Lawrence Livermore National Laboratory

Design and Prototyping of the ILC baseline target system

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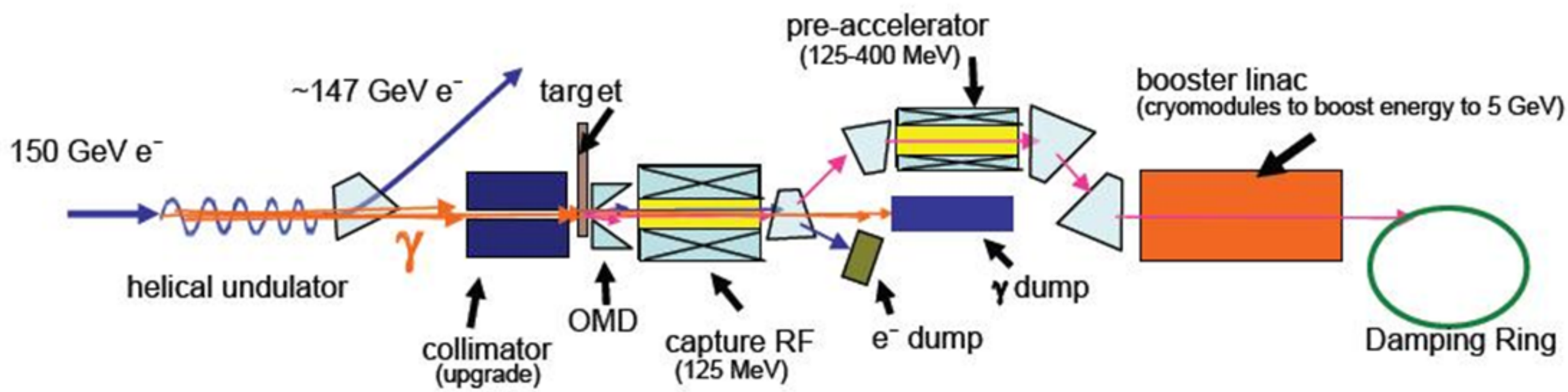
UCRL-XXXX-12345

The photon beam from the helical undulators presents challenges for the target and capture magnet

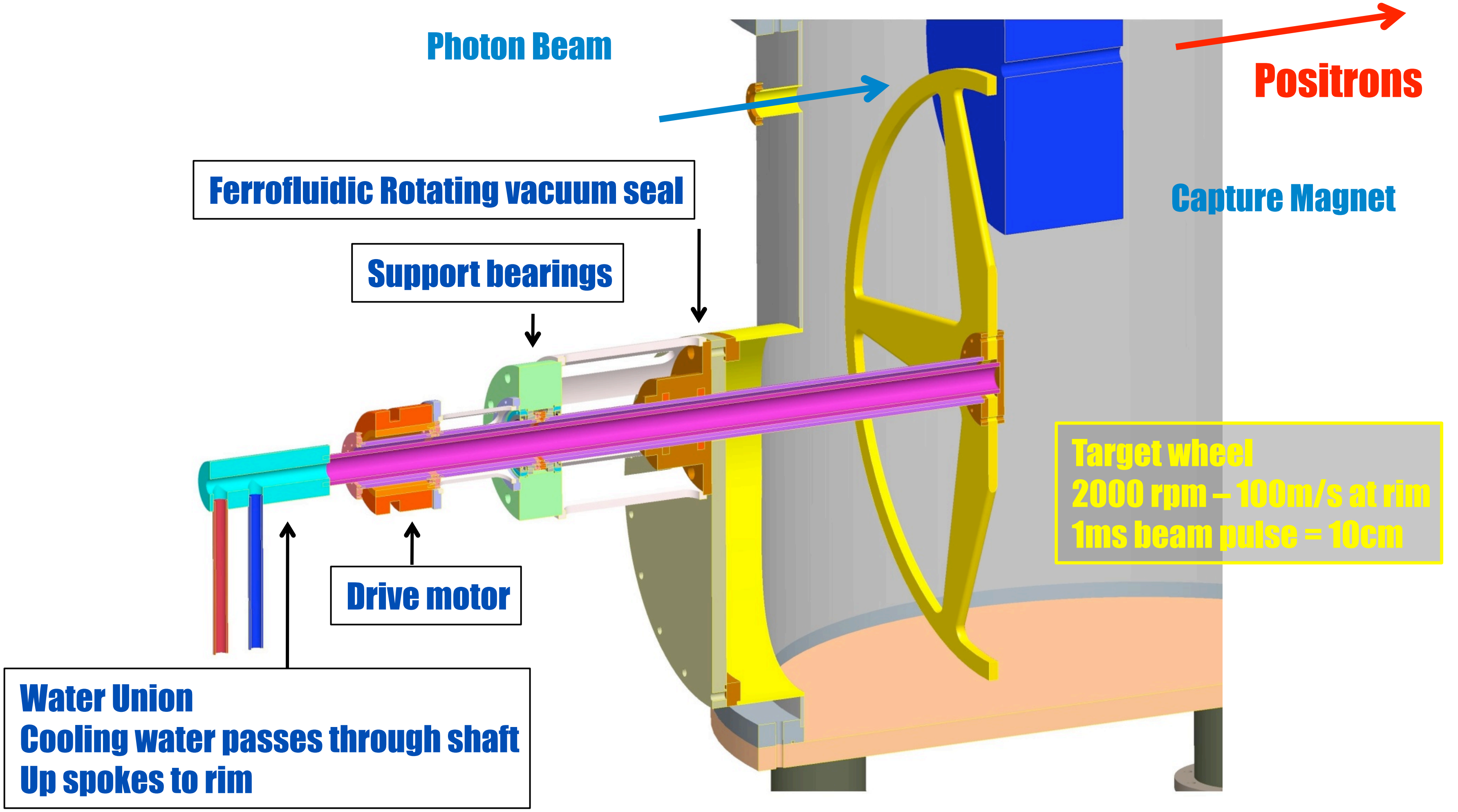
Helical undulator to generate a circularly polarized photon beam

Optical Matching Device to get high capture efficiency

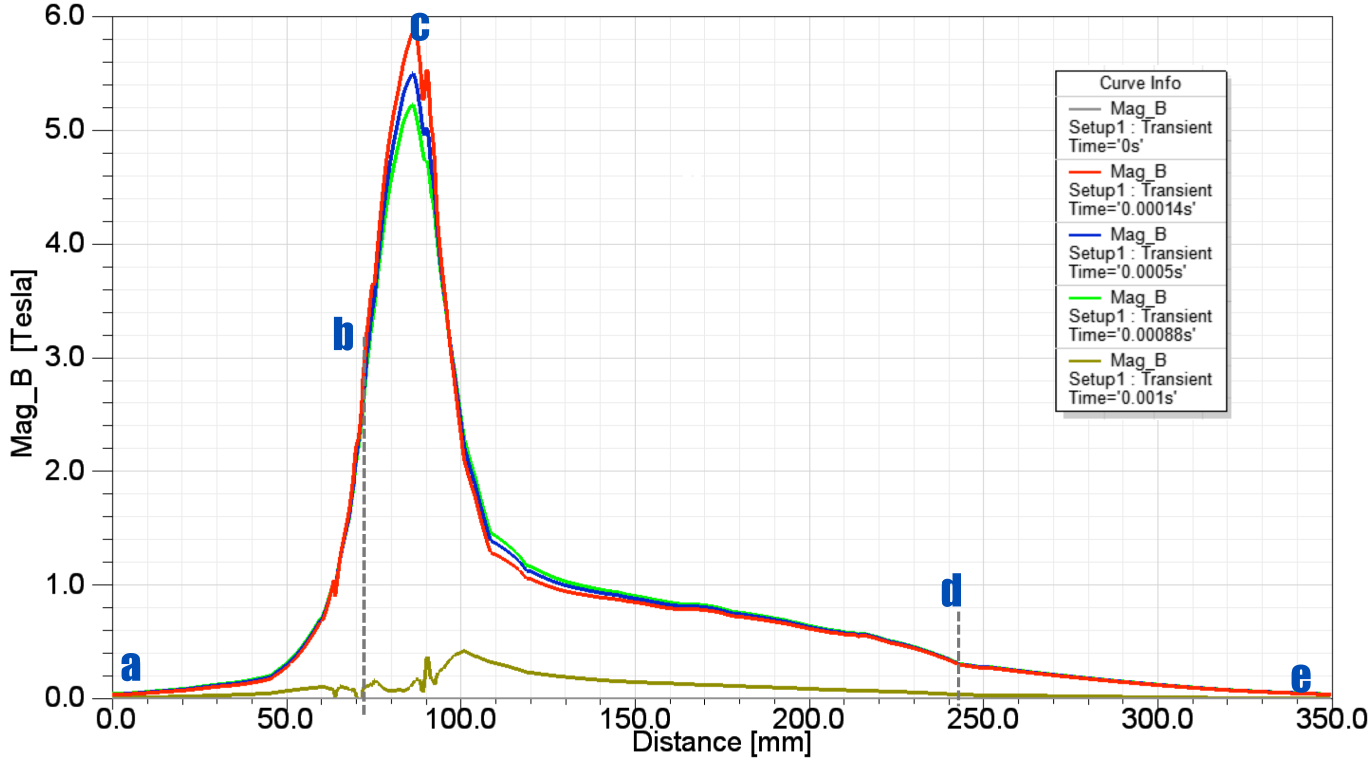


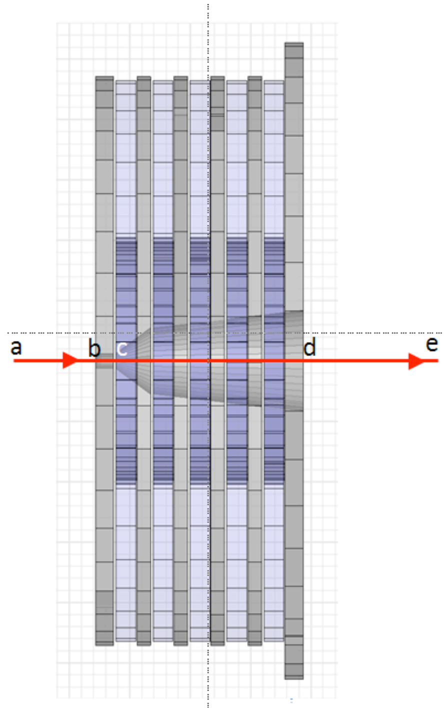
Rotating target to smear out the long 1ms pulse

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



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





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

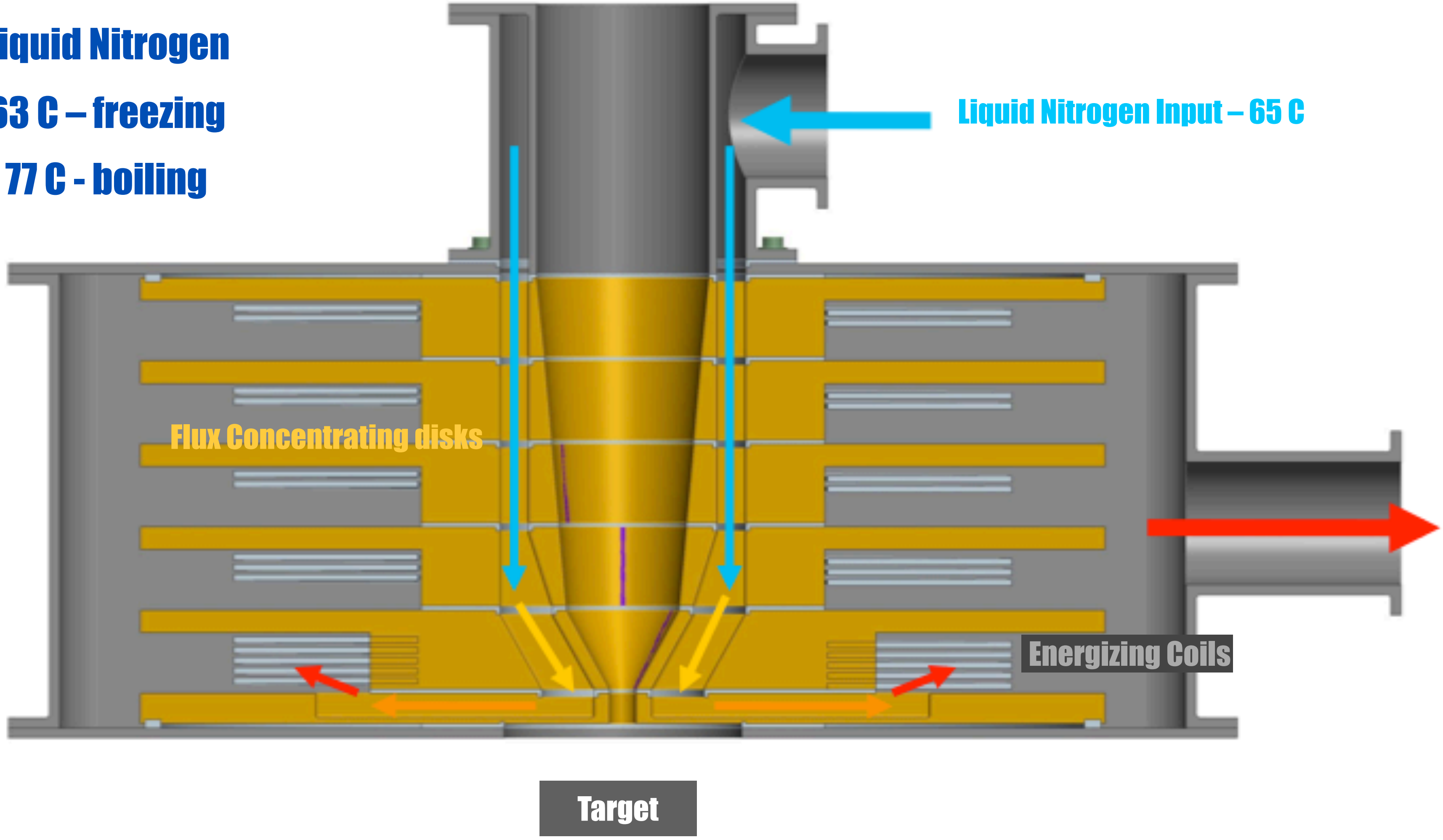
- Pulsed flux concentrators are a known technology that work well for short pulses
- We want a constant magnetic field profile over the 1 ms beam pulse
  - Induced currents in the concentrating plates will decay as stored energy is converted into ohmic heating
  - B field strength will decay as L/R
- Nitrogen cooling to minimize R was pursued as a solution
  - Based on a magnet designed by Brechna

The previous concept of the flux concentrator - liquid nitrogen cooled to reduce the droop

Liquid Nitrogen

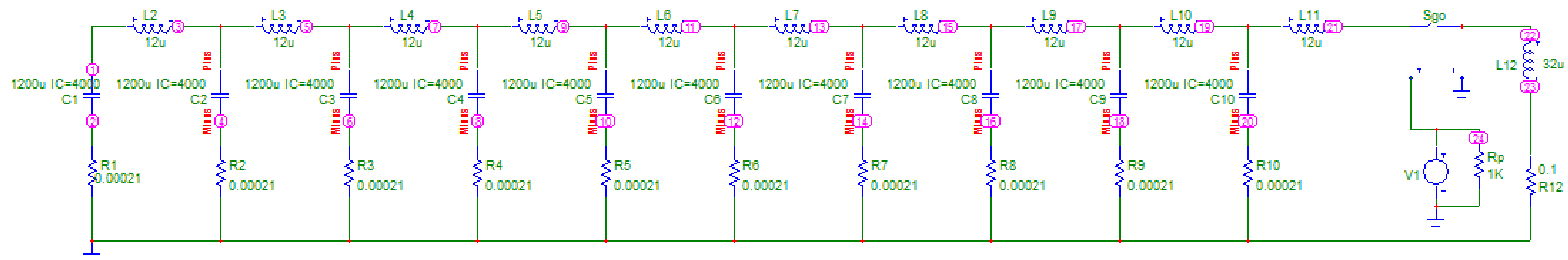
63 C – freezing

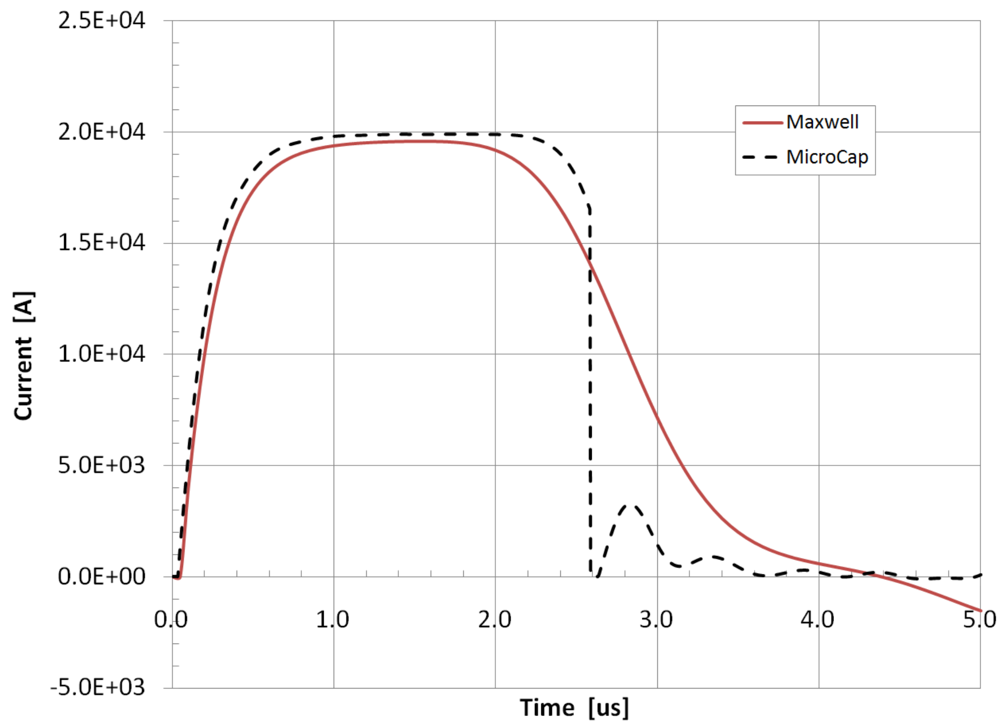
77 C - boiling



Original concept for the pulser was a 2 ms flat top of 20 kA

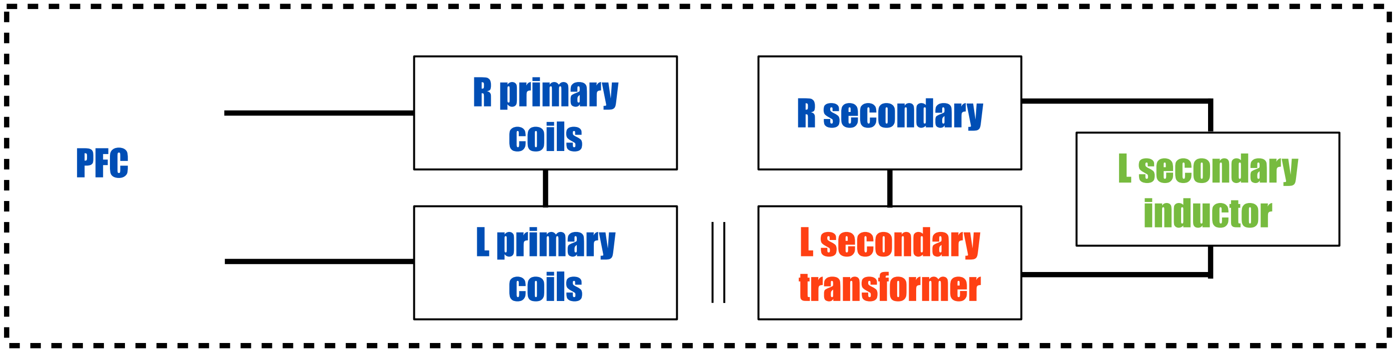
Verification of Current from Maxwell with Equivalent Microcap Circuit

