RF WINDOWS

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- Frequency dependence
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Introduction

- Beryllium windows are used in muon cooling to reduce surface gradients and improve shunt impedances
- These windows are heated by ohmic losses of rf surface currents
- With vacuum rf this heat is only removed by radial conduction in the beryllium
- With inadequate cooling the central temperature can induce serious stresses and window bowing
- This sets minimum window thicknesses that depend on the edge cooling temperature

Calculation of heating from rf fields

Power per unit surface area (From Rick):

$$\frac{dP}{dA} = f_d \frac{\mathcal{E}^2}{\mathrm{Z_o}} \frac{\pi}{2} \frac{\delta}{\lambda} \, J_1^2 \left(x_{01} \frac{r}{r_{cav}} \right)$$

Power conducted outward

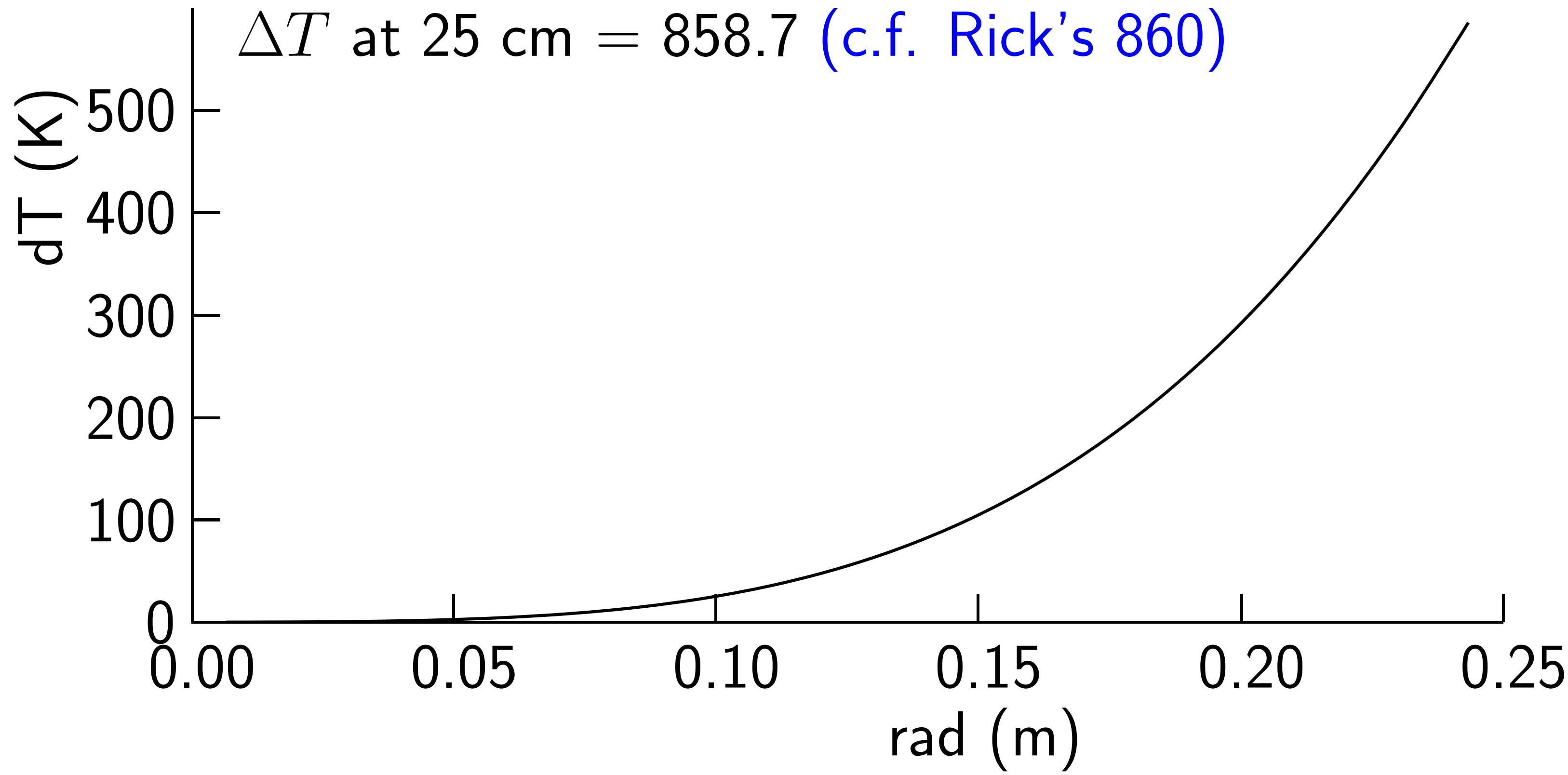
$$J(r) = \int_o^r 2 \, \pi \, r \, \frac{dP}{dA} \, dr$$

