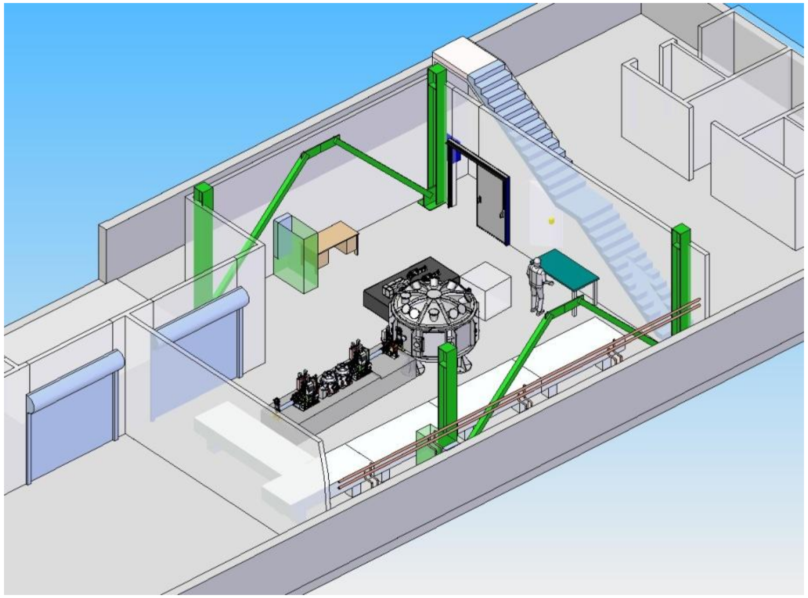
Matter in Extreme Conditions (MEC) Instrument in SLAC

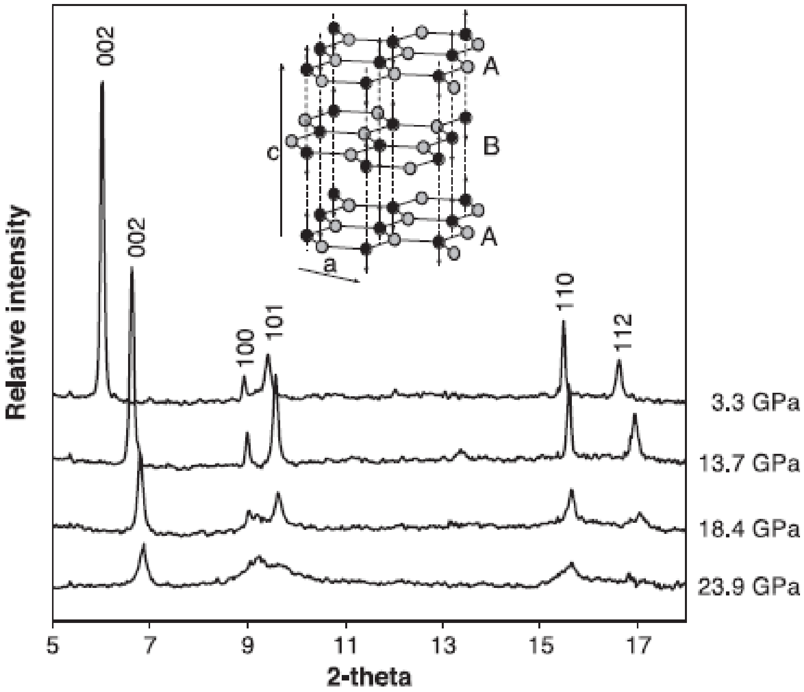
Hae Ja Lee



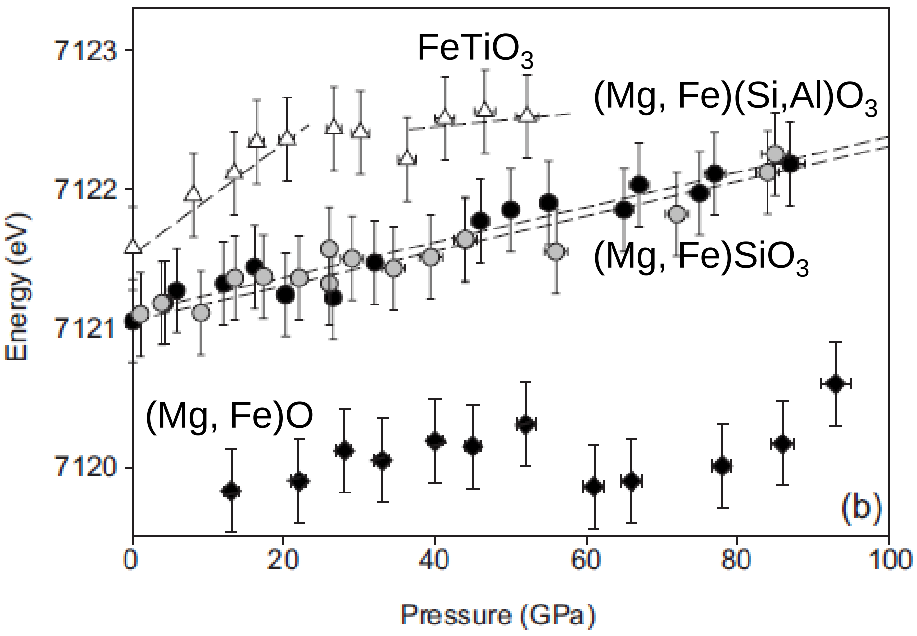
Outline

- Introduction
  - Novel behavior in extreme condition
  - LCLS in SLAC
  - MEC Instrument Goal / Requirement
- MEC Instrument : x-ray transport and laser system
- MEC science and target diagnostics
  - X-ray Scattering Spectrometer
  - X-ray Emission Spectroscopy
  - XUV Spectroscopy
  - FDI
  - VISAR
- Summary
  - Parameters of MEC Instrument

Mao et al. Science (2004)



Narygina et al. PRB (2009)



Colossal enhancement of piezoelectricity under pressure

…(Mg,Fe)SiO_3 >120 GPa, Ultrahigh pressure behavior of CO_2, Carbon Polymorphism

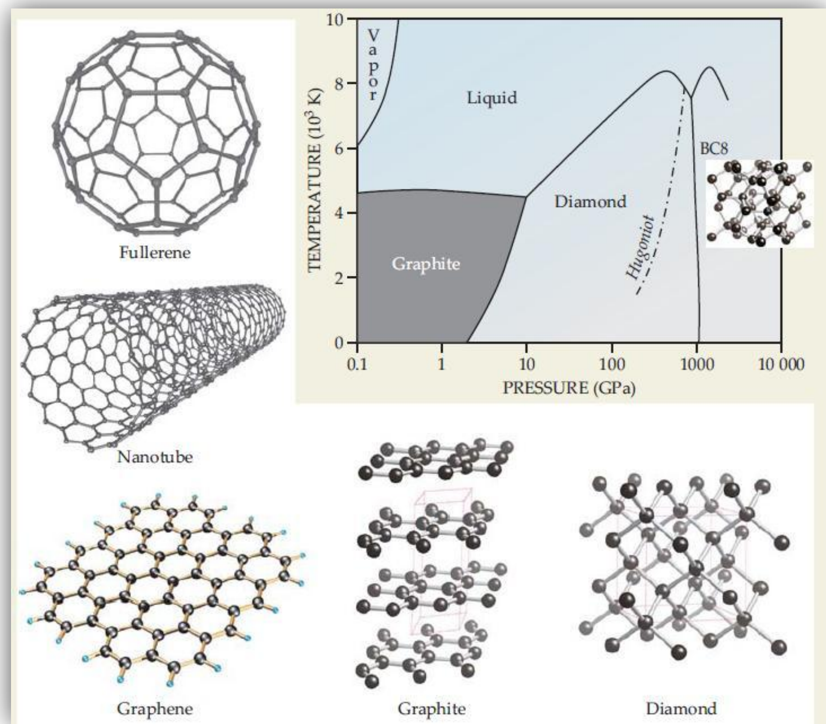
X-ray Raman, Mao, science 2004: conversion of half π bond to σ bond

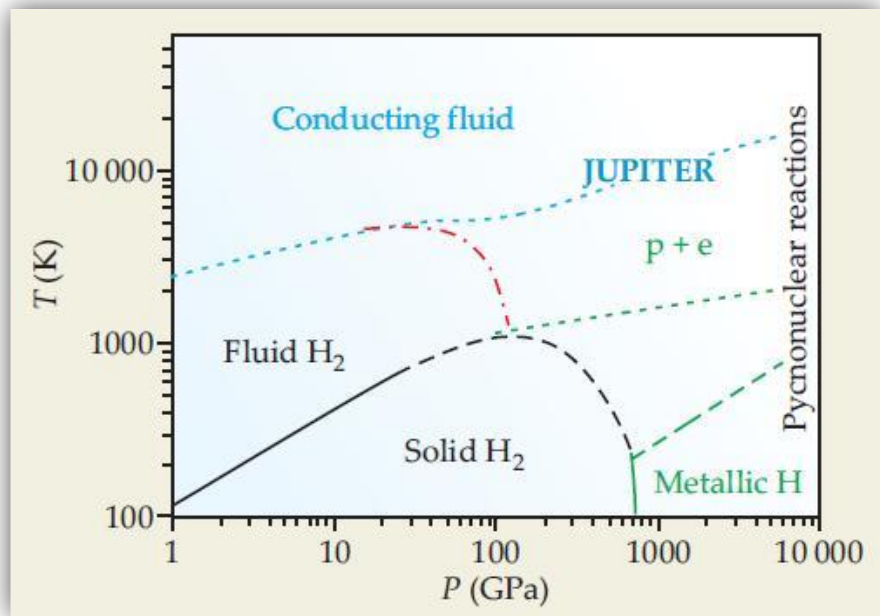
Evolution of K-edge position with pressure for several iron oxides

More extreme conditions, new diagnostics, theory & experiment, stability/metastability

Molecules are stable to 300 GPa, low T , > 400 GPa : combined superfluidity and superconductivity

Matter in Extreme Conditions

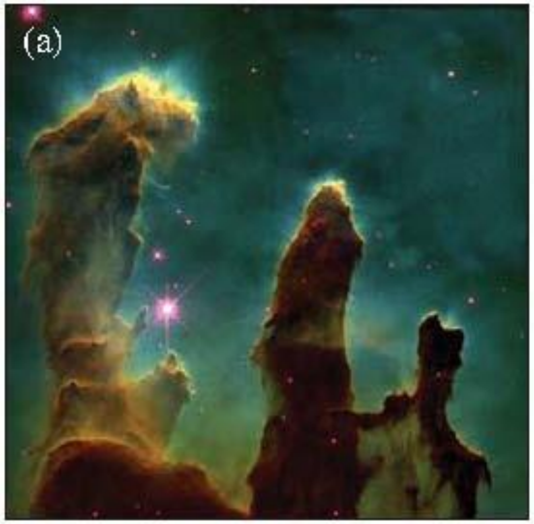


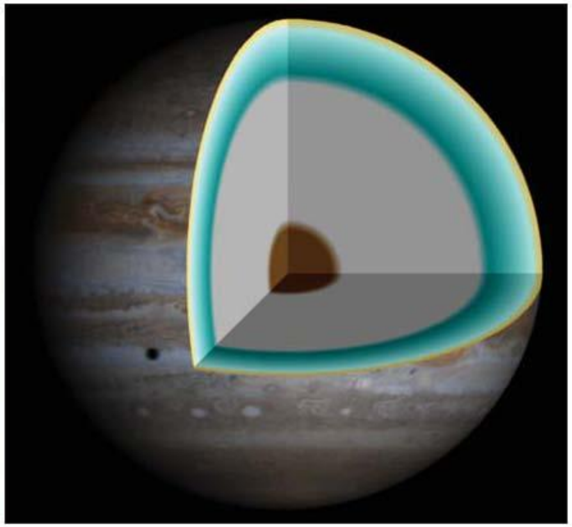


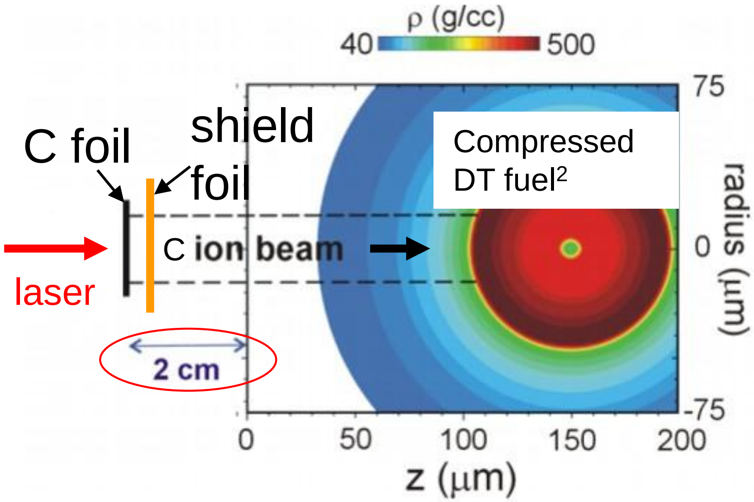
- **There have been growing interest in the material under extreme environments**
- **Extreme environments: pressure, temperature, flux, stress, strain, magnetic field, …**
- **In Nature, phenomena in harsh condition happen around us no matter what we recognize**
- **We often intentionally create similar extreme environment**

