Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Coil Impregnation Processes and Experiences at FNAL

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Nb_3Sn Technology for Accelerator Magnets

11 October 2018

Outline

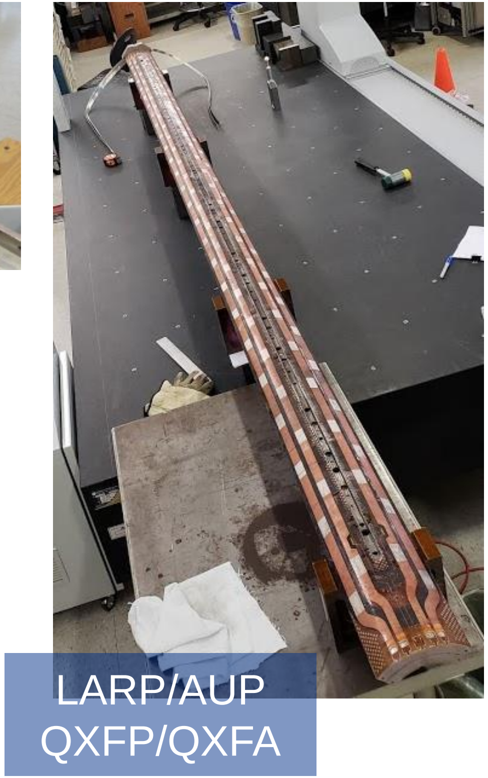
Coil Impregnation

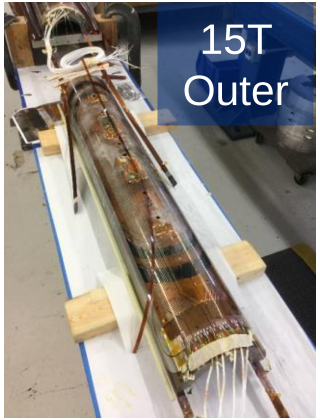
- Background
- AUP/HFM procedure
- Typical CMM

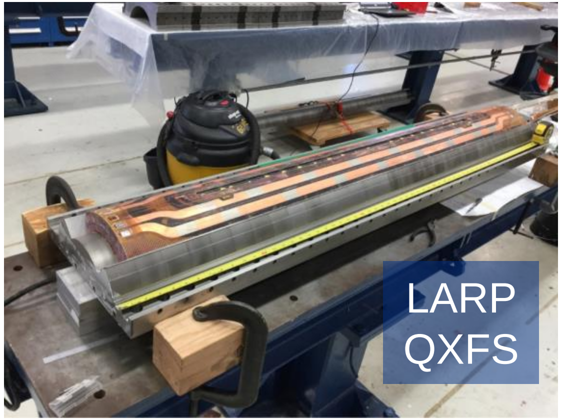
Designing for epoxy impregnation

Things we have found do and do not work

Fermilab Nb_3Sn Coil Fabrication Experience

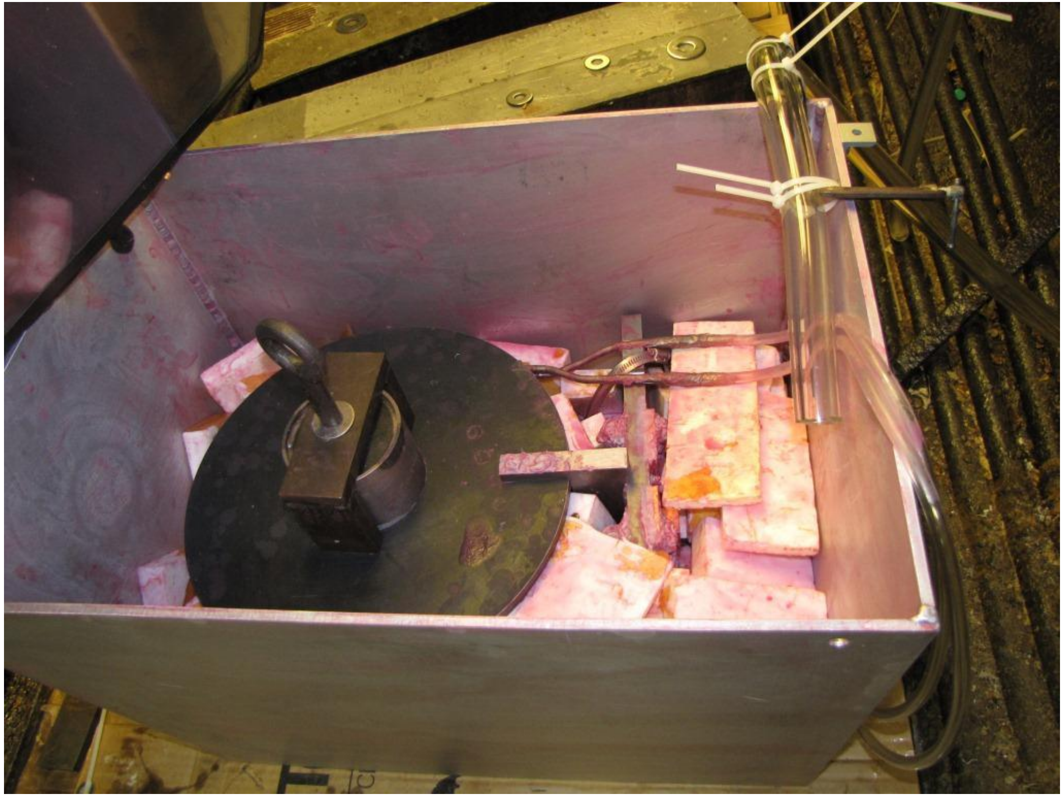






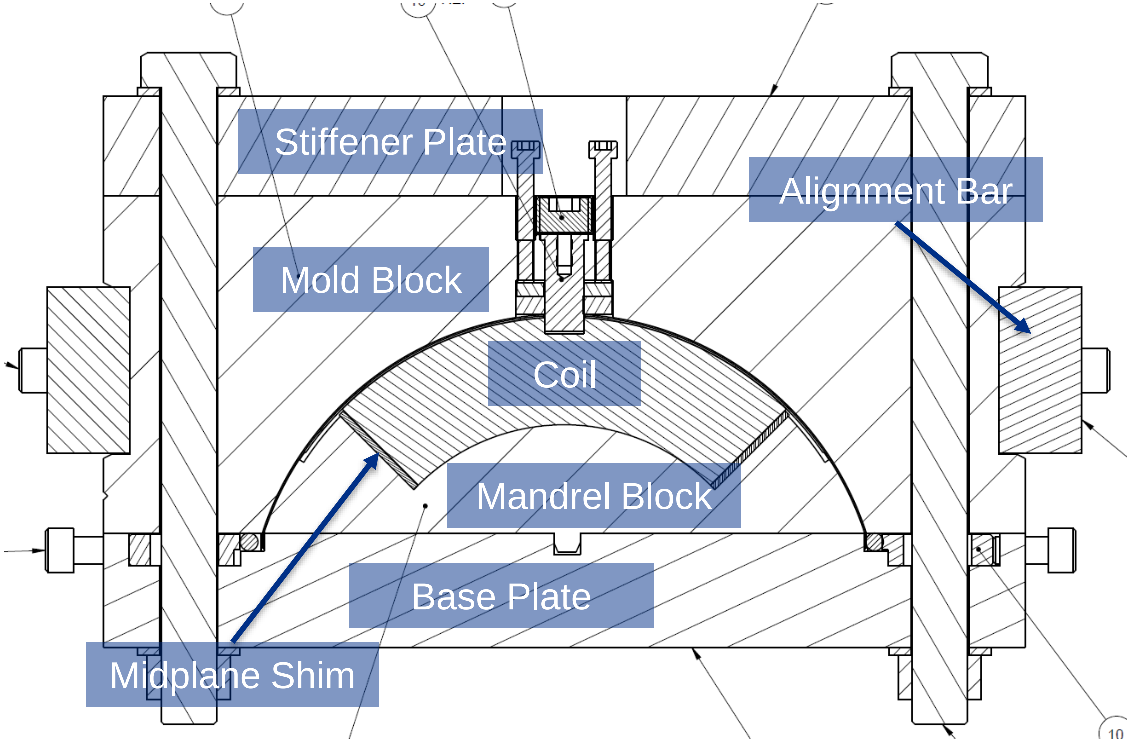
Lots of coils!