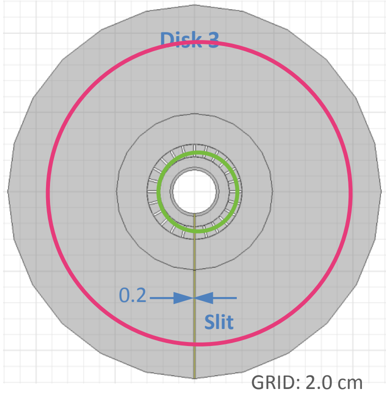




- 96 kJ/pulse
  - 480 kW at 5 Hz
- 12,000 microF at 4000 V
  - 48 C/pulse

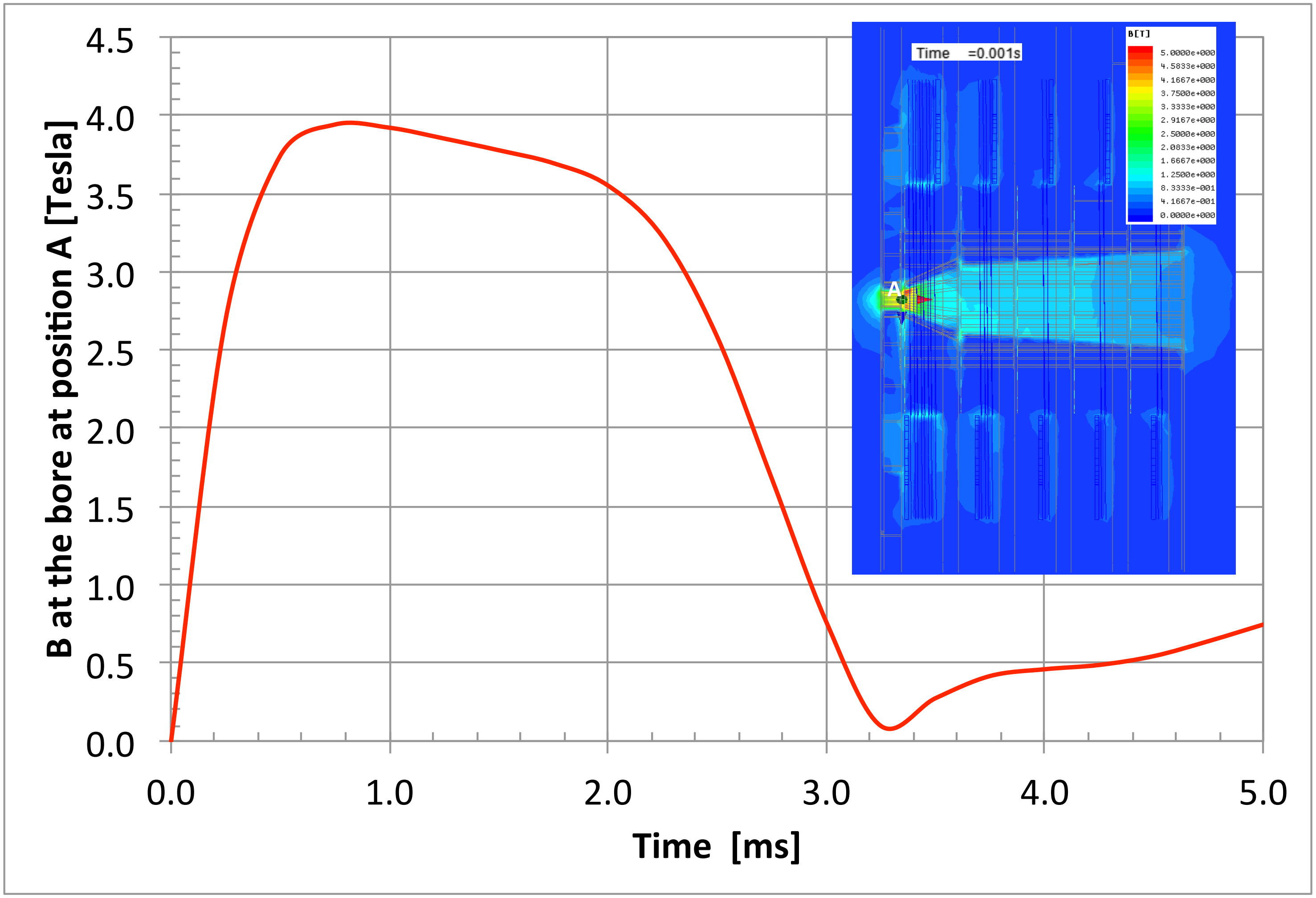
PFC equivalent circuit





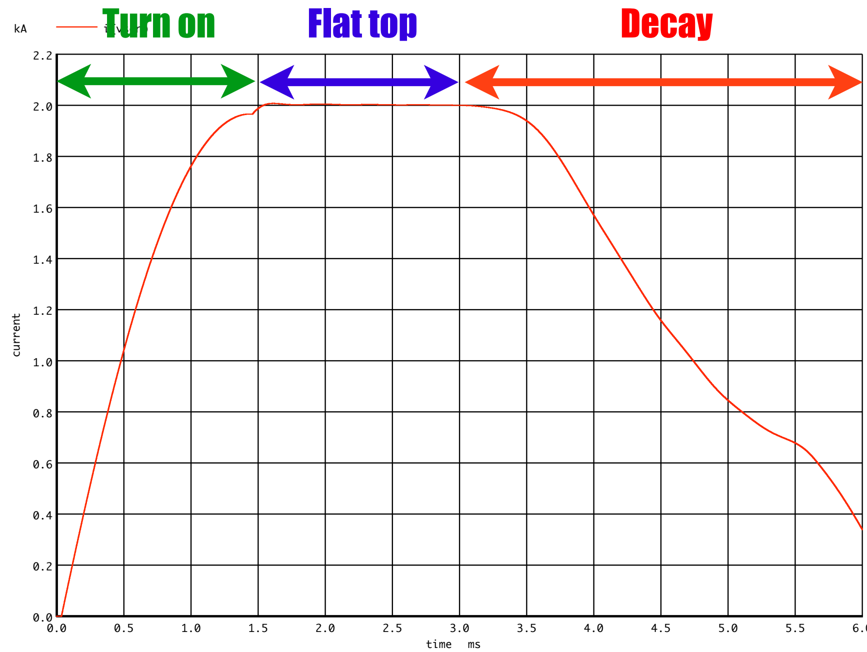
- The PFC is equivalent to a transformer with a highly inductive load.
  - The coils are the transformer primary
  - The outer part of each plate is the transformer secondary
  - The inner bore forms the inductive load
- Will look like an inductor with ohmic losses to a sine wave
- For a square pulse will look like
  - an inductor on the rising edge
  - stored energy will dissipate on the flat top
  - a different inductor on the falling edge

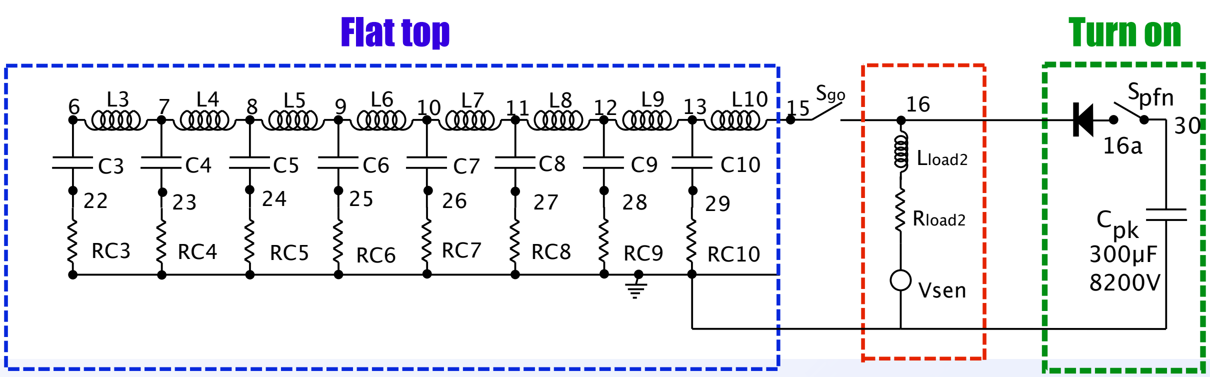
Liquid nitrogen cooling minimizes the problem but there is still a droop to the B field



Splitting the circuit greatly improved the performance

- Turn on fires first
- Flat top fires at peak
- Allows higher number of turns - lower current
  - 2 kA - 1.5 ms flat top





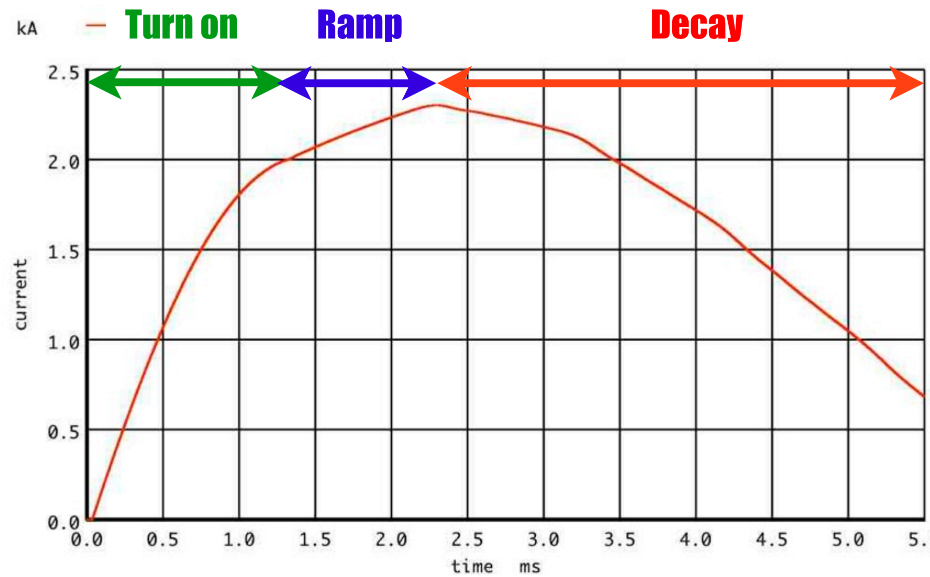
17 kJ / pulse

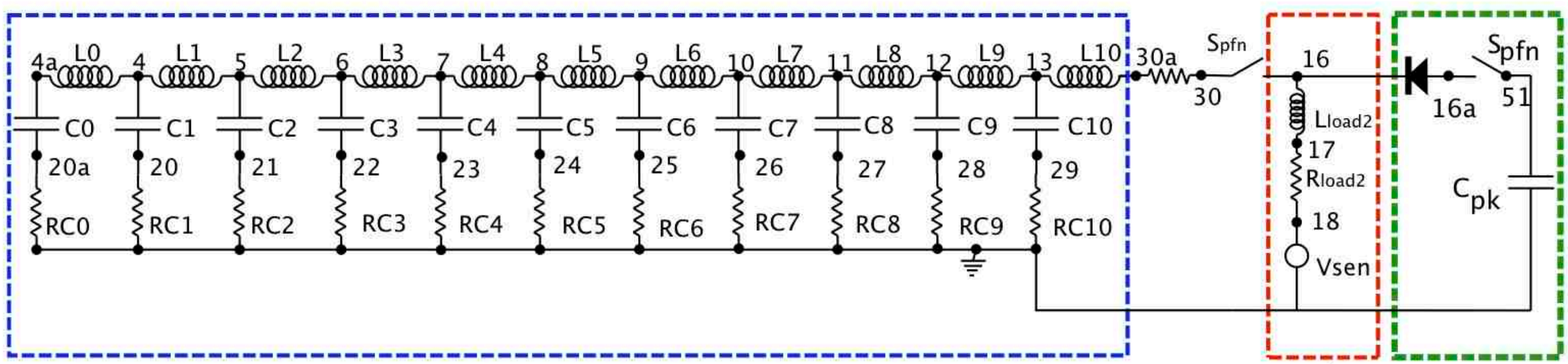
85 kW at 5 Hz

2,000 microF at 4000V

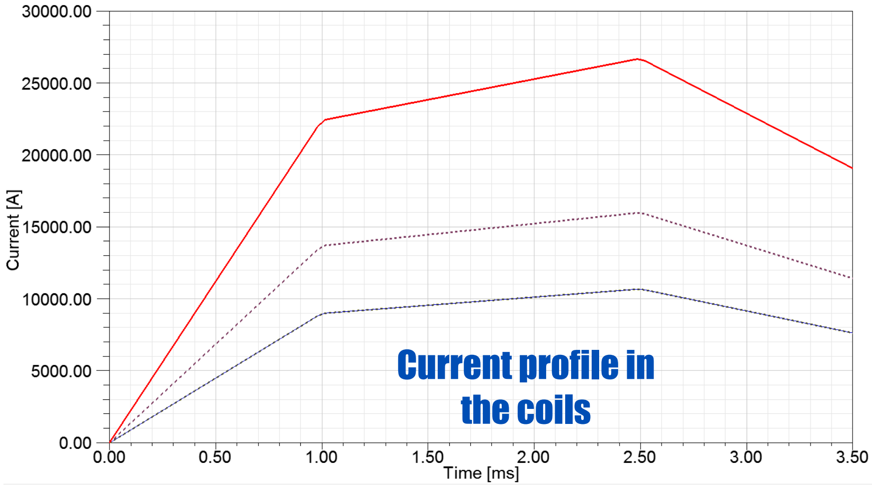
A current ramp can be created by varying the impedances of the pulse forming network

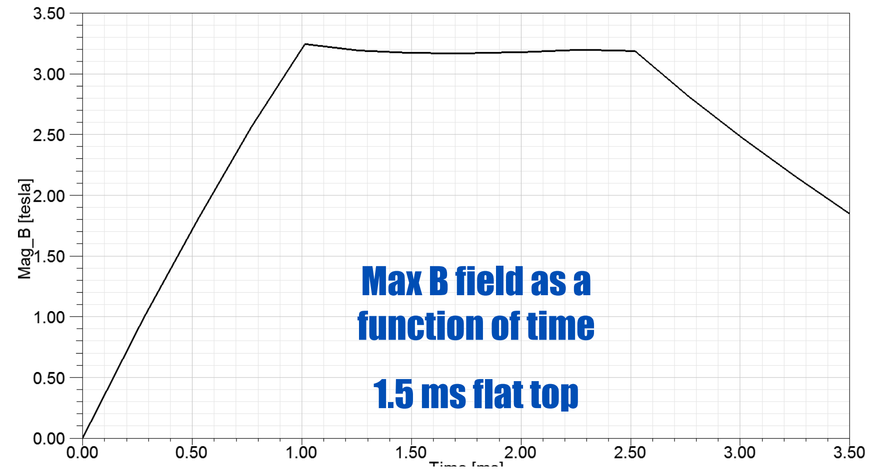
- Splitting the circuit makes a ramp over the 1 ms possible
- We can try to counteract the magnetic field droop using the pulse forming network





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***

The design phase space has now expanded

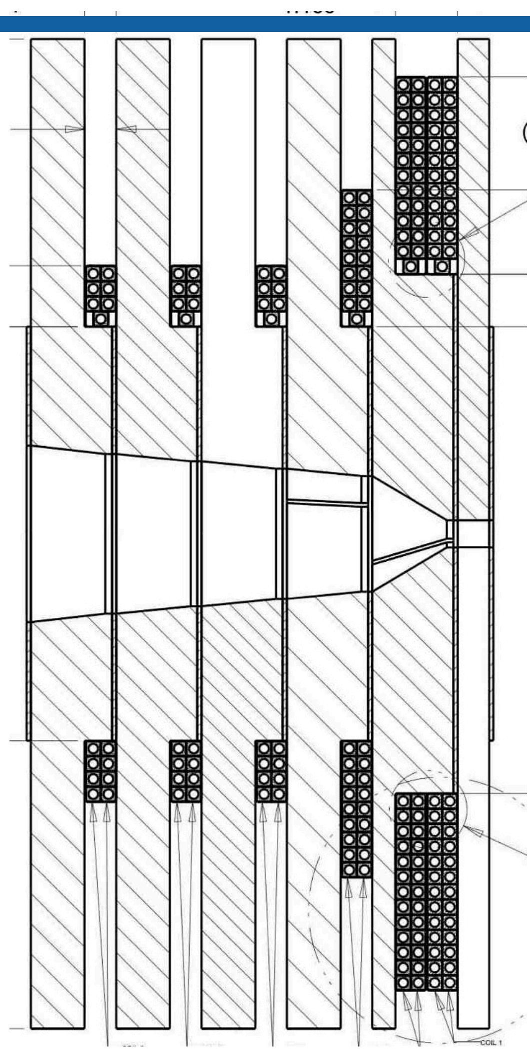
- Liquid Nitrogen was pursued to reduce the droop of the magnetic field over the ILC pulse
- The right pulse forming network can eliminate it, even at room temperature
- So why not go to a room temperature device?