Potential Impact of understanding WDM

Understanding the nature of WDM advances our understanding of the universe and enables important applications







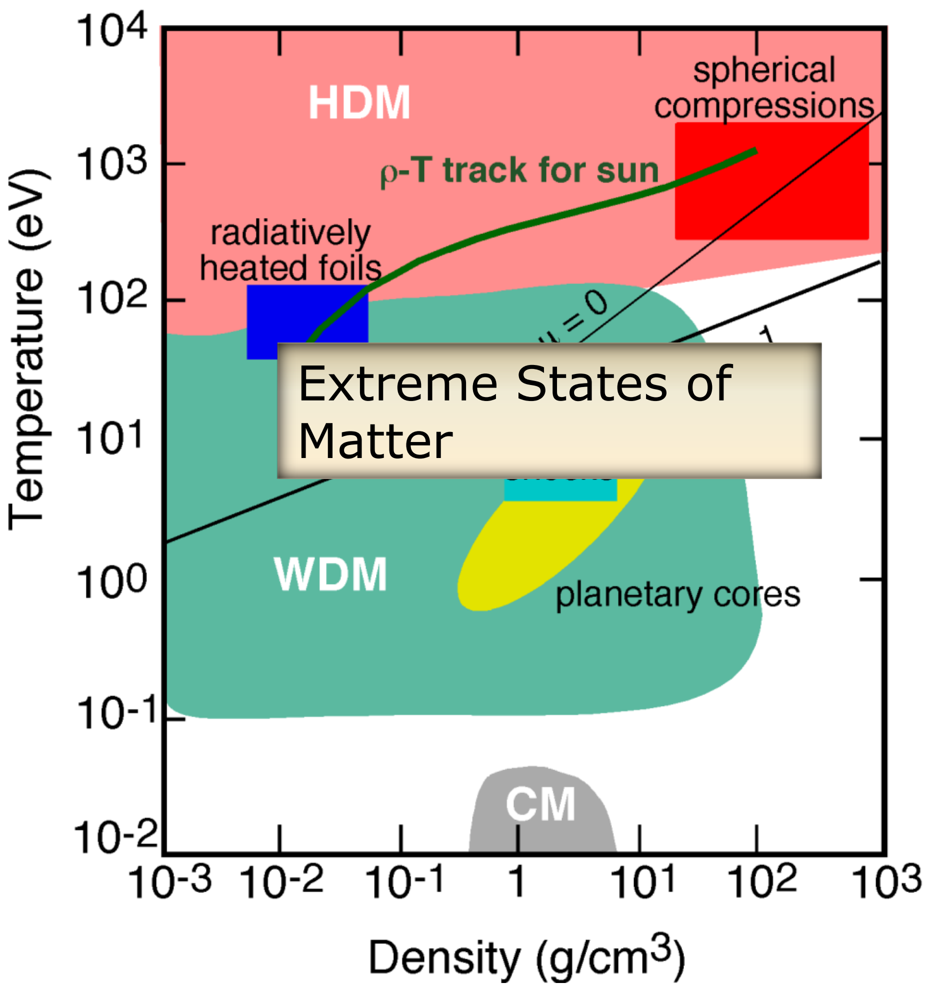
Understanding the Universe:

- Start creation and evolution
- Planetary physics

Advances use-inspired research

- Inertial fusion
- Material damage, manufacturing, functioning and controlling
- Explore new materials

Warm Dense Matter in Extreme condition



Warm Dense Matter Physics

High Pressure Research

High Energy Density Physics

Equation of state
Material properties of WDM/HDM
Electron-ion equilibrium
Transport phenomena

MEC diagnostics capability will address these scientific issue by measuring conditions of extreme states of matter

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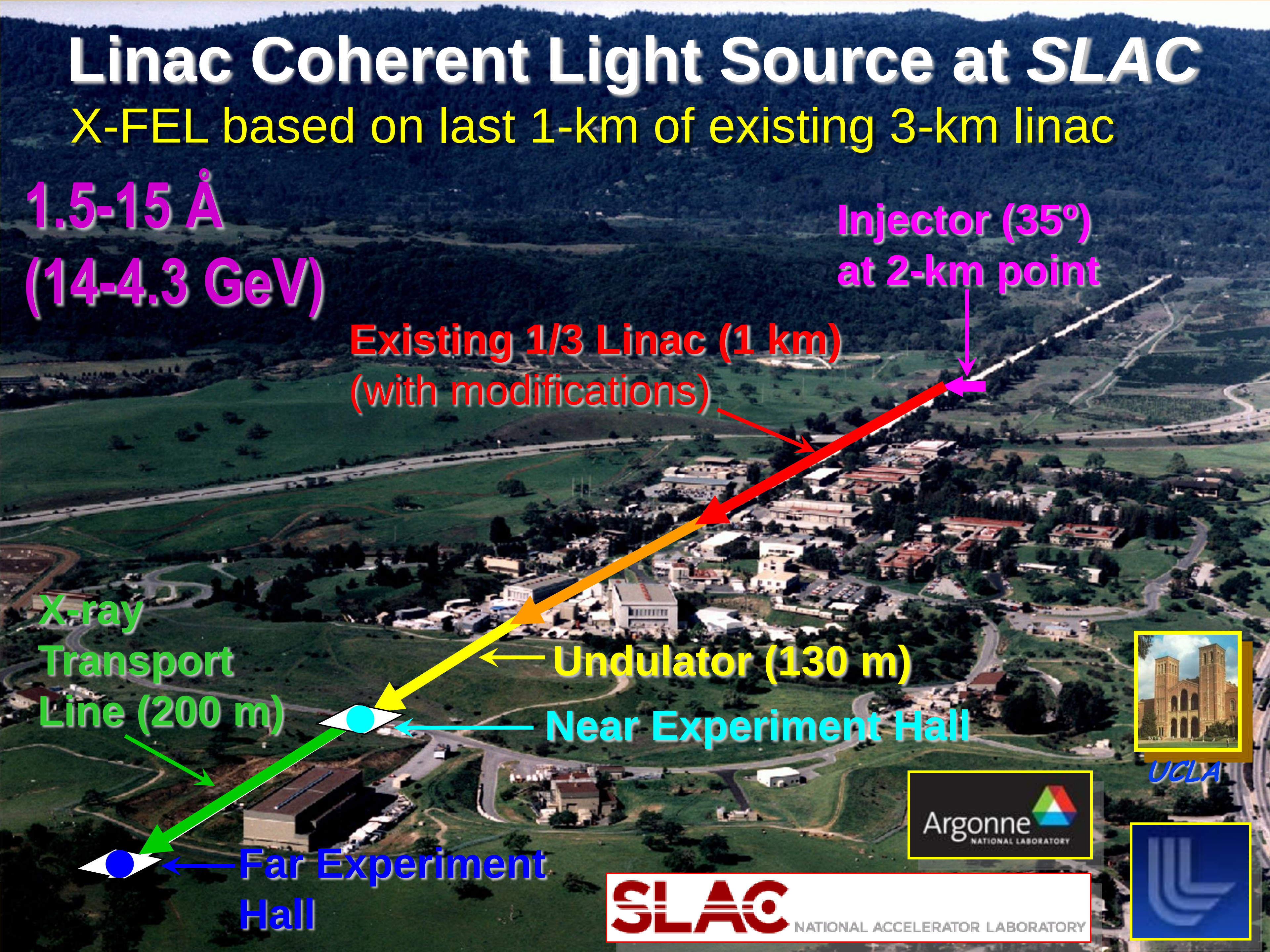
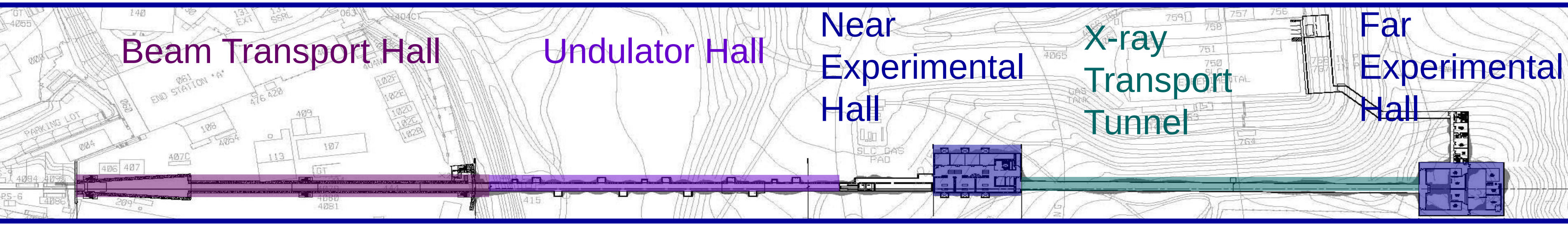
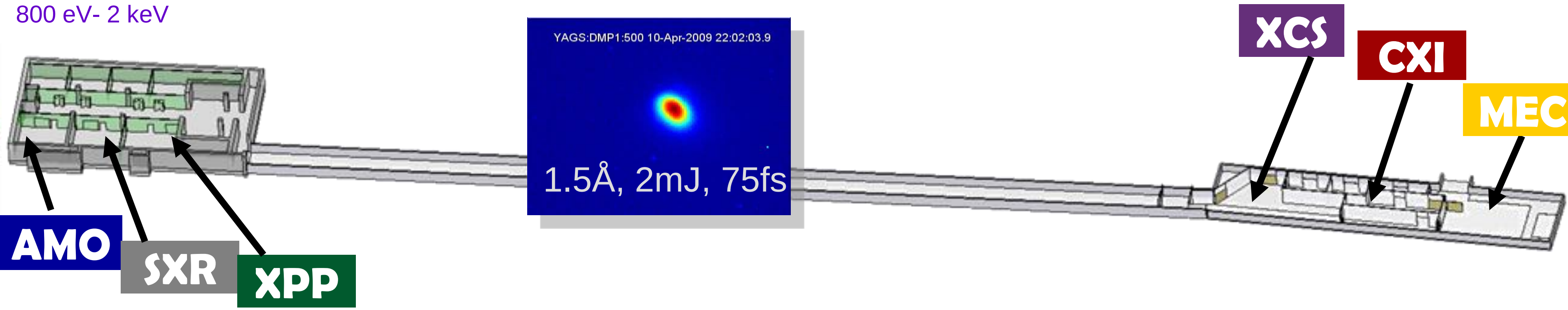
Linac Coherent Light Source at *SLAC*

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







AMO

Operating with users

Matter Exposed to Ultra Intense X-ray Pulses

Ionic Charge States of Atoms, Molecules and Clusters

Electron Energy Measurements of Highly Excited States

X-ray Emission Measurements of Highly Excited States

Ultrafast Dynamics of Simple Systems:

Atoms, Molecules & Clusters

Two-Photon Excitation/Ionization of Atoms & Molecules

X-ray Ionization of Adiabatically Aligned Molecules

SXR

Commissioning, Operate with users in July

Pump-Probe Ultrafast Chemistry

Clusters as New Materials

Magnetic Imaging

Correlated Materials

Coherent Imaging

XPP

Commissioning, Operate in October

Condensed Phase Photochemistry

- Charge Transfer Reactions
- Photosynthetic Reactions/Photovoltaics

Lattice Dynamics and Phase Transitions

- Order/Disorder
- Metal/Insulator

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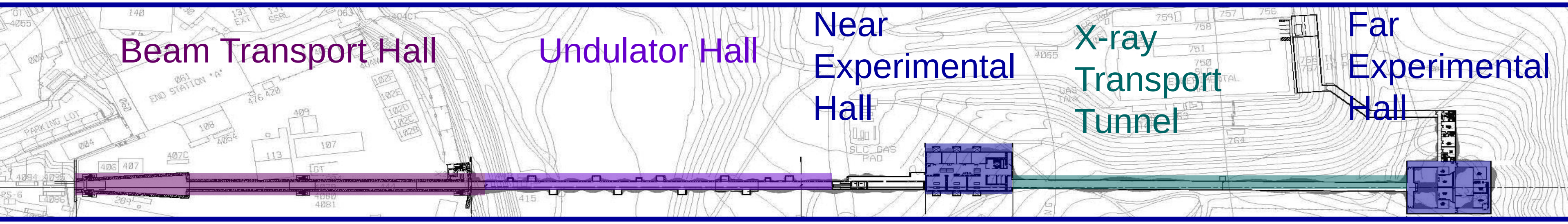