Temperature difference edge to center

$$dT = \int_o^{rmax} \frac{J(r)}{2\pi \; r \; \kappa \; t(r)} dr$$

Assuming a constant values of skin depth $\delta = 9 \; \mu m$ and thermal conductivity $\kappa = 201$ W m^{-1} deg^{-1}, $Z_o = 377 \; \Omega$, $x_{01} = 2.405$, duty factor $f_d = 1.9 \; 10^{-3}$, $\mathcal{E} = 15.25 \; \mathrm{MV/m}$, $r_{cav} = 58$ cm & $\lambda = 1.49$ m (for freq=201 MHz), window radius 25 cm

Rick's result

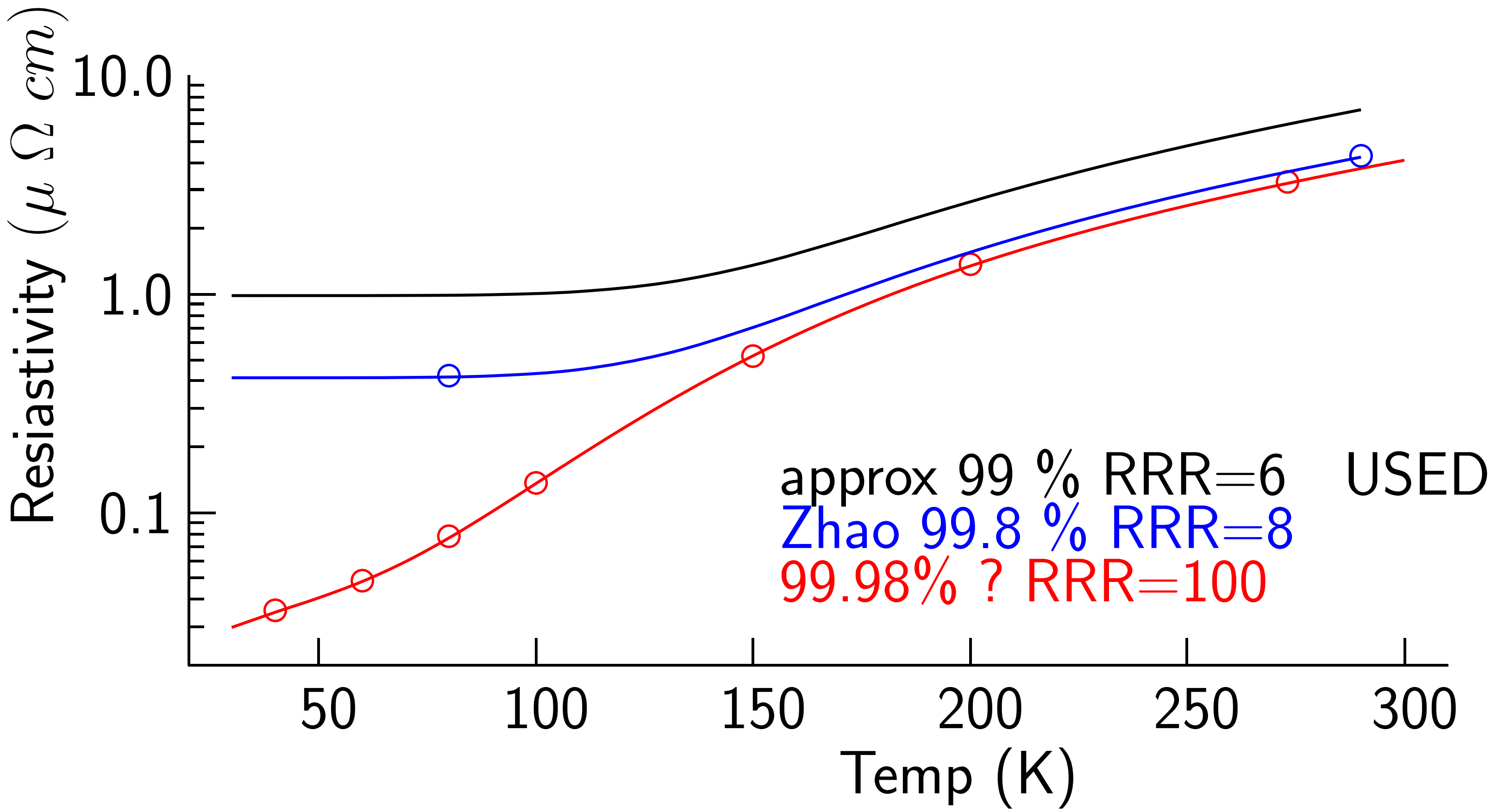


Good agreement with Rick with his values, but his electrical resistance $\rho = 5.89$ micro ohm cm giving $\delta = 9$ mm κ, as a function of temperature is calculated from ρ. At 273 K this gives $\kappa = 200$ W/m/deg, agreeing with Rick.

Beryllium Purity

- Single crystal Be has an RRR of 8000 or more
- I had assumed data with RRR=100, but the purity was not specified
- Zhao had measured Brush Wellman strip samples with purities of 99.8 and 99.9% and measured resistivity using rf Q, but he does not seem to say which was used for his given results giving RRR=8 (DOC030614-030620 14164225 Derun has scanned it)
- Several papers suggest that for 99% Be an RRR=6 is typical, and will be used here
- The room temperature resistivity is also sensitive to purity with values from 2.8 to 5.89 quoted. I will use the highest figure, as used by Rick Fernow.