Room Temperature vs Liquid Nitrogen

- About 4 times as much heat deposition in the plates at room temperature
- But water is a much better coolant than liquid nitrogen

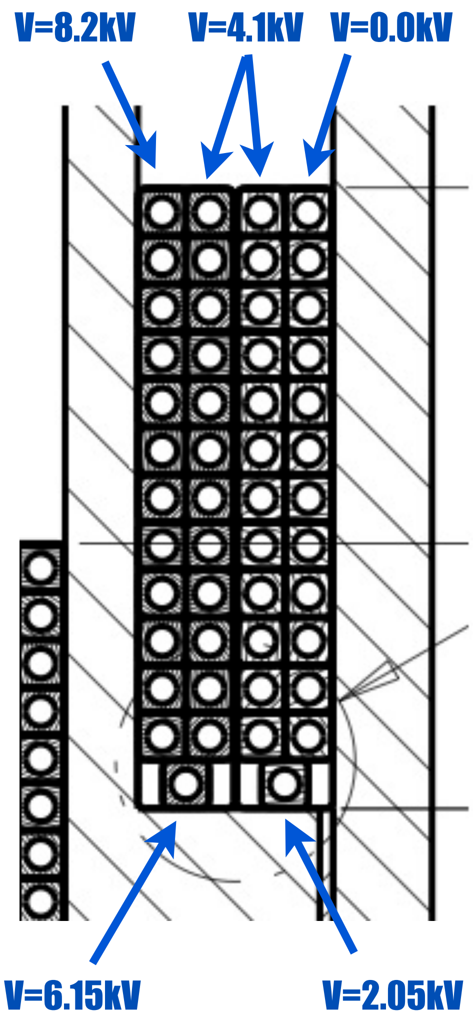
Property:	liquid nitrogen	water
Thermal Conductivity (W / m K):	0.137	0.58
Heat Capacity (J / gm K):	2.054	4.18
Temperature Range, solid to gas: (C)	14	100
Max Gradient (W/m)	1.92	58.0

Water cooling and room temperature greatly simplifies the design



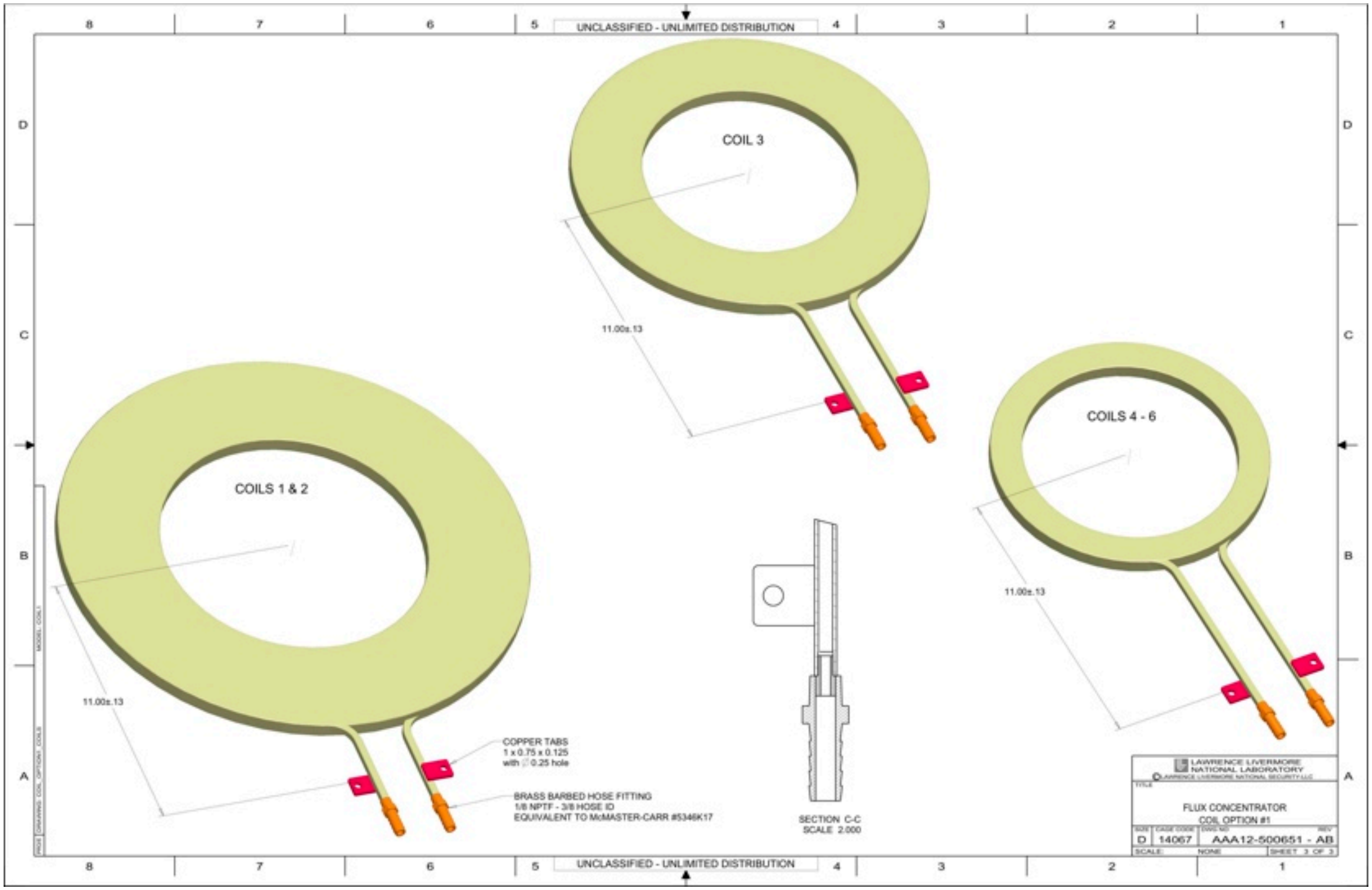
- Device sits in the vacuum
- All power and cooling connections move to the rim
  - Coils are kapton wound, hollow copper, water cooled
  - Plates are OFHC copper with water cooling pipes soldered in
  - Only metal in the high radiation areas
- Plates and coils stack and bolt together

Coils are kapton wrapped, center cooled copper, up-set winds



- The pulser turn-on stage operates at 8 kV and the PFC will see the full voltage
- Each wire has 100 microns of kapton thickness wound so that there is 2.5 cm of surface path to hold off 8.2 kV
- The whole two column assembly is wound with kapton

Two coil sub-assemblies for the first coil, one each for the other coils



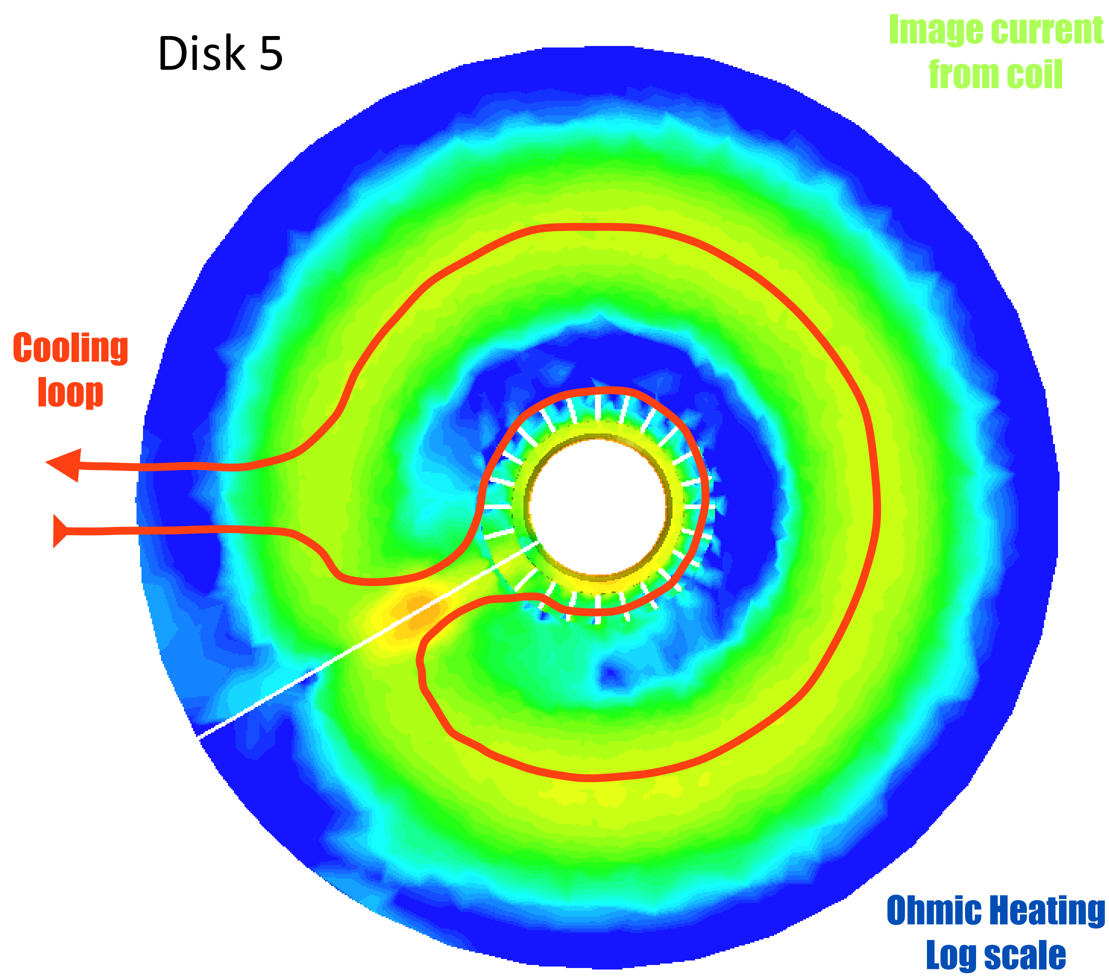
Coil cooling is not a problem

- 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

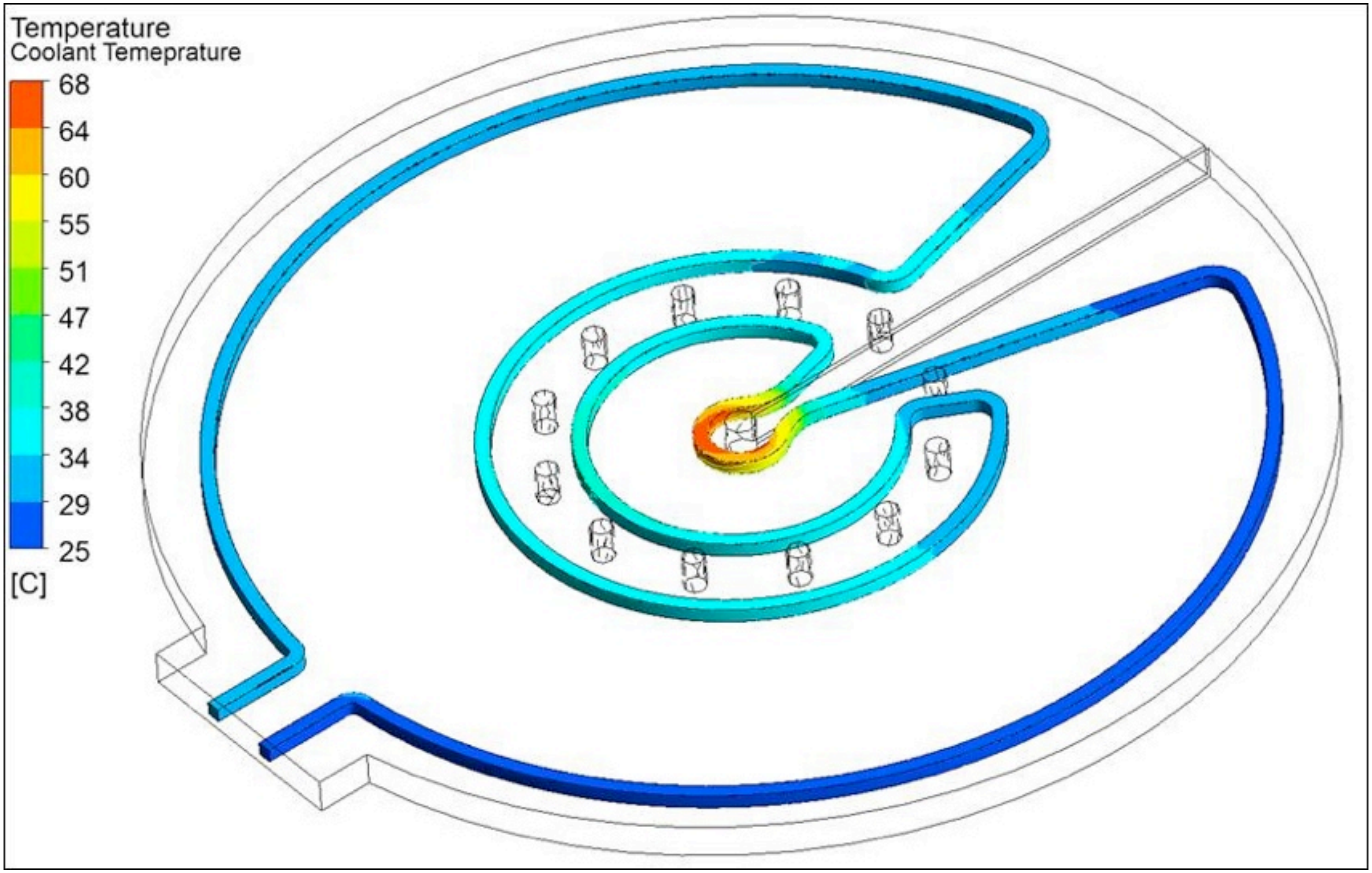
- Largest 25 turn coil
  - 27.8 m long wire
  - will dissipate ~800W
  - 5 mL/s flow - 30 cm/s - 18 kPa
  - 50 K ΔT = 900 W

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

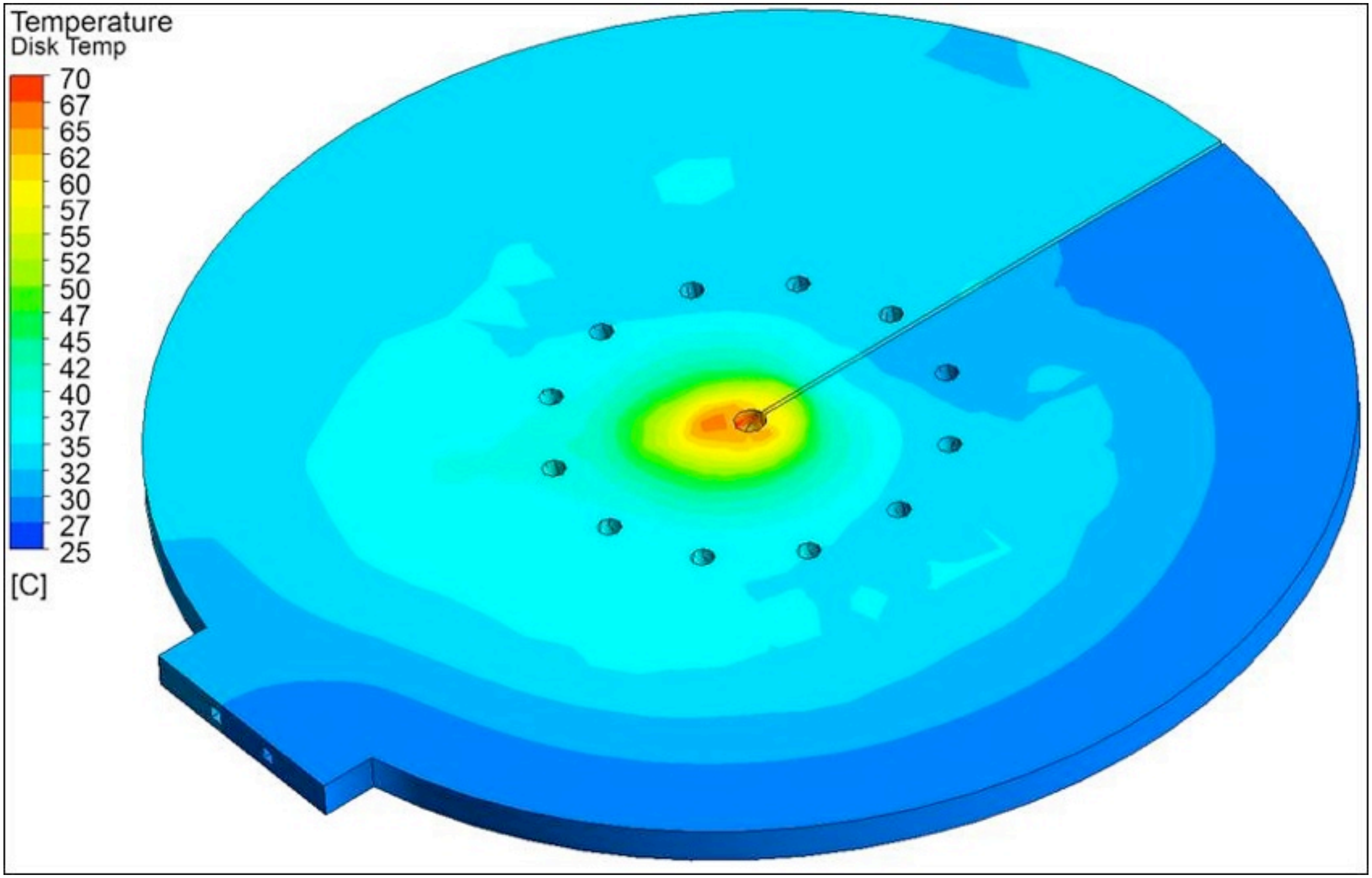
- Cooling lines should go where the heat is.
- A loop should run around the region of the coil image current.
- Up and down the side of the slit
- Around the bore