- **FNAL has been building Nb_3Sn accelerator magnet coils for quite a while. These generally use a closed mold in vacuum**
  - Mostly Cos-Theta, but some common coil designs
- **They mostly follow the same process using the same general tooling design**
  - If it ain't broke, don't fix it.
- **We also build significant quantities of impregnated conventional magnets.**
  - Mix of closed molds and open vessel potting
- **Lots of oddballs as well**
  - CLAS12



QXF Tooling Cross Section

- **Full Length Pieces**
  - Stiffener Plate
  - Base Plate
  - Alignment Bars
  - Midplane Shim
  - Shells
- **Mold Blocks and Mandrel Blocks are thick (~50mm) laminations**
- **Mold blocks located to mandrel blocks by tight tolerance on arcs on either piece.**
- **O-Ring along either side with pusher bar to make longitudinal seal.**
- **End seals are accomplished by O-ring in grove and Extra RTV for insurance.**



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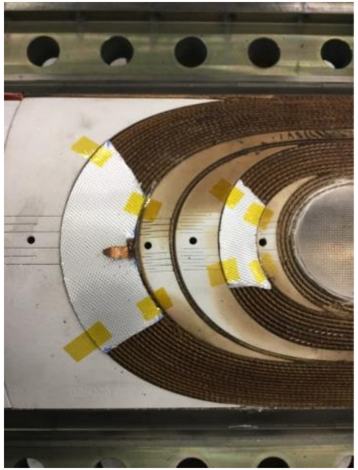
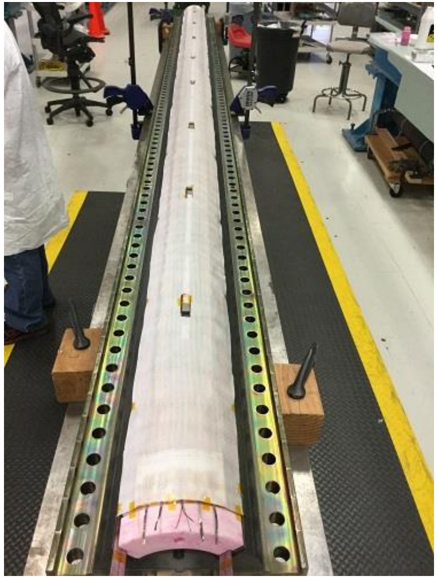
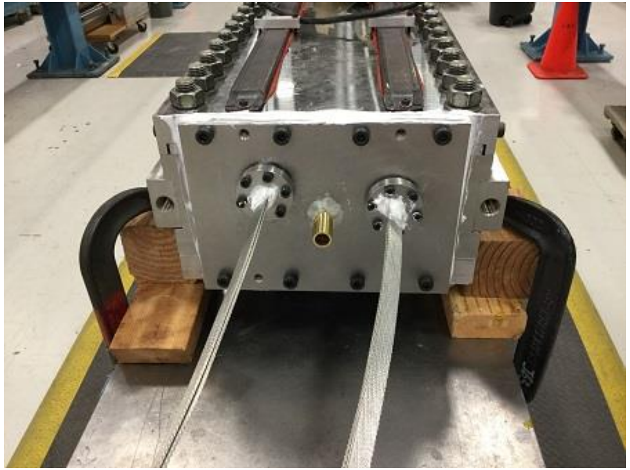
Procedure: Impregnation Preparation



Fill all voids of reasonable volume with Laser cut glass



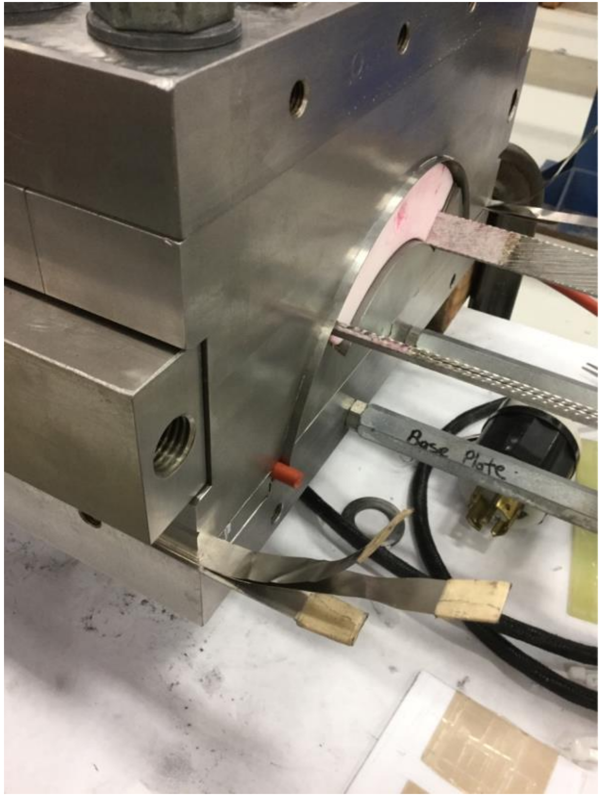
Install trace, Teflon Fillers, Fiberglass, shell, mold blocks…