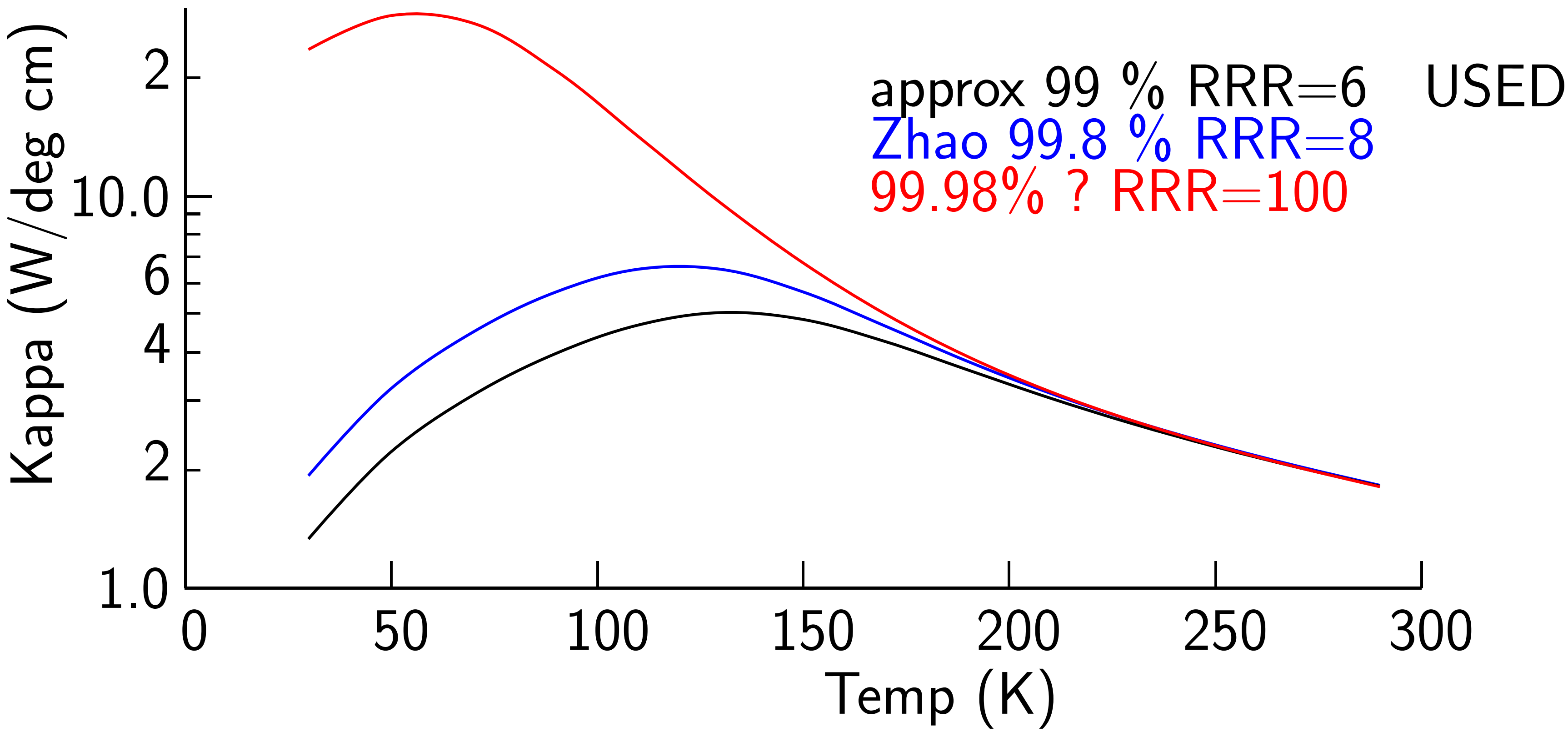
Temperature dependency of resistivity ρ



Black line appears to be that used by Rick and is probably for 99% material. We will use this for the following calculations.