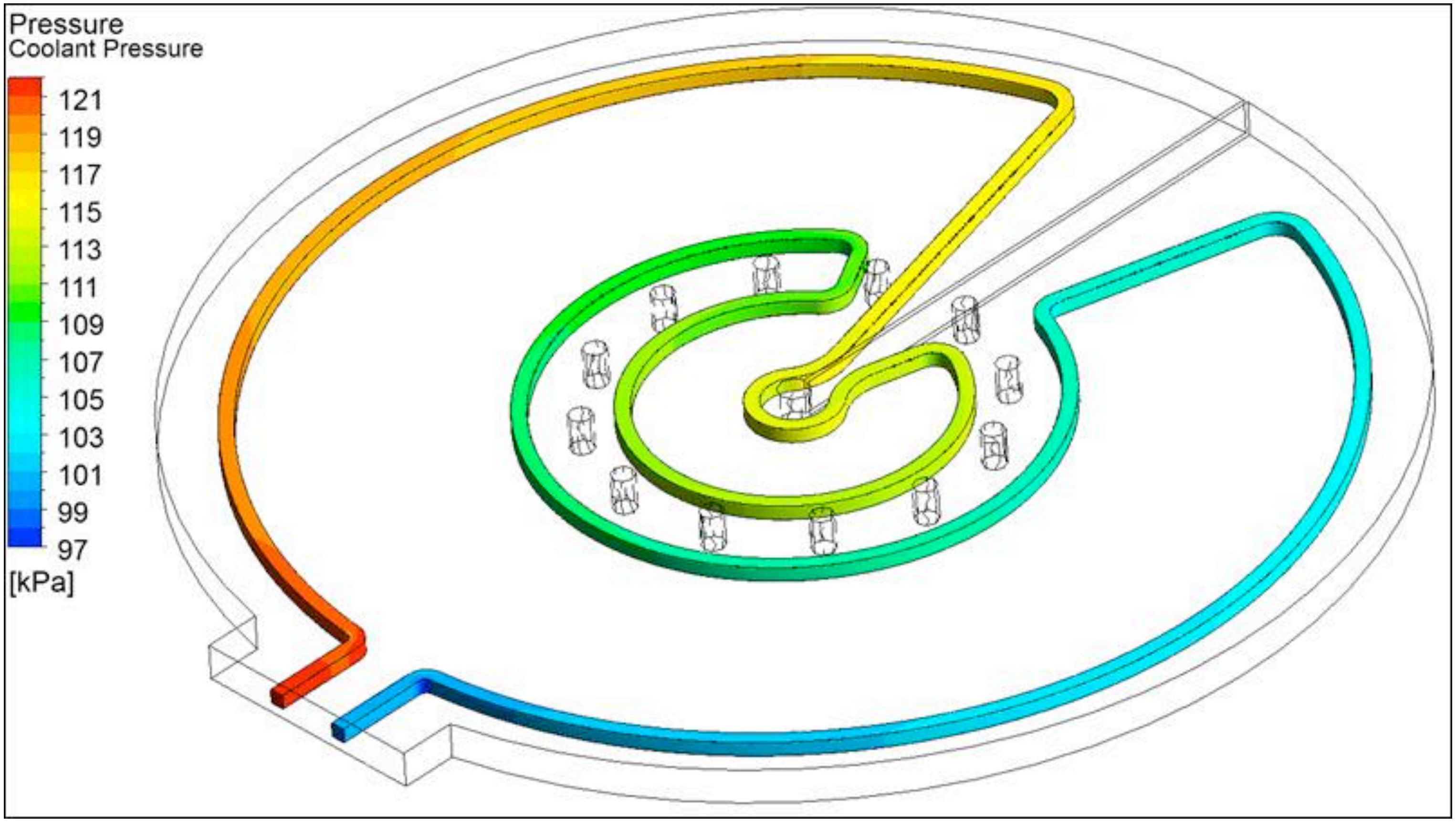
Initial cut at room temperature cooling with internal water channels - 1500W



Steady state disk temperature

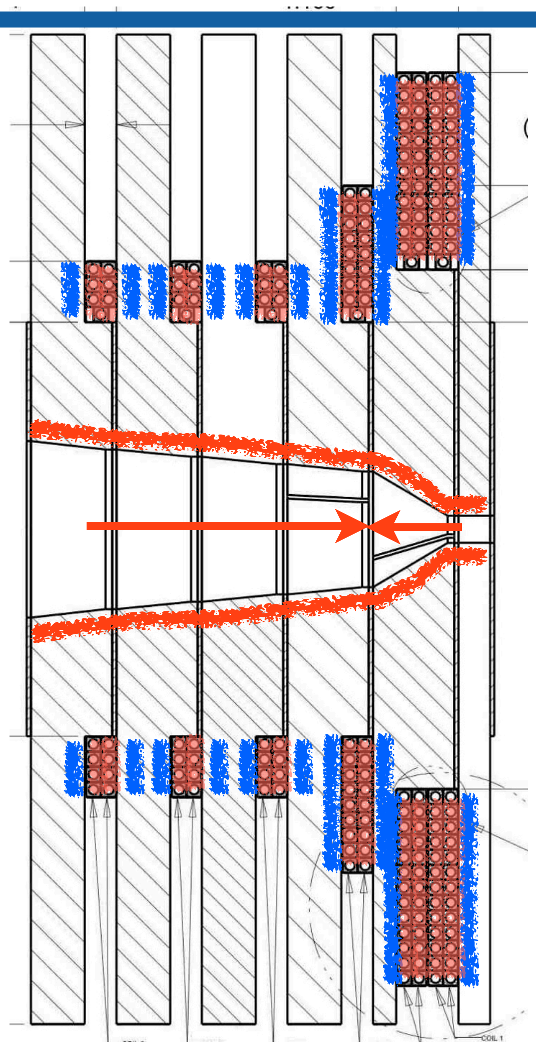


0.2 atmospheres pressure differential

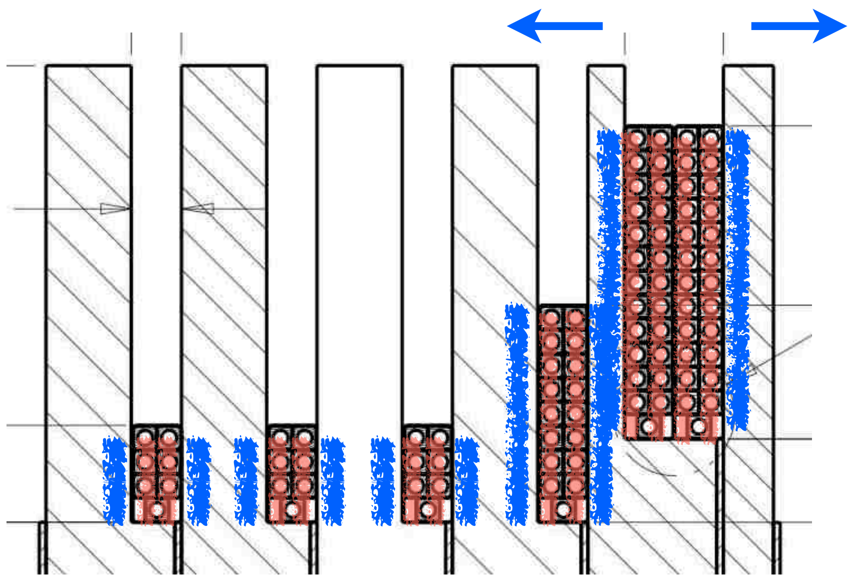


- Internal water cooling of the plates is feasible

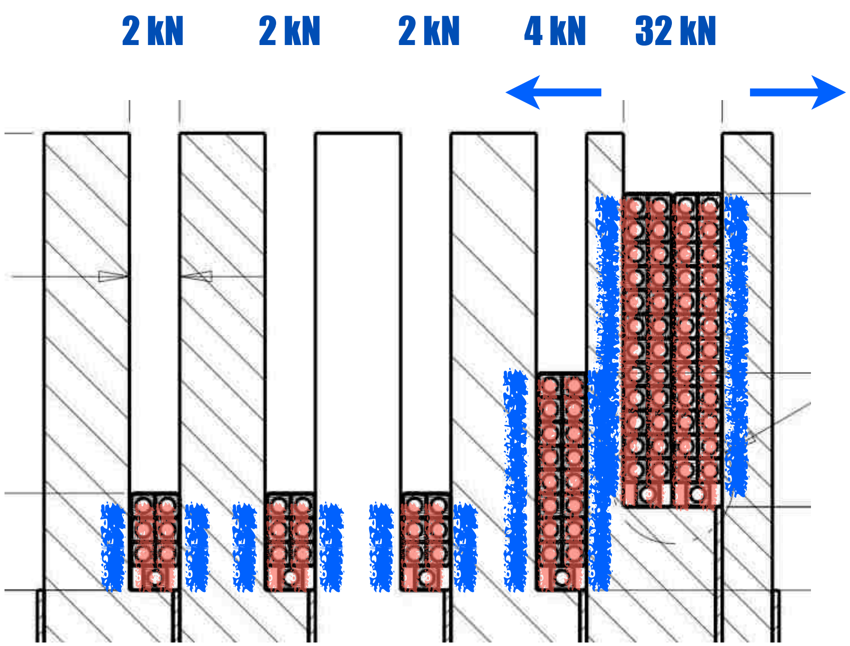
Need to hold the assembly together against the J x B forces



- Bore currents create a compressive force
- Every coil will repel the image currents in the adjacent plate
  - the coils and plates try to tear each other apart
  - force applied at center of coil

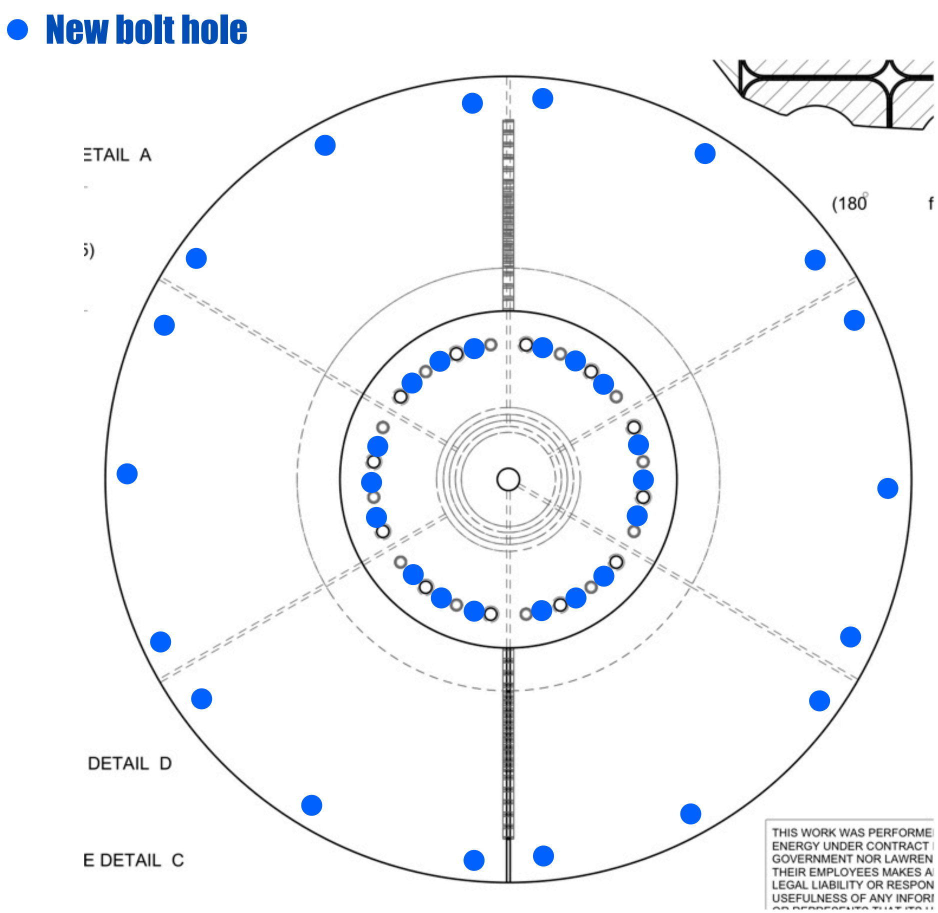


Majority of the force is between plates 1 and 2



- 32 kN is the maximum expansive force at 2 kA
  - It will be partially compensated by compressive force from the bore currents
  - Bolts will need to be positioned to take up this force

Modify bolt pattern for better cooling and stress relief of the opening forces

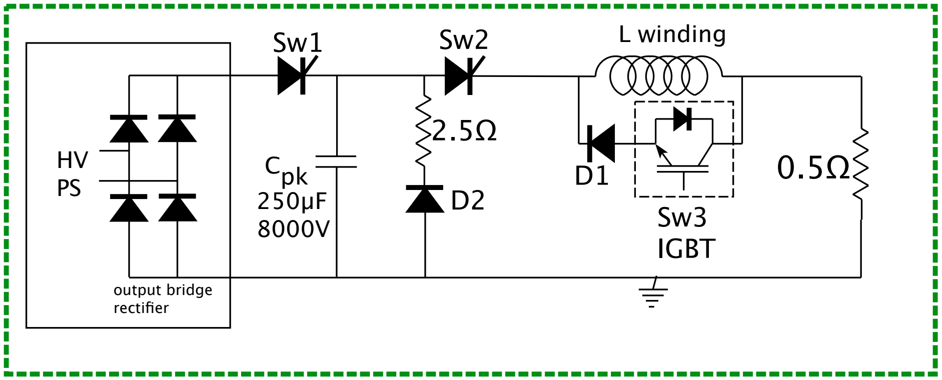


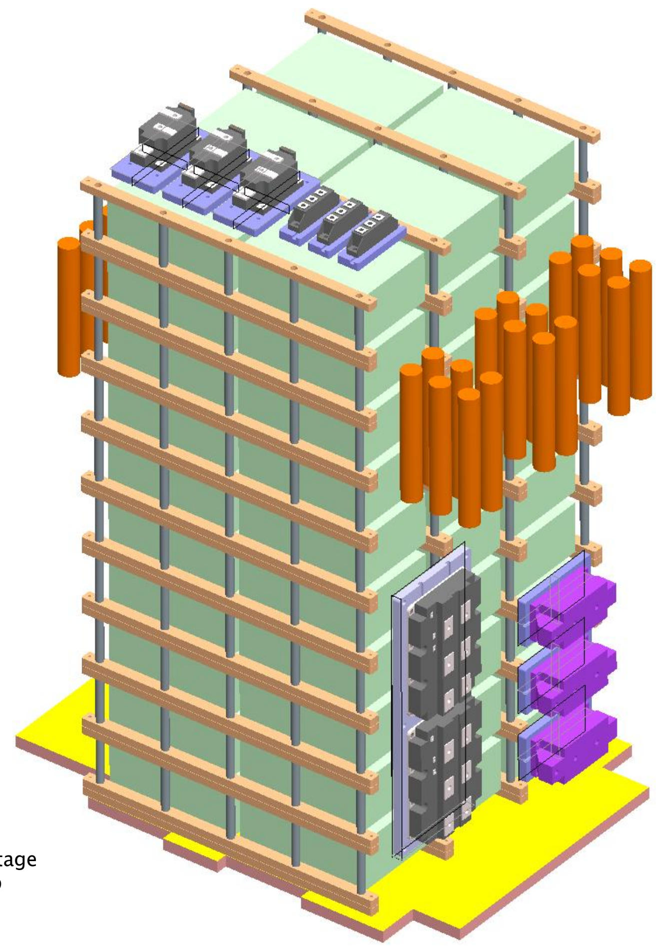
- 18 bolts at the bore
  - 3 per hexant
  - leave space along the slits for cooling lines to run
- 18 bolts along the rim
  - 3 per hexant
  - strain relieve the opening forces at the coils
  - only connects plates 1 and 2
- 36 total
  - aim for safety factor of 6

