A 60,000 RPM X-ray chopper

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Project Objectives

- Philip Coppens group at SUNY Buffalo needs an X-ray chopper for time-resolved crystallography
- Enables study of molecular structure in excited states
- General specifications:
  - 60,000 RPM disk rotation rate
  - aperture timing jitter of < 23 nsec

Solution components

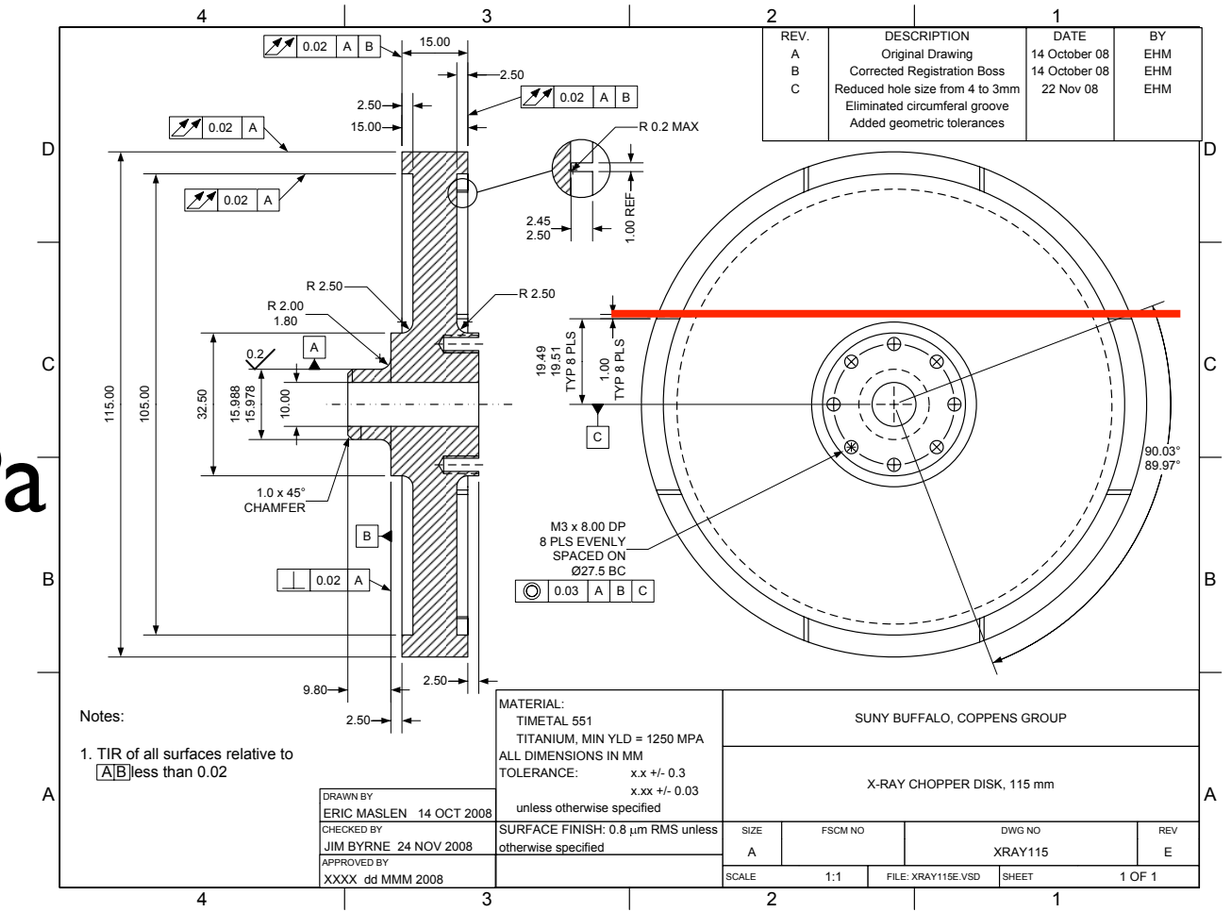
- Chopper disk rotates perpendicular to beam-line
- Wanted to eliminate ball bearings (speed too high) and air bearings (vacuum...)
- Hard to find suitable commercial or custom spindle

