirements for HEV/EV/PHEV power modules that do not need internal cooling.
- Leverage the substantial investment has occurred in flat panel display glass for the development for high-temperature capacitors. Addresses the DOE PEEM requirements for low cost.
- Specific March 2011 – May 2012 objective is to demonstrate that glass can be wound into a capacitor configuration, similar to polymer film capacitors.

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*DOE-PEEM published capacitor specs are in supplemental slides

Milestone Slide

Month/Year	Milestone or Go/No-Go Decision
May-11	Milestone: High temperature dielectric breakdown system. Design and construct a system with 30 kV max voltage and at temperature range of 25ºC to 150ºC
Dec-11	Milestone: Construction of a coiled capacitor prototype. Co-wind the glass sheet conducting layer. Test capacitance, loss and high temperature performance of prototype.
Dec-12	Milestone: Test coiled glass capacitor at high voltage (>1kV) and 140ºC.

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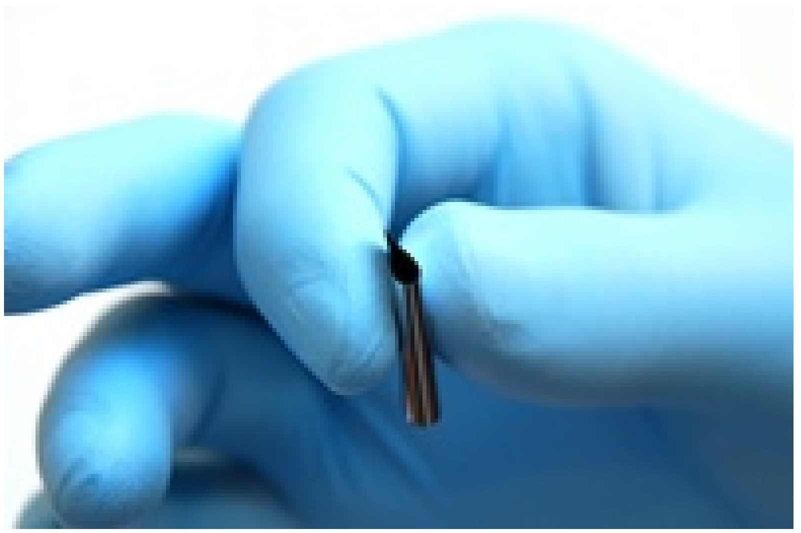
Approach and Strategy

- Approach: Glass is a promising high temperature material that can be incorporated into a capacitor structure.
- FY12 approach is to demonstrate a coiled capacitor from flexible flat panel display glass.

Flexibility demonstration of flat panel display glass

Commercially available thicknesses of 50 μm

Experimental glass available in thicknesses of 5 μm



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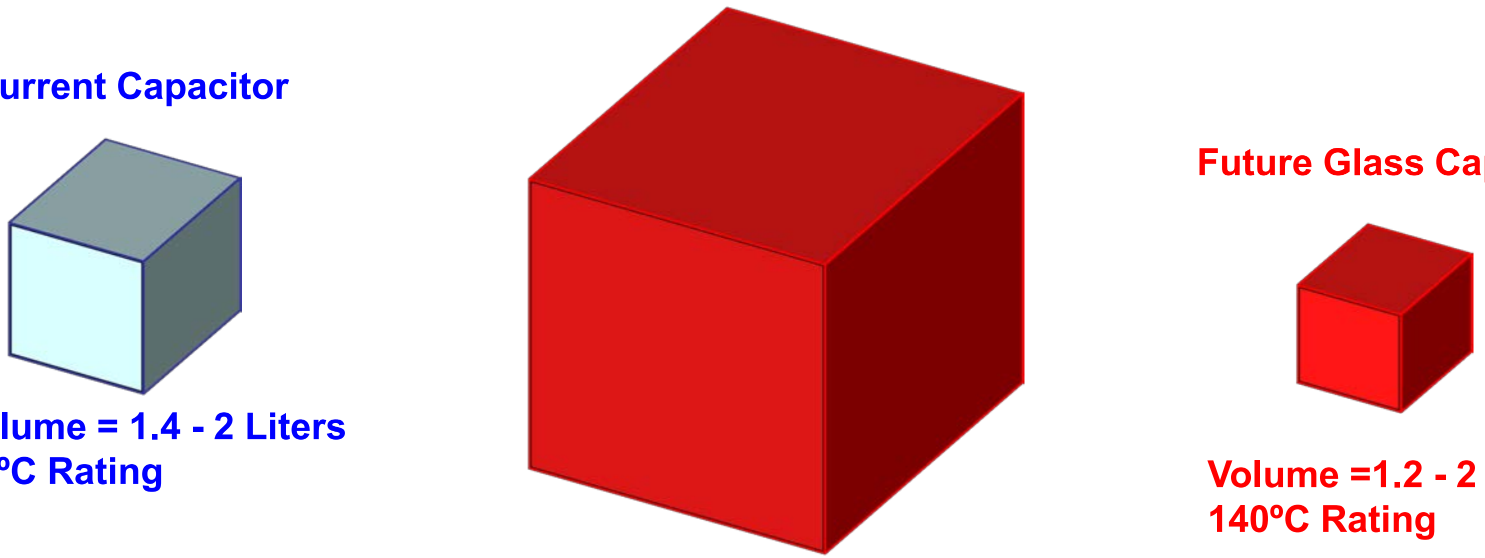
Approach and Strategy