Prototyping for the rest of this year

- Pulser
  - Just the turn-on circuit, low rep rate
- Aluminum dummy PFC
  - first three plates, first two coils, no cooling
- Full size PFC
  - kapton wrapped, center cooled coils
  - concentrating plates with internal cooling

The pulser includes a circuit to allow the PFC to source its own current at peak



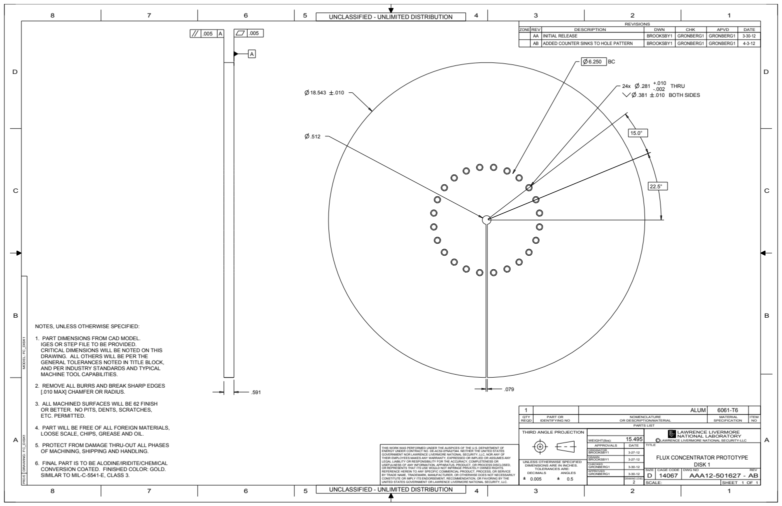


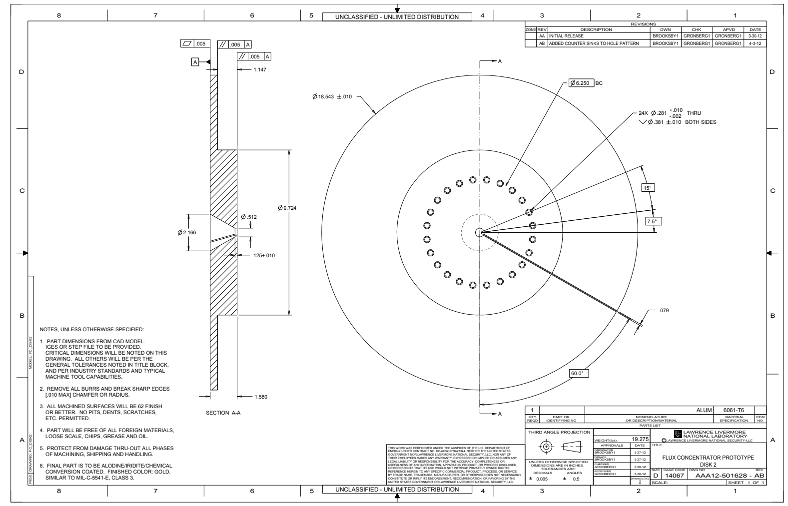
DeQue Operation:

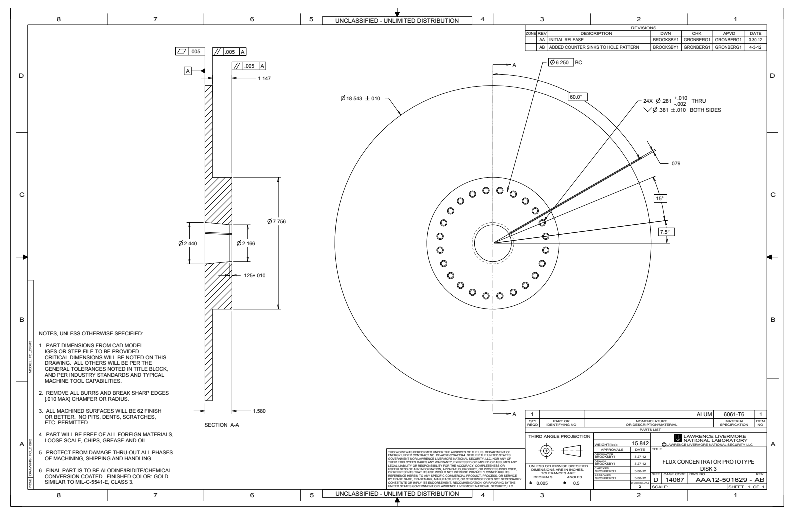
1. Sw1 closes - allows HV PS to charge Cpk - Sw1 opens after charge
1. Sw2 closes - current ramps up in the winding inductance
2. when current reaches 2kA, Sw3 closes, Sw2 stays on(triggered if necessary)
3. since the resistance in the inductor-Sw3 loop is much less than 0.5Ω, current circulates in that loop with the new L/R time constant
4. When the needed pulse width is met, Sw3 opens, and current now flows in the loop with the inductor, 0.5Ω, diode, 2.5Ω (in parallel with Cpk),and Sw2

note: D1 is required to prevent current from flowing in the intrinsic anti-parallel diode in Sw3
Sw 1 is required to prevent the voltage reversal appearing on Cpk from damaging the output bridge rectifier in the power supply
Cpk has been reconfigured as 3 capacitors in series and 20 in parallel since the voltage reversal caused a peak-to-peak voltage that exceeds the rating for 2 capacitors in series. In the future we would be able to eliminate the resistors from the circuit and, by capturing the almost full voltage reversal, reduce the power requirements to only a few KW. Provided of course the voltage droop was acceptable.

Aluminum Dummy PFC







- First Three Concentrating Plates
  - Full Size, Aluminum, No cooling
- First Two Coils
  - Litz wire, Hand wound, No cooling
- Plate spacers
  - Either stainless steel or insulator

Draft schedule for PFC prototyping

<table>
<tr><th>Month:</th><th>Mon</th><th>Tue</th><th>Wed</th><th>Thu</th><th>Fri</th><th>Pulser stage 1:</th><th>Al Dummy PFC:</th><th>PFC Coils:</th><th>PFC Plates:</th></tr>
<tr><td>April</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td rowspan="2">Request for Quotes</td><td rowspan="3">Procurement</td><td rowspan="3">Request for Quotes</td><td rowspan="4">Final design cooling channels and mechanical</td></tr>
<tr><td>April</td><td>30</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>May</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td rowspan="5">Procurement</td></tr>
<tr><td>May</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td rowspan="4">Assembly</td><td rowspan="12">Procurement</td></tr>
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<tr><td>July</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td colspan="2" rowspan="4">Commissioning</td></tr>
<tr><td>July</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td></tr>
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<tr><td>July</td><td>30</td><td>31</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td>August</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td></td><td></td><td colspan="2" rowspan="3">Assembly</td></tr>
<tr><td>August</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td></td><td></td></tr>
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<tr><td>August</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td></td><td></td><td colspan="2" rowspan="5">Operations and Characterization</td></tr>
<tr><td>September</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td></td><td></td></tr>
<tr><td>September</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td></td><td></td></tr>
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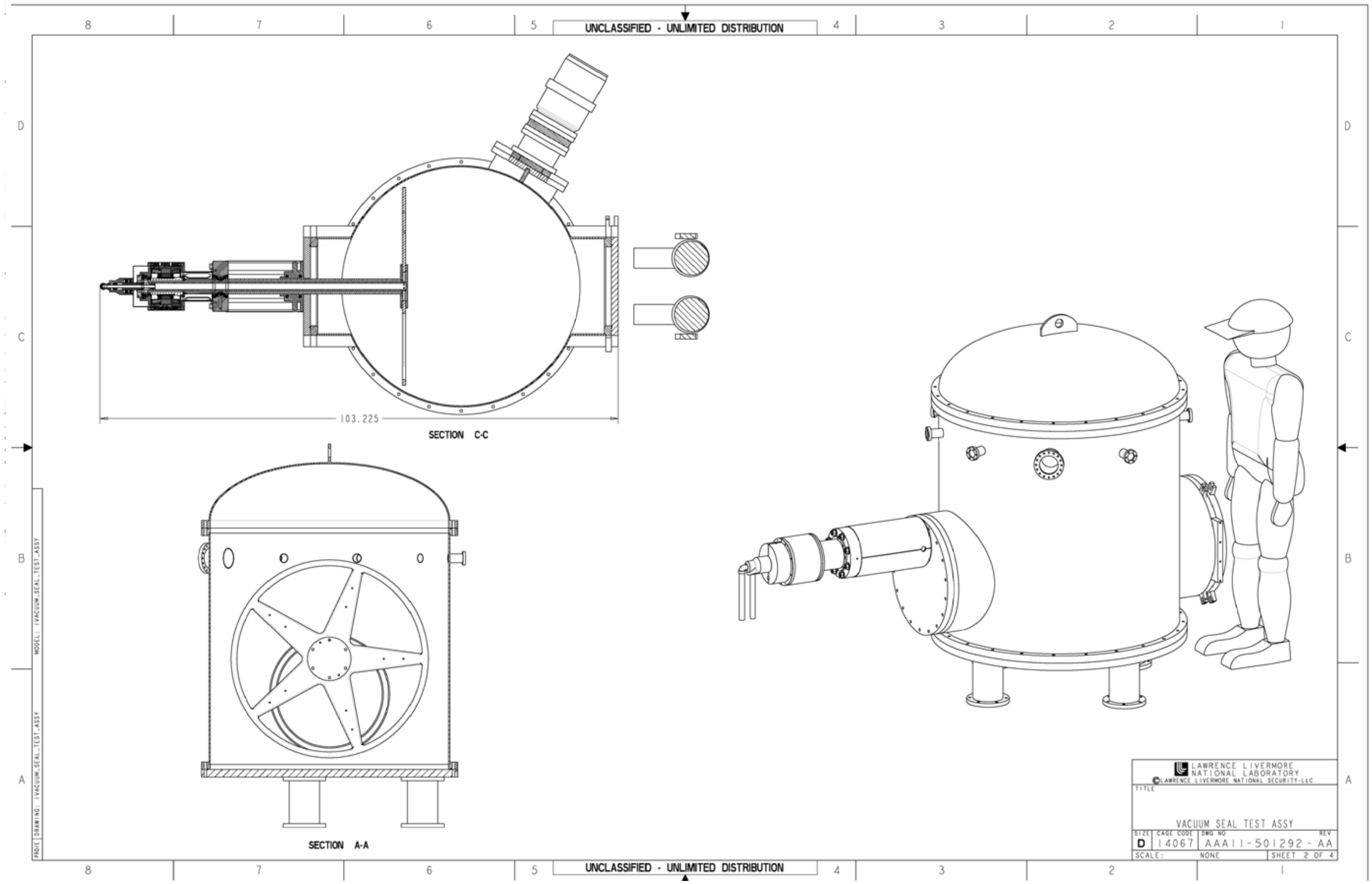
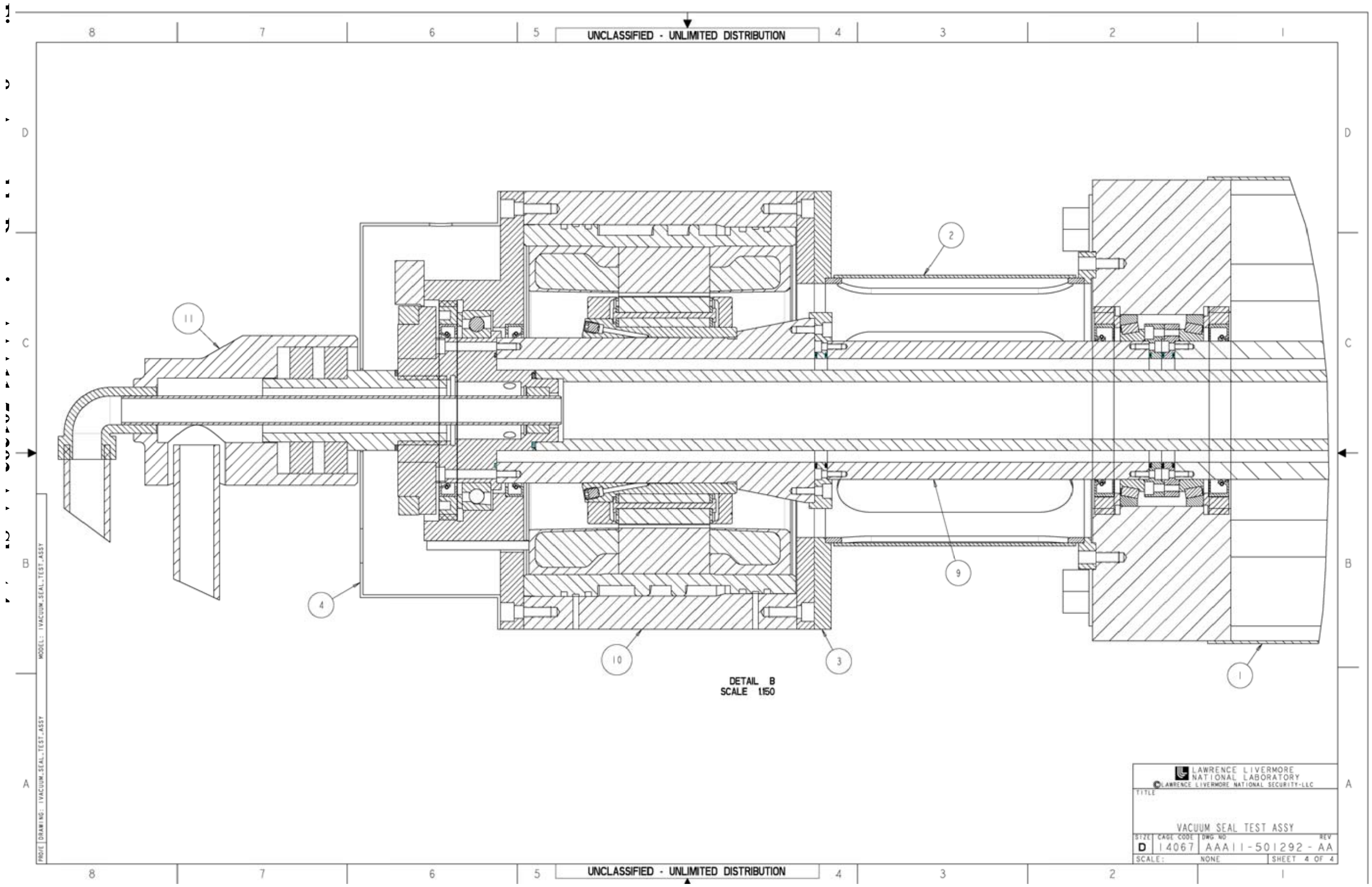
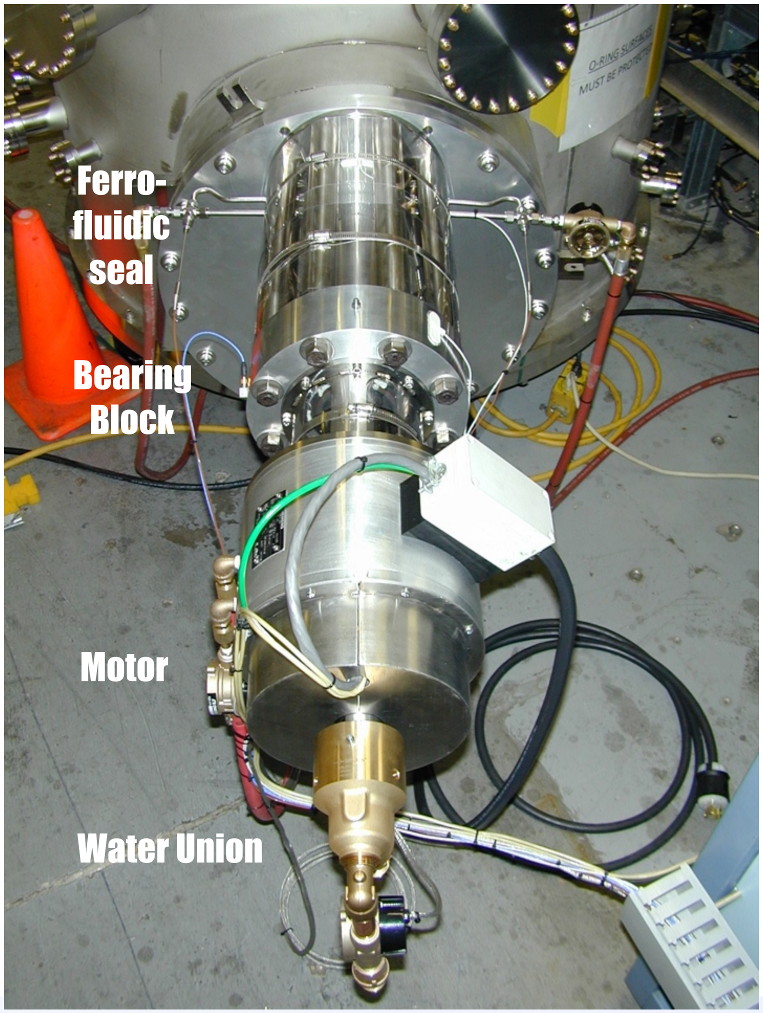
In parallel we are prototyping the rotating shaft with the ferro-fluidic vacuum seal