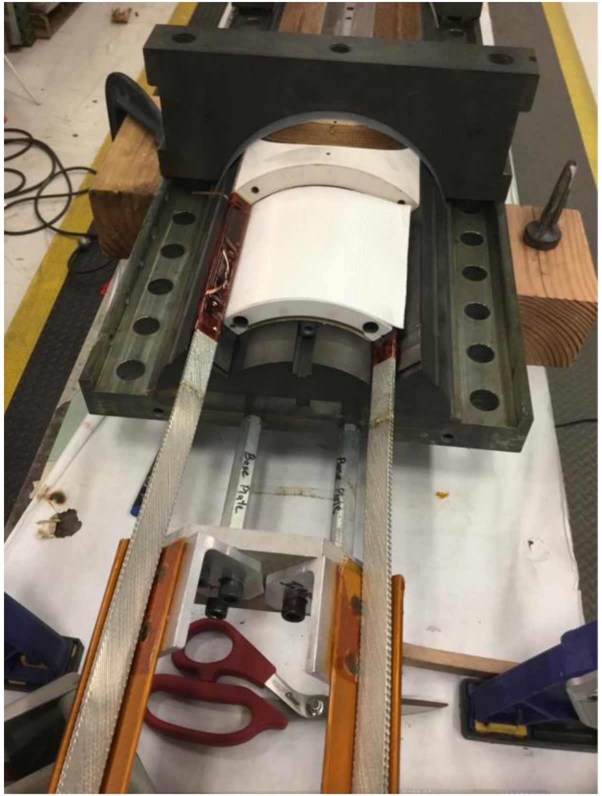


Seal tooling. O-rings and RTV. Check that we can pump to <500mTorr (no "large" leaks)

Lead Soldering

Coil Leads are soldered and arranged such that a seal can be made against the cable





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Coil Setup in Oven

- **FNAL uses a large vacuum oven for coil potting. Radiant heat is available, but no longer used.**
- **We apply a slight tilt at FNAL**
  - ~0.75m is as much as we can do for ~4.5m of tooling
  - BNL has coil hung vertically
- **Small Epoxy line runs from feedthrough to RE of coil**
- **Large outlet line serves as reservoir for any changes in epoxy level**

Fill

- **10 ml/minute for ~5 hour fill time for long coils (fill rate set to utilize 8 hour day)**

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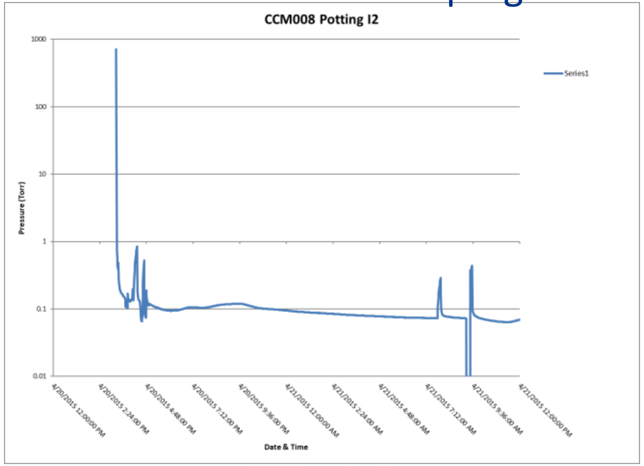
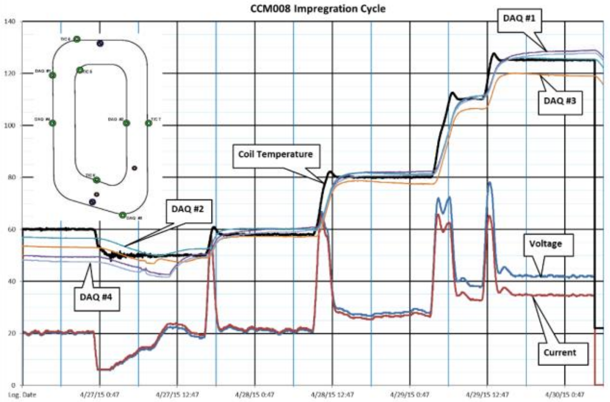
Coil Outgassing/Drying

- Water and other volatiles present in a coil during impregnation may lead to micro-voids in the coil cross section.
- Reacted coils should be free of problematic materials after reaction, but exposure to humidity will lead to water being adsorbed in the glass.
- Added materials (plastics, fiberglass sizing mold release) may also bring along additional volatiles that are problematic.
- An increased temperature under vacuum can accelerate the removal of this stuff
- More difficult in a vacuum chamber to measure than a vacuum sealed mold.

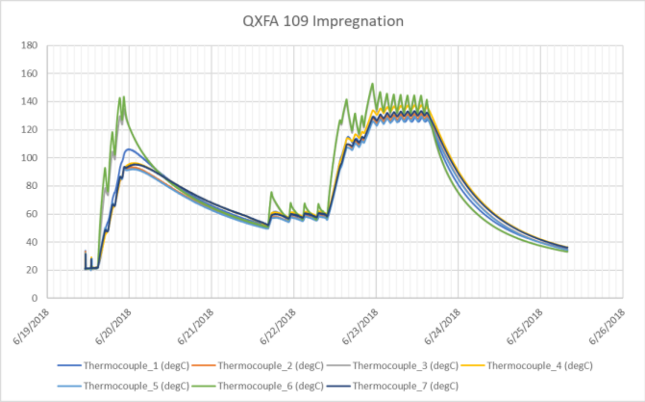
Data From CLAS12 Coil Impregnation

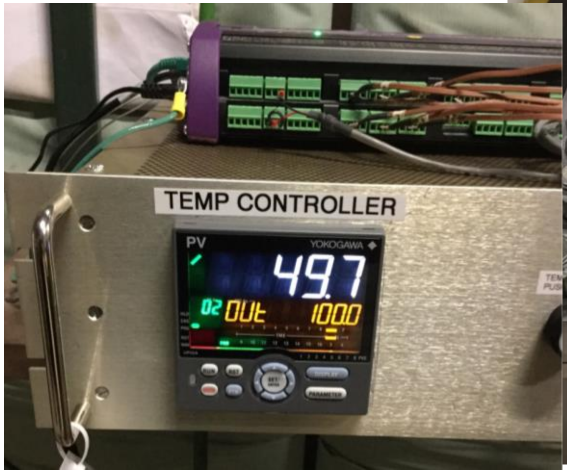


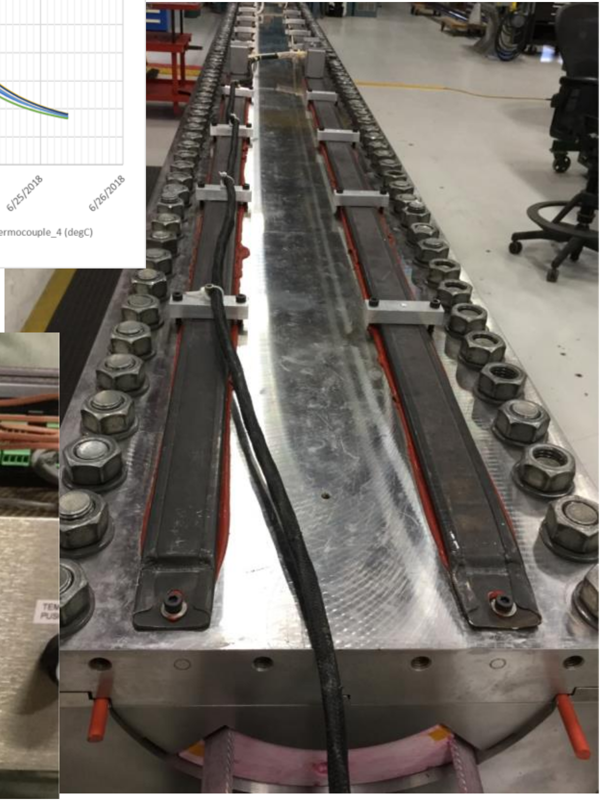


Coil Temperature Control

- **AUP has implemented electric heat on tooling for curing of QXF coils**
  - Allows curing in place with our infrastructure
  - Powered by PID controller with ramps and soaks pre-determined
  - Allows reasonably fast ramp. We use 10° C/hr (limited by power)
- **Works quite well in vacuum for outgassing.**
- **Tooling monitored by 7 or 14 thermocouples and coil resistance**
  - Resistance gives an indication of coil average temperature, could be calibrated







