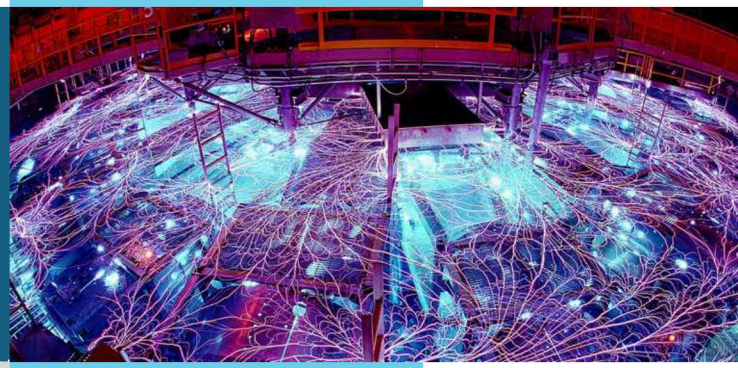
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2018-8445C

Understanding the Earth's Core and Beyond through Iron



Sean Grant[1,2], Tommy Ao[2], Aaron Bernstein[1], Jean-Paul Davis[2], Todd Ditmire[1], Daniel Dolan[2], Jung-Fu Lin[3], Andrew Porwitzky[2], Christopher Seagle[2]

[1]University of Texas at Austin, Center for High Energy Density Science

[2]Sandia National Laboratories

[3]University of Texas at Austin, Department of Geological Science

PRESENTED BY

Sean Grant

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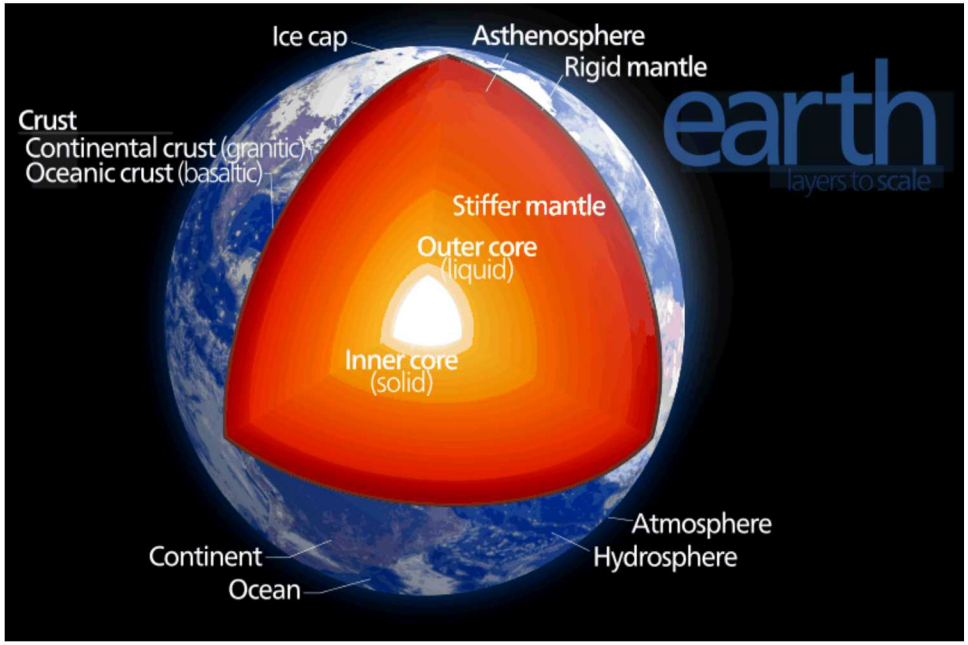
Iron is an important material for planetary sciences and many other high energy density applications

What are we doing?

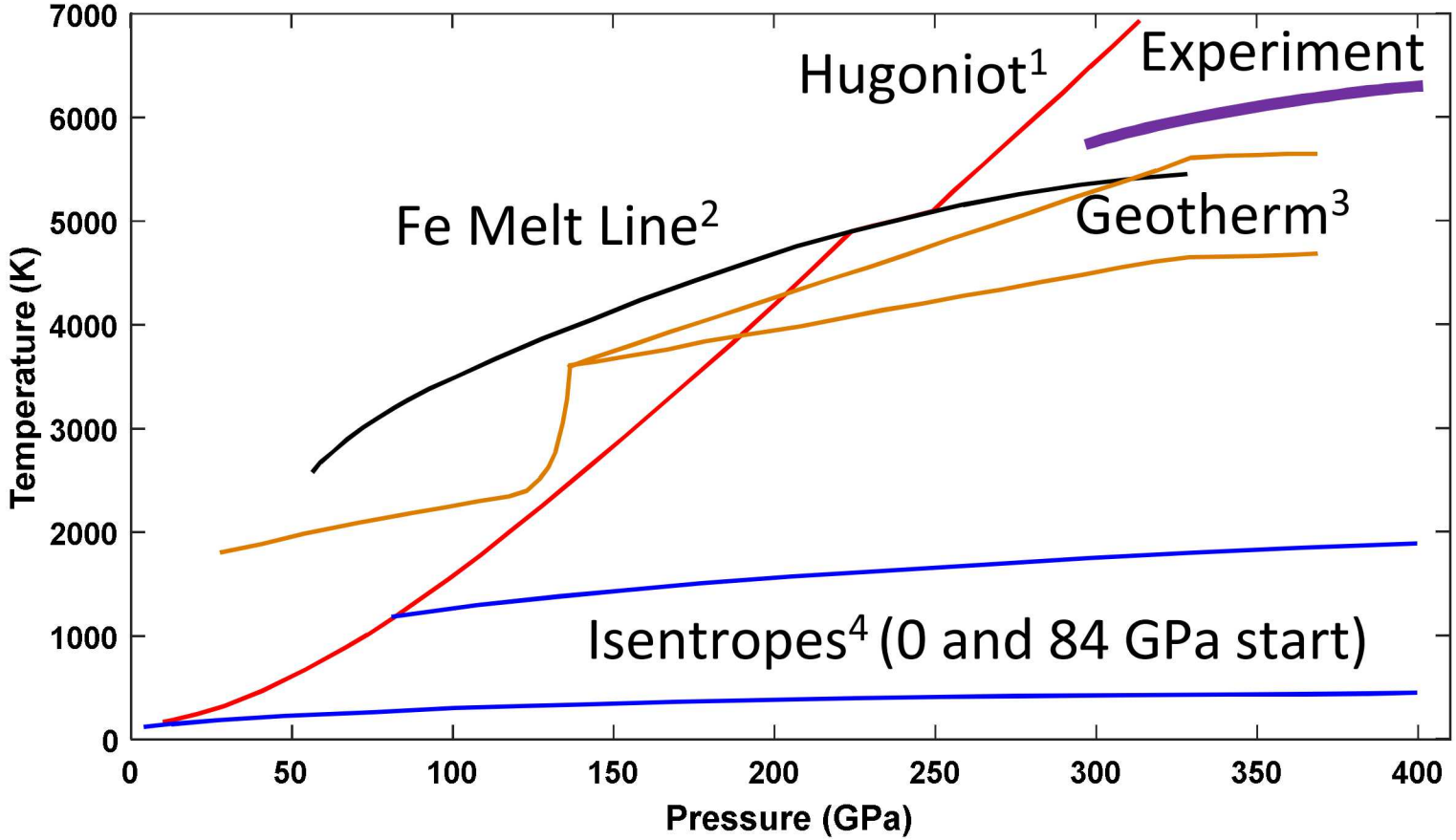
- Measuring the equation of state (EOS) of liquid iron at high pressures by studying samples at off-Hugoniot isentropes
- Developing methods to simultaneously measure the optical conductivity



Why?

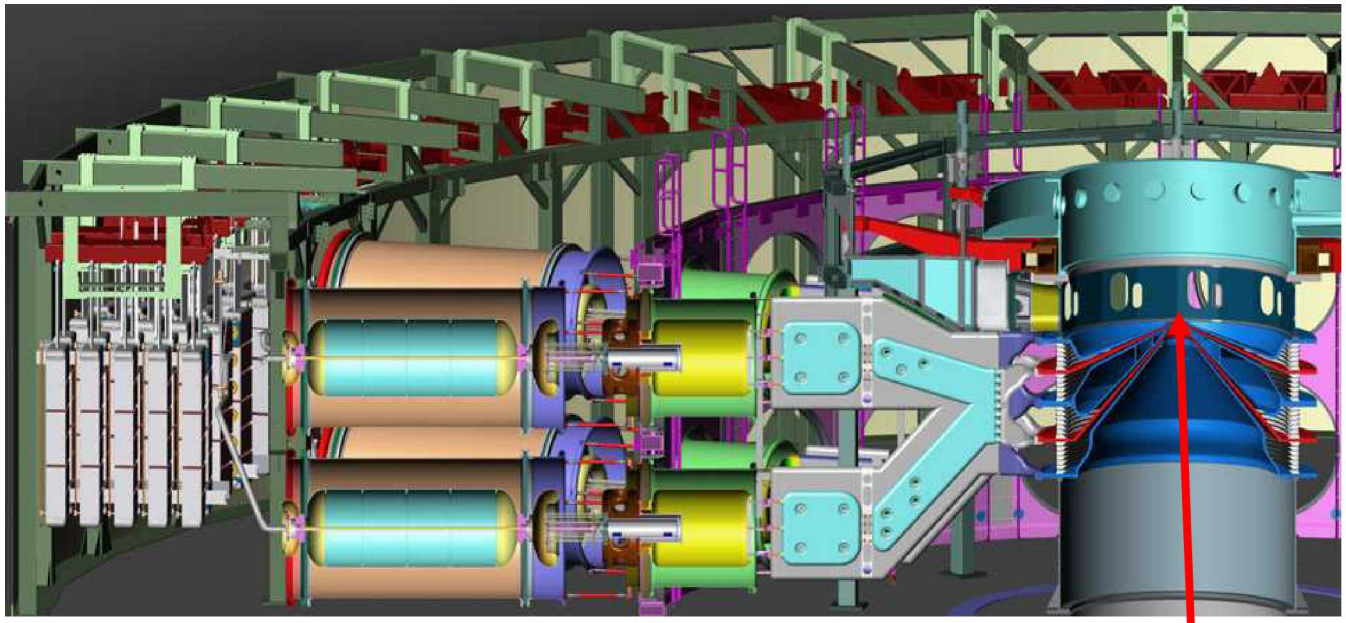
- Expanding the region of measured EOS values allows for the refinement of broader EOS models which are used in many high energy density applications
- Iron is the primary constituent of rocky planet cores
- The thermal conductivity of the iron and the Earth's core continues to be a controversial subject, with values almost spanning an order of magnitude (33 W/m K, Konopkova 2016; and 226 W/m K, Ohta 2016)

Estimations of our experimental path are close to the conditions of the Earth's core



[1]J. M. Brown and R. G. McQueen, J. Geophys. Res. 91, 7485, doi:10.1029/ JB091iB07p07485 (1986).
[2]G. Shen, H. K. Mao, R. J. Hemley, T. S. Duffy, and M. L. Rivers, Geophys. Res. Lett. 25, 373, doi:10.1029/97GL03776 (1998).
[3]F. D. Stacey, *Physics of the Earth*, 4th ed. (Cambridge University Press, Cambridge, 2008).
[4]J. Wang, R. F. Smith, J. H. Eggert, D. G. Braun, T. R. Boehly, J. Reed Patterson, P. M. Celliers, R. Jeanloz, G. W. Collins, and T. S. Duffy. Journal of Applied Physics, 114(2), p.023513. doi.:10.1063/1.4813091 (2013).

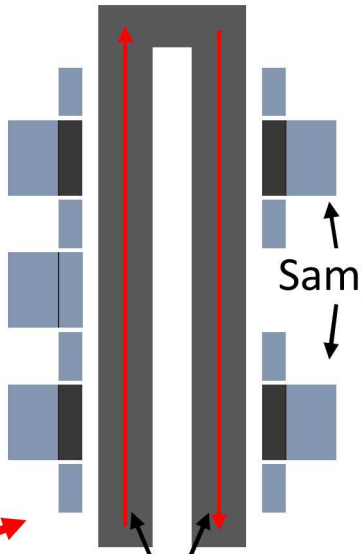
Sandia's Z machine is a pulsed power driver that provides a unique opportunity for driving dynamic material experiments to extreme pressures



Marx Banks

Triggering and Pulse Shaping

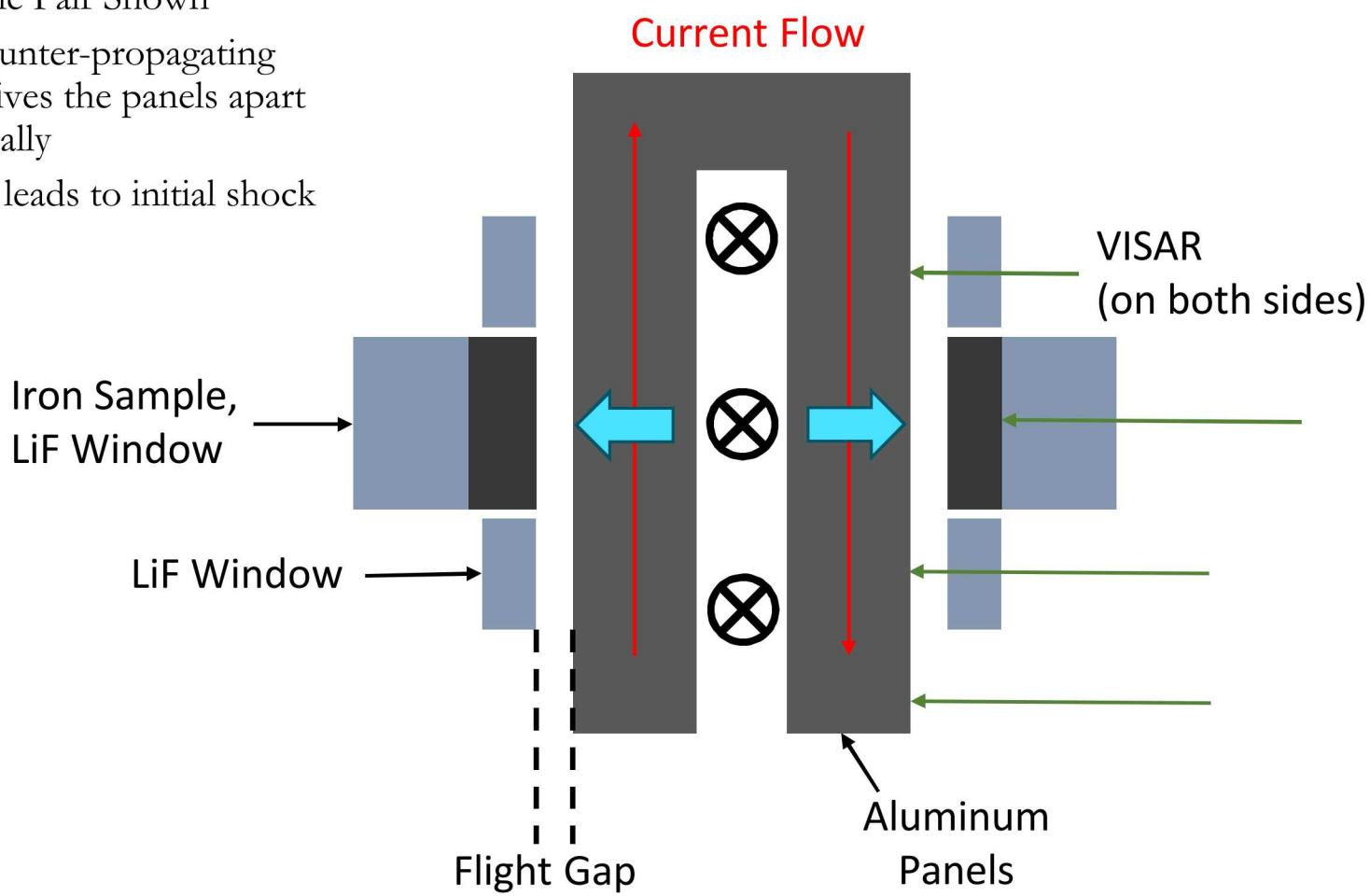
Center Section: Load Hardware



The strip-line target configuration is a common method of driving planar samples to high pressure and density states on Z

