Lawrence Livermore National Laboratory

Design and Prototyping of the ILC Positron Target System

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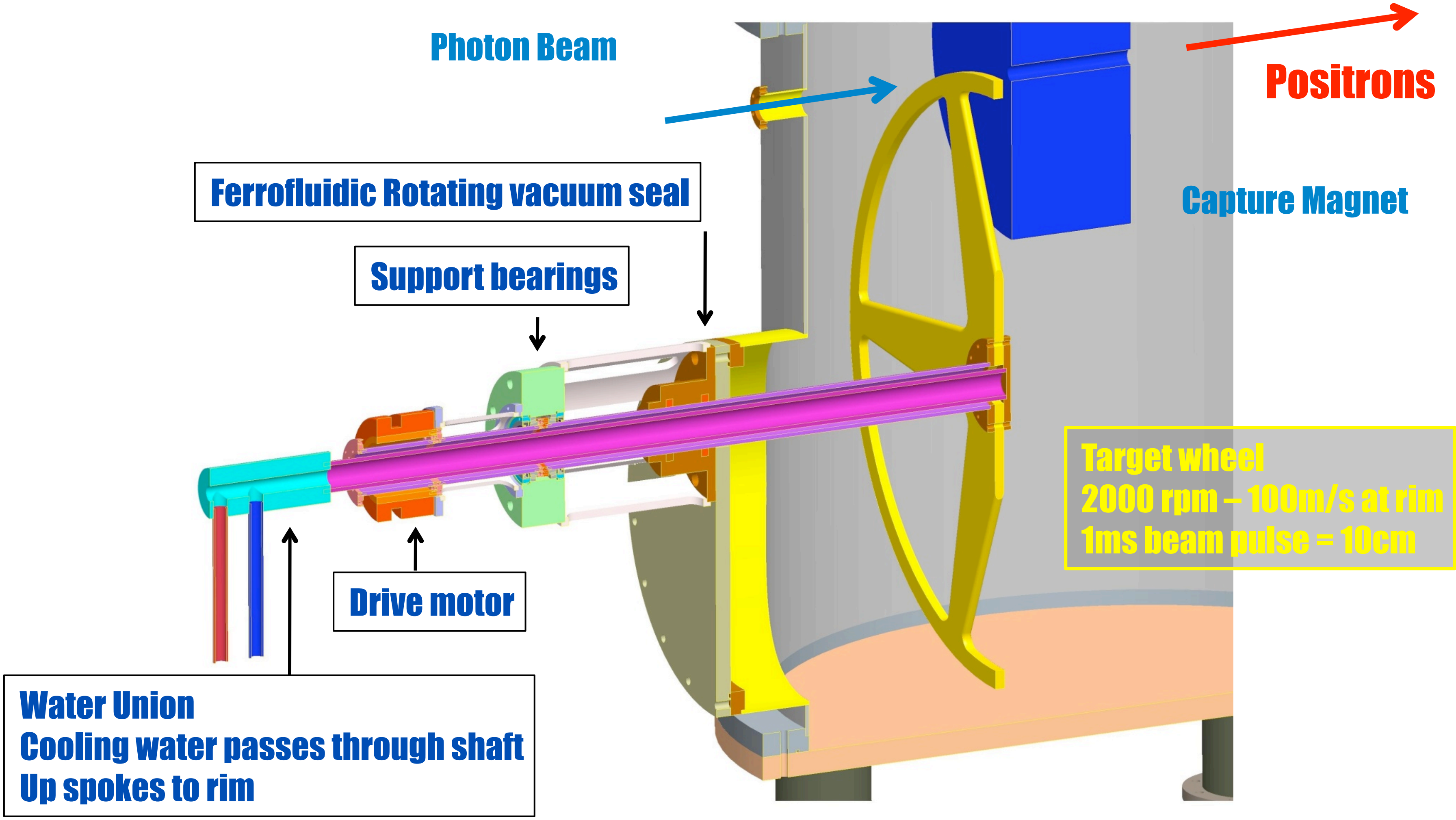
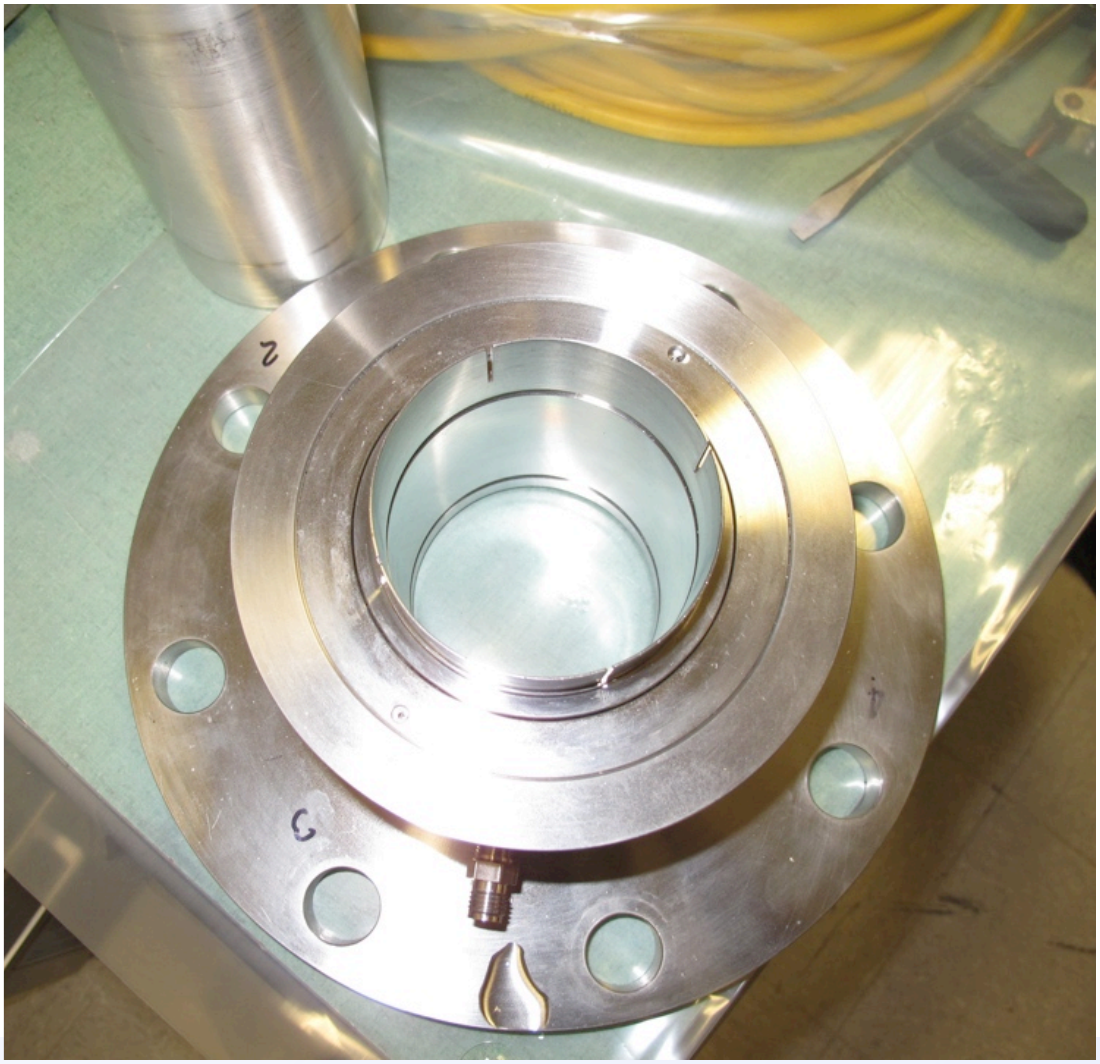
UCRL-XXXX-12345

We are doing design and prototyping of the rotating shaft seal and the capture magnet

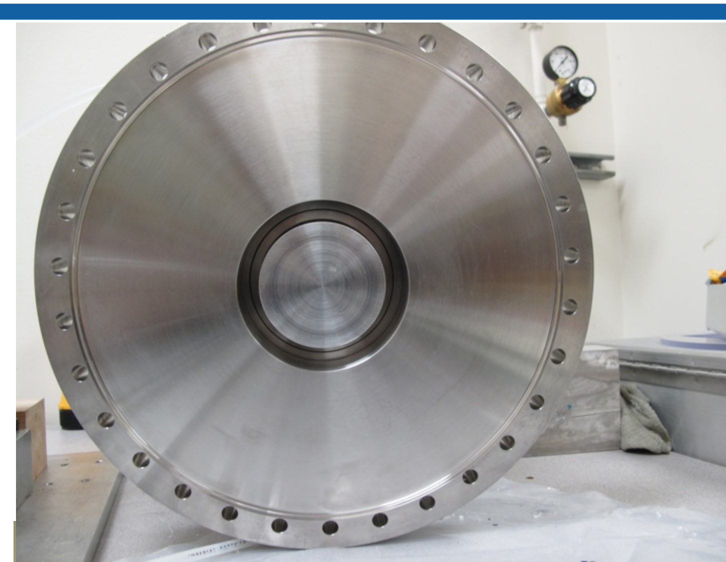


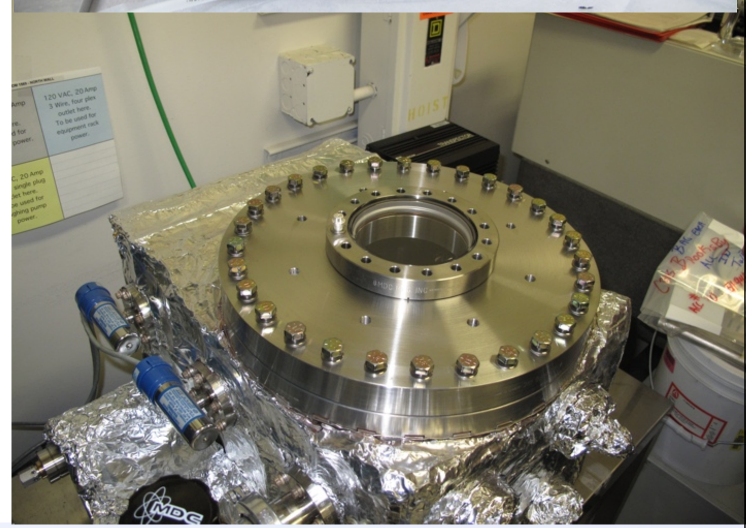
We started testing of the Rigaku Ferro-fluidic Seal for outgassing when it arrived



- A magnetic fluid is held between the inner and outer ring by permanent magnets
- There is significant torque and heat dissipation
- The ferrofluid can be expected to outgas

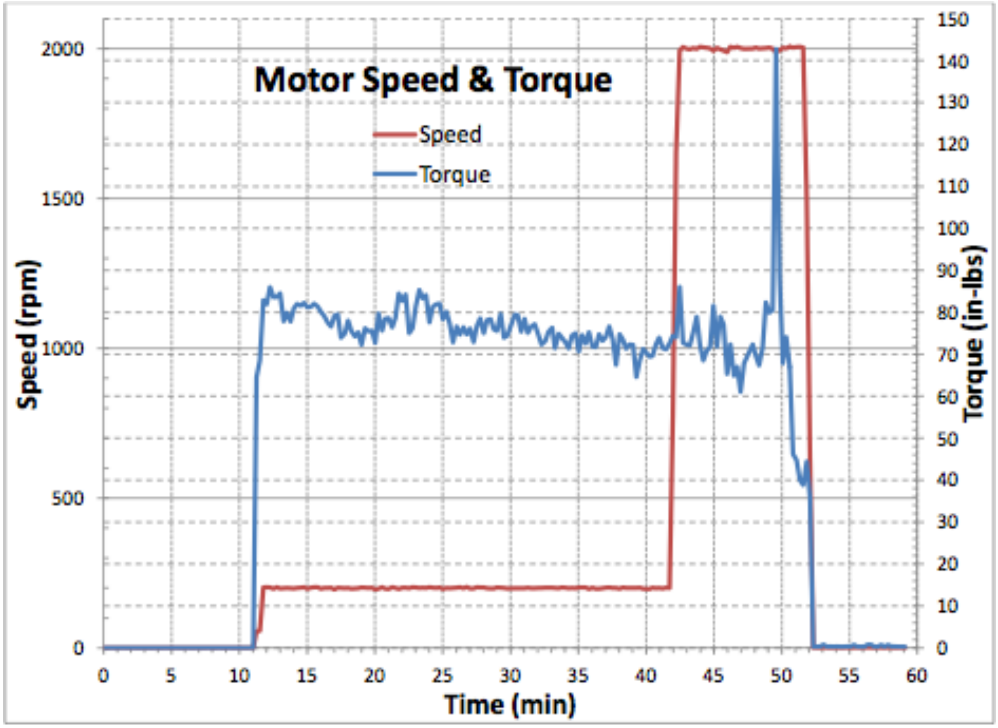
The test stand allows us to rotate the seal up to 2000 RPM with pressure and outgassing measurements





October 3rd, 2011 we did our first full test of the Rigaku seal

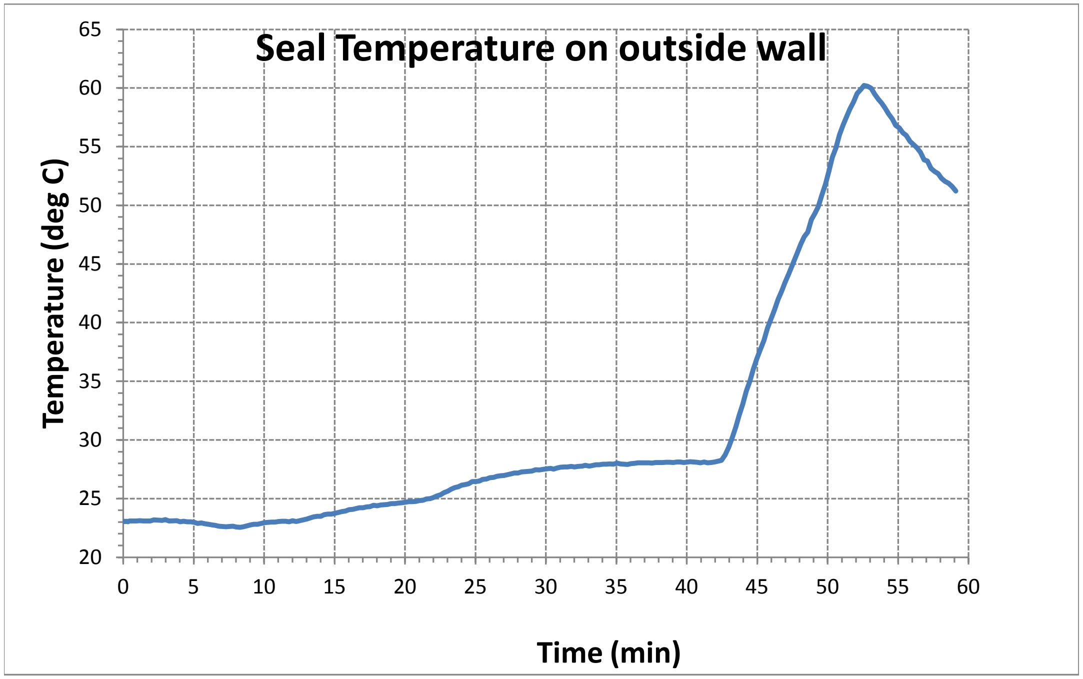
Scan #	Time	Time	Speed	
	H:M:S	min	rpm	Comments
1	10:32	0	0	started data recording
17	10:35	3	0	took full RGA Scan
20	10:36	4	0	took full RGA Scan
40	10:41	9.2	0	took full RGA Scan
43	10:42	10.2	0	took full RGA Scan
47	10:43	11.2	200	
123	11:03	30.5	200	took full RGA Scan
162	11:13	40.5	200	took full RGA Scan
168	11:14	42	2000	
191	11:20	48	2000	took full RGA Scan
197	11:22	49.6	2000	Torque ramped up & vacuum leak occurred
208	11:24	52.3	0	Stopped motor
235	11:31	59.1	0	Ended data recording



