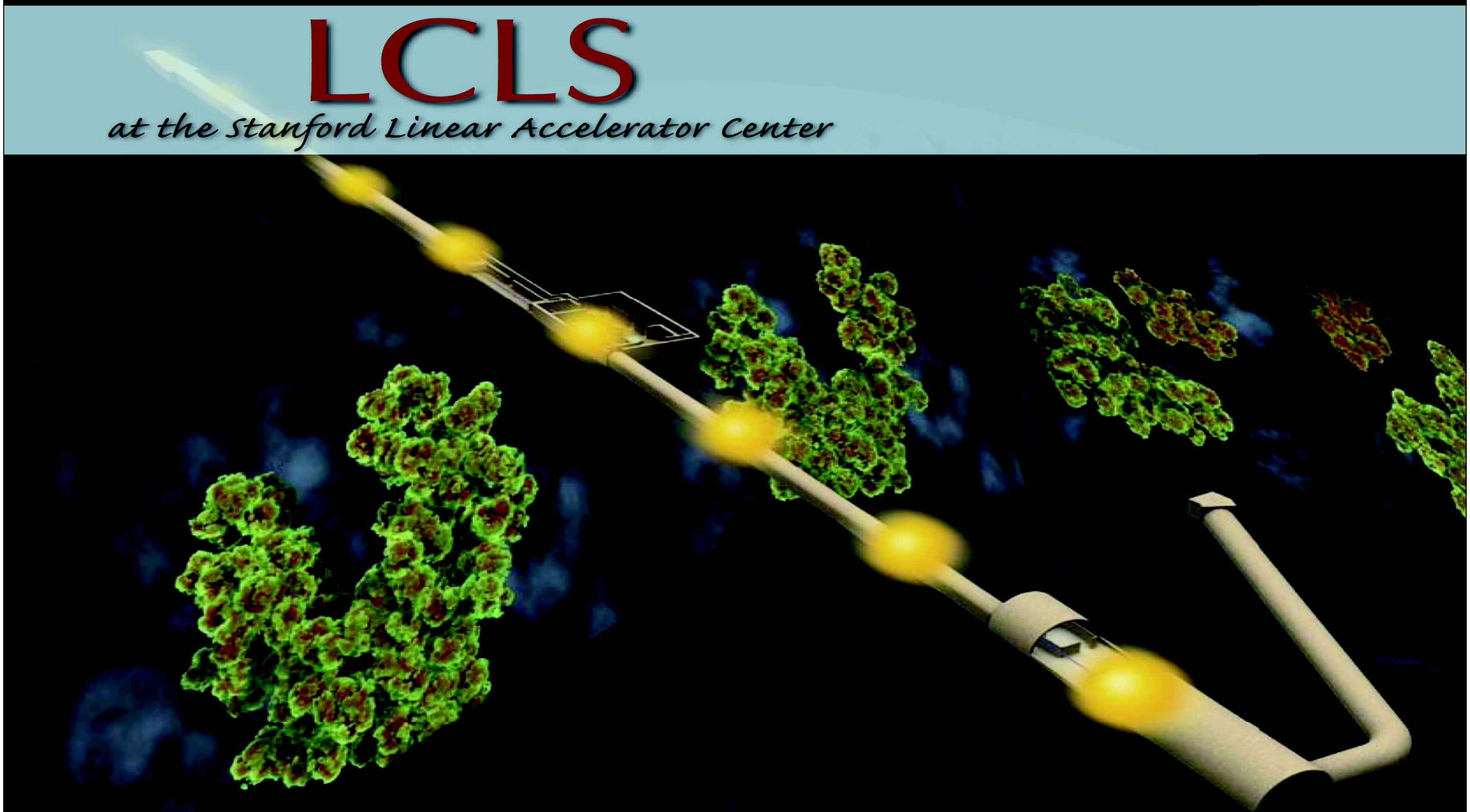
The MEC endstation at LCLS
New opportunities for high energy density science



Bob Nagler
BNagler@slac.stanford.edu
SLAC national accelerator laboratory

Singapore, fttp-5, April 20th, 2011

Overview

- Motivation for MEC
  - Why study Warm Dense Matter
  - Why use Free Electron Laser for these studies
- Overview of the Linac Coherent Light Source
- Design of the Matter in Extreme Conditions station
- Conclusion

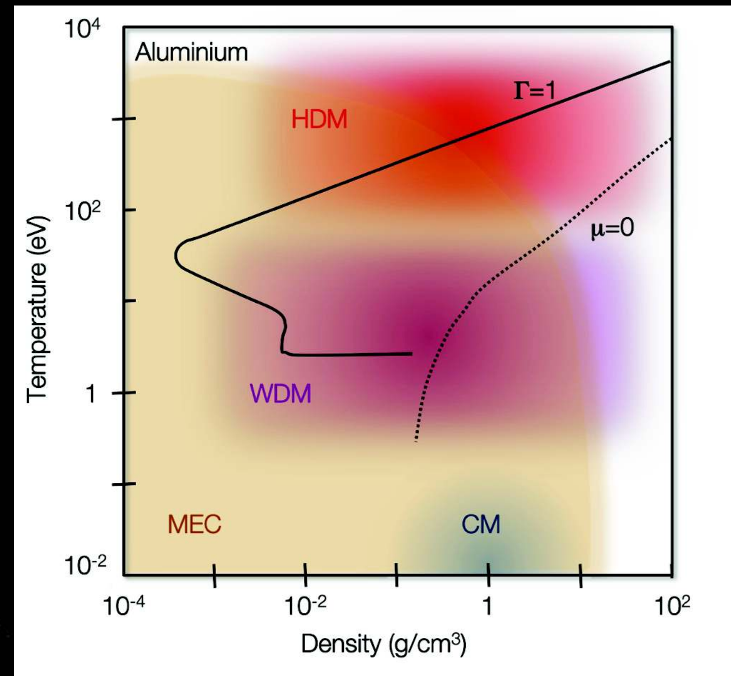
High Energy Density matter occurs widely

Hot Dense Matter (HDM) occurs in:

- Supernova
- Stellar interiors
- Accretion disks
- Plasma devices
- Laser produced plasmas,
- Z-pinches,
- Inertial confinement fusion experiments

Warm Dense Matter (WDM) occurs in:

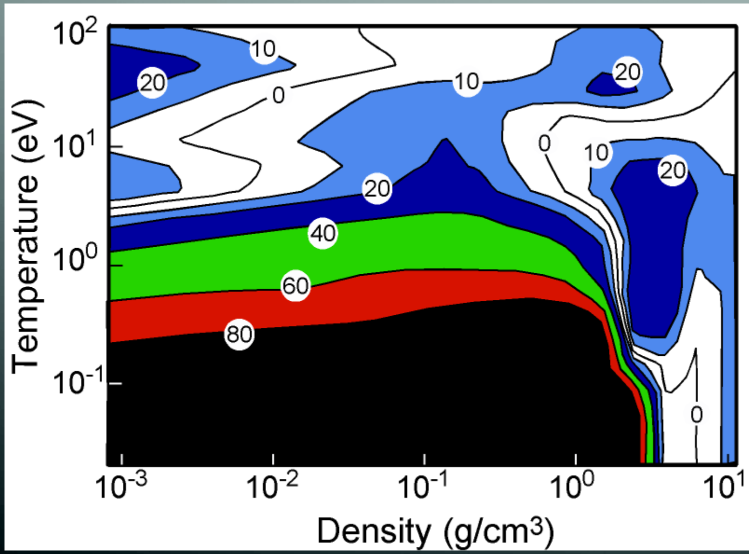
- Cores of large planets
- Systems that start solid and end as a plasma
- X-ray driven inertial fusion experiments