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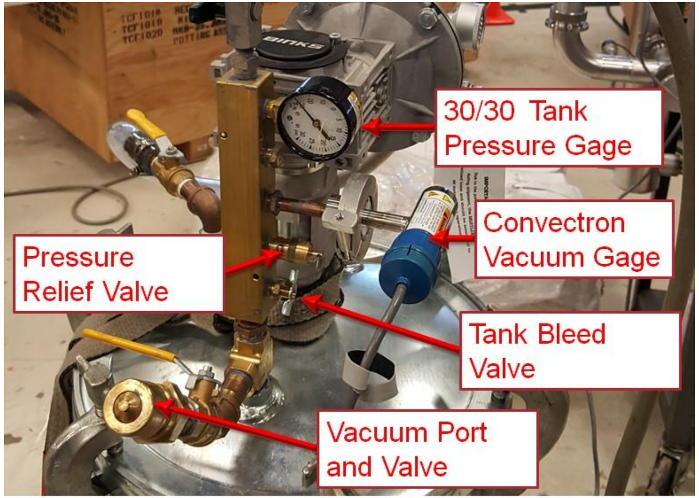
Epoxy

FNAL Uses CTD-101K as a baseline for all Nb_3Sn Coils

- **Epoxy components are preheated overnight to 55 °C**
- **~7 liters of epoxy are mixed per coil**
- **Mixing and degassing are done for 1 hour under vacuum of ~800 mTorr and ~55 °C**
- **After degassing, mixing and heating are stopped. Tank is let up to atmosphere**
  - No agitation under atmosphere after degassing
    - No heating without mixing
      - Solid blocks of epoxy may result…

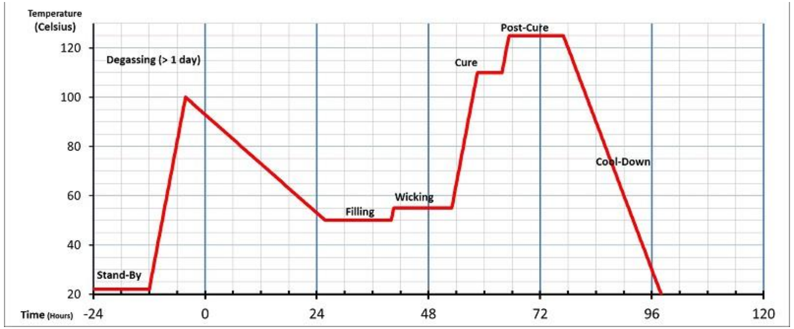


Peristaltic Pump

- **FNAL adopted using a peristaltic metering pump as it was in use at Brookhaven and they liked it.**
- **We like it too!**
- **Allows calibrated flow rate**
- **Eliminates leaks as implemented**
    - We run a single piece of tube from the Epoxy Tank>RTV Potted Vacuum Feedthrough>Coil
- **Flow cross checked against tank weight**
- **It helps contribute to a boring impregnation process**
    - A good thing!
- **A duty cycle control box has been added to the pump to use larger tube at lower flow rates**
    - Over the length of the ~1/8"(3mm) ID tube, differential pressures could approach 3 bar
    - 3/16" (4.7mm) drastically reduced pressure drop at the cost of having a minimum flow rate of 20ml/minute
        - We run at 50% duty cycle for filling operation for a fill time of ~5 hours

Coil Curing in Oven

- For curing we adjust the coil to be horizontal as we found convection to be problematic on a tilted coil.
- Epoxy level is marked and observed
- Generally ~2-4 inches of change (~20ml) throughout the cure cycle (~0.6% total epoxy volume)
- Slight amount of insulation added on ends as otherwise they run cold



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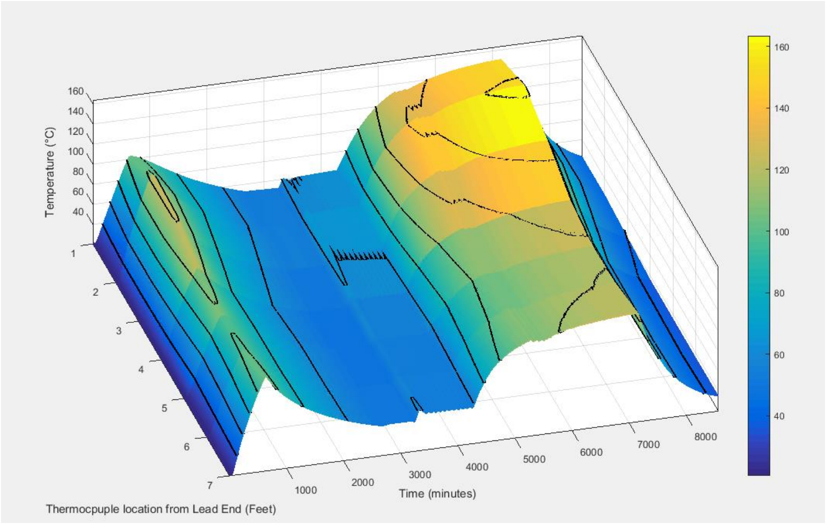
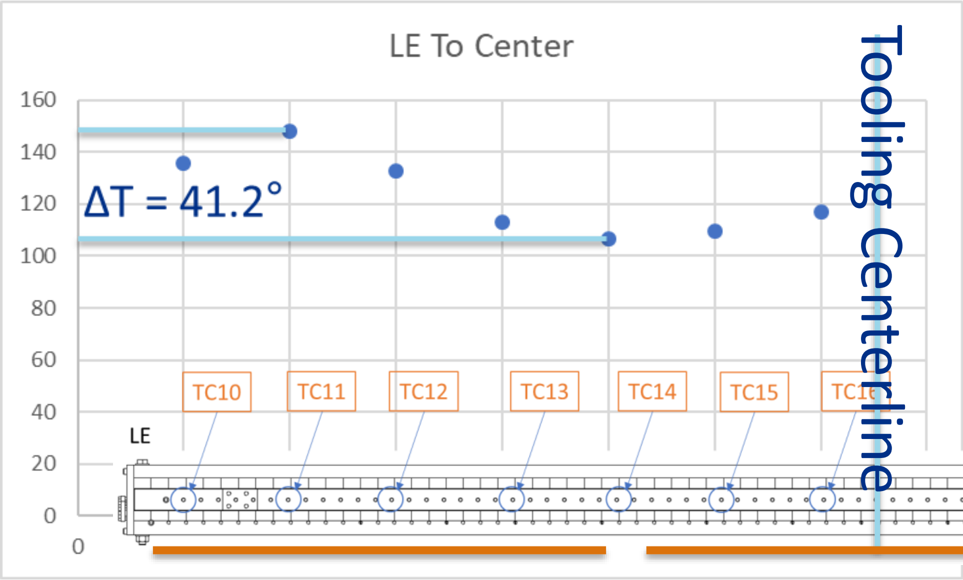
On Temperature Uniformity