Load hardware details

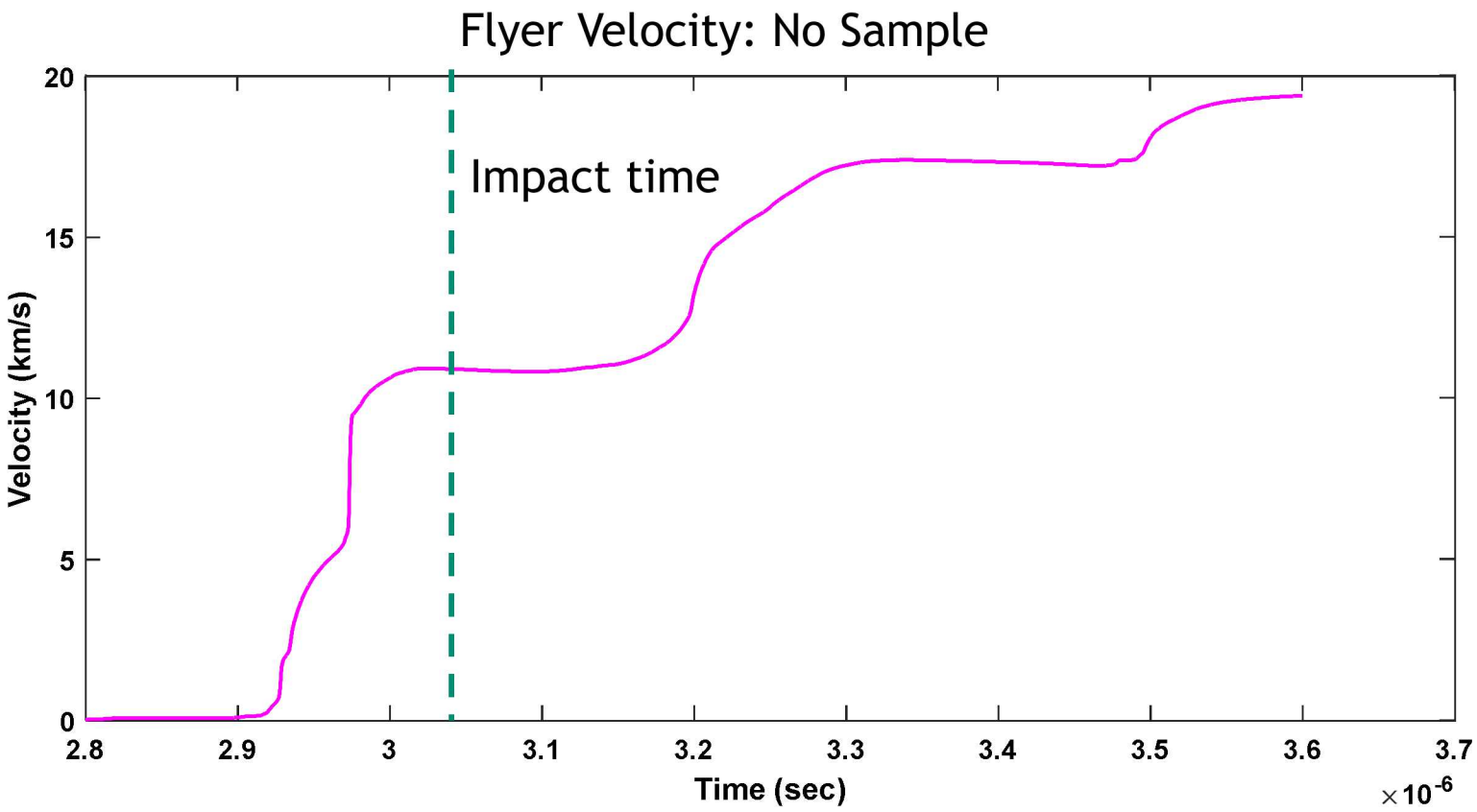
- Top Sample Pair Shown
- Parallel counter-propagating current drives the panels apart symmetrically
- Flight gap leads to initial shock



The shock-ramp drive takes full advantage of Z's pulse shaping capabilities to compress a sample along an elevated isentrope

Load hardware details

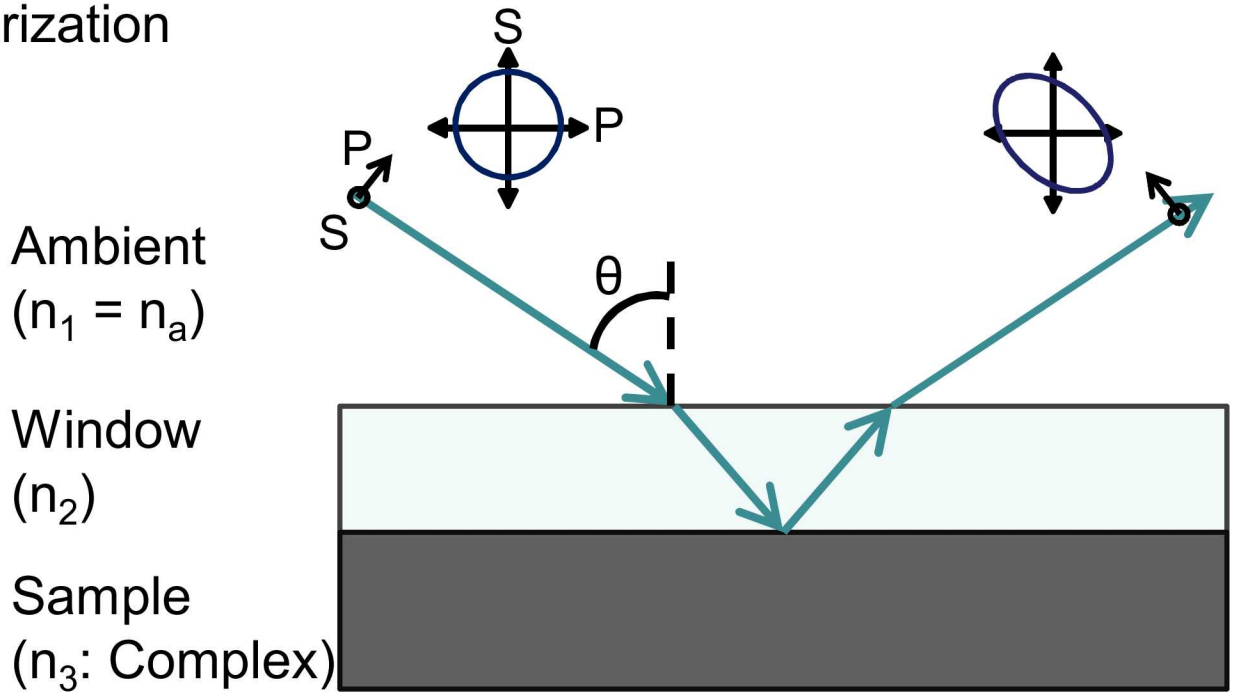
- The drive panel is accelerated to a steady velocity at impact, and then subsequently continues to ramp up, driving a quasi-isentropic ramp into the shocked sample



Conductivity and Ellipsometry

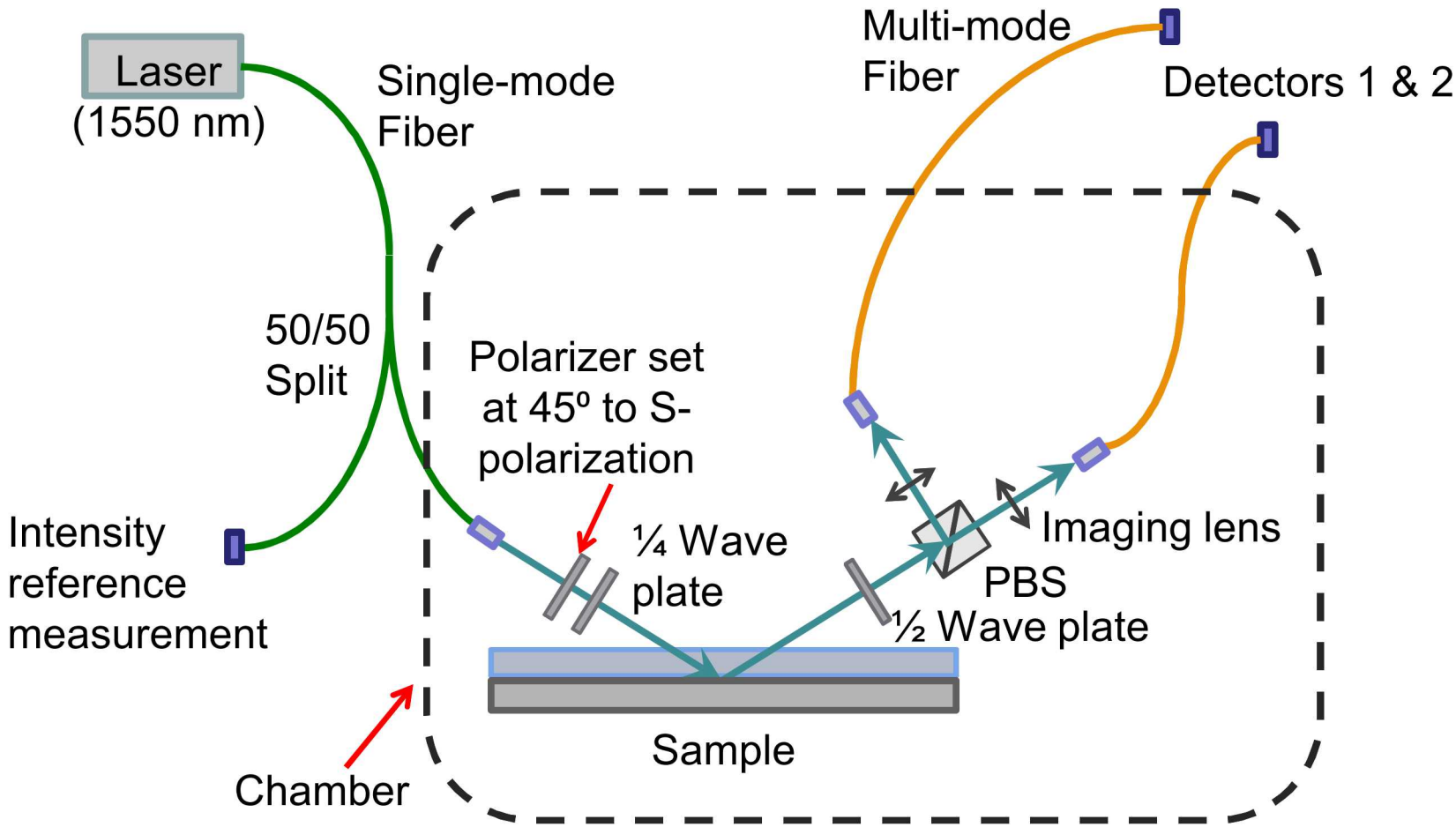
Ellipsometry uses a polarized laser to probe material dielectric properties

- The beam must have a non-zero incidence angle
- Input: Circular polarization
- Output: Phase shift and amplitude changes lead to an elliptical polarization



Directly obtains full complex refractive index at a single wavelength, unlike common reflectivity techniques that require a wide range of wavelengths and the use of the Kramers-Kronig relation to obtain complex information

The basic design is a fiber/free-space hybrid



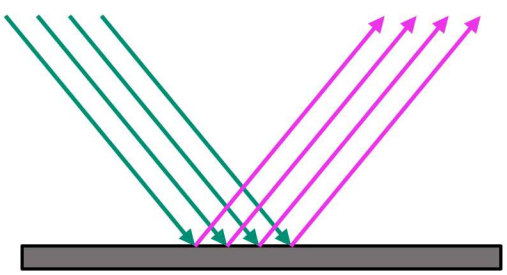
Obtaining specular reflections on dynamic experiments is difficult

Surface roughness and impactor tilt can severely hinder such measurements

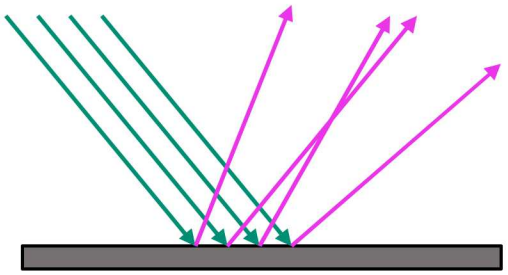
- Surface roughness can be propagated through the shock wave
- Tilt will lead to a sudden change of the reflected beam
- For ellipsometry, cannot simply increase the collection

Ensure all surfaces are as smooth as possible

- Diamond turned metals (maybe lapping too)
- Polished single crystal LiF



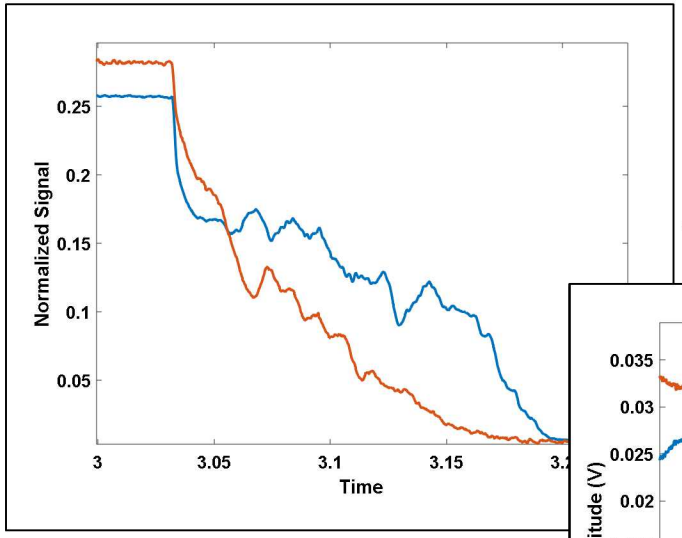
Specular Reflection



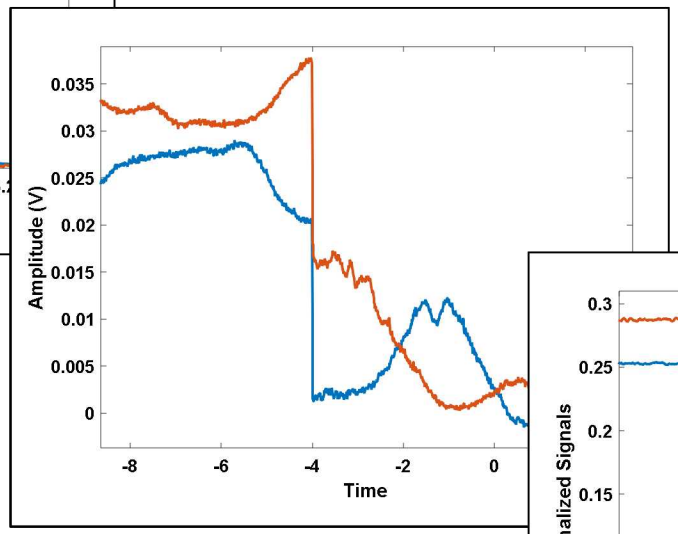
Scattered Reflection

Past experiments have had variable success, but almost always saw significant losses at high shock speeds