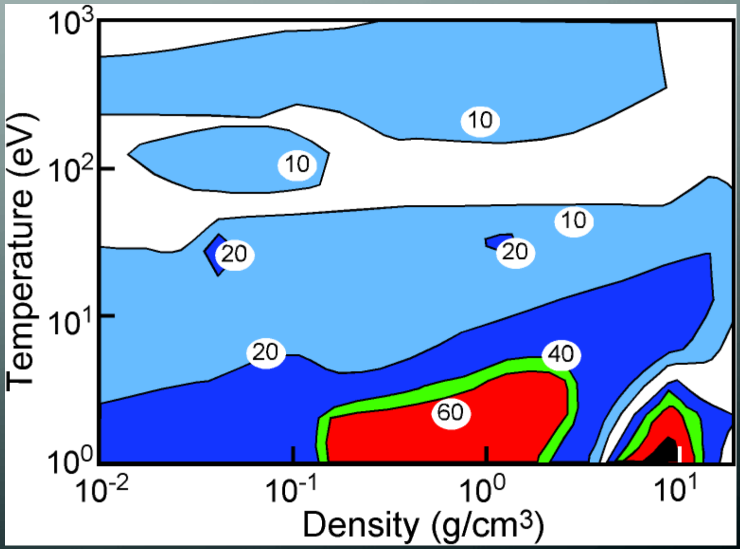


- Phase space diagram of Aluminum. Red region is Hot Dense Aluminum, the purple is Warm Dense Aluminum, and blue normal condensed matter (cold solid aluminum). The solid line shows where the strong coupling parameter reaches unity (i.e. thermal energy of the ions becomes equal to their coulomb interaction energy, and the dotted line shown when the chemical potential reaches zero (i.e. where the electron temperature equals the Fermi temperature and the electron gas becomes degenerate). The gold shaded region is where experiments at MEC can be done.

Overview

A comparison between the Equation of State predictions between different codes. The codes calculate the pressure in Warm Dense Matter for a given Density and Temperatur. Plotted are the differences in percent between the prediction of the different simulation codes for iron and copper.





Differences larger than 80% in the Equation of State are common in the Warm Dense matter region are common.

Where data exist, along the principal Hugoniot which can be reached by shock experiments, the different codes agree, showing the importance of experimental validation of Equation of State tables.

What would be an ideal photon pump to create Warm Dense matter ?

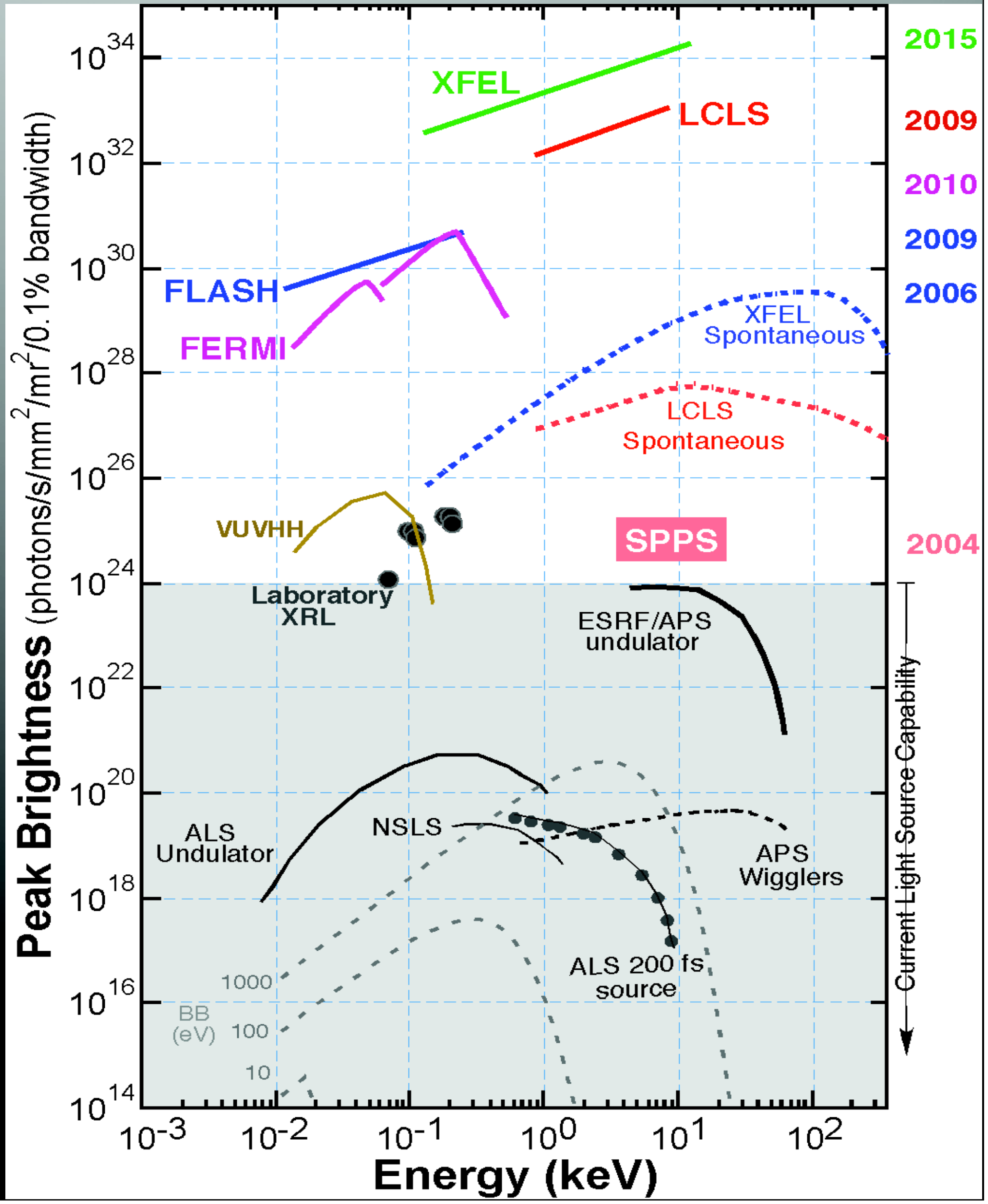
- photon frequency needs to be bigger than the plasma frequency. If not, the photons cannot penetrate bulk of the matter, but are reflected and can only heat a boundary layer, leading to lange gradients of temperature, density and pressure.
- Short pulses are needed, so matter can be heated isochorically, before thermodynamic expansion occurs.
- High photon number is needed to heat matter between 10-100eV

What is an deal probe for WDM?