- Use low-cost flat panel display glass in a DC Bus capacitor
- Reduce the total volume of a DC Bus capacitor by incorporating glass materials in the capacitor construction
- Glass has a substantially higher melting point (1400°C) than the melting point of plastics (150ºC) that are presently used in capacitors

Volume of 1000 µF 600V capacitors in a Hybrid Electric Power Converter



Technical Progress: Benchmarking State-of-the-Art Power Capacitors

- Specifications for State-of-the-Art SBE capacitors*
  - Volume of the 600 V 1000 μF component is 1.8 L
  - Ripple current at 105ºC is 20% of the 85ºC value. Excellent performance for a capacitor made from polypropylene.

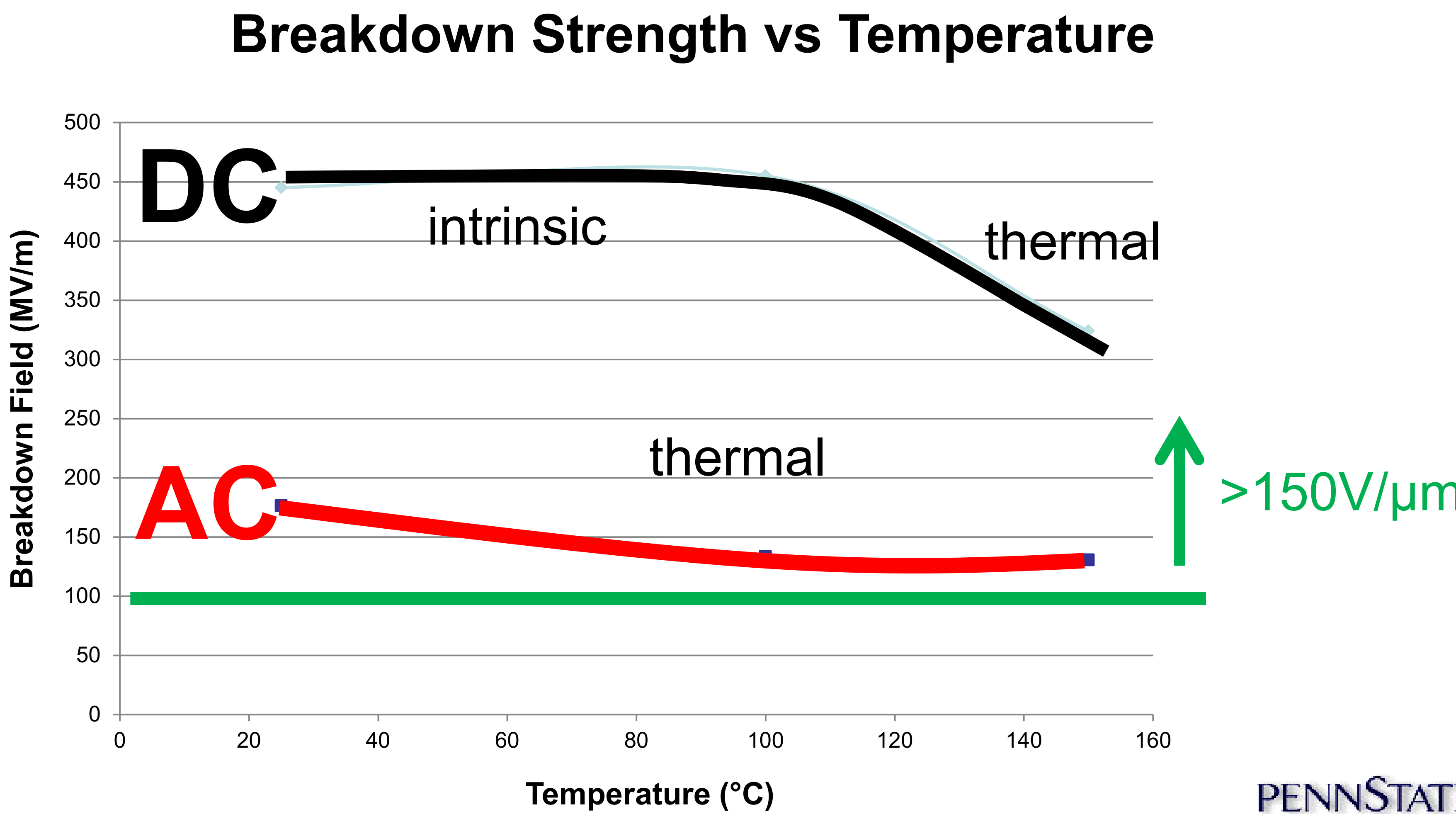
- Glass capacitor projected performance
  - Dielectric volume for a 600 V 1000 μF capacitor with 10 μm thick glass film is 1.9 L.
  - No ripple current decrease between 85ºC and 140ºC. Projection based on dielectric breakdown data and dielectric loss data at high temperature.