The blue line is taken from Zhao's rf loss experiment

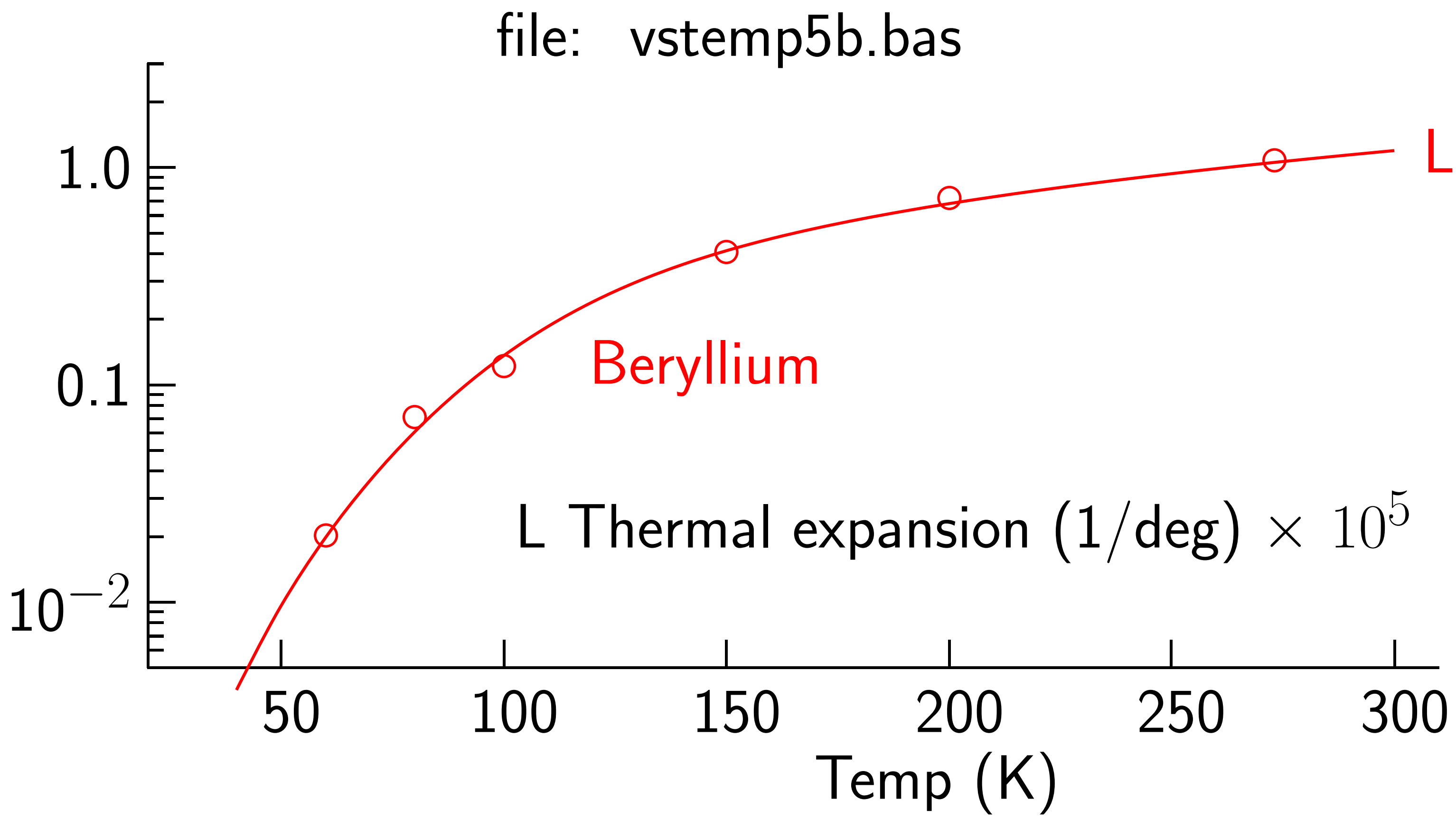
Temp. dependency of thermal conductivity κ



from

$$\kappa \propto \frac{T}{\rho}$$

Temp. dependency of coeff. of expansion η



Assumed dependences

With f in Hz:

$$r_{cav} = .58 \left(\frac{201\ 10^6}{f}\right) \qquad \text{(m)}$$