• Photon frequency needs to be larger than the plasma frequency, such that the probe can penetrate the bulk
• Short pulses are needed to achieve the required time resolution of the measurement, since the WDM will evolve and expand rapidly
• High photon number are needed for many probes to overcome small cross sections of the probing mechanism (e.g. X-ray Thomson scattering)

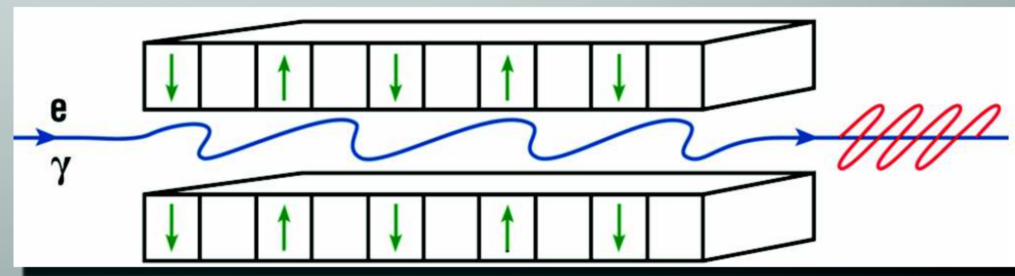
4^{th} Generation Light Sources

4th Generation light sources perfectly match these three requirements. They have peak brilliances of 10 orders of magnitude larger than standard synchrotrons.

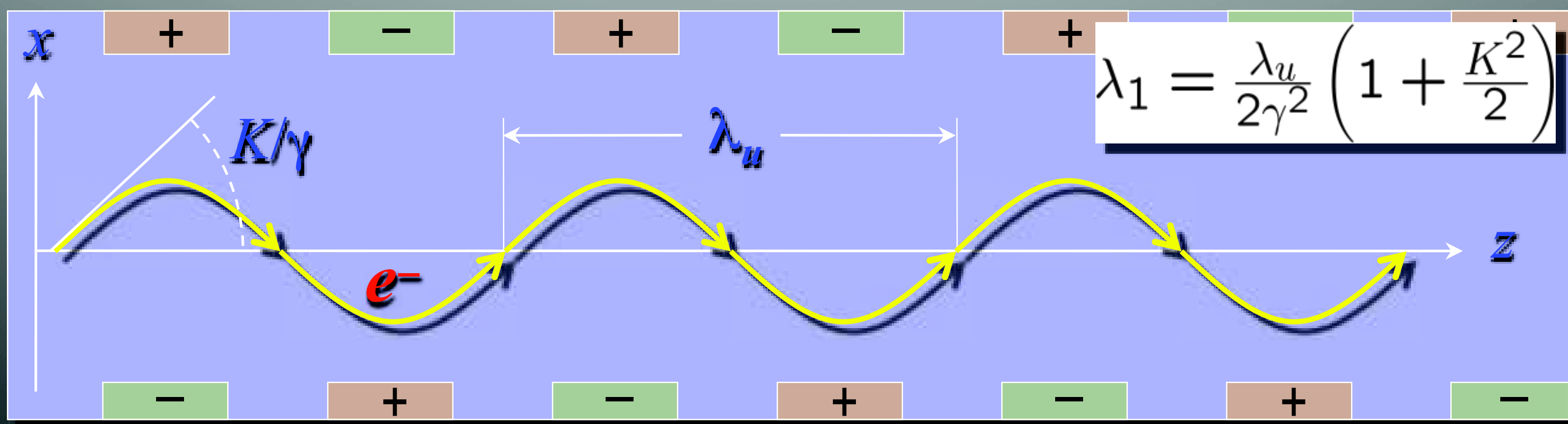


FEL Principles

Z. Huang



- Electrons slip behind EM wave by λ_1 per undulator period (λ_u)

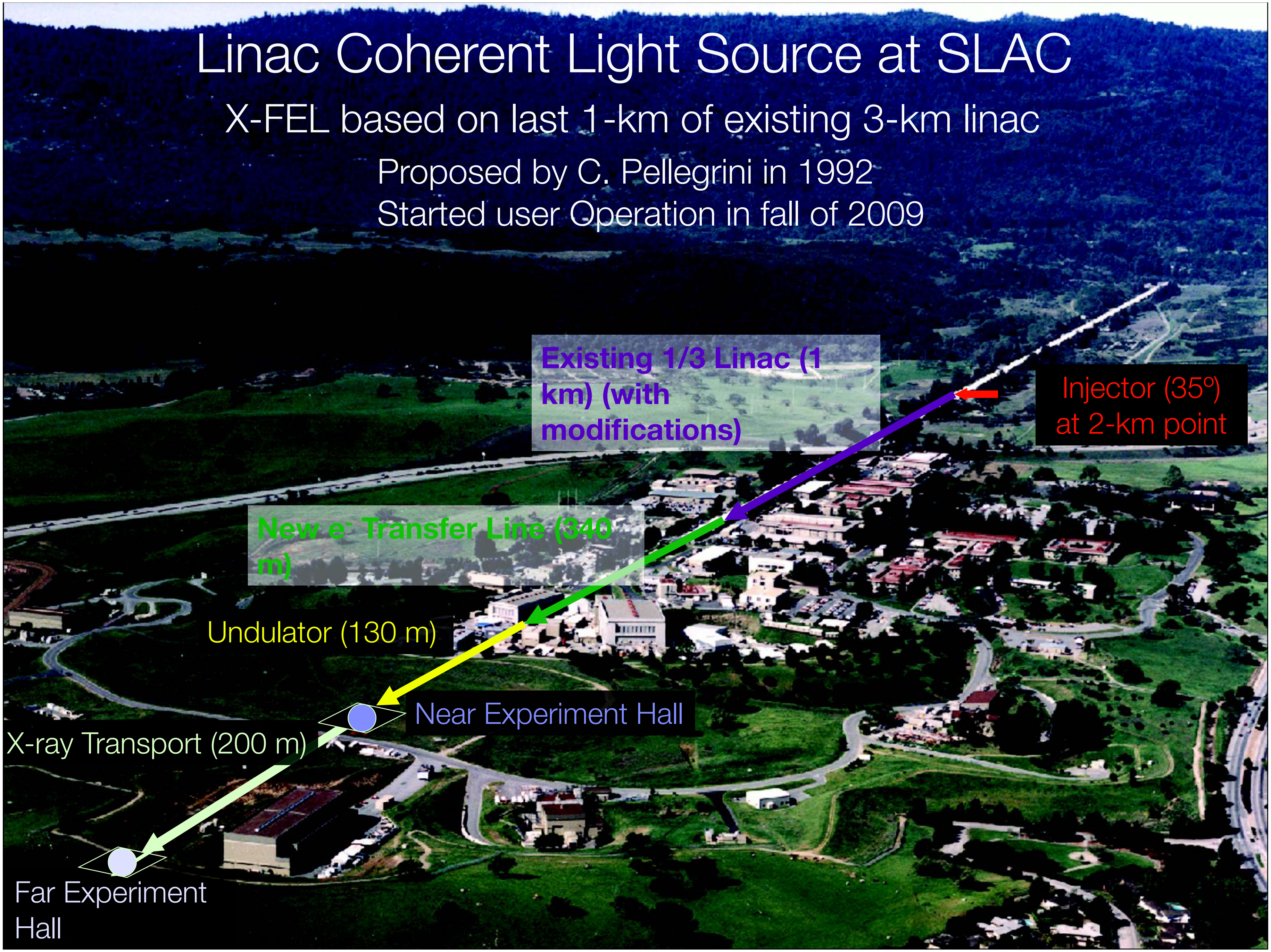


- Due to sustained interaction, some electrons lose energy, while others gain ➔ energy modulation at λ_1
- e^- losing energy slow down, and e^- gaining energy catch up ➔ density modulation at λ_1 (microbunching)
- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ exponential growth of radiation power

Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing 3-km linac

Proposed by C. Pellegrini in 1992
Started user Operation in fall of 2009



Parameters of LCLS and tunability

Repetition Rate: 120Hz, 60Hz, single shot

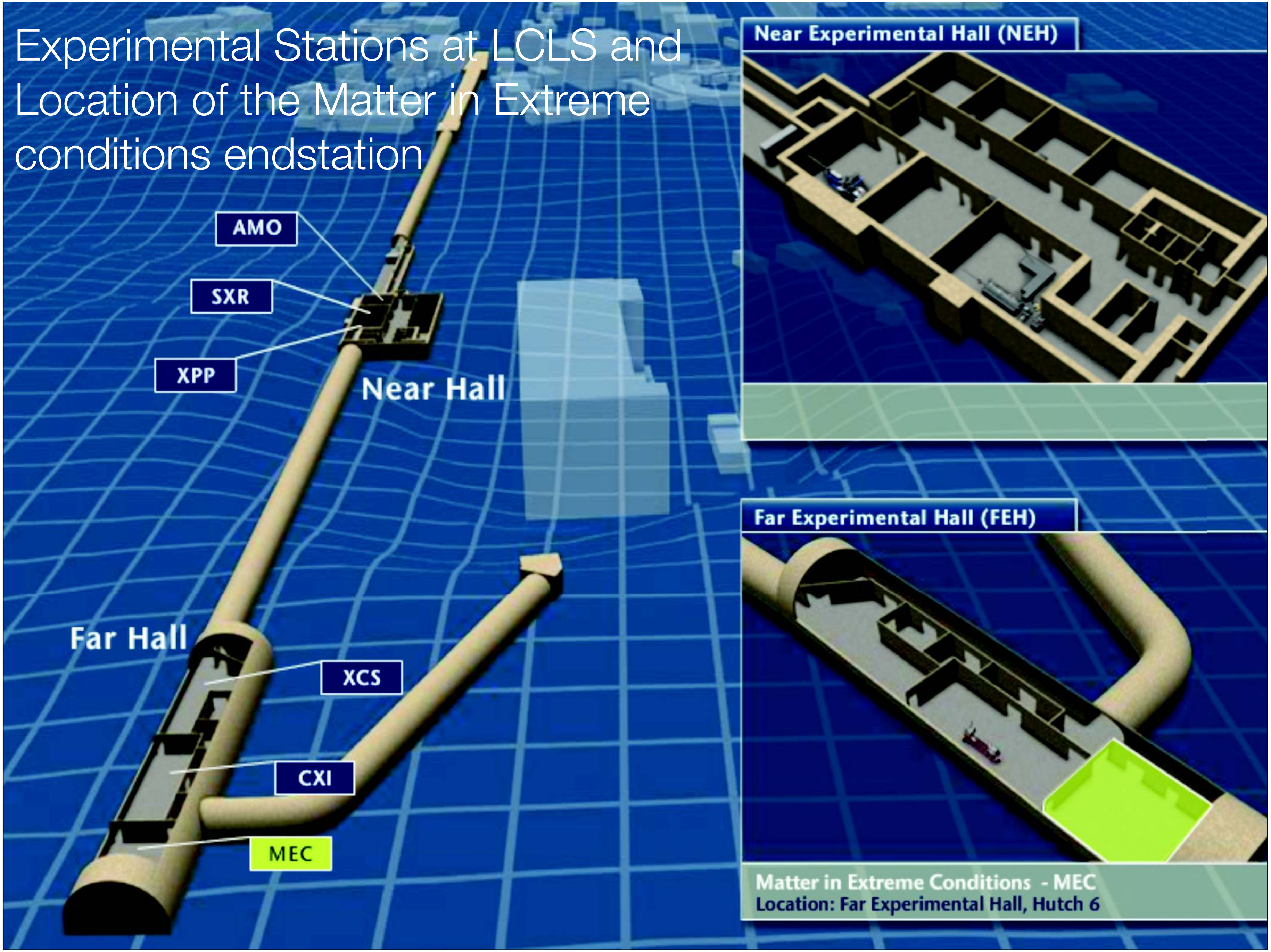
Photon Energy: 540 - 8000 eV, changed in 5-30 minutes.

Pulse Energy / Photon numbers: 0 - 3 mJ, 2.10^{12} photons, easily lowered, but may take 1-2 hrs to achieve >2.5 mJ (depends on wavelength, etc).

Pulse Length: 70 - 300 fs FWHM, easily changed in 1 minute (closed loop control with bunch length monitor after BC2).

Ultra-Short Pulse Length : <10 fs FWHM, requires 1 hour to establish with 20pC beam, or minutes with slotted spoiler.

Experimental Stations at LCLS and Location of the Matter in Extreme conditions endstation



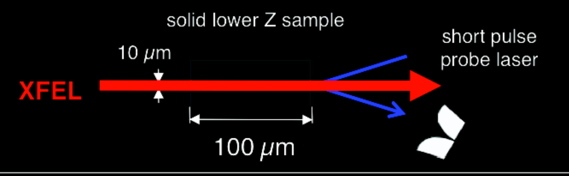
Many meeting were held over the last 10 years to plan and define the MEC instrument at LCLS

10/10/99	1st XFEL HEDS Talk	SLAC	1st workshop on next generation applications
3/1/01	LCLS Instruments	SLAC	
3/21/01	TESLA/XFEL Colloq.	DESY	Official introduction of HEDS to Europeans
11/9/01	HEDS for VUV-FEL	DESY	
4/3/02	WDM Workshop	LLNL	Get LLNL, LANL, and SNL interested
6/18/02	WDM Expt planning	SLAC	1st focused planning meeting for MEC
2/15/03	XFEL HEDS Wkshp	DESY	
9/13/03	VUV/LCLS exp plan	Lisbon	
8/22/04	VUV-FEL PBC	DESY	Peak Brightness Collaboration
11/28/05	XFEL HEDS Mtg	Paris	
12/6/06	NNSA HEDS instr.	LLNL	Generated mission need document
1/24/07	XFEL PBC	DESY	
5/19/08	UK NLS on HEDS	Oxford	
10/5/08	PBC	DESY	
1/26/09	MEC workshop	RAL	
3/30/09	HEDS for XFEL	Oxford	

MEC 5 Science Drivers of the MEC end station

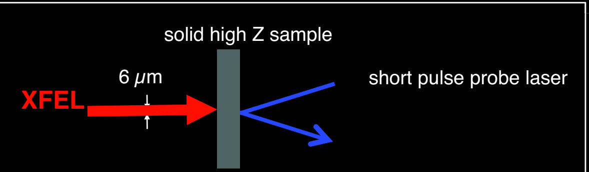
• Creating and Probing WDM

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



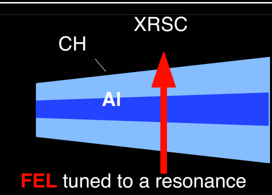
• Creating and Probing HDM

- Generate ~ 100's eV solid density matter
- Generate hot, dense, high-pressure matter with the FEL



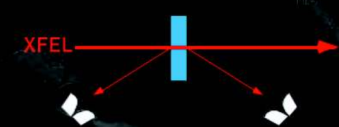
• Radiative Properties Studies of HDM

- Use high energy laser to create uniform HED plasmas
- Measure collision rates, redistribution rates, ionization kinetic