- Glass has a substantially higher melting point (1400°C) than the melting point of polymers (150ºC) that are presently used in film capacitors

* SBE Power Ring Part # 700D10896-348

Benchmarked in FY11

Dielectric Strength Characterization of Flat Panel Glass Under Conditions Relevant to Electric Vehicles



Data obtained in FY12

Glass Coil Capacitor Fabrication

Draw Glass Ribbon

- Thin glass ribbon is manufactured by a down-draw process and redrawn to reduce the ribbon thickness.
- The key challenge is to produce glass ribbon from 50μm to 10 μm.

Deposit Electrode

- Electrodes are placed on top and bottom surfaces of glass ribbon and candidate electrodes include copper foil, aluminum and silver film.
- Equivalent Series Resistance (ESR) and self-healing mechanisms are controlled by the electrode properties.

Wind glass

- Glass ribbon up to a 100 meters in length has been produced by glass manufacturers, which will need to be coiled into a capacitor configuration.
- Coil diameters of 1 cm have been demonstrated for 50μm thick ribbon. Substantially smaller diameters (<1 cm) are possible with thinner glass.

Package

- Packaging includes end termination, lead attachment and encapsulation.
- Thermal, mechanical and electrical performance must be considered in package design.

Test

- The capacitance and loss is characterized as a function of frequency, temperature and AC voltage strength.
- Reliability tests to predict capacitor performance under operating conditions.

Coiled Glass Capacitor

- NEG-OA 10 glass ribbon
- 50 µm thick
- 2.9 m long
- 30 mm wide

Coiled glass capacitor fabricated at Penn State by spraying Ag ink on the glass ribbon and then winding the ribbon around a mullite mandrel.
Right side: free standing glass ribbon section
Left side: fully packaged coiled glass capacitor

Fabricated in FY12

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Coil Characterization at 23ºC

Frequency		1 kHz	10 kHz	1 MHz
Capacitance		67.1 nF	67.0 nF	67.1 nF
Loss		0.001	0.002	0.004

- Calculated value of 70 nF

$$\text{Capacitance}= \frac{\varepsilon_o \varepsilon_r A}{t} = \frac{\varepsilon_o 5.3 * 2.9 m x 2 cm}{50 \mu m} = 70nF$$

- Next step is to scale to longer lengths
- Projected ESR for 10 µF capacitor = 3 mΩ

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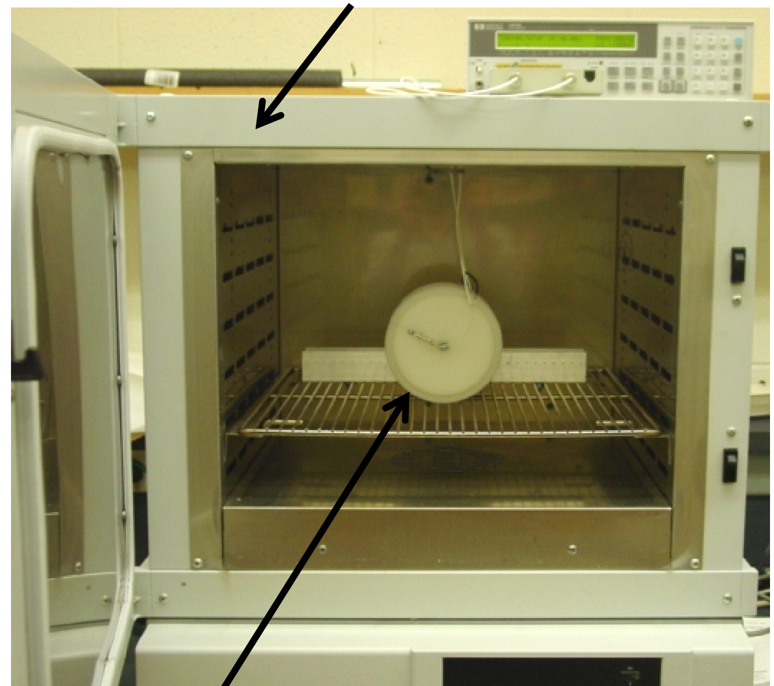
Data obtained in FY12

