Superconducting Undulator - Design and Validation

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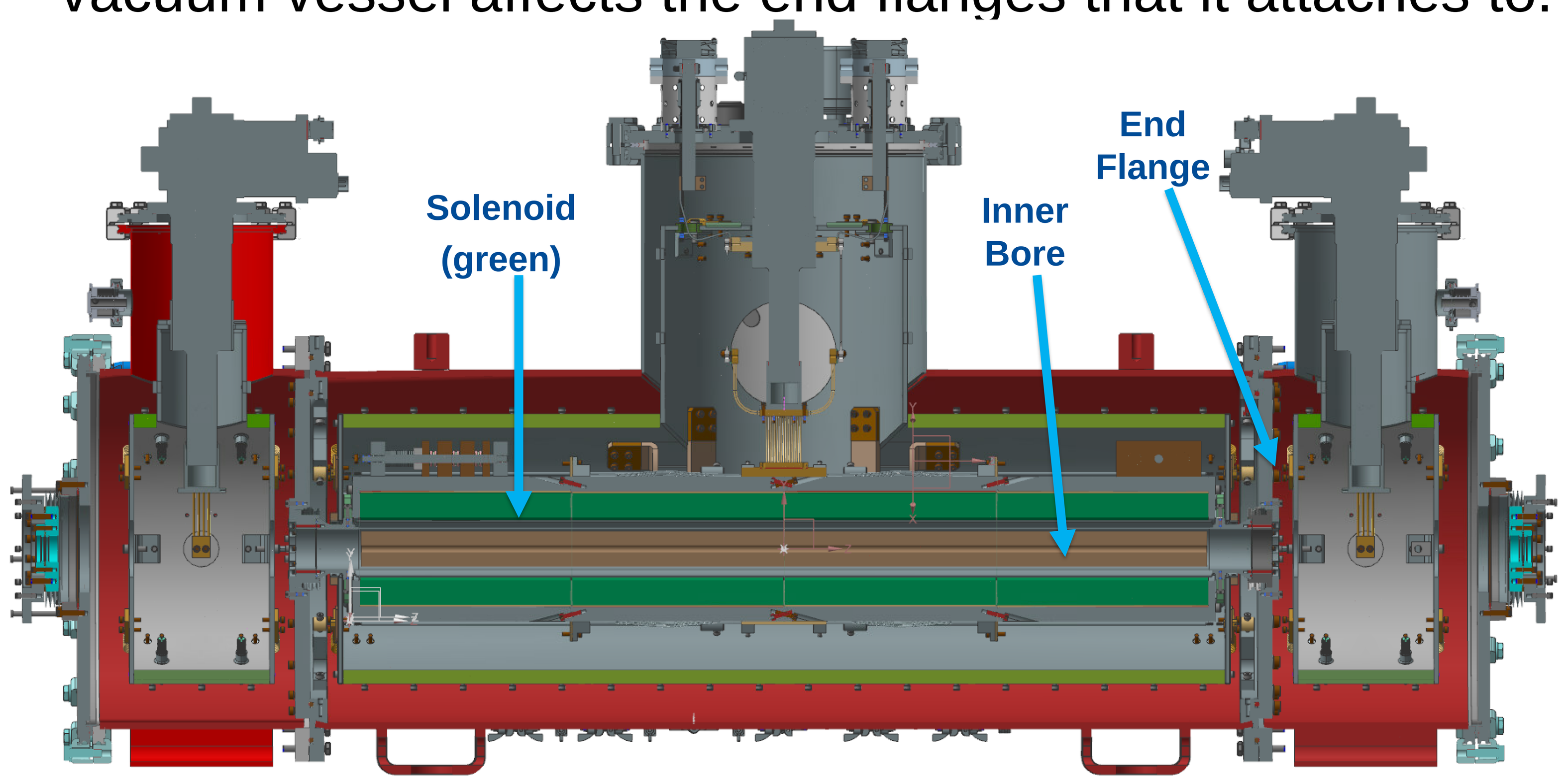
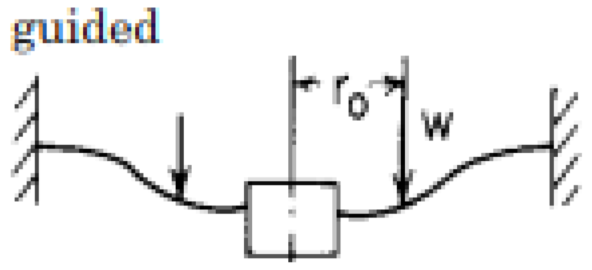
Introduction

