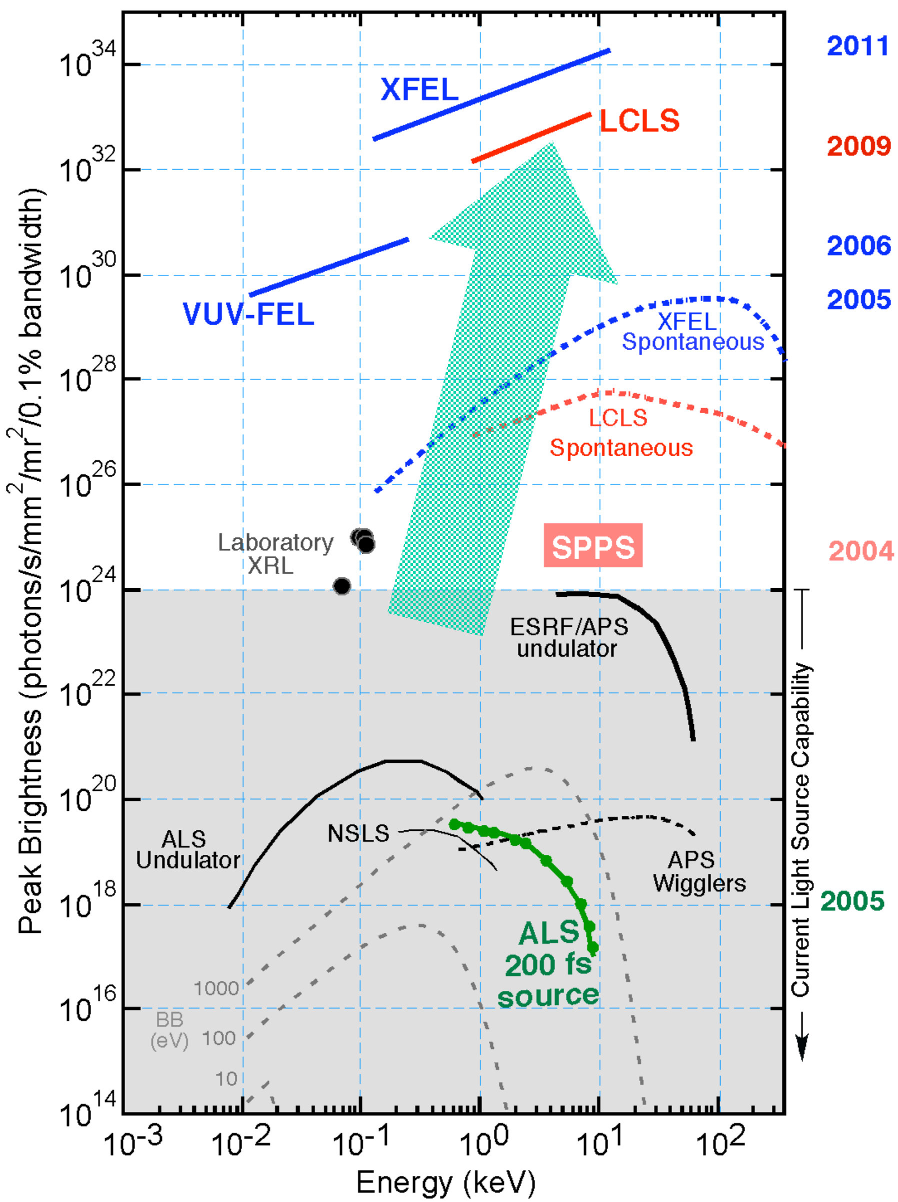
Warm Dense Matter on Light Sources

- **Been done (3rd generation sources)**
- **Being done (4th generation VUV-FEL)**
- **Will be done (4th generation LCLS)**

Richard W. Lee February, 2006

Next generation x-ray light sources will be FELs $\Rightarrow 10^{10}$ *increases in Peak Brightness*

- Current light sources are synchrotron radiation based
  - Circular machines
  - High duty cycle (> MHz)
  - Tunable over wide energy ranges
  - Low # of photons per bunch
  - Long bunch duration (≥ 50 ps)
- Next generation: FEL based
  - Short bunch duration (~100 fs)
  - Full transverse coherence
  - Low repetition rate (~100 Hz)
  - Tunable
  - High # of photons per bunch
- ***Possibilities for HED studies***



FELs are unique for short pulse intense x-ray sources

	LXRL (5.9 nm)	SPPS (0.2 nm)	ALS/UXS (0.25 nm)	VUV-FEL (6.0 nm)	LCLS (0.1 nm)	EU-XFEL (0.1 nm)
mJ/pulse	0.3	3.8×10^{-5}	2.4×10^{-10}	0.3	2.6	3.7
Photons/pulse	9×10^{12}	3×10^{7}	3×10^{2}	9×10^{12}	2×10^{12}	2×10^{13}
Pulse Length (fs)	10^{5}	80	100	200	230	100
GW	0.006	0.5	2.4×10^{-6}	1.5	11	37
Peak Brightness	2.0×10^{25}	1.2×10^{25}	1.0×10^{19}	2.0×10^{30}	1.2×10^{33}	8.7×10^{33}
Bandwidth (%)	0.01	0.01	0.001	0.6	0.3	0.1
Hz	<< 1	30	10^{4}	50	120	50
Date	now	2003	2005	2005	2009	2012

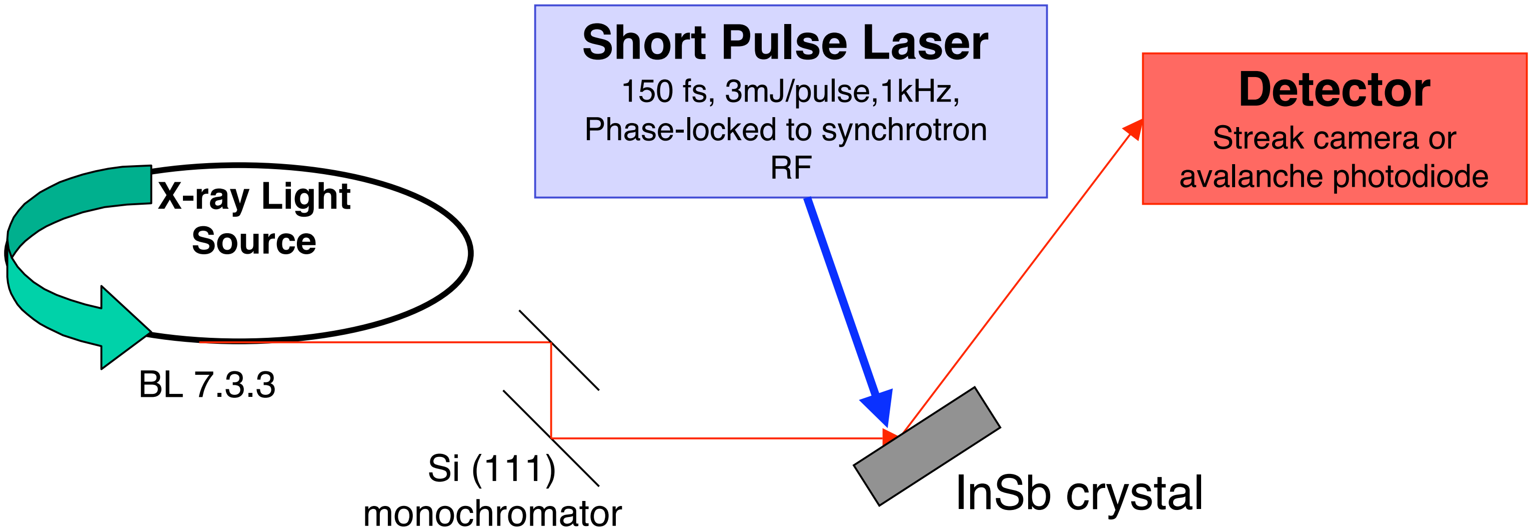
- LXRL = Laboratory X-Ray Laser
- SPPS, ALS / Slicing Source = modified 3rd generation sources
- VUV-FEL, LCLS, and EU-XFEL = 4th generation sources