High Temperature Properties

Temperature	Frequency	Capacitance, nF	Loss
50°C	1 KHz	67.2	0.001
	10 KHz	67.1	0.002
100°C	1 KHz	67.6	0.004
	10 KHz	67.4	0.003
150°C	1 KHz	68.2	0.005
	10 KHz	67.9	0.003

Environmental Chamber



Coiled Capacitor

Data obtained in FY12

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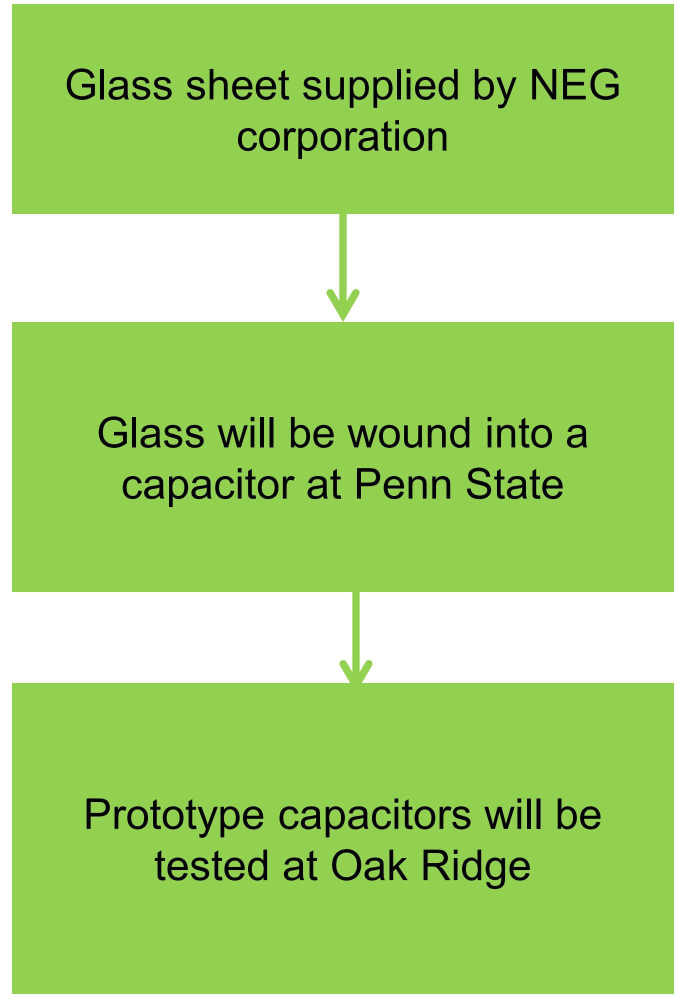
Collaborators

- Argonne National Laboratory
  - Prime contractor
  - Penn State characterizes Argonne capacitors
- Sandia National Laboratory
  - Collaborate on the defining capacitor specifications for PEEM
- Oak Ridge National Lab
  - Independent validation of capacitor measurements
- Industry
  - SPS (capacitor manufacturer)
  - NEG (glass manufacturer)

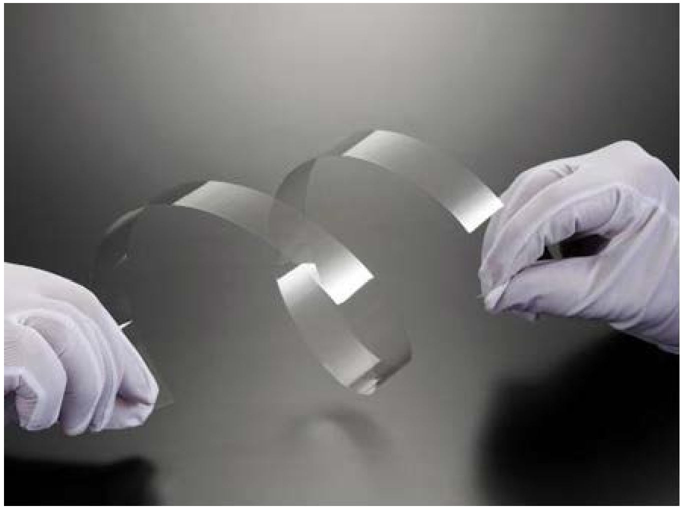


Proposed Future Work

- Highly Accelerated Life Test (HALT) of 10 μm thick glass.
  - Temperatures up to 450 C
  - Voltages up to 5 kV
  - Life predictions for DC bus capacitors in electric vehicles
  - Complementary studies of ppm level sodium migration
- Characterization of coiled glass capacitors at high voltage (>1000 V)and high temperature (140ºC)

Bend radius is inversely proportional to the glass sheet thickness.