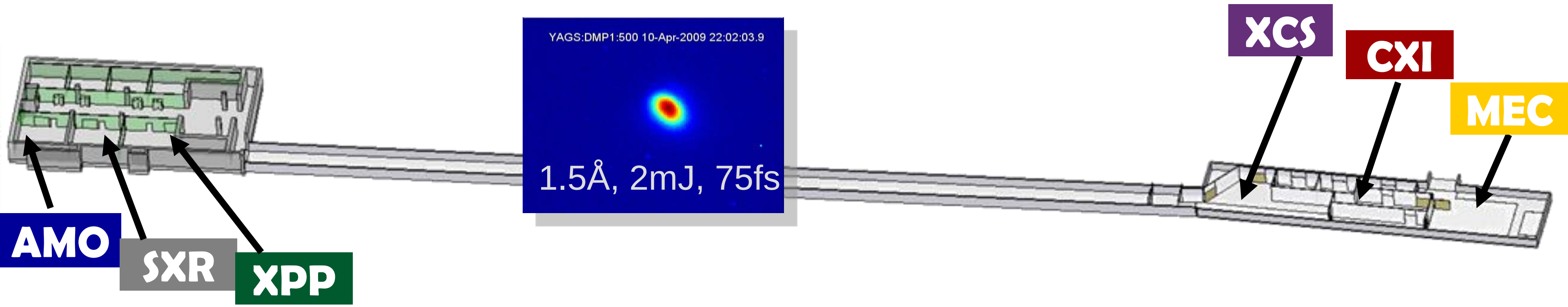

XCS

Goal: Time-resolved observation of coherent diffraction patterns using LCLS coherent hard x-ray (6-25keV)

Coherent preservation of x-ray optics
Detector with small pixel size/large sample-detector distance

Nanoscale/sub ns dynamics

User operation start planned for October 2011

CXI

Goal: Perform imaging of single particles at highest spatial resolution achievable using single LCLS pulses .
Image biological nanoparticles beyond the classical damage limit .

Particle injector

User operation start planned for 2011

MEC

High Pressure
Shock phenomena
Warm Dense Matter
High Energy Density Matter

User operation start planned for 2013

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MEC Instrument Goals/Requirements

Goals

- Deliver capabilities for the creation and measurement of warm dense matter or high energy density matter.

Primary Aspect of the Instrument (SP-391-001-89)

- LCLS beam : Unique capability to create, probe and selectively pump HED states
- Optical laser : Create HED states by irradiation in several ways; Provide diagnostics capability
- Target Diagnostic : Provide the measurement capability
  - High pressure, Warm dense matter, High energy density matter

Key Performance Parameters

- X-ray transport system: 4-20 keV energy range
  - Using the fundamental and third harmonic, 0.1% energy resolution
- MEC Laser system: short pulse and long pulse laser system
  - 35fs/150mJ/800nm, 2-20ns/2x25J/527nm
- Target Diagnostics:
  - Shock velocity (5×10^4-5×10^6ccm/s), surface motion (4Å resolution)
  - Temperature (0.1-2000 eV)

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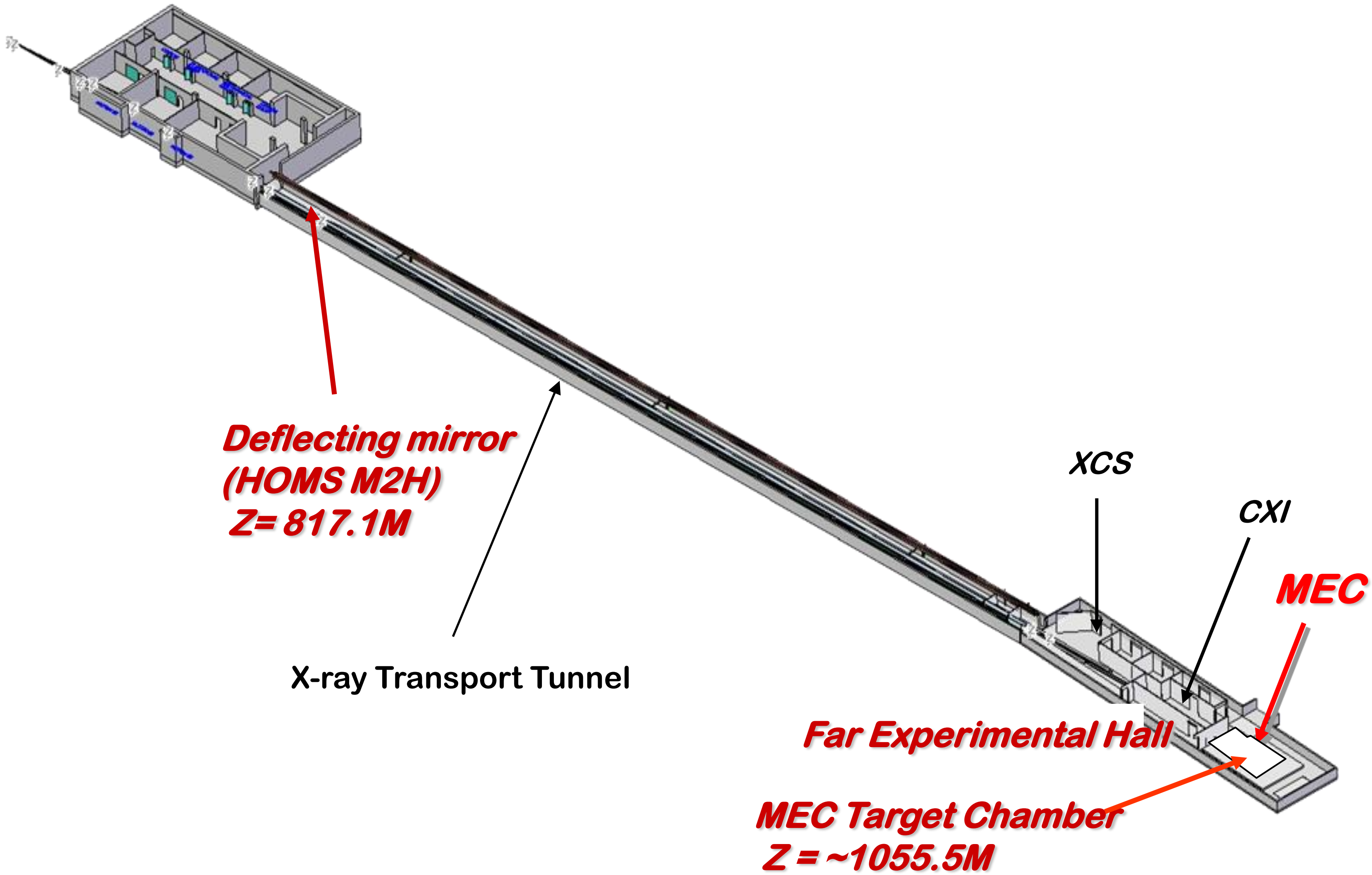
LCLS source for MEC instrument

MEC instruement provides capabilities to create and diagnose matter in extreme conditions in various experimental geometries.



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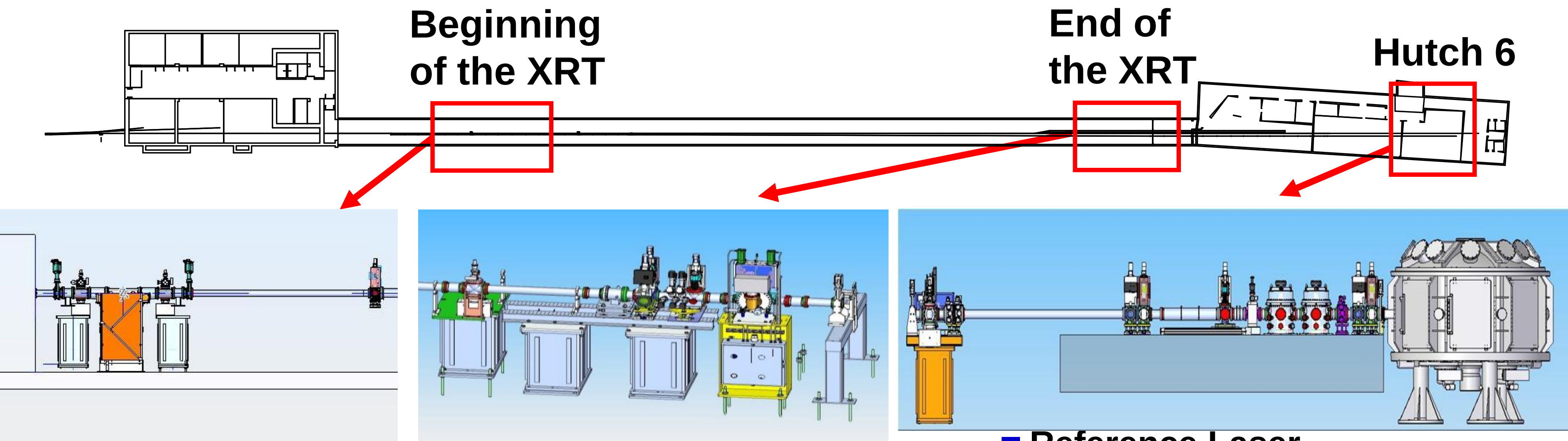
X-ray Optics System Description

- The x-ray transport is a vacuum system designed to deliver the x-ray FEL beam to a target chamber
- Diagnostics and optics can be used to tailor the x-ray beam in size and intensity as it reaches the target chamber



- Gate valve
- Collimator
- Deflecting mirror
- Collimator
- Gate valve
- Profile monitor

- Ion pump
- Collimator
- Intensity Position Monitor
- Pulse Picker/Attenuator
- Beam Stopper
- Gate valve

- Reference Laser
- Double Slit Ass'y
- Profile - Intensity monitors
- Be focusing lens
- Harmonic Rejection Mirrors
- Single Slit Ass'y
- Profile - Intensity monitors

X-ray Optics description

Item	Purpose	Specification
Deflecting Mirror	*Separate MEC beam from central line*	*Reflect the both 1st and 3rd harmonic of the LCLS beam*
Vacuum transport	*Vacuum for transport of x-ray beam through XRT*	*Vacuum below 10^{-5} torr*
Intensity-pos monitor	*Normalization of x-ray energy fluctuations*	*Relative accuracy of better than 1%*
Harmonic rejection mirrors	*Eliminate 3rd harmonic of LCLS beam*	*Reduce 3rd harmonic by a minimum of x 100 over the LCLS operating range*
Be focusing lens	*Provide experiment appropriate LCLS beam on target*	*Waist less than 1 micron, off waist 50 micron beam size, energy range 4-25 keV*
Target Chamber	*Vacuum environment for target, lasers, diagnostics*	*Minimum pressure: $1x10^{-5}$ torr*

MEC Laser Systems

Item	Purpose	Specifications
Short Pulse laser System	TW-class short pulse laser for target driver and short pulse diagnostics	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 Enclosed optical transport to target chamber

Science Team

- Target Diagnostics Concept and Specifications developed with the science team and through a workshop.