Bulk high temperature superconductors (HTS) as undulator magnets have the potential to produce higher intensity x-rays with smaller period lengths. The HTS undulator being designed with Paul Scherrer Institute includes a Nb_3Sn solenoid to magnetize the bulk HTS. The solenoid operates at 4 K and the HTS undulator at 10 K requiring the tube that separate them to be cooled down to 50 K, thus potentially leading to mechanical failure if thermal contraction is not accounted for in the design. This project investigated how thermal contraction of the inner bore through the solenoid and vacuum vessel affects the end flanges that it attaches to.



Methods

- Calculate contraction of inner bore for 293 K to 4 K cooling using temperature dependent CTE and standard linear expansion equations
- Calculate reactions on end flange when contraction is applied using analytical methods in literature:



$$\theta_b = 0, \quad Q_b = 0, \quad y_a = 0, \quad \theta_a = 0$$

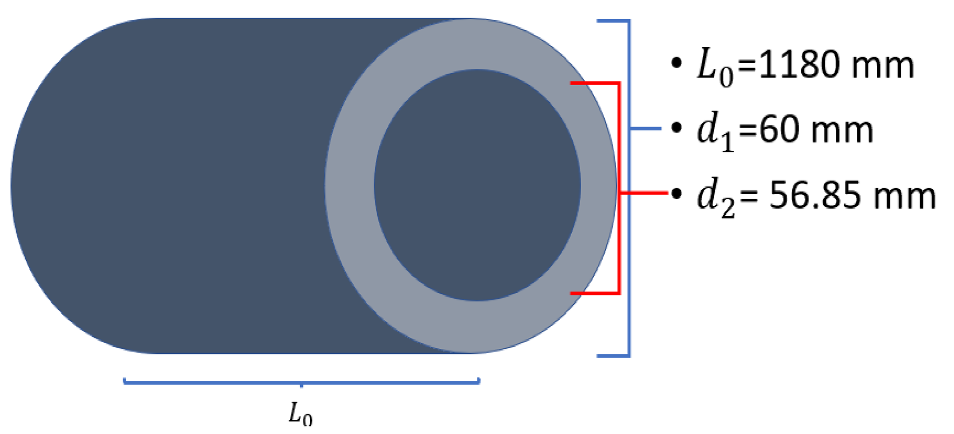
$$y_b = \frac{-wa^3}{D}\left(\frac{C_2 L_6}{C_5} - L_3\right) \qquad M_{ra} = -wa\left(L_9 - \frac{C_8 L_6}{C_5}\right)$$