- 4th generation is as much *laser* as light source

ON GOING

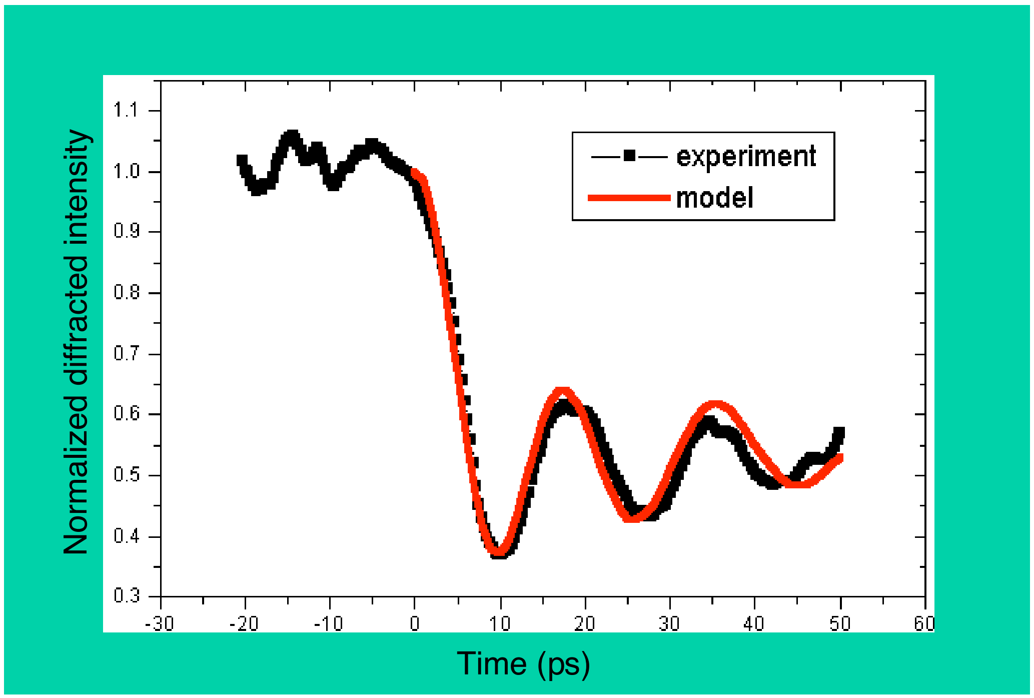
3rd generation light source probes what a short-pulse laser warms

- The original set-up was developed to look at rapid structural changes in solid (APS, ESRF, ALS)
- Method was extended to look at melting in other material
- Independent study of nanoparticle formation & metal-insulator transitions in supercritical fluids has been started



ALS WDM experiments lead to an understanding of the heating process

Phonon Spectroscopy

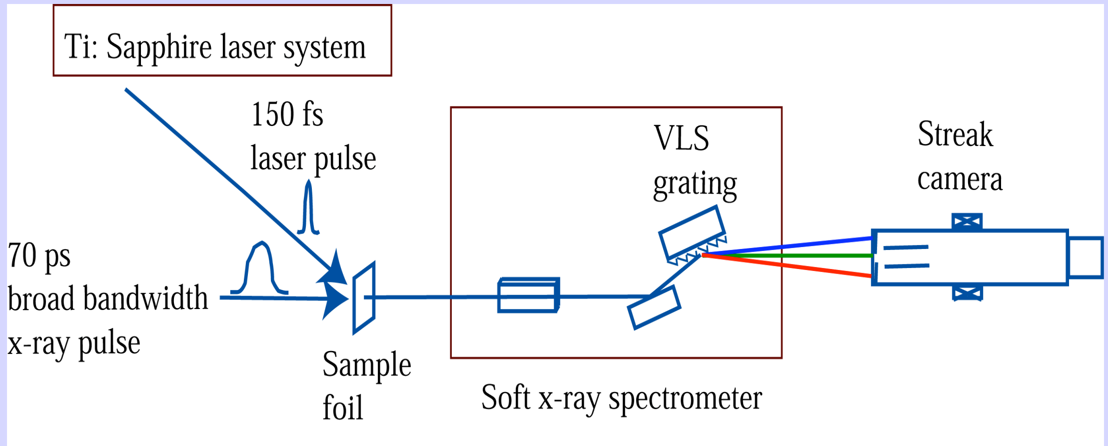


- Laser heats the crystal
- Crystal planes change their spacing
- Diffraction is thus modulated

- Measurement of phonon dispersion relations under highly non-equilibrium conditions
- Sensitive probe of electron-phonon coupling strengths.
- Structural probe of order-disorder laser-induced phase transitions.

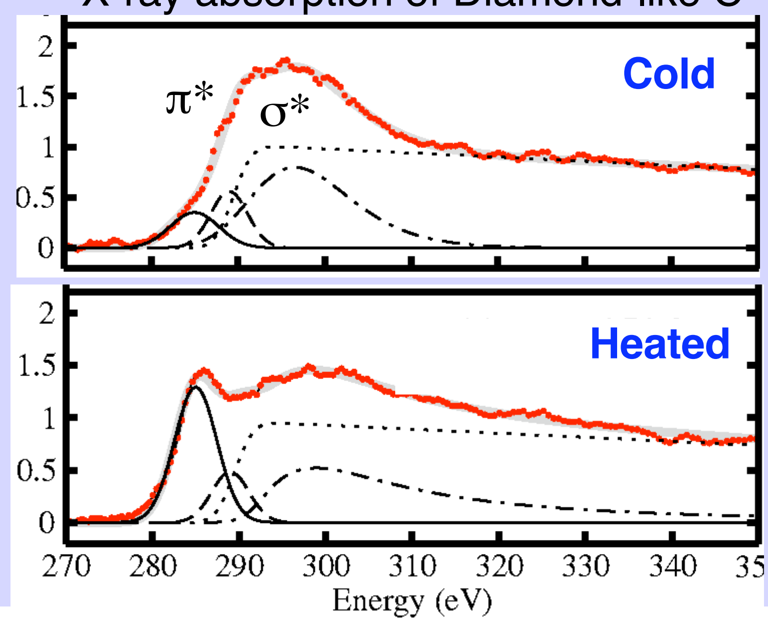
HEDS absorption experiments are possible on current x-ray light sources

- Need a short pulse laser to warm sample
- Need a fast detector for < 50 ps time resolution
- Set-up for structural changes in solid
  - ALS, APS, ESRF



- Measurement of the X-ray Absorption Near Edge Structure (XANES)
- Sensitive probe of unoccupied electronic states
- Probe of phase transitions

• X-ray absorption of Diamond-like C



In the next 5 years there will be some new capabilities for WDM research

- Petawatt laser facility development will provide more places for SPL studies
  - Primary interaction is with surface
    - Can not interact directly above the critical density $n_c \sim 10^{29}/\lambda(\text{Å})^2\ \text{cm}^{-3}$
  - Protons beams produced by 100 fs SPLs have pulse duration > 5 ps
    - Effort will be to develop quasi-monoenergetic short pulses for WDM production

- Short pulse 3rd generation light sources will allow studies of weakly perturbed WDM on sub-ps times scales
  - Slicing source at ALS at LBNL (now)
  - Can not perturb matter due to low number of photons per bunch
  - Basically for average brightness experiments

- **First 4th generation VUV-FEL is starting up at DESY**
  - 40 fs, 10^{13} photons, initially at 40 eV and eventually at 200 eV energies