A downside to electric heat is that it operates at fixed power, not fixed temperature

- Since several heater strips are used along length of tooling, a temperature ripple can be observed with local hotter spots at the center of the heaters and cool spots between and at the ends.
- Axially laminated stainless steel tooling makes for horrendous heat transfer
- A smallish piece of copper bar can increase longitudinal heat transfer by 2-3X





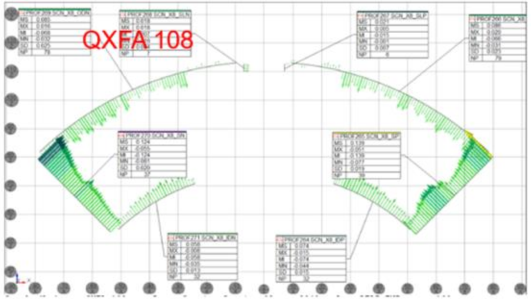
Coil Demolding

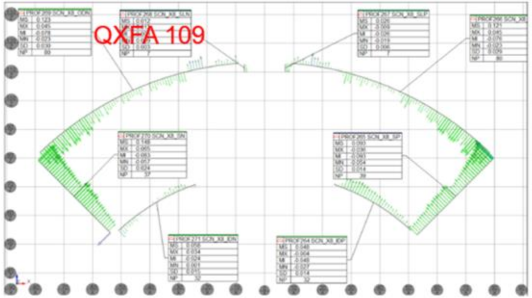
After curing, coils are demolded

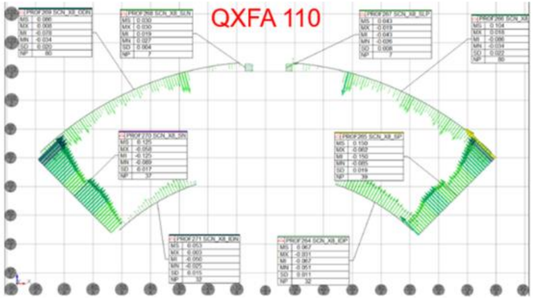
- **Remove Teflon follers**
- **Drill out holes**
  - Screw counterbore bits work well for clean hole edges
- **Carefully trim overhanging fiberglass**
  - Scalpel and a straightedge
- **On larger more robust coils we have used more aggressive methods**
  - Surform
  - Vibrating sander

On CMM

- **How you align the data changes how things appear substantially**
  - Plots to the right use fit to OD and midplanes
- **In AUP Coil to coil deviations are small ~3um on ID and midplane, ~9um on OD**
  - ID is defined by single EDM cut block per section.
  - Midplanes have stainless shim and Kapton shim
  - OD is defined by 3 layers of material and mandrel block
    - Stainless shell, Stainless filler, 250um mylar
    - Mandrel block has some freedom on base plate
      - Slight rotation is allowed
      - Slight side to side shift is allowed







From F. Nobrega

Design for Impregnation: Darcy's Law

Impregnating a coil really only involves two things:

1. **Get gas out.**
2. **Get resin in.**

We accomplish the first with vacuum.

We accomplish the second with by flowing resin into the coil.

As coils present a porous medium to and epoxy is a fluid flowing in it, Darcy's law is a great way to direct your methods.

If we assume some potlife, we can integrate over the working time of the epoxy to compare or normalize different epoxy systems

How do we do better on large or long coils?

More fill ports?

- $Q = \frac{-\kappa A}{\mu}\frac{\Delta P}{L}$ or $\frac{-\kappa A}{\mu}\frac{\partial p}{\partial l}$
  - Q is the discharge rate
  - κ is the permeability constant of the porous medium
  - A is cross sectional area perpendicular to the flow direction
  - ΔP is applied pressure
  - μ is viscosity
  - L is the length scale in the flow direction

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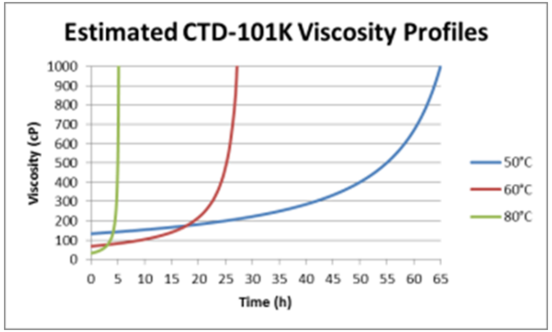
On Viscosity and time

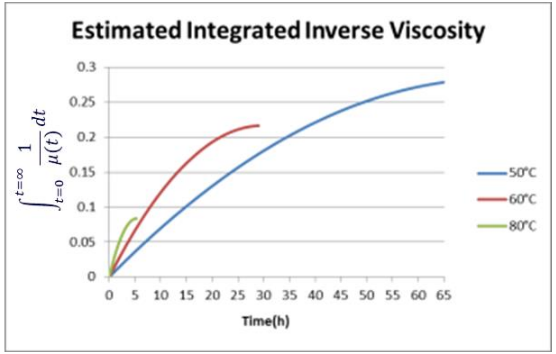
Since we are transitioning from not filled porous media to filled stuff and we want to finish filling some volume (~A*L) of porosity *n*, in some before the pot life runs out, the time to fill something in a 1d case looks like this:

$$t = \frac{\mu * l^2 * n}{2 * \kappa * \Delta P}$$

- **Everything is roughly constant except for viscosity**
- **We can compare resins based on the integrated inverse viscosity from t=0 to t=∞ or viscosity is ~infinite**



Fits to data provided by CTD



Matrimid Coil

- **A quest for a more radiation resistant magnet**
- **Coil potted with Matrimid 5292**
    - Bilmaleimide (pretty much a polyimde)
    - Very nonlinear viscosity
    - 90 minute pot life at 125° C
- **Tested to ~98% SSL in mirror structure**
- **Made with leftover coil**
- **Utilized above information to select flow resin temperature based on viscosity. Potted coil in 15 minutes**

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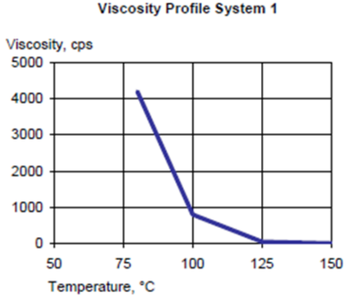

