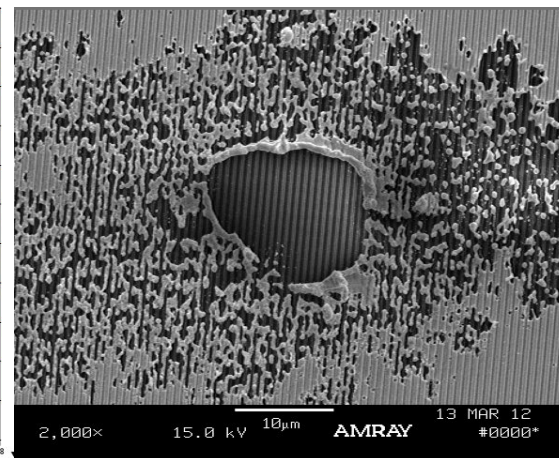
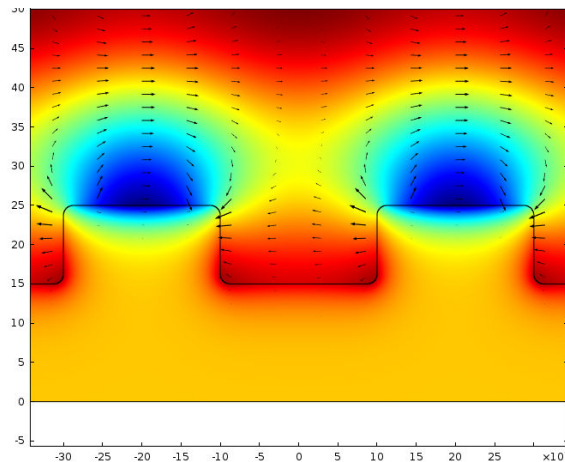


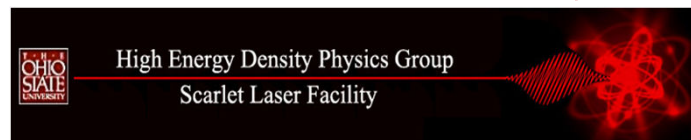
Ultrashort Pulse Laser-Matter Interactions Program Review

Dr. Riq Parra | December 18 - 20, 2012 | Potomac, MD

Understanding the femtosecond laser-solid
interaction
near and beyond the material damage threshold.



Enam Chowdhury
Department of Physics
The Ohio State University



Outline

- Goals
- Background
- Proposed Experimental Thrusts
- Modeling efforts to date
- Summary

Ultimate Goal

BRI Topic: techniques for ultrafast- laser processing (e.g. machining, patterning)



Need material X ,
with property Y and
structure Z

Femtosecond Laser
with optimized
Parameters

Complete
Understanding of Laser-
Matter Interaction

Raw material

XYZ

Ultimate Goal II



Ever Increasing
demand for optics
for high power
femtosecond
applications

Femtosecond Laser
Damage Studies of
systems

Thin films,
materials and
surface
structure
technologies

Complete
Understanding of Laser-
Matter Interaction

*Optics with
High LDT in
femtosecond
regime*

Project Goals

To develop a new, fundamental understanding of intense field laser *ablation/damage* in the femtosecond regime.

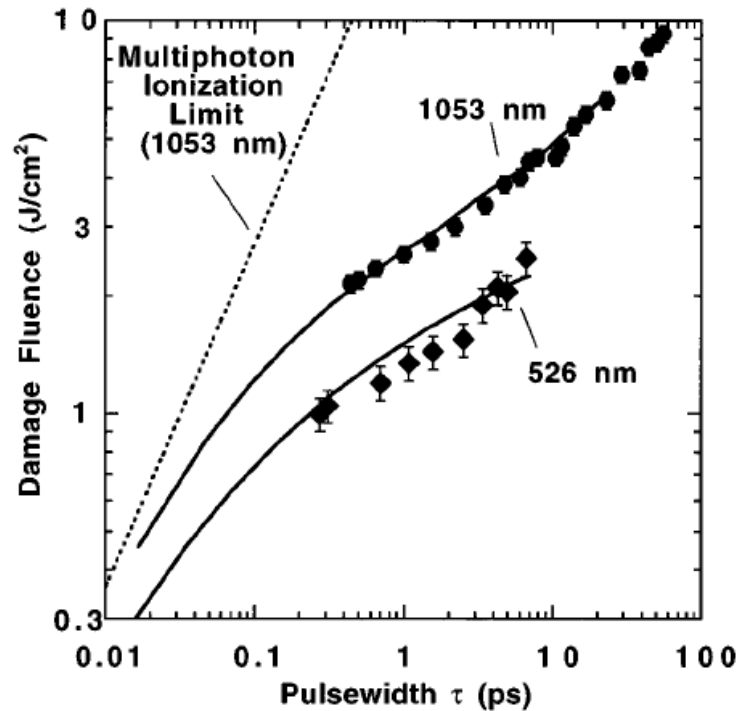
- Understand dynamics of *ionization*: First step in interaction
- Understand creation and effect of *defect states* in *multi-pulse* interaction
- Use micro and nano scale structured surfaces to study *effect of structures on laser damage*
- Use innovative experiments and realistic computer models to capture *dynamics of laser ablation*

