Warm Dense Matter: Concepts and Fundamentals

Syllabus

Fall 2025: August 26 – December 4

Graduate/Senior undergraduate level course delivered by the University of South Florida (USF), the University of California San Diego (UCSD), and High Energy Density Science Center at Lawrence Livermore National Laboratory (LLNL)

Course coordinators: Ivan Oleynik (USF), Frank Graziani (LLNL), Farhat Beg (UCSD), Sebastien Hamel (LLNL), Federica Coppari (LLNL), Michael Murillo (Michigan State University (MSU))

Course Description

This unique interdisciplinary course explores Warm Dense Matter (WDM) – a scientific frontier at the crossroads of condensed matter and plasmas, where conventional theories break down. Found at pressures above 1 Mbar and temperatures of thousands of Kelvin, WDM is key to understanding planetary interiors, white dwarf atmospheres, high-velocity impacts, and inertial confinement fusion. Lectures, delivered by world-class experts, will present background physics, theory, advanced simulations, and cutting-edge experiments using high-power lasers, pulsed power, synchrotrons, and X-ray free-electron lasers, alongside major applications in High Energy Density Science.

The WDM bootcamp, held during the first five weeks of the course, offers a focused refresher on core subjects - classical and quantum mechanics, thermodynamics and statistical mechanics, hydrodynamics, and transport phenomena. Students will also learn Python fundamentals and develop proficiency with the scientific Python ecosystem using Jupyter notebooks, equipping them with the skills to efficiently complete course assignments, *and to document, analyze, and present results in their future research*.

The homework will balance conceptual, theoretical, and computational problems involving Jupyter notebooks.

Who should take the course:

- Students taking course **for credit (3 credit hours).** Credit-seeking students on the semester system should contact Ivan Oleynik (oleynik@usf.edu), and those on the quarter system –Farhat Beg (fbeg@ucsd.edu)

- Scientific personnel for professional development and general public for personal enrichment - **not for credit**

Course meeting times: Two lectures per week on Tuesdays and Thursdays at 12:30-1:45 pm ET (9:30-10:45 am PT)

Course classroom at USF: ISA 2023 (Even though the course is delivered online, USF students are strongly encouraged to attend the lectures in person to have the opportunity to interact with the USF instructor and fellow students before and after the class.)

Delivery method: synchronously online via WebEx. Although lectures will be recorded and made available to students, attending the live online sessions is strongly recommended, as they provide an opportunity to interact with the lecturers and ask questions. **Students are required to register for access to the WebEx platform** by emailing their name and institution to Jessica Karlton (karlton1@llnl.gov).

Prerequisites: Calculus-based Physics

Homework: Problem sets will be given once per week and due at the end of the next week.

Exams: There will be one mid-term exam and final exam

Grading: Homework: 30%, Mid-term exam: 30%, Final exam: 40%. Only students taking the course for credit are required to complete the homework and take the exams.

Office hours: by appointment (oleynik@usf.edu)

Texts and instructional materials: Students will receive the lecture slides one day before each class. The lecture recordings will also be available on the course website.

Recommended texts:

1. Jan Vorberger, Frank Graziani, David Riley, et al., *Roadmap for Warm Dense Matter Physics*, (2025) http://arxiv.org/abs/2505.02494
2. Jeff Colvin and Jon Larsen, *Extreme Physics: Properties and Behavior of Matter at Extreme Conditions*, Cambridge University Press (2014**) DOI:** https://doi.org/10.1017/CBO9781139095150
3. David Ruley, *Warm dense matter : laboratory generation and diagnosis*, IOP Publishing (2021) **DOI:** https://dx.doi.org/10.1088/978-0-7503-2348-2
4. Werner Ebeling, Vladimir E. Fortov, Vladimir Filinov, *Quantum Statistics of Dense Gases and Nonideal Plasmas*, Springer (2017) **DOI:** https://doi.org/10.1007/978-3-319-66637-2
5. Frank Graziani, Michael P. Desjarlais, Ronald Redmer, Samuel B. Trickey, *Frontiers and Challenges in Warm Dense Matter*, Springer (2014) **DOI:** https://doi.org/10.1007/978-3-319-04912-0

Course topics and schedule

Bootcamp (required for students taking the course for credit in semester-based system, strongly recommended for other attendees)

Date	Topic	Lecturer
8/26/25	Course overview	Ivan Oleynik (USF)
8/26/25	Python Language Fundamentals	Michael Murillo (MSU)
9/2/25	Python in Jupyter Notebooks for Physics	Michael Murillo (MSU)
9/4/25	Classical mechanics & quantum mechanics refresher	Ivan Oleynik (USF)
9/9/25	Thermodynamics/Statistical Mechanics refresher	Ivan Oleynik (USF)
9/11/25	Hydrodynamics/continuum mechanics, transport, hydrodynamic instabilities refresher	Ivan Oleynik (USF)
9/16/25	Elemental shock physics refresher	Ivan Oleynik (USF)
9/18/25	Basic plasma and atomic physics refresher	Michael Murillo (MSU)
9/23/25	Molecular Dynamics tutorial: Equation of state, phase transitions and shock MD simulations	Ivan Oleynik (USF)

Main lecture course

Date	Topic	Lecturer(s)
9/25/25	Introduction and overview: What is Warm Dense Matter (WDM) and why we should study it	Frank Graziani (LLNL)
9/30/25	States of matter (gas, liquid, solid, plasma)	Lorin Benedict (LLNL)
10/2/25 10/7/25	Background introductory physics: Quantum mechanics & statistical mechanics	Aurora Pribram-Jones (UC Merced), Burkhard Militzer (UC Berkeley)
10/09/25 10/14/25	Equilibrium properties of WDM: Equation of States (EOS), phase transitions	Rip Collins (U. of Rochester)
10/15/25* 10/16/25	Extreme matter, hydrodynamics, shocks, other techniques to experimentally generate WDM	Jon Eggert (LLNL)
10/21/25 10/23/25	Kinetics, transport, and optical properties of WDM	Tobias Dornheim (Helmholtz-Zentrum Dresden)
10/28/25	Simulations of WDM: Quantum mechanical density functional theory (DFT)	Sebastien Hamel (LLNL)

10/30/25	Simulations of WDM: Classical molecular dynamics (MD)	Ivan Oleynik (USF)
11/04/25 11/06/25	Examples of experimental studies of WDM: Dynamic compression (nanoseconds–microseconds	Federica Coppari (LLNL) Marcus Knudson (SNL)
11/13/25	Examples of experimental studies of WDM: Static compression (seconds–hours)	Zsolt Jenei (LLNL)
11/18/25	New experimental capabilities: synchrotrons, XFELs and high-power lasers	Jon Eggert (LLNL)
11/20 11/25	Properties and diagnostics of strongly coupled plasmas	Michael Murillo (MSU), Tilo Doeppner (LLNL)
12/2	Applications: WDM in astrophysics and planetary science	Dan Shim (ASU)
12/4	Applications: WDM and inertial confinement fusion	Omar Hurricane (LLNL)

*Special Wednesday lecture to make up for the holidays (11/11 Veterans Day and 11/27 Thanksgiving).