The MEC science team

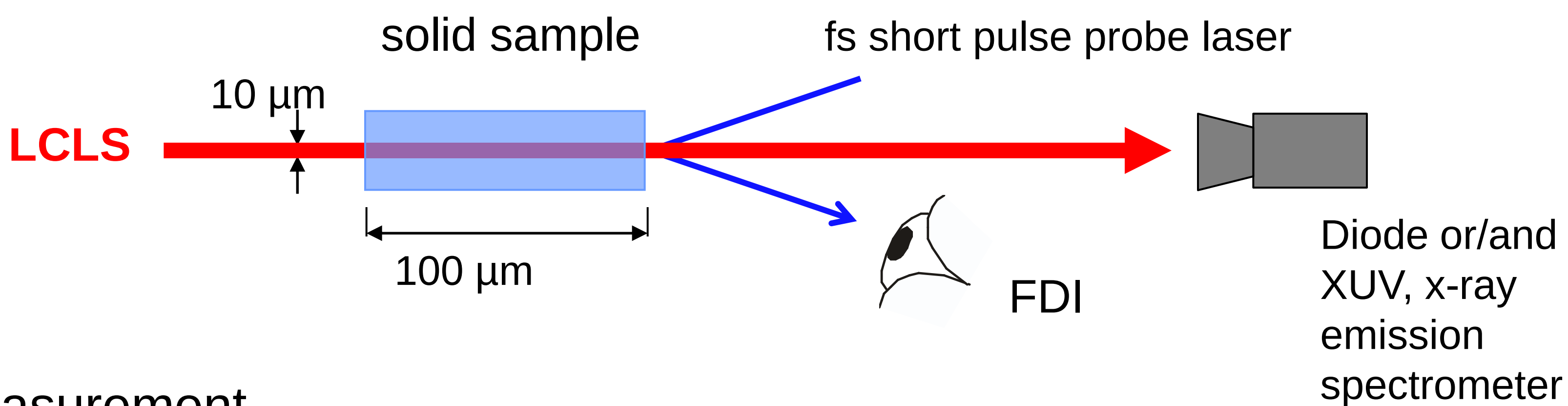
- Richard W. Lee, LLNL (MEC Team Leader)
- Jerry B. Hastings, SLAC
- Bob Nagler, STFC, UK

MEC Science with diagnostics

Research category	Source beam	Interesting phenomena/physics properties	Measurement tools
Warm Dense Matter (WDM)	LCLS	Creation of WDM : Heated uniformly and rapidly. Release before hydrodynamic expansion	FDI (surface expansion) XUV, X-ray spectroscopy (emission line) Diode (Flux change)
	Optical laser	Compression, electron transport	X-ray Thomson scattering (T_e, n_e, Z) XUV, X-ray spectroscopy (emission line) VISAR (surface expansion)
High Energy Density Matter	Optical laser LCLS pumping	Redistribution of population by pumping within a transition. Low Density of Plasma, high temperature (T_e>100 eV)	XUV, X-ray spectroscopy (emission line) VISAR (surface motion during ns, EOS) FDI (reflectivity & phase change)
High Pressure	Optical laser	Shock compression Disorder: dislocation dynamics High strain rate phenomena, shear modulus under compression	VISAR (shock velocity, Pressure, EOS), X-ray Thomson scattering (T_e, n_e, Z) FDI (surface motion) Diffraction (lattice dislocation, strain)

MEC Science

- WDM or High Energy Density Matter by LCLS beam
  - WDM by LCLS beam
    - Heated uniformly and rapidly: constant ρ (isochores), T_e<10 eV
    - Release before hydrodynamic expansion: constant entropy (isentropes)
  - Hot Dense Matter by LCLS pumping
    - Redistribution of population by pumping within a transition : emission line
    - Low density of plasma, high temperature (T_e>100 eV)



- Measurement
  - FDI : The isentropic expansion
  - XUV or/and x-ray spectroscopy : Electron temperature, redistribution of population
  - Diode detector : flux change in transmission, reflection or scattering geometry

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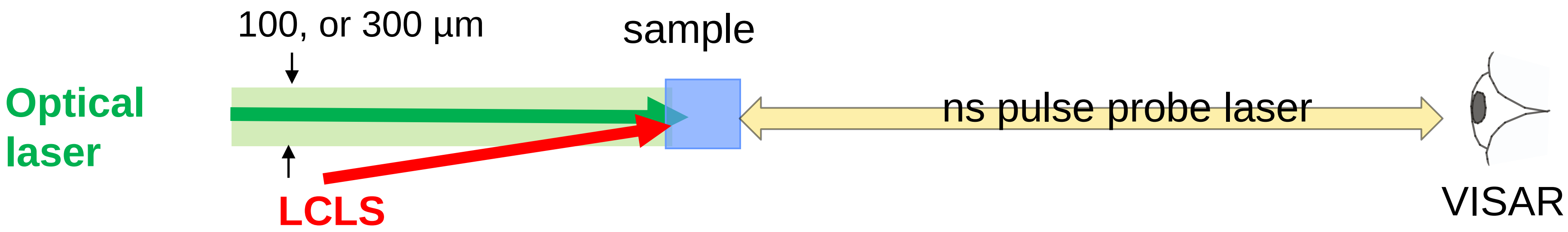
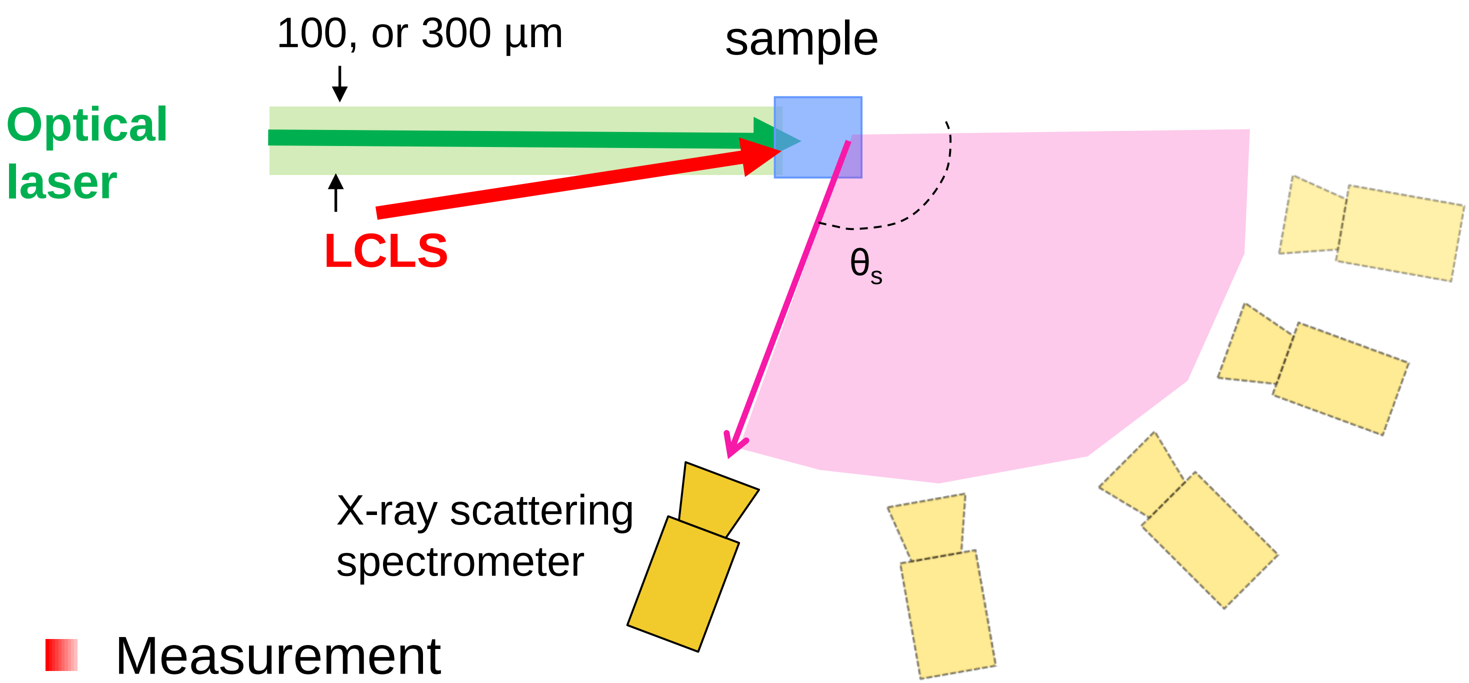
- WDM or High Pressure generated by optical laser
  - WDM by Optical laser
    - Surface velocity



- Measurement
  - VISAR : Shock velocity during nanosecond, equation of state

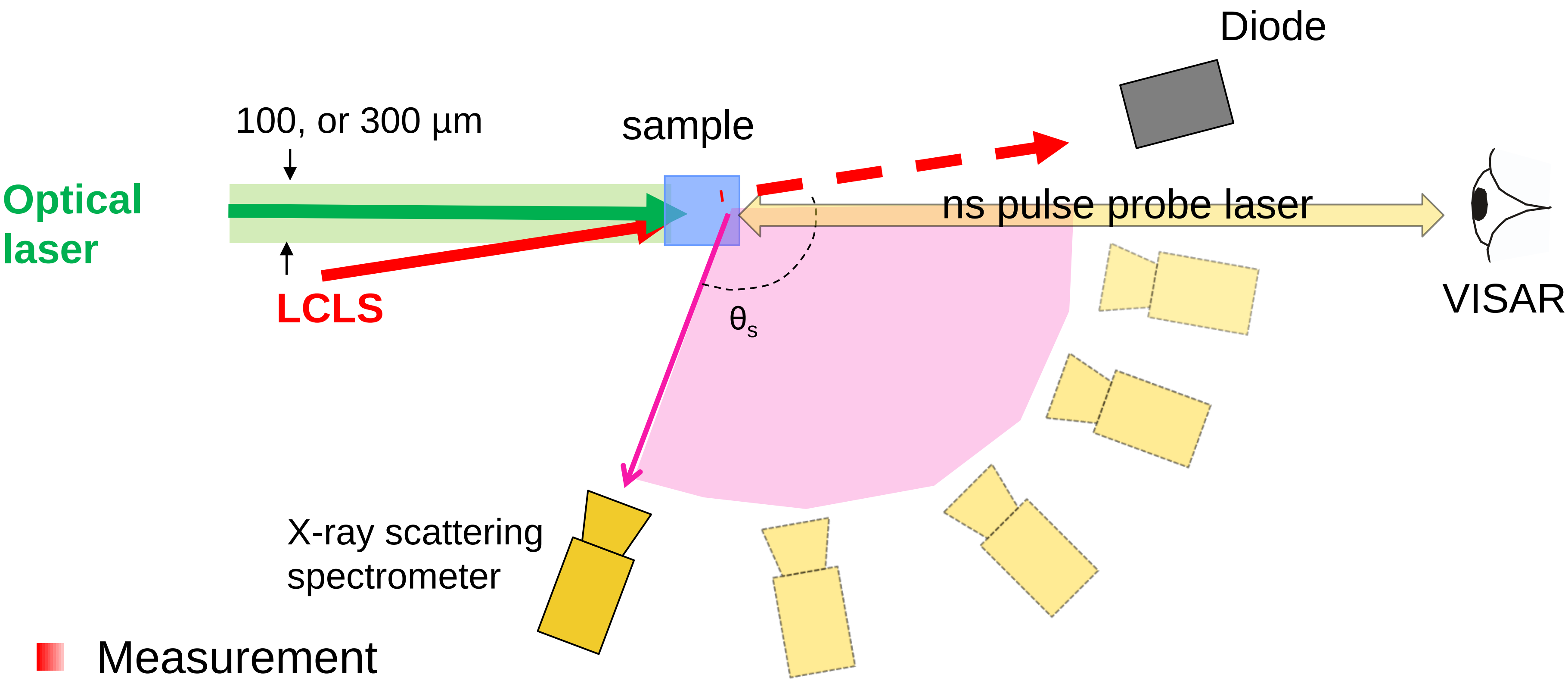
- WDM or High Pressure generated by optical laser
  - High pressure by Optical laser
    - Compression (n_e and T_e, Z)



- Measurement
  - X-ray scattering spectrometer : Electron temperature, density, collisionality

MEC Science

- WDM or High Pressure generated by optical source



- Measurement
  - VISAR : Shock velocity during nanosecond, equation of state
  - X-ray scattering spectrometer : Electron temperature, density, collisionality