General Configuration

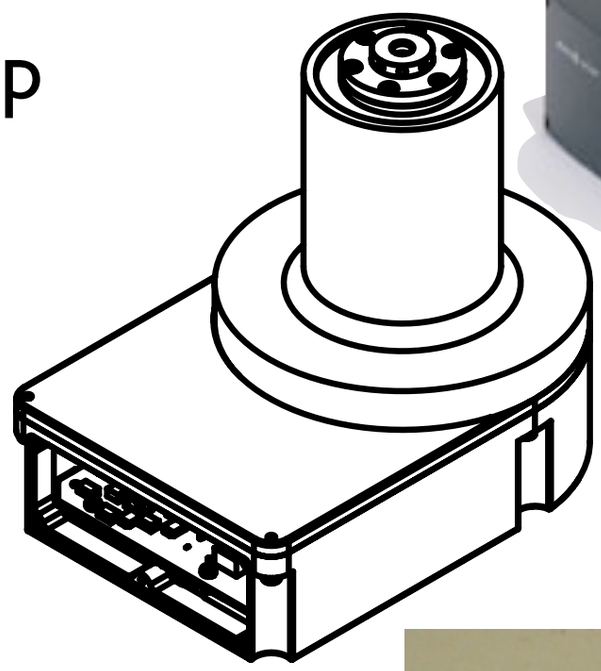
- motorized spindle in magnetic bearings
- chopper disk with chordal apertures
- phase detection using reference laser
- control using National Instruments RT control system

The chopper disk

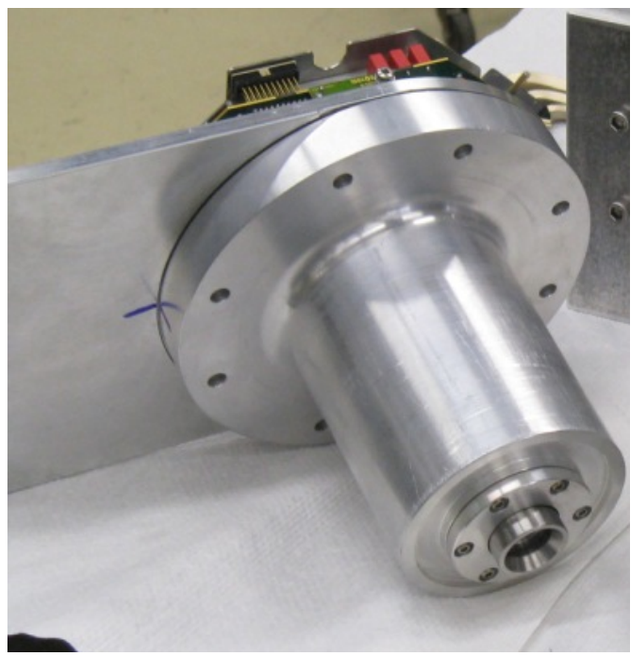
- made of Titanium alloy (Timetal 551)
- yield strength = 1250 MPa
- burst speed estimated at 84 kRPM
- hard to find a suitable machine, balancing shop!



The spindle



- commercial turbomolecular pump
- supplied by MECOS AG
- designed for vacuum operation
- discarded shroud and blading
- modified motor drive to permit fine adjustment of speed:
  - two bit digital interface
  - 00_2 = hold, 01_2 = accelerate, 10_2 = decelerate