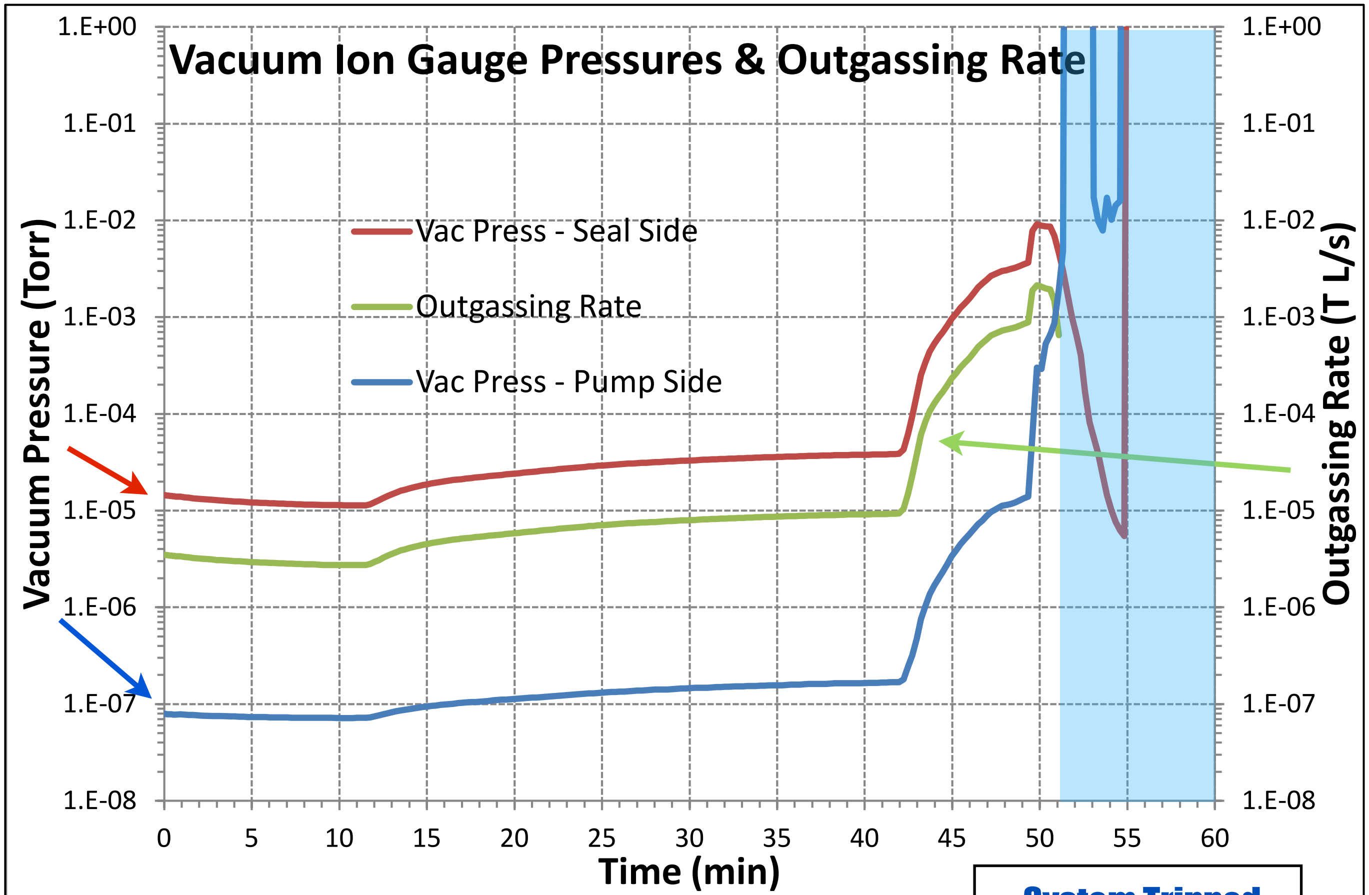
... and we killed it.

Temperature data was disturbing

- Rigaku reported running at 55 ℃ without problems
- Temperature was still rising when we turned it off



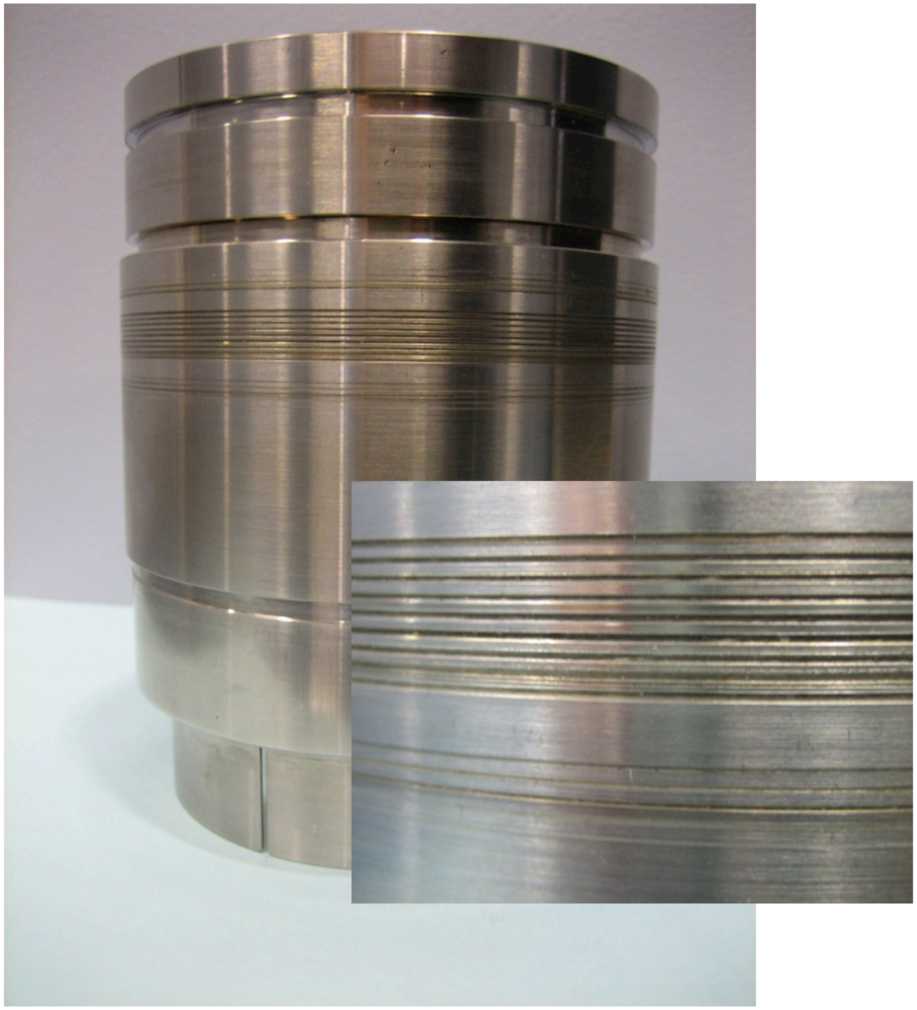
Outgassing looked like it was stabilizing when the seal failed



System Tripped

Gate Valves closed

Rigaku post-mortem shows a design flaw

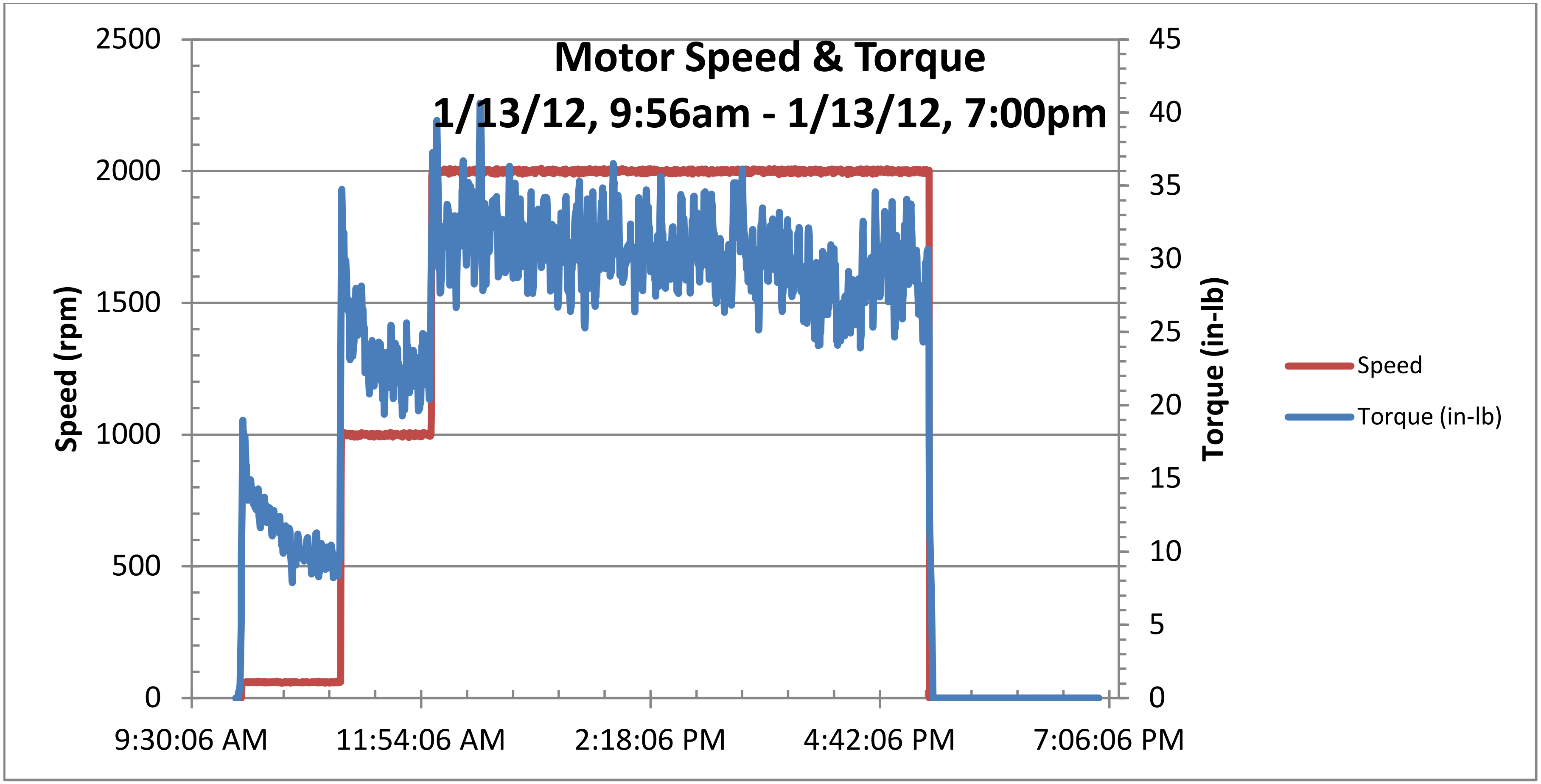


- Differential expansion between dissimilar metals caused contact between pieces at high temperature
- Grinding occurred leading to failure
- Rigaku agreed to rework the piece under warranty

While waiting for feedback from Rigaku we acquired a second plug compatible seal from FerroTec

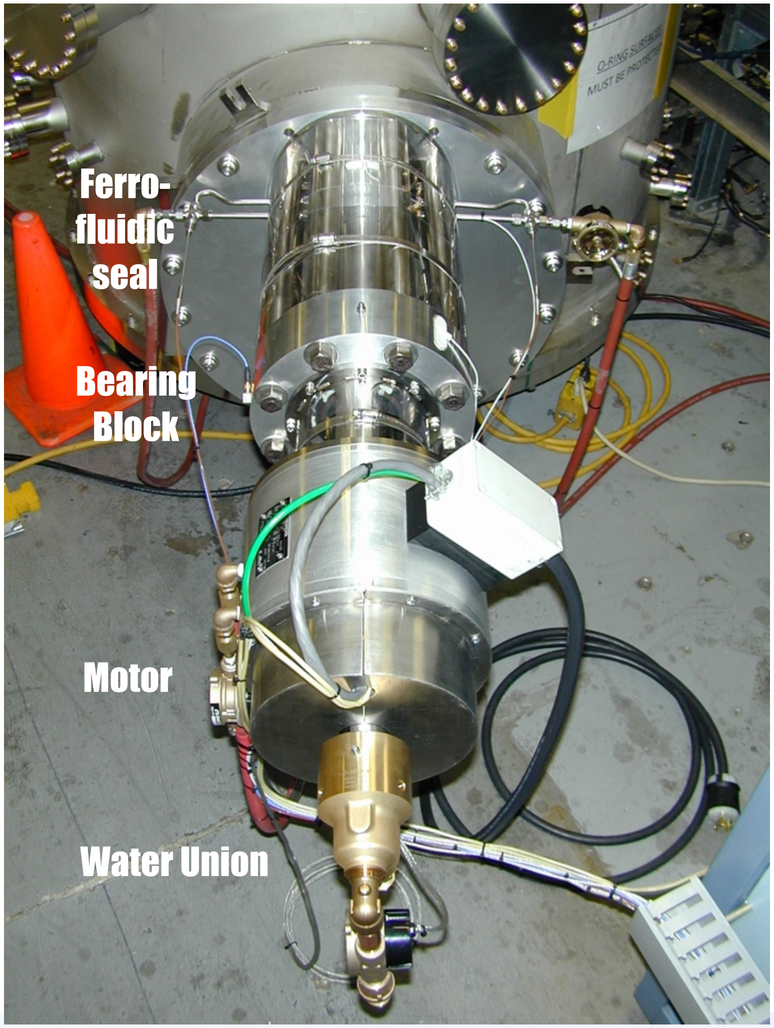
- Since it seemed that we had a heating problem with the Rigaku seal we chose a lower viscosity / higher outgassing ferrofluid.

The ferrotec seal ran without significant problems at 2000 RPM



We logged about 38 hours total running time at 2000 RPM

Operation of FerroTec seal #1 on the full test stand began in May 2012



- The DAQ records the system state every 30 seconds.
- Slow control is designed to shut down the wheel if any limits are exceeded
  - Unmanned operation is standard

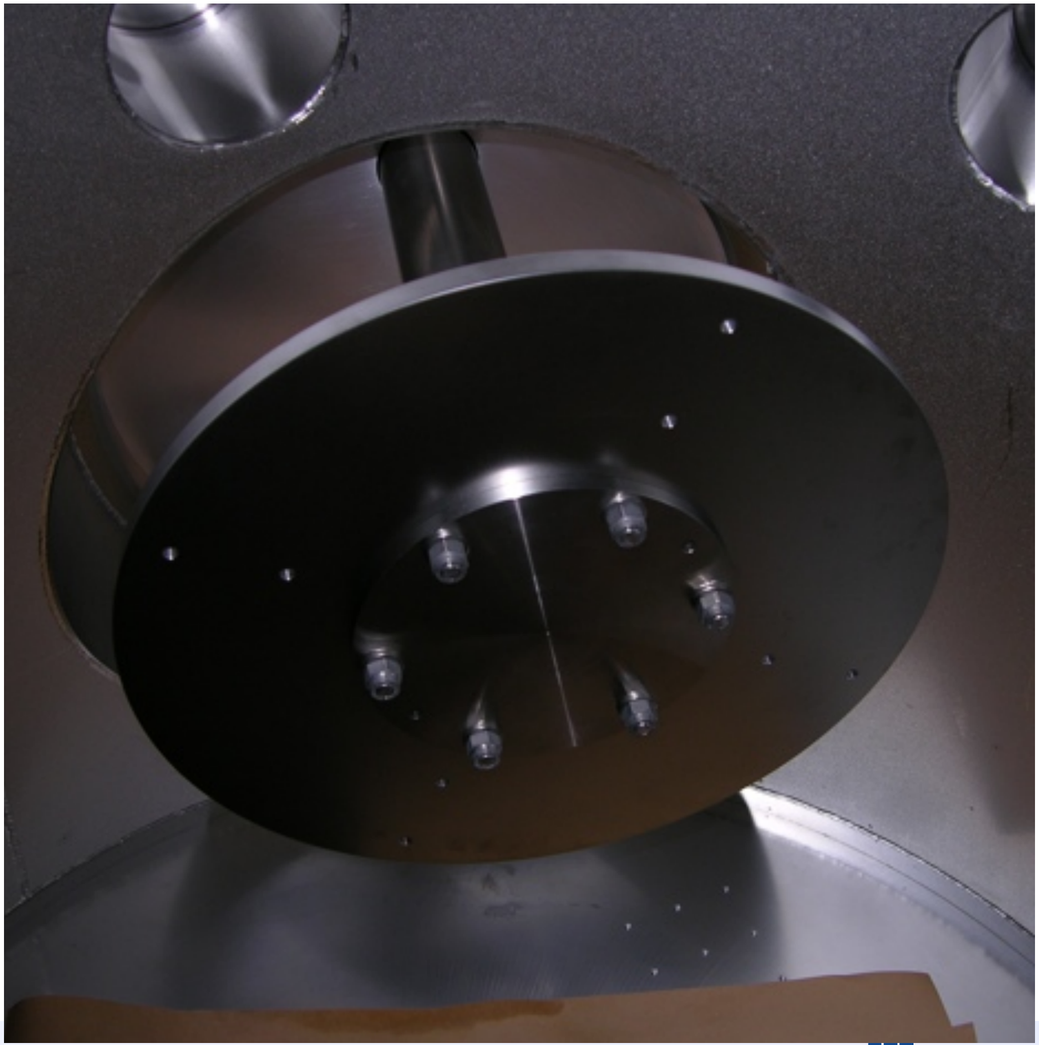
We monitor:

- Motor
  - RPM
  - Power
  - Torque
- Vibration
  - Three axis sensors on motor, bearing block, seal
- Vacuum Pressure
- Temperature
  - Ambient, Seal, Bearing Block, Motor, Cooling water inlet and outlet
- Residual Gas Analyzer currents
- Cooling water flow rate
  - Seal, Bearing Block, Motor, Shaft

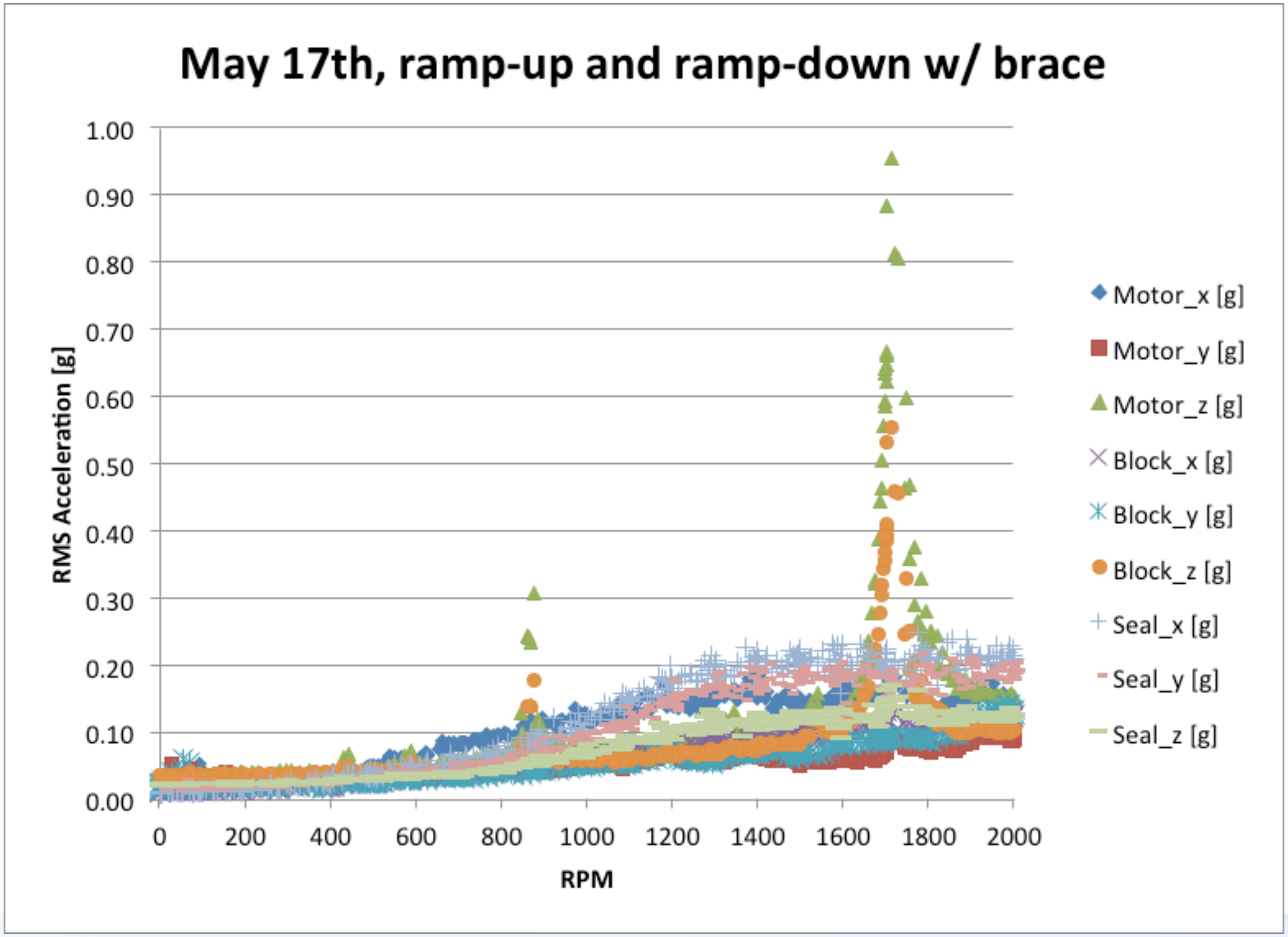
Medium disk was installed and balanced

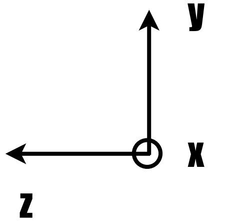
- Same weight as titanium wheel
- No shielding required for safety

- Cooling water in the shaft has an effect on the balancing
- Not quite as stable a balance point as a solid shaft would have



Balancing data from the FerroTec seal



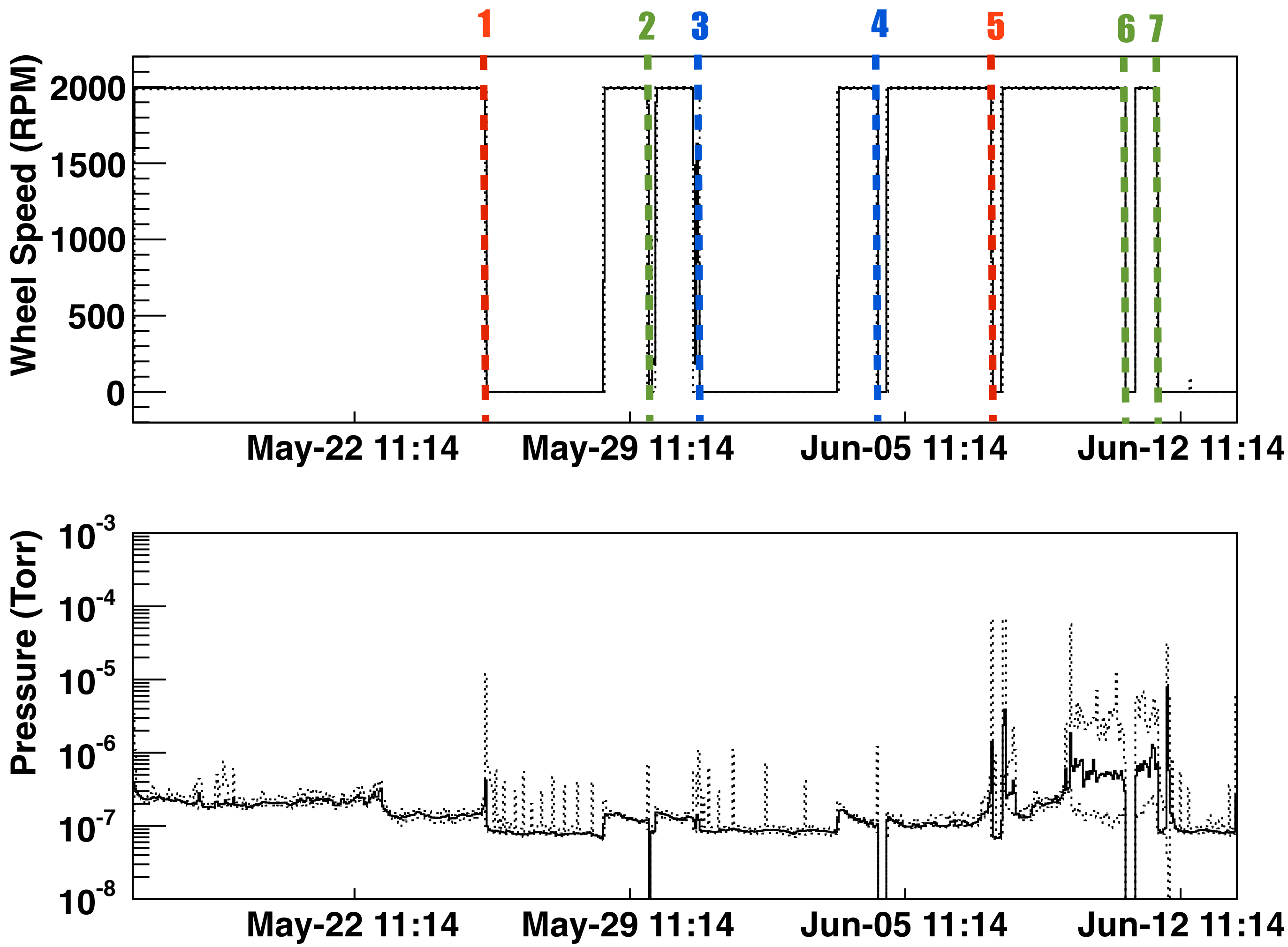


x = along shaft

y = vertical

z = horizontal

FerroTec Seal #1 ran for 1 month (450 hours up)



Pressure Trip

System Trip

Planned Down

1 - Pressure Spike

2 - DAQ software change

3 - Cooling water flow

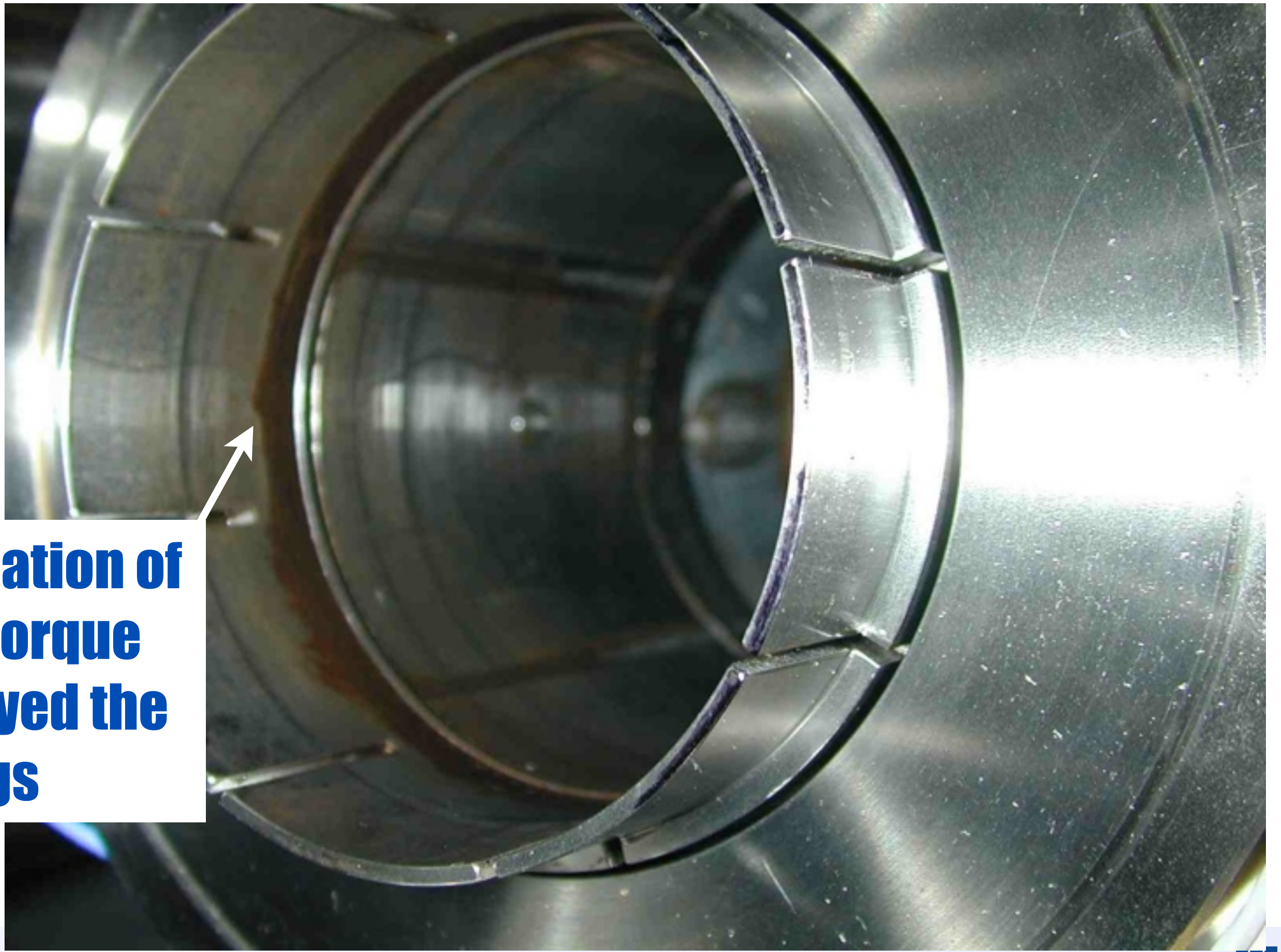
4 - Vibration Limit

5 - Pressure Spike

6 - Wheel stopped for pressure test

7 - System down for rework

We dismounted the shaft to look for failure of the O-rings that sit inside seal

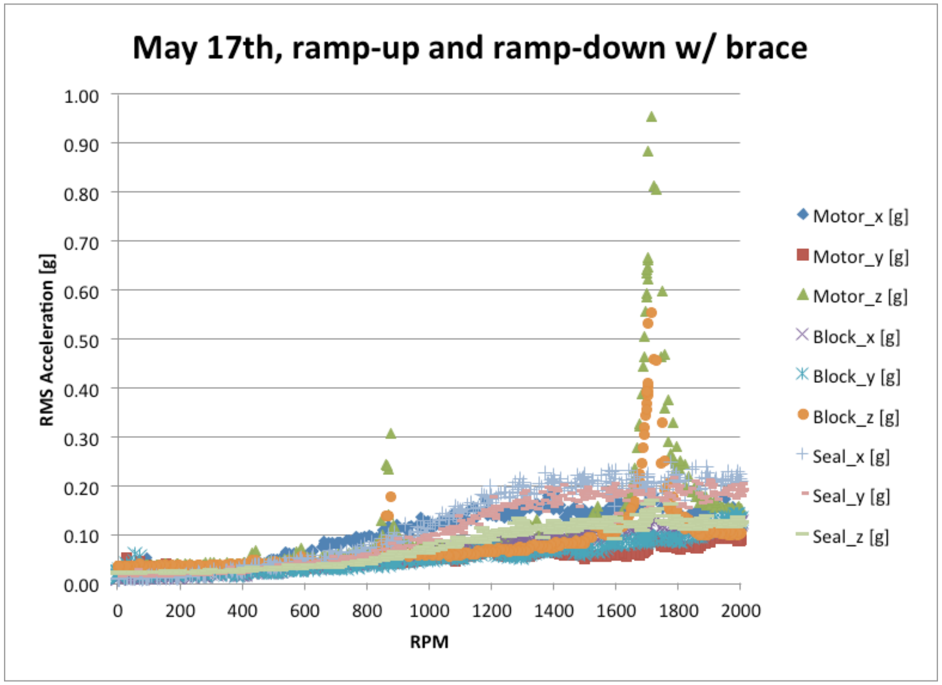


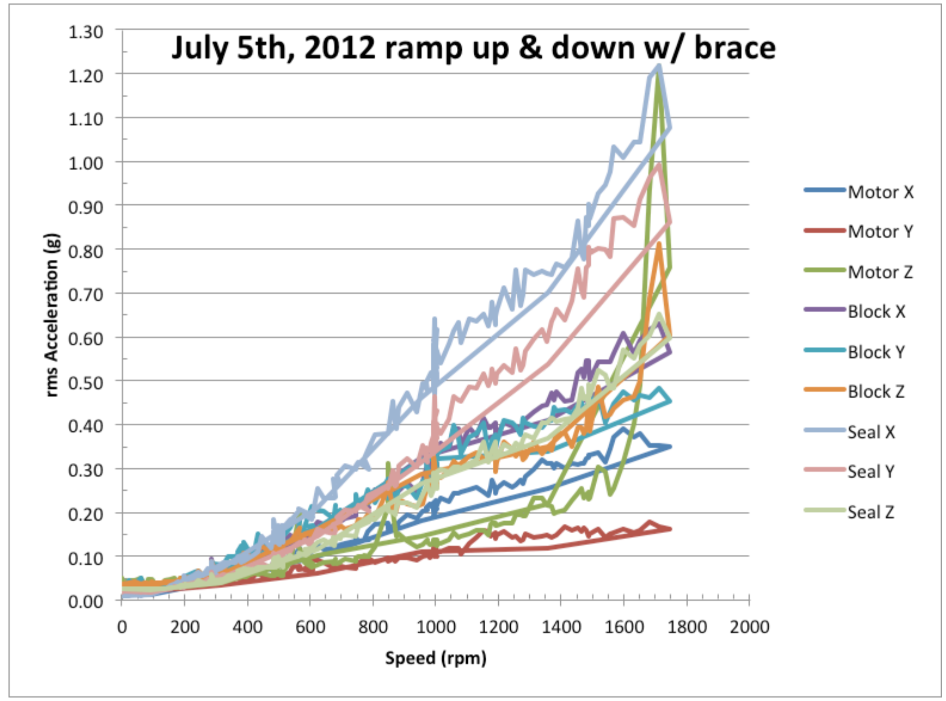
The combination of heat and torque had destroyed the O-rings