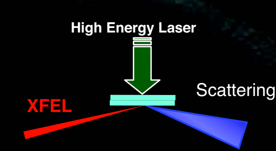
• HEDS Diagnostic Development

- Perform 'Thomson' scattering from solid density matter
- Measure n_e, T_e, T_i, <Z>, f(v)
- Phase-Contrast Imaging to obtain nm-scale resolution

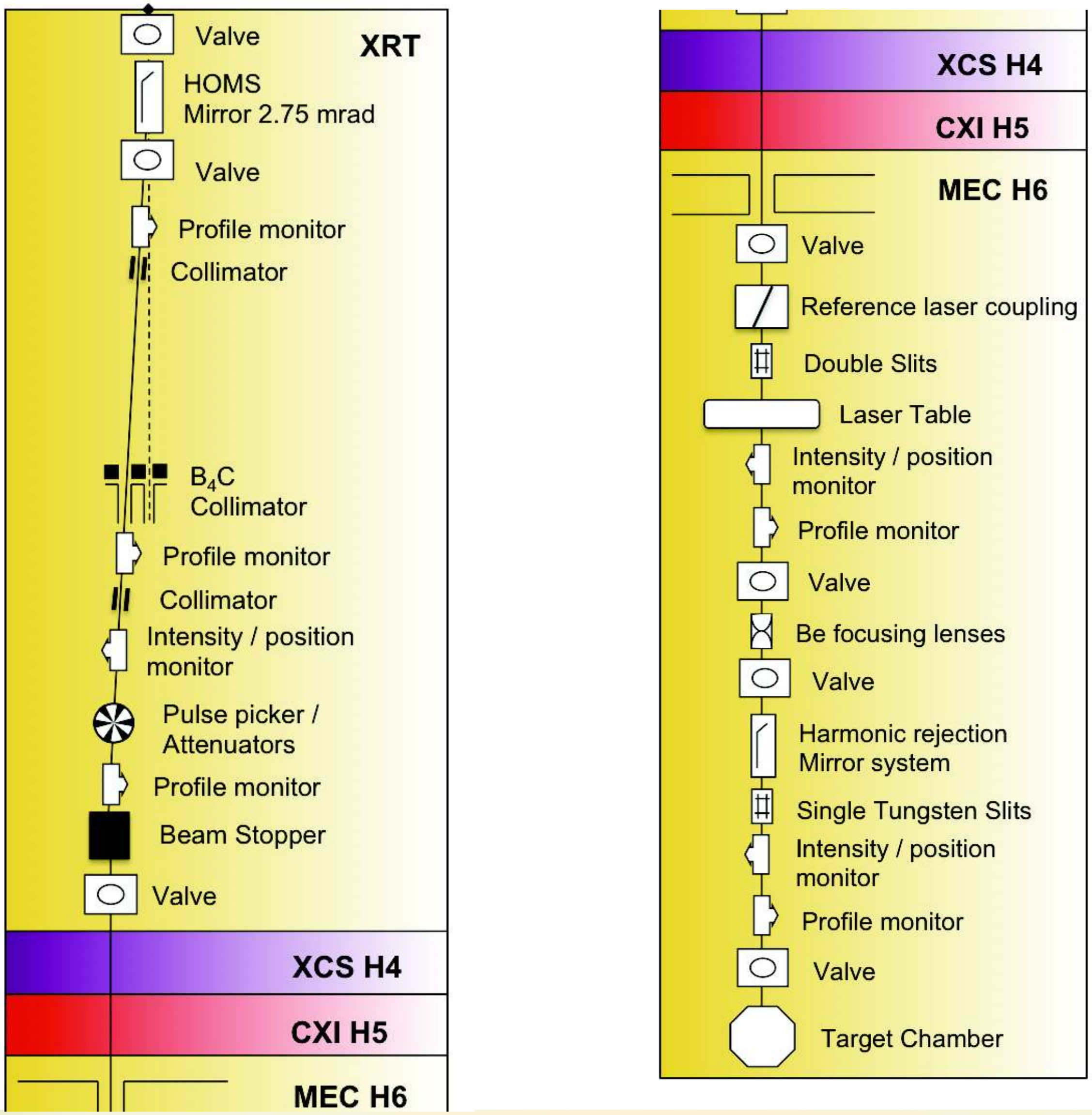


• Probing High Pressure Phenomena

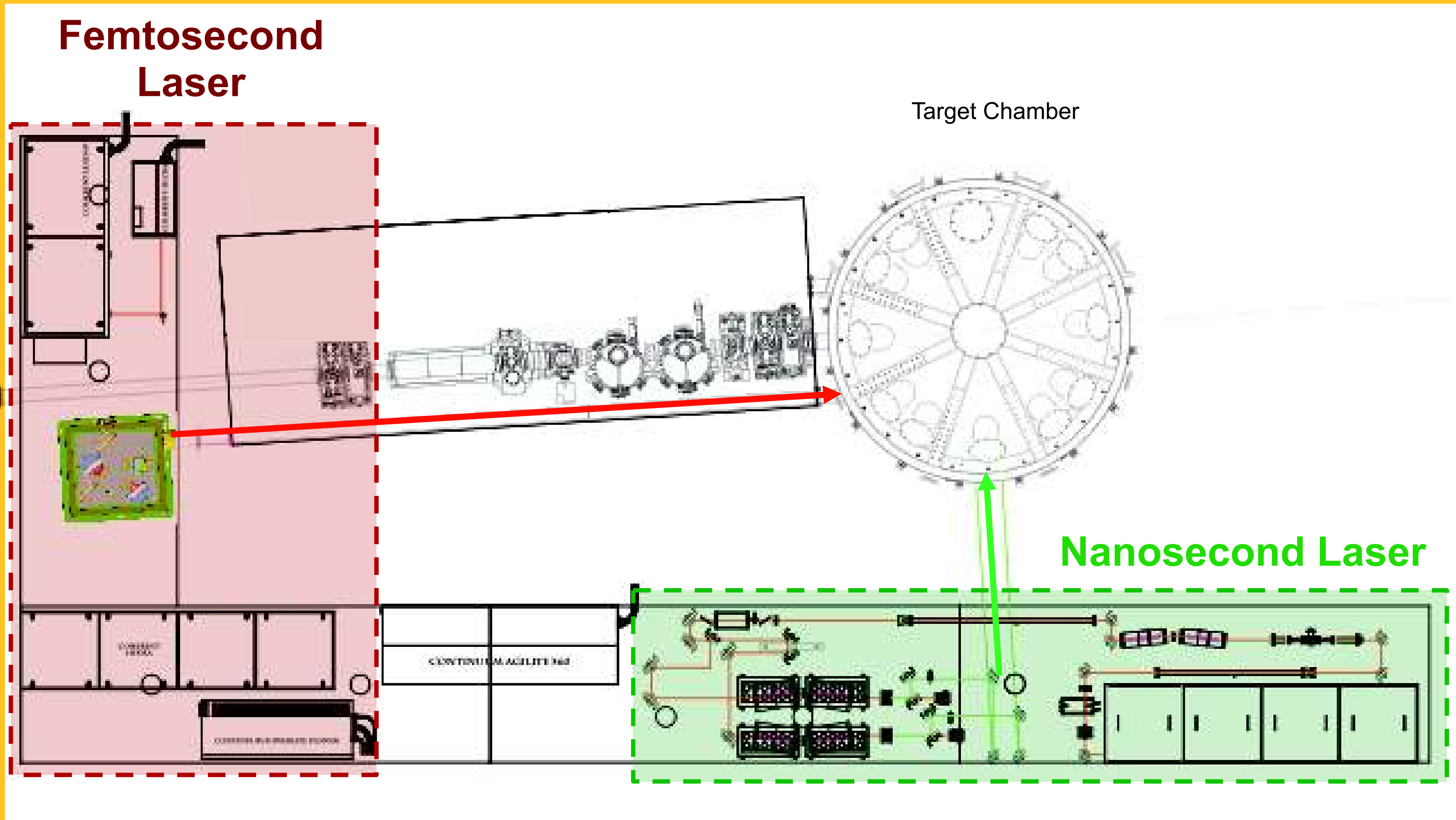
- Use high energy laser to create steady high pressures
- Produce shocks and shockless high pressure systems
- Uniquely use Thomson Scattering and Phase Contrast imaging