$$M_{rb} = \frac{wa}{C_5} L_6 \qquad Q_a = \frac{-wr_o}{a}$$

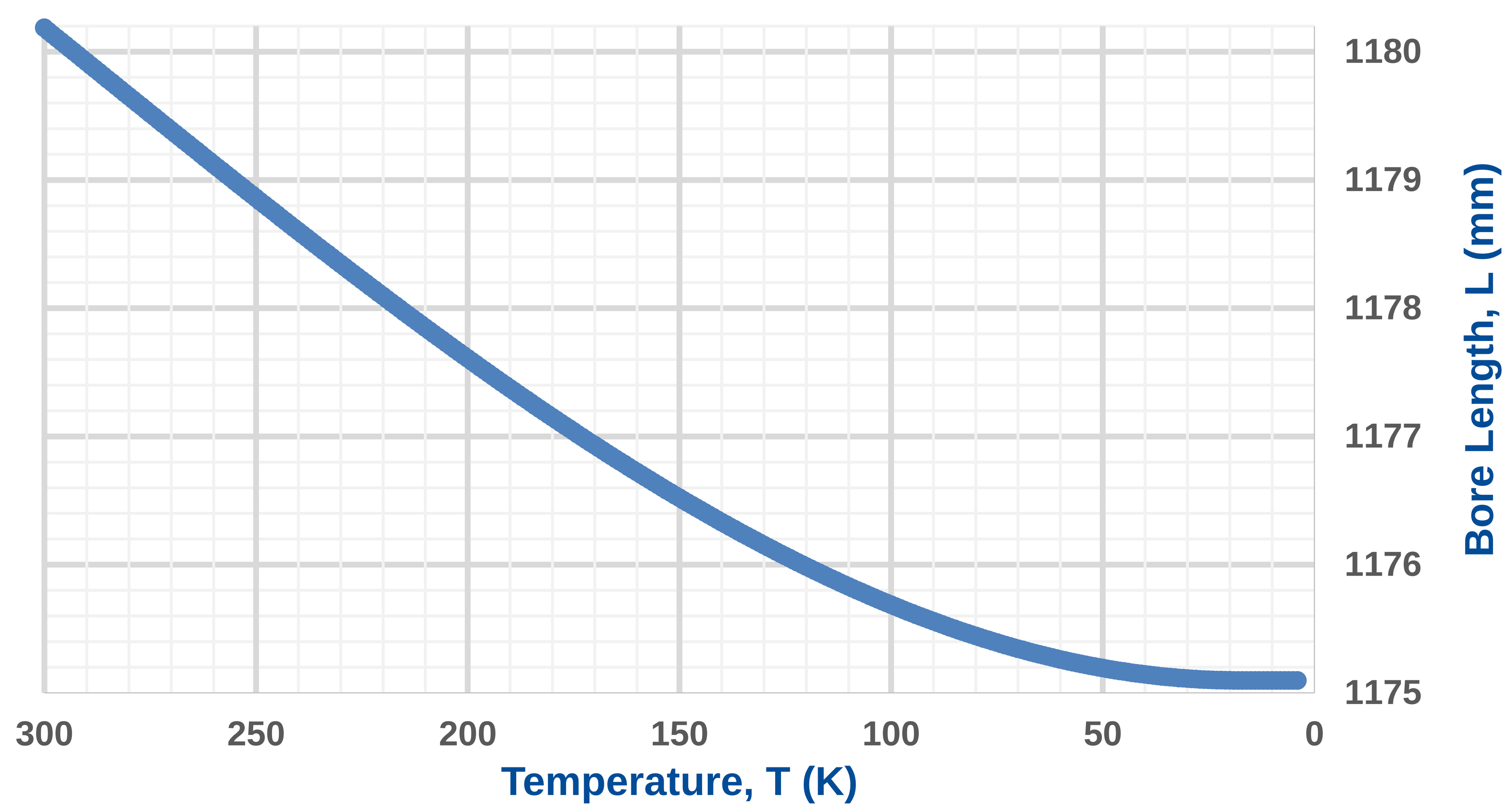
- Simulate end flange in COMSOL for stress analysis
- Perform parameter sweeps and optimization studies in COMSOL to investigate stress reducing designs
- Consider bellows designs to allow movement of flange