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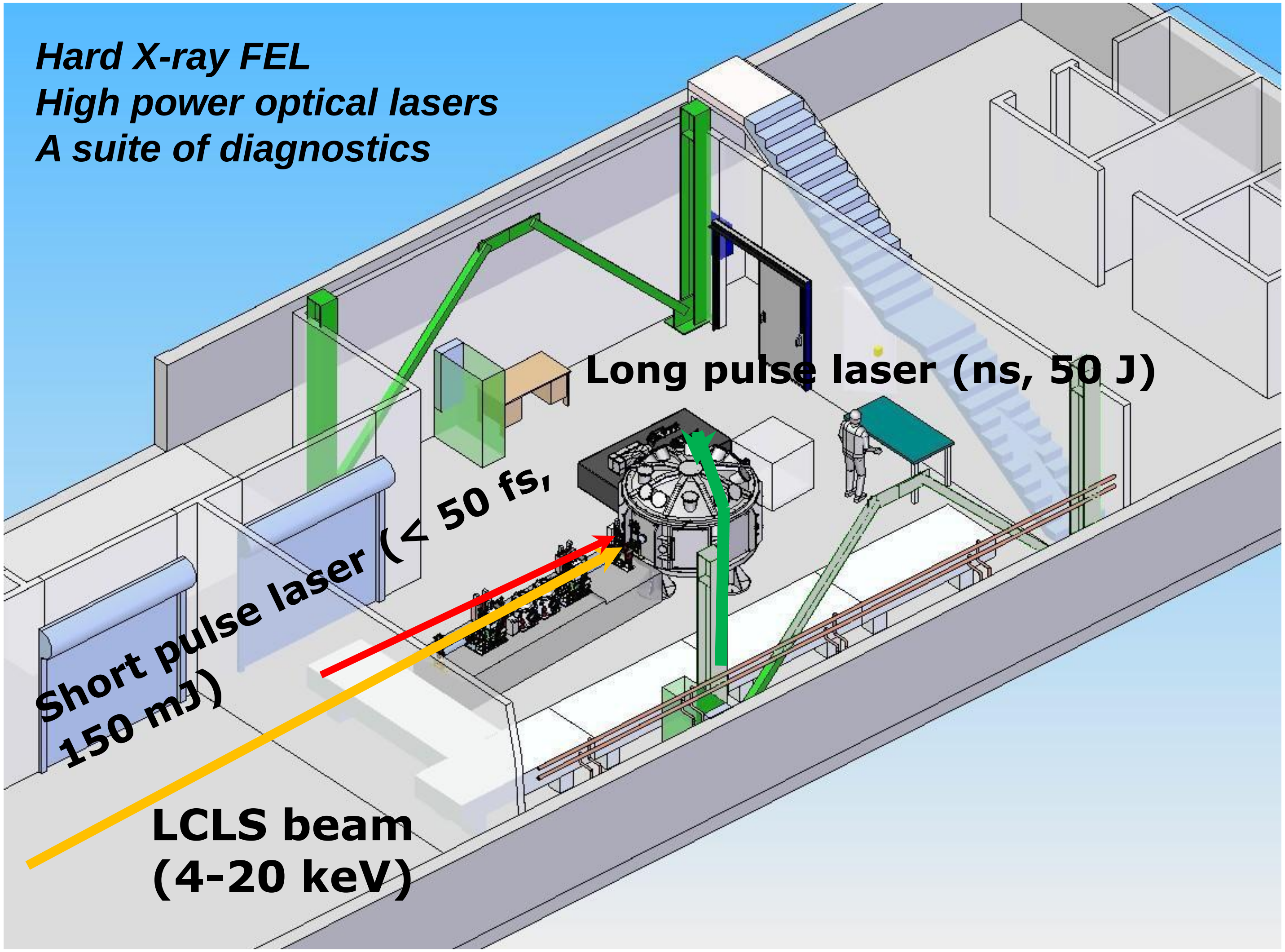
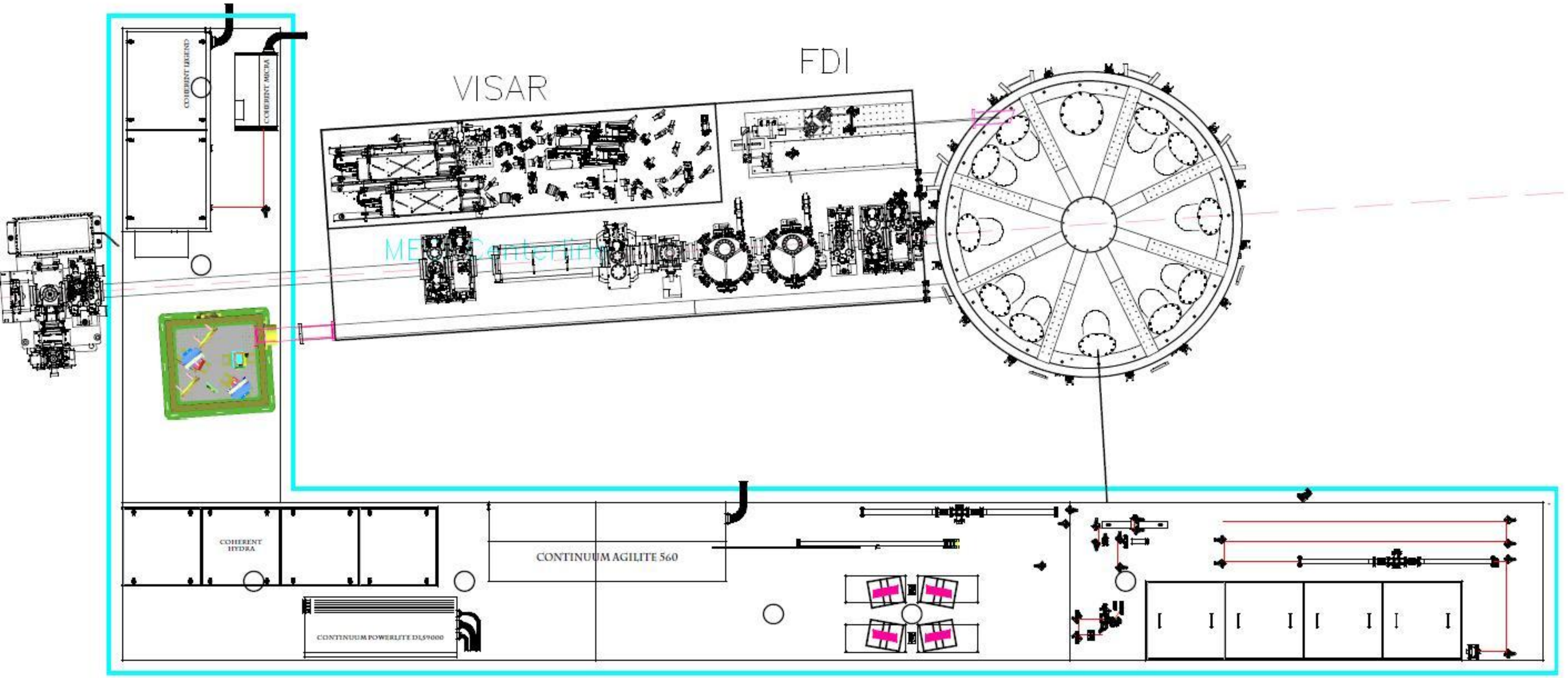
Target Diagnostics in hutch 6

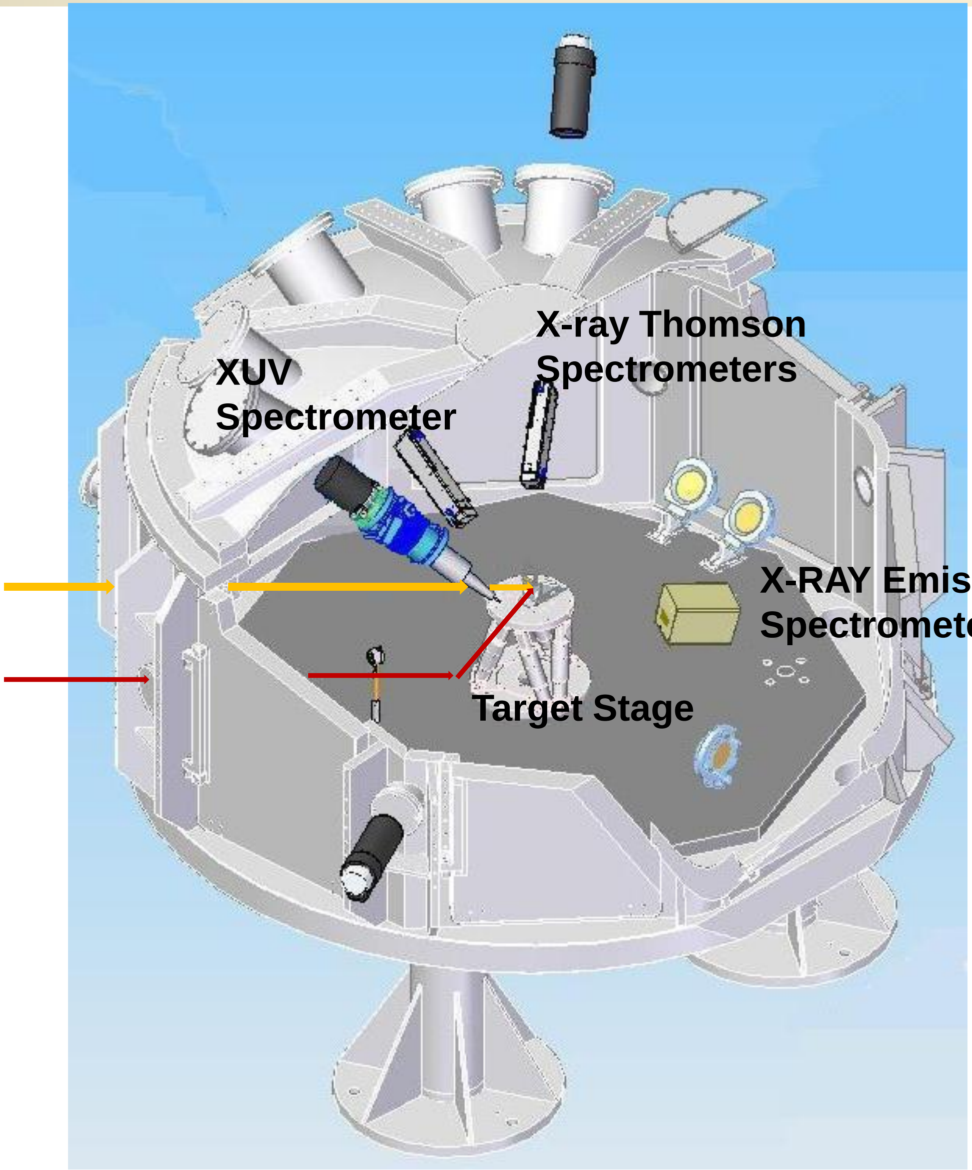
Target Diagnostics provides capabilities to create and measure matter in extreme conditions in various geometries.



Target Diagnostics with target chamber

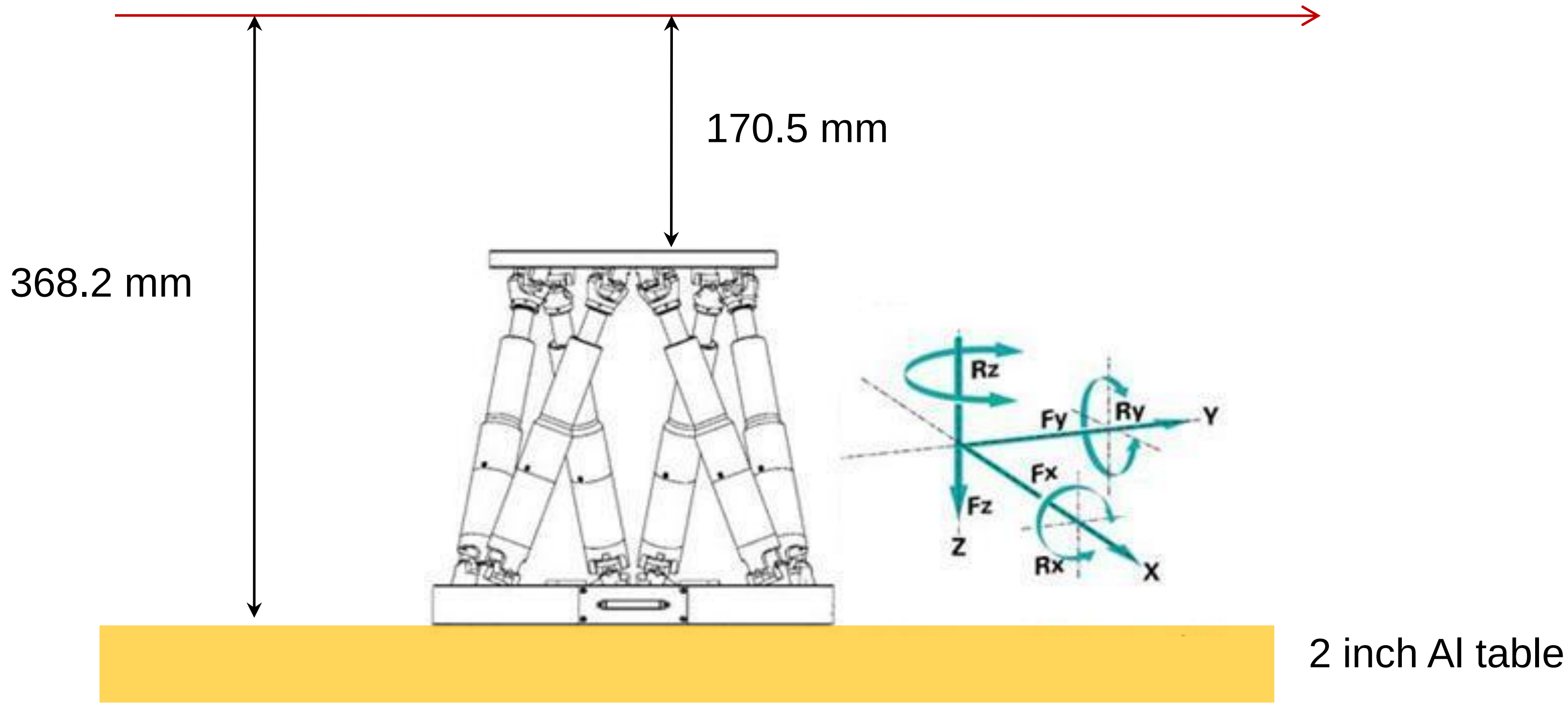


Target Diagnostics with target chamber



Target Stage

LCLS beam: ~ 500 µm without focusing, 0.5 µm with focusing Be lens at center



The MEC Target stage provides 6 degrees of freedom, x, y, z, pitch, yaw, and roll for target alignment.