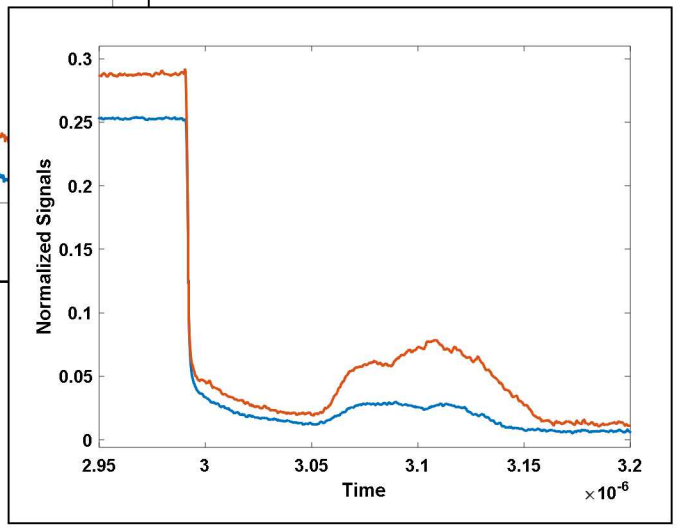
The "good": ~20% loss



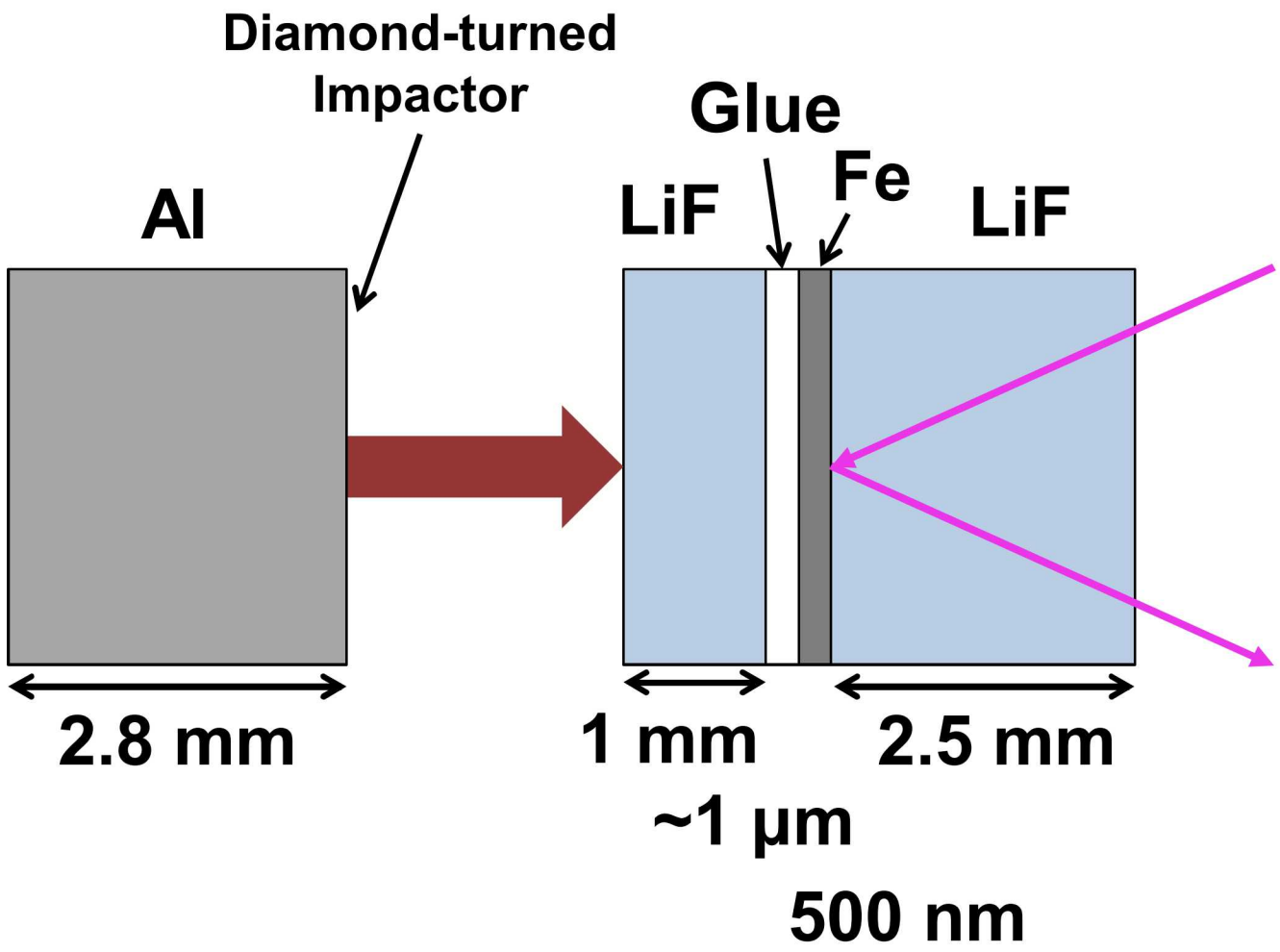
The bad: >50% loss



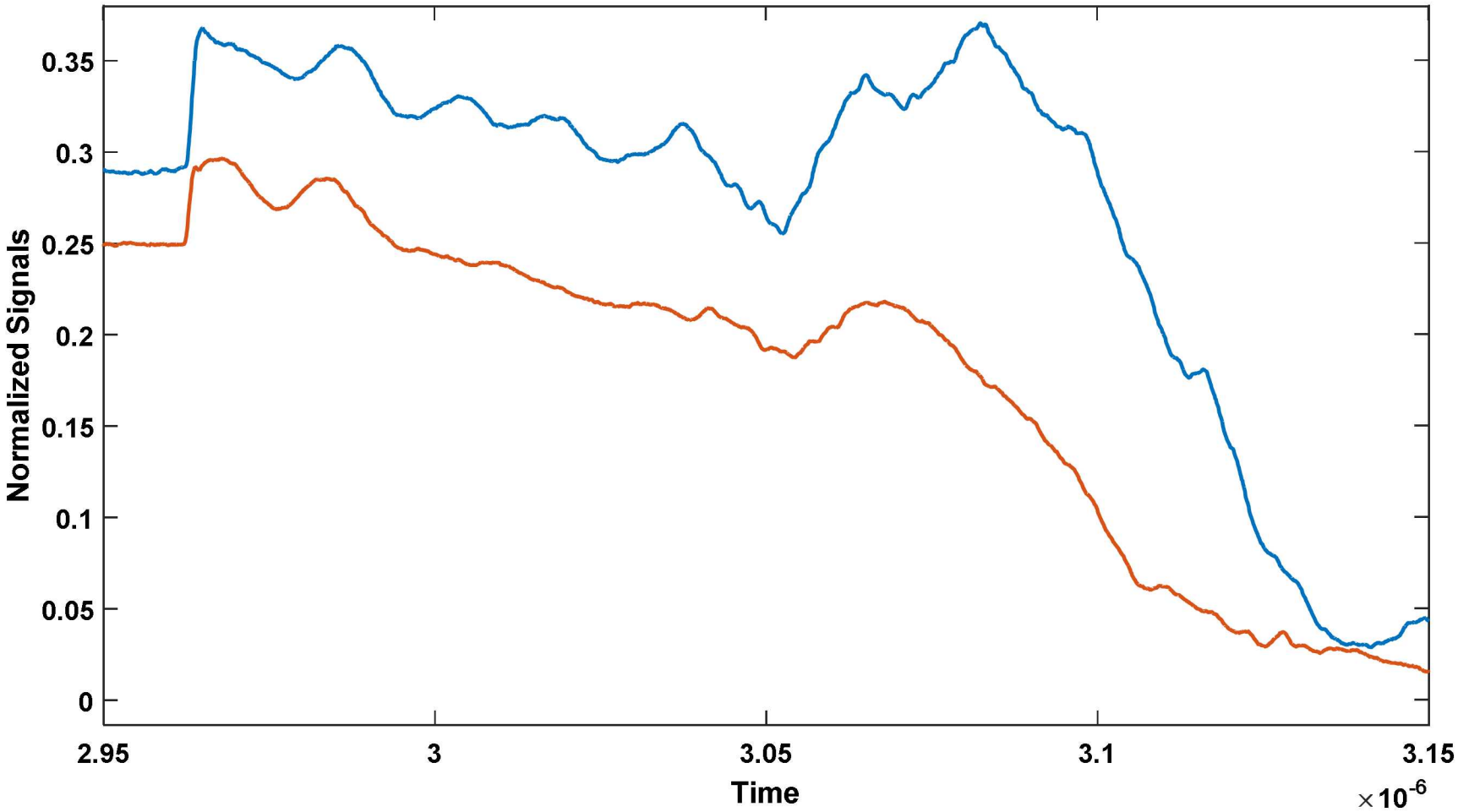
The ugly: 80% loss



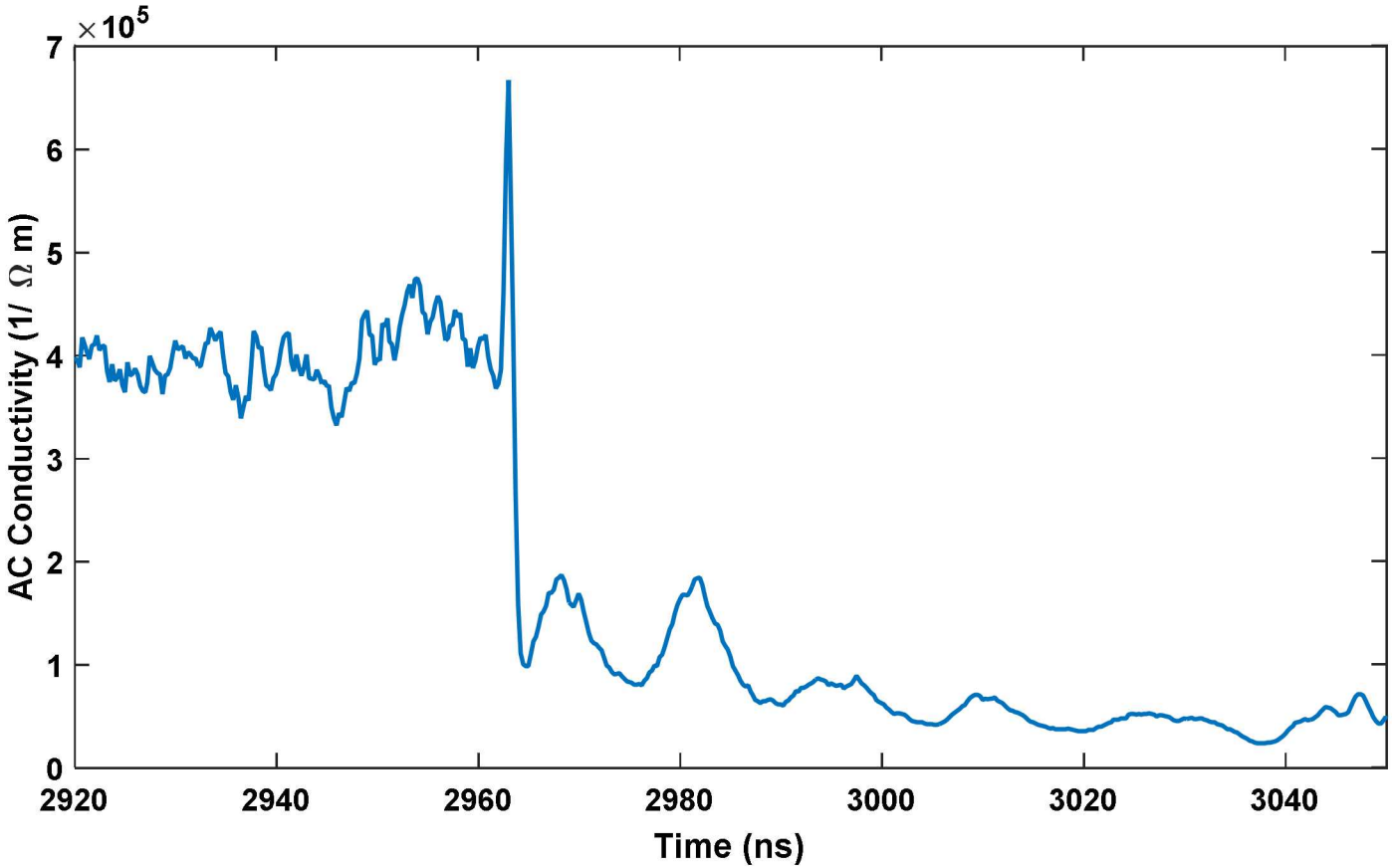
We opted for the best we could do easily



With this sample stack setup we obtained the best collection yet



We calculate the AC electrical conductivity directly from the data

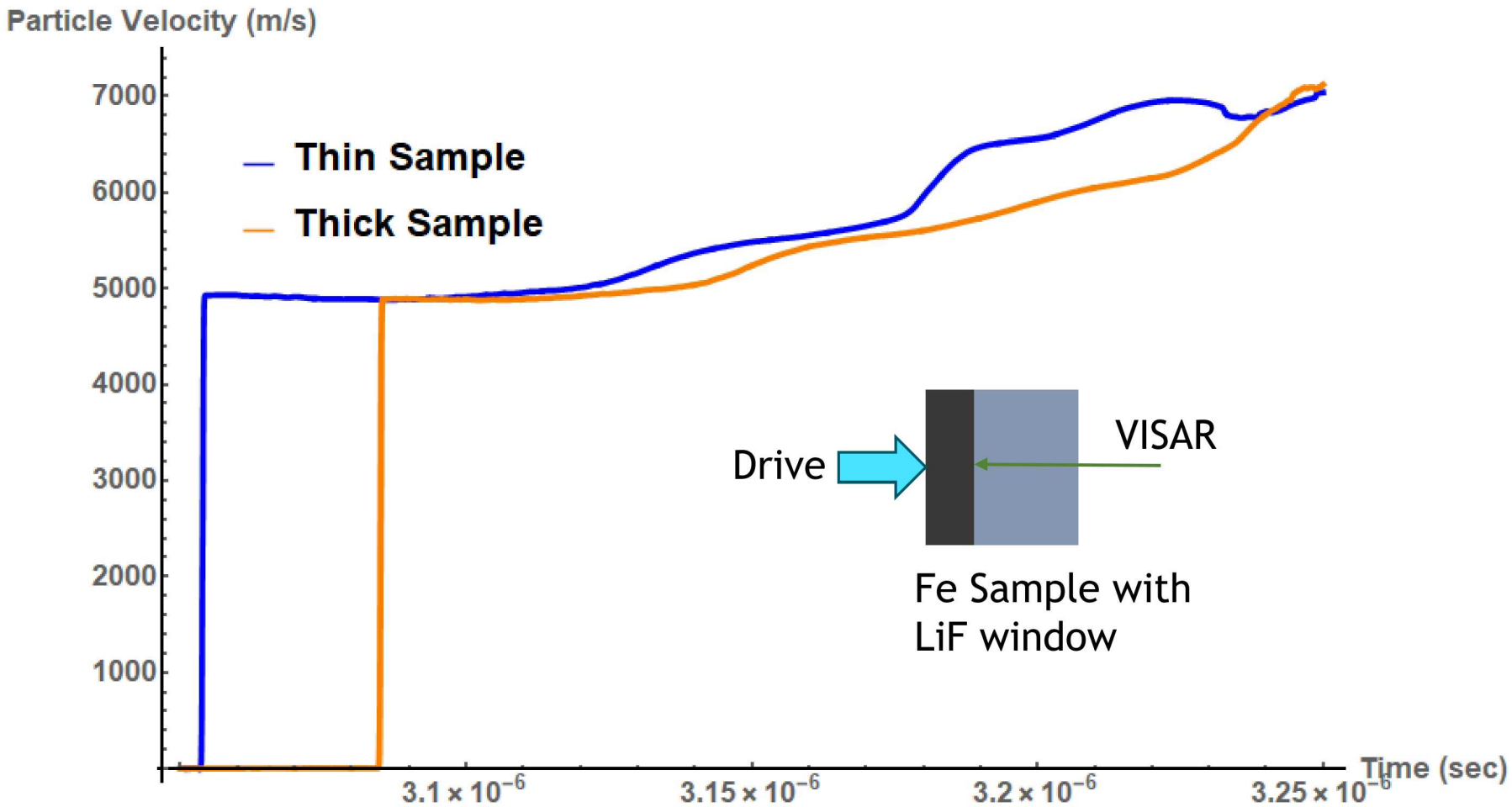


If we rely on Wiedemann-Franz Law and simulations that show a relatively flat DC-to-AC electrical conductivity (Pozzo 2013), we get a DC thermal conductivity of 15 +8/-5 W/m K.