NEW WORK

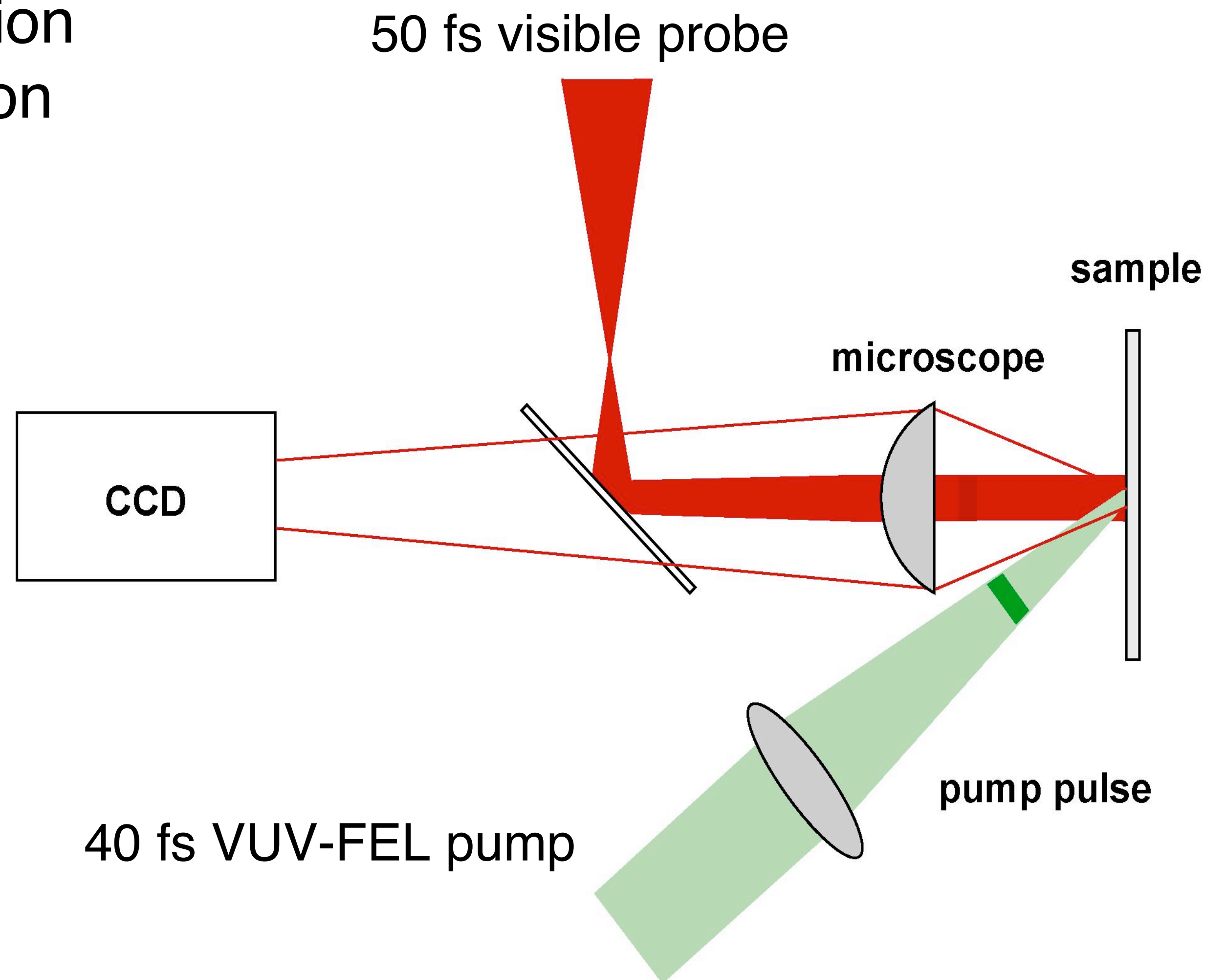
VUV-FEL experiment schedule includes HEDS addressing the WDM regime

- Participation in proposal process included > 100 participants from Europe and North America

	Experiment	Brief Description
Condensed Matter	Warm Dense Matter Creation	Using the FEL to uniformly warm solid density samples
	EOS Measurements	Use an optical laser to heat a sample and the FEL to provide a diagnostic of the bulk
	Near Edge Absorption	Use an optical laser to heat a solid and the FEL to probe the structural changes
	Femtosecond Ablation	Probe the nature of the ablation process on the sub-ps time scale
Plasma	Trapped, High Γ Plasmas	Use EBIT/laser-cooled trap and probe highly-charged strongly-coupled Coulomb systems
	Diagnostic Development	Develop the FEL for Thomson scattering, interferometry, and radiographic imaging
	FEL /Gas-Jet Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
	FEL / Solid Interactions	Use the FEL directly to create extreme states of matter at high T and ρ
	Plasma-Spectroscopic Studies	Use the FEL as a pump to move bound state populations and study radiation redistribution
Bio-related	Coulomb Explosion	Study Coulomb Explosion process with emphasis on biological imaging problems
	Optics Damage	Study structural changes & disintegration processes of solids under FEL irradiation

Time-Resolved Microscopy used to study ablation of VUV-FEL irradiated samples

- fs-temporal resolution
- μm-spatial resolution



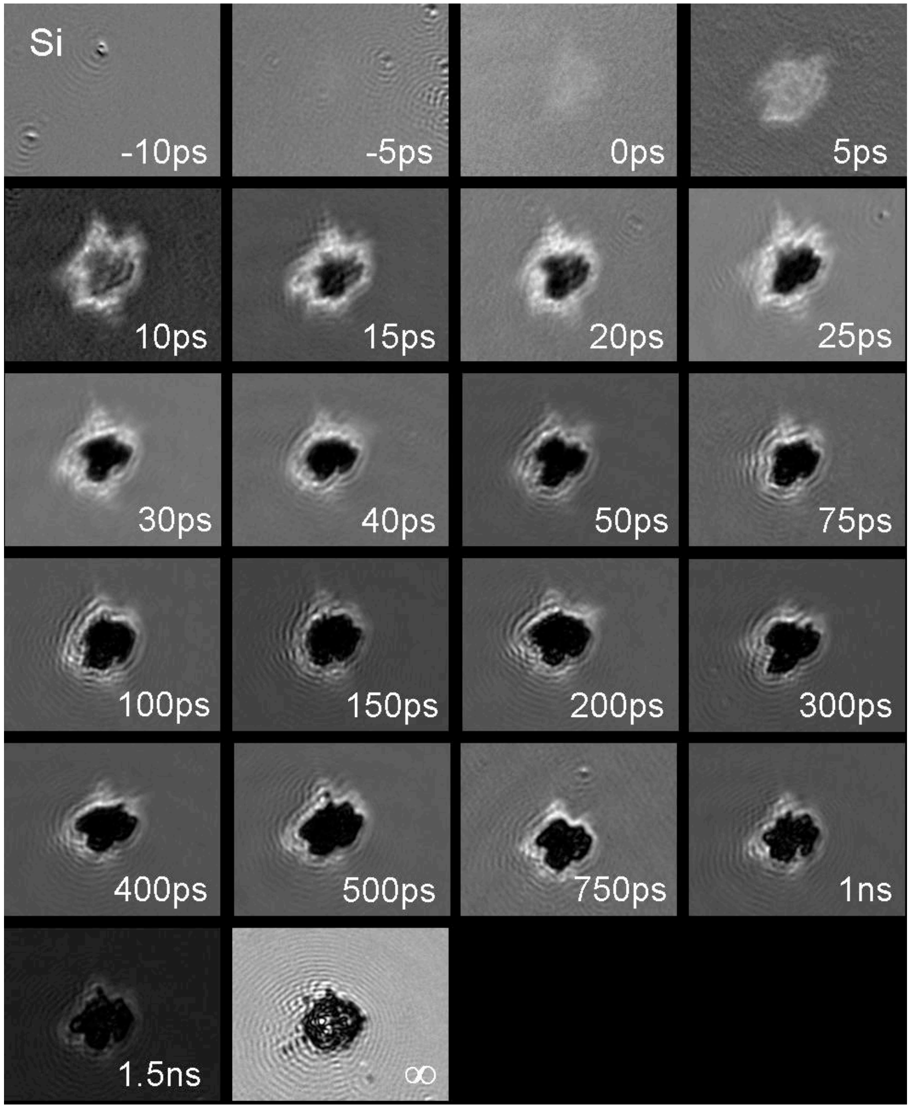
- By varying the time delay between the VUV-FEL and the Probe a time history is generated.