Team of Experts

- **Chowdhury (OSU Physics):** femtosecond laser matter interaction experiment (**PI**)
- **Schumacher (OSU Physics):** Simulation of femtosecond dynamics
- **Shvets (UTA Physics):** Simulation of femtosecond dynamics of Structured Surfaces
- **Akbar (OSU MSE):** Fabrication and characterization of nano-structured surfaces
- **Yi (OSU IE):** Fabrication and characterization of micro-machined surfaces
- **Smith (PGL):** Fabrication and characterization of ultra-precise periodic surface structures

Background

Physics of femtosecond Damage



B. C. Stuart et. al. *PHY REV B* **53**, 1996

Fs: multi-photon ionization/non-equilibrium electron transport and lattice damage via electron phonon coupling, and or non-thermal melting

Ns: material heating via collision, diffusion, melting and removal

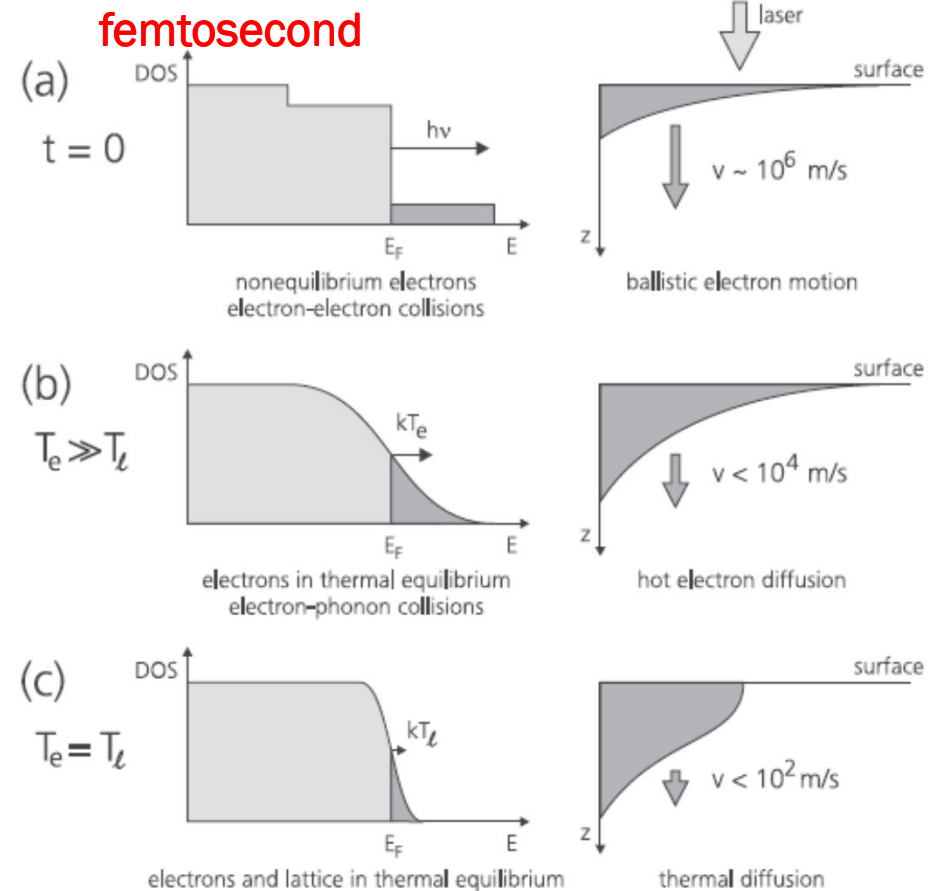