This is lower even than the lower literature values (33 W/m K, Konopkova 2016), and significantly lower than the upper values (226 W/m K, Ohta 2016)

Iron Equation of State

VISAR provides measurements of the particle velocity at all of the sample/window interfaces



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Iterate

- The process is then repeated with this new EOS, iterating until the EOS reaches convergence

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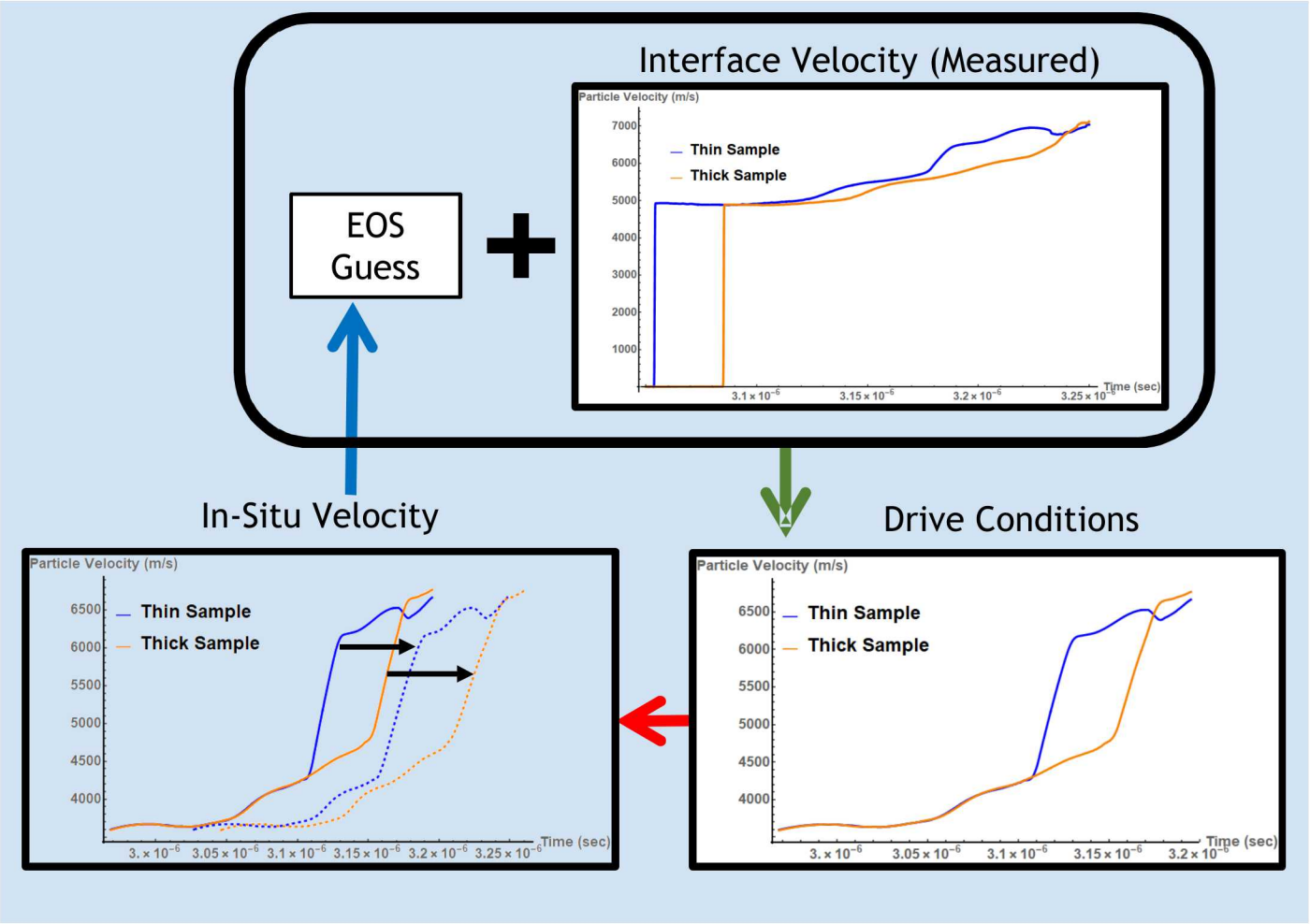

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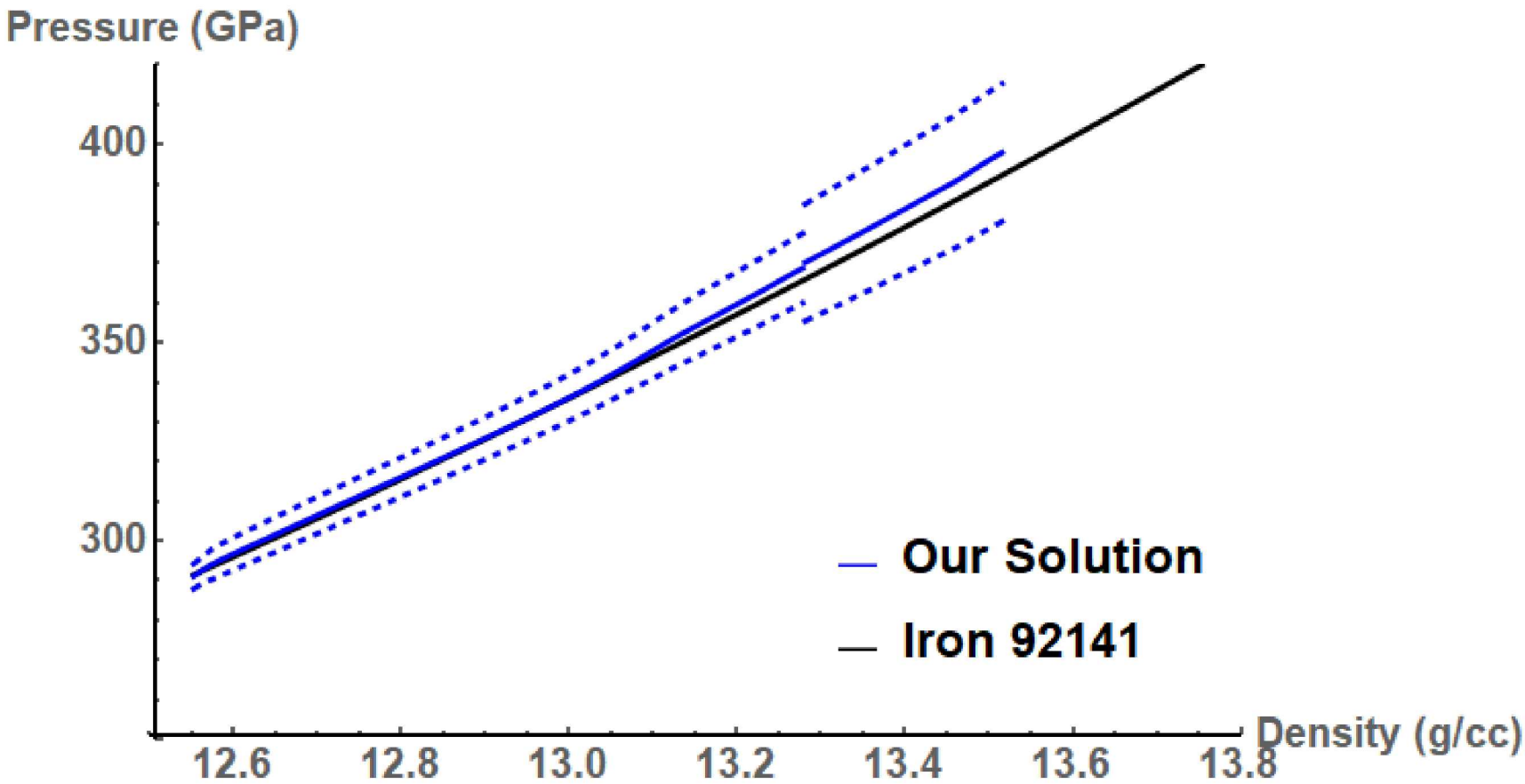

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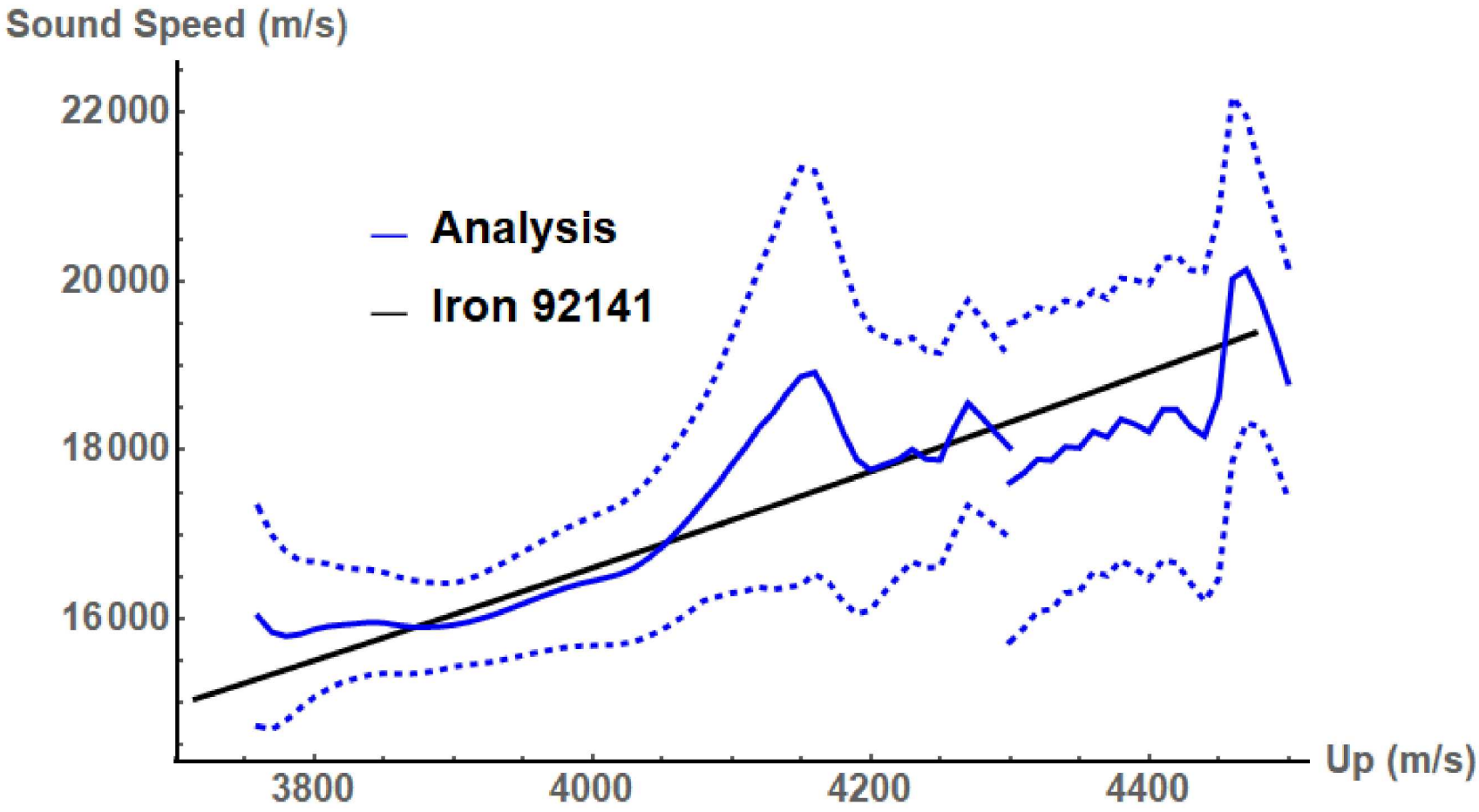

Conclusions and Future Work

Conclusion:

- We have performed shock-ramp experiments on Sandia National Laboratories' Z Machine to evaluate the equation of state of liquid iron along an elevated isentrope near Earth core pressure and temperature conditions. The results agree well with current EOS tables, validating their use at and near these conditions.
- We have gotten the best light return yet with ellipsometry by focusing on creating smooth sample interfaces

Future Plans:

- We would like to try reaching higher pressures
- It would be even more beneficial to planetary models to get better measurements on iron alloys

In-depth questions: Wednesday planetary science break-out session

Acknowledgements

Sandia:

NSTech: Sheri Payne and Richard Hacking

DICE team: Randy Hickman, Nicole Cofer, Keith Hodge, and Josh Usher

Managers: John Benage and Dawn Flicker

SEERI Program: Trish St. John and Kristy Martinez

Iron Equation of State (Extra Slides)