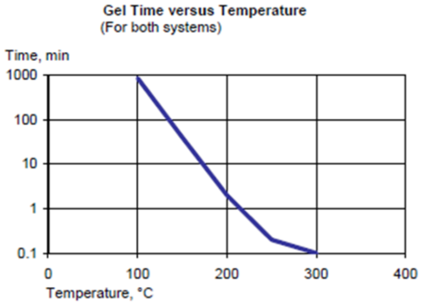

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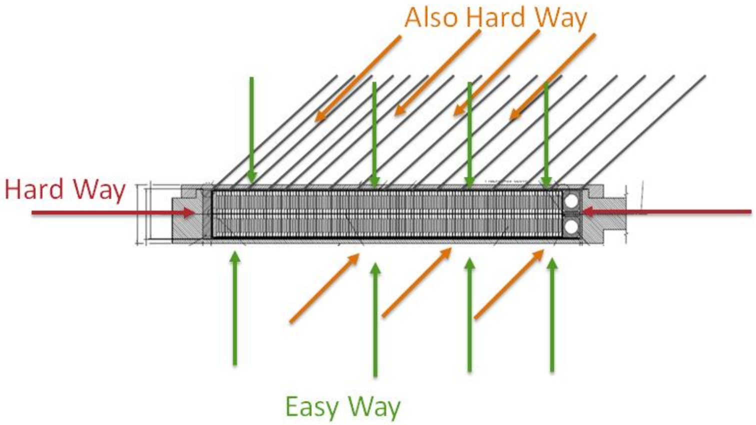
Be careful about permeability and coil pack density!

Whenever possible, try not to make things difficult.

- **Solid conductor has 0 permeability**
- **Big coils can be tricky**
- **Allow opportunity for inspection after potting**



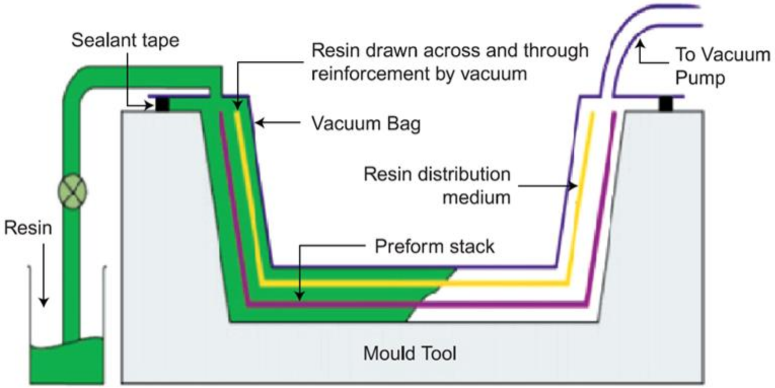
In the case of CLAS12, there were 2 sheets of **tightly packed** fiberglass on either side of the coil that all of the resin had to pass through.

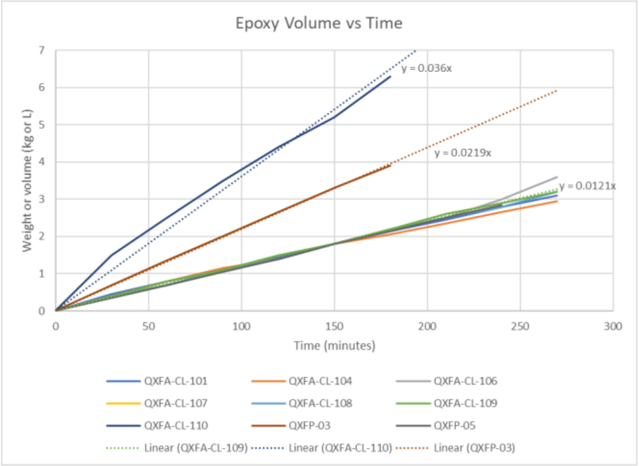
Cheating Darcy's Law

$$t = \frac{\mu * l^2 * n}{2 * \kappa * \Delta P}$$

Low viscosity resin is nice, but…

- We could work a lot faster of we change the length scale of the flow direction.
- An AUP Quadrupole is ~40mm thick and ~4000mm
- This is a factor of 10000 for the same pressure drop
- Add another factor of 10-100 for pressurized resin injection or over pressure processing
- We can add at least another factor of 3 from experience filling coils with less pump control
- All of these assumptions are for Newtonian fluid in isotropic media
- Still a factor of 3,000,000 +1/-99% wouldn't be bad…





QXF Coil Fill rates. Flow controlled by pump, inlet absolute pressure remains below ~2 bar in all cases

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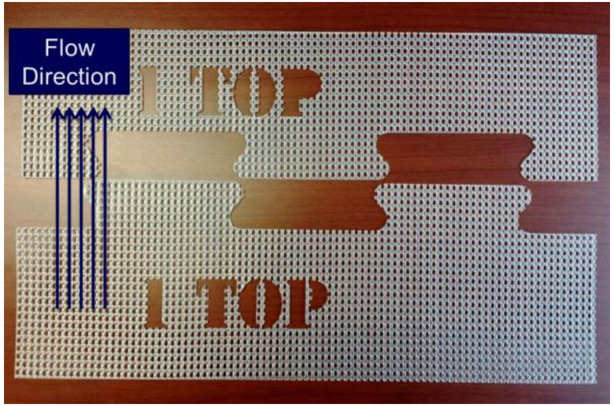
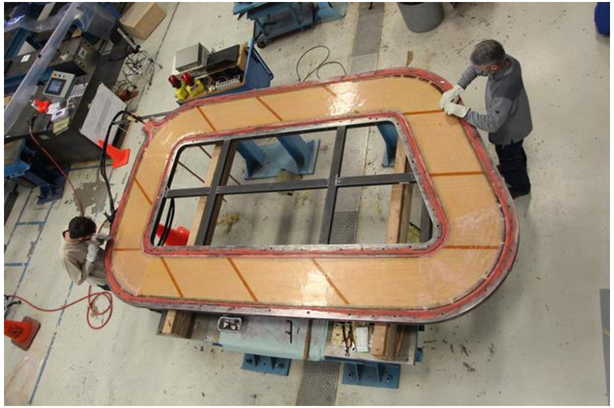
Introduction of “infusion media” to both sides of the coil

- **Solid Copper sheets on both sides of the coil were temporarily replaced with highly permeable mesh to allow resin to saturate coils from the coil faces**
- **Peel ply/ perforated FEP Release film was used to strip mesh after potting**
  - FEP and mesh came off in a matter of minutes
  - Coils ready for CMM within 8 hours of demolding