MEC X-ray beamline schematic



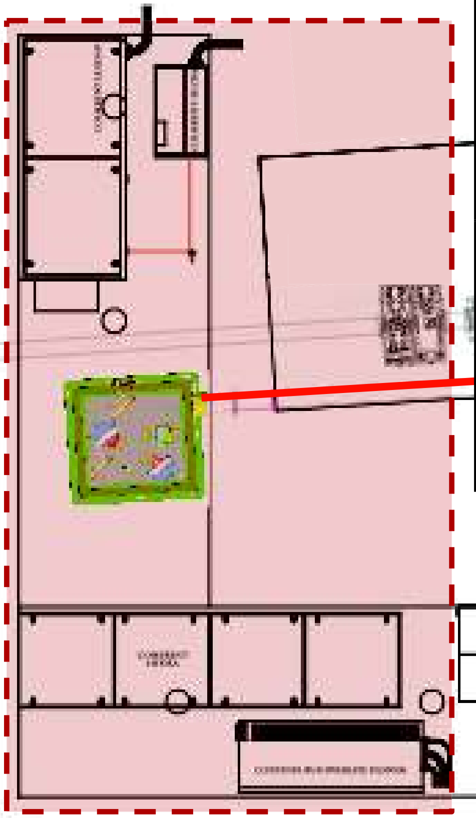
MEC Laser Systems



15

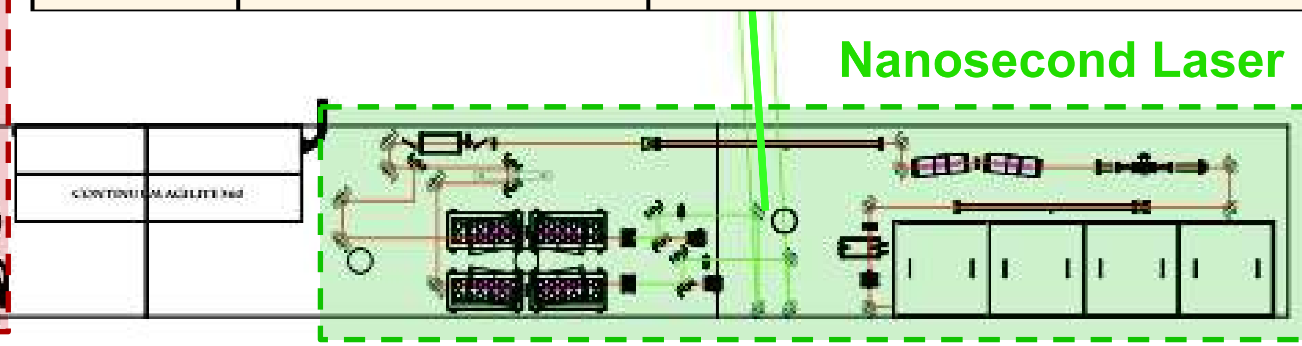
MEC Laser Systems

Femtosecond Laser



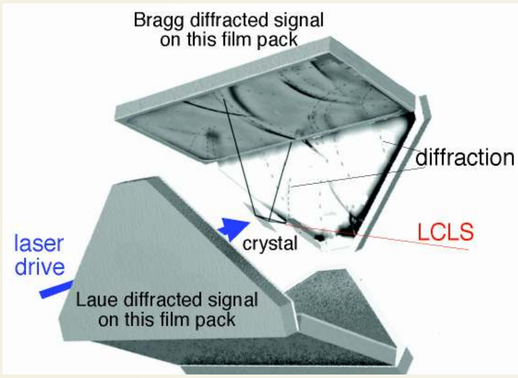
Item	Purpose	Specifications
Short Pulse Laser System	TW-class short pulse laser for target driver and short pulse diagnostics	Wavelength: 800 nm Pulsewidth: ≤40 fs Energy: ≥150 mJ per pulse Repetition Rate: 10 Hz Vacuum optical transport to target chamber
Long Pulse Laser System	Multi-Joule high-intensity shock driver for target interactions	Wavelength: 527 nm Pulsewidth: Variable 2-20 ns Variable Temporal Pulse Shape Energy: ≥ 50J per pulse Repetition Rate: 1-shot per 10 min

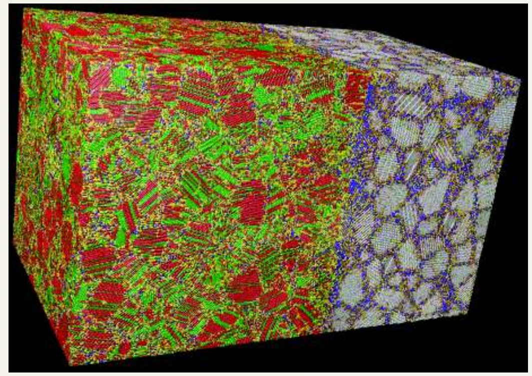
Nanosecond Laser



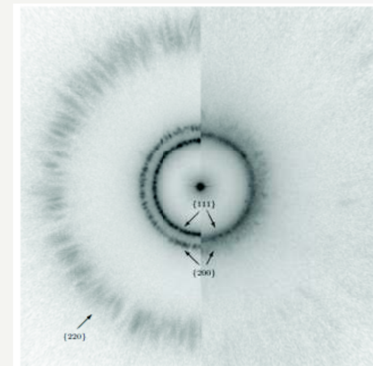
16

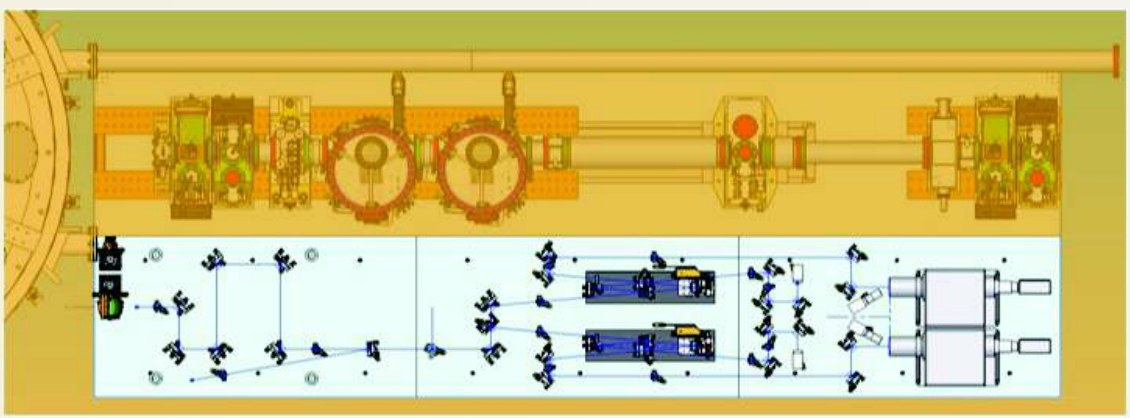
VISAR diagnostic for High Pressure Physics