Analysis Steps and Results

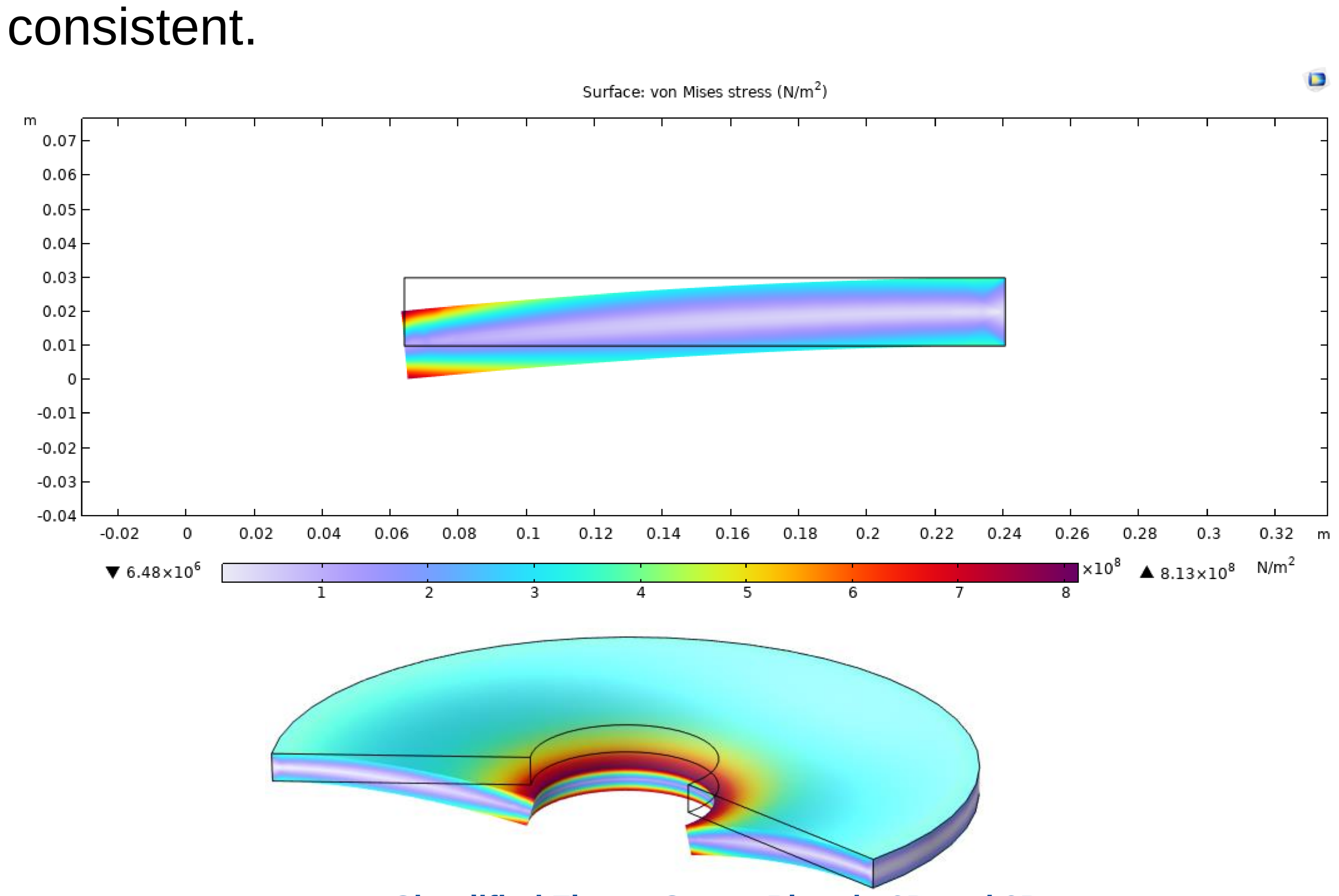
Length change was calculated for this simplified bore geometry using Al 6061 T-6 material properties.



Aluminum Bore Length as a Function of Temperature, L(T) (relative to 293 K)