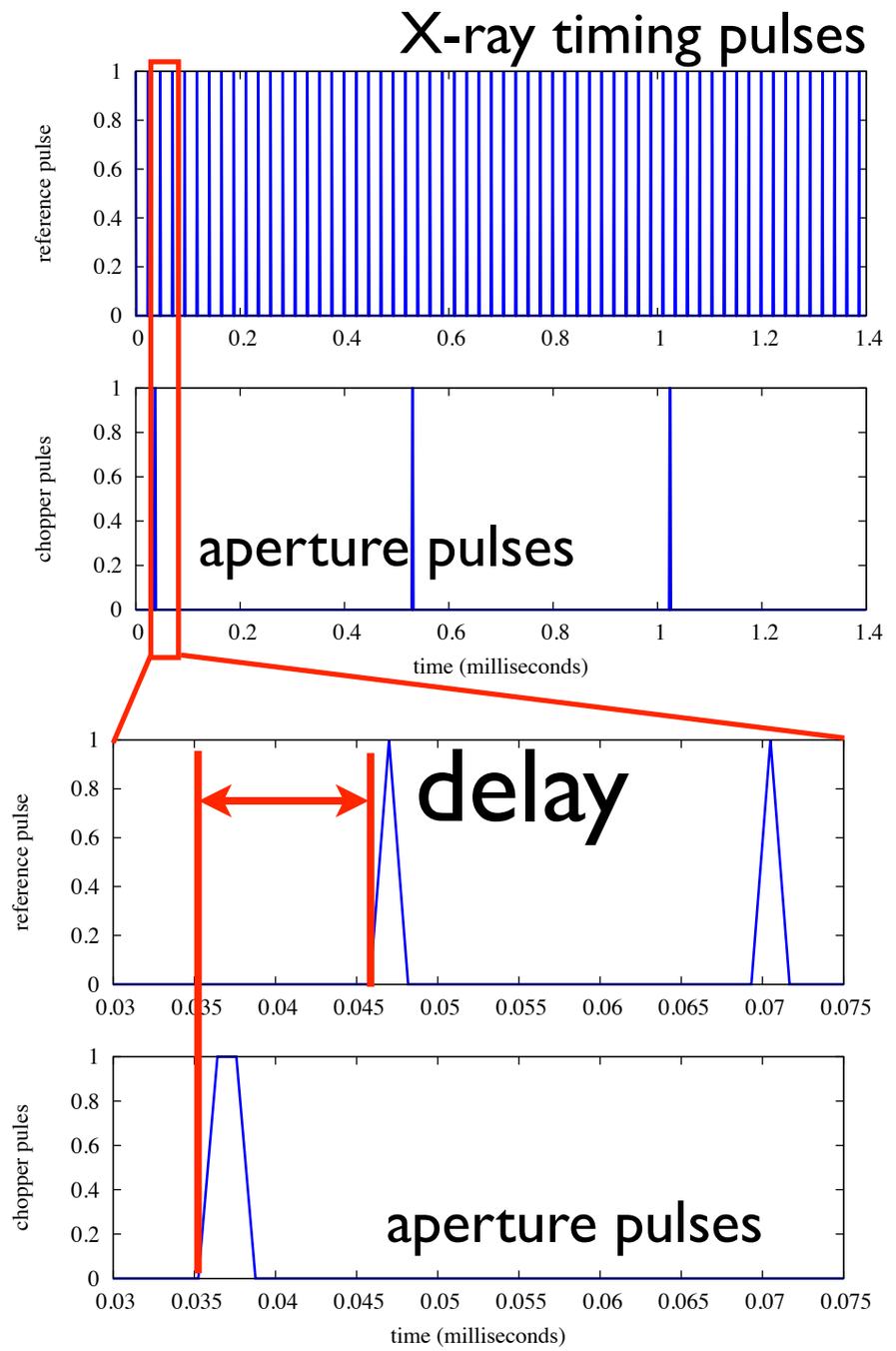


Speed Control

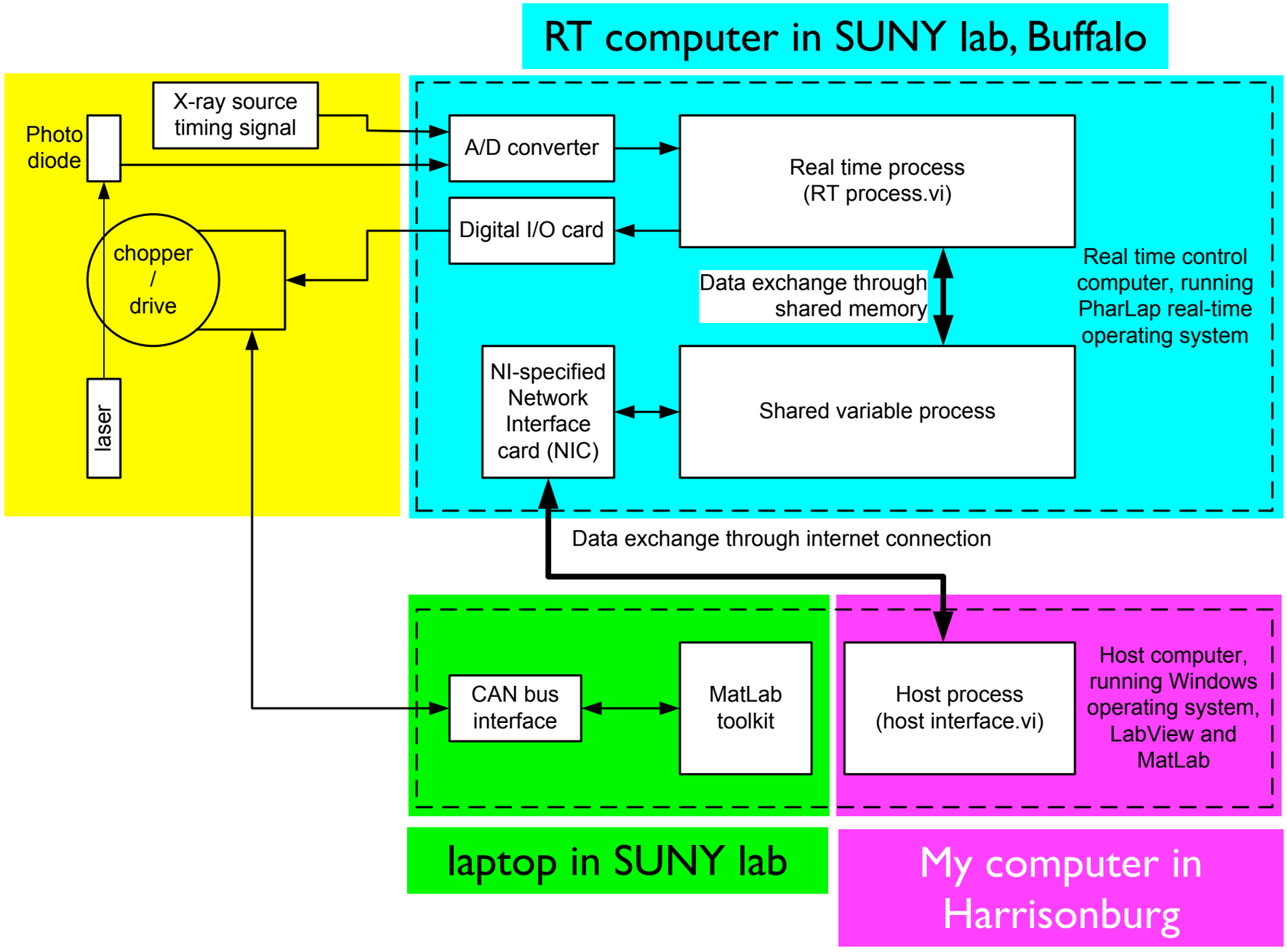
- Maybe biggest challenge
- Nominal speed control much too coarse for this purpose: +/- 1%
- To get 25 nsec jitter, speed needs to be controlled to $\delta f = 25$ ppm
- Need to stay synchronized so average speed error must be zero.

Approach

- Detect aperture arrival with laser interrupter
- Trigger 1 GSa/sec A/D converter on aperature, capture next X-ray timing pulse
- Measure delay
- Adjust spindle speed up or down to get delay to target value