Photo from collaborator T. Murata, NEG



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Summary Slide

- **There has been a substantial world-wide expansion in flat panel display glass in the past decade. This plentiful material has excellent high temperature dielectric properties.**
- **In FY12, coiled glass capacitors were fabricated and tested**
- **Future work for the remainder of FY12 will focus on life testing and long-term aging of flat panel display glass. This is important for capacitor performance over the HEV lifetime.**
- **In FY13, coil capacitors will be tested at high temperature and under high AC voltage.**

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Technical Back-Up Slides

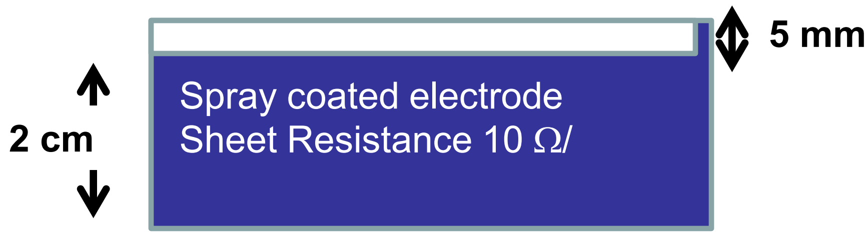
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Table 1: DOE Vehicle Technologies Program DC Bus Capacitor Targets

Typical Capacitor Bank Requirements	
Capacitance, µF	1000 +10% / -0%
Operating voltage, VDC	450
Peak transient voltage, VDC for 50 ms	650
Leakage current at operating voltage, mA	≤ 1
Dissipation factor at 10 kHz[1], %	< 2
Equivalent series inductance (ESL), nH	≤ 5
Ripple current, amps RMS continuous	90
Temperature range of ambient air, °C	-40 to +140
Volume requirement, l	≤ 0.6
Cost	≤ $30
Failure mode	Benign
Life @ operating conditions, hr	>13,000

Coil Fabrication

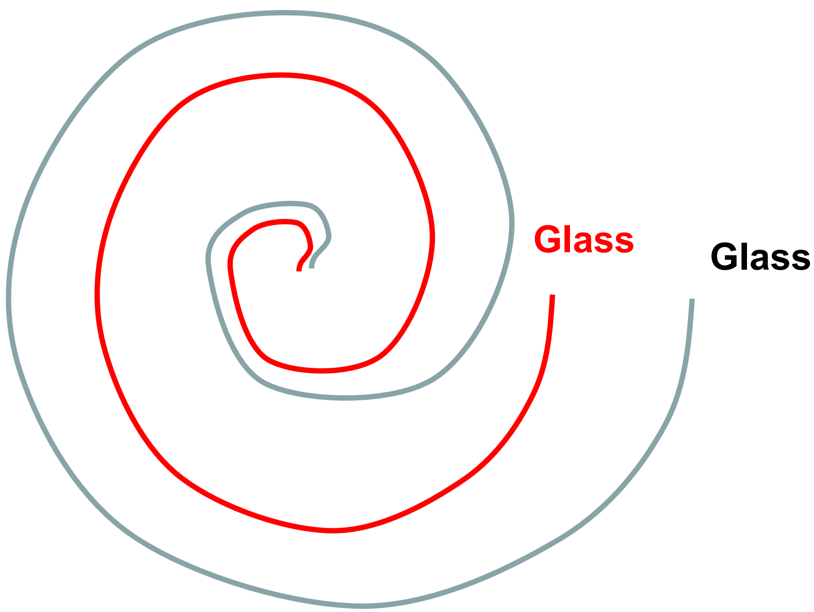
Glass Sheet Side 1



Glass Sheet Side 2

Uncoated margin on opposite sides for voltage isolation

Co-wind glass



Glass Sheet

Steve Perini and Amanda Baker

Coil Measurement Procedure

- Glass spacer layer is required to separate + and – sides of glass layer.
- Connections are made at several points along the length of the glass ribbon
- Excellent frequency response expected in this configuration