Surface ablation data shows distinct mechanism from visible laser-matter ablation

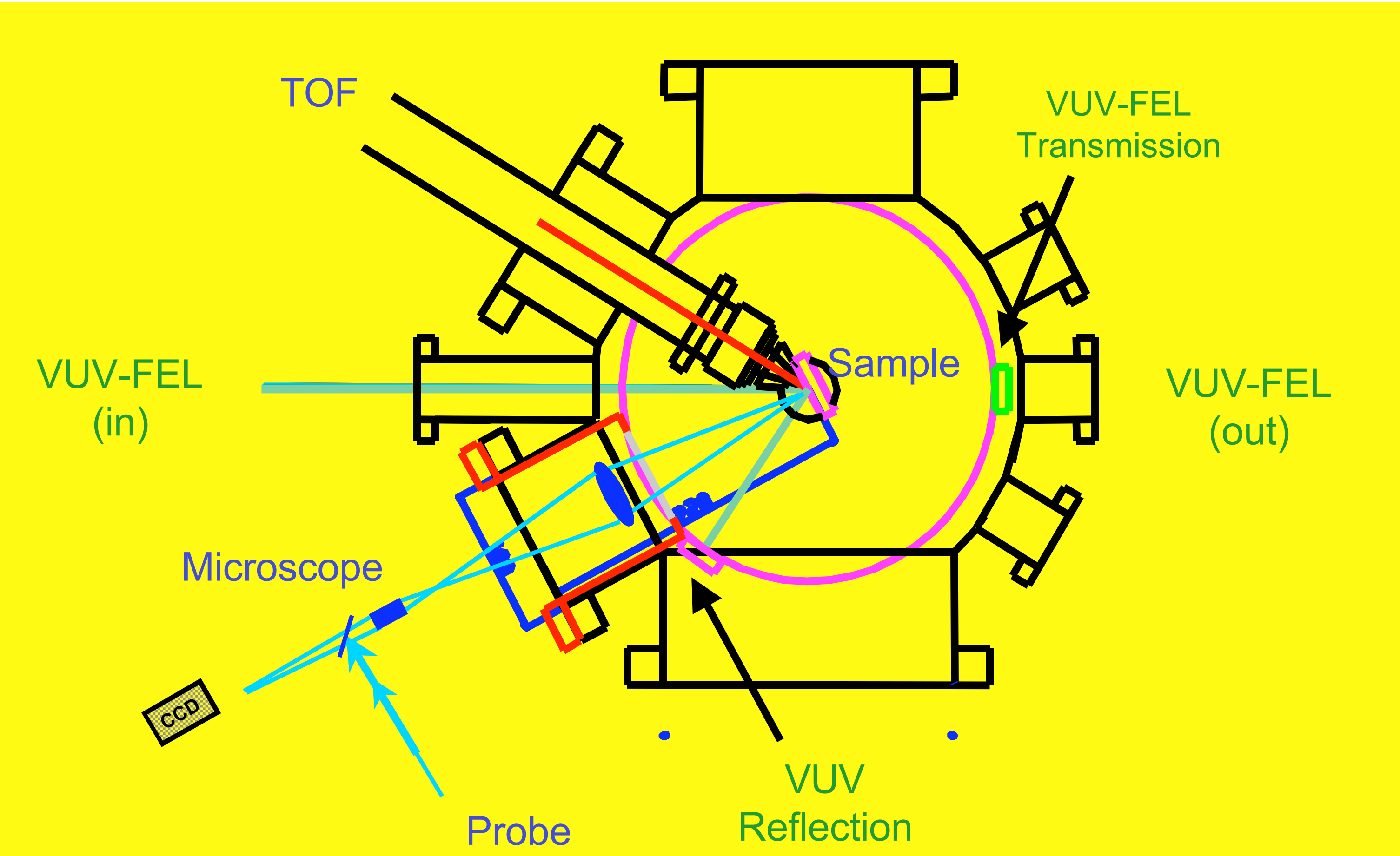
- Time dependent data shows broadly similar ablation pattern as a function of time

- New aspect shown in lateral spread of the ablation

- These are still preliminary results



Surface damage studies are critical to applications of the VUV-FEL

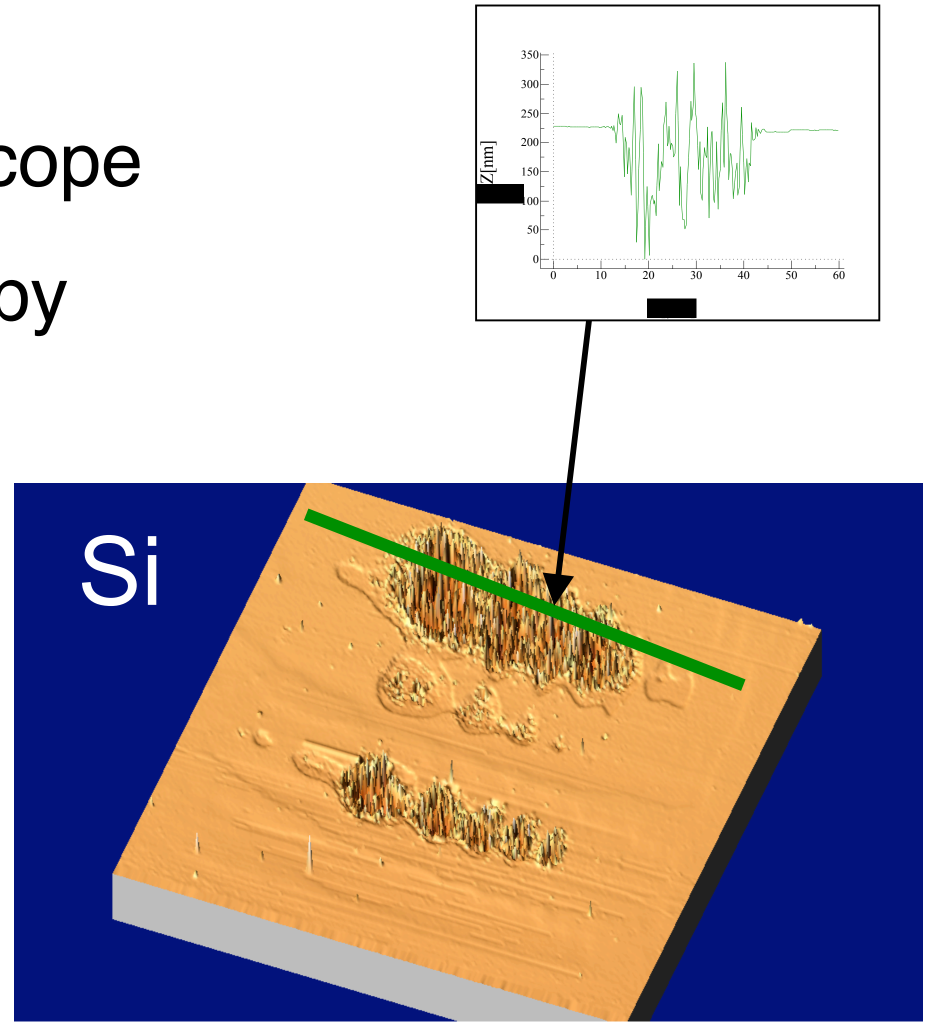


- VUV reflection can be rotated and set in front of the VUV transmission, allowing calibration of both devices

Off line analysis is performed to investigate damage mechanisms

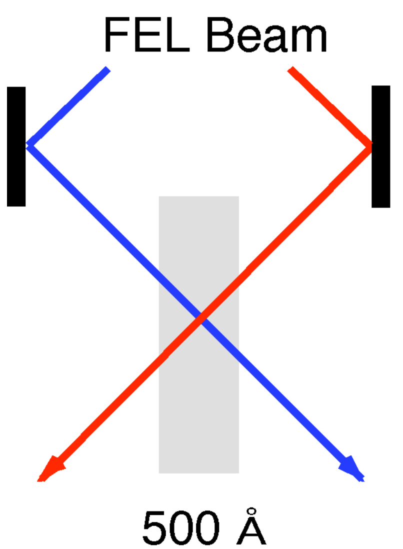
- Nomarski-type spectroscopy
- Atomic force microscope
- Electron scanning microscope
- Micro-Raman Spectroscopy
- Micro-x-ray diffractometry