Fig. 2a–c. Relaxation phases following optical excitation of metals. At $t = 0$ a highly non-equilibrium state is generated (a) which deexcites by $e-e$ collisions to form an electron temperature (b). This, in turn, cools by $e-ph$ interaction until it reaches thermal equilibrium with the lattice (c). The energy distributions inside the material and transport velocities are indicated on the right

Wellershoff et. al. *App. Phys. A* **69** S99 (1999)

Experimental Consideration: Need for Vacuum

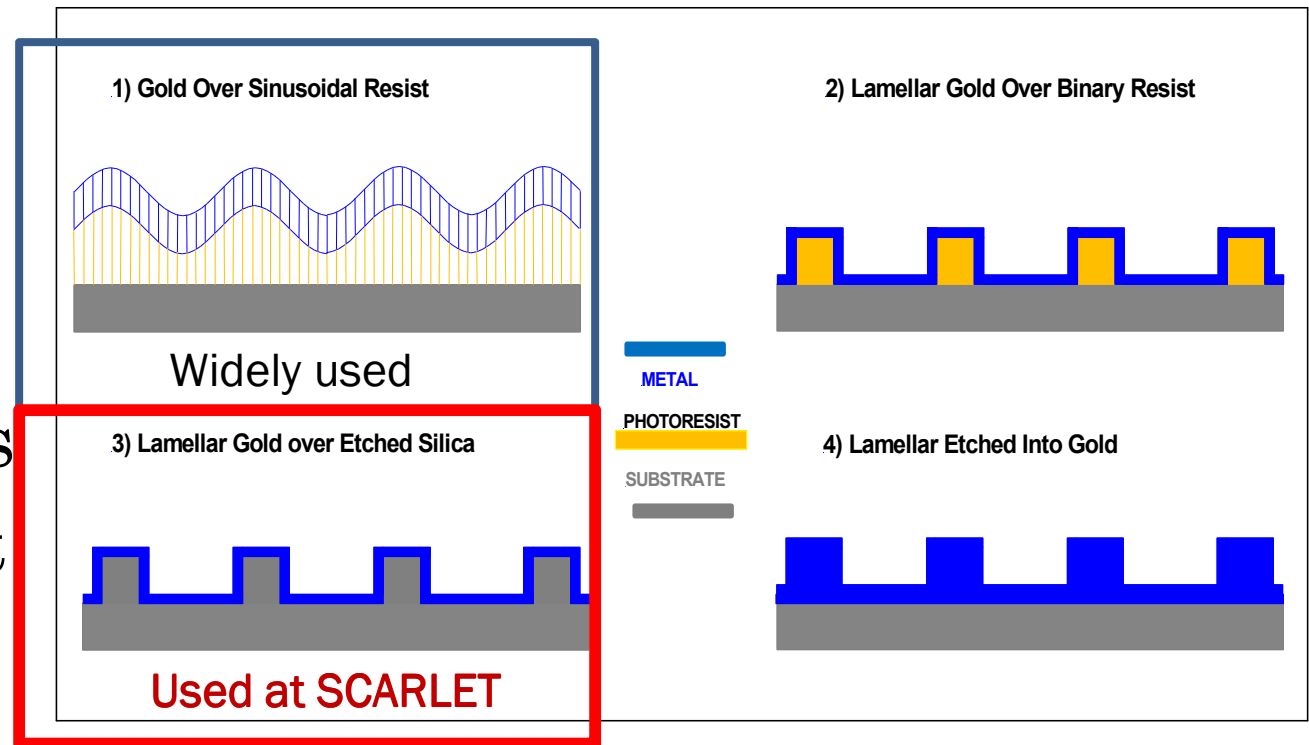
- Laser matter interaction with short pulse lasers, and femtosecond laser LDT test often require focusing the beam.
- Although most realistic machining would happen in air, it can also act as an *extra variable*, where broad bandwidth of the pulse allows a focusing beam to react to the non-linear index of air, causing non-linear phase accumulation of wave-front and ultimately the breakup of the beam into multiple self-focusing filaments.

