Design for solid-state Rayleigh-Taylor experiments in tantalum at Omega

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Abstract. We have designed an experiment for the Omega-EP laser facility to measure the Rayleigh-Taylor (RT) growth rate of solid-state Ta samples at ~1 Mbar pressures and very high strain rates, $10^7$-$10^8$ s$^{-1}$. A thin walled, hohlraum based, ramp-wave, quasi-isentropic drive has been developed for this experiment. Thick samples (~50 µm) of Ta, with a pre-imposed sinusoidal ripple on the driven side, will be accelerated. The ripple growth due to the RT instability is greatly reduced due to the dynamic material strength. We will show detailed designs, and a thorough error analysis used to optimize the experiment and minimize uncertainty.

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1. Introduction
There are large uncertainties in our understanding of material strength at high strain rates and pressures. Models agree where data exists, below strain rates of $10^5$ s$^{-1}$, but diverge at strain rates larger than $10^5$ s$^{-1}$. Somewhere between $10^5$ s$^{-1}$ and $10^8$ s$^{-1}$, the movement of dislocations switches from the thermal activation regime to the phonon drag regime, with a corresponding change in the slope of $\frac{d \ln(\text{strength})}{d \ln(\text{strain rate})}$. We have chosen to measure material strength by its effect on the growth rate of Rayleigh-Taylor instabilities [1]. The yield strength acts like an effective viscosity that slows down the Rayleigh-Taylor growth rate [2]. Classical growth, with out strength, has a growth rate given by $\gamma = \sqrt{gkA}$. In the presence of strength, the growth rate is $\gamma = \sqrt{gkA + \nu^2k^4} - \nu k^2$ with an effective viscosity of $\nu = Y/(\rho\varepsilon\sqrt{6})$. For comparison, liquid Al has a viscosity of 0.01 poise, while a strength of 3 kb at a strain rate of $10^7$ s$^{-1}$ has an effective viscosity of 120 poise.

To keep the material solid, we need to keep it close to the isentrope while bringing it up to the desired pressure. Thus we use a technique developed by Barnes [3,4], in which we shock up a reservoir to high pressure, let it rarify across a vacuum gap, and have it gently stagnate against the sample, driving it along a quasi-isentrope.

2. Experiment
We have designed a 1 Mb Ta Rayleigh-Taylor Omega experiment driven by a thin-walled hohlraum. Fig. 1 shows the hohlraum with the laser rays from 3 distinct cone angles, along with the backlighter. The hohlraum wall consists of a 1 µm layer of Au backed by 160 µm of CH. 19.2 kJ of 0.35 µm light enter the hohlraum in 1 ns, bringing the internal temperature up to 135 eV and dropping to about 50 eV after the laser turns off (fig. 2). This temperature drives our target, which consists of a reservoir made of 25 µm Be and 200 µm C$_6$H$_3$Br, a 400 µm gap, and a target consisting of 12 µm CH$_2$ preheat.
shield, 50 \( \mu \text{m} \) Ta, and 500 \( \mu \text{m} \) LiF tamper. The interface between the CH\(_2\) heat shield and the Ta has a pre-imposed ripple with amplitude 1.5 \( \mu \text{m} \) and wavelength 50 \( \mu \text{m} \) to seed the Rayleigh-Taylor growth. The Ta reaches a pressure of 1.3 Mb about 35 ns after the start of the laser pulse.

The hohlraum had only 1 \( \mu \text{m} \) of Au, instead of a thick Au wall, because previous hohlraum shots in March 2008 and May 2008 showed that the temperature of the hohlraums stayed unexpectedly high after the laser turned off. This elevated temperature launched successive shocks into the target. The thinner wall becomes more transparent after about 10 ns, reducing the temperature and the late time shocks.

On June 1, 2009, we got our first backlit image from a Rayleigh-Taylor shot, taken 70 ns after the start of the laser pulse. The ripples grew by a factor of 2\( \pm \)0.3, less than expected.

### 3. Error analysis

To analyze the data, we need to measure the drive, the ripple contrast, the MTF of the radiography image, and the spectrum of x rays that produced the image. We found that the growth factor is roughly inversely proportional to the Ta strength, as shown in Fig. 3 so that the percent error in growth factor is the same as the percent error in strength.

The drive temperature is measured with Dante[7], and these measurements are good to about 1.2 eV, or 3.5% in flux. Late time temperature measurements are good to about 2.6 eV out of 40 eV, or about 30% in flux. Collectively, these errors add up to about 9% uncertainty in the drive. This can be reduced by measuring the velocity of the back surface with a VISAR[8] interferometer. Velocity can be measured to about 1%, resulting in a 2% error in the drive. Although we plan to measure velocity simultaneously with the x-ray radiography of the ripple growth, to date we have used separate drive shots to measure the drive, correcting for changes in the overall laser energy. This introduces an error due to fluctuations from shot to shot of about 4% in drive, which is still less than the uncertainty from the temperature measurements.

The MTF is about 75% at a wavelength of 50 \( \mu \text{m} \). An uncertainty of 10% in MTF translates into a 10% uncertainty in growth factor, and 10% uncertainty in material strength.

Fig. 4 shows 2 possible spectra for the backlighter source. Each spectrum is multiplied by the transparency of the target as a function of photon energy, then by the response function of the detector. The derivative of the final spectrum with respect to Ta thickness is plotted as a function of Ta thickness in Fig. 5. Since we’re using the contrast in x-ray image to deduce the growth of the RT ripples, any error in how much a Ta ripple causes a difference in x-ray brightness directly impacts our estimate of ripple growth. Fig. 5 shows that there’s about a 6% difference between the two spectra. Furthermore, any error in Ta thickness affects the spectrum as well, with each extra micron of Ta reducing the overall x-ray ripple contrast by 2.6%. Thus a 3 \( \mu \text{m} \) error in Ta thickness results in an 8% error in growth factor.