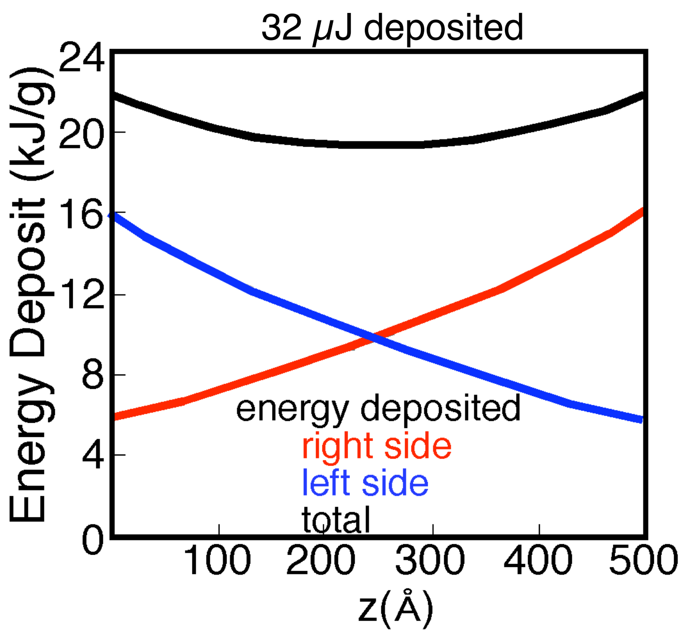
Structural modification and Crater formation



Creating WDM can be difficult: VUV-FEL can access this regime

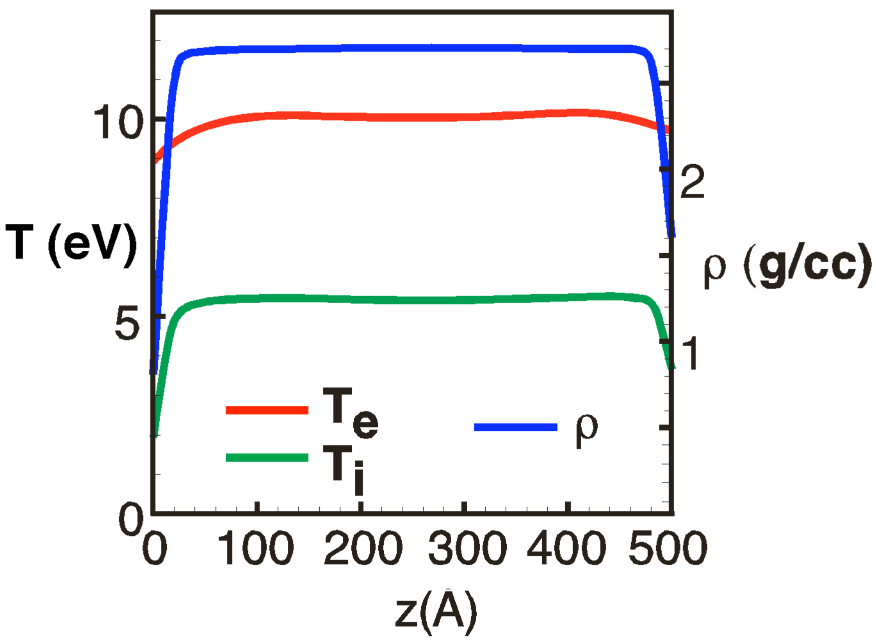
- Isochoric heating
  - Uniformly heat 500 Å Al foil using the 200 fs FEL tuned to 60 Å
    - $\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_P^i \Rightarrow$ $(10^{12} \times 200 \text{ eV}) / \text{Volume} = 3/2\ (1.7 \times 10^{23}) \times 1\text{eV}$
    - Volume = Area x 500 Å ⇒ Area = 140 μm spot
  - For a 10 eV plasma a 50 μm spot is needed
- Isentropic expansion
  - A optical FDI probe measures the isentropic expansion

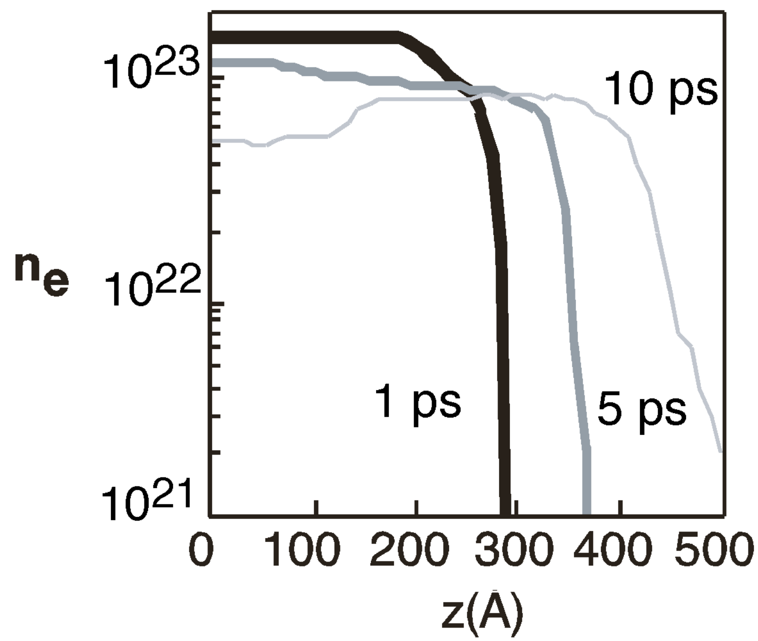




Simulations indicate that the Al sample stays uniform for ~ 1 ps

- For 50 μm spot the sample T_e reaches ~ 10 eV
  - T_i reaches only 1/2 of T_e and equilibrates in > 500 fs
- Sample uniformity is excellent for up to 1 ps
  - Sample tamping, e.g., 100 Å CH, would mitigate gradients in Al





• Sample stays in the WDM regime and thus the simulations must be tested

Plan to build experimental VUV-FEL capability is a broad based effort

LLNL, UCB, LBNL, DESY

- VUV UHV chamber capability
- Sample fabrication
- Diagnostic complement

At LBNL / UCB

- Pump: sub-ps visible laser
- Probe: sub-ps VUV harmonic source

At LLNL

- Pump: ps VUV laboratory x-ray laser
- Probe: ps VUV laboratory x-ray laser
- Probe: sub-ps visible laser

At DESY

- Pump: sub-ps VUV-FEL
- Probe: sub-ps VUV-FEL
- Probe: sub-ps visible laser

FUTURE

On the horizon several new facilities will become available

- SCSS@RIKEN VUV FEL similar to DESY VUV-FEL (soon)
- Petawatt IR laser capabilities, several with high energy will be developed - kJ energy in ps pulses - (> 2008)
- **LCLS**@SSRL the 1st x-ray FEL with 100 fs pulses of 10^{12} photons of 10 keV at 120 Hz - mJ energy (2009)
- NIF@LLNL with ~2 MJ of energy in ns pulses (2009/2010)
- Spring8 XFEL@RIKEN with 500 fs pulses of 10^{12} photons of < 22 keV at 60 Hz (~ 2010)
- SIS100@GSI upgrade to an intense heavy ion beam capability (> 2010)
- XFEL@DESY with specifications similar to LCLS (> 2012)

LCLS project includes 5 scientific thrusts

Thrust areas:	Team Leaders:	LCLS Contact:
1) Coherent scattering at the nanoscale	G.B. Stephenson	S. Brennan K. Ludwig
2) Pump/probe diffraction dynamics	K. Gaffney D. Reis J. Larsson	A. Lindenberg
3) (HED) Science	**R. Lee** **P. Heimann**	**J. B. Hastings**
4) Nano-particle/single molecule (non-periodic) imaging	J. Hajdu J. Miao H. Chapman	J. Arthur
5) Atomic, molecular, and optical science	L. DiMauro N. Berrah	J. B. Hastings

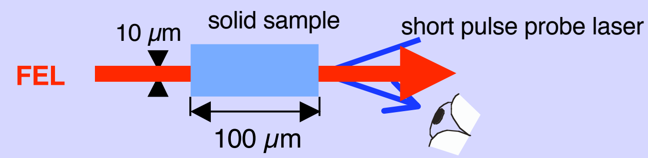
Proposed LCLS HEDS experimental station covers broad swath of the regime