Damage Threshold of Optics

		Air Fluence (J/cm ²)	Vacuum Fluence (J/cm ²)	Air Intensity (W/cm ²)	Vacuum Intensity (W/cm ²)
Protected Au Mirror	Single shot	1.5	1.7	6.0E+13	6.7E+13
	(30-30k) Multi shot	1.0	1.5	3.9E+13	5.8E+13
Au Grating	Single shot	0.30		1.2E+13	
	(30-30k) Multi shot	0.27	0.3	1.1E+13	1.2E+13
Dielectric Mirror	Single shot	0.62	1.2	2.5E+13	4.7E+13
	(30-30k) Multi shot	0.55	0.7	2.2E+13	2.6E+13

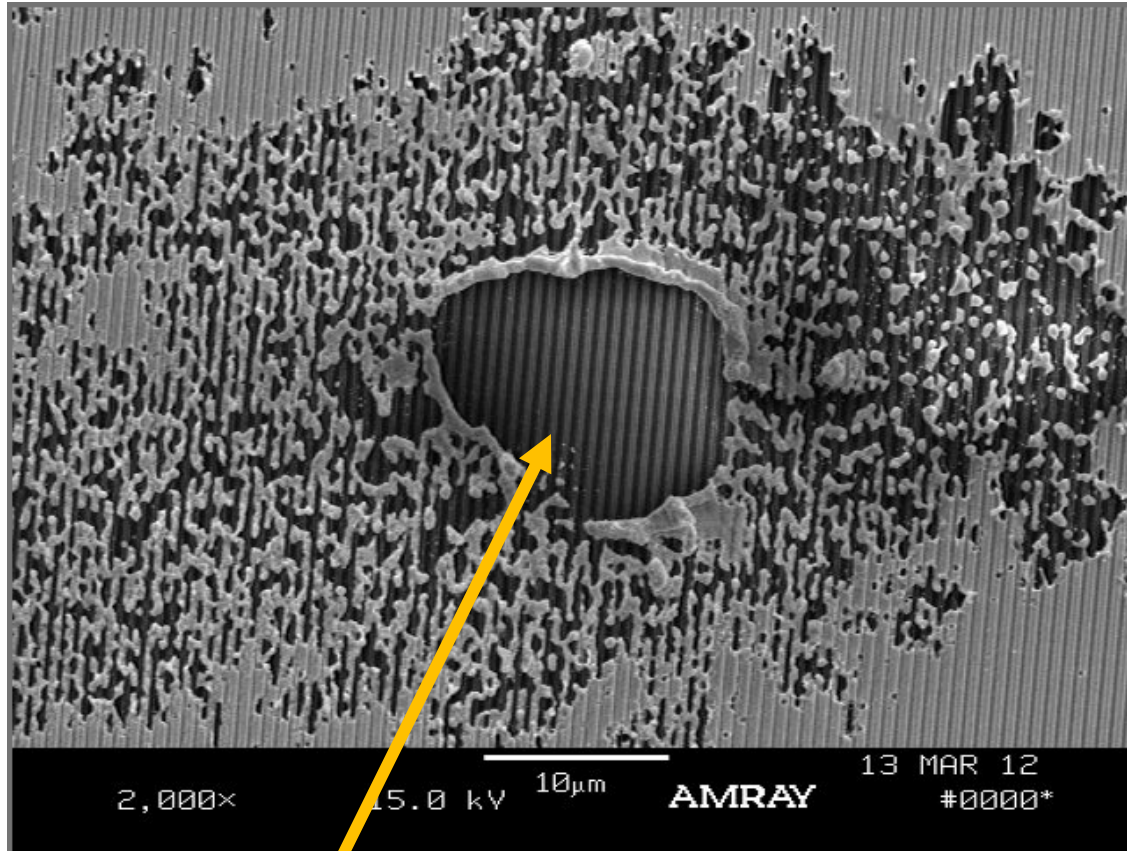
Conformal Gold coating over an Etched Silica Grating