Table I below lists many parameters of the experiment that affect the estimate of the growth factor, the extent of their affect, the uncertainty of each parameter, and the contribution of that uncertainty to the total uncertainty in the growth factor, and thus the material strength. If the errors were all uncorrelated, then the total uncertainty in growth factor would just be the quadrature sum of the individual errors, about 16%. However, several of the errors are correlated, and these correlations must be taken into account. The three hohlraum temperatures, peak, mid time and late time, are correlated since any problems with a Dante channel will affect all three temperatures. Although the correlations are not 100%, we will assume they are to be conservative in our overall estimate. Thus we will add these three uncertainties linearly to get 9% overall uncertainty due to hohlraum temperature.

The other main correlations are with the Ta thickness. Ta thickness has two effects on the overall error budget. A thicker Ta sample has more mass, thus moves more slowly, so the RT ripple grows more slowly. A thicker Ta sample also affects the spectrum of the backlighter used to measure the RT ripple. In addition, the glue thickness between the Ta and LiF tamper is estimated by measuring the thickness of the entire target – the CH\(_2\) heat shield, the Ta, the glue and the LiF thickness is
measured, and the CH₂, Ta, and LiF thicknesses are subtracted to get the glue thickness. Thus the error in glue thickness is negatively correlated with the Ta thickness. Therefore, these three error contributions from the Ta thickness are linearly added to get \((1.14+1.08+2.6)\times 3 = 14.5\%\). The remaining errors are assumed independent, and are added in quadrature. This yields a total error estimate in the growth factor of \(\sigma = 22.6\%\). The probability of the error in growth factor, and thus in yield strength, being greater than \(x\%\) is then \(\text{erfc}(x/\sigma/)\). Thus there is a 27% chance that the error in yield strength is greater than 25%, as shown in fig. 6.

There are several things we can do to reduce this overall error of 22.6%. With more careful measurements, we could reduce the MTF error from 10% to 5%. We plan to use simultaneous VISAR measurements with our Rayleigh-Taylor growth measurements, which will eliminate the uncertainty due to temperature and shot-to-shot fluctuations in drive. We also will be imaging Ta steps of 35, 45, 55 and 65 \(\mu\)m thickness so we can interpolate the Ta thickness variations from the x-ray image of the ripple. This replaces the uncertainty in backlighter spectrum with the uncertainty in Ta step thickness and density of about 5-10%. With these improvements, the overall uncertainty reduces to 16.6%. Then the chance that the error in yield strength is greater than 25% reduces from 27% to 13%. Fig. 6 shows how the error probability improves with these changes.

**Table I.** Affect on growth factor, expected error, and total error of growth factor due to each uncertainty

| Description                          | \(\frac{\delta \alpha}{\delta x}\) (unit) | \(\delta x\) | \(\delta \sigma\) (%) |
|--------------------------------------|-----------------------------------------|------------|-----------------|
| Be thickness (\(\mu\)m)              | -0.2                                    | 0.5        | 0.1             |
| Glue thickness (\(\mu\)m)            | -0.13                                   | 2          | 0.3             |
| C₂H₂Br thickness (\(\mu\)m)          | -0.14                                   | 1          | 0.14            |
| Gap thickness (\(\mu\)m)             | -0.08                                   | 5          | 0.4             |
| CH₃ thickness (\(\mu\)m)             | -0.27                                   | 2          | 0.54            |
| Ta thickness (\(\mu\)m)              | -1.14                                   | 3          | 3.4             |
| Glue thickness (\(\mu\)m)            | +1.08                                   | 2          | 2.2             |
| LiF thickness (\(\mu\)m)             | -0.011                                  | 2          | 0.02            |
| Ripple amplitude (\(\mu\)m)          | 0.75                                    | 0.15       | 0.1             |
| Peak Tr (eV)                         | 0.83                                    | 1.15       | 0.95            |
| Mid-time Tr (eV)                     | 1.2                                     | 1.15       | 1.4             |
| Late-time Tr (eV)                    | 2.6                                     | 2.55       | 6.6             |
| Spatial nonuniformity (%)            | 6.9                                     | 1          | 6.9             |
| Timing errors (ns)                   | 1.1                                     | 1          | 1.1             |
| EOS errors (EOP/LEOS)                | 2.0                                     | na         | 2.0             |
| 1.3*strength surface layer (\(\mu\)m)| 0.24                                    | 1          | 0.24            |
| Thermal conductivity (%)             | -0.008                                  | 100        | 0.8             |
| Ripple contrast (PSL)                | 12.                                     | -0.2       | 0.24            |
| MTF error (%)                        | 1.0                                     | 10         | 10              |
| Photon statistics                    |                                         |            | 2.3             |
| Backlighter spectrum                 |                                         |            | 5.8             |
| Spectrum, Ta thickness (\(\mu\)m)    | -2.6                                    | 3          | 8               |
| VISAR error (%)                      | 0.98                                    | 2          | 2.0             |
| VISAR drive \(\neq\) RT drive (%)    | 0.71                                    | 6          | 4.2             |
| Heat shield strength                 |                                         |            | 0               |
| Grain structure (anisotropy)         |                                         |            | 0.4             |
| Model dependence                     |                                         |            | 3.2             |
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