Experiment	Description	PARTICIPANTS
Warm Dense Matter Creation	Using the XFEL to uniformly warm solid density samples	H.-K. Chung, S. Glenzer, G. Gregori, S. Moon, O. Landen. K. Widmann, P. Young, M. Murillo, J. Benage, A. Lindenberg, A. Correa, R. Falcone, W. Nellis, W. Rozmus, A. Ng, T, Ao, J. Wark, J. Sheppard, R. Redmer, D. Schneider, F. Rosmej…
Equation of State	Heat / probe a solid with an XFEL to provide material properties	K. Widmann, K. Budil, G. Collins, S. Glenzer, G. Gregori, M. Koenig, A. Bennuzi, A. Nelson, O. Landen, W. Nellis, A. Ng, P. Young, J. Benage, M. Taccetti, S. Rose, D. Schneider…
Absorption Spectroscopy	Heat a solid with an optical laser or XFEL and use XFEL to probe	P. Heimann, S. Johnson, R. Lee, S. Tzortzakis, S.Bastiani-Ceccoti, C. Chenais, P. Audebert, F. Rosmej, R. Falcone, R. Schuch, A. Lindenberg, D. Chambers, J. Wark, S. Rose…
High Pressure Phenomena	Create high pressure matter with a high-energy laser and probe with the XFEL	G. Collins, H. Lorenzana, J. Belak, P. Celliers, C.-S. Yoo, K. Budil, M. Koenig, A. Bennuzi, S. Clark, P. Heimann, R. Jeanloz, P. Alivisatos, R. Falcone, W. Nellis, A. Ng, T. Ao…
Surface Studies	Probe ablation/damage process to study structural changes and disintegration	A. Nelson, J. Kuba, A. Andrejczuk, J. B. Pelka, J. Krzywinski, R. Sobierajski, K. Sokolowski-Tinten, L. Juha, M. Bittner, J. Krasna, T. E. Glover…
XFEL / Gas Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas	R. London, S. Hau-Riege, P. Young, H. K. Chung, W. Rozmus, R. Fedosejev, H. Baldis, V. N. Shlyaptsev, T. Ditmire, H. Fiedorowicz, M. Fajardo, A. Bartnik, F. Dorchies, J.-C. Gauthier, P. Audebert, V. Bychenkov, D. van der Spoel, C. Caleman, T. Möller, T. Tschentscher, H. Merdji…
XFEL / Solid Interaction	Use XFEL directly to create extreme states of matter at high temperature and density	S. Glenzer, K. Budil, H.K. Chung, J, Dunn, S. Hau-Riege, R. London, K. Sokolowski-Tinten, J. Krzywinski, H. Fiedorowicz, A. Bartnik, V. Letal, K. Rohlena, K. Eidmann, D. Chambers, N. Woolsey, A. Andrejczuk, F. Dorchies, J. Gauthier, M. Fajardo, J. Dias, N. Lopes, G. Figueira, M. Bergh, T. Tschentscher…
Plasma Spectroscopy	Use XFEL as a pump/probe for excited bound state populations	R. W. Lee, M. Foord, H.K. Chung, D. Riley, F. Y. Khattak, E. Förster, F. Dorchies, J.-C. Gauthier, S. Tzortzakis, S.Bastiani-Ceccoti, C. Chenais-Popovics, P. Audebert, S. Rose, J. Wark, N. Woolsey, R. Schuch, K. Eidmann, F. Rosmej, S. Ferri…
Diagnostic Development	Develop Thomson scattering, SAXS, interferometry, and radiographic imaging	S. Glenzer, G. Gregori, R. Bionta, H. Baldis, P. Heimann, H. Padmore, U. Bergmann, H. Merdji, P. Zeitoun, J. Seely, E. Förster…

HEDS proposed for XFELs will cover a range of WDM experiments

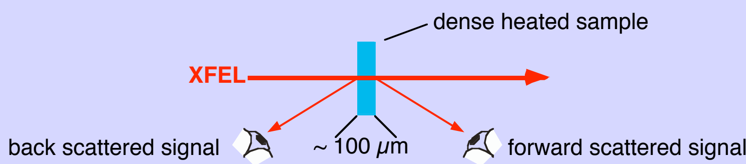
• Creating Warm Dense Matter

- Generate ~ 10 eV solid density matter
- Measure the equation of state



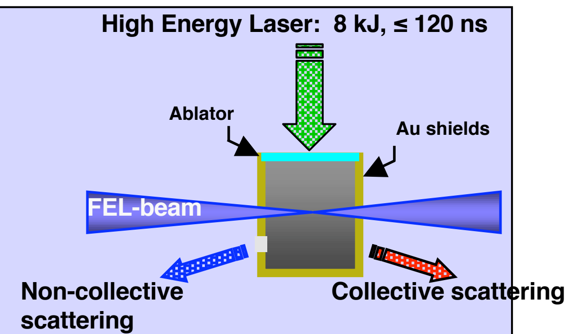
• Probing dense matter with Thomson Scattering

- Perform scattering from solid density plasmas
- Measure n_e, T_e, <Z>, *f*(v)



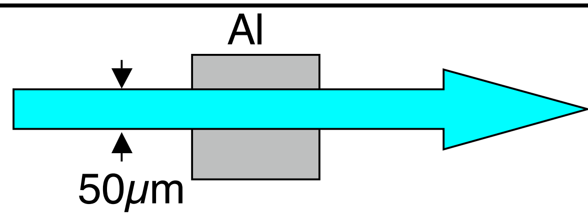
• Probing High Pressure phenomena

- Use high energy laser to create steady high pressures
- Produce shocks *and* shockless high pressure systems
- Study high pressure matter on time scales < 1 ps
- Diagnostics: Diffraction, SAXS, Diffuse scattering, and Thomson scattering

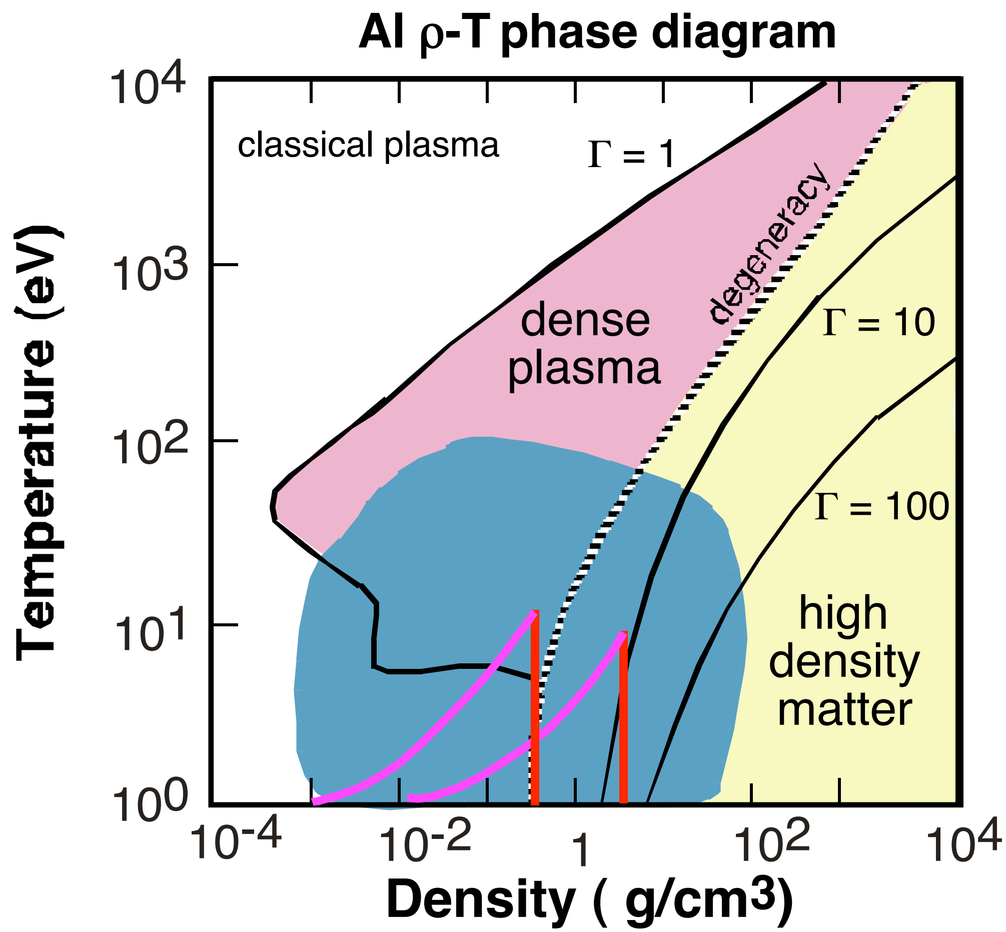


WDM created by isochoric heating will isentropically expand sampling phase space

- Concept is straightforward



- XFEL can heat matter rapidly and uniformly to create:
  - Isochores (constant ρ)
  - Isentropes (constant entropy)