$$\mathcal{E} = 17 \sqrt{\frac{\mathrm{f}}{201\ 10^6}} \qquad \text{(MV/m)}$$

$$\lambda = c/f \qquad \text{(m)} \qquad\qquad c = 3\ 10^8 \ \text{(m/s)}$$

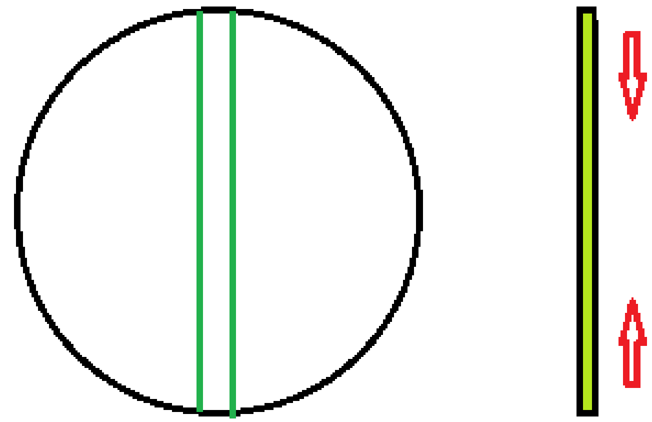
$$\delta = \sqrt{\frac{\rho}{\pi \mu_o\ f}}$$

$$\mu_o = 4\ \pi\ 10^{-7}$$

$$f_d = 15(Hz) \times 126(\mu s) \left(\frac{201\ 10^6}{f}\right)^{1.5} \qquad \text{Duty factor}$$

