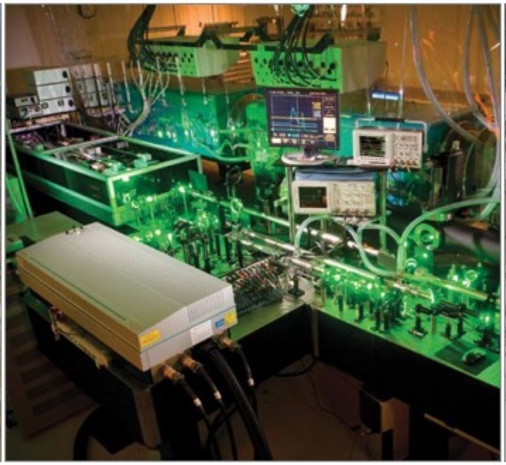
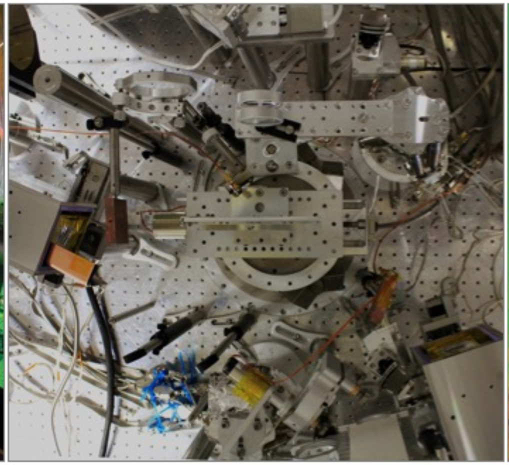
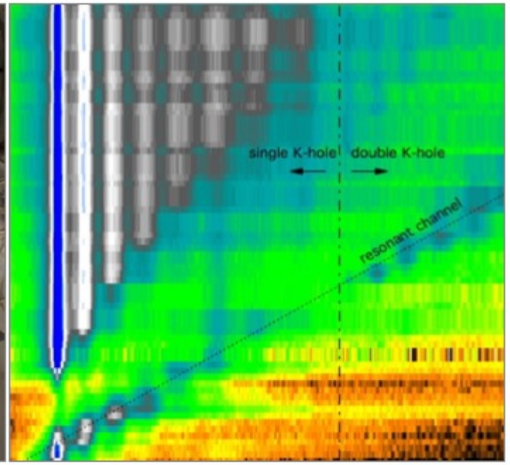
High Energy Density Physics with Extreme Light







Byoung-ick Cho

Dept. Physics & Photon Science, GIST

SNU Physics Colloquium **11/18/2015**

Acknowledgement

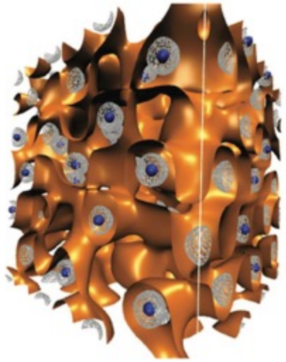
- GIST: Leejin Bae, Jongwon Lee, Minju Kim, Young Hoon Kim, Minsang Cho, Jaehyung Chung
- CoReLS - IBS : Chang Hee Nam and CoReLS members

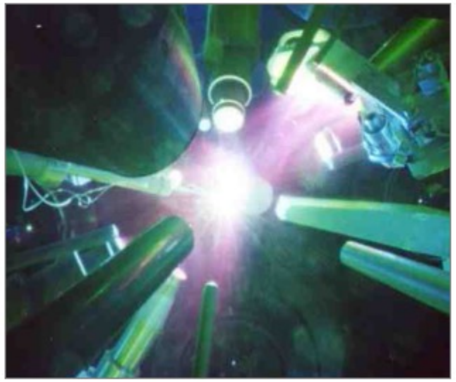
- ALS / UC Berkeley : Roger Falcone, Richard Lee
- LCLS : Philip Heimann, Hee Ja Lee, Bob Nagler
- LLNL : Tadashi Ogitsu, Alfredo Correa, Yuan Ping

- Oxford: Justin Wark, Sam Vinko, Orlando Ciricosta
- Univ. Bordeaux/CEA: Jerome Gaudin, Fabien Dorchies