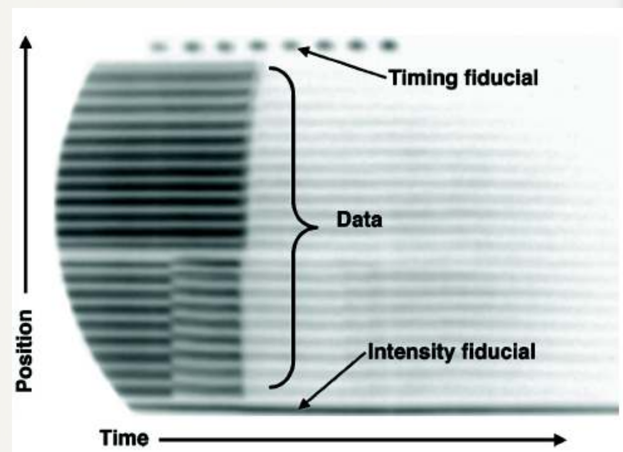




$\mathcal{F}(r)$



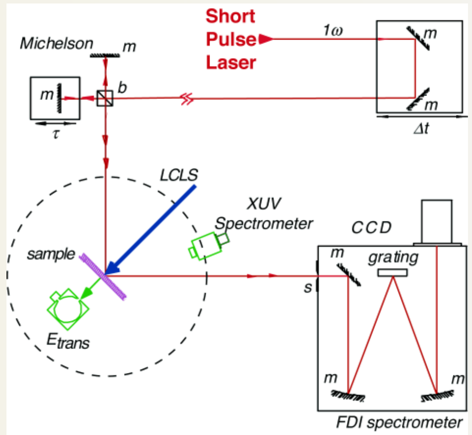


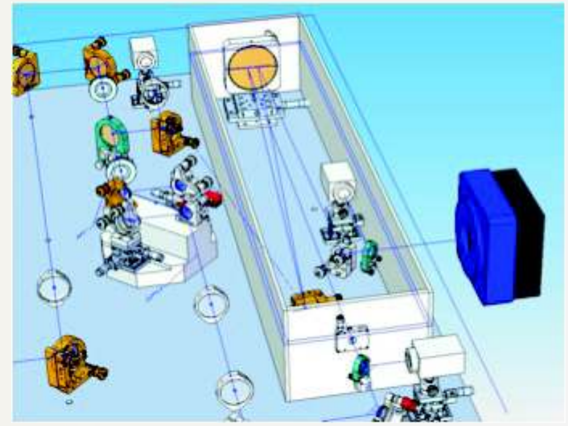


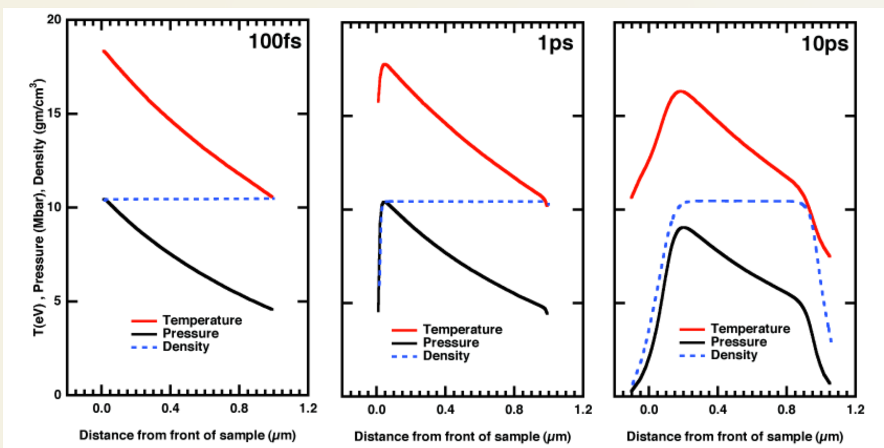
Line-imaging velocimeter for shock diagnostics, P. Celliers et al., Rev. Sci. Instr., 4916, **75**, (2004)
Courtesy of Wark et al.

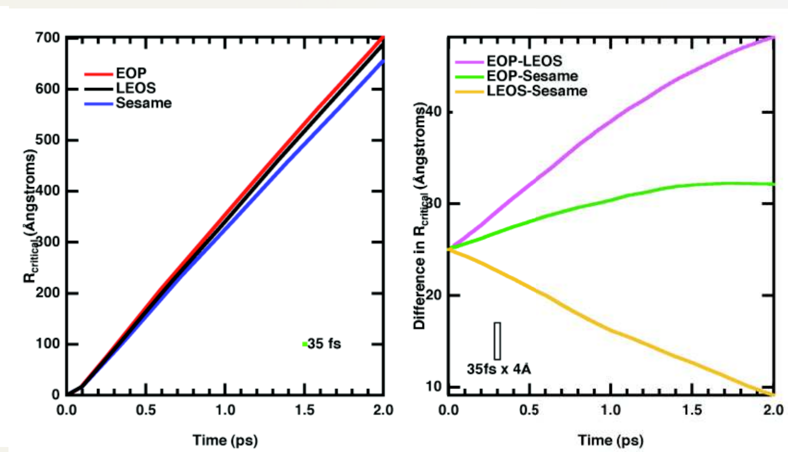
Fourier Domain Interferometry

- Measure the motion and velocity of the critical density surface of target with 4A resolution
- Used to determine the EOS