The ferrofluid seal didn't fail

- The collar which is supposed to clamp the seal to the shaft had been left off
- The O-rings became the components that transferred torque from the shaft to the seal
- Eventually the O-rings were destroyed

The vibrational characteristics of the seal changed dramatically after the rework

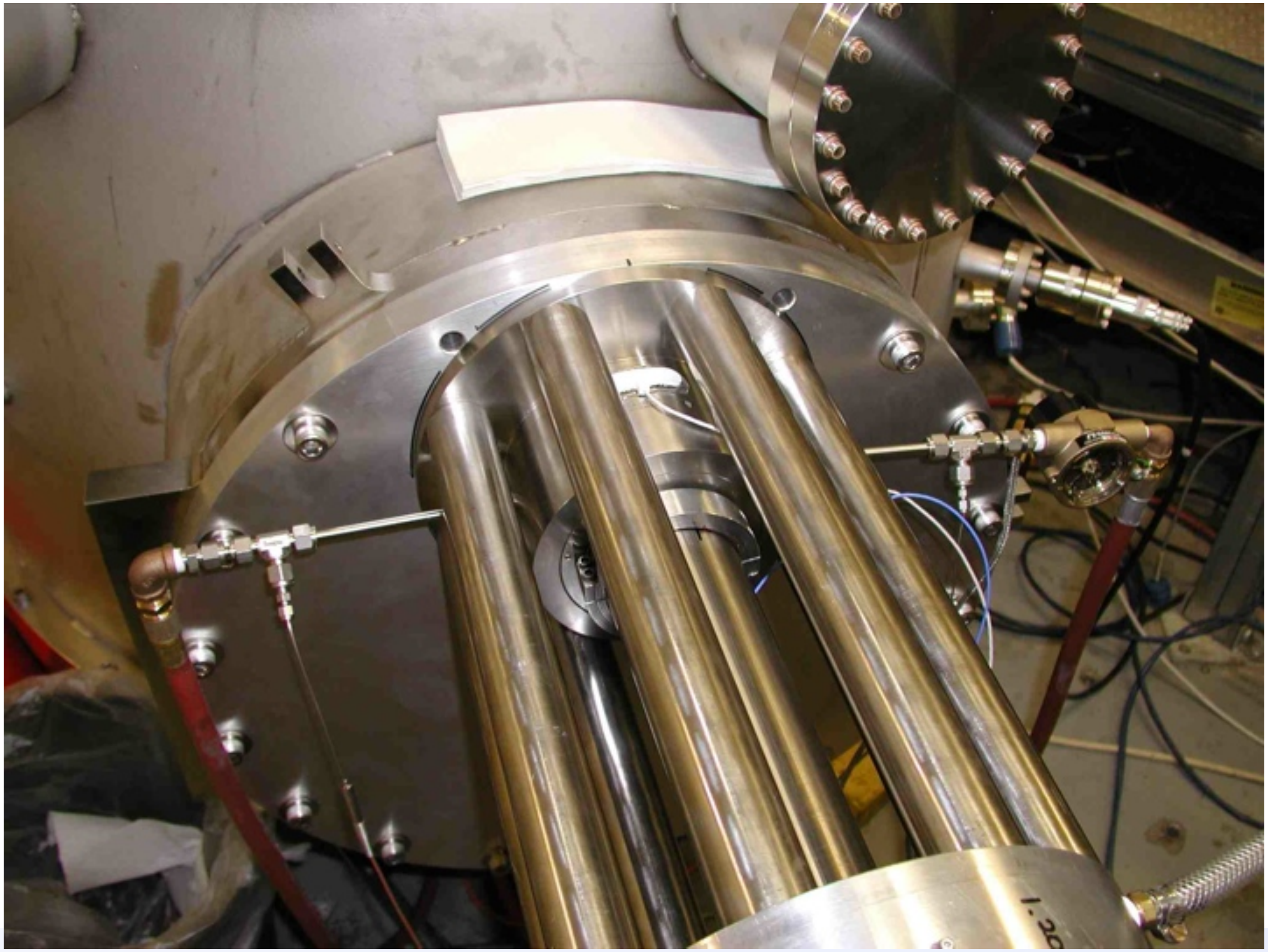




Vacuum was still good but system vibration became unacceptable

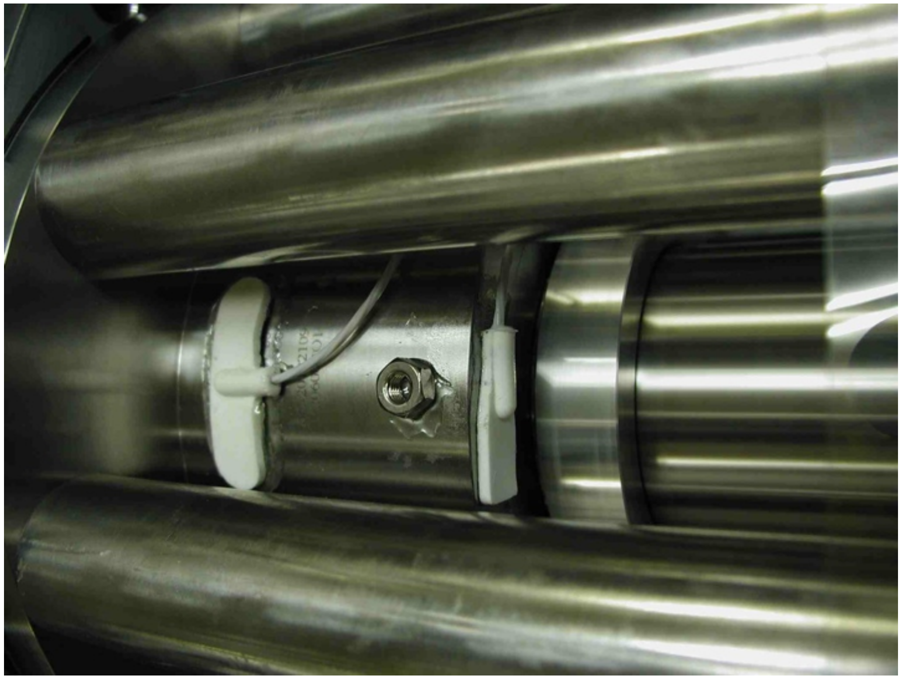
After investigating other possible sources of vibration we concluded that the force of extracting the shaft had damaged the seal bearings

The FerroTec seal #1 was dismounted and the refurbished Rigaku seal was installed



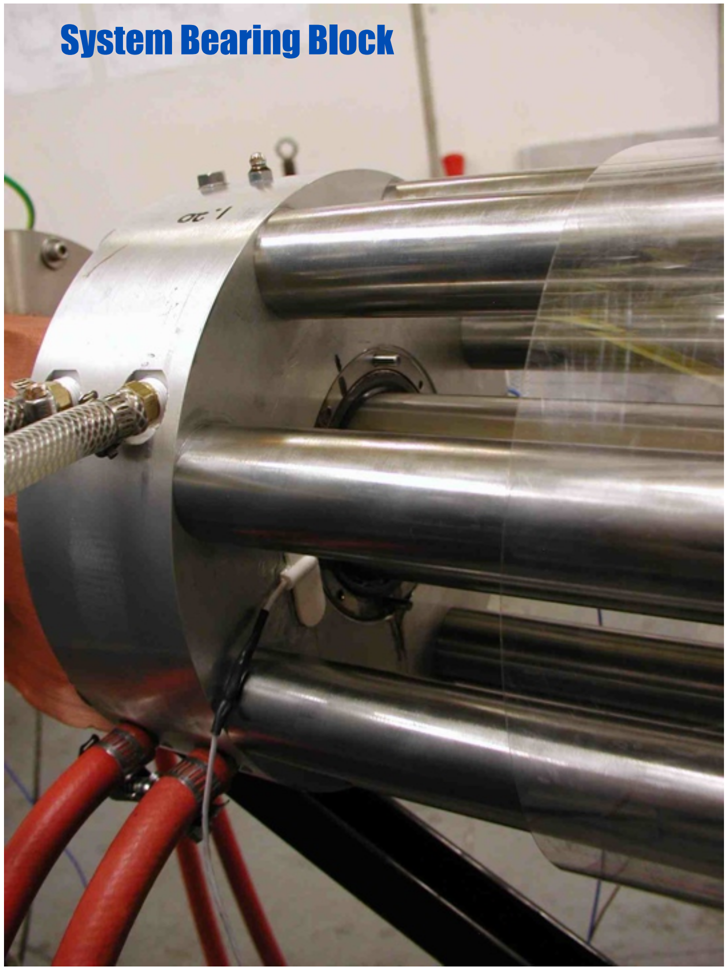
The Rigaku seal was not able to be run successfully at 2000 RPM

- Seemed OK when run unloaded on the vertical test stand
- Under load there was a large acoustic noise from the bearings
- Repeated pressure spikes
- High Temperatures on the case at 1000 RPM
  - 31 C on case
  - 46 C on the end



Rigaku seal was dismounted, FerroTec seal #3 was installed

- Installation completed August 30th
- Ran at 500 RPM over the weekend with no seal problems but developed a water leak in the central shaft at the bearing block
- Once the leak is fixed we will balance and run at 2000 RPM
- We will allow the system to run until it develops a problem



Lessons Learned

- Ferrofluidic seals are not boring, each one has its own individual personality
  - We would prefer them to be anonymously interchangeable and predictable
- They all have outgassing spikes
  - A differential pumping region just after the seal would be a useful modification
- We are pushing them to speeds at which there is significant heat dissipation
  - Off-the-shelf models do not seem to be well designed for this.
  - Improved cooling design is a must for any future system

History and Status of our Available Seals

- Rigaku #1
  - Catastrophic failure after 15 minutes at 2000RPM on the outgassing test stand
  - Rigaku analysis indicates differential expansion of components lead to failure
- Rigaku #1 reworked
  - Switched fluid for low viscosity type
  - Unacceptable behaviors seen on the test stand
- Ferrotec #1
  - Low viscosity fluid
  - Normal operation for 38 hours at 2000 RPM on the outgassing test stand
  - Higher outgassing than Ferrotec expected
  - Ran normally on the test stand until O-ring failure, damaged during rework
- Ferrotec #2
  - Ran rough on the outgassing test stand, better outgassing than Ferrotec #1.
  - Returned to Ferrotec for analysis
- Ferrotec #3
  - Currently mounted on the test stand
  - Good vacuum
  - Vibration spikes

Future Work

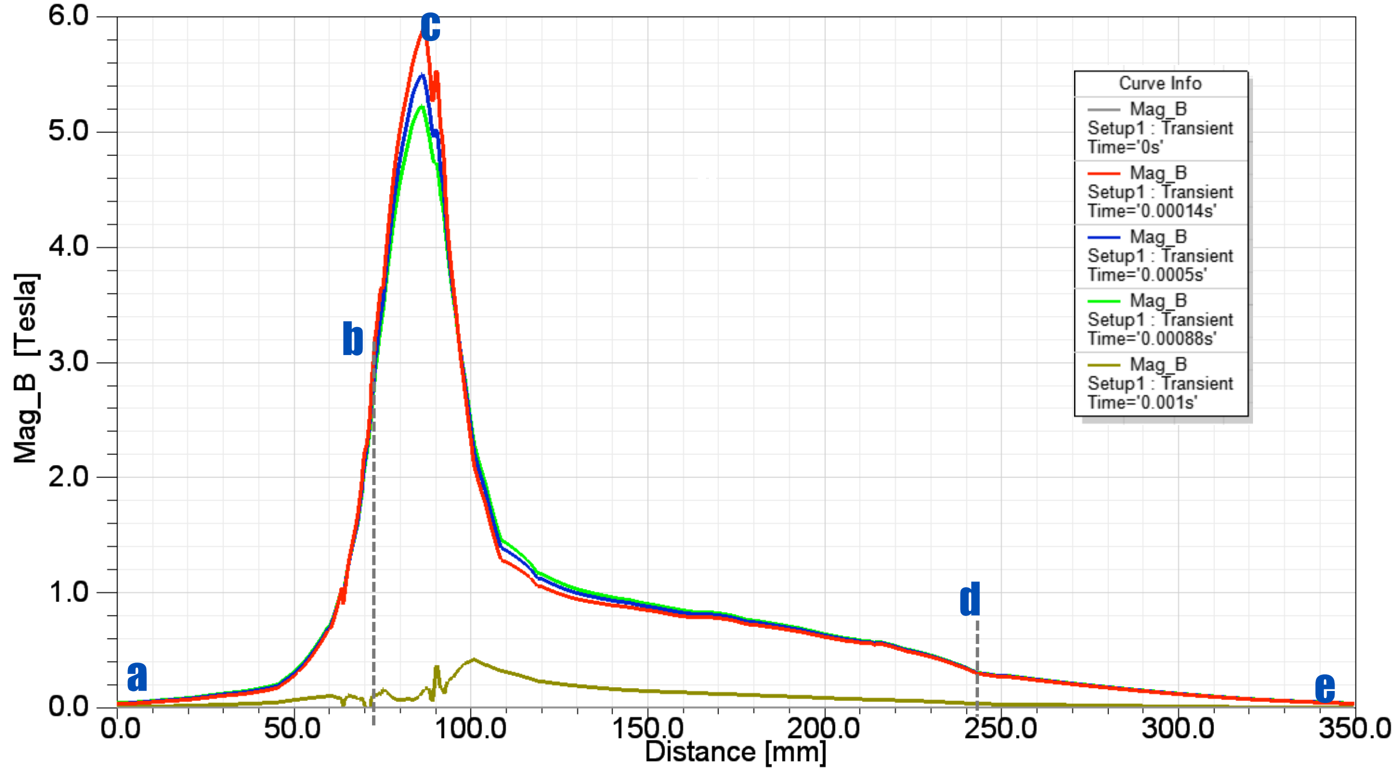
- As long as the current seal is working properly it will be allowed to run and collect data if we can understand the vibration spikes

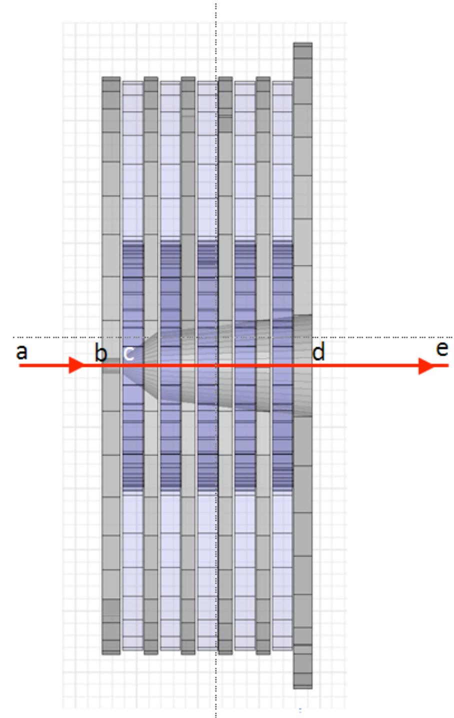
- Any future development of the Ferrofluidic seal concept will need to be in partnership with manufacturers to create a device optimized for our needs.
  - Improve cooling channel routing in the stationary section to dissipate heat from the ferrofluid and the bearings
  - Replace the inner rotating section with one designed to be the outer sleeve of the shaft.
    - This will eliminate the O-rings
    - This will improve contact with the shaft cooling water for additional cooling

A pulsed flux concentrating magnet is a challenge for the ILC beam structure

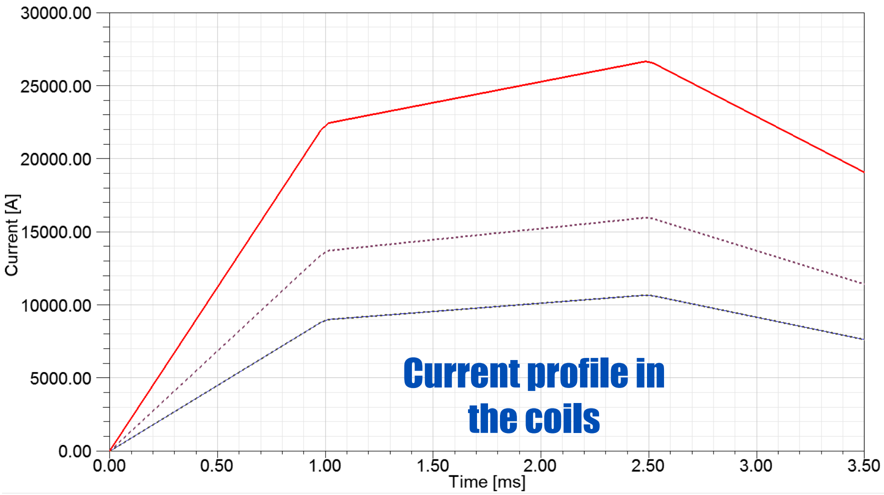
- Pulsed flux concentrators are a known technology that work well for short pulses
- We want a constant magnetic field profile over the 1 ms beam pulse
  - Induced currents in the concentrating plates will decay as stored energy is converted into ohmic heating