Note that it is assumed that this rf pulse length is NOT lengthened when the resistivity changes with temperature

Stress estimation



Correct stress and deformations will require finite element analysis, but we can calculate the order of magnitude of stresses from the constrained accumulated increase in length of a strip across the window:

$$\Delta R = \int_0^{rmax} \left(\int_{T(r)}^{T(rmax)} \eta \;\; dT \right) dr$$

where the expansion coefficient:

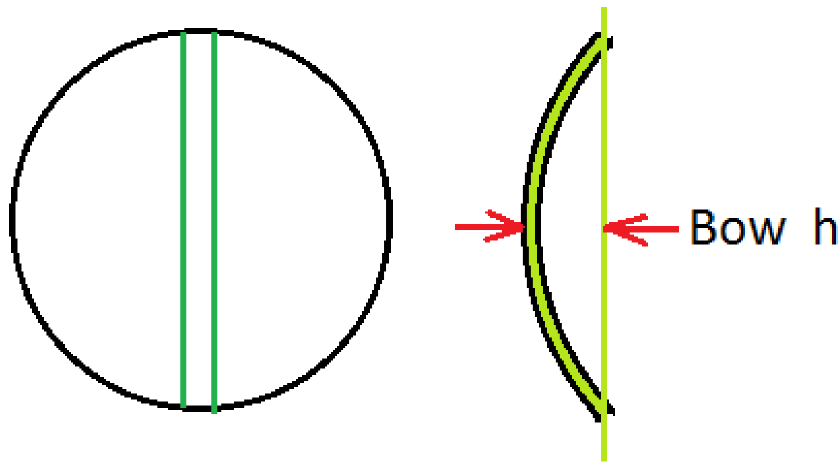
$$\eta = \frac{dL/L}{dT} \quad \text{is a function of T}$$

Using this and the Young's modulus E we calculate a Stress S:

$$S = E \, \frac{\Delta R}{rmax}$$

Estimated Change in bow of window

Assuming a spherical bowed window, we calculate the bow's is increase to give an increased length of a strip across the window that is given by the calculated temperature profile. Again this is only an order of magnitude calculation



Using ΔR from above:

$$dh = \frac{3}{4} \frac{\Delta R}{h}$$

These are only 'order of magnitude' calculations
ANSIS analysis will be needed

Assumed rf parameters

freq	r_{cav}	grad	duty
MHz	cm	MV/m	
325	35.9	21.6	0.92E-03

freq	r_{cav}	grad	duty
MHz	cm	MV/m	
650	17.9	30.6	0.33E-03

These are our standard assumptions

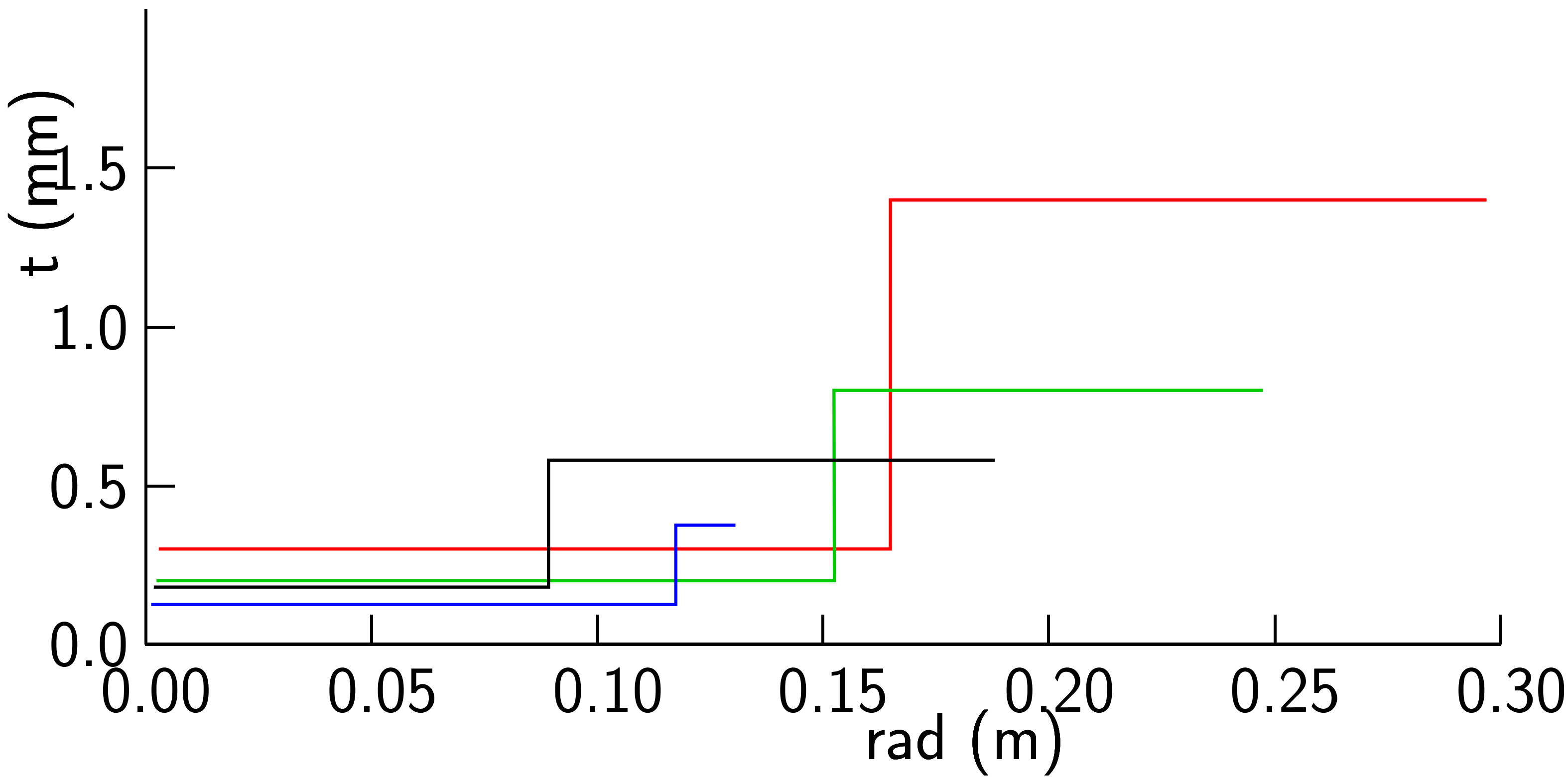
Possibly acceptable parameters for 4 stages of pre-merge 6D cooling

	t1	t2	step	rmax	T2	T1	ΔT	exp	stress	h	dh
	mm	mm	cm	cm	K	K	K		MPa	mm	mm
1	0.30	1.40	16.0	30.0	188.7	80	108.69	0.49E-03	139.785	20	1.9655
2	0.20	0.80	15.0	25.0	189.0	80	108.96	0.51E-03	146.982	20	1.7222