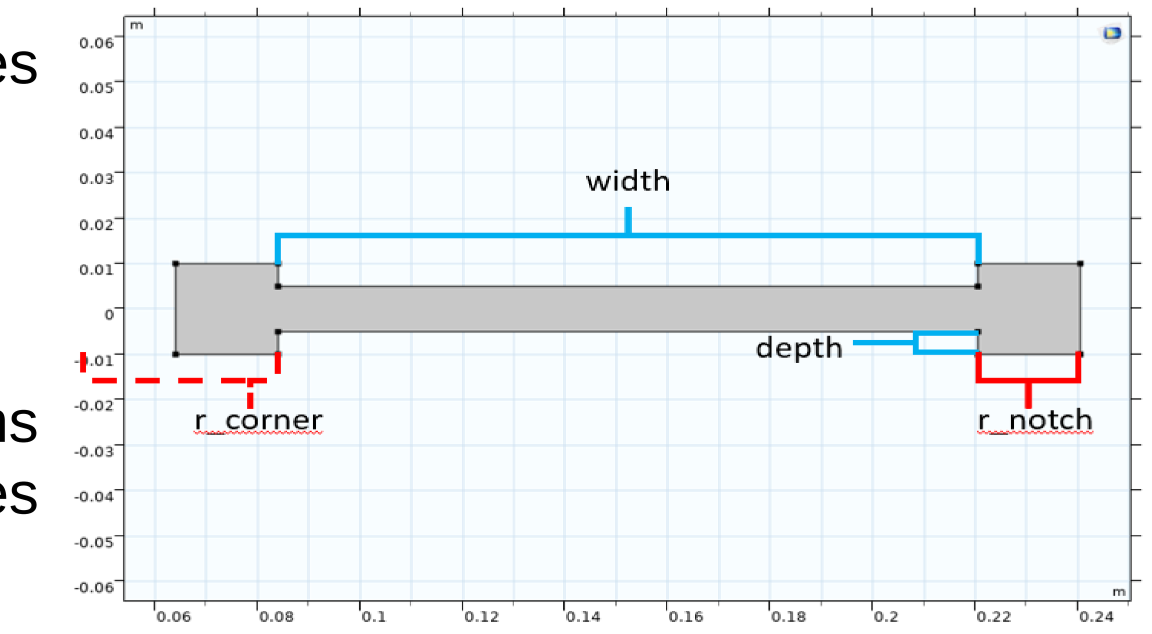


The maximum length change is a **2.45 mm contraction per side**. Applying this displacement to the inner edge of the flange gives a max von Mises stress of **~800 MPa** (4x yield stress for 316L stainless steel at 293 K). Analytical and 2D axisymmetric simulation results were consistent.

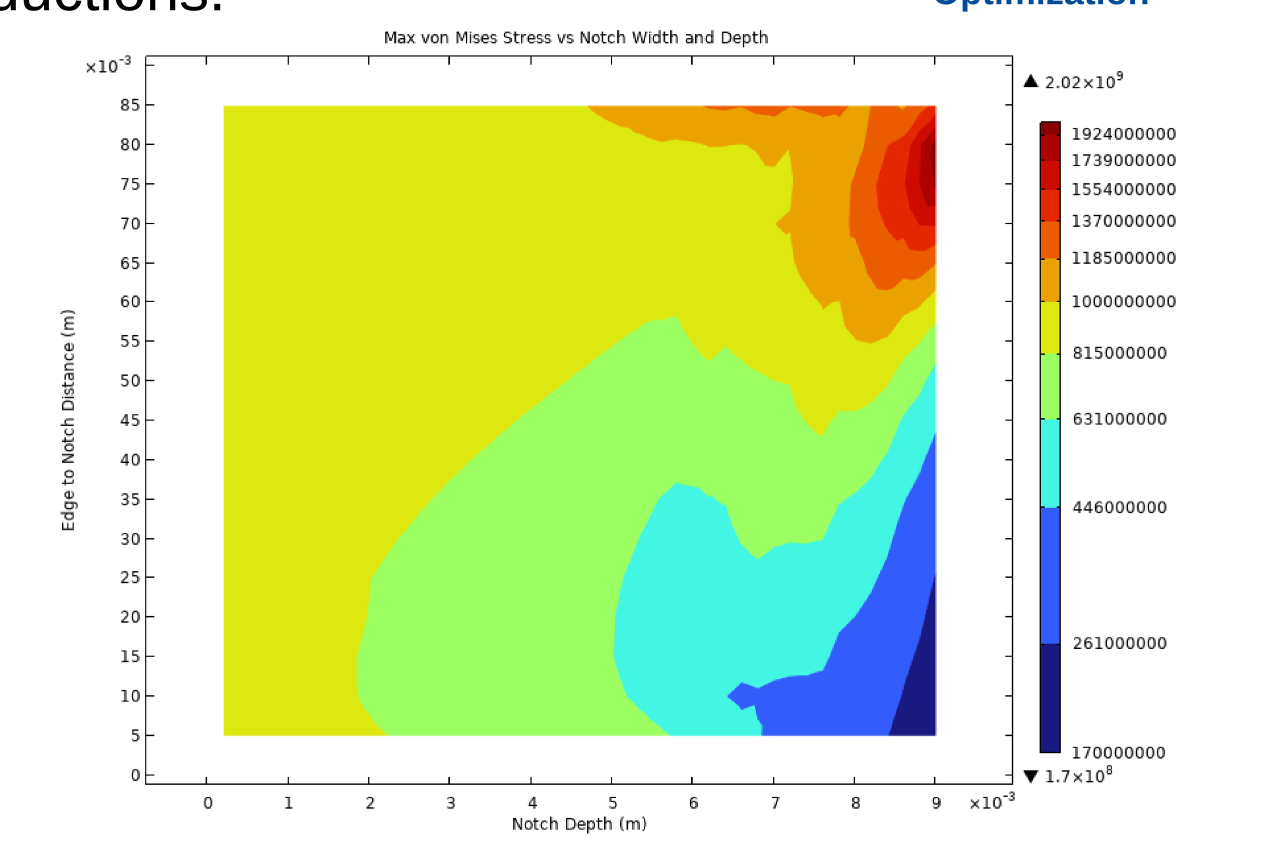


Simplified Flange Stress Plots in 2D and 3D

Stress relief notches were insufficient. With stress being proportional to thickness, large thickness reductions across wide notches led to the most significant stress reductions.