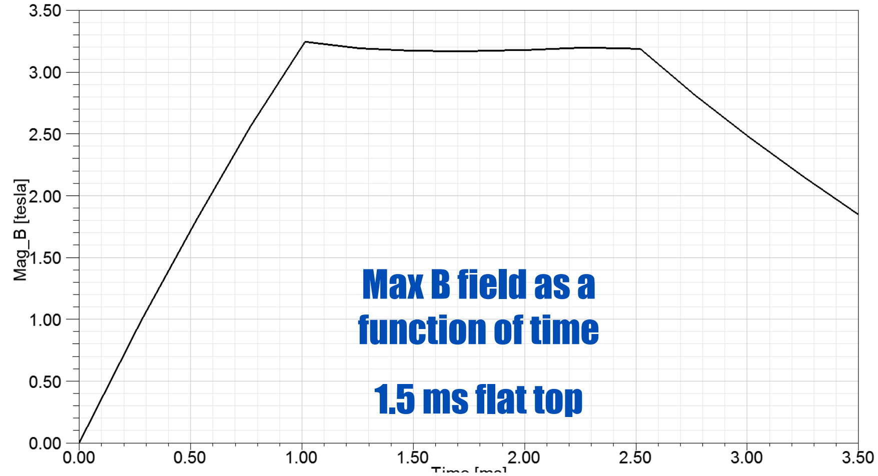
Pulsed Flux Concentrator to increase capture efficiency and reduce magnetic field at the target





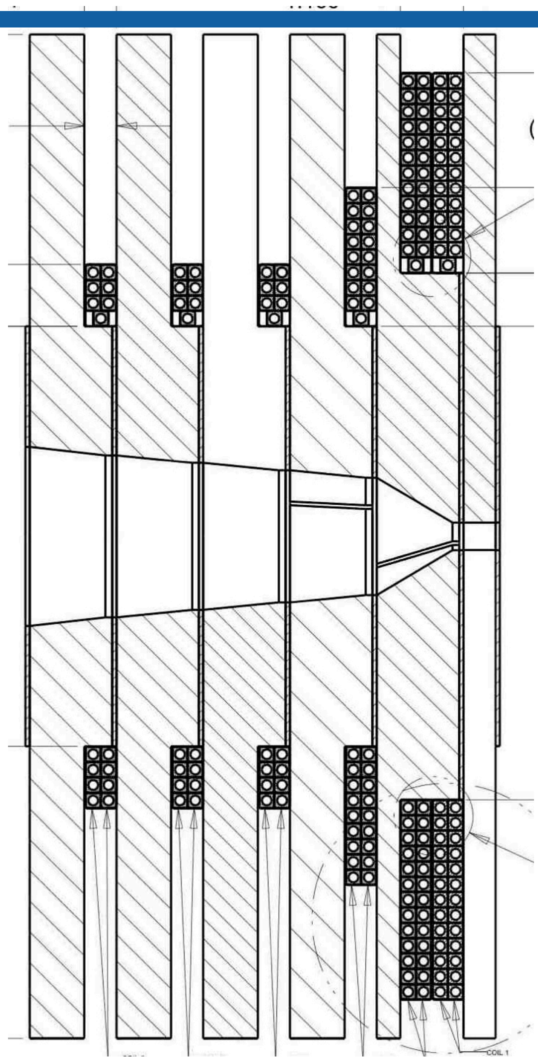
A 20% current ramp over 1.5 ms leads to a constant magnetic field during that period





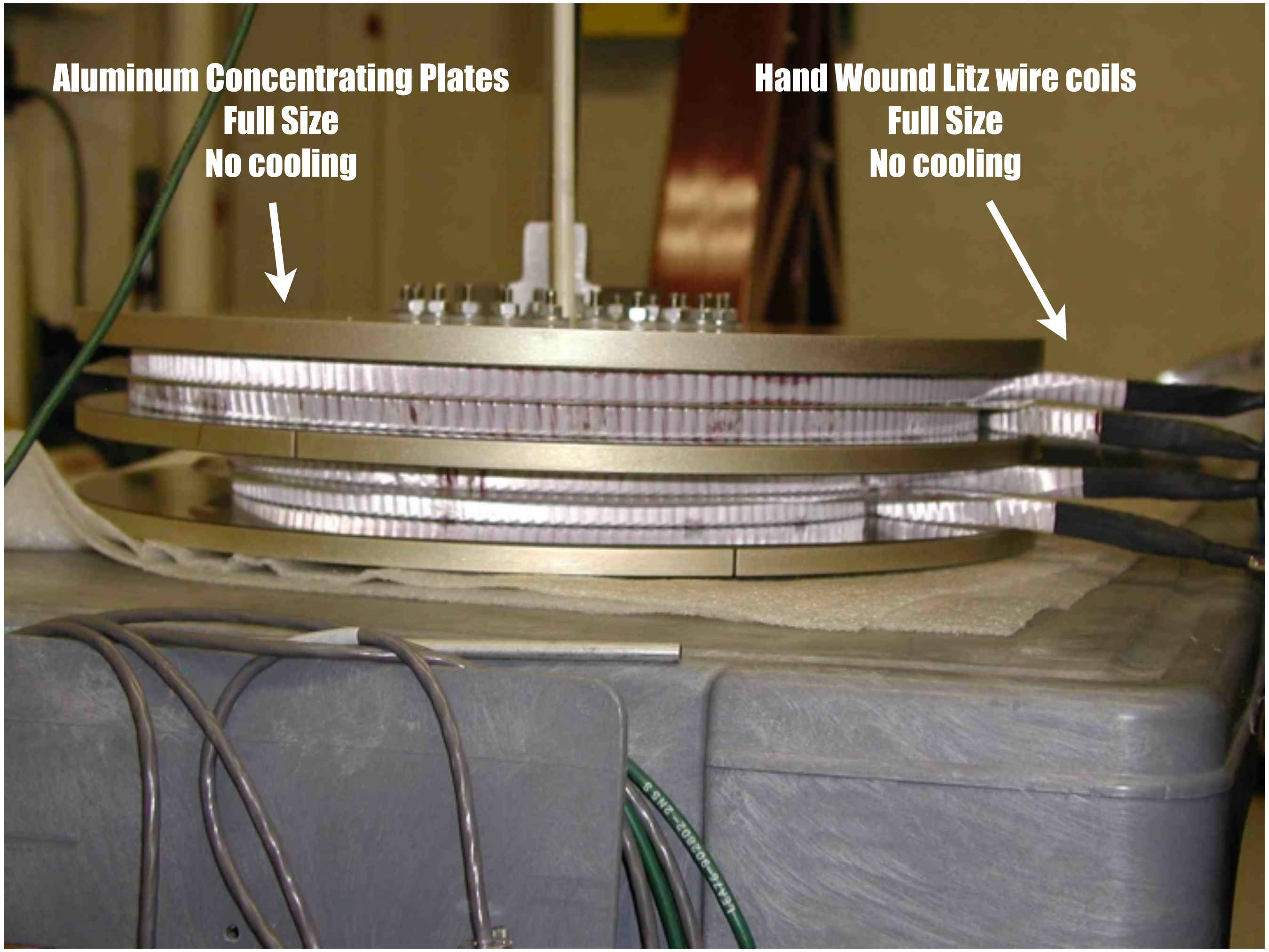
- A current ramp from the pulse forming network can counteract the magnetic field droop - even at room temperature

Water cooling and room temperature greatly simplifies the design



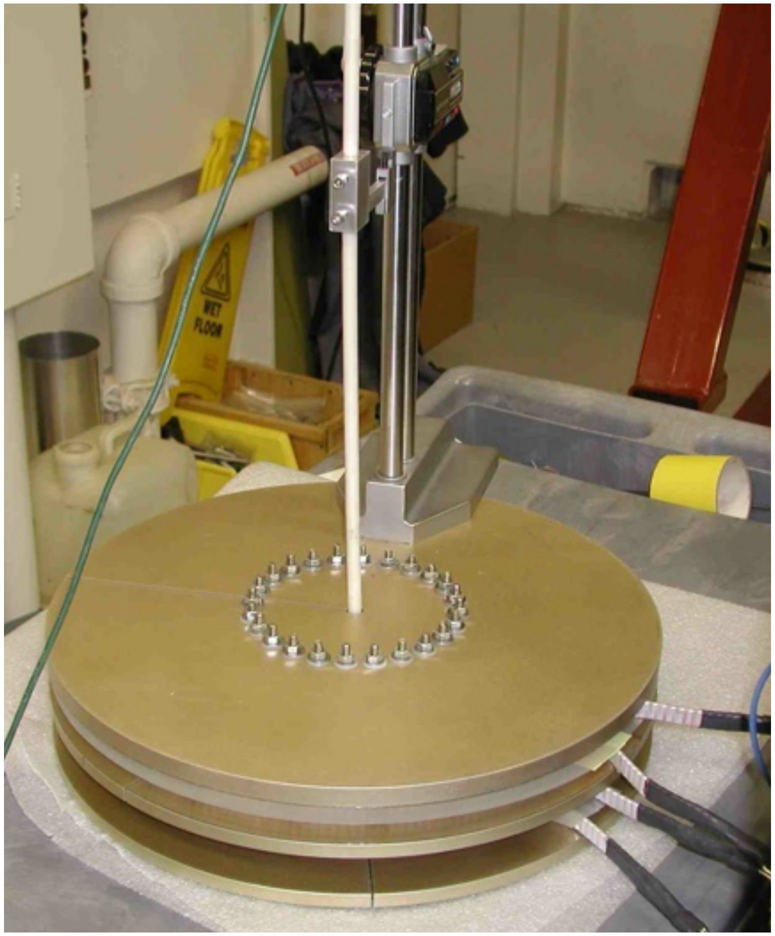
- Device sits in the vacuum
- All power and cooling connections move to the rim
  - Coils are kapton wound, hollow copper, water cooled
  - Plates are OFHC copper with water cooling pipes soldered in
  - Only metal in the high radiation areas
- Plates and coils stack and bolt together

We built a test stack of 3 Aluminum concentrating plates and 2 Litz-wire coils

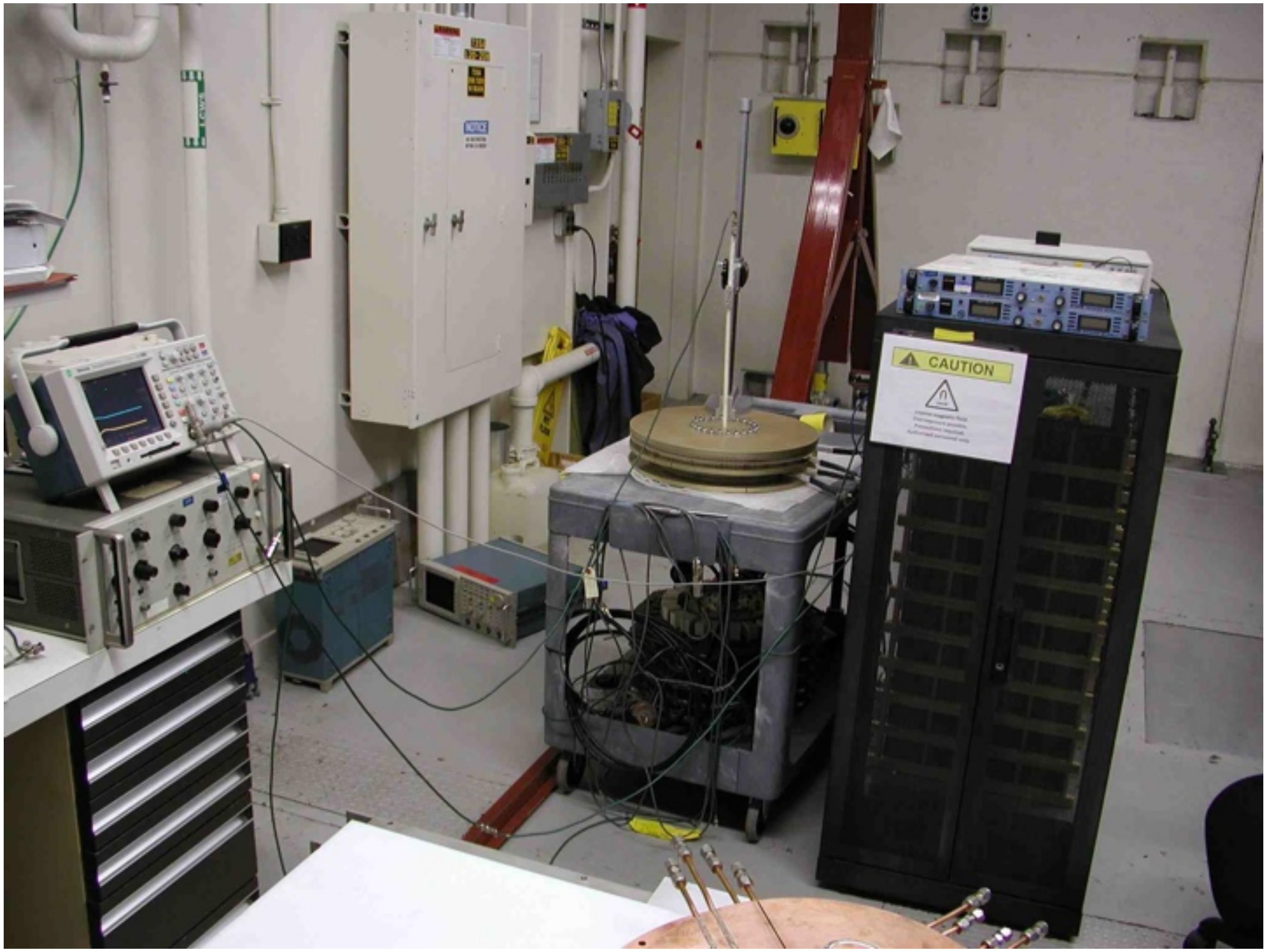


We use a wire loop to measure the time-dependent magnetic field in the bore

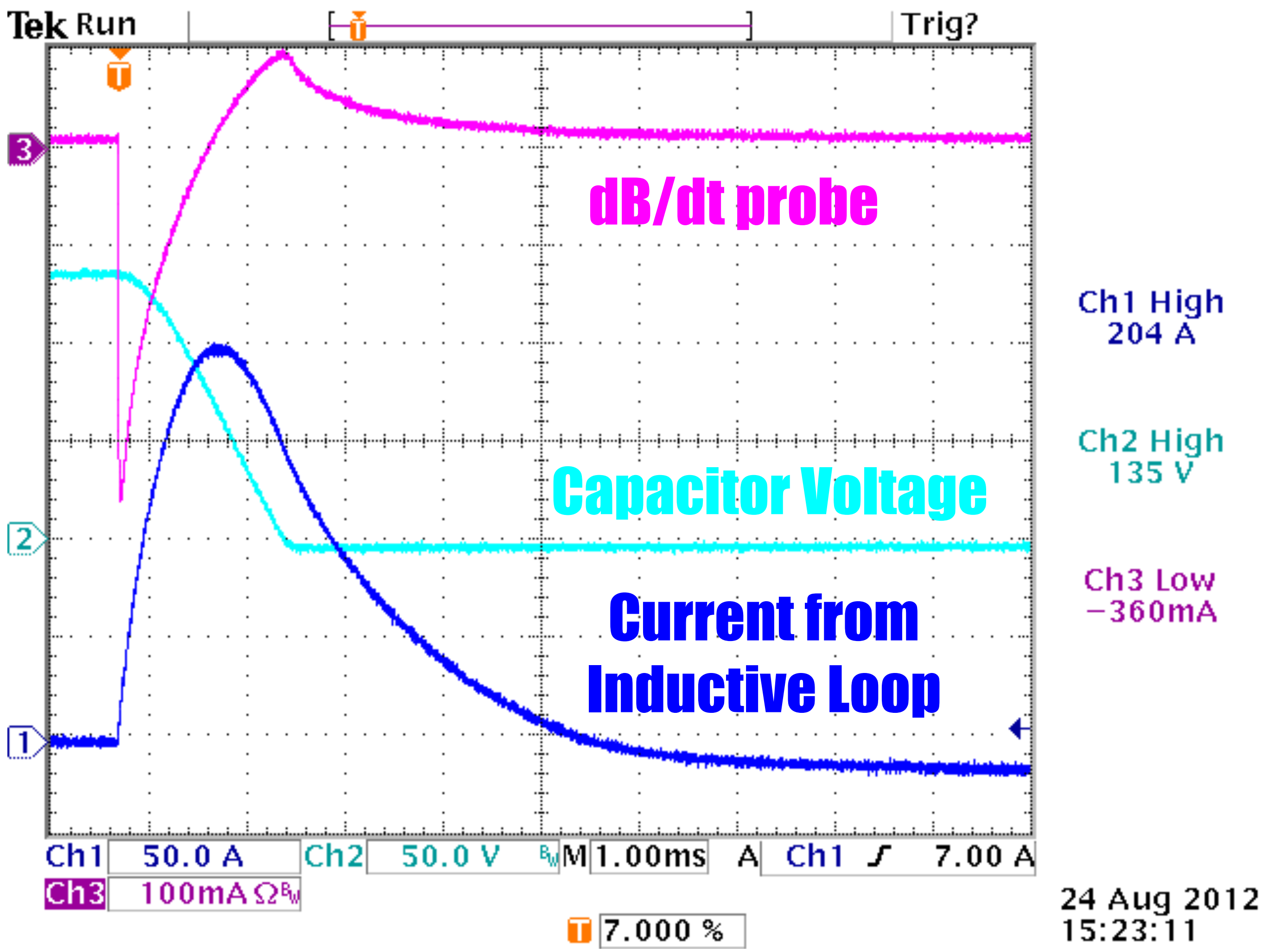
- Wire loop:
  - 5 turns
  - 3/8” diameter = 7.12×10^{-5} m^2
  - B(T) = 2809 x Volt-seconds