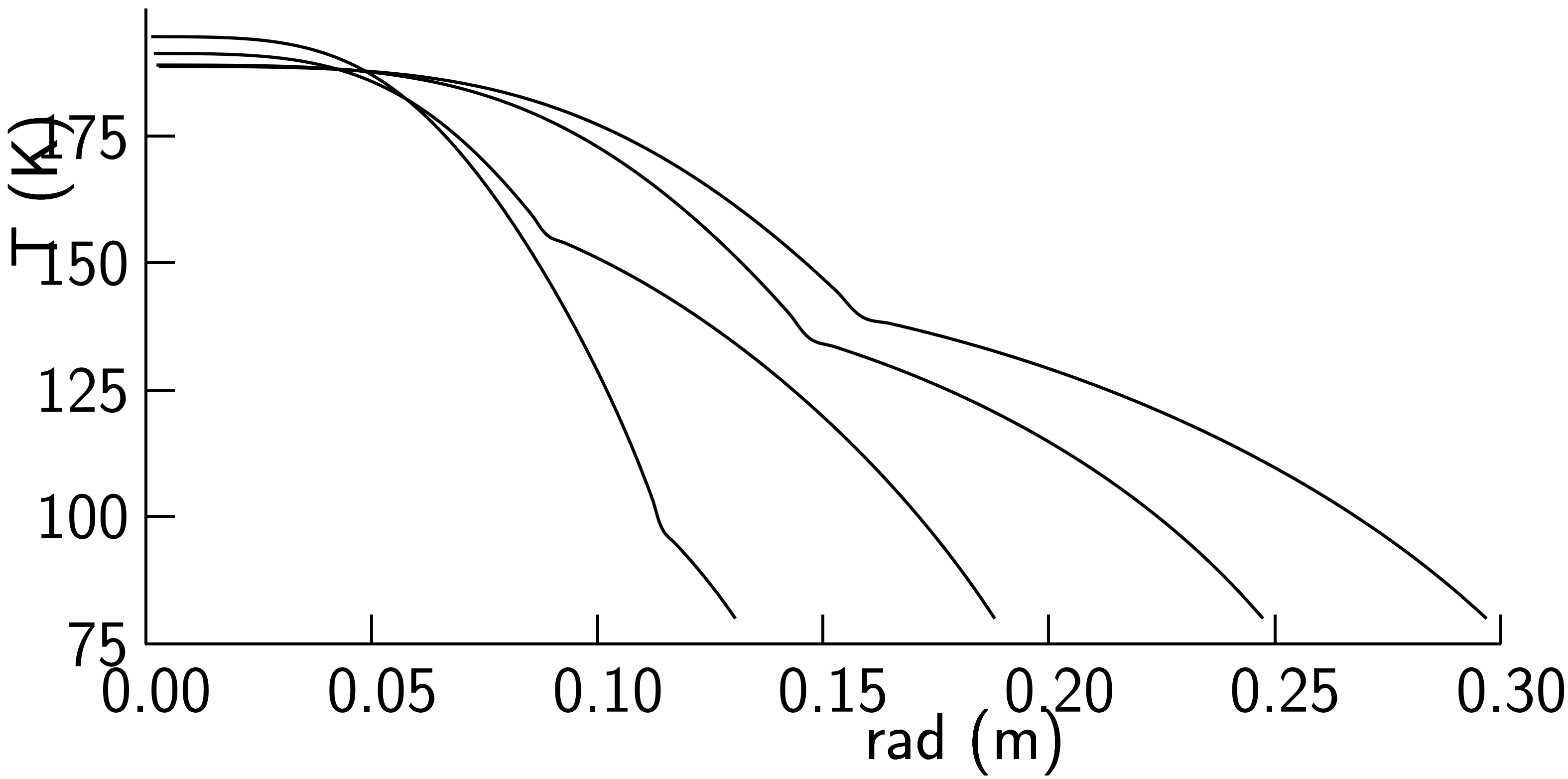
	t1	t2	step	rmax	T2	T1	ΔT	exp	stress	h	dh
	mm	mm	cm	cm	K	K	K		MPa	mm	mm
3	0.18	0.58	9.0	19.0	191.2	80	111.24	0.53E-03	151.444	10	1.3486
4	0.125	0.38	11.5	13.2	194.5	80	114.54	0.64E-03	184.382	10	1.1407

ANSIS study needed to see if this is really ok

Stepped thicknesses



Temperatures



Conclusion

- An earlier study assuming ≈99.99% Be with RRR=100:
  - 30 cm windows must be 10 mm thick if cooled at room temp.
  - 30 cm windows could be 100 microns thick if cooled at 80 K
  - But the material is probably not available in such sizes, and probably too expensive
- A new analysis using data for ≈98% Be with RRR=6
  - Stg 1 30 cm windows: 300 μm center if 1.4 mm at edge
  - Stg 2 25 cm windows: 200 μm center if 0.8 mm at edge
  - Stg 3 19 cm windows: 180 μm center if 0.56 mm at edge
  - Stg 4 13 cm windows: 125 μm center if 0.38 mm at edge
- Simulation needed for these windows