- Diffraction Gratings are the **weakest link** in Ultra-intense lasers
- Also the most expensive
- Develop new type of Diffraction gratings with high LDT



- A *conformal* gold coating is essential to both Diffraction Efficiency and short-pulse laser damage performance

SEM Examination Of Damaged Sites

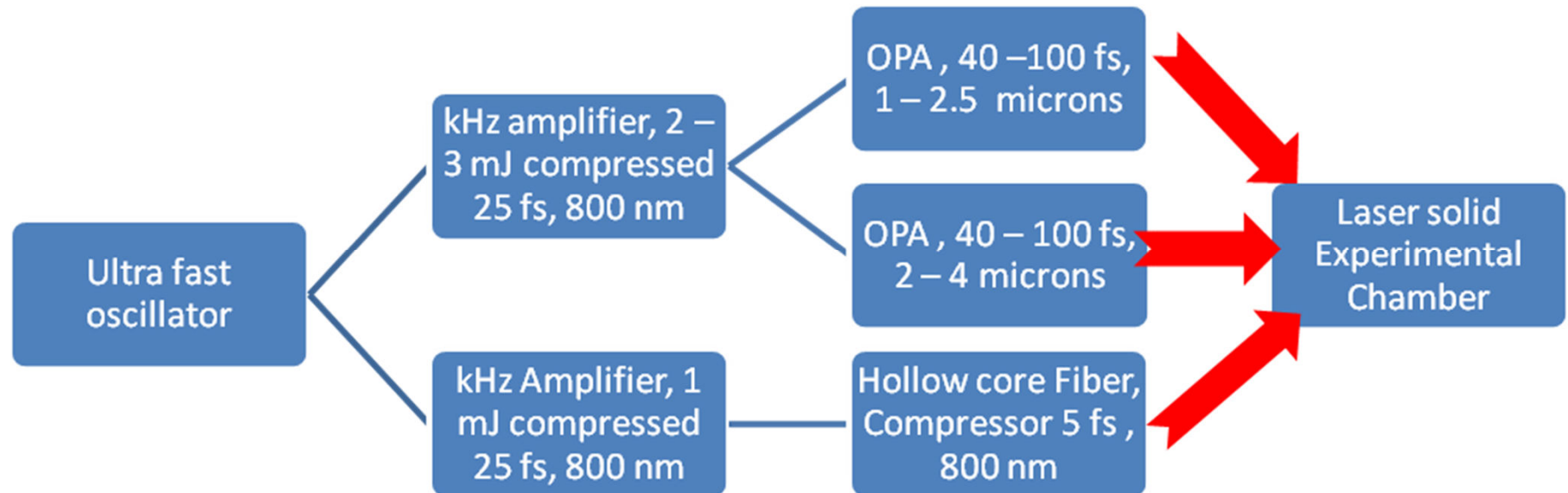


- The lighter material is gold. The underlying Silica grating remains intact.
- Full size gratings with damaged gold have been successfully stripped and recoated

The Underlying Silica Grating structure Is Intact

Experimental Thrusts

Experimental System Schematics

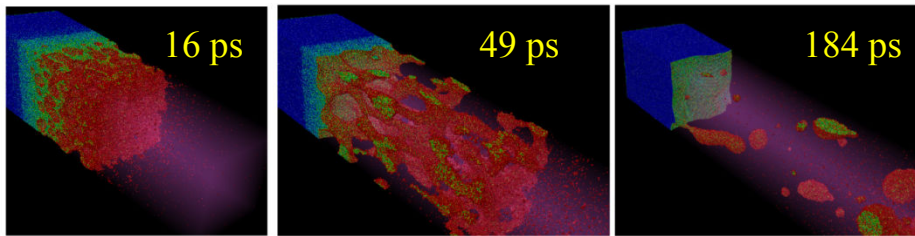


- Extend experiments from 400 nm – 4000 nm
- Study pulse width dependence effects from 5 – 1000 fs
- Housed in a dedicated 700 sq. ft. modern Lab space within SCARLET facilities