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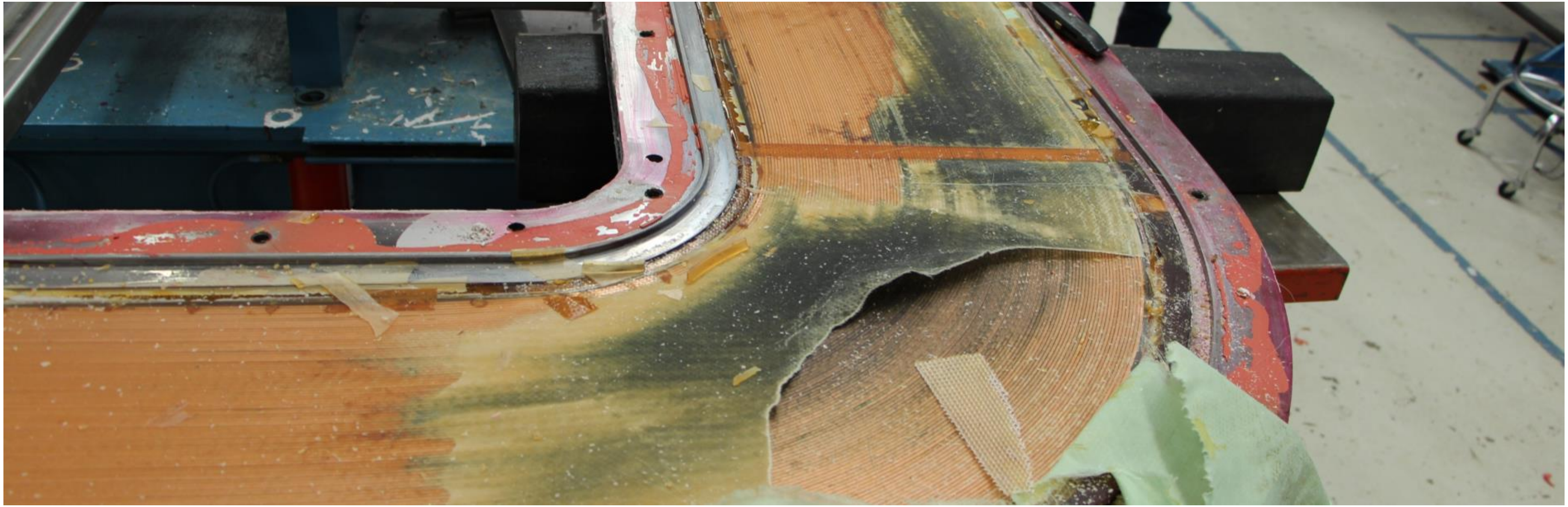
Things sometimes do not scale well from models…



Aggressive pre-impregnation outgassing cycle led to concentration of substances extracted from peel-ply at cold spots in the coil. Measured on samples of ~6% by weight.

- **Stable, well known inert things are good: Metal, Teflon/FEP, Mylar, polyethylene, polypropylene…**

Switched to lower temperature outgas as well as from green peel ply to FEP.

Nice Features: End Part Flow Channels

There is a tendency to pack as much material into a cross section as possible.

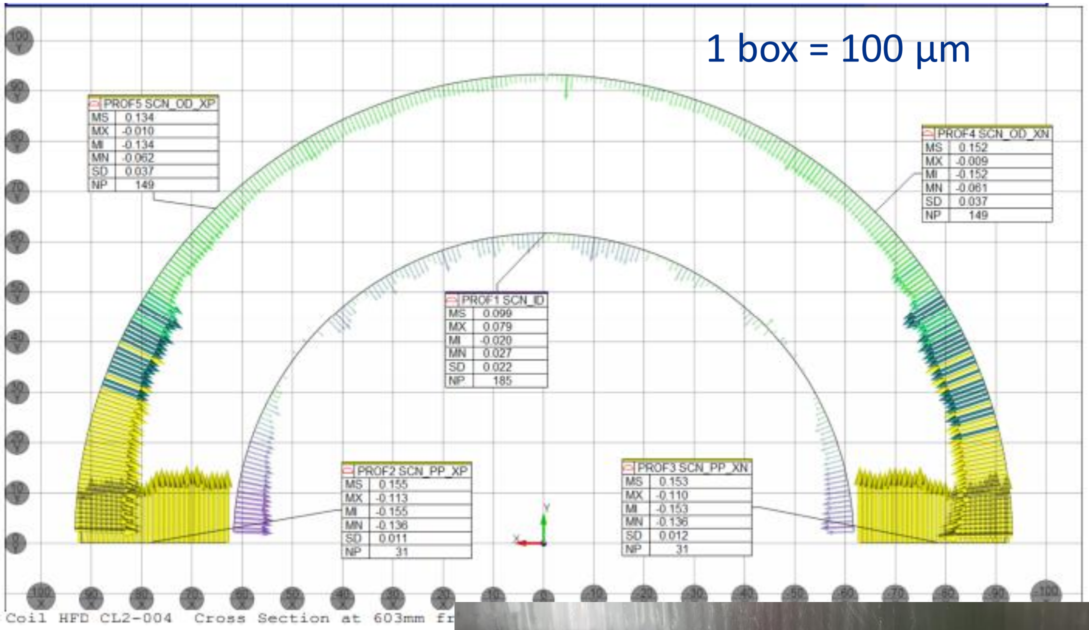
With drastically reduced flow cross section around the ends of a coil , this is a place that is likely to cause trouble

15 Tesla has implemented small slits in the coil end parts to allow resin to easily pass the solid metal end parts and reach the more permeable coil.

Rigid tooling

With Teflon film on the impregnation mandrel, the ID Surface is excellent

- **Measures undersize from nominal**
  - ~12 µm from undersize Teflon film with silicon adhesive
  - ~60 µm undersize from mandrel actual radius
- **Essentially 25 µm from where the tooling should have put it**
- **Use the fewest layers(pieces) practical for defining coil size.**
- **If using a mix of soft/flexible materials and stiffer, more rigid materials, place rigid materials against the coil when possible**
  - Metal shells are less likely to deform or ripple and lead to better final dimensions.



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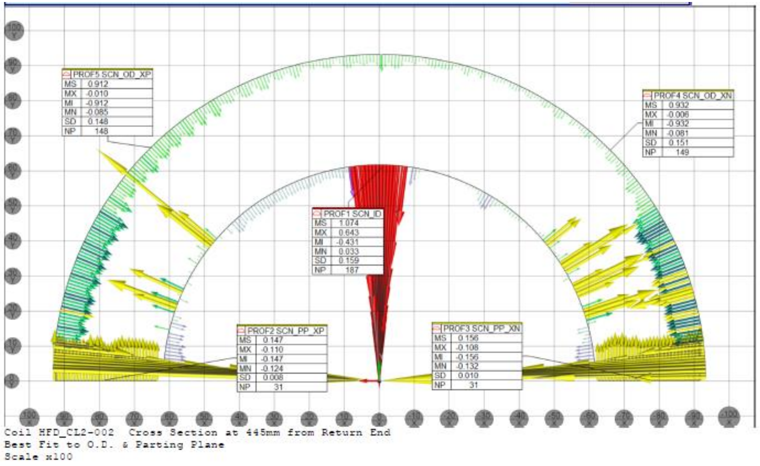
If things can move, they will

- Coils are soft (at least softer than solid stainless tooling)
- Coil cross sections often naturally have radial space as a result of block andgle
- Past coils have used thin sheets of filler material to set final coil size. This had worked well enough…
- During compression mold closure on this coil, the Kapton sheet came unstuck and rippled in the space available