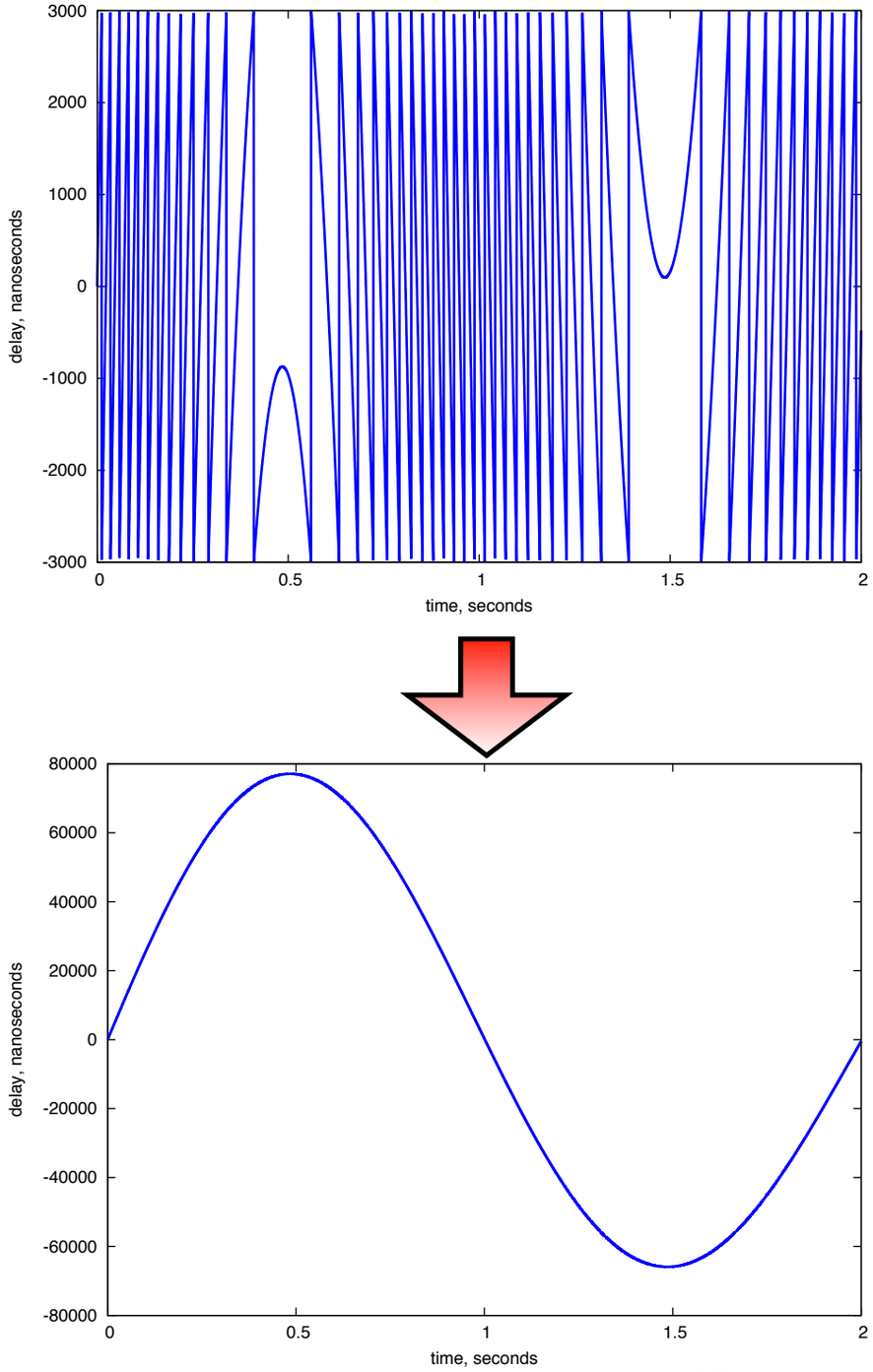


Physical Realization



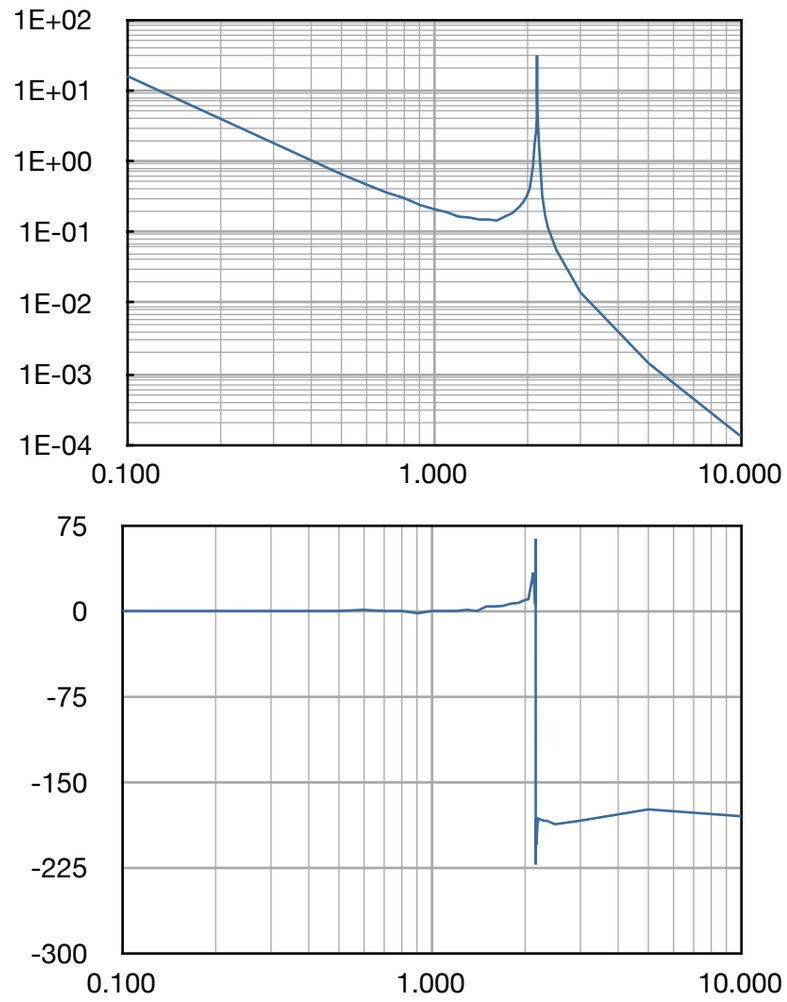
Problems

- Phase detection: must unwrap extremely large delay errors at startup when speed error is large.
- Without unwrapping, can't capture from large speed errors.
- We are able to reliably unwrap about 6 msec of delay.
- Maximum rate of delay error accumulation we could detect was 2.25 msec/second.
- Corresponding speed error is 22,500 RPM