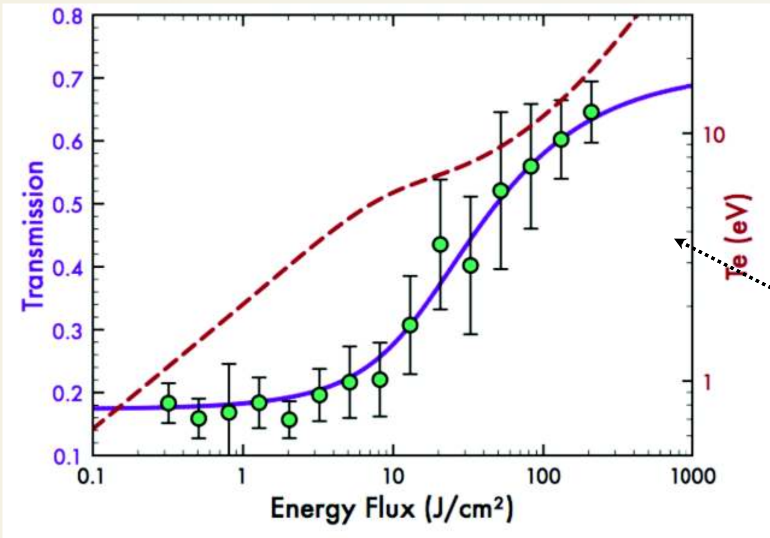


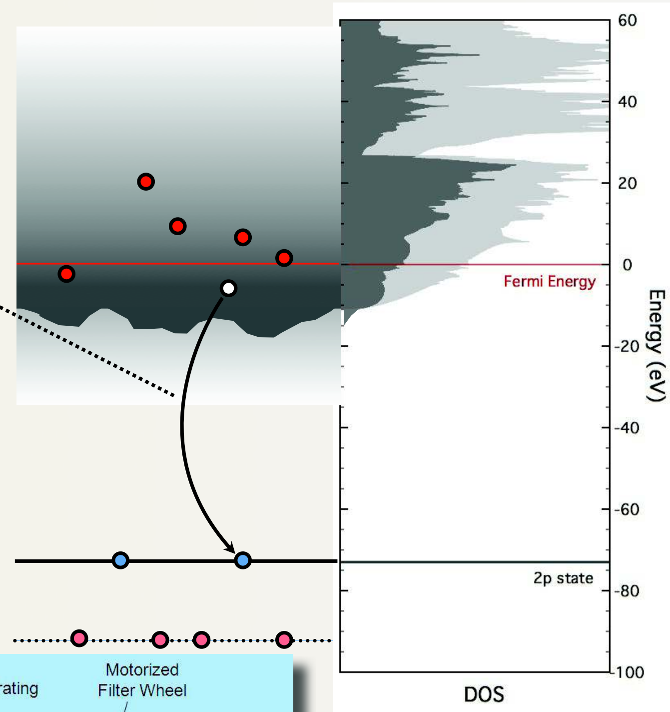


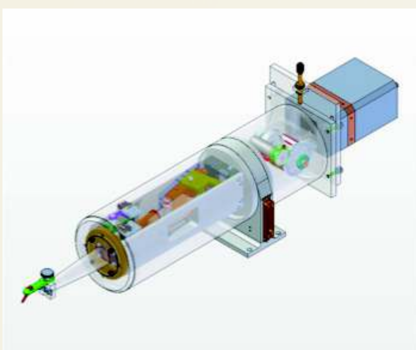


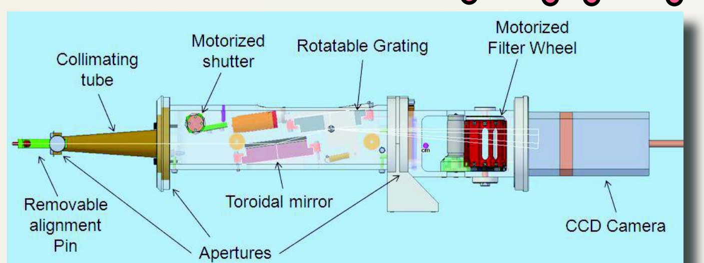
Courtesy of R. Sheppard, P. Audebert et al.

XUV emission from WDM at Flash







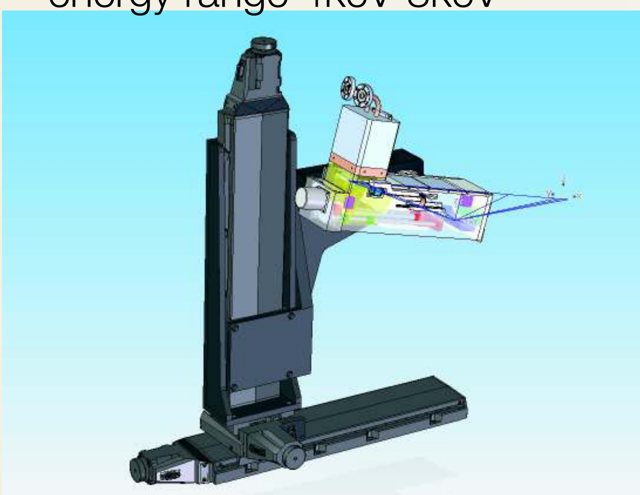


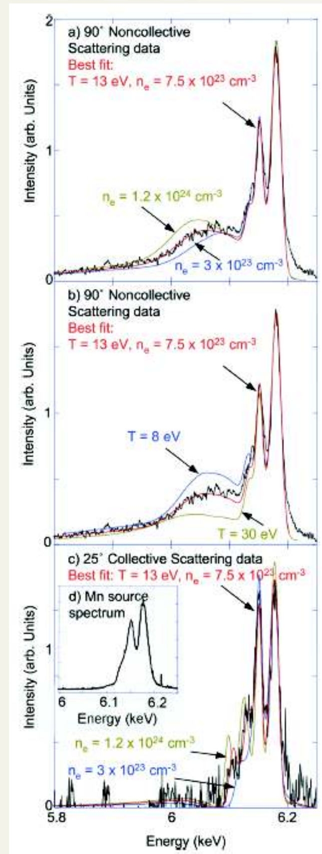
- Based on design by U. Zastrau, R. Fauestlin, et al.
- Remote control of XYZ stage
- Main component: various line space (VLS) grating of 800 l/mm and toroidal mirror, resolution L/DL=300
- X-ray CCD detector: 27.6x27.6 mm (2048x2048, 13.5 µm pixel size))

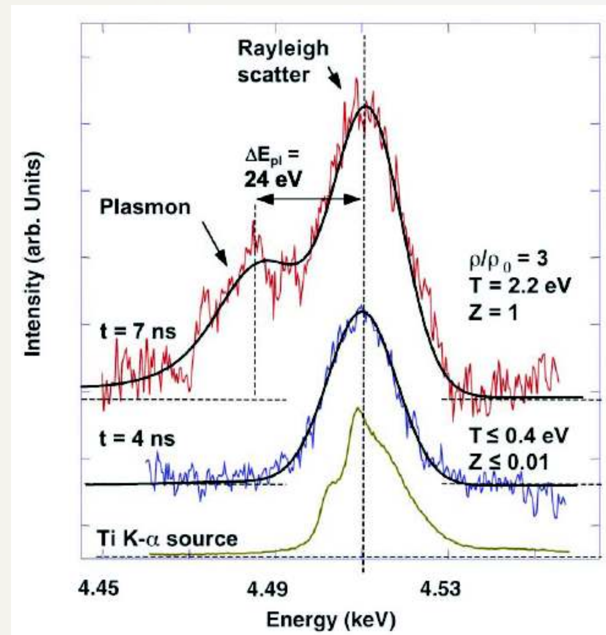
B. Nagler et al., Nature Phys., 693, **5**,(2009), U. Zastrau et al, Phys. Rev. E, 78,066406, (2009)

X-ray Thomson Scattering of WDM / HDM

- Measure the full structure factor S(k,ω)
- Fully motorized to change scattering angle
- energy range 4keV-8keV







H. J. Lee et al., Phys. Rev. Lett. 115001, **102**, (2009); A. L. Kritcher et al., Science, 69, **322**, (2008)

Summary

- MEC specifically designed for WDM / HDM research
- Unique combination of LCLS beam, high power lasers, diagnostics
- First users in April - May 2012

- User facility : next proposal deadline **13 September 2011**

- MEC science team:
  Hae Ja Lee, Dick Lee, Jerry Hastings, Despina Milathianaki,
  Greg Hays, Bill White

BNagler@slac.stanford.edu
HaeLee@slac.stanford.edu