Drive motor and rotating cooling water coupling will mount directly on the shaft

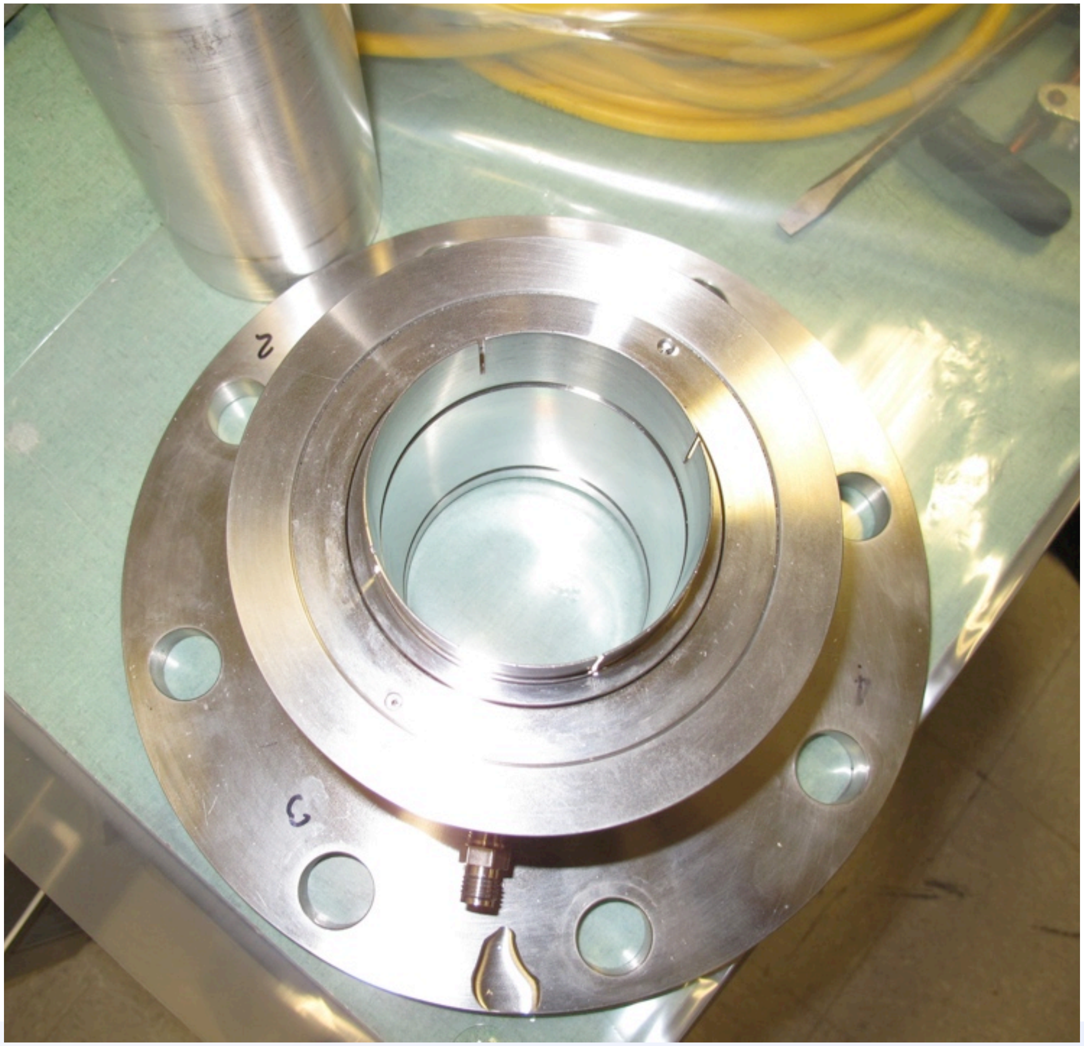


Commissioning of the ferro-fluidic seal test stand



- System assembled
  - Ferrotec seal #1
  - no flywheel
- Under vacuum
  - 10^{-7} torr
- Commissioning of the DAQ and slow controls underway
  - 100 RPM operation
    - 4 days of running
  - recording: temperatures, water flow, vacuum
  - fixing: torque and rpm measurement
  - adding: vibration sensors, residual gas analyzer

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

We have an existing outgassing test stand that we have modified to test the ferro-fluidic seals

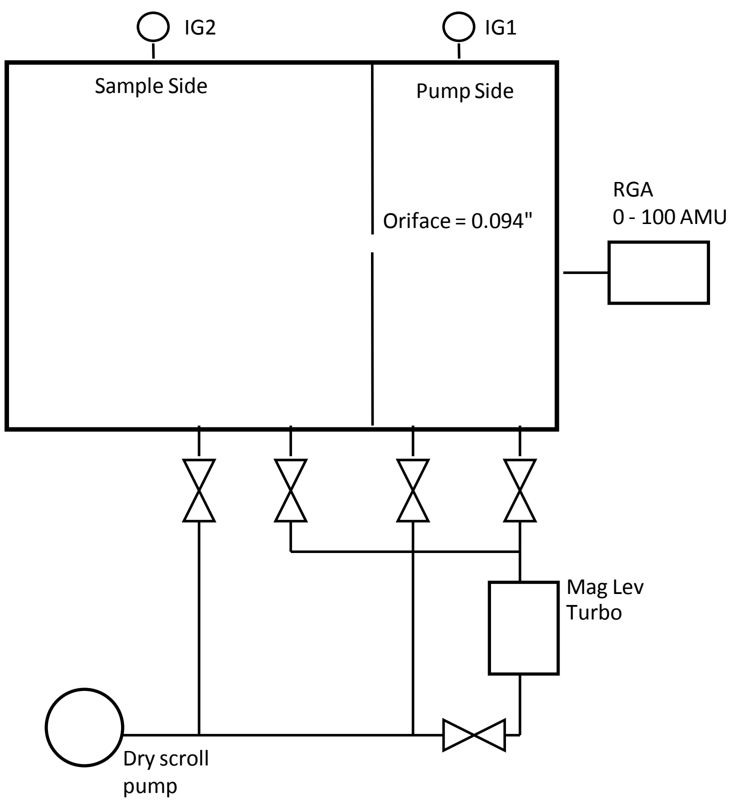
Vacuum Sciences and Engineering Lab Outgassing Measurement Test Stand

Sample Side Volume = 216 Cu. in.

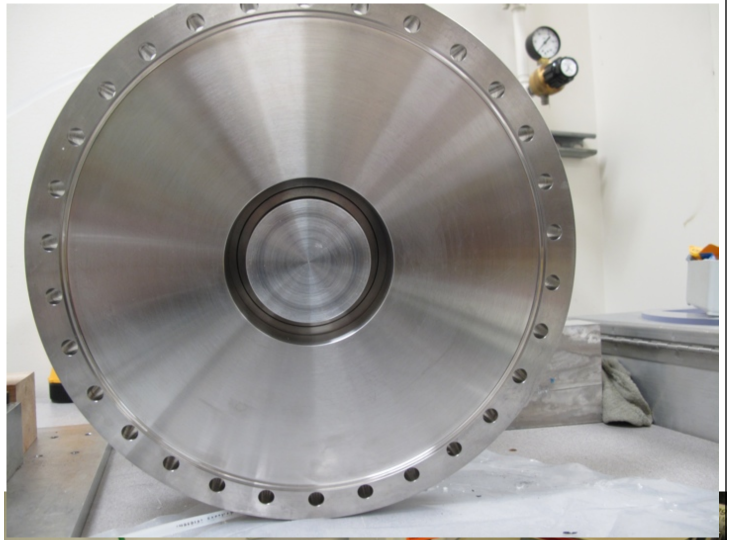
Sample Side Surface Area = 5,575 cm^2

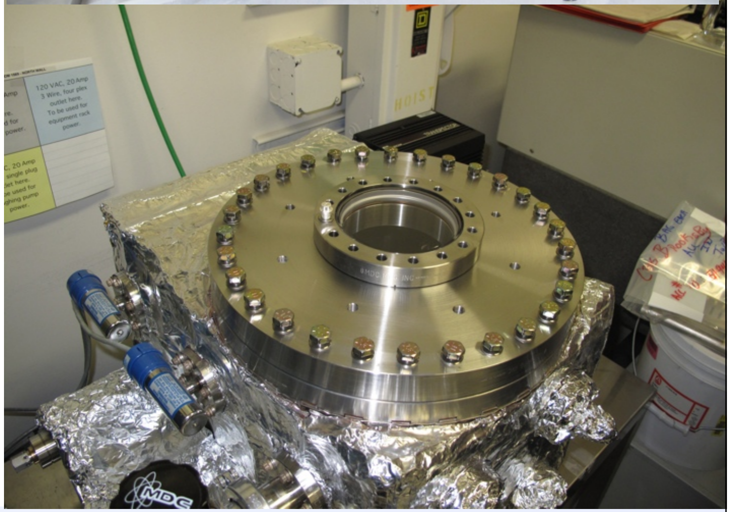
Conductance = 0.52 L/s for air at 20C

$Q = C(P_{IG2} - P_{IG1})$



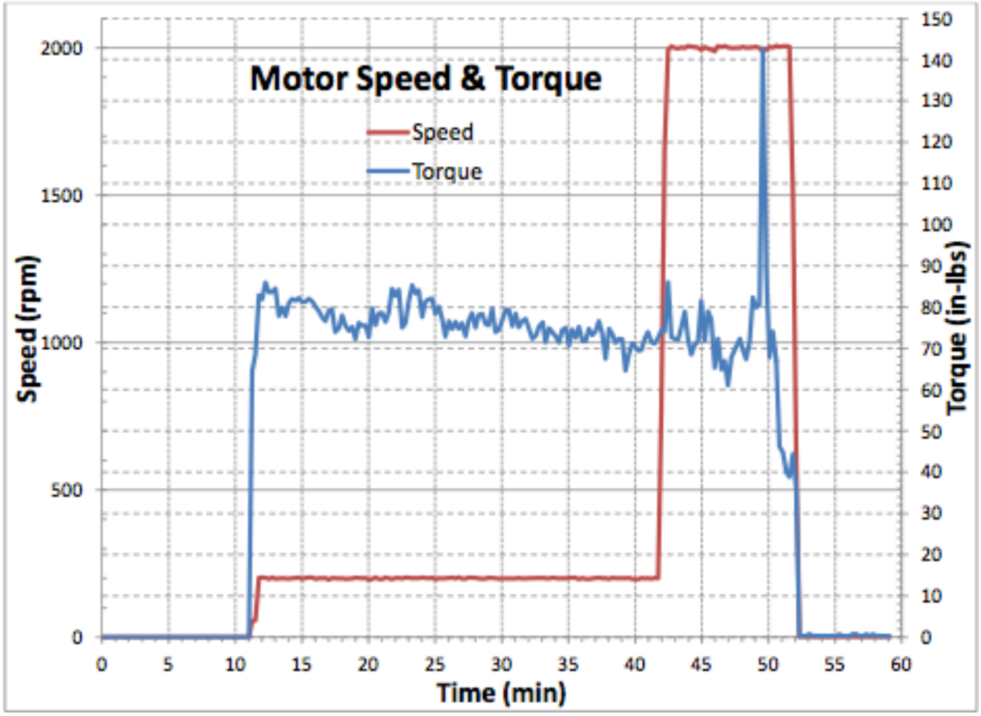
The test stand allows us to rotate the seal up to 2000 RPM with pressure and outgassing measurements





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

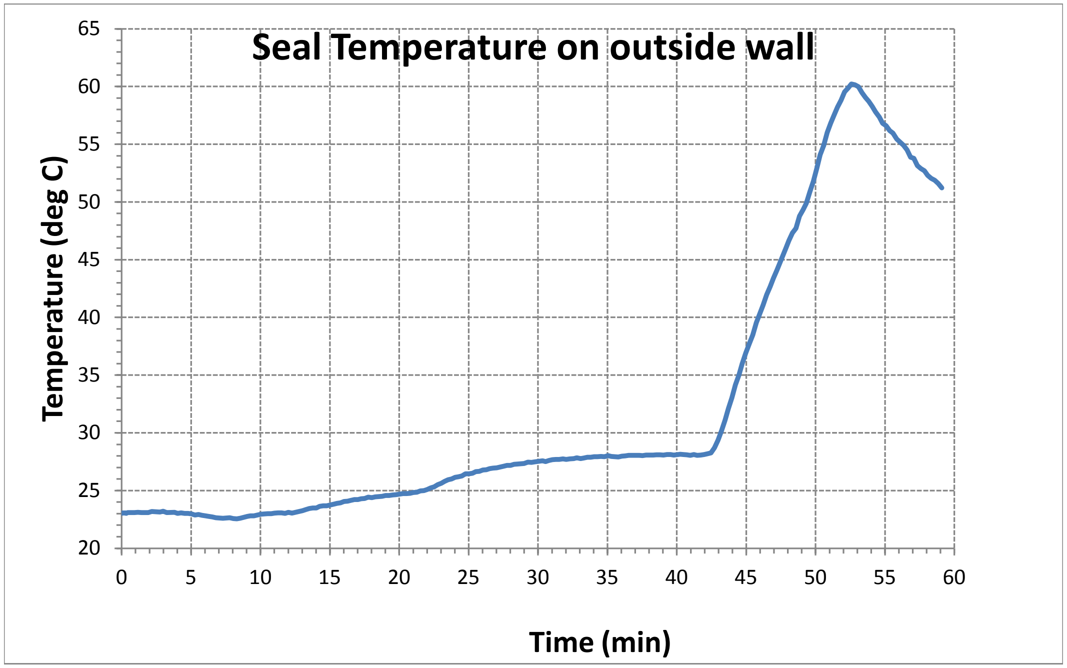
Scan #	Time	Time	Speed	
	H:M:S	min	rpm	Comments
1	10:32	0	0	started data recording
17	10:35	3	0	took full RGA Scan
20	10:36	4	0	took full RGA Scan
40	10:41	9.2	0	took full RGA Scan
43	10:42	10.2	0	took full RGA Scan
47	10:43	11.2	200	
123	11:03	30.5	200	took full RGA Scan
162	11:13	40.5	200	took full 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



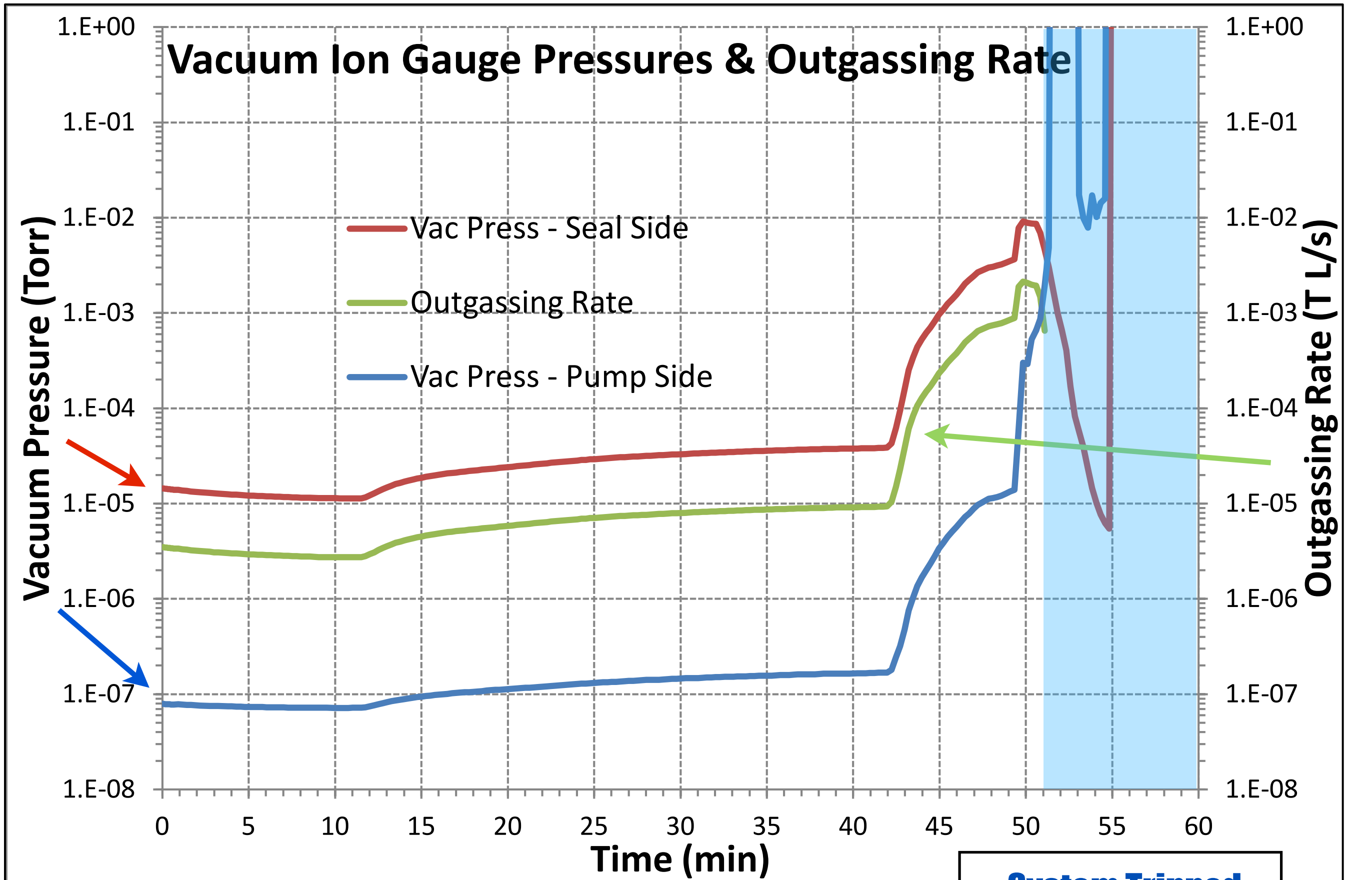
... and we killed it.