X, Y: ±25 mm, Z: ±14 mm,
Min. incremental motion: 0.5µm, Max spped: 1 mm/s

X-ray Scattering Spectrometer

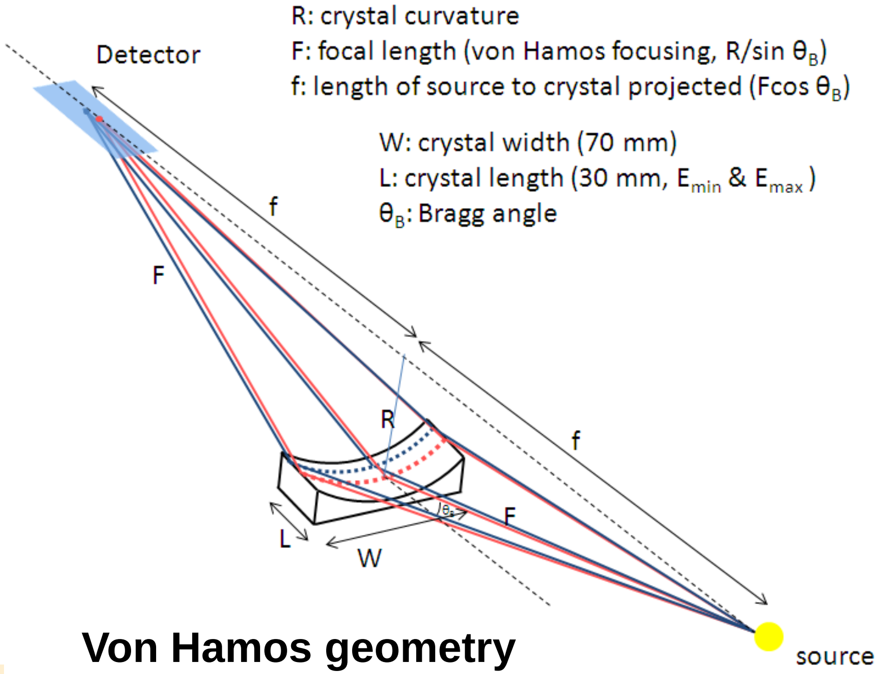
pump	probe	spot size of laser	spot size of lcls	target	target thickness	Detector
Long or short pulse beam	LCLS beam	100-400 μm	50 μm	polycrystalline, single crystal, and liquid jet	< a few 100 μm	Spectrometer + x-ray CCD

Compton and plasmon feature depending on k-vector change

Measure electron density, temperature, and further ionization state of dense matter

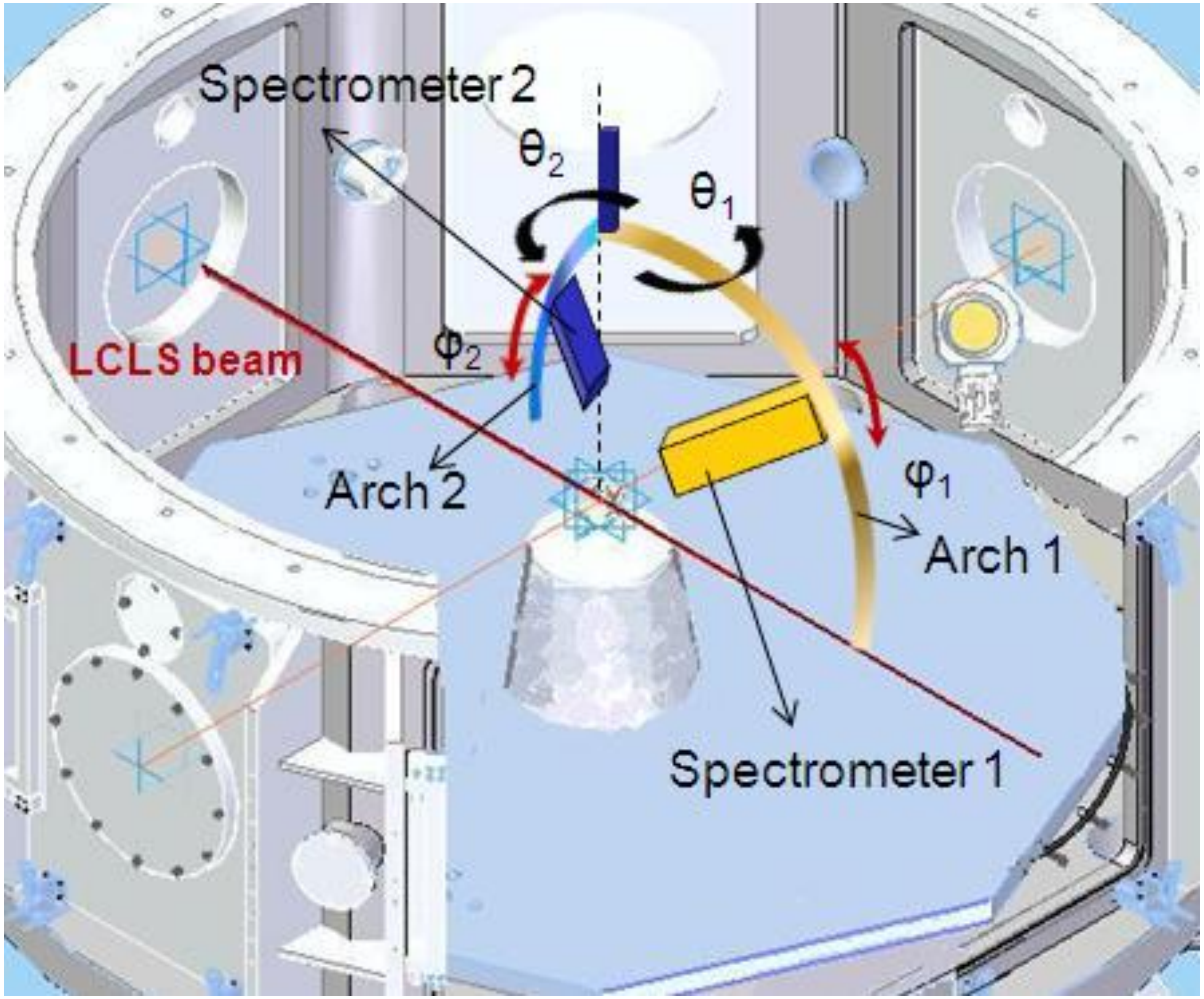
- Specification
  - HOPG spectrometer
    - Available energy range: 4-20 keV
    - Spectral resolution~ $\Delta E/E \sim 3\times10^{-3}$ at 8 keV
  - X-ray detector
    - Readout frame rate: 1 to 10 Hz
    - High quantum efficiency > 80 % at 8 keV
    - Dynamic range $>10^3$
    - Pixel Pixel size: 110 μm

    - Commercial CCD camera
    - 2048x2048 (13.5 or 24 μm)
    - Imaging area 27x27 mm
    - QE>20 % at 8 keV



Von Hamos geometry

X-ray Scattering Spectrometer



X-ray Emission Spectroscopy

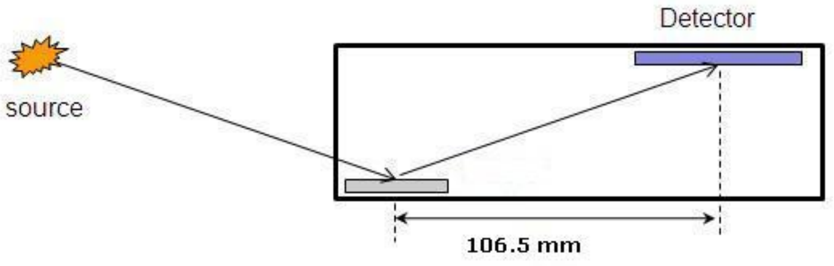
beam	Minimum of spot size	target	target thickness	Detector
LCLS or optical laser pulse beam	0.5 μm	polycrystalline, single crystal, and thin foil	100 nm - bulk	CMOS x-ray detector

X-ray spectrum

Measure K-shell x-ray emission lines and study charge state distribution

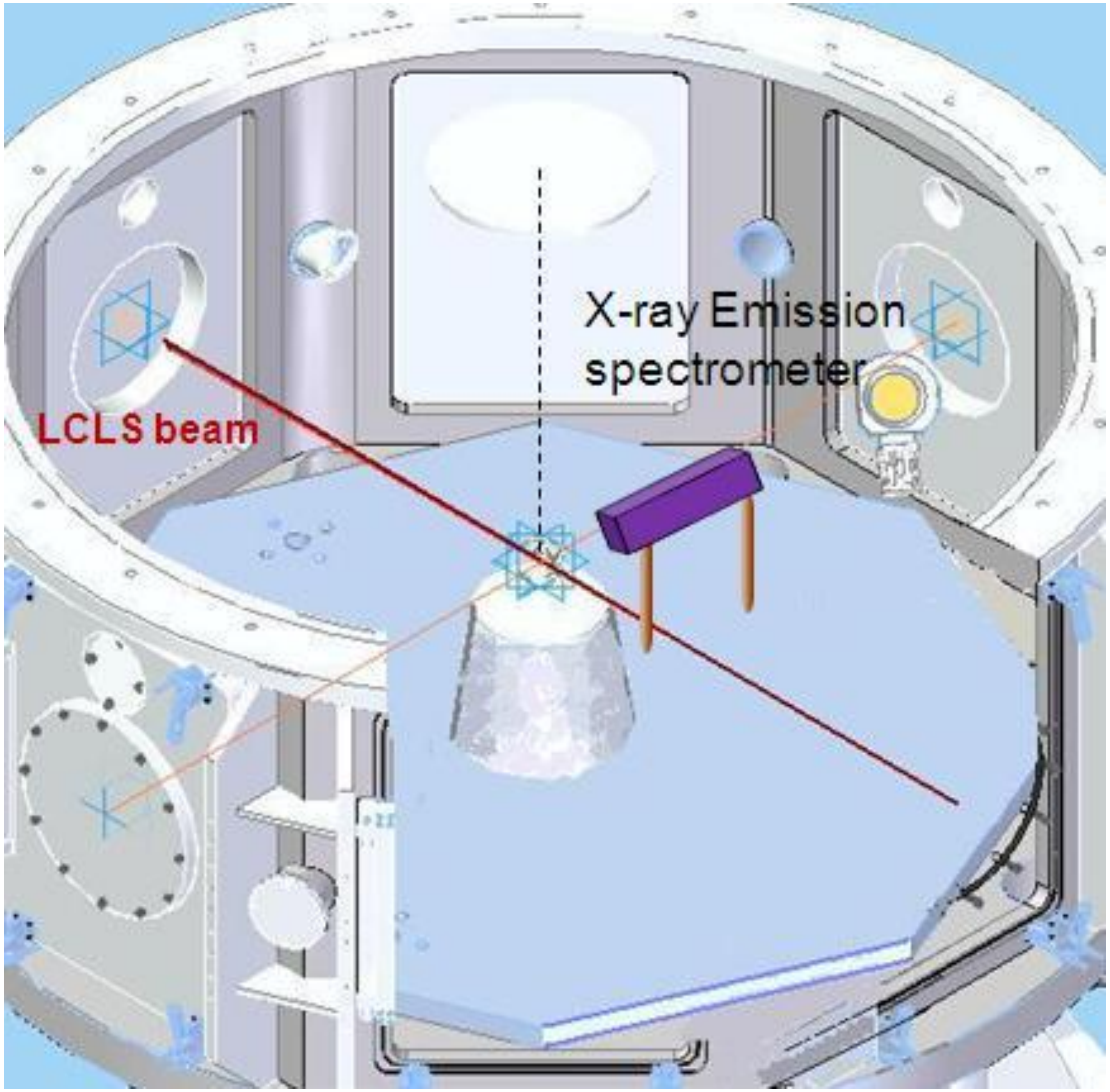
The same geometry with x-ray scattering spectrometer:

Curved crystal, Von Hamos geometry



- Specification :
  - X-ray Emission spectrometer
    Energy range:
    ADP (101)-1.2~13 keV
    Optimize 1.5 keV
    Energy window ~200 eV
    Energy resolution~ 0.4 eV
  - X-ray detector
    the same detector with scattering detector