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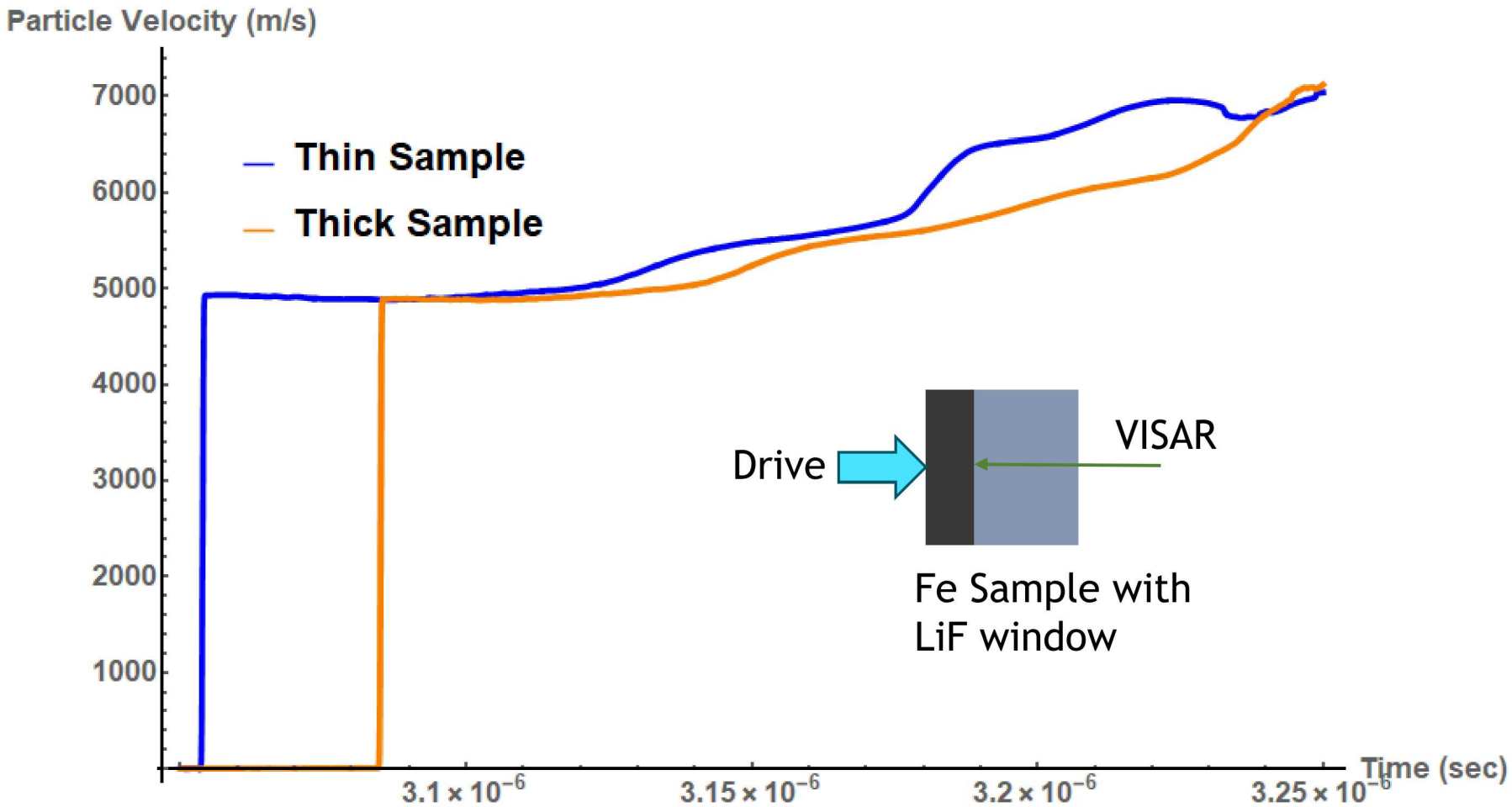


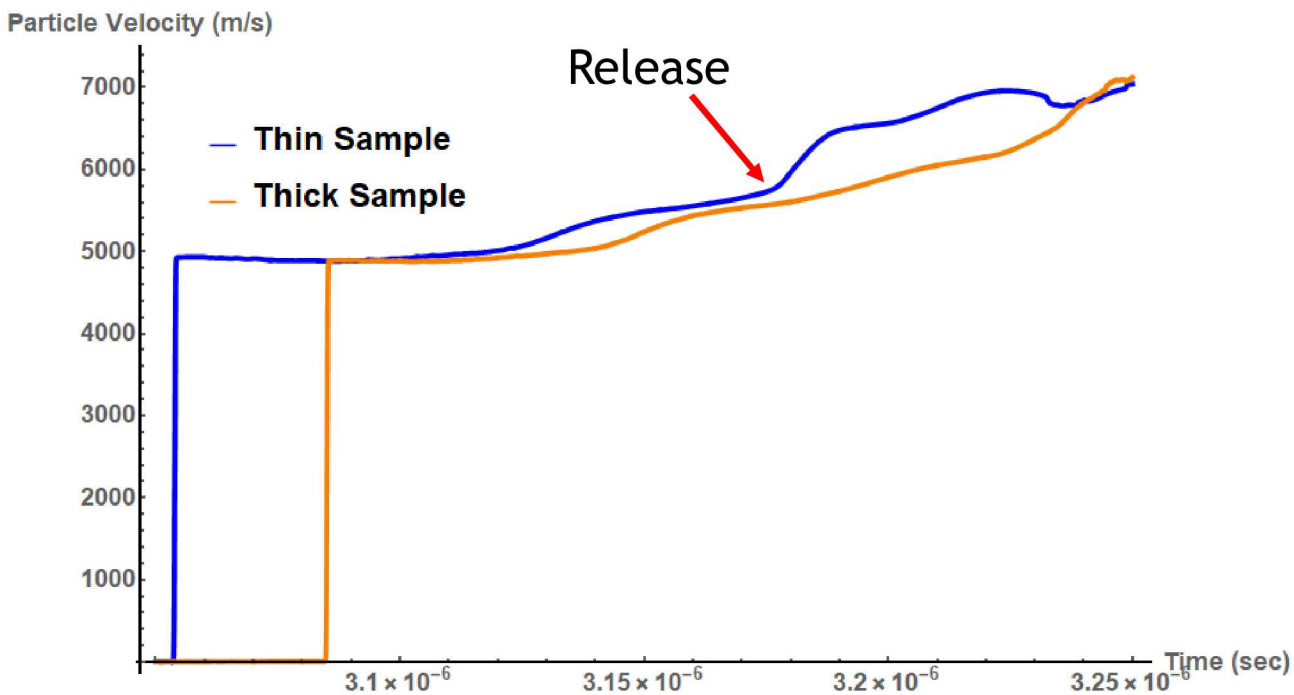
Sample thicknesses are optimized to balance data output and error

The thicknesses of the samples have to balance a few factors

- Thicker samples risk having the ramp drive shock up
- Thinner samples release quicker, leading to a lower maximum pressure
- Larger thickness difference between a given sample pair reduces error

We used two sample thickness pairs to optimize this balance

- 1.2 mm and 0.9 mm (smaller error)
- 1.2 mm and 1.0 mm (higher pressure range)



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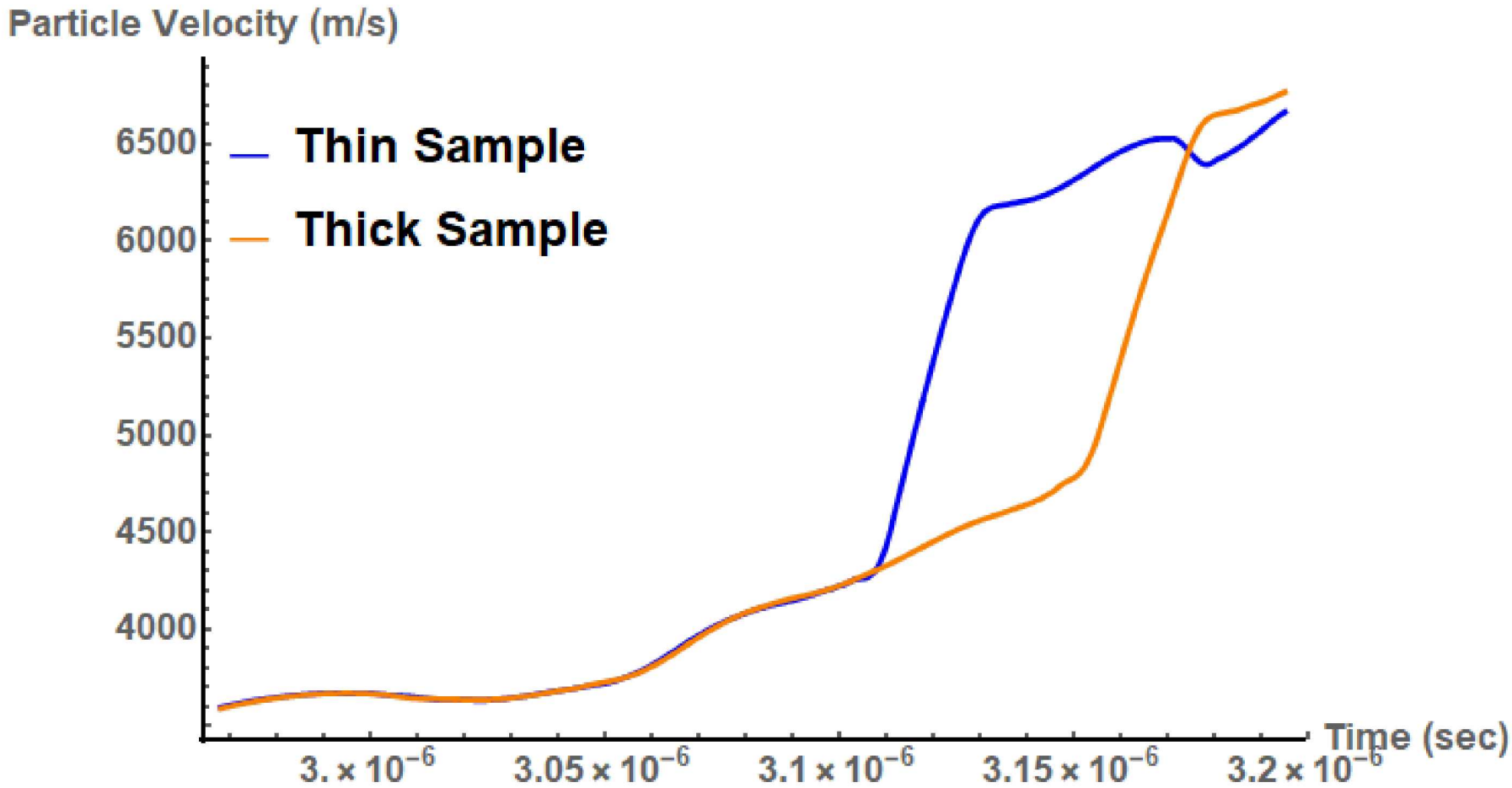
The drive conditions for the two samples should be equal until the release wave from the thin sample reaches this interface



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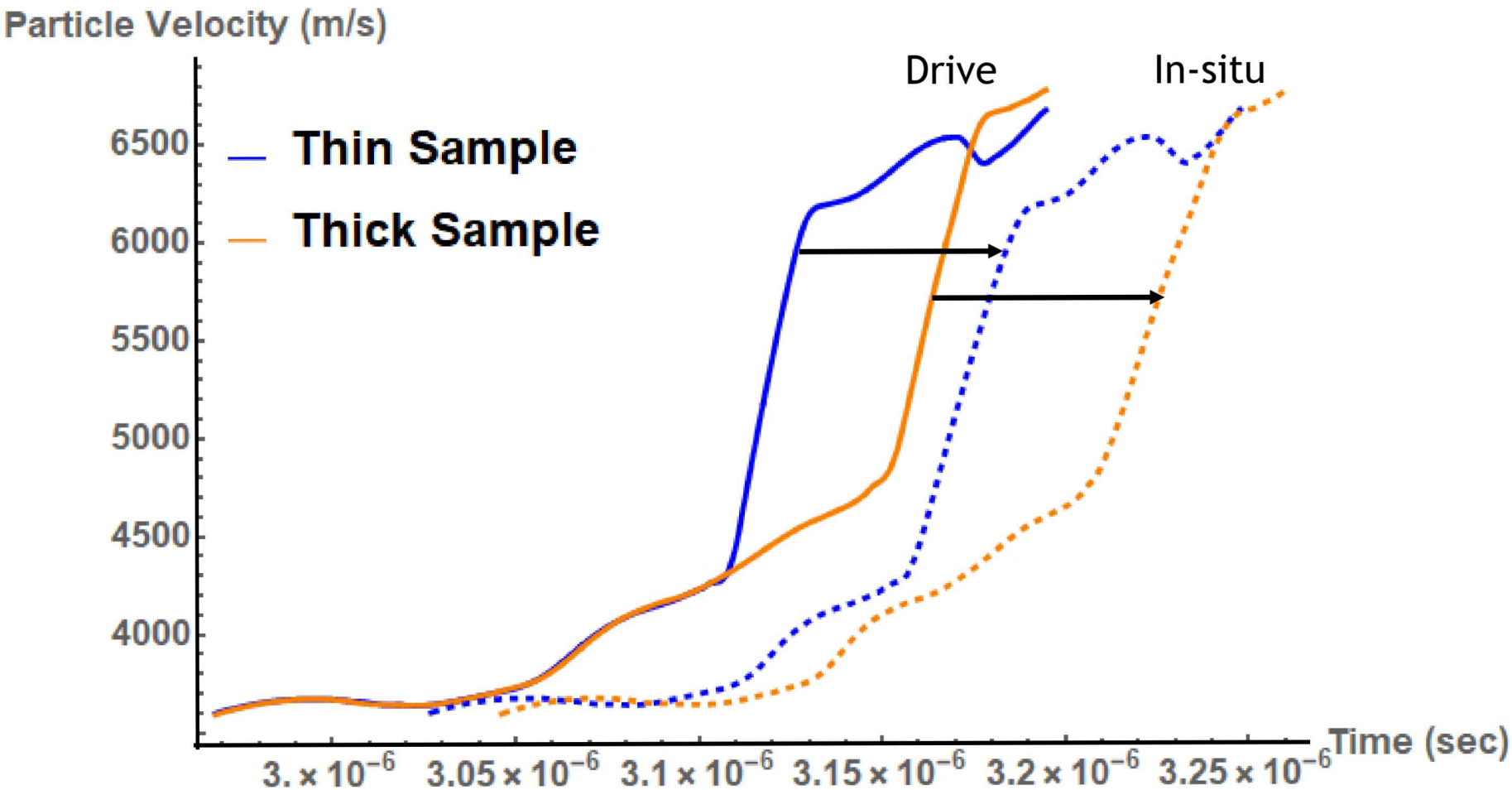
The drive condition is propagated forward to the sample-window interface location



