Why Beryllium?

- Graphite radiation damage issues caused LBNE to look at Beryllium for target use.
  - Complete structural failure at $10^{21}$ p/cm$^2$ during BLIP run.

- Simulations with beryllium components do not seem to line up with the ‘real world’.
Beryllium tests and past uses at FNAL

- Beam windows
- Pbar Lithium lens windows
  - Possible damage seen at 0.15mm sigma spot size, no damage at 0.19mm sigma.
Beryllium test

- 1999 testing of NuMI prototype target

- Beam sigmas of 0.16mm, 0.22mm in x,y at 120GeV
- 180 pulses, 1.03e13 POT/pulse, 10us pulse
- Each fin is approx 2mm x 6mm x 25mm
Light microscope images show ‘dark spot’ on first fin, upstream side.

- No marks on other upstream or downstream faces.
1999 NuMI Test – Physical Inspection

- SEM images of the spot (left).
- Also found another spot (right) with similar discoloration.
1999 NuMI Test – Modeling

Diagram showing the workflow for modeling beryllium for target and beam window applications. The inputs include beam parameters, energy deposition, and geometry. The models are six fin extended geometry, energy deposition, and internal heat generation table plots for MARS; Energy deposition generation table, plots for Custom Python Code; Beam heat generation for ANSYS Thermal; and Temperature, geometry for ANSYS Structural. The outputs are energy deposition, internal heat generation table plots, temperature, and stress/strain.
Output from MARS and Python Script

- Parse MARS output for energy deposition values.
- Build a list of locations and corresponding EDep.
- Generate ANSYS input tables and plots for verification.
ANSYS Beryllium Material Properties

- Temperature dependent material properties used up to 600°C.
- Bilinear Kinematic Hardening
Temperature from MARS energy deposition results

- Maximum temperature approximately 560°C.
- Let fin cool to 20°C before next pulse. Times are not ‘real’.
1999 NuMI Test - Modeling

- Maximum principal stress – typical views
  - Deformations shown at ~50x
  - Bulge is ~5µm high, 1mm in diameter after 16 pulses.

End of pulse – 560°C
1999 NuMI Test - Modeling

- Maximum principal stress – typical views

After cooldown to 22°C

Large tensile preload for next pulse
1999 NuMI Test - Modeling

- Plastic strain – at end of 1st pulse

![Image showing plastic strain distribution and a graph of plastic strain vs. time for a 16 Pulse Run.](image-url)
1999 NuMI Test - Modeling

- Estimates of life from plastic strain cycling:
  - Very conservative estimates from Coffin-Manson relation

Point of max displacement: >1M pulses
Max plastic strain on surface: 18k pulses
Center of fin at beam center: 14k pulses
Global maximum plastic strain: 10k pulses
What’s wrong here?

- Other Beryllium components have seen comparable beam for many more than 14,000 pulses without failure.

- Is thickness a factor?
  - Modeled a thin Be window (.5mm) and compared to a thick window (5mm used on Li lens).
  - Thin windows no not appear to fare better.
Areas for improvement

- **Beryllium material properties**
  - Strain rate dependency with temperature effects.

- **Incorporating radiation damage**
  - Lithium lens saw ~10M pulses, corresponds to 1DPA in beam center.

- **Move to explicit dynamic simulation package**
  - LS-DYNA, AUTODYN, etc

- **Accurate failure mechanism**
  - Need more data points with failures of Beryllium.
  - Any beryllium failures from audience?
Going forward

- Expand the NuMI test simulation to find number of pulses until plastic strain remains consistent.

- Sensitivity studies for NuMI test simulation:
  - Beam location, spot size, beam profile (gaussian, flat top, etc), fin geometry, simulation mesh size

- Look into the possible beryllium window failure in lithium lens.

- Ultimate goal:
  - Reliable prediction of Beryllium failure given beam parameters and geometry.
Thank you!