X-ray Emission Spectroscopy



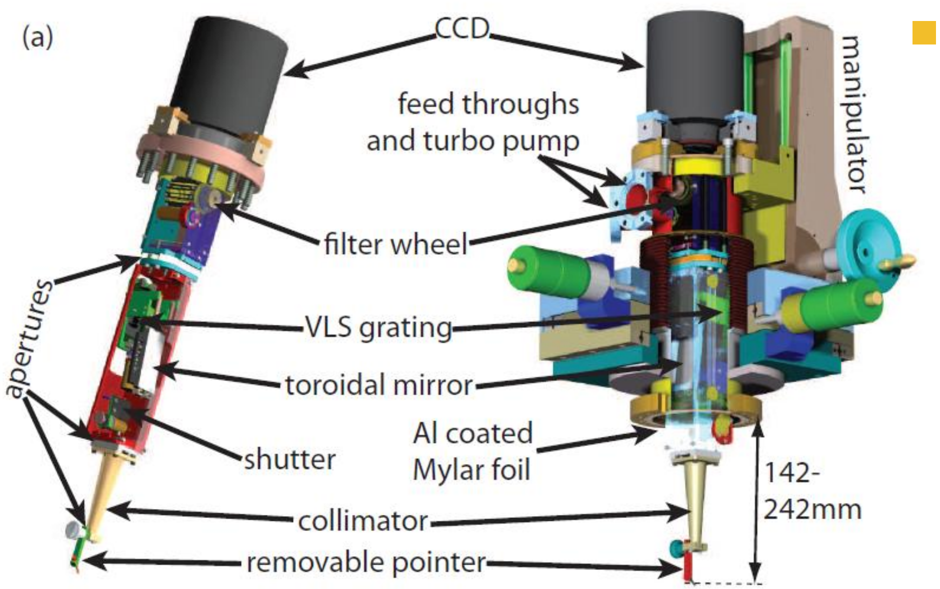
XUV Spectroscopy

Main Components: Toroidal mirror, Gratings, filters, x-ray CCD, manipulator, shielding
Existing design (DESY, NRL)

beam	Minimum of spot size	target	target thickness	Detector
LCLS or optical laser pulse beam	0.5 μm	polycrystalline, single crystal, and thin foil	100 nm - bulk	X-ray CCD camera

XUV spectrum

Measure emission lines and study multiphoton ionization, charge state distribution

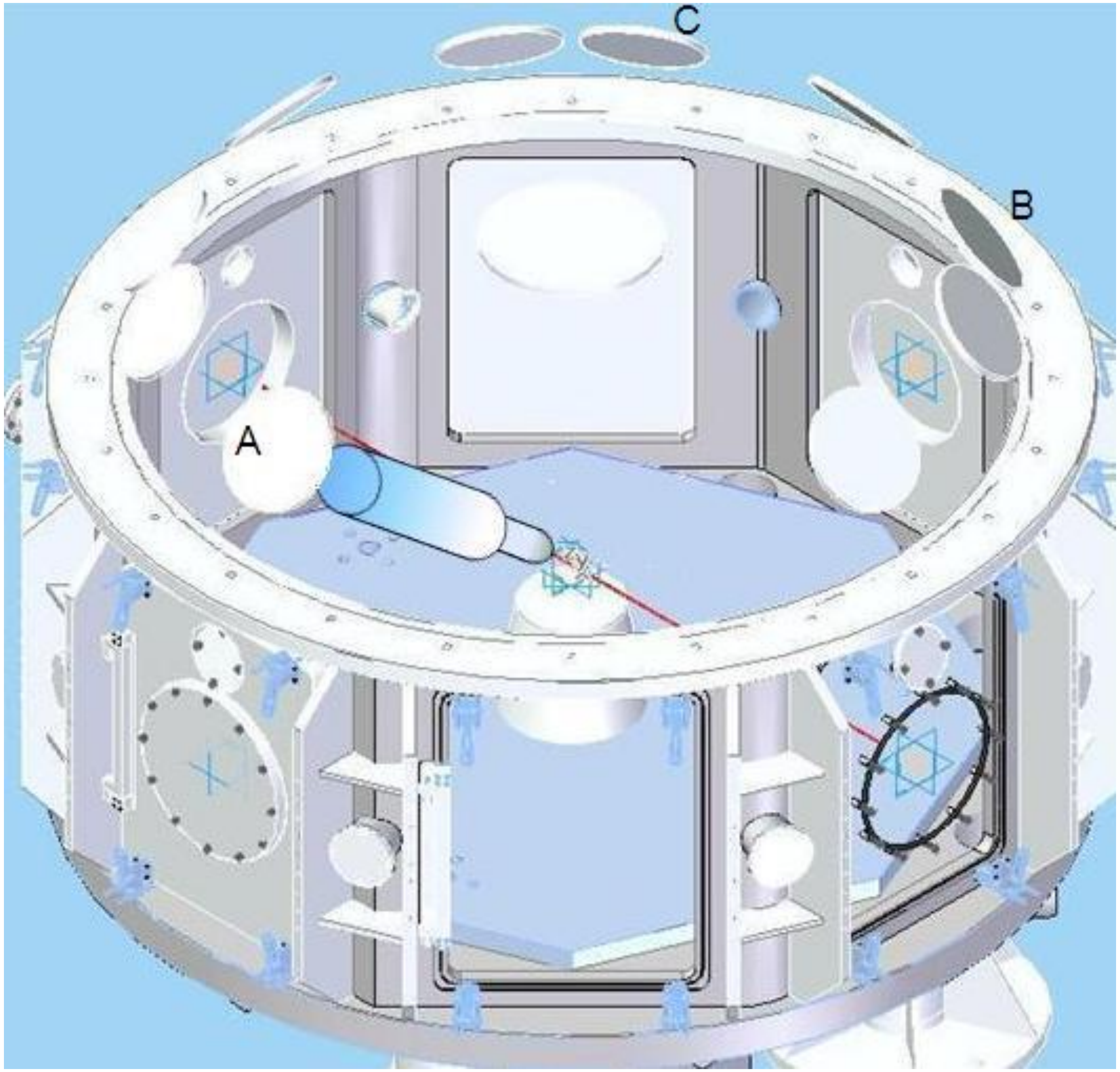


- Specification
  - XUV spectrometer

    Available range: 3-35 nm
    Spectral resolving power~ $\lambda/\Delta\lambda$~300 at 21 nm
  - X-ray CCD camera

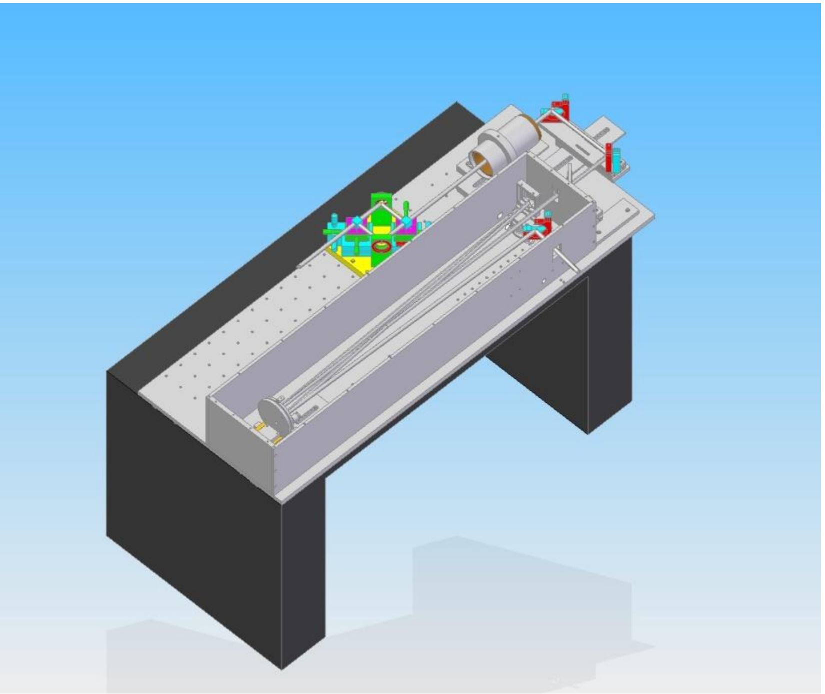
    Readout frame rate: 1 to 10 Hz
    Pixel size: 13.5 μm
    Image area: 27.6x6.9 mm (2048x512)

XUV Spectroscopy



Fourier Domain Interferometer

Main components: short pulse laser probe, Mach-Zehnder Interferometer, Optical spectrometer, CCD camera
Existing design (LLNL, LULI)

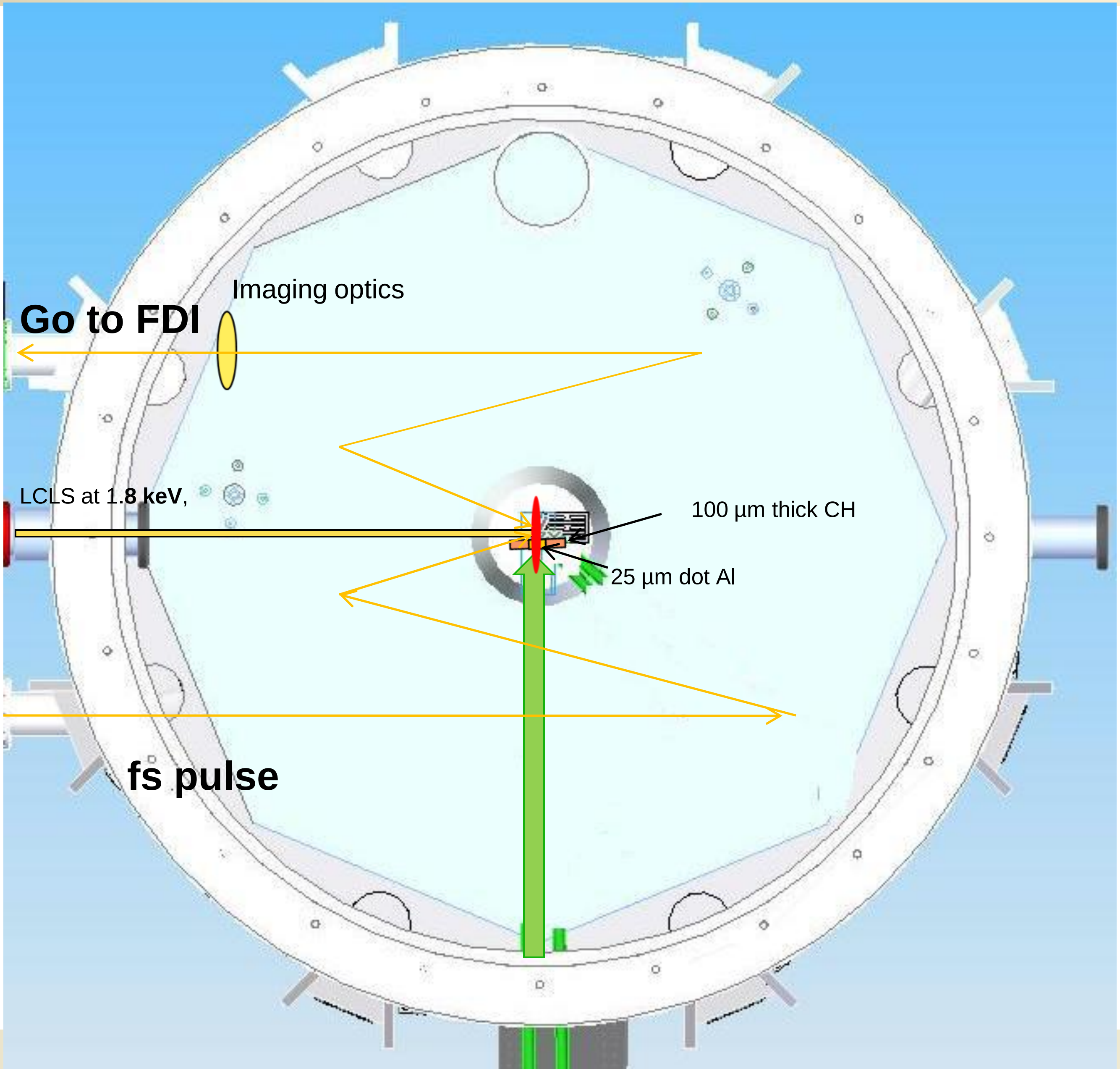


Time resolved measurement of reflectivity and phase shift
Critical surface motion

- Specifications

Time resolution : 40fs
Spatial Resolution: better than 10um
Dynamic range: 500:1
Sensitivity : better 1% of fringe (4Å resolution)