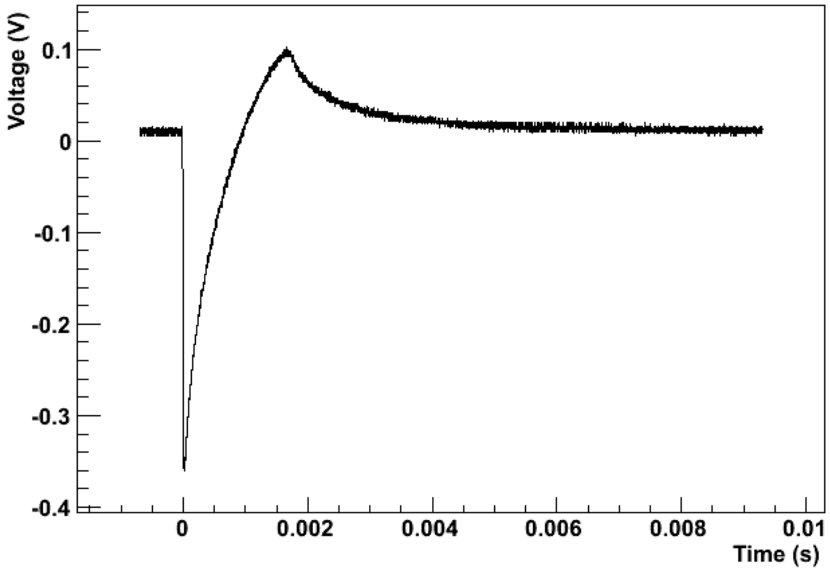
Capacitor stack configured for a single pulse

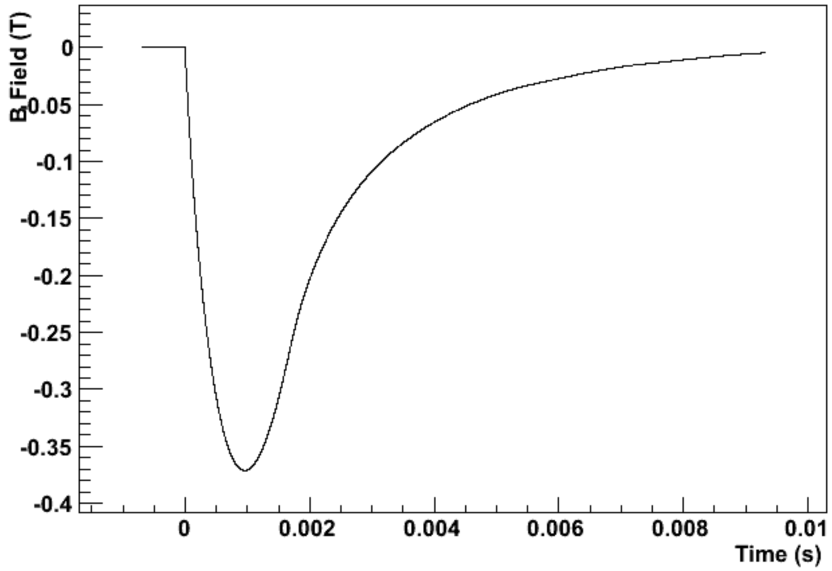


Example measurements from 200A peak pulse

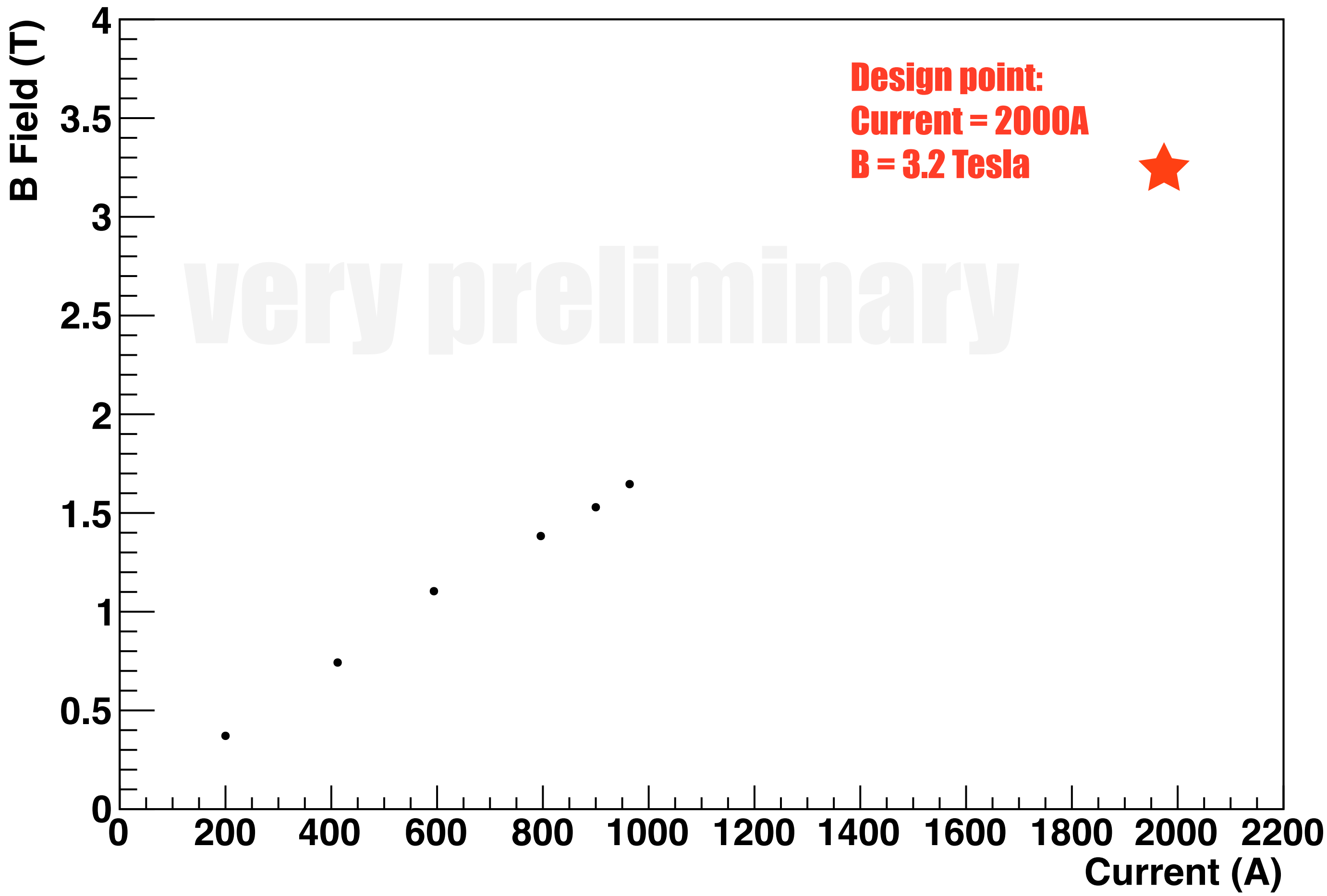


The voltage of the dB/dt probe is integrated over time to measure the time dependent B Field

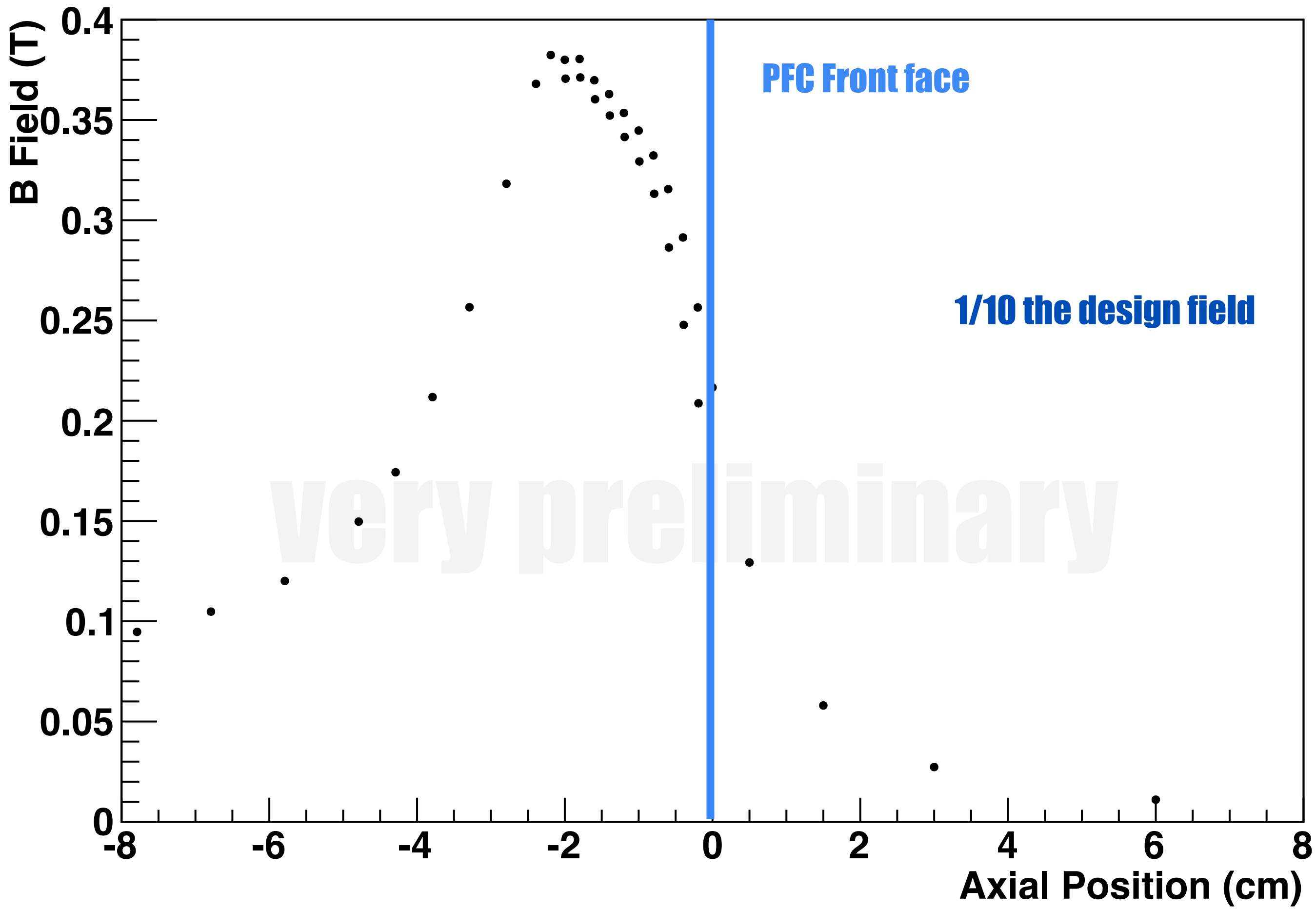




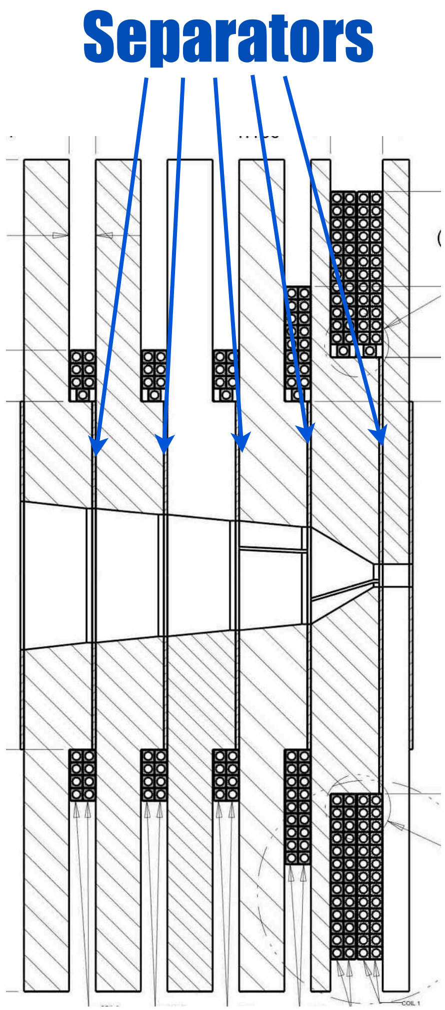
Measured peak axial magnetic field out to 1000A peak current



We mapped out the axial magnetic field in the bore as a function of position for a 200A pulse



All measurements were done with Stainless Steel separators between the concentrating plates



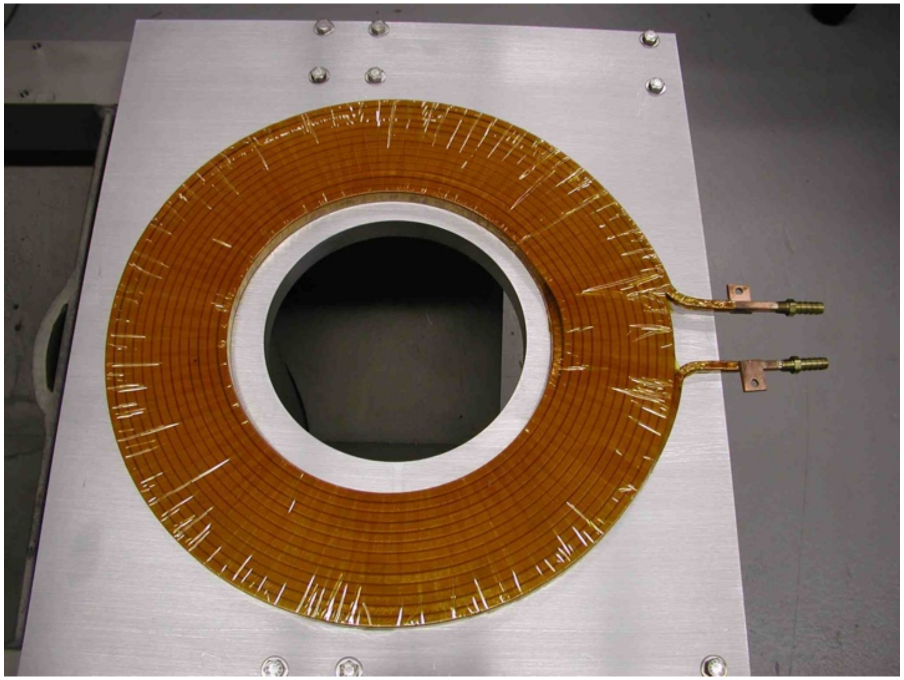
- Insulating Zirconia Toughened Alumina insulators between the concentrating plates
  - Prevent current flows between the plates
  - Potential problem with fracturing under 5 Hz repetitive stress
- Stainless Steel is a poor electrical conductor.
  - More robust to repetitive stress and radiation
  - Allows current to flow between the plates

We are done with the aluminum dummy and are moving on to the copper stack with cooling loops