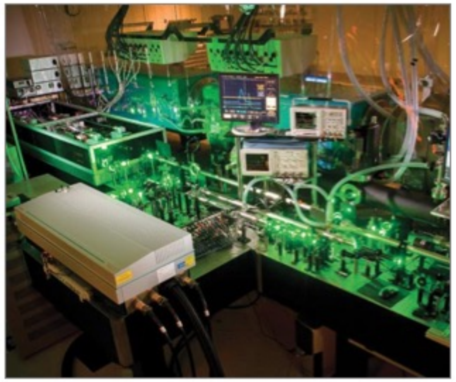
Contents

- **What is HEDP?**

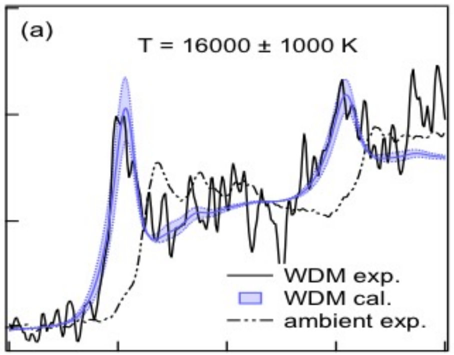


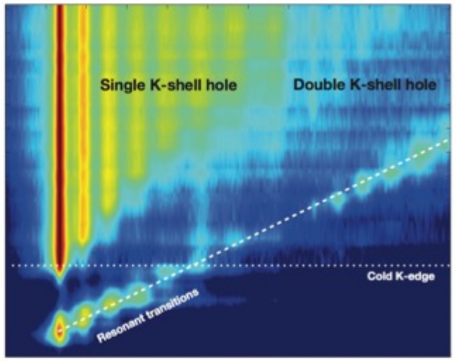


- **Extreme Light:**
  X-ray Free electron laser & High power laser



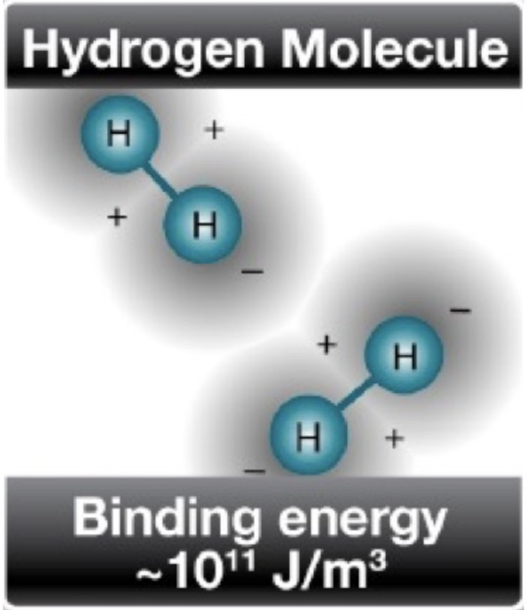
- **Ultrafast X-ray spectroscopies**
  for IPD, x-ray transmission,
  el-ph coupling of HED matters, etc





High Energy Density Physics (HEDP) can be defined as study of matter at energy density ~ 10^{11} J/m^3

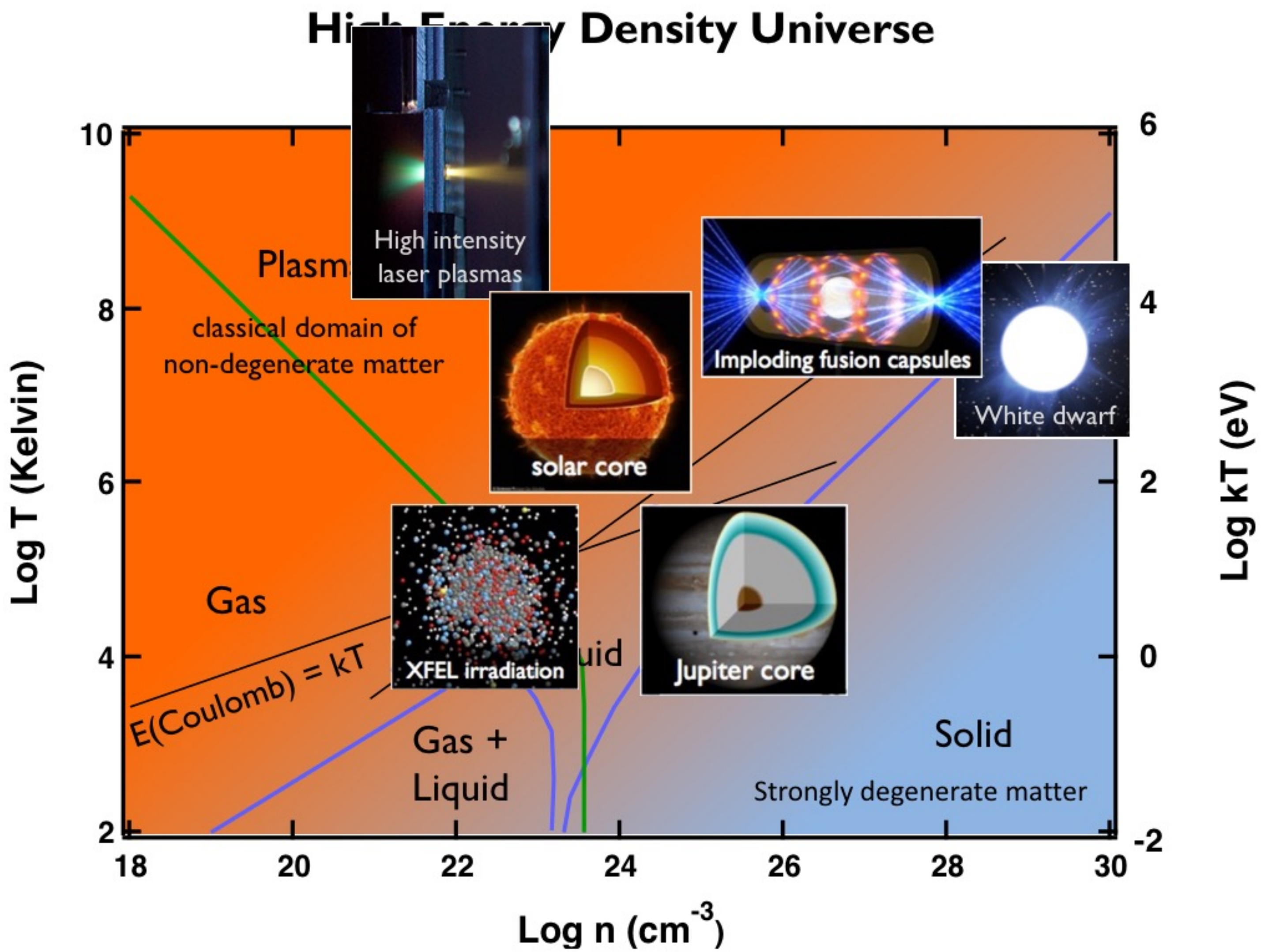
HED conditions



Energy density parameters corresponding to ~ 10^{11} J/m^3	**Values**
Pressure	1 Mbar
Electric field strength	1.5×10^{11} V/m
Magnetic field strength	5×10^{2} T
Laser intensity at 1 μm wavelength	4×10^{12} W/cm^2
Blackbody radiation temperature	75 eV

Frontiers in High Energy Density Physics - The X-Games of Contemporary Science
(National Academies Press, 2003)