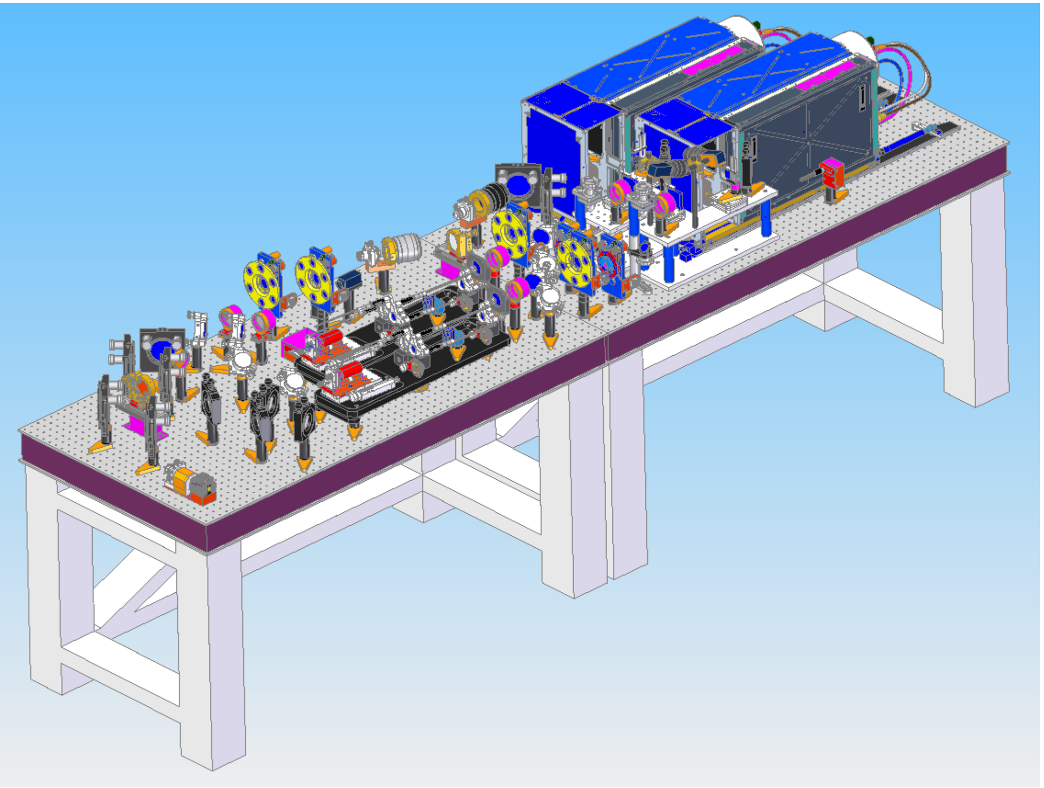
Fourier Domain Interferometer



VISAR

Main components: Agilite 560, Optical streak camera, Mach-Zehnder Interferometer, relay and fiber optics
Existing design (Omega)

Free Surface velocity of shocked or compressed targets, shock wave velocity, shock breakout timing



- Specifications

1 Visar bed
Line Visar
Velocity/Fringe :
0.5 to 20 km/s/fringe
Resolution:
f/3 for 1mm field of view
Field of view: 1-5mm
Dynamic range: 500:1

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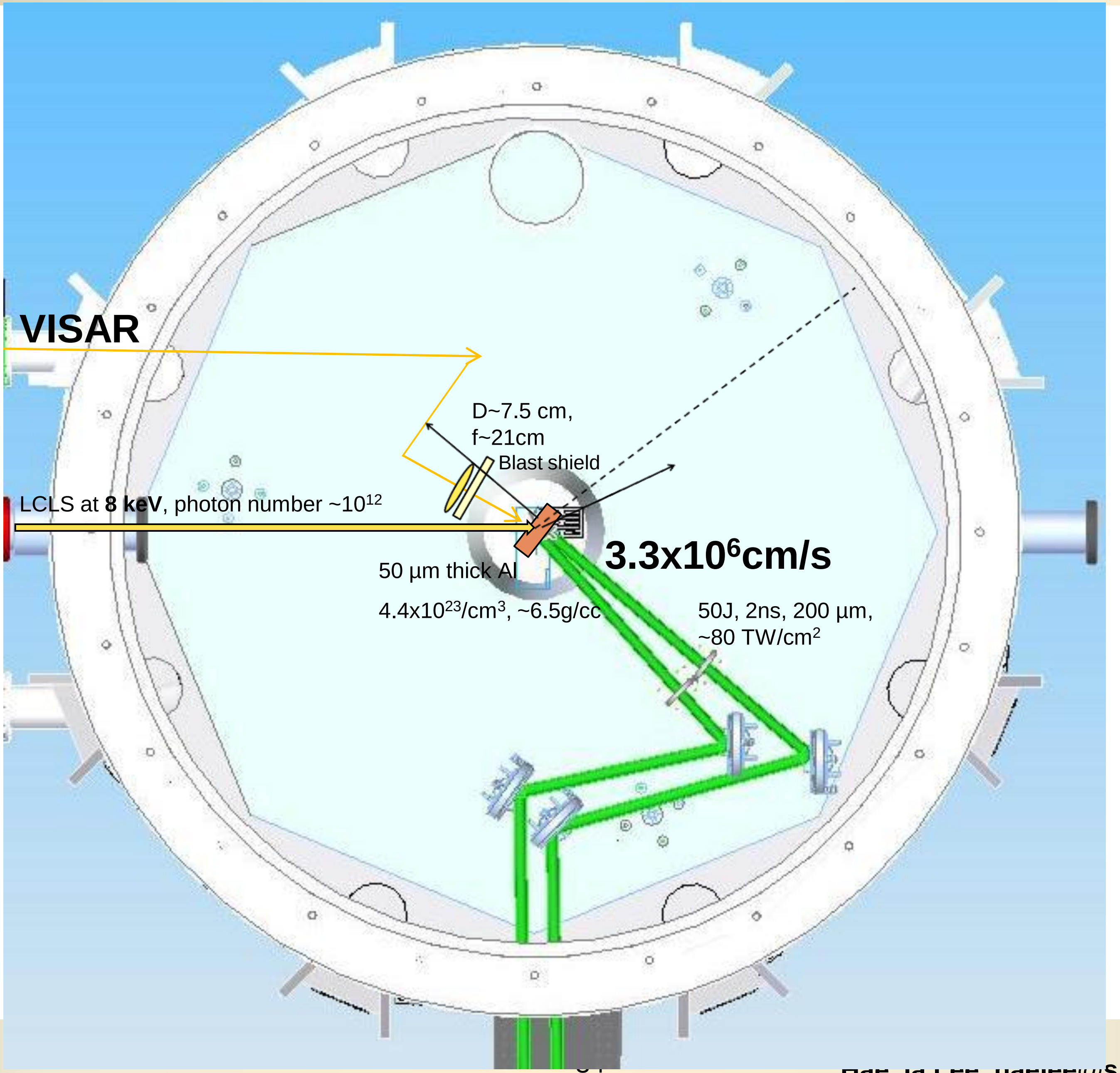
VISAR

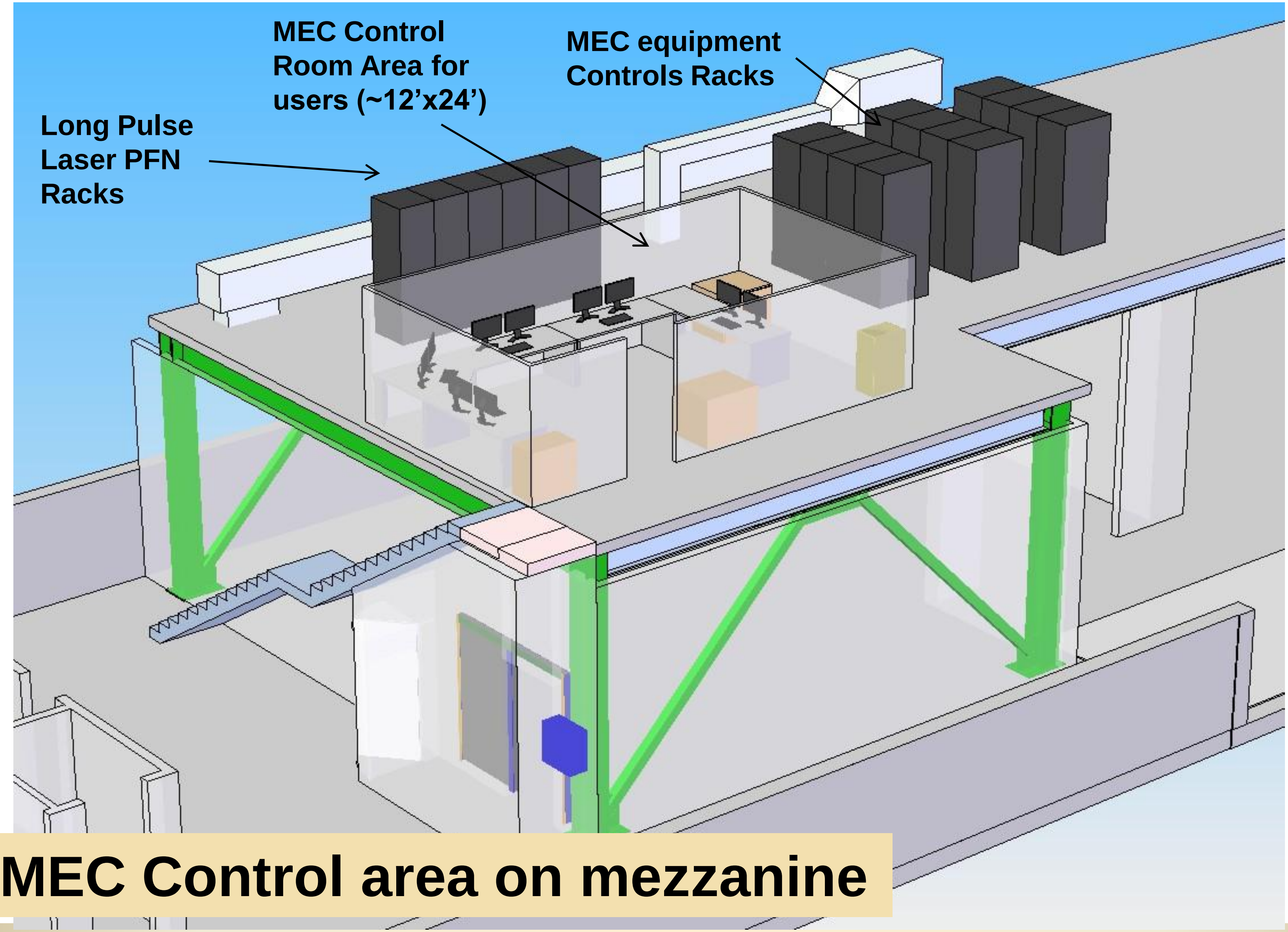


VISAR
D~7.5 cm,
f~21cm
Blast shield
LCLS at **8 keV**, photon number ~10^{12}
$3.3x10^6$cm/s
50 μm thick Al
$4.4x10^{23}$/cm^3, ~6.5g/cc
50J, 2ns, 200 μm,
~80 TW/cm^2

MEC Target Diagnostic

Item	Purpose	Specification
X-ray Thomson Spectrometer	*Measure electron density and temperature*	*Spectral resolution of $\Delta E/E \sim 3\times10^{-3}$ at 8 keV*
XUV spectroscopy	*Study electronic band structures*	*Spectral resolving power of $\lambda/\Delta\lambda \sim 300$ at 21 nm*
X-ray Emission Spectroscopy	*Measure x-ray emission line*	*Spectral resolving power of $\Delta E/E \sim 1\times10^{-3}$ at 1.5 keV*
Fourier Domain Interferometer (FDI)	*Measure surface motion*	*Accurate to $\lambda_{Å}/2000$ for 800 nm probe*
VISAR	*Measure shock velocity*	*Nanosecond time scale*
Diode detector	*Measure flux change of x-ray and optical beams*	*Repetition rate of 120 Hz*
Alignment Diagnostics	*Align and monitor position of sample, optics, and diagnostics*	*Spatial resolution ~ 10 μm*
Target Stage	*Accurately orient and move sample*	*6 degrees of freedom in orientation*

Project Description – Hutch Facilities



MEC Control area on mezzanine

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Summary

- The unique strength of MEC instrument
  - LCLS beam : intense x-ray, short pulse, coherent, and tunable (4-20 keV)
  - MEC Laser system : 35fs/150mJ/800nm, 2-20ns/2x25J/527nm
  - Target Diagnostics : provide cutting edge research capabilities of warm dense matter, high energy density physics and high pressure

    Shock velocity (5×10^4-5×10^6 cm/s), surface motion (4Å resolution)
    Temperature (0.1-2000 eV)

- MEC Instrument Target Diagnostics are based on proven design developed at LLNL, LULI, LANL, NRL and DESY.

End of Presentation