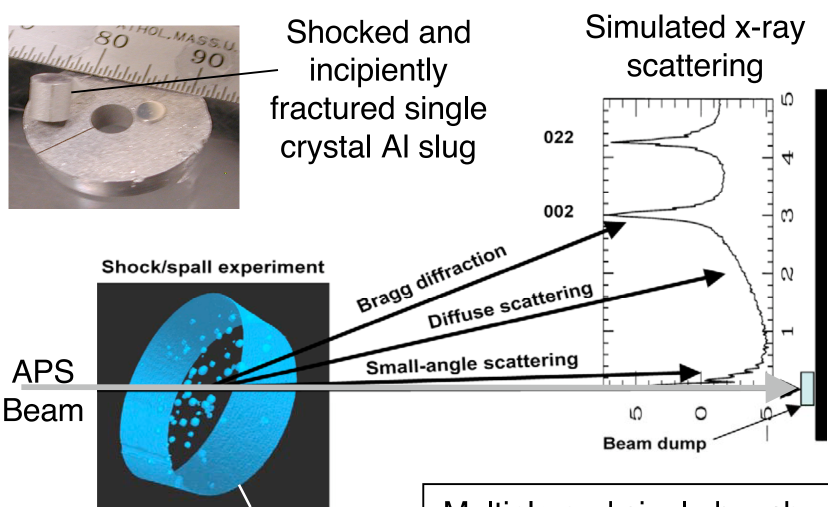


- Using underdense foams allows more complete sampling
  - Isochores (constant ρ)
  - Isentropes (constant entropy)

High pressure studies: material strength, spall and phase transitions

Current:

Post Processing x-ray scattering



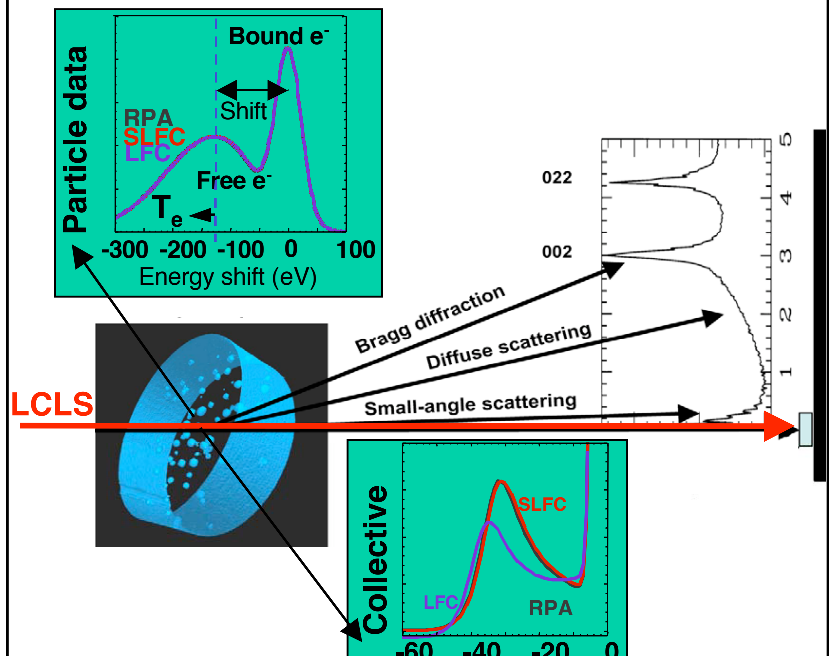
3-D x-ray tomographic reconstruction of dynamic fracture

Multiple and single bunch x-ray scattering from shock recovered samples in progress

- ***Diffraction → lattice compression and phase change***
- ***SAXS → sub-micron defect scattering***
- ***Diffuse → dislocation content and lattice disorder***

Future:

Measure during pressure pulse

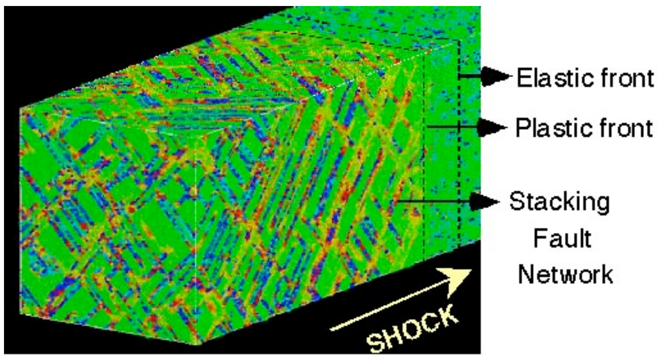


- **LCLS will provide unprecedented fidelity to measure dynamics of the microstate with sub-picosecond resolution**

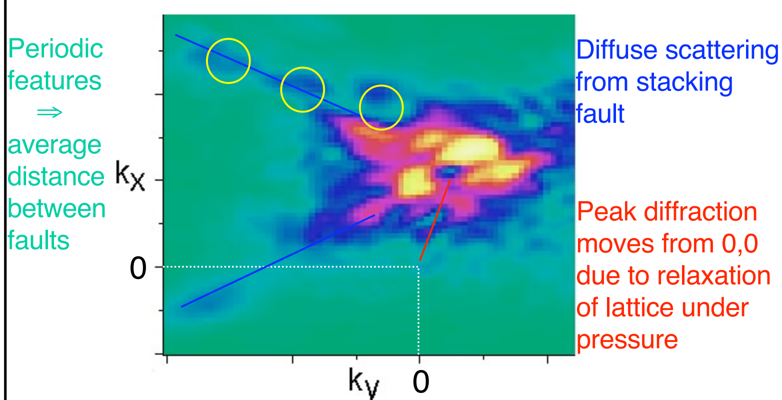
- **LCLS with HEDS end station: sufficient signal to noise for measurements during the high pressure phase**

Challenge is to match experimental and theoretical capabilities for HEDS studies

Current Status
Simulation Classical scattering



- MD simulation of FCC Cu taking 400,000 CPU hours



- X-ray diffraction image using LCLS probe of the (002) shows *in situ* stacking fault information

Future with LCLS
Unique capabilities

- **Imaging capability**
  - **Point projection imaging**
    - **Phase contrast**
    - **High resolution (sub-μm)**
  - **Direct determination of density contrast**
- **Diffraction & scattering**
  - **Detection of high pressure phase transitions**
  - **Lattice structure, including dislocation & defects**
  - **Liquid structure**
  - **Electronic structure**
    - **Ionization**
    - **T_e, $f(v)$**

These complement the standard instruments, e.g., VISAR and other optical diagnostics