HED condition is prevalent throughout the Universe

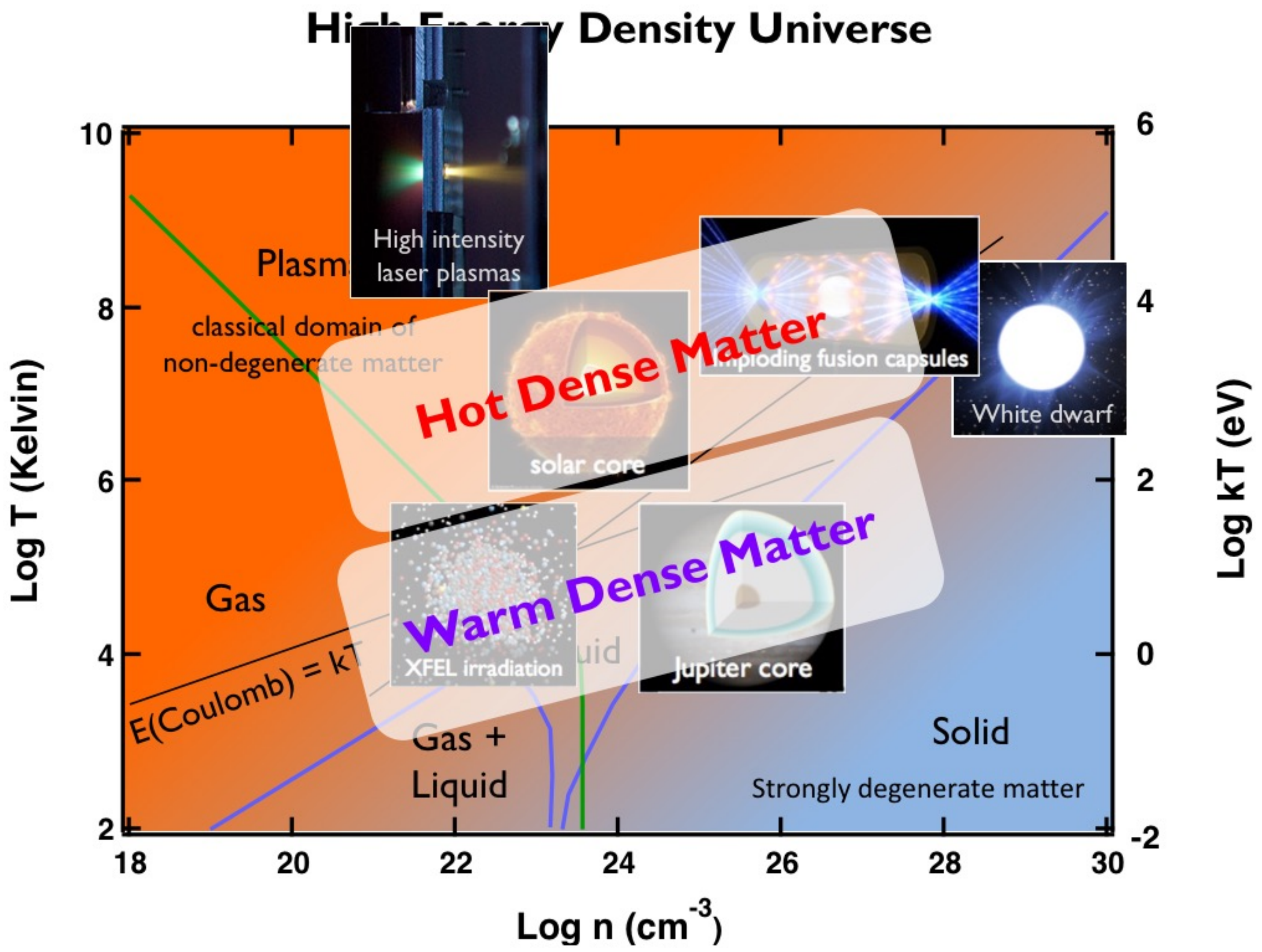


Basic Research Needs for High Energy Density Laboratory Physics, DOE Office of Science and NNSA (2010)

Frontiers in High Energy Density Physics - The X-Games of Contemporary Science (National Academies Press, 2003)

Byoung-ick Cho, bicho@gist.ac.kr

The complicated interplay of the physical processes creates a malfunction junction for description of states between solid and plasmas

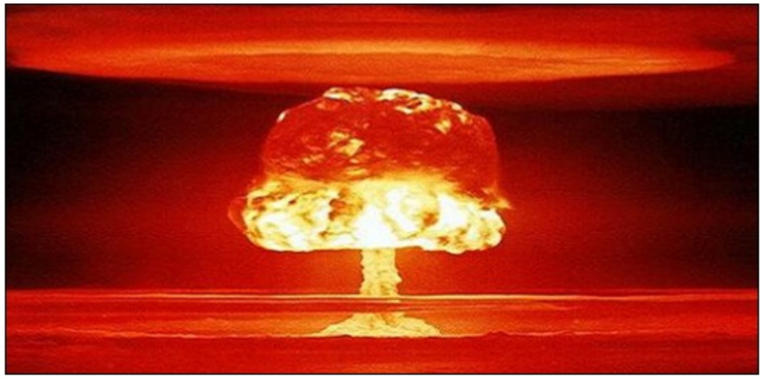


Basic Research Needs for High Energy Density Laboratory Physics, DOE Office of Science and NNSA (2010)
Frontiers in High Energy Density Physics - The X-Games of Contemporary Science (National Academies Press, 2003)

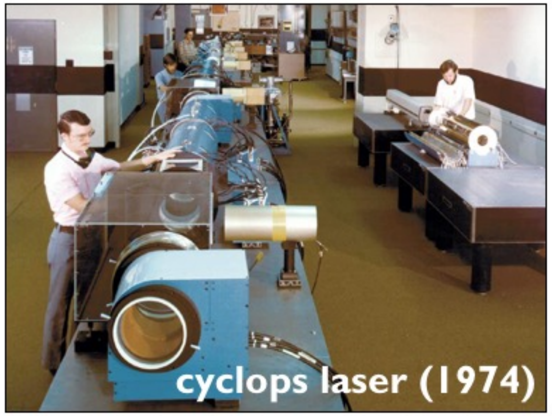
Precursors to high energy density physics

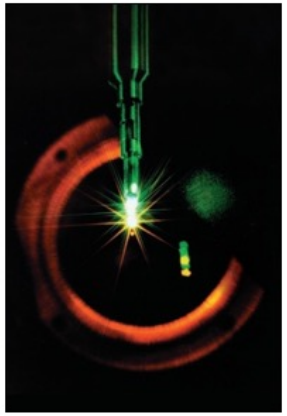
- **First half 20th Century: Stellar structure**
  - Eddington, Chandrasekhar, Schwarzschild, among others

- **Mid-20th Century: Nuclear weapons**
  - Oppenheimer, Sakharov, Teller, Bethe, Fermi, others: Compressible metals
  - Zel'dovich and Raizer: Physics of Shock Waves and High Temperature Phenomena (1966)