Temperature data was disturbing

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



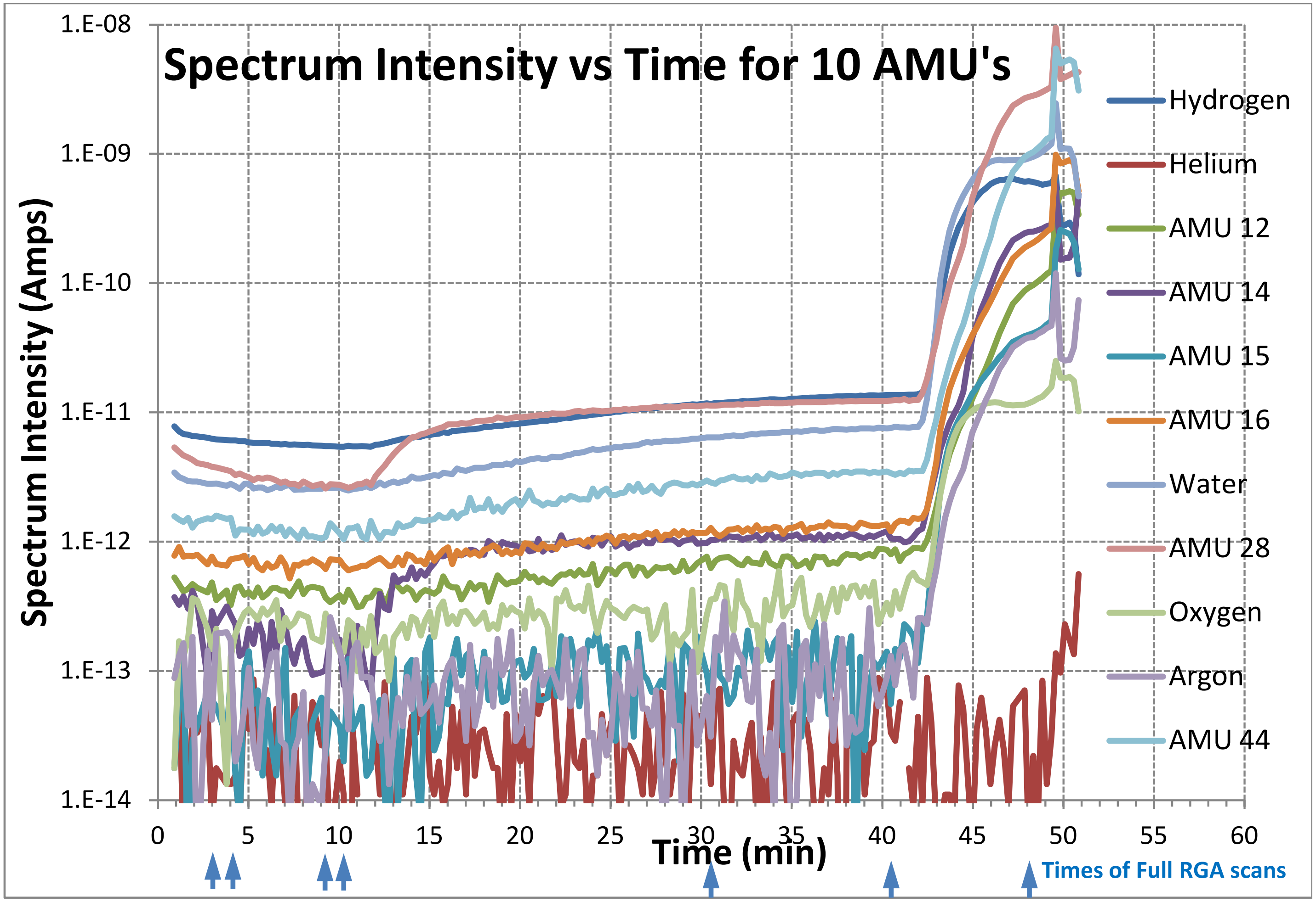
Outgassing looked like it was stabilizing when the seal failed



System Tripped

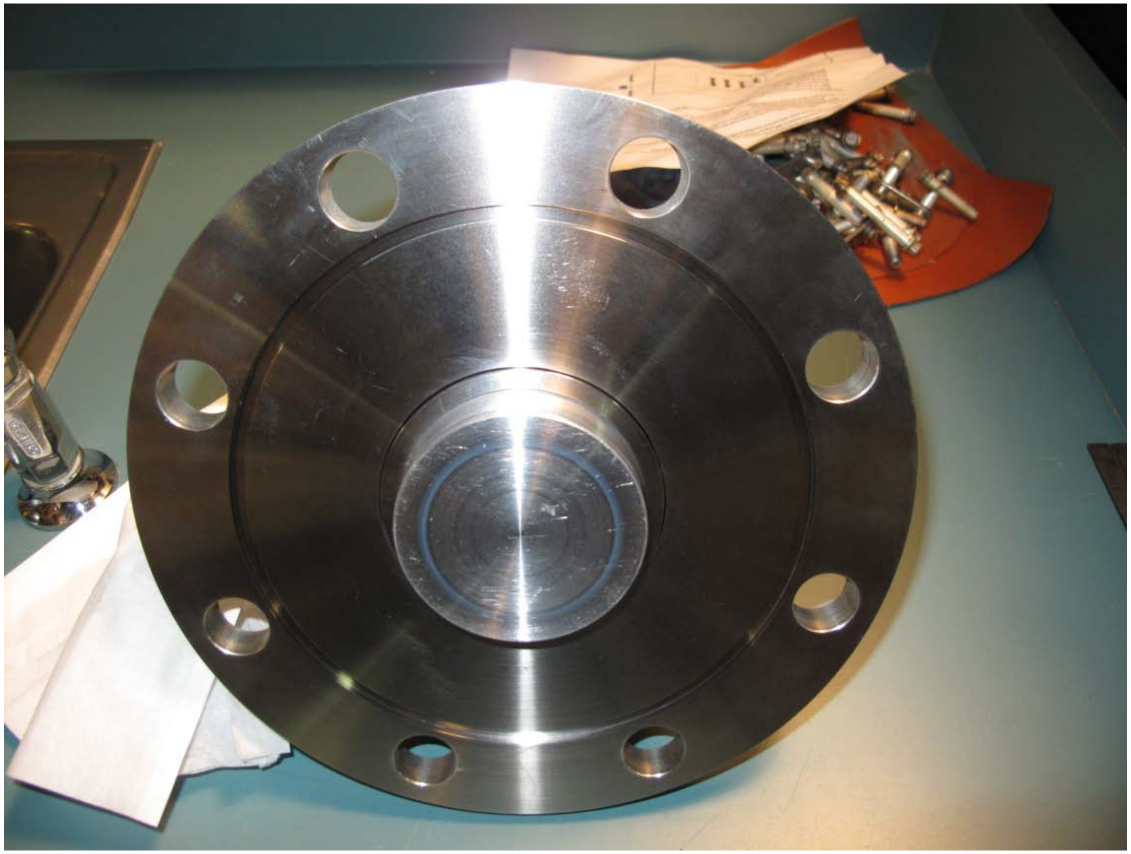
Gate Valves closed

Residual Gas Analyzer output showed a spike



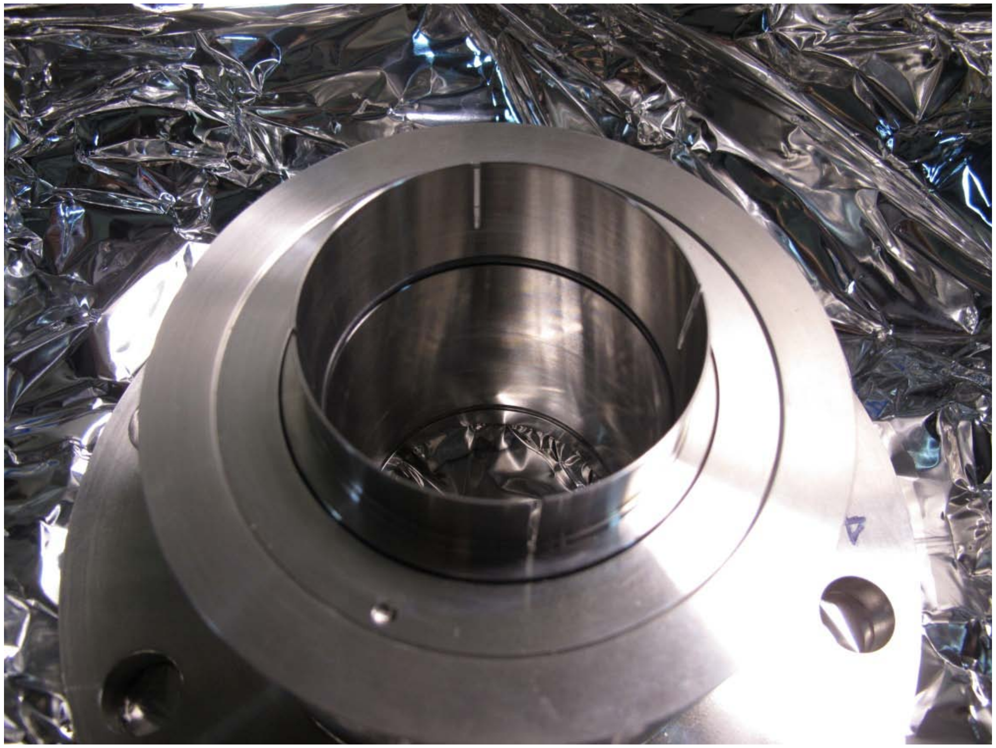
Seal inspected after failure

- No visual signs of failure or residue
- No signs of residue inside the chamber

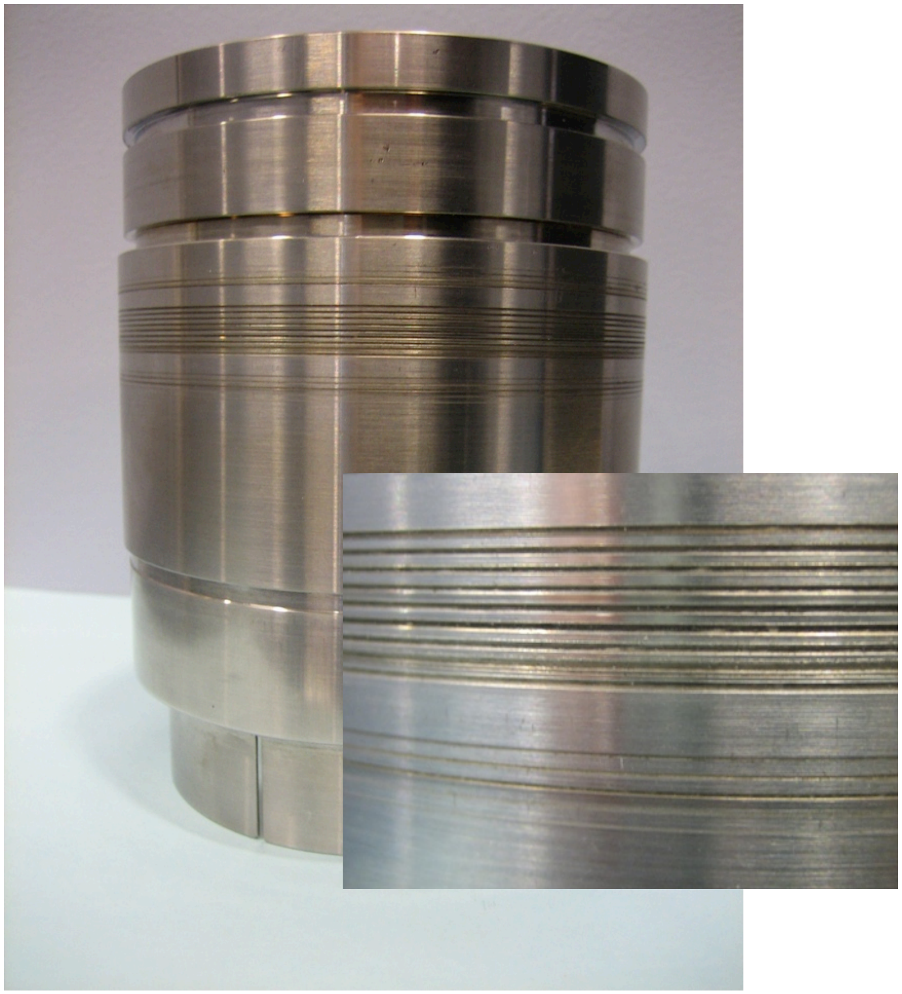


Checked whether there was a problem on the shaft seal

- O-rings were good.
- No sign of slipping
- No indication of any problem here



Rigaku post-mortem shows a design flaw

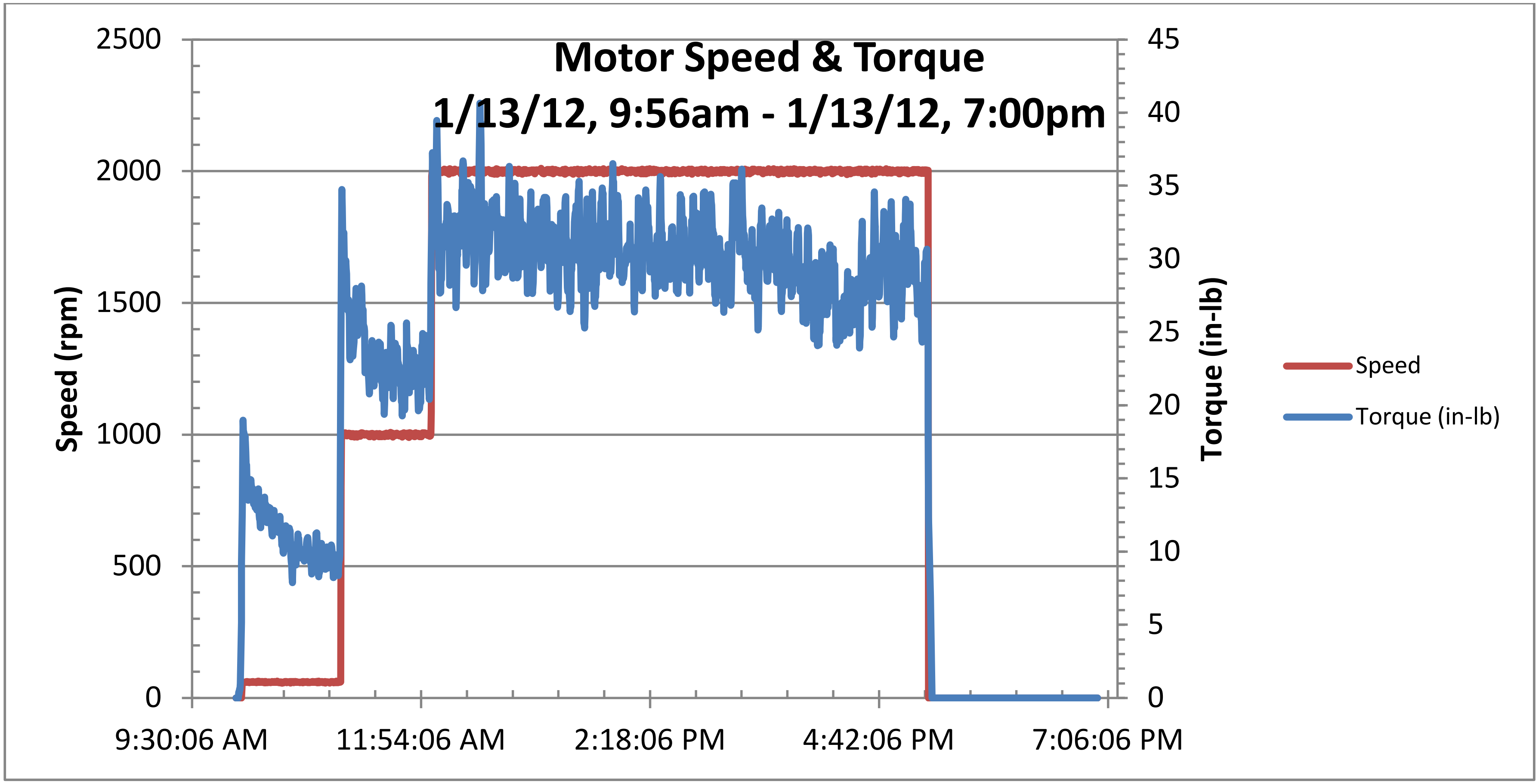


- Differential expansion between dissimilar metals caused contact between pieces at high temperature
- Grinding occurred leading to failure
- Rigaku agreed to rework the piece under warranty

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

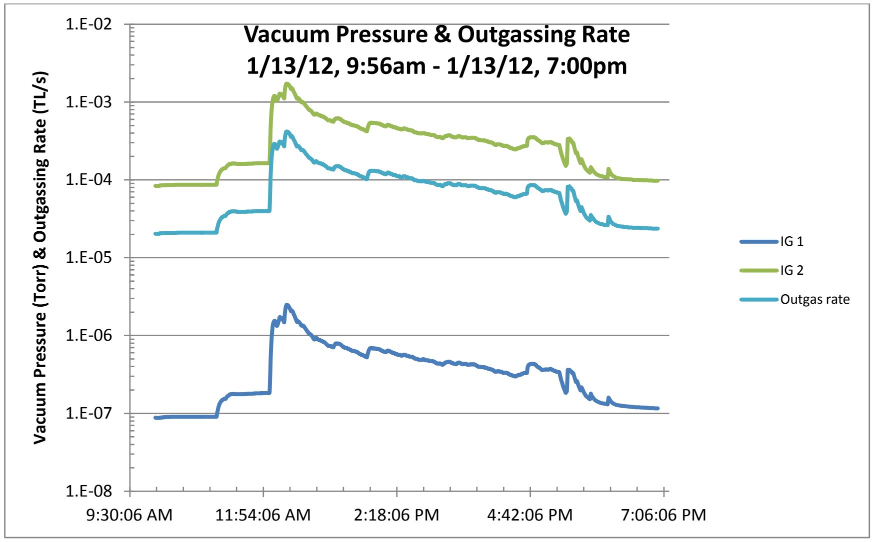
- Since it seemed that we had a heating problem with the Rigaku seal we chose a lower viscosity / higher outgassing ferrofluid.