- Using the aluminum dummy we have:
  - Verified the magnetic field versus current
  - Validated the use of Stainless Steel as a separator material
- Copper has the correct resistivity to test:
  - The energy deposition
  - The 1 ms flat top magnetic field
- We have a design for the cooling but will not be able to test it in the current program

Coils are kapton wrapped, center cooled copper, up-set winds, cooling is not a problem

- Wire dimensions:
  - 7 mm x 7 mm square
  - 4.5 mm dia inner hole
  - resistivity 1.68e-8 Ωm
  - skin depth between 5-6.5 mm
- Largest 25 turn coil
  - 27.8 m long wire
  - will dissipate ~800W
  - 5 mL/s flow - 30 cm/s - 18 kPa
  - 50 K ΔT = 900 W



Cooling of the concentrating plate must remove the ohmic heating around the bore

- Cooling lines should go where the heat is.
- A loop should run around the region of the coil image current.
- Up and down the side of the slit
- Around the bore

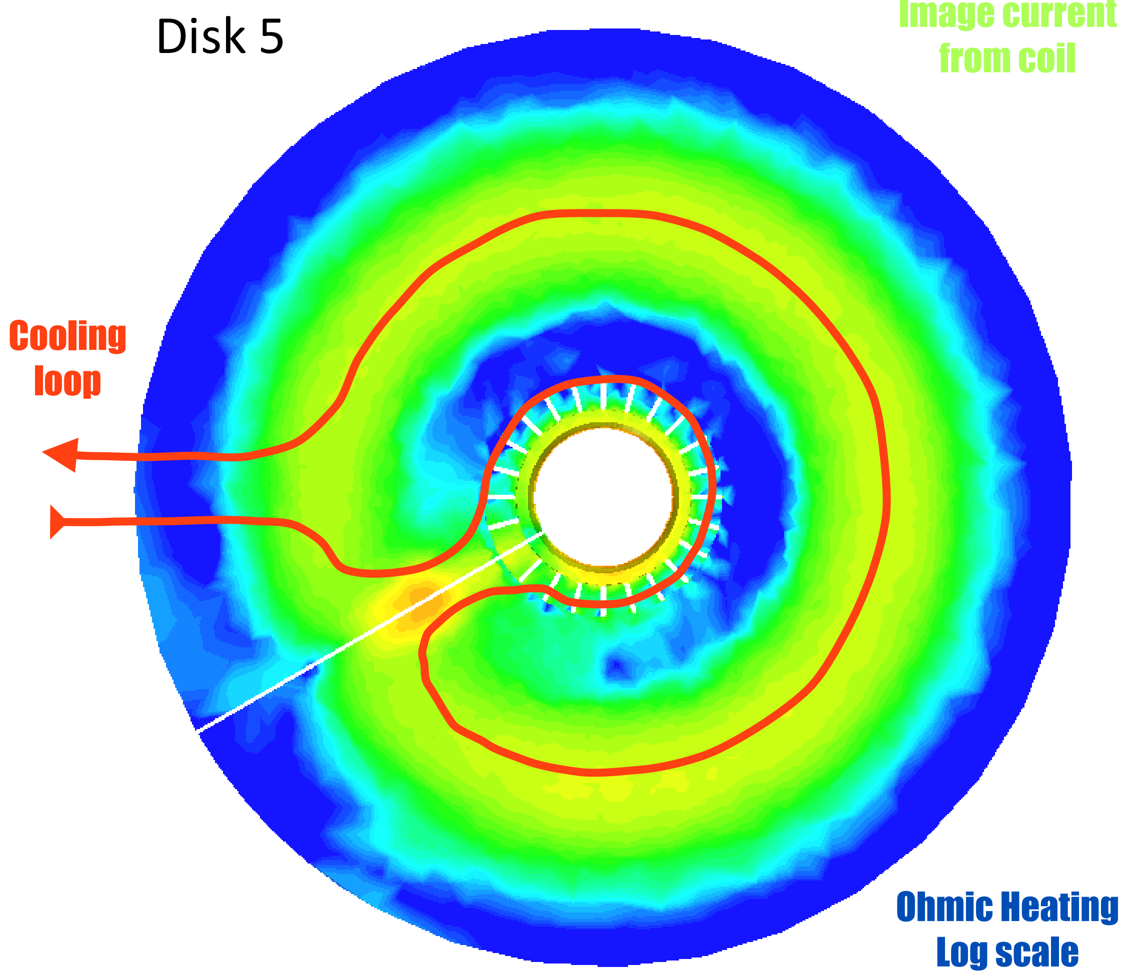
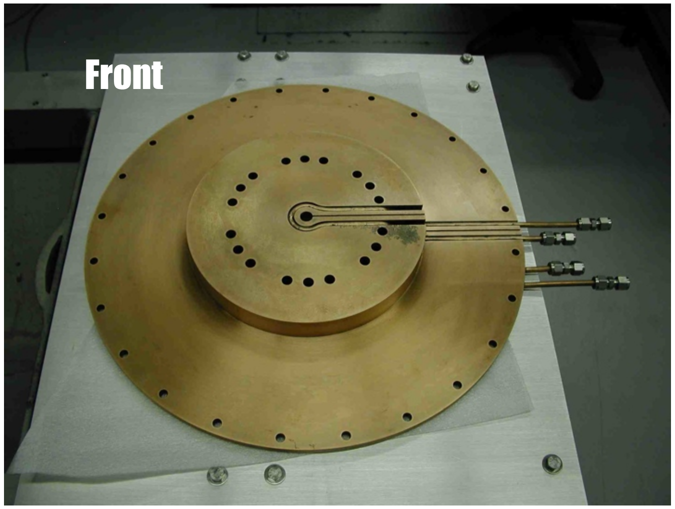


Plate 2 has two separate cooling loops

- Front loop:
  - Runs along slit and around the bore



- Back loop:
  - Runs around the bore and in the region of the coil image currents

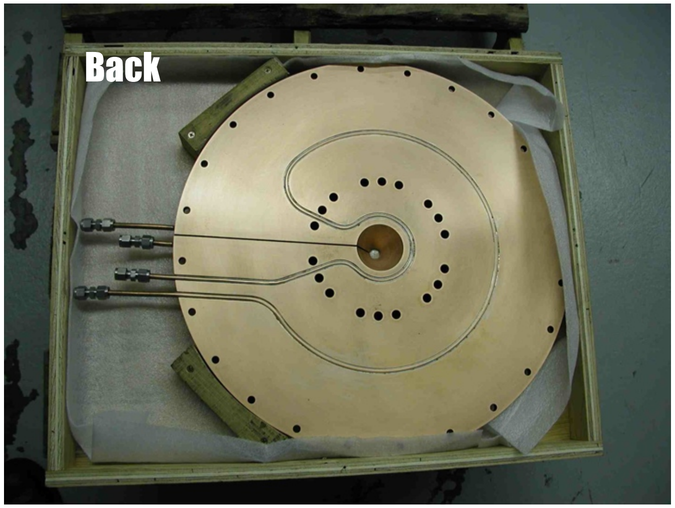


Plate 2 with 50 turn energizing coils in place

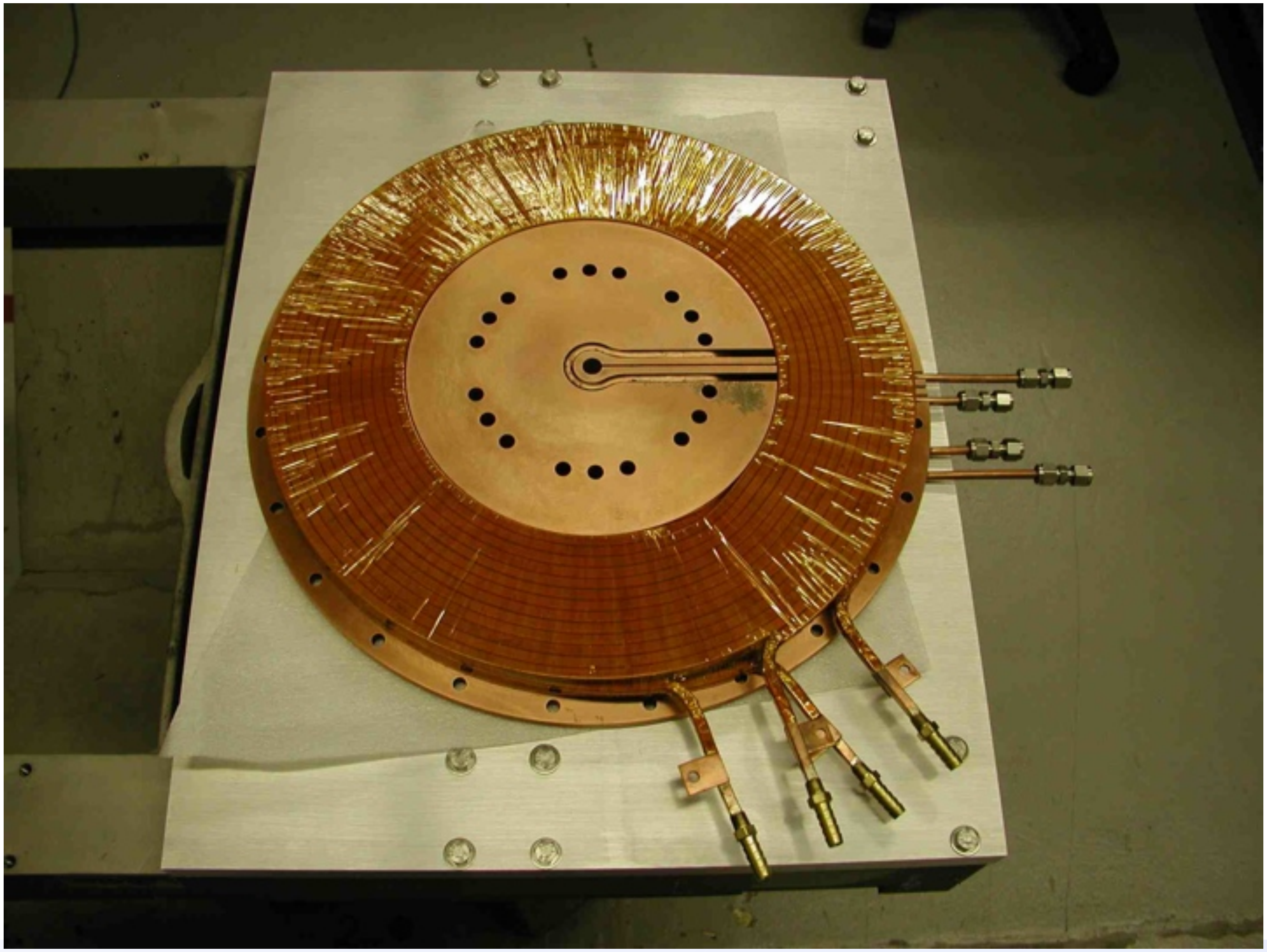
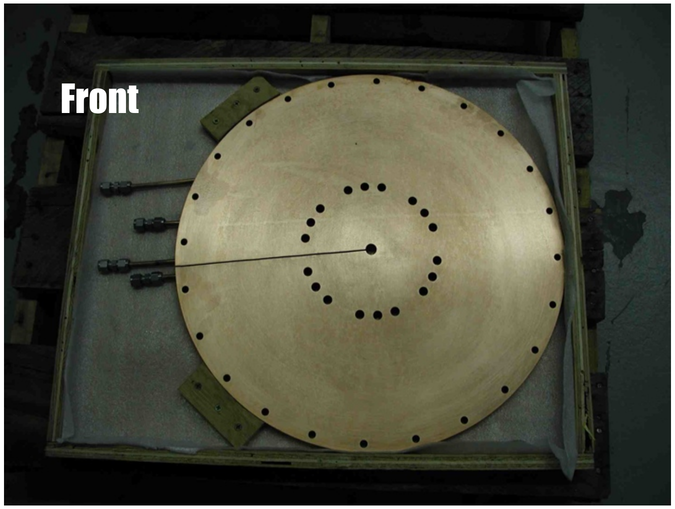
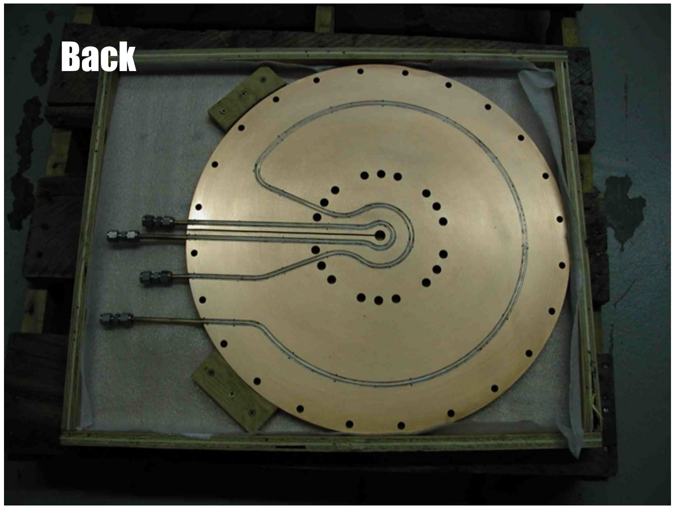


Plate 1 has both cooling loops on the back

- Front:
  - Bare metal to provide maximum shielding against beam particles

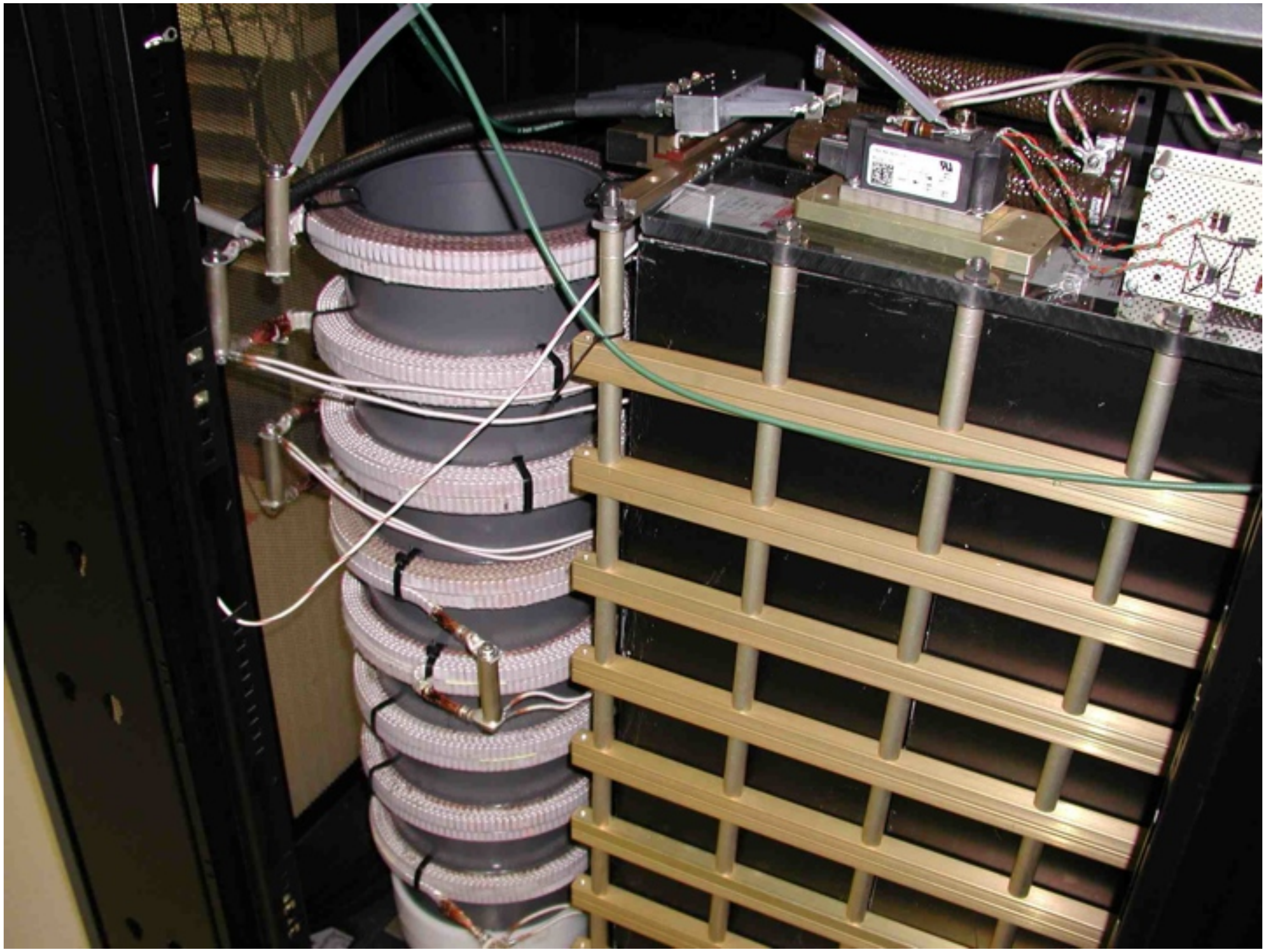


- Back:
  - One loop around bore and along slit
  - One loop around the bore and in the image current region