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Fixing the inside ripples

- **From prior experience with LARP and CLAS12**
  - Putting rigid mold surfaces give excellent surface quality
  - Teflon/FEP gives excellent release properties and is available as an adhesive
- **We needed 5 mils of shim (to replace 5 mils of Kapton) so we used 4 mil Teflon with silicone adhesive (4.7 mil nominal)**
  - Excellent release properties
  - No bubbles
  - Could be reusable in some cases
  - Note that under high pressure it can and will flow a little bit

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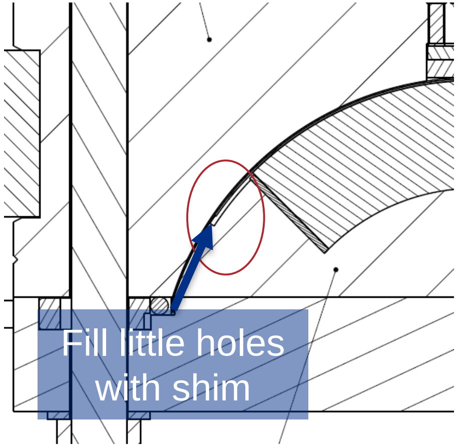
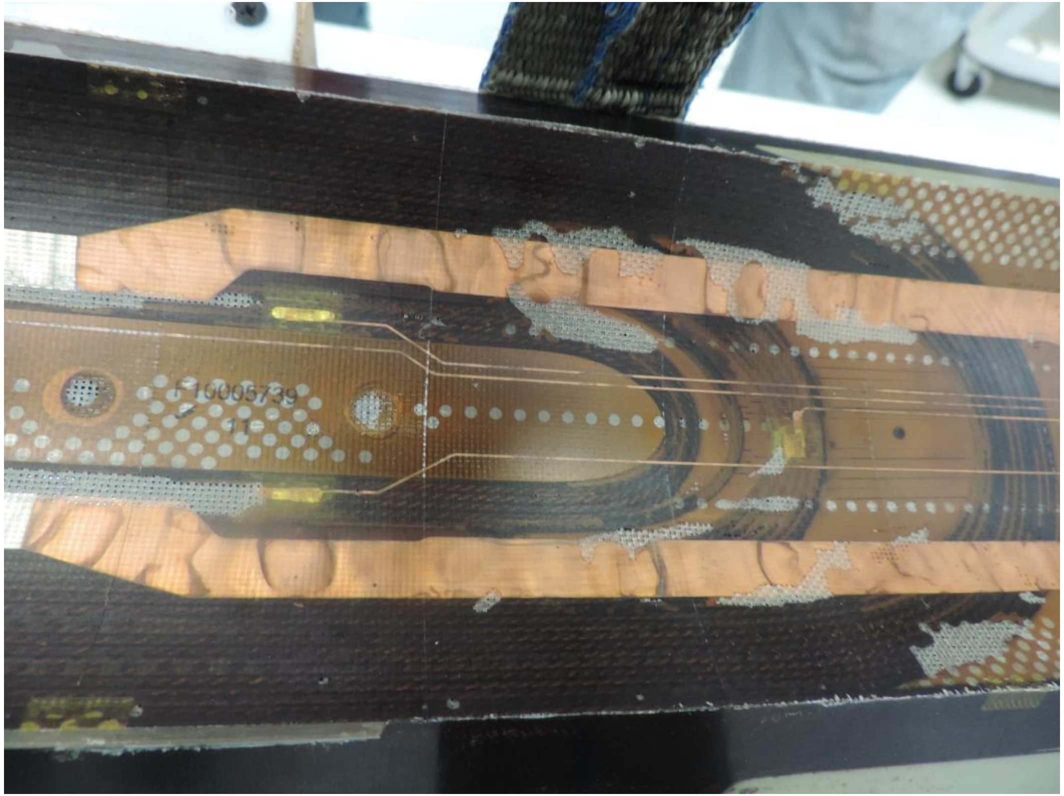
Avoid Race-Tracking

Small channels alongside tooling allowed resin to skip flowing into the coil. Upon applying 1 atmosphere of pressure, a large amount of epoxy receded into the coil. Some voids were trapped.





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Look out for Over compression

Don't stuff too much stuff into the mold cavity.

- **Compressing glass by ~10% can lead to it not wetting from substantially reduced permeability.**
- **Nominal thickness is generally larger (safer) than measured thickness**
    - This holds for reaction as well

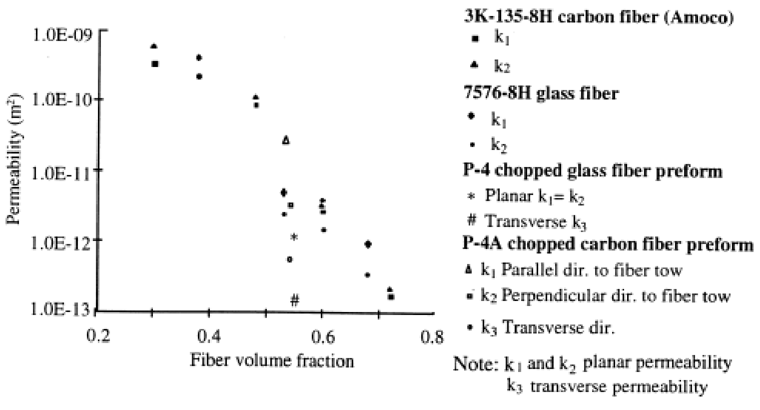


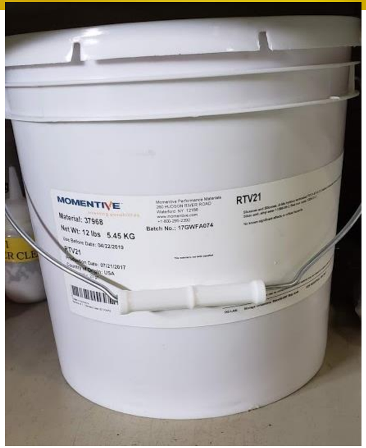
Fig. 6. Fiber preform permeability.

From K. Ken Han, *Measurements of the permeability of fiber preforms and applications*

My Favorite (Epoxy Related) Things

There are some things that we have found work well for several applications

- **Favorite RTV**
  - Momentive RTV11/RTV21 Catalyst cure RTV with STO for fast cure or DBT for slow cure
  - Momentive RTV157 –General Purpose air cure
- **Favorite fiberglass**
  - Hexcell 4522 plain weave S2 glass
    - Excellent wetting, cuts clean on laser, roughly 125µm thick
- **Mold release**
  - Zyvax Enviroshield
    - Excellent release properties and finish
    - Should be able to save time
- **Laser Cutter**
  - Cleanly cuts dry fiberglass and prevents fraying.
  - Allows detailed flexible fillers to be fabricated



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In Summary

- Coil impregnation is a generally simple process that is highly technique dependent
  - Therefore not really easy
- Processes which have worked in past designs may not work in future designs
  - Luck? Trial and Error?
  - Design decisions from experience
- There is lots of room for improvement in allowing for substantially better performing (more challenging) resins