Modeling femtosecond laser interaction with solids

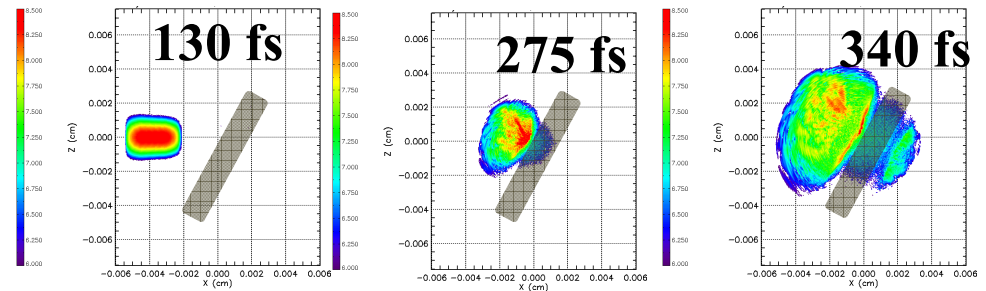
Efforts in Modeling

Molecular Dynamics



M. D. Shirk, et al, ICALEO (2003)

LSP hybrid PIC: *This Project*



Parameters	Molecular Dynamics (MD)	Hybrid Particle-in- Cell (PIC) LSP
Laser Coupling	Some prescribed energy coupling	Self consistent field interacting with moving charges
Ionization	Can be handled	Incorporated (OSU)
Inter-particle interaction	Realistic Potentials	different scattering models including binary collisions or Monte Carlo sampling
Spatial Dimension	~10 nm	Realistic sizes
Intensity (Wcm ⁻²)	Typ. ~10 ¹⁴ or below	arbitrary

Particle-In-Cell (PIC) Simulations

- We are developing PIC simulations of planned experiments using LSP.
 - Good parallelization
 - Inter-particle effects can be incorporated empirically
- LSP is a commercial code developed by Voss Scientific.¹ Purchase includes the source code so it can readily be modified by the user.
 - Supports 1D, 2D, 3D in various geometries.
 - Hybrid operation with two fluid models: hydrodynamic treatment.
 - Advance algorithms and particle pushers, including explicit and implicit algorithms.
 - Multiple collision models and rates, including binary and LMD.
 - Can treat different media including conductors and dielectrics.

¹ D. R. Welch, et al, Nuclear Instruments and Methods in Physics Research A **464**, 134 (2001).

PIC Simulation Challenges

- Ablation/damage studies require a highly unusual regime for PIC: solid density materials initially at room temperature that must be modeled for times as long as, sometimes well exceeding, 100 ps.
- Cold systems are very hard to treat due to runaway heating instability. Initial simulation temperatures of 12 million Kelvin and transient electron temperatures of 1 MeV are commonplace.
- Simulations involving a laser beyond a few ps are rare.
- PIC can handle entire laser ablation morphology
 - Entire region of interaction
 - Multiple pulse modifications
 - Long time evolution using fluidics package

PIC Simulation Progress So Far

- Our initial program called for:

- ✓ Finding a stable mode of operation in 1D
- ✓ Extending to 2D
 - Extending to 3D

- Results

1D - Can now run out to hundreds of ps with good energy conservation.

Observe threshold damage behavior and evaporation.

2D - Careful treatment of boundary conditions is required, including the use of PML (perfectly matched layers).

We currently have demonstrated stable simulation of a 10 μm wide \times 5 μm thick gold target with a 10^{13} W/cm^2 laser, 2 μm waist, injected onto the grid that runs stably out to 200 ps. (Run was halted arbitrarily at 200 ps.)

~1 day using 48 cores. LSP scales well up to thousands of cores.

Modeling femtosecond laser interaction with nano-structure



Modeling Parameters

- Laser Parameters:
 - AAA
- 1-D periodic metallic (Ag) structured surface
- VLPL (Very Large Plasma Laboratory)
 - 2-D Particle-In-Cell (PIC) simulation self-consistent E&M fields
- COMSOL
 - Multiphysics FEA solver to determine local E&M fields of complex structures with high resolution
- PIC code to benchmark COMSOL solutions



Summary: Progress



- Dedicated lab is being setup
- 3 Students joined recently
- Laser system being designed, major components ordered
- Preliminary ionization experiments being setup with existing laser system
- Characterizing surface nano-structures
- VLPL and COMSOL benchmarked in modeling fs light interacting with periodic structures
- Hybrid PIC code LSP running stably in laser ablation regime

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