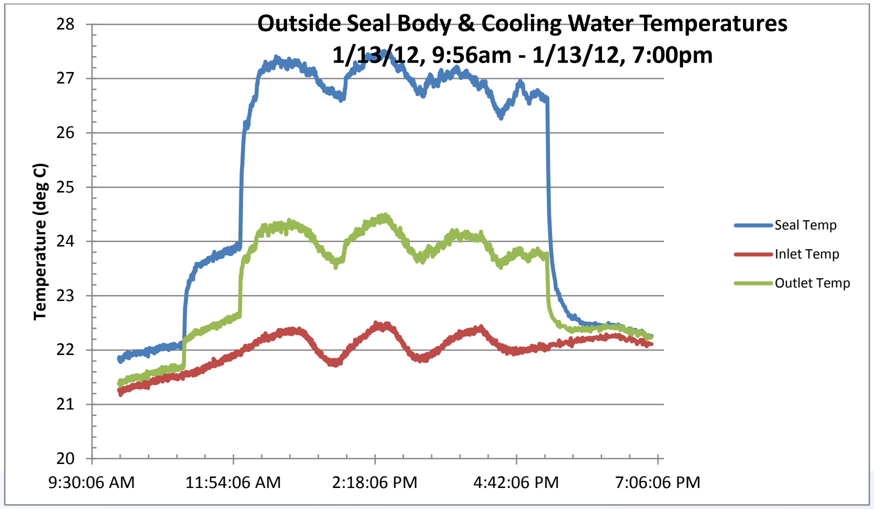
The ferrotec seal ran without significant problems at 2000 RPM



We logged about 38 hours total running time at 2000 RPM

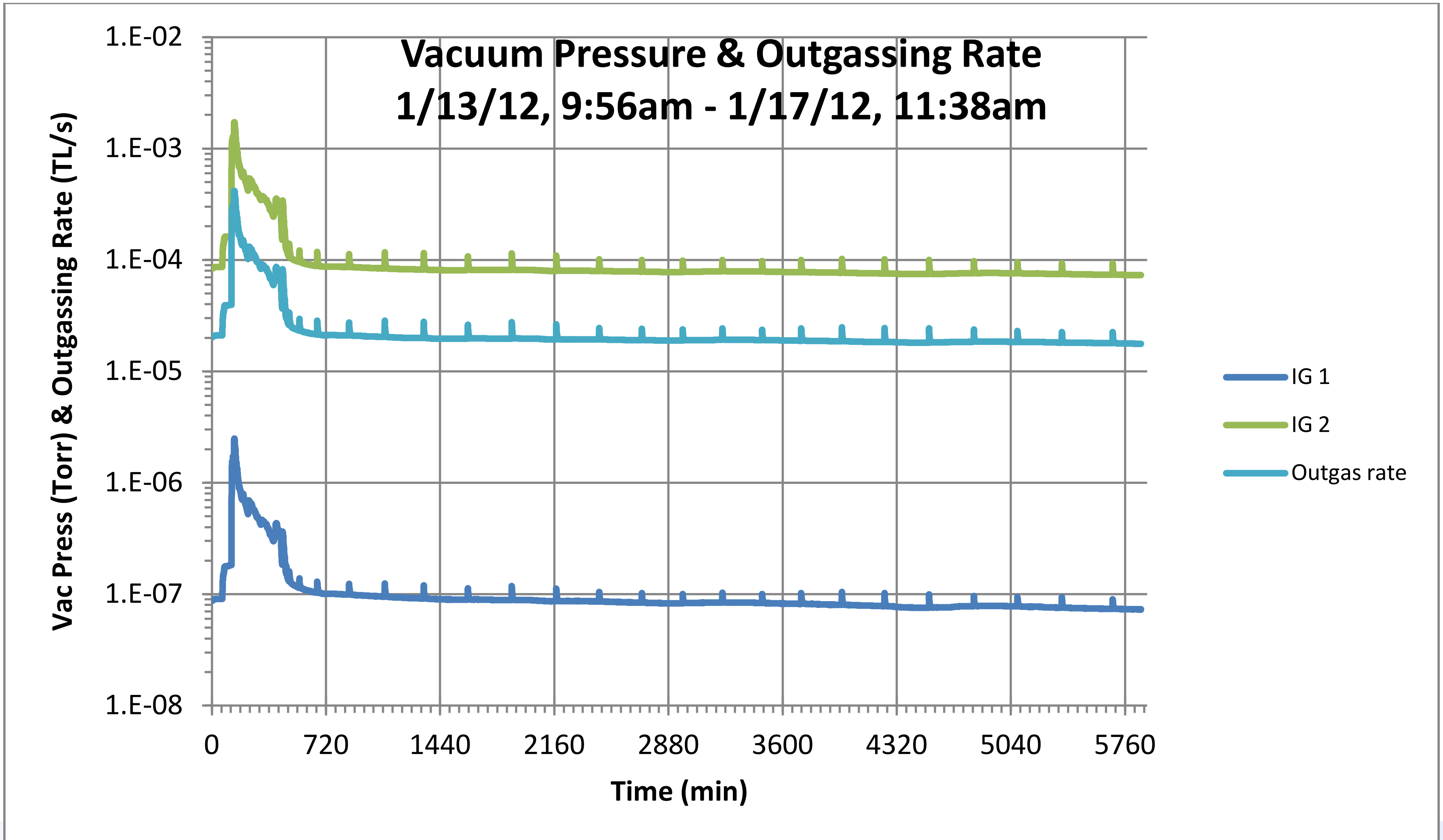
Temperature was stable, outgassing rate was falling over the 5 hours at 2000 RPM





- Seal seemed to be performing normally

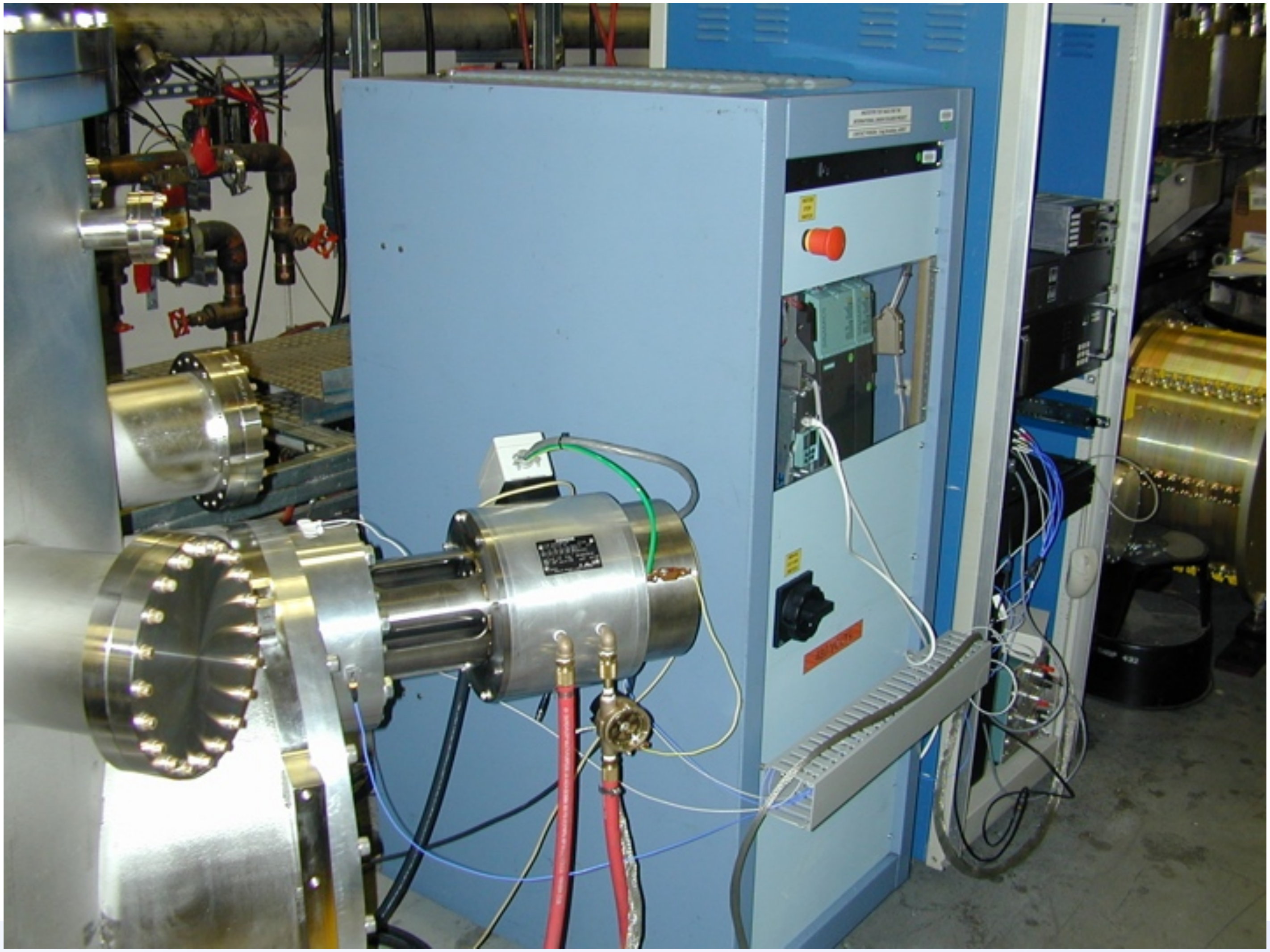
After operation took data at 0 RPM: outgassing was stable but the seal burps regularly



History and Status of our Available Seals

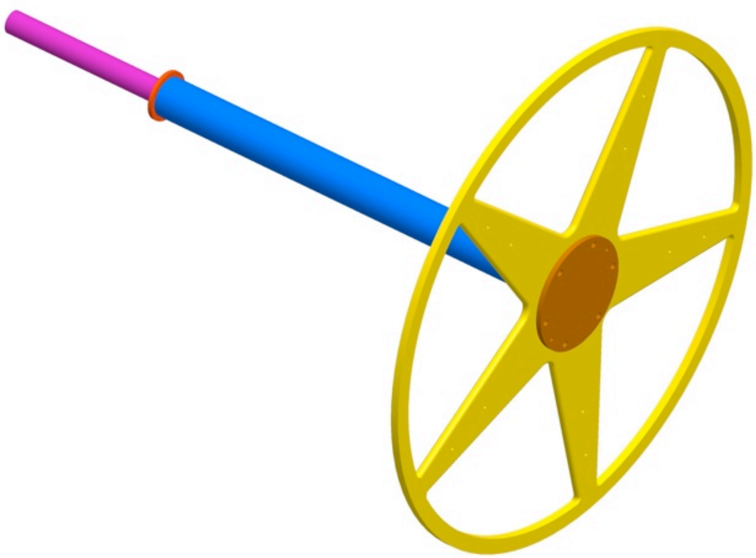
- Rigaku #1
  - Catastrophic failure after 15 minutes at 2000RPM on the outgassing test stand
  - Rigaku analysis indicates differential expansion of components lead to failure
  - Rigaku does not recommend using high viscosity fluid above 1450 RPM
  - Switched fluid for low viscosity type
  - At LLNL waiting for outgassing test
- Ferrotec #1
  - Low viscosity fluid
  - Normal operation for 38 hours at 2000 RPM on the outgassing test stand
  - Higher outgassing than Ferrotec expected
  - Currently mounted on the full test stand
- Ferrotec #2
  - Currently on the outgassing test stand
  - Better outgassing than Ferrotec #1 initially
  - Ran rough at one point until motor mount was loosened to relieve side stress

We now have working seals and an operational test stand

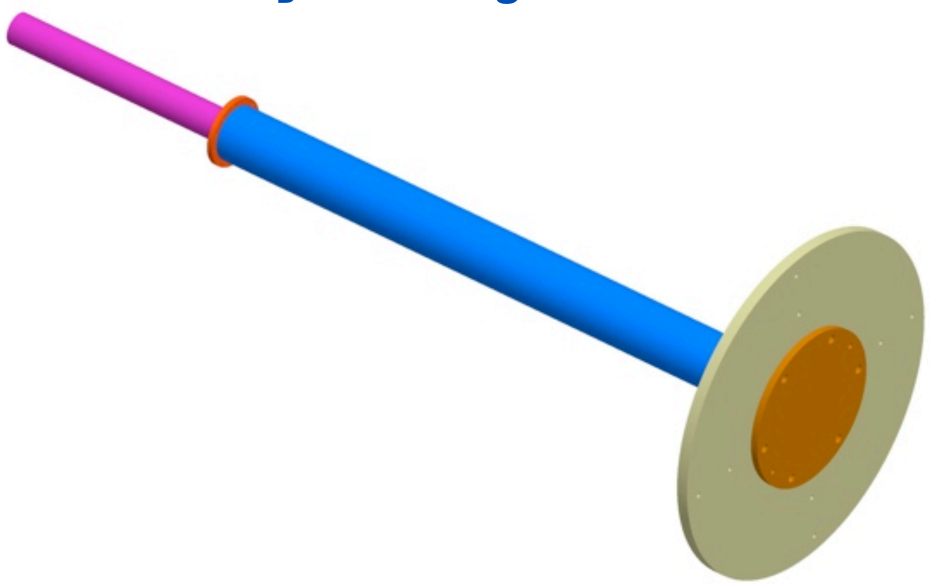


Safety of the flywheel is an issue for operation of the flywheel at LLNL

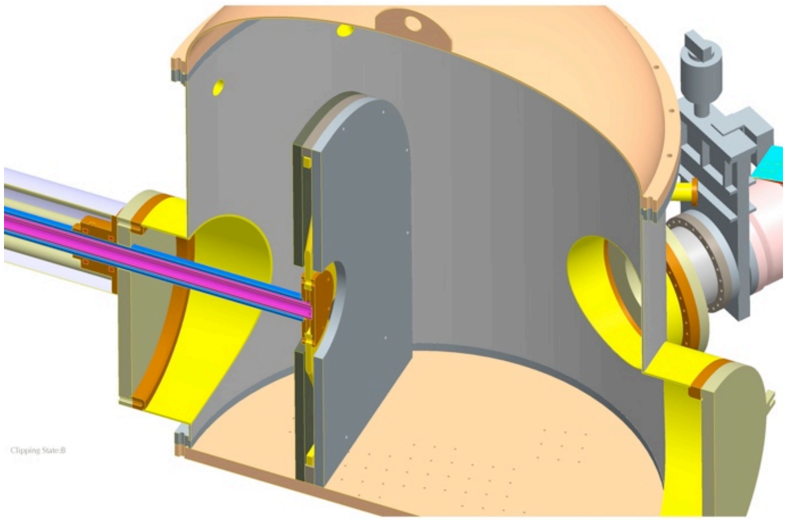
Flywheel - Factor of 2 away from yield strength

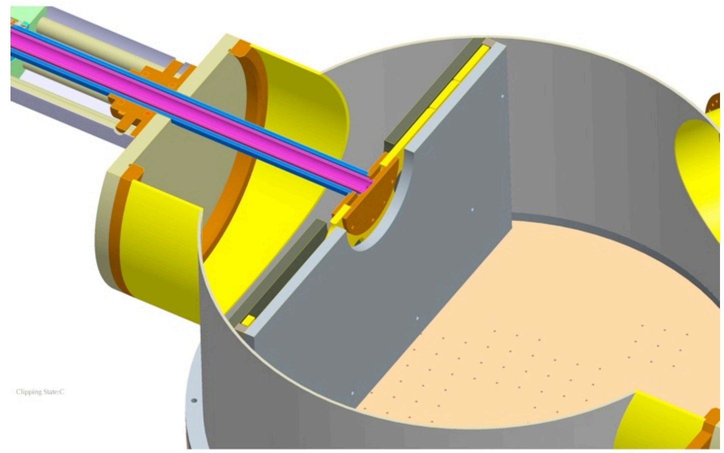


Medium disk - stainless steel, same weight as flywheel, similar rotordynamics. Factor of 20 away from yield strength



Additional shielding must be installed before we can operate the target wheel at 2000 RPM





- 100 m/s fragments can penetrate the vacuum vessel
- Additional 1" thick steel plates are required to contain fragments if there is a failure

Draft schedule of operations for the rest of our funding period

Month:	Mon	Tue	Wed	Thu	Fri	
April	23	24	25	26	27	Outgassing tests
April	30	1	2	3	4	Installation of medium wheel and Ferrotec Seal #2
May	7	8	9	10	11	
May	14	15	16	17	18	Operations
May	21	22	23	24	25	
May	28	29	30	31	1	
June	4	5	6	7	8	
June	11	12	13	14	15	**8 weeks**
June	18	19	20	21	22	
June	25	26	27	28	29	
July	2	3	4	5	6	
July	9	10	11	12	13	Installation of target wheel, shroud and Rigaku seal #1
July	16	17	18	19	20	
July	23	24	25	26	27	Operations
July	30	31	1	2	3	
August	6	7	8	9	10	
August	13	14	15	16	17	
August	20	21	22	23	24	**10 weeks**
August	27	28	29	30	31	
September	3	4	5	6	7	
September	10	11	12	13	14	
September	17	18	19	20	21	
September	24	25	26	27	28	

Summary

- Pulsed Flux Concentrator
  - A ramped pulse allows us to compensate the magnetic field droop at room temperature
  - Design change from
    - cryogenic, liquid nitrogen cooled to
    - room temperature, water cooled
  - Prototyping efforts for the rest of this year
- Ferro-fluidic seal
  - Low vapor pressure, high viscosity fluids are a problem at 2000 RPM.
    - Success with lower viscosity fluids
  - Long term running is about to begin and continue for the rest of the year