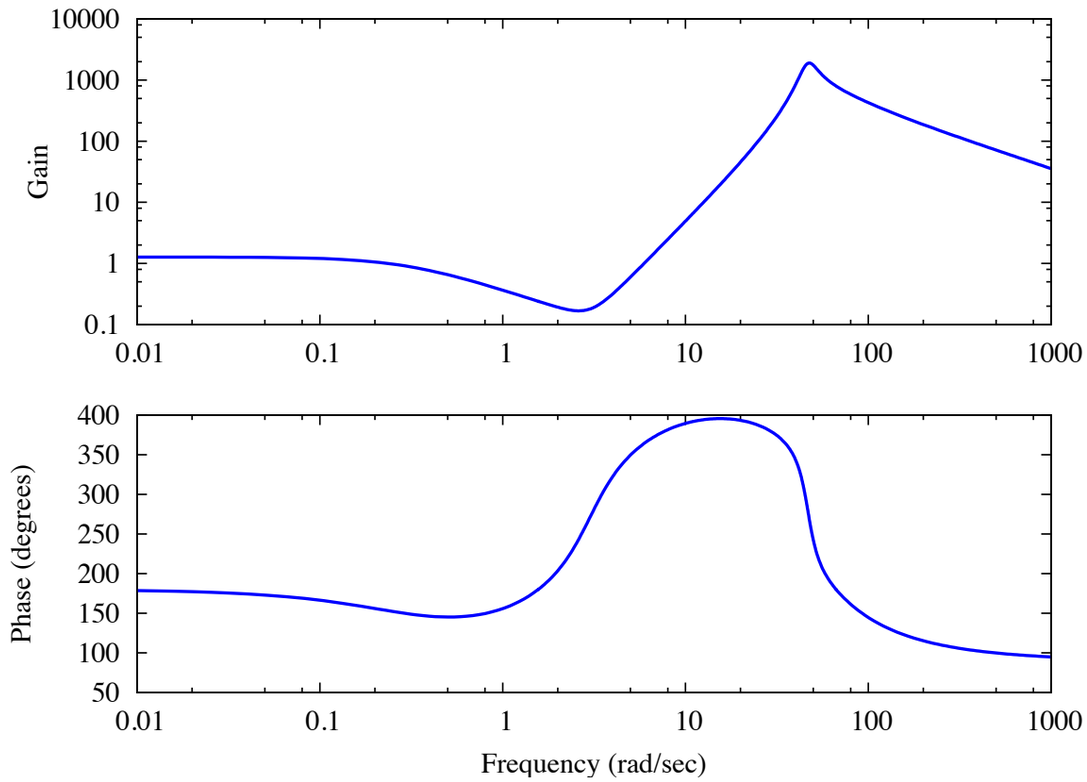
Problems

- Motor / disk system has a torsional resonance due to magnetic stiffness at 2.33 Hz relative to the motor instantaneous magnetic axis
- Motor control must detect this oscillation and provide torque modulation to kill the oscillation



Control Solution

- Can't stabilize oscillation with PID control: too much phase lag in the plant.
- At large delay error: $\mathcal{H}_\infty$ controller
- At small delay error: add an integrator to the controller to ensure zero mean delay error