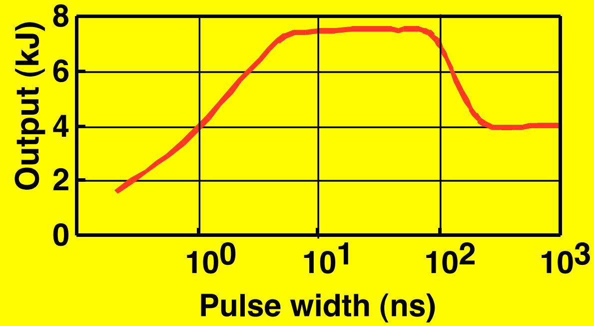
UPDATE LCLS HEDS EFFORT

HEDS end station proposal endorsed by the LCLS Science Advisory Committee

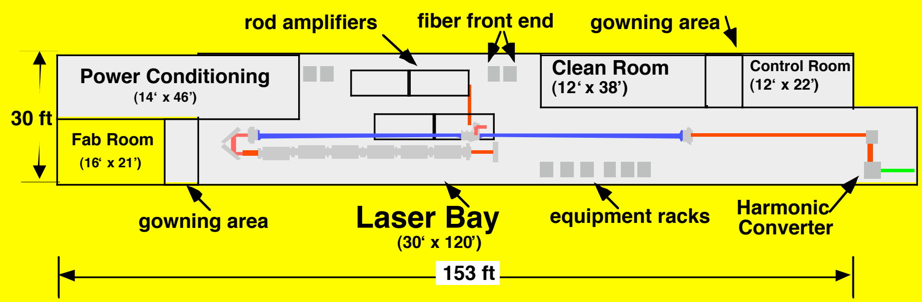
- Serves the need to develop a community in HED science in the US
  - Will be only dedicated user facility in the US
  - Will be operated by SSRL as a light source
- Proposal is broad-based with many facets of HDM/WDM research possible at the end station
- Current efforts are to solicit support at NNSA

LCLS HEDS end station: high-energy and intense short-pulse lasers to access space

- **Components for HED experiments**
  - High Energy Laser 13.0
    - ≤ 8 kJ in ≤ 120 ns

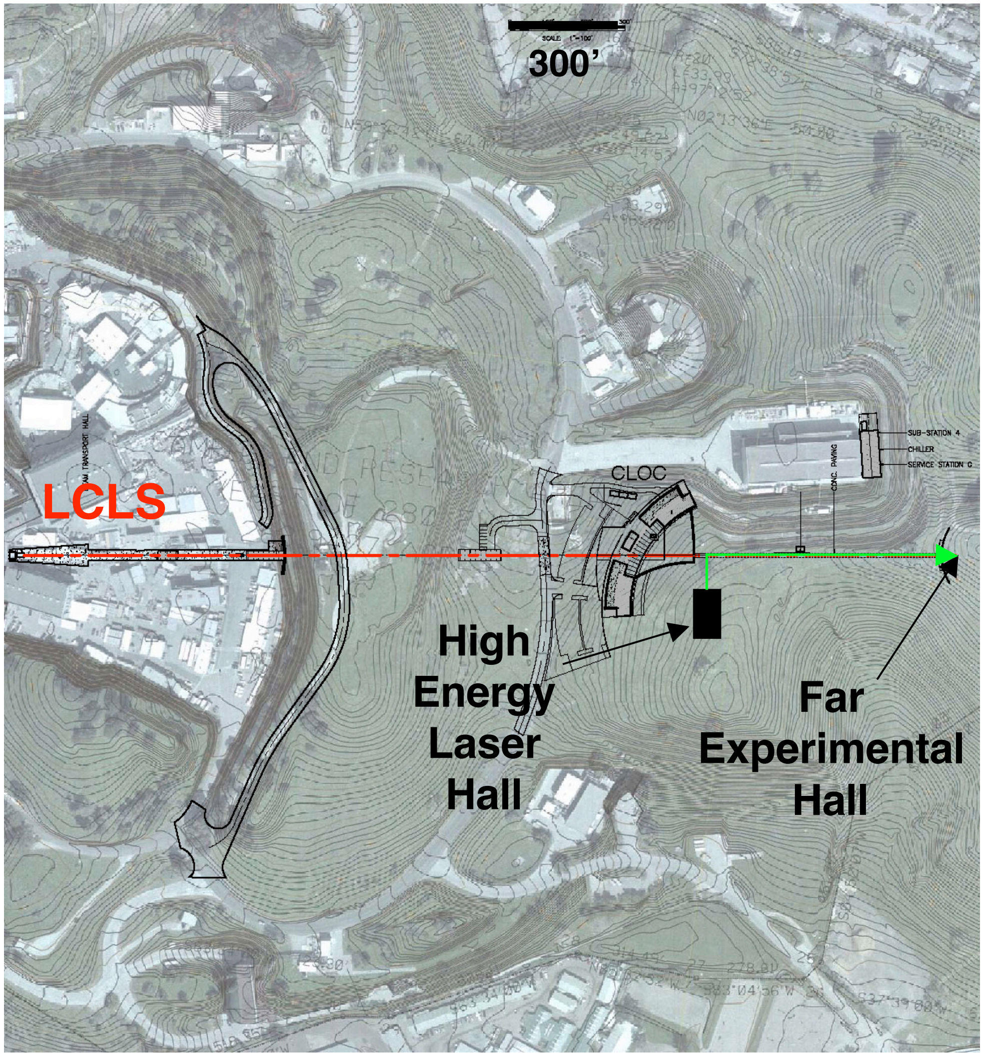


  - Intense Short Pulse Laser 1.5
    - ~ 10 J in 30 fs
  - Laser Hall 6.0
    - ~ 153' x 30' feet



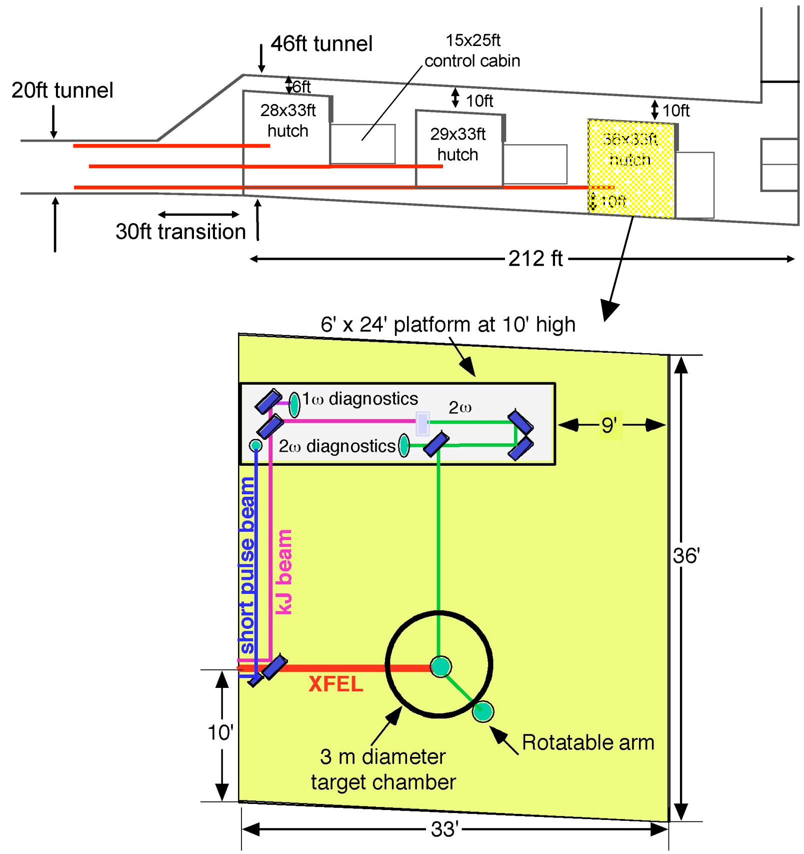
  - Experimental End Station 4.5
  - ***TOTAL COST*** ***$25 M***

Laser Hall can be ‘far’ from the hutch



Aerial view of SLAC site

- Transport is efficient over long distances
- Lasers can be transported to Far Experimental Hall



Steps toward an HEDS end station and a Center for HEDS

- Presented the case to LLNL management
- Presented the case to the LCLS SAC
- Presented the case to the SLAC Proposal Review Panel
- Presented the case to DOE/NNSA management
- Presented the case to the UCOP Forum
- Presented the case at the UCOP
- Presented the case at LANL
- …

Timeline for development of the HEDS endstation and Center

- Ongoing:
  - Experiments on compression, heating to melt, and solid-liquid transitions:
    - ALS (2 ps streak camera)
    - SPPS (80 fs x-ray diffraction work)
- New :
  - VUV-FEL initial experiments
  - Slicing Source initial experiments
- Future:
  - LCLS initial experiments