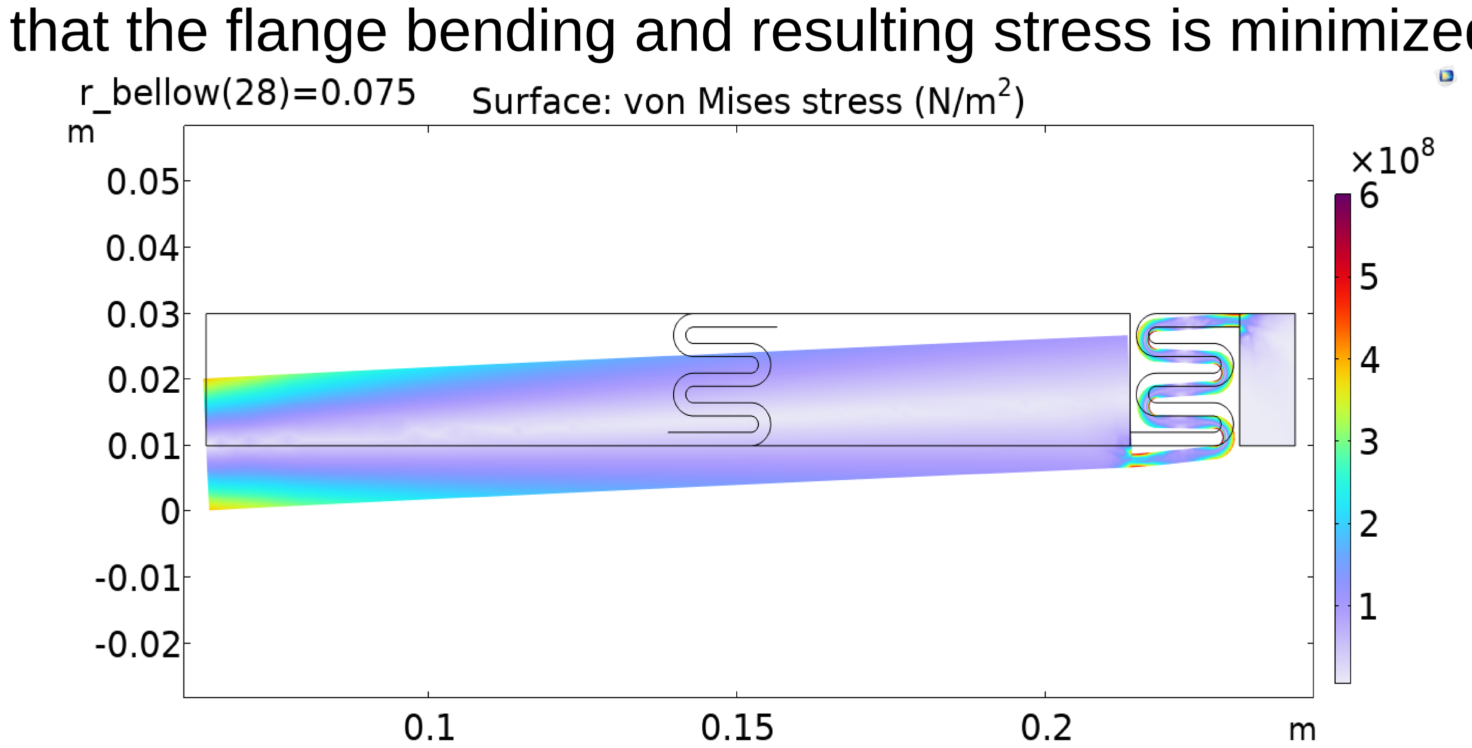


2D Axisymmetric Model with Labeled Notch Parameters for Optimization



Parametric Study of Notch Depth and Width (Edge to Notch Distance) for a Centered Notch. The lowest stress range (170-261 MPa) is for 5-25 mm notch to edge distance and 8.5-9 mm depth. This is at least an 85% thickness reduction across over 70% of the flange.

A bellows redesign was also considered; the bellows should take as much of the displacement as possible so that the flange bending and resulting stress is minimized.



Example of Unoptimized Bellows Design Reducing Stress on the Flange

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