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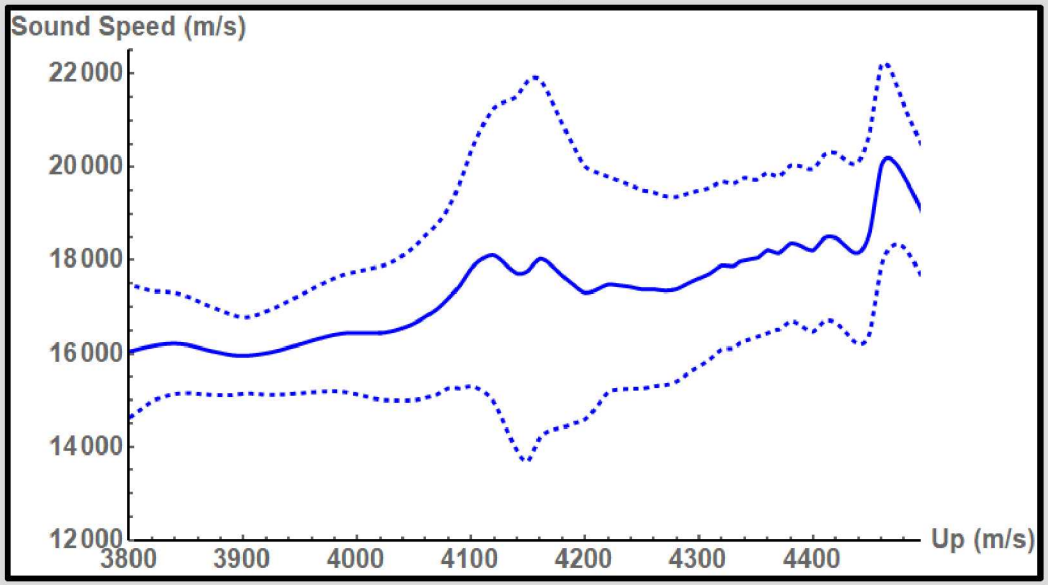
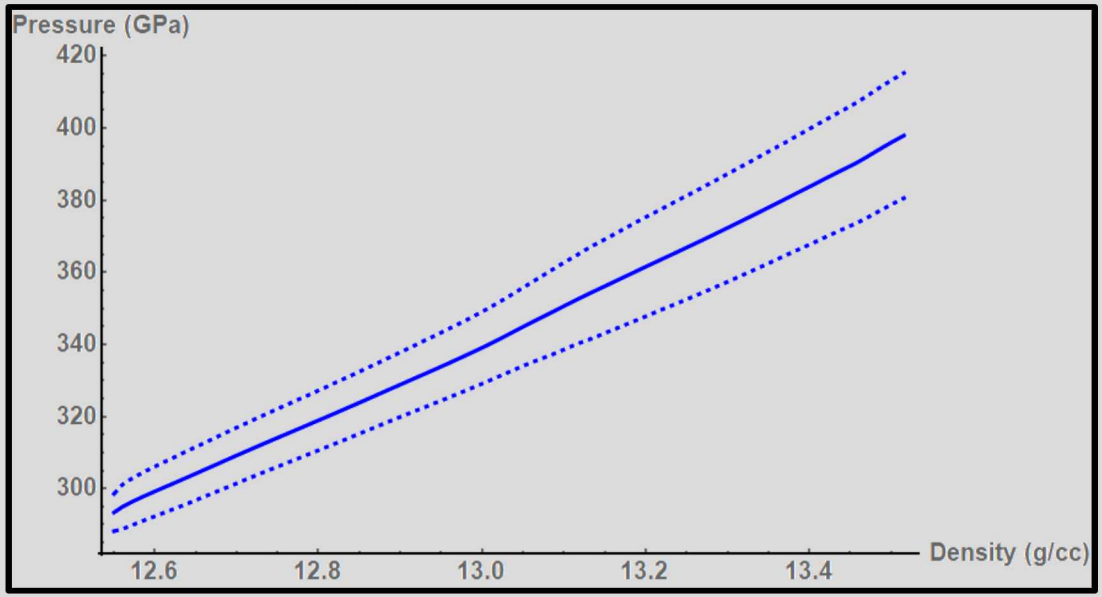
Lagrangian sound speed is determined, and used to calculate the equation of state

Sound Speed



Equation of State



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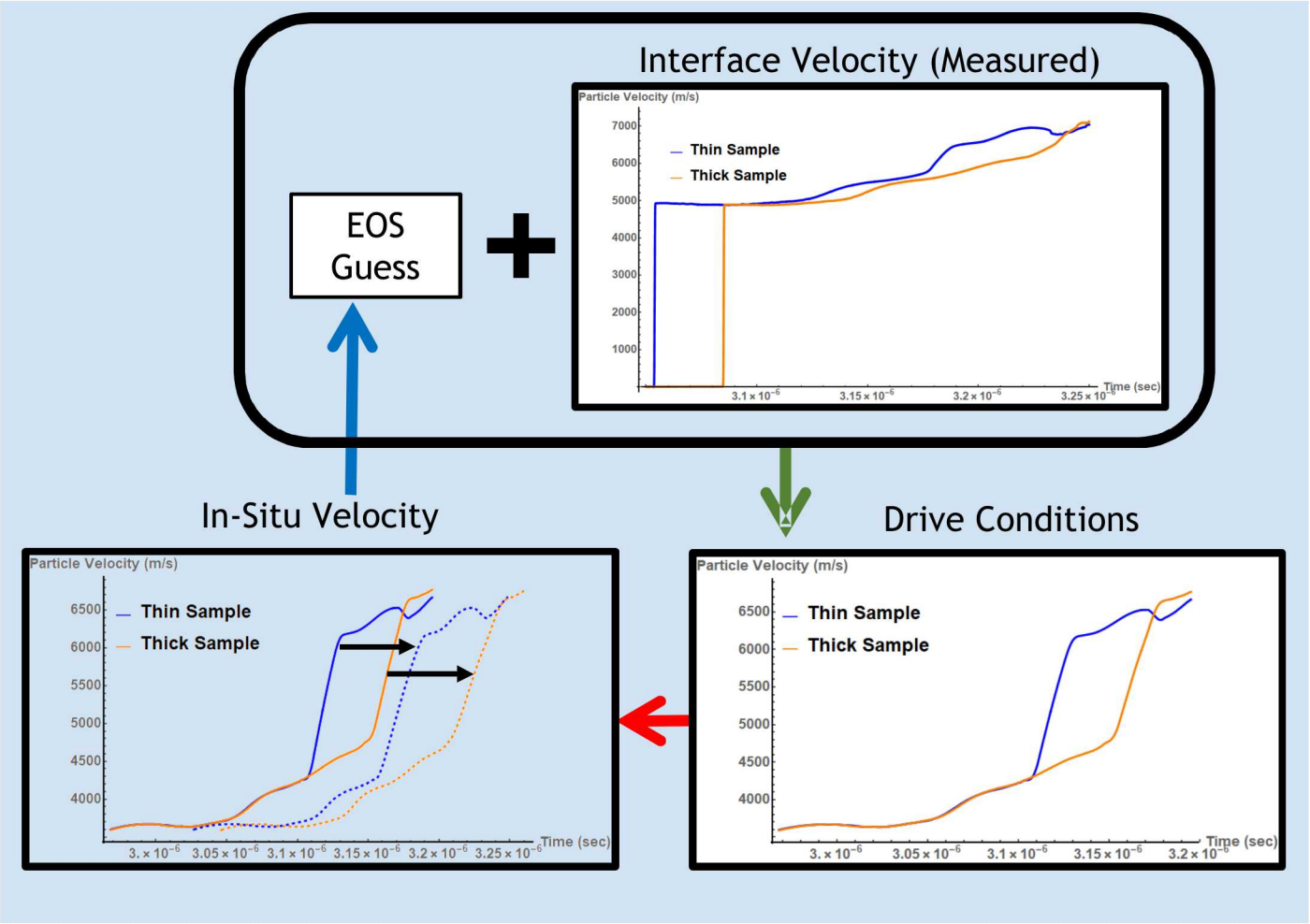

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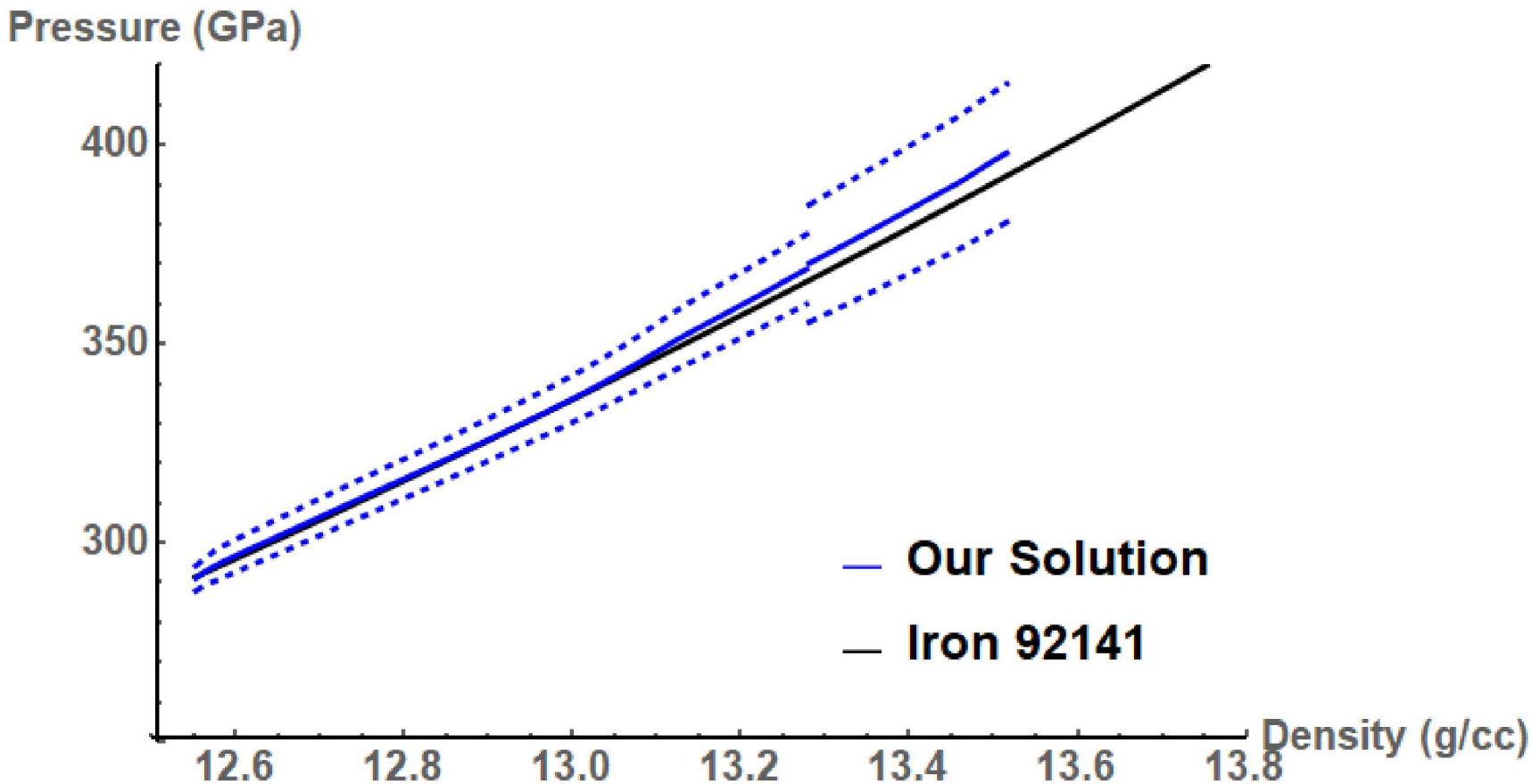

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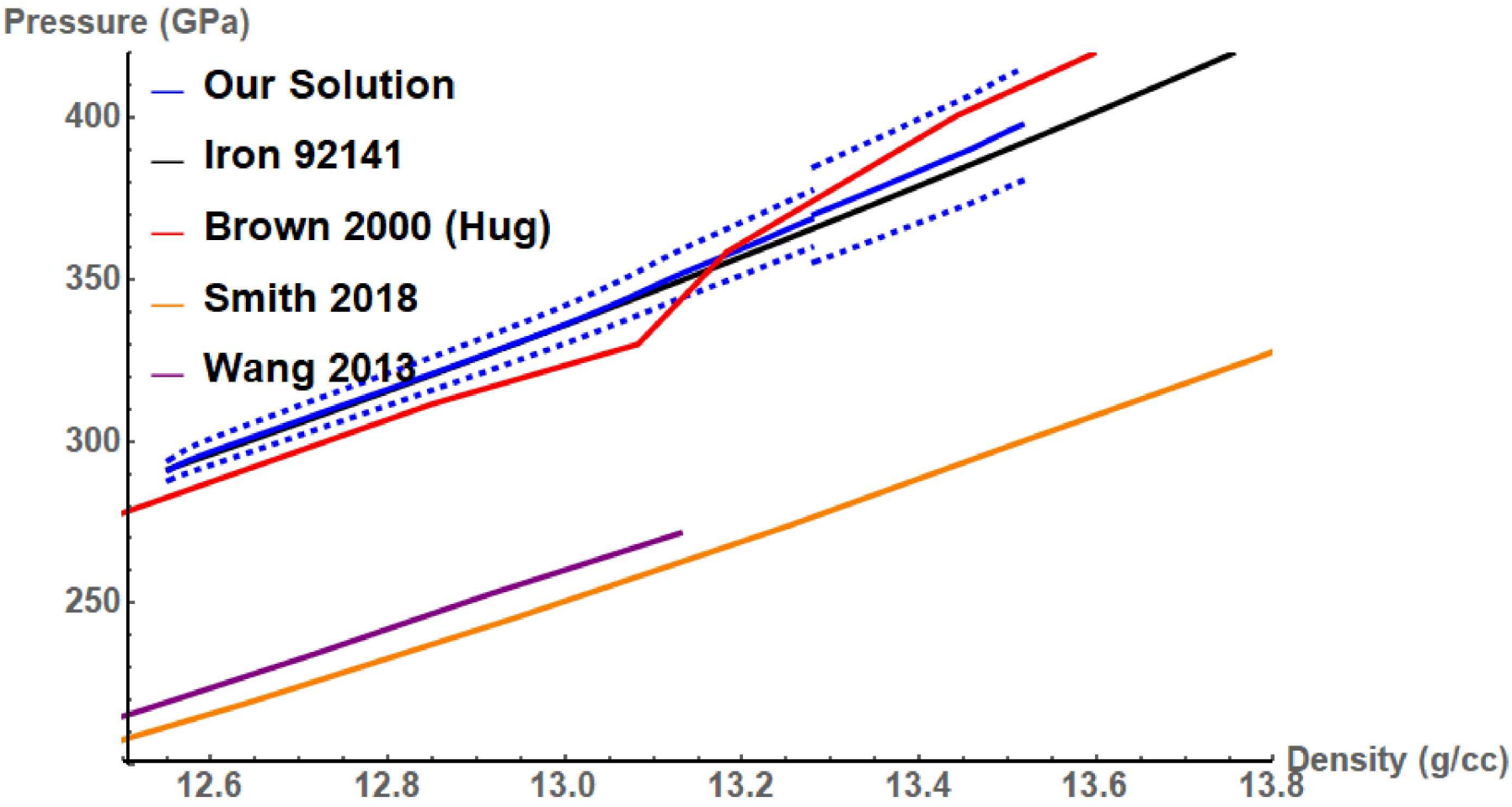
- 1.2 mm and 1.0 mm (higher pressure range)