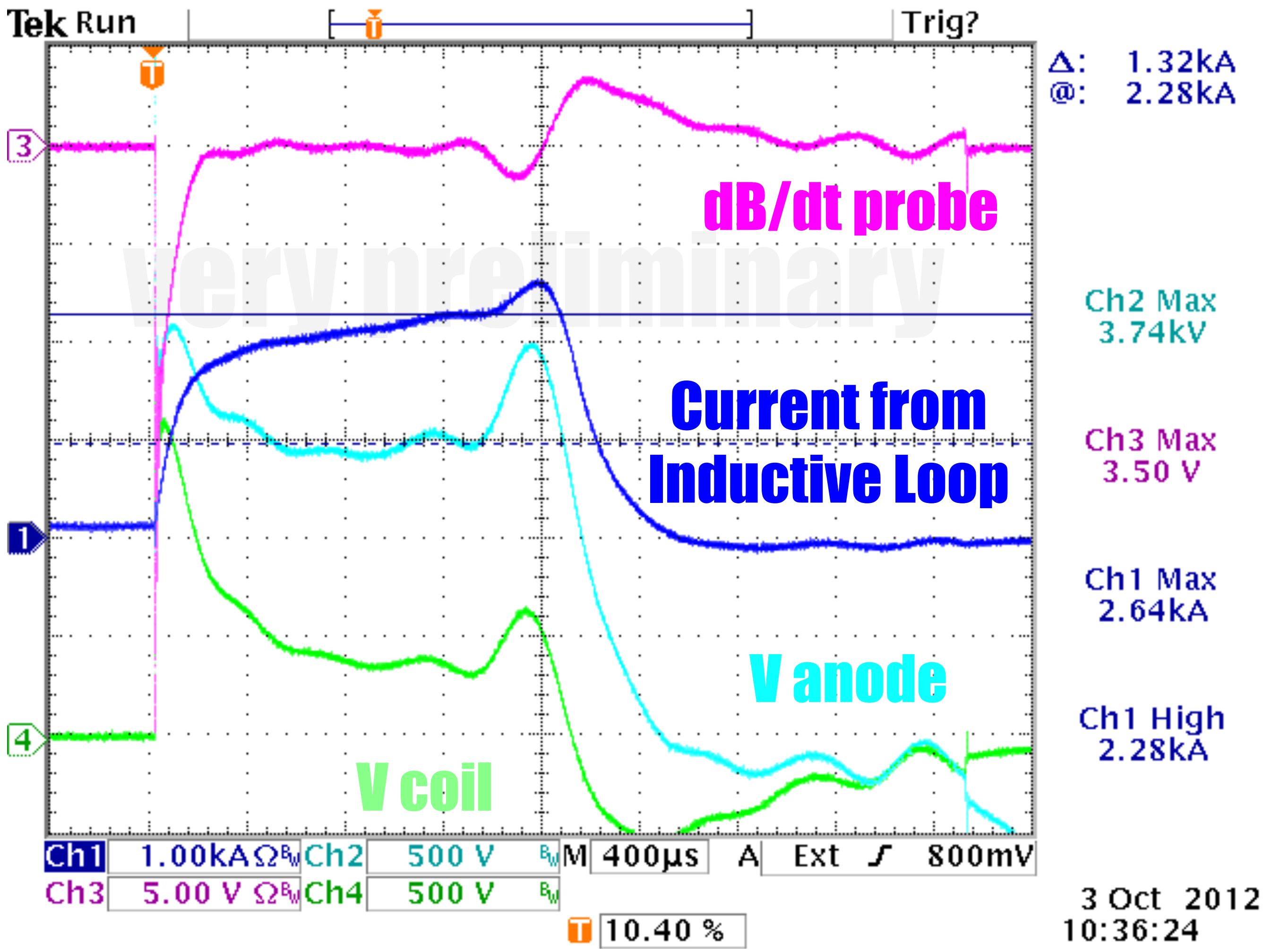


The 3 copper concentrating plate and 2 center cooled copper coil test stack

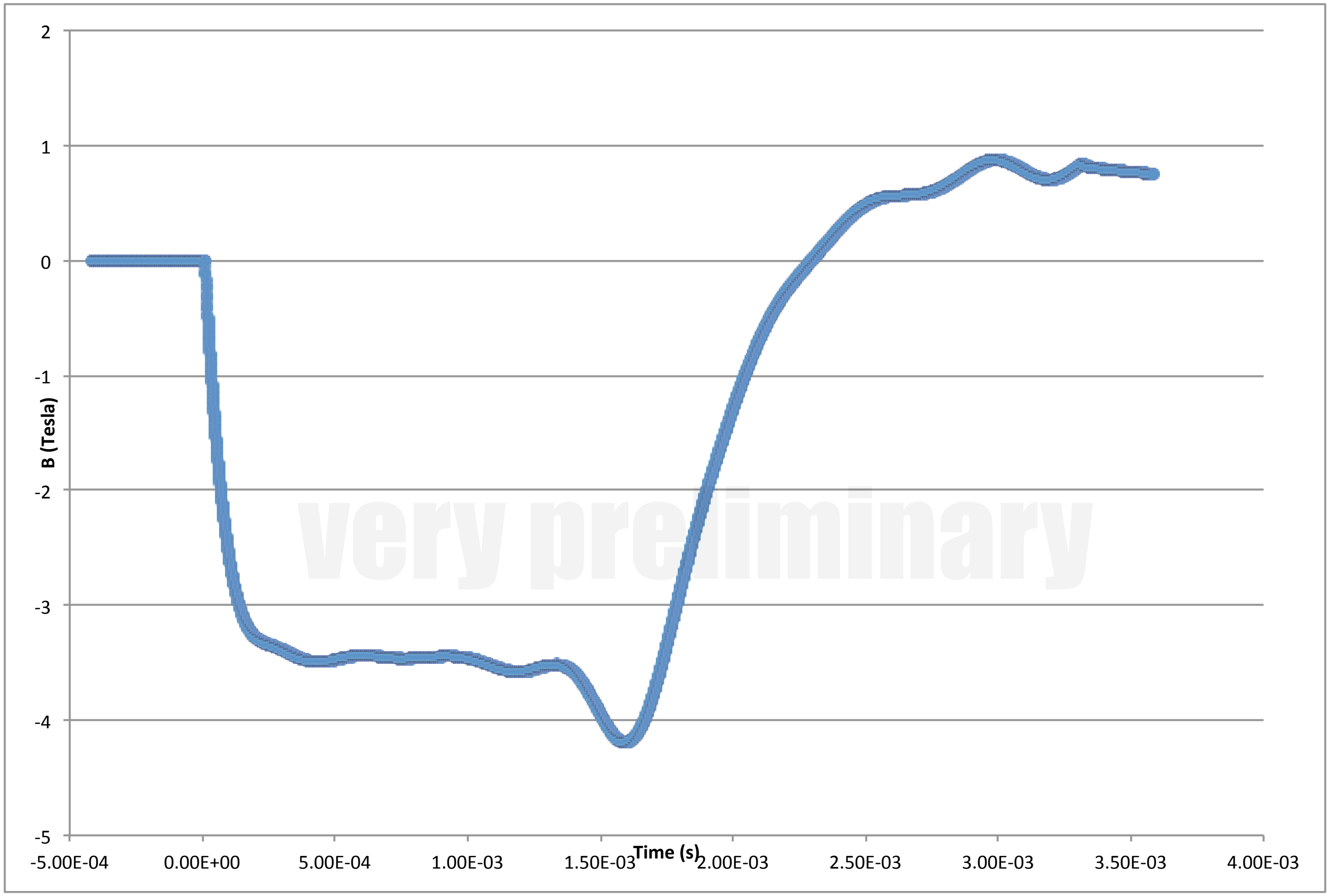
Pulser modified to form a ramped pulse forming network



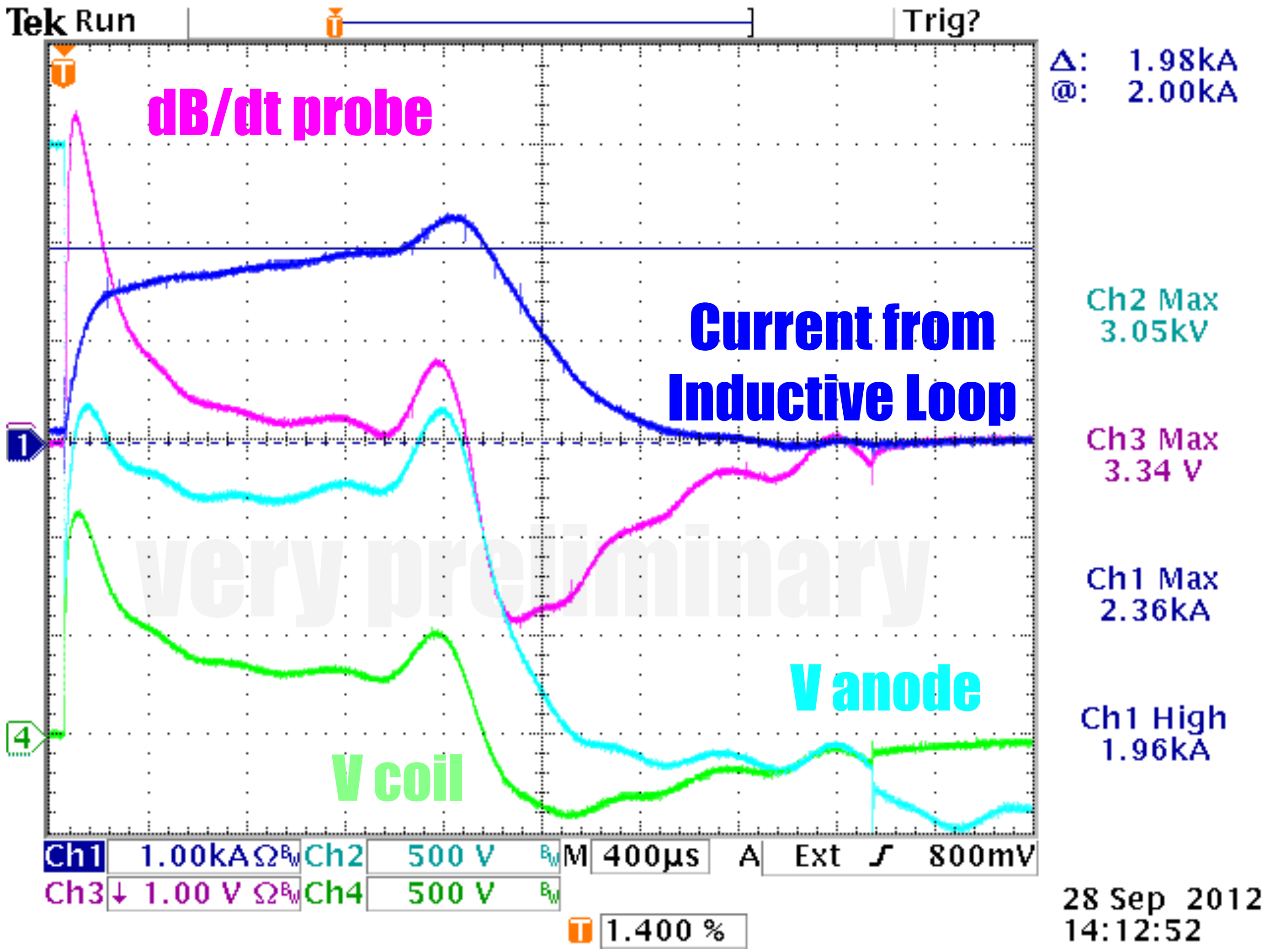
The device has a flat top when we use the insulating spacers



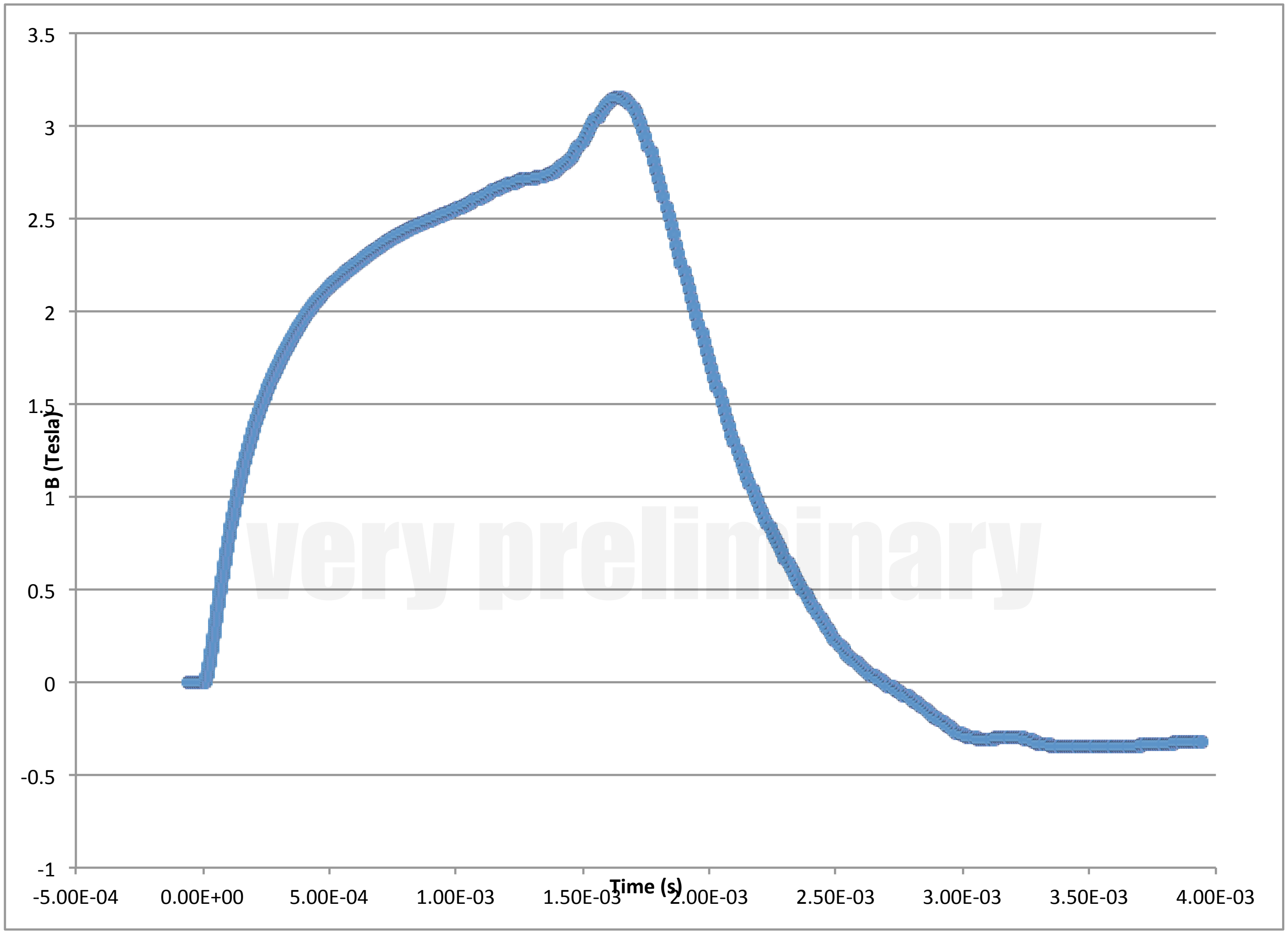
The magnetic field has a 1 ms flat top



The conductive Stainless Steel spacing plates change the magnetic field behavior



There is now an LR time constant in the concentrating plate



Status

- We have built a ramped pulse forming network and have observed a flat top magnetic field in the device at full current
  - Insulating plates are necessary to achieve the flat top using the ramped PFN
  - Stainless steel separators introduce an LR time constant in the plates
- 5 Hz operation will not be possible
  - full test of the cooling will not happen in this program

Final Simulations

- The magnetic fields and energy deposition of the final configuration has been simulated
- Heat flow and temperatures with the final cooling will be calculated
- Forces and stresses will be calculated

Work that should still be done

- The slit in the first plate allows a path for radiation to travel from the target to the kapton insulator in the coils
  - Shielding for the slit needs to be designed

- Particle energy deposition in the plate 1 cooling lines should be evaluated for shock wave damage

- Existing prototype should be run at 5 Hz, full current for an extended period