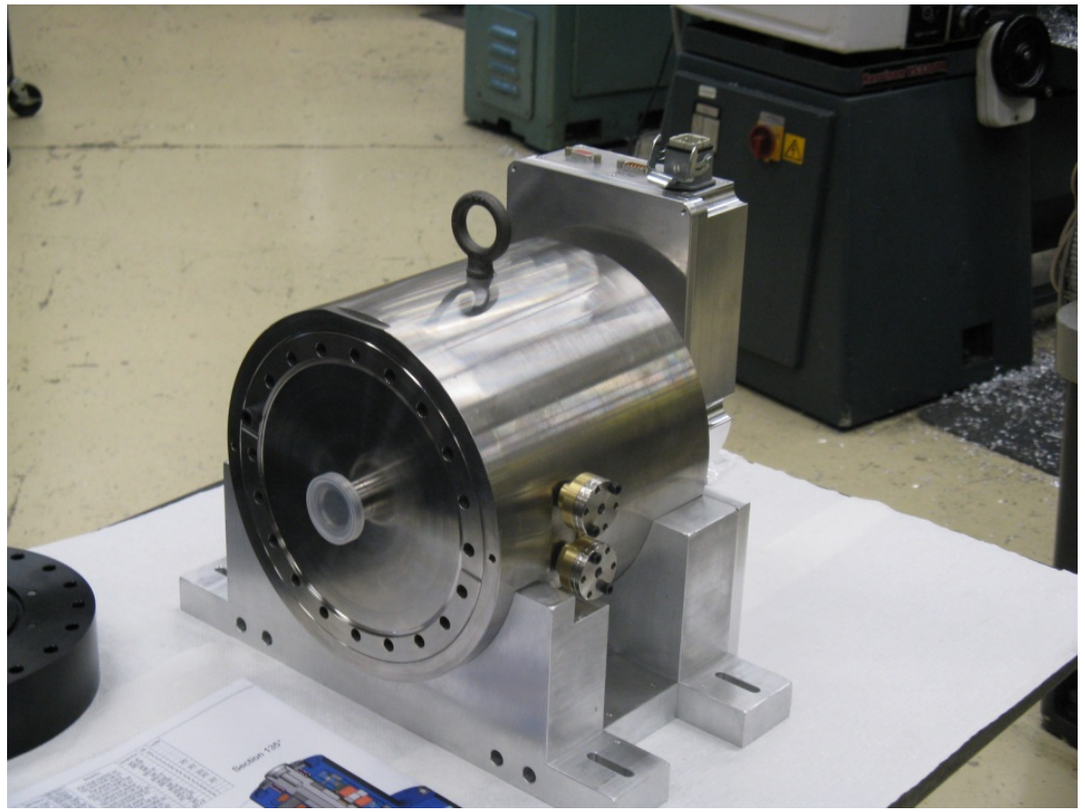


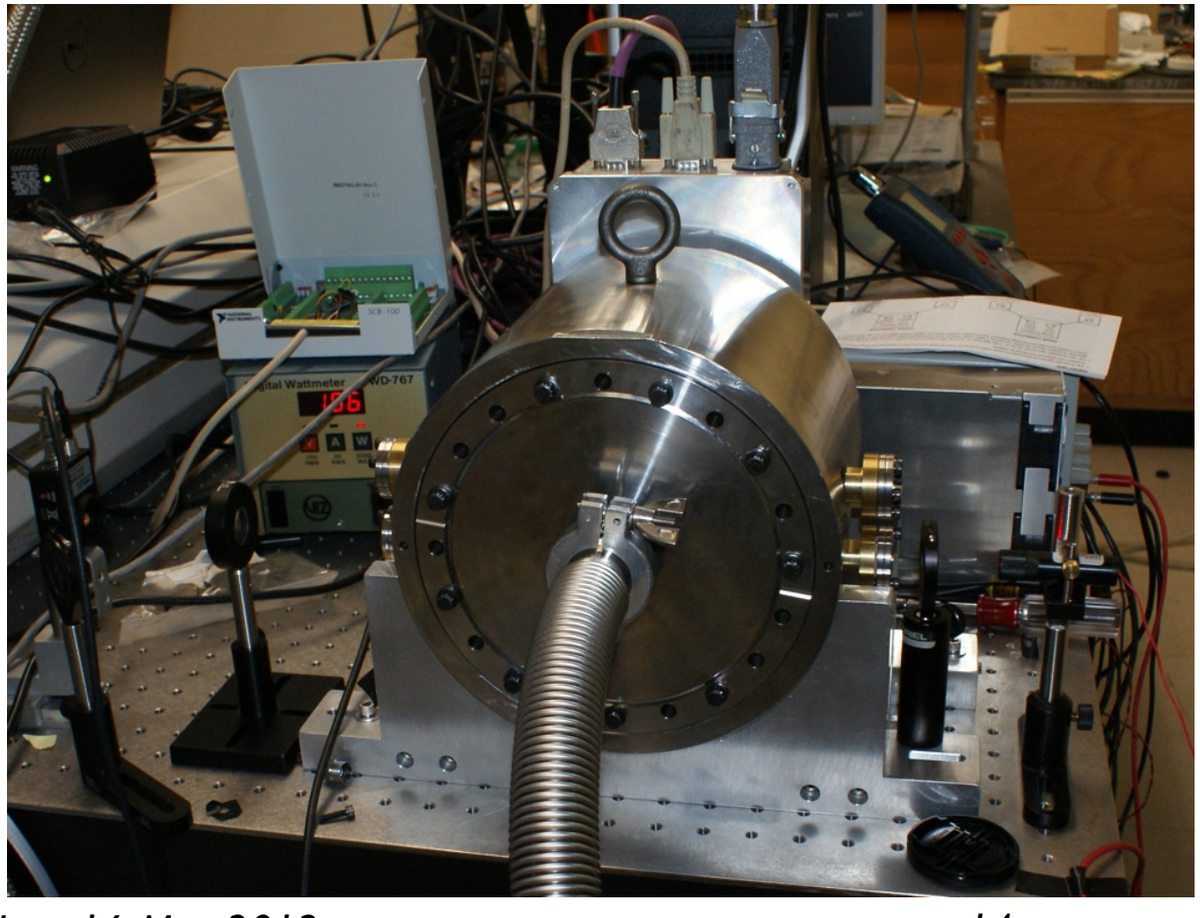
Teleoperation

- Torsional resonance problem discovered during commissioning at SUNY Buffalo
- Required extensive testing, some experimentation with control
- Very expensive to do this in Buffalo!
- NI RT control software enabled teleoperation: all experiments, control design, implementation, and testing done from Harrisonburg.

Apparatus

- Vacuum/burst containment
- Two beam ports: one for X-rays, one for timing laser
- Measured delay jitter:
  - mean < 0.1 nsec
  - stdev = 23 nsec





Summary

- Nearly everything was off-the-shelf
- Commercial TMP spindle modified to implement external accel/decel signal
- Delay controller: standard Dell box with NI digitizer (1 GSa/sec A/D) and digital I/O board
- wheel and containment are custom built
- performance: 60,000 RPM with 23 nsec jitter

Acknowledgements

- At SUNY Buffalo:
  - Philip Coppens
  - Jason Benedict
  - Milan Gembicky
- At MECOS AG:
  - Vincent Chenal
  - Philipp Buehler
- At BRG Machinery
  - Hunter Cloud
  - Jim Byrne
  - Bob Rockwell