Comparison with some past work



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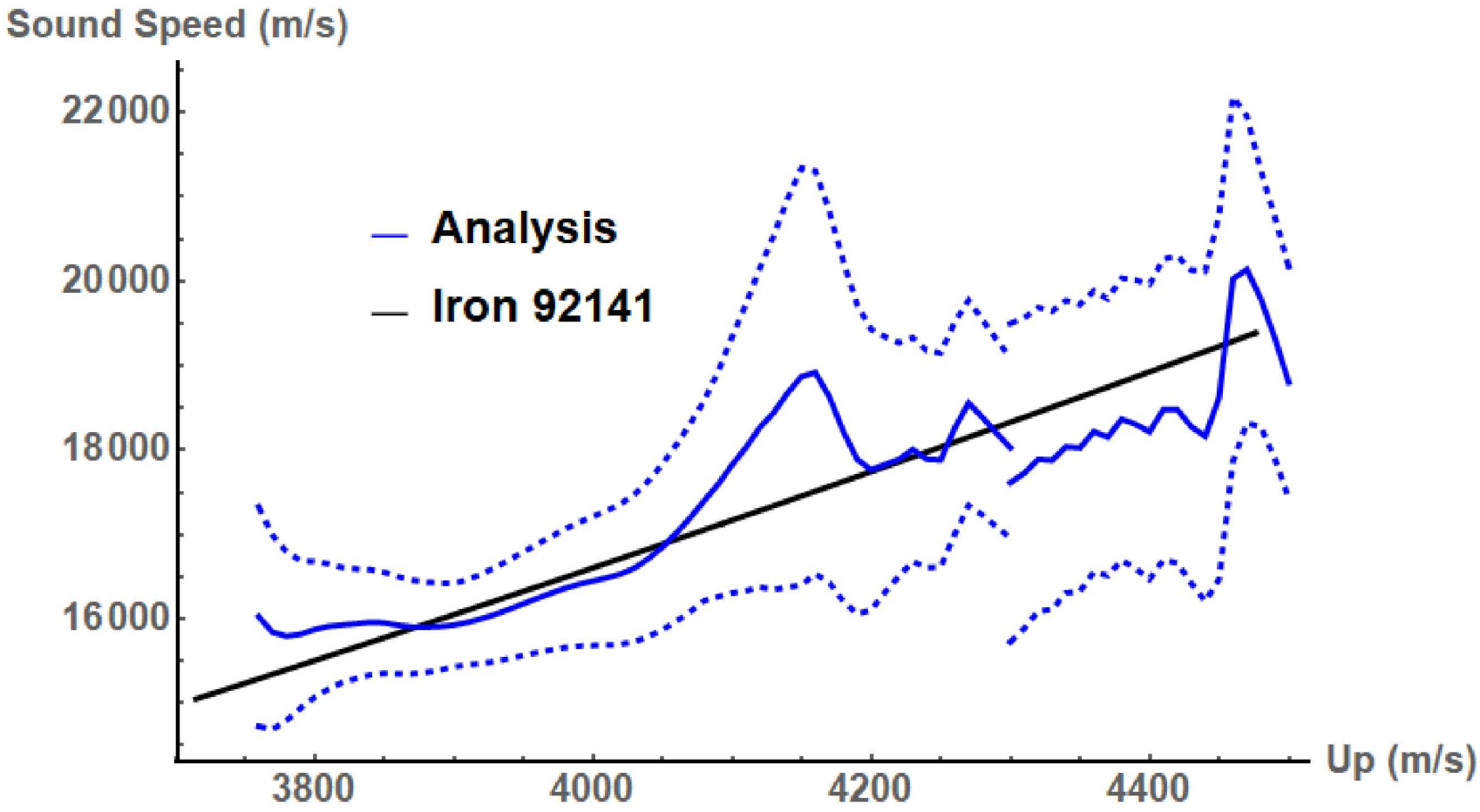

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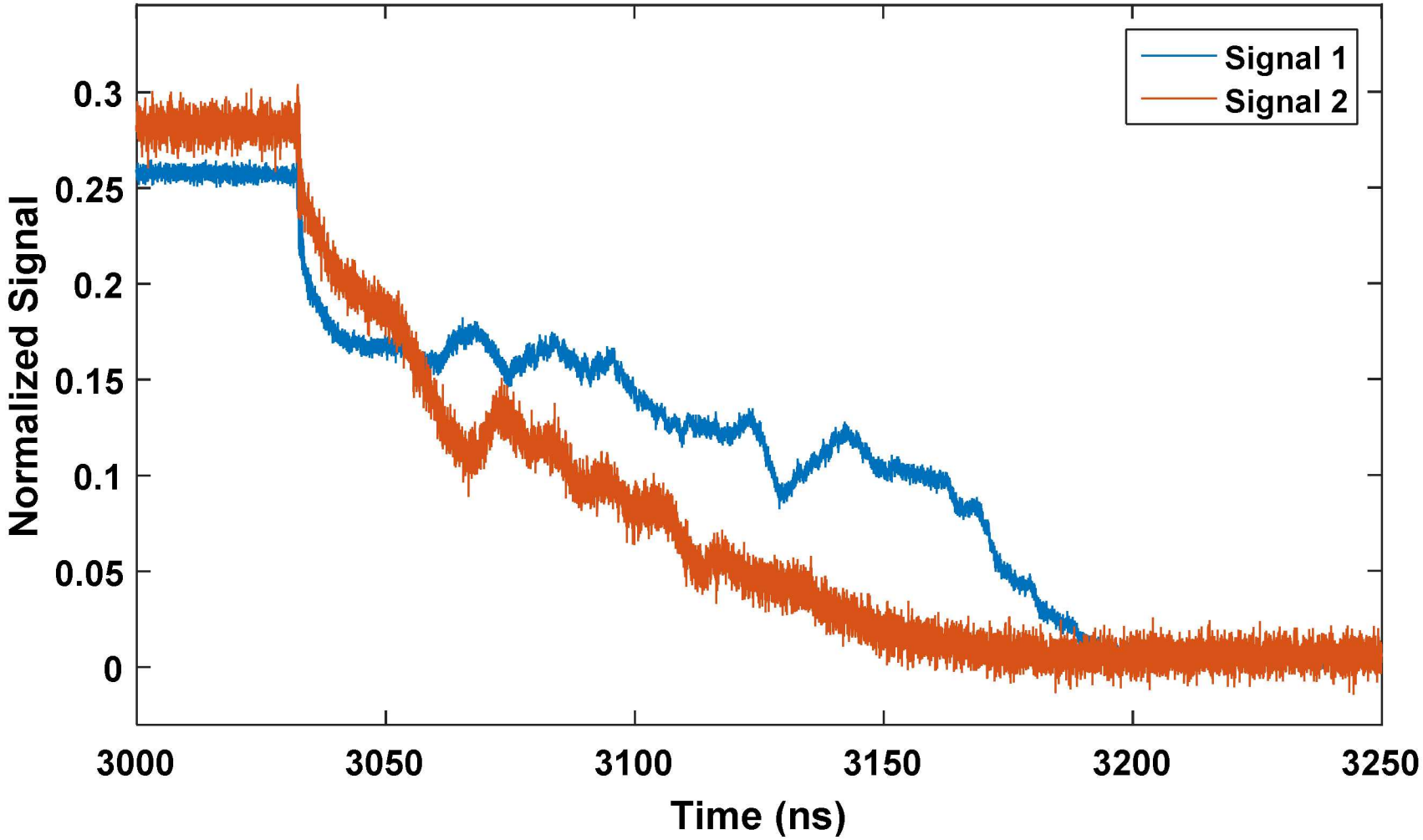
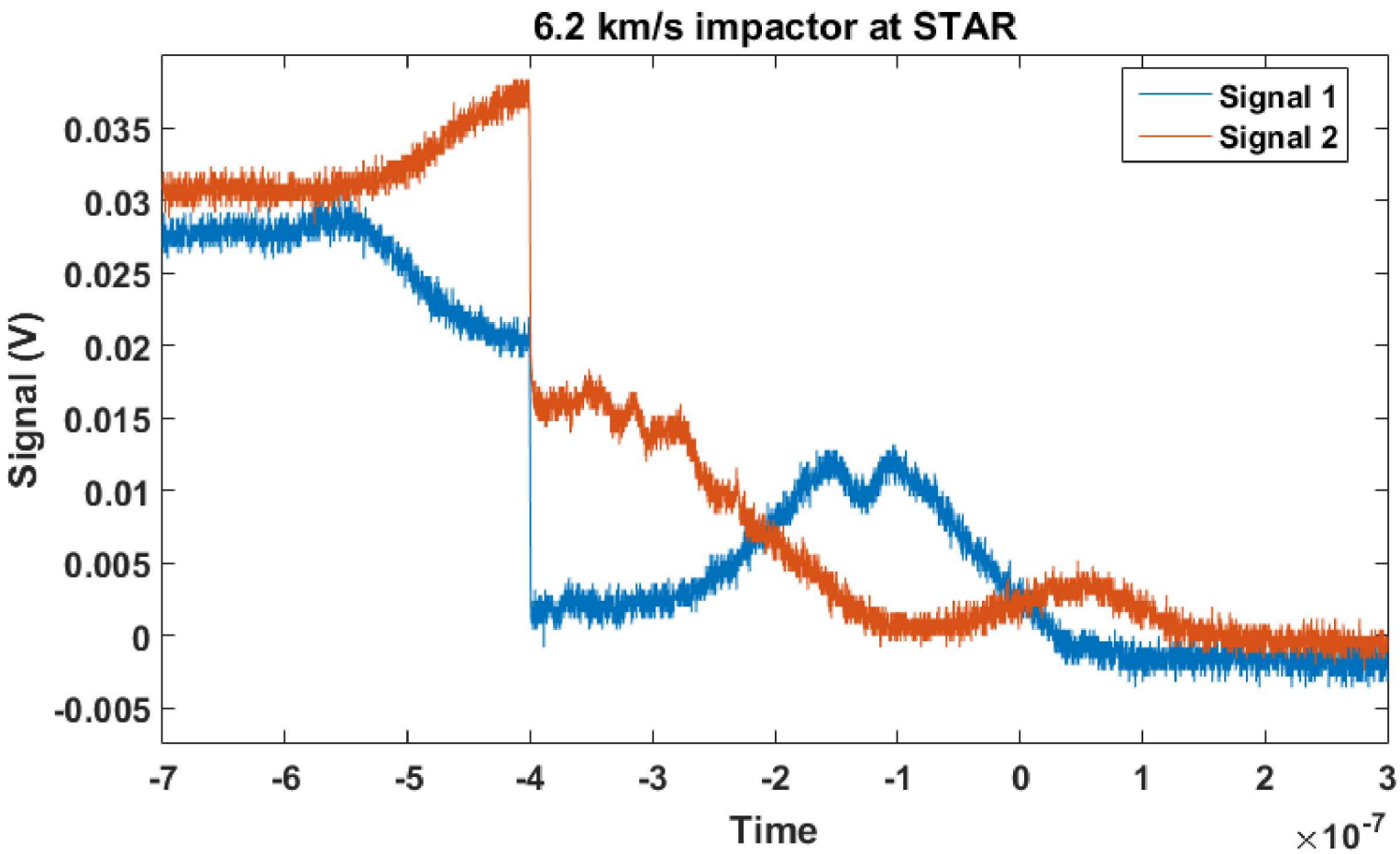
Extra Slides

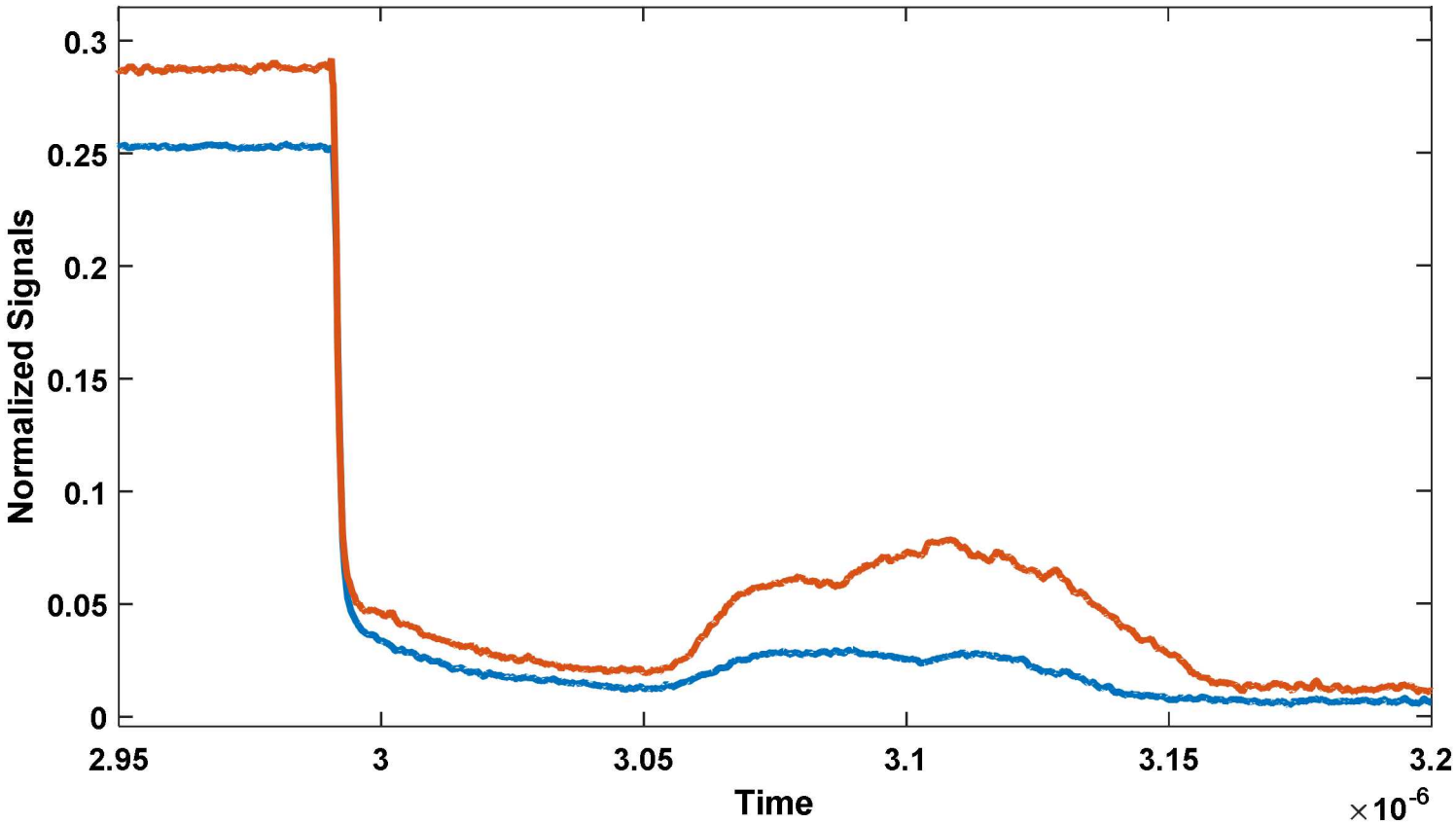
The "good"


Signal 1
Signal 2
Normalized Signal
0.3
0.25
0.2
0.15
0.1
0.05
0
3000
3050
3100
3150
3200
3250
Time (ns)