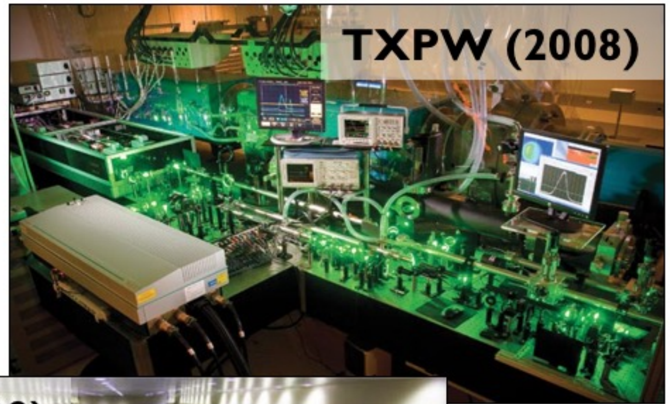
- **Post Mid-20th Century (1960-1980): Inertial confinement fusion origins**
  - Lawrence Livermore National Lab

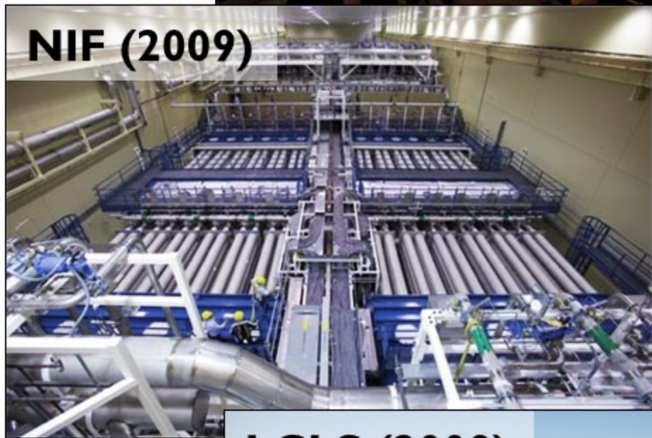




Post 1980s: Extreme light in the laboratory
Complex quantitative *physics* experiments became feasible

- **1984: Chirped Pulse Amplification**
  - *Gerard Mourou and Donna Strickland*
- **1990s: Tabletop Terawatt class lasers**
  - *10^{12} Watt in laboratories, <100 fs pulses*
- **late 2000s: Petawatt lasers**
  - *10^{15} Watt, U.Texas, GIST, etc*
- **2009: National Ignition Facility (NIF)**
  - *LLNL*
- **2009: X-ray free electron laser**
  - *LCLS @ SLAC, 10^9 brigher than any other x-ray sources*



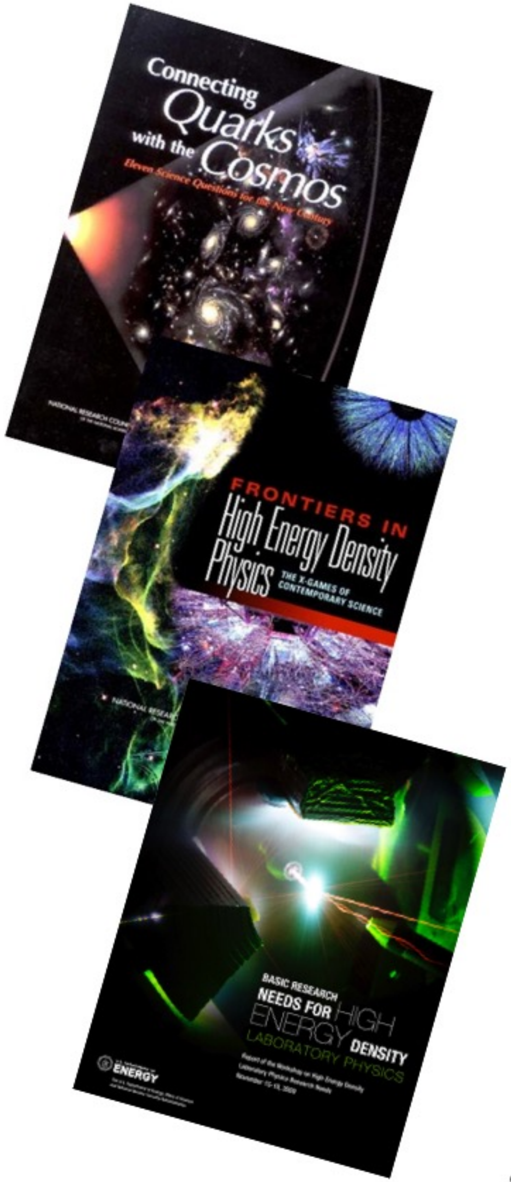


21st centry: HEDP as a discipline

- **1995: 1st comprehensive report on HEDP (energy density > 10^{11} J/m^3)**
  - *Science on High Energy Lasers* (Lee, Petrasso, & Falcone)

- **2003: Two NAS reports highlighted HEDP**
  - *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*
  - *Frontiers in High Energy Density Physics: The X-Game of Contemporary Science*

- **2009,10: DOE reports for HED experiments**
  - *Advancing the science of High Energy Density Laboratory Plasma*
  - *Basic Research Needs for High Energy Density Laboratory Physics*

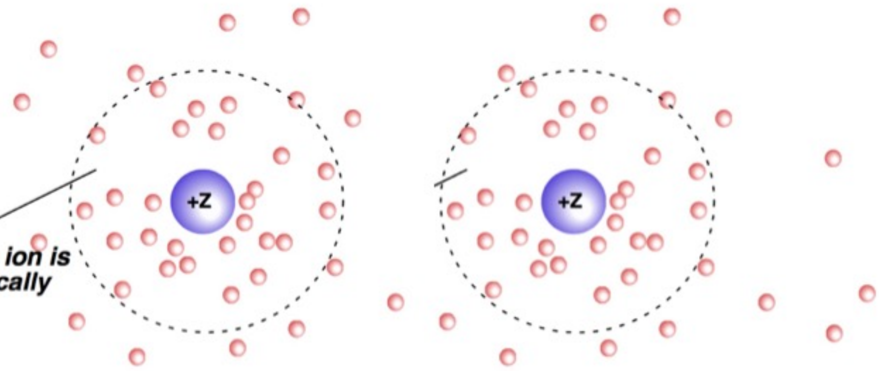


From a "plasma point-of-view", HED matter can not be described by classical, two-body interactions

Debye length

$$\lambda_D = \sqrt{\frac{kT_e + kT_i}{4\pi e^2 Z n_o}}$$

Distance over which an ion is a plasma is electrostatically shielded by electrons



Plasma pamater

$$\Lambda_p = \frac{1}{\sqrt{Z n_o}}\left(\frac{kT_e}{4\pi e^2}\right)^{3/2}$$

# of e- within a sphre with radius of the Debye legnth

Strong coupling parameter

$$\Gamma = \frac{V_{ii}}{k_B T} = \frac{Z^2 e^2}{r_o k_B T}$$

Ratio of the interaction energy between particles V_{ii} to the kinetic energy T

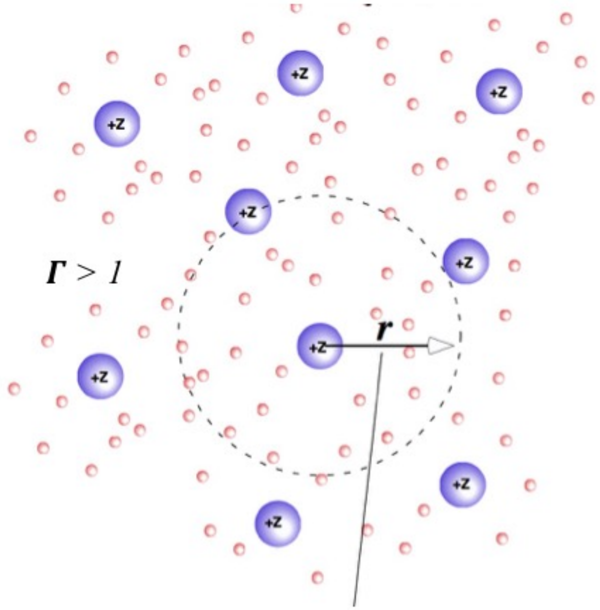
Tokamak plasma	HED plasma
$kT_e = 10\ keV$	$kT_e = 100\ eV$
$n_e = 10^{14}\ cm^{-3}$	$n_e = 10^{22}\ cm^{-3}$
$\Lambda_p = 4 \times 10^7$	$\Lambda_p = 4$
$\Gamma << 1$	$\Gamma > 1$

Some cases, $\Lambda_p < 1$

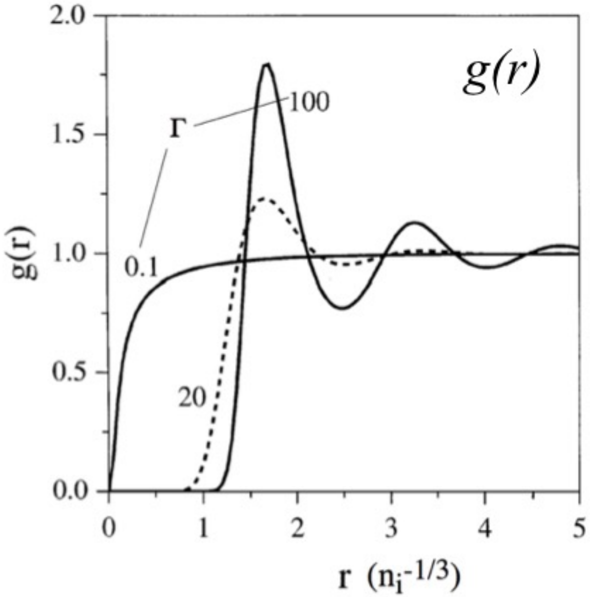
Classic Cluster expansion (BBGKY hierarchy) leading to usual kinetic equations (Vlasov; Fokker Plank) is not valid

Quantum degeneracy effects & ion correlation can become important in some HED matter

Coulomb force lead to correlations in radial position



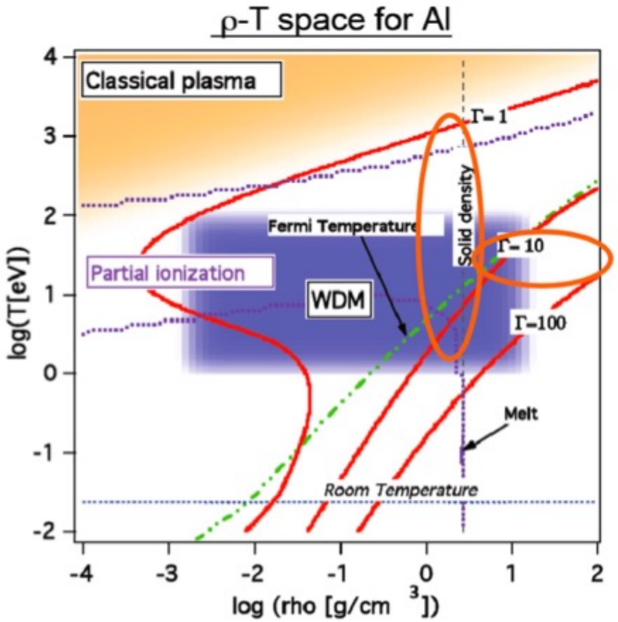
Radial distribution function of ions
g(r) : prob of finding ion at radius r



Reproduced from Murillo and Weisheit Phys. Rep. 302, 1 (1998)