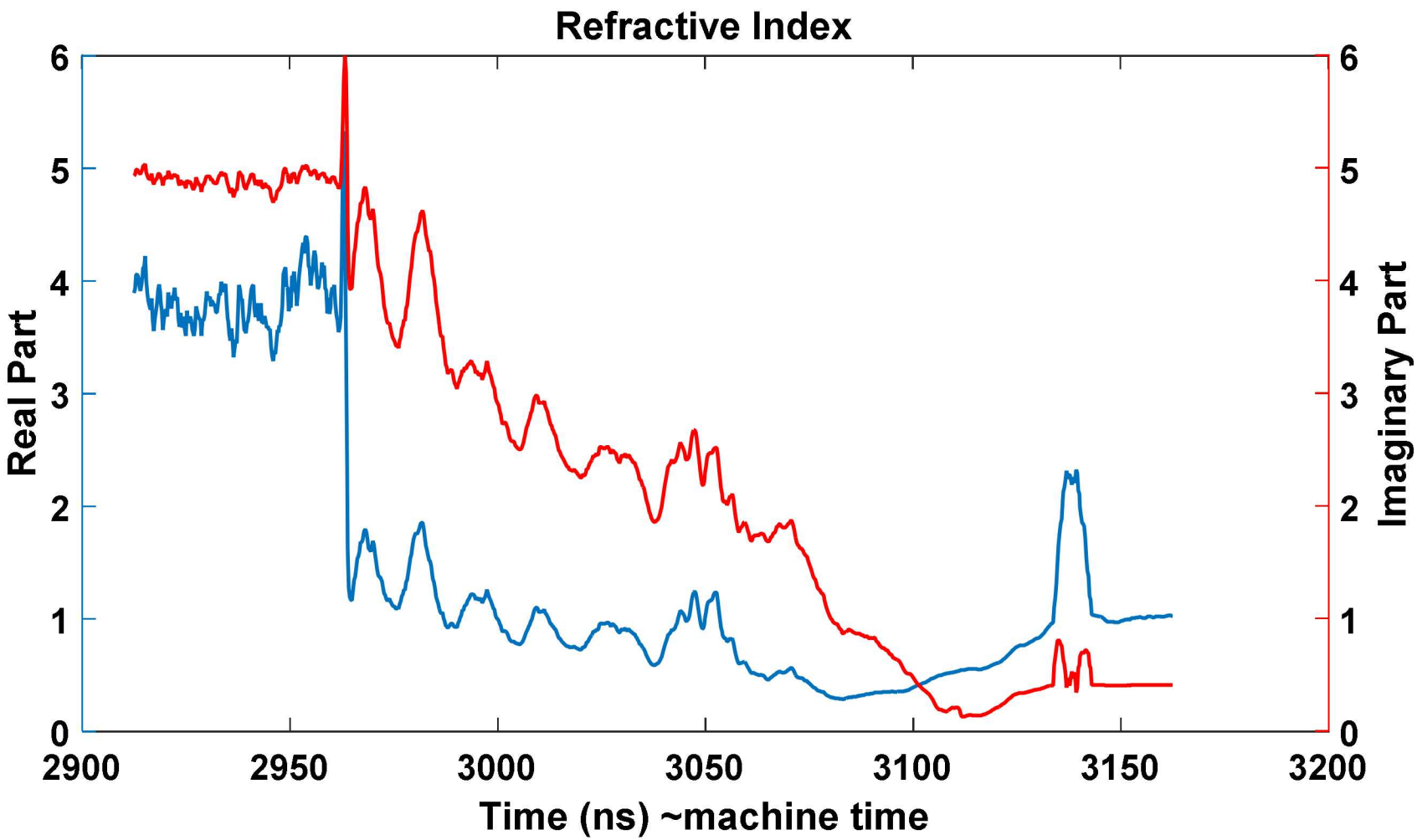
The bad


6.2 km/s impactor at STAR
Signal 1
Signal 2
Signal (V)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
Time
×10^-7

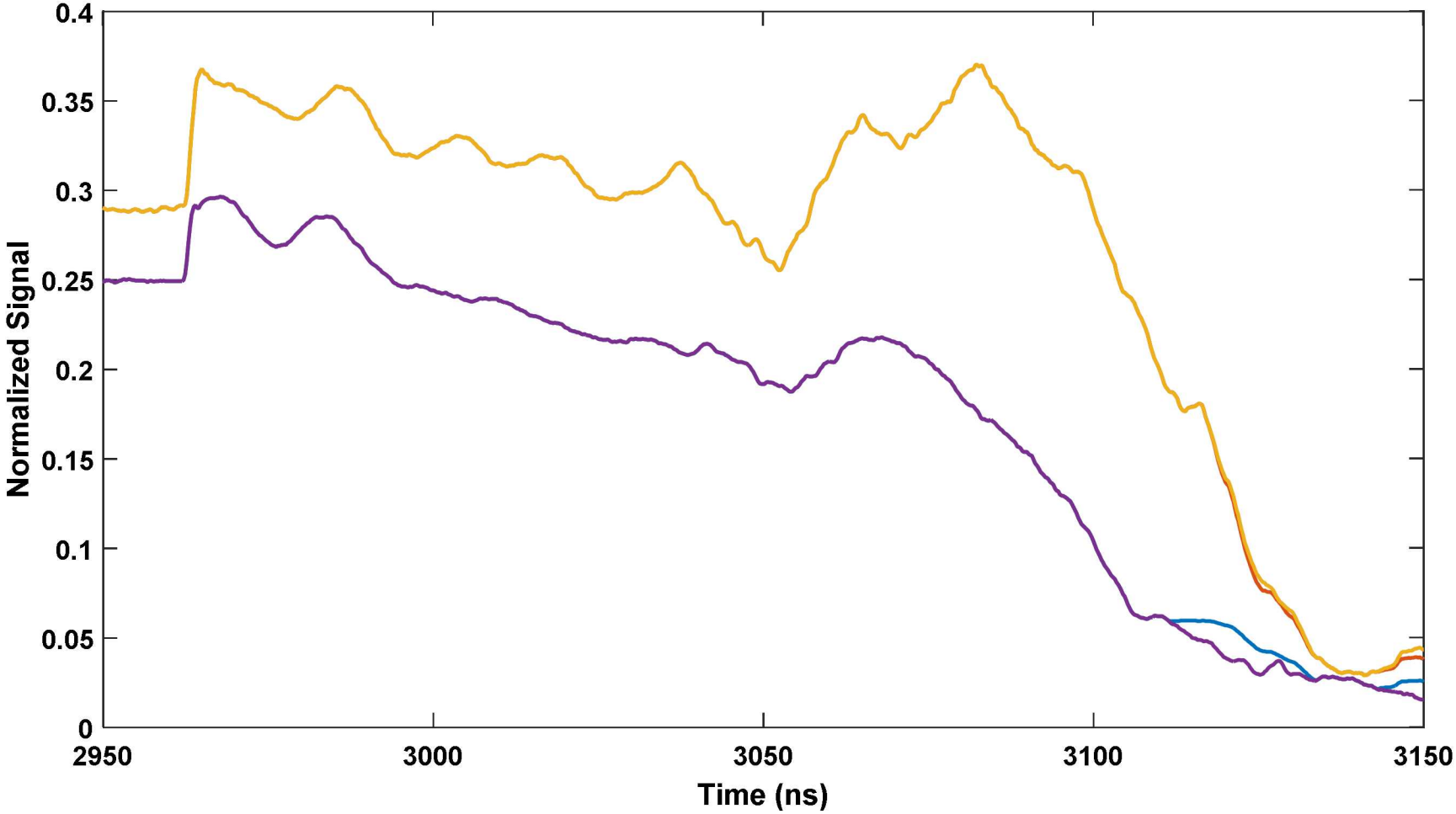
The ugly


0.3
0.25
0.2
0.15
0.1
0.05
0
Normalized Signals
2.95
3
3.05
3.1
3.15
3.2
Time
×10^-6

We convert this data into complex refractive index

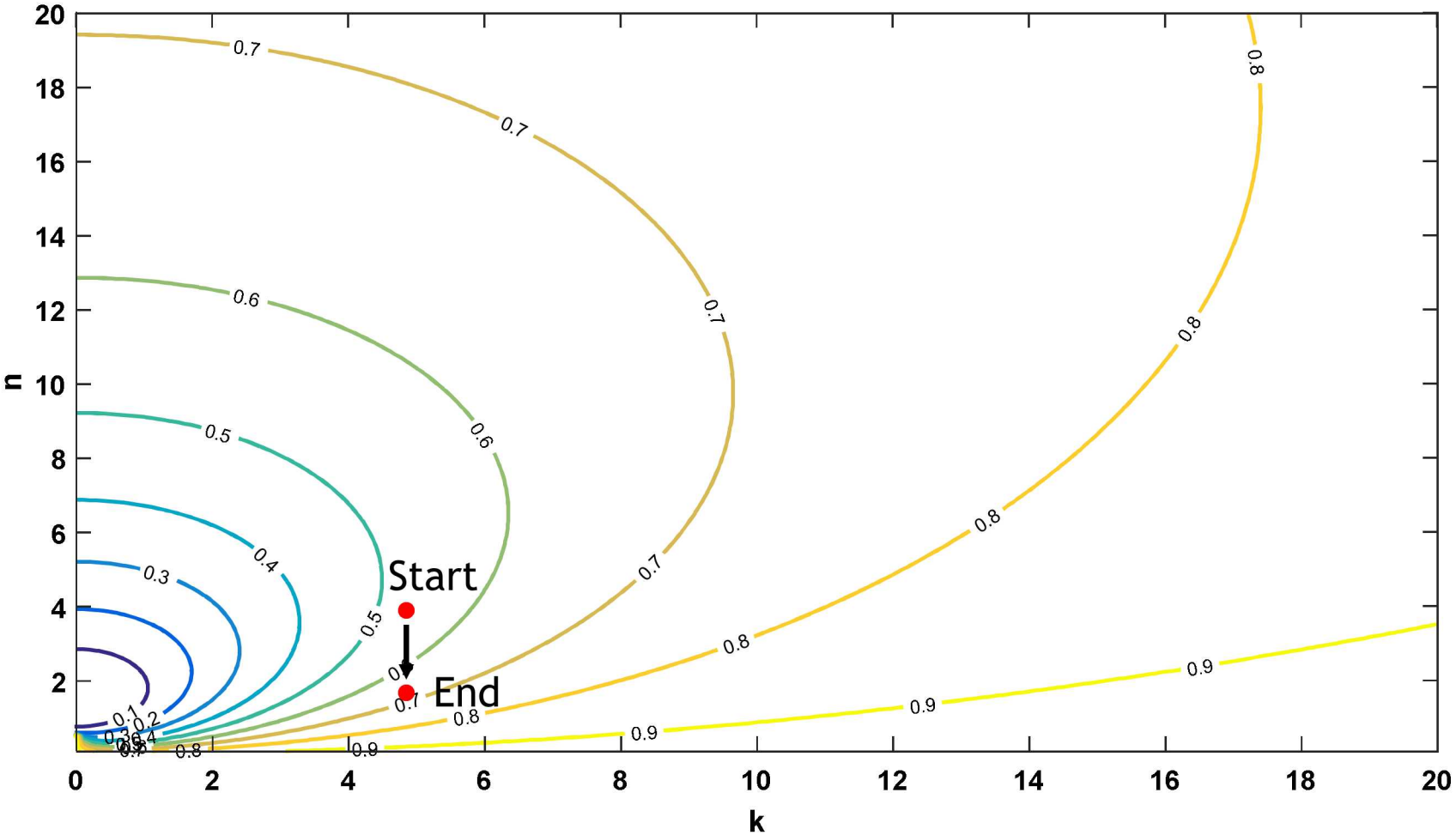


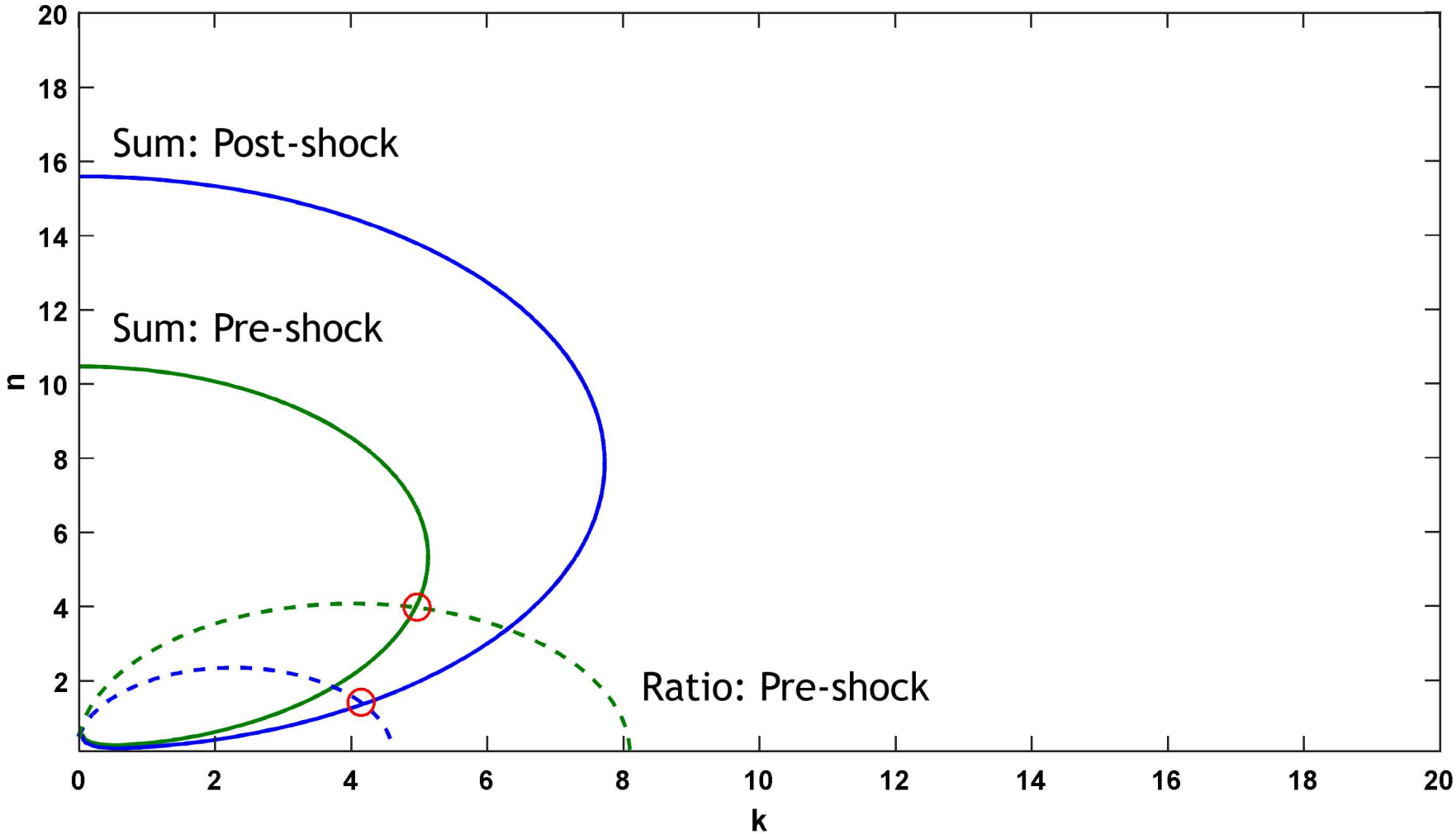
A good local minima was found (at least)



The refractive index solution was put back through my functions to solve for output signal. These match the data over the relevant time range.

Reflectivity Contours



The reflectivity can increase despite decreasing n and k values – especially if n decreases more. (Start and end point illustrated are estimates)

Sum and Ratio Contours