Too far from ground state

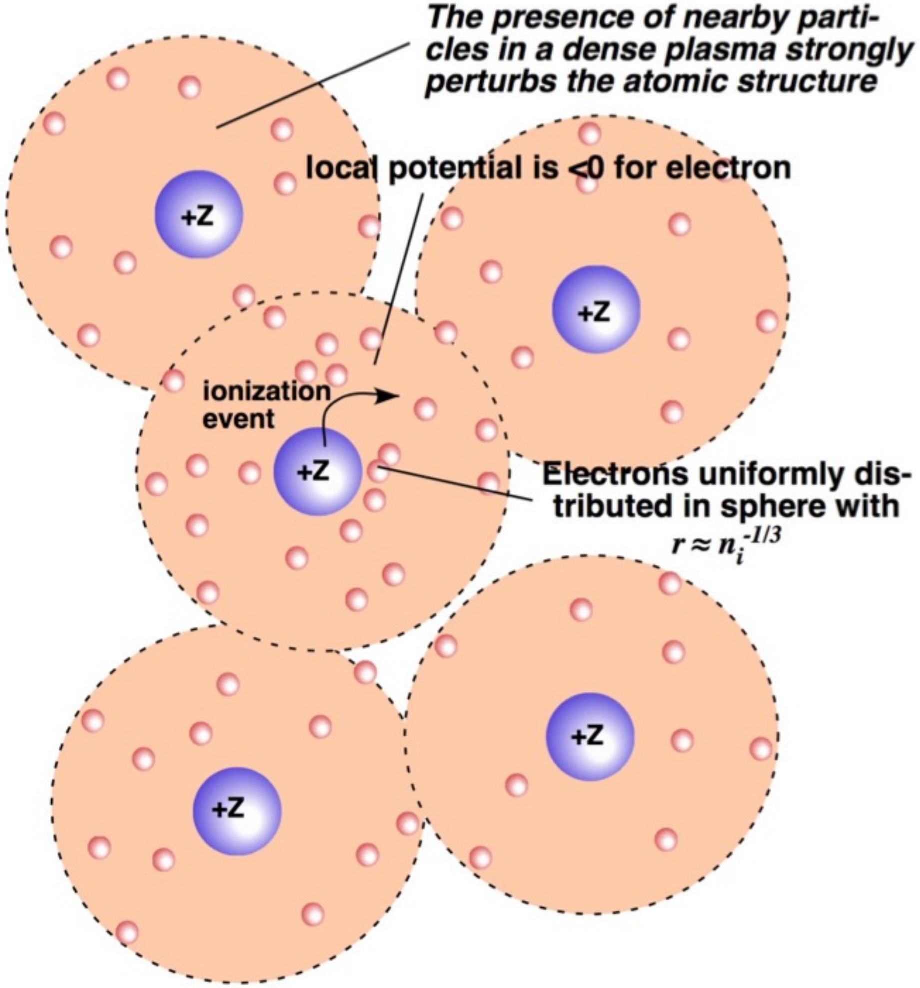
$kT \sim E_F$



A strongly coupled plasma will exhibit ion correlations and structure akin to solid ~ liquid

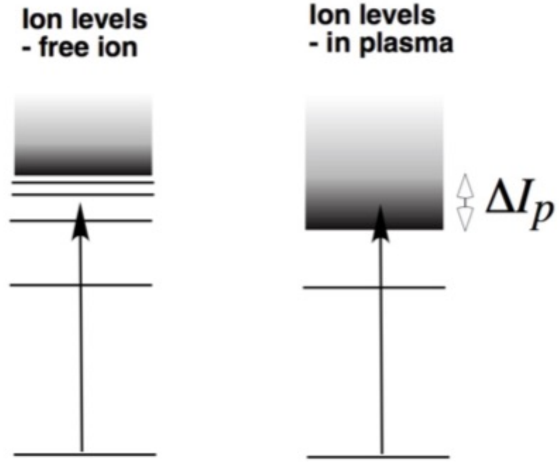
At solid density, Fermi energy is ~ 10 eV. Many HED matter have temperature in this vicinity, mandating a QM treatment of the plasma

A significant question in dense plasmas is the extent to which the ionization potential of the ions is altered

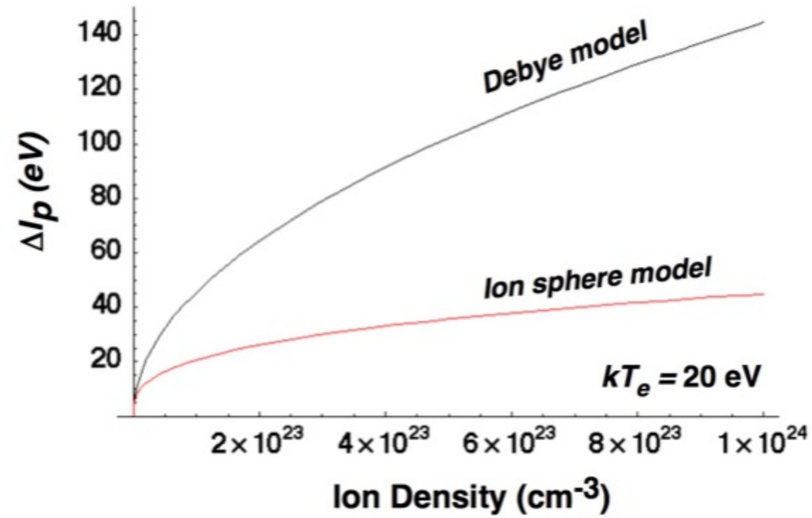


effective energy needed for ionization is lowered

One significant effect is the lowering of the ionization potential: "Continuum lowering"



Continuum lowering predictions with a Saha model for ionization



Ionization models do not converge in the HED plasma regime

Saha equilibrium equations for ion charge states

- Low to moderate density
- High temperature

$$\frac{n_e n_Z}{n_{Z-1}} = 2\frac{W_Z(T)}{W_{Z-1}(T)}\left(\frac{m_e k T_e}{2\pi\hbar^2}\right)^{3/2} \exp\left[-\frac{I_p^{(Z-1)} - \Delta I_p^{(CL)}}{kT_e}\right] \qquad n_e = \sum_{j=1}^{Z_{nuc}} n_j$$

"Average Atom" picture based on Thomas Fermi Model

- High density
- Low to moderate temperature

$$\frac{d^2\chi}{dr^2} = \frac{4}{3\pi\hbar^3}(2m_e e^2)^{3/2}\frac{Z^{1/2}}{r^{1/2}}\chi^{3/2}$$

These models are complicated by many other factors

Co-existing constituents in a dense plasma:

- Ions
- Neutrals
- Negative ions — Electron affinity of Au: 2.3 eV
- Dimers — Bond strength of Al_2: ~ 5 eV
- Negatively charged dimers

When steep temperature gradients exist in hot dense plasmas, the heat transport becomes nonlocal

Moderate temperature plasmas/soft temperature gradients:

The heat flux is given by a local formula

$$\longrightarrow Q_{Diffusive} = \kappa_{SH} \nabla T_e$$

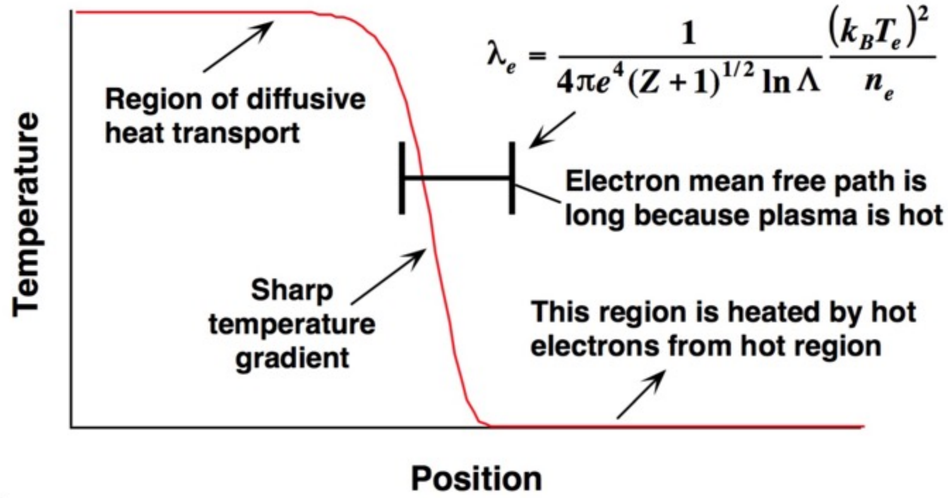
Spitzer-Härm conductivity

Sharp gradients: heat flux exceeds the maximum possible free streaming flux

$$\longrightarrow Q_{\max} = {}^{3}\!/_{2}\, n_e k_B T_e v_{therm}$$

electron thermal velocity

When the mean free path of electrons exceeds the temperature gradient, standard diffusive heat transport breaks down



Heat transport in a sharp gradient: Nonlocal heat flux formula

$$q_{nonlocal}(x) = \int q_{Spitzer}(x') G(x,x') dx' \longrightarrow G(x,x') = \frac{1}{2\lambda_e} \exp\left[-\frac{|x-x'|}{\lambda_e} \right]$$

Typical form of kernel $G(x,x')$*

*Luciani, Mora, and Virmont, Phys. Rev. Lett. 51, 1664 (1983)

In many HED plasmas:

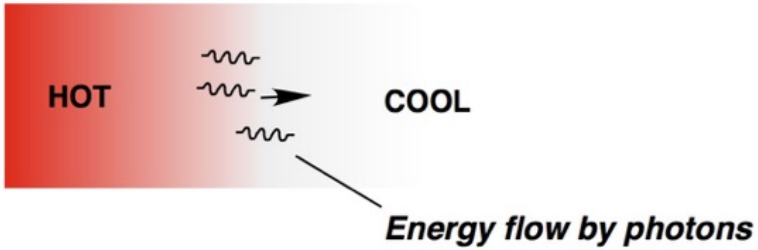
$T_e \sim 10 - 100$ eV

$n_e \sim 10^{21} - 10^{23}$ cm^{-3}

$\delta x \sim 1 - 100\ \mu m$

$\lambda_e \sim 1 - 10\ \mu m$

Radiation energy flow in HED plasmas is an extremely complex phenomenon



Radiative heat flux

Rossland Mean Free Path: effective photon propagation distance

$$\mathbf{Q}_{rad} = -16\frac{\sigma_{SB}\lambda_R T^3}{3}\nabla T$$

$$\lambda_R = \frac{15h^5}{4\pi^4 (k_B T)^5}\int_0^\infty \lambda(\nu)\frac{\nu^4 e^{-h\nu/k_B T}}{\left(1-e^{-h\nu/k_B T}\right)^3}d\nu$$

Photon frequency-dependent mean free path

Photon Absorption Mechanisms

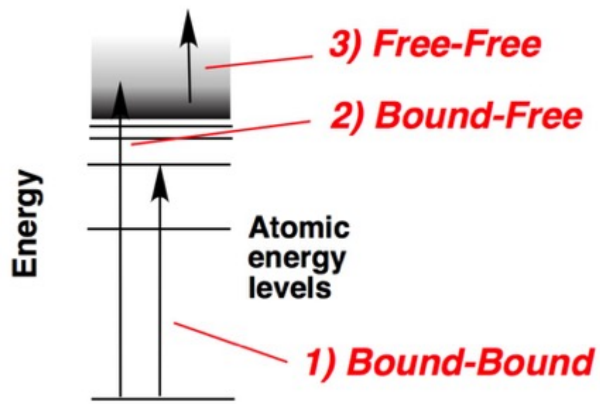
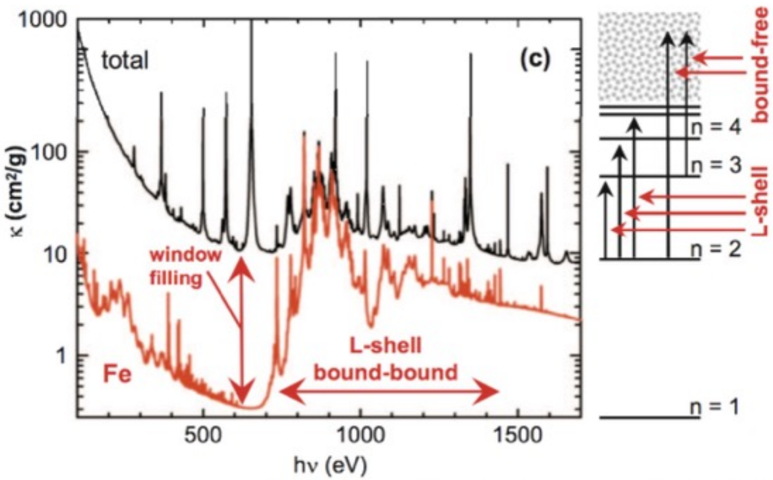


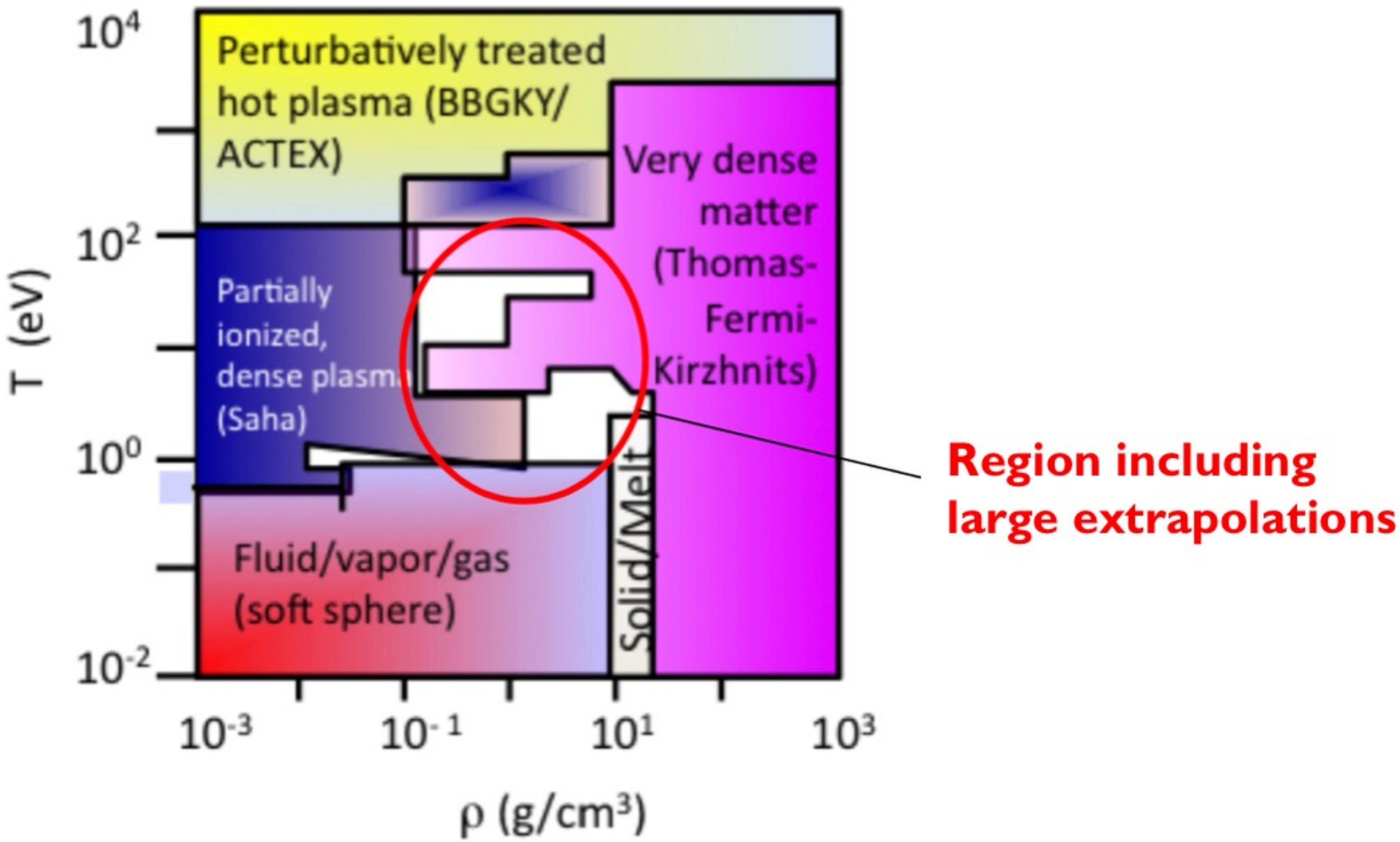
Photo-absorption spectrum of dense Fe



J. E. Bailey et al. Phys. Plas. **16**, 058101 (2009)

The common theoretical practice is to piece together many different models in the Warm, Hot Dense Matters

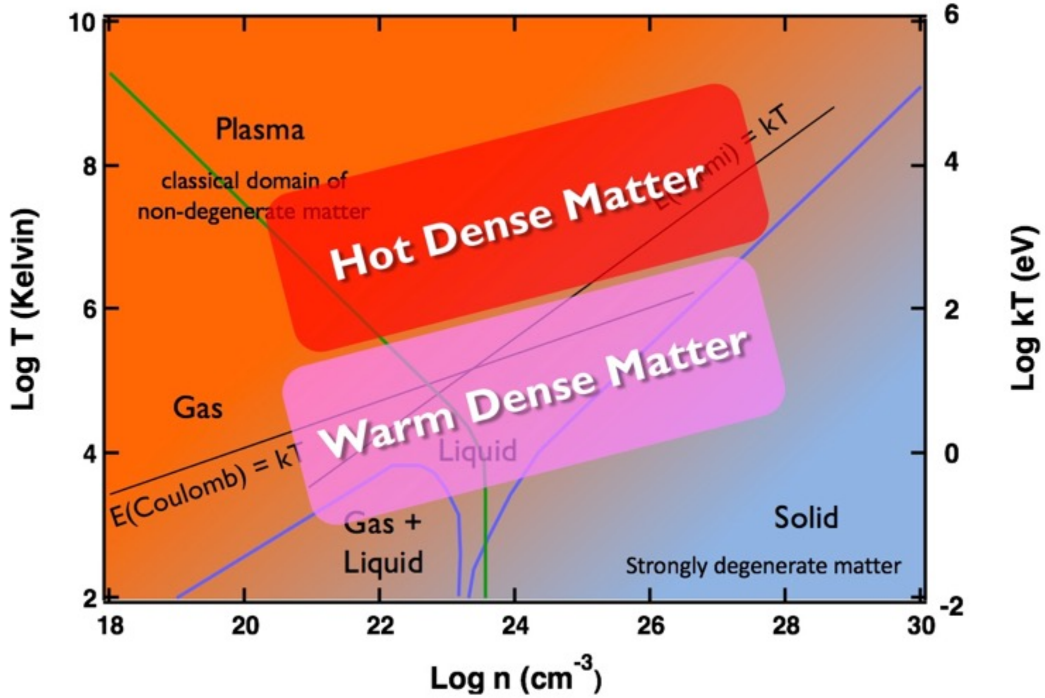
ρ-T diagram (copper) :
The range of application for the best theories in each region



The challenge of HED science centers on difficulties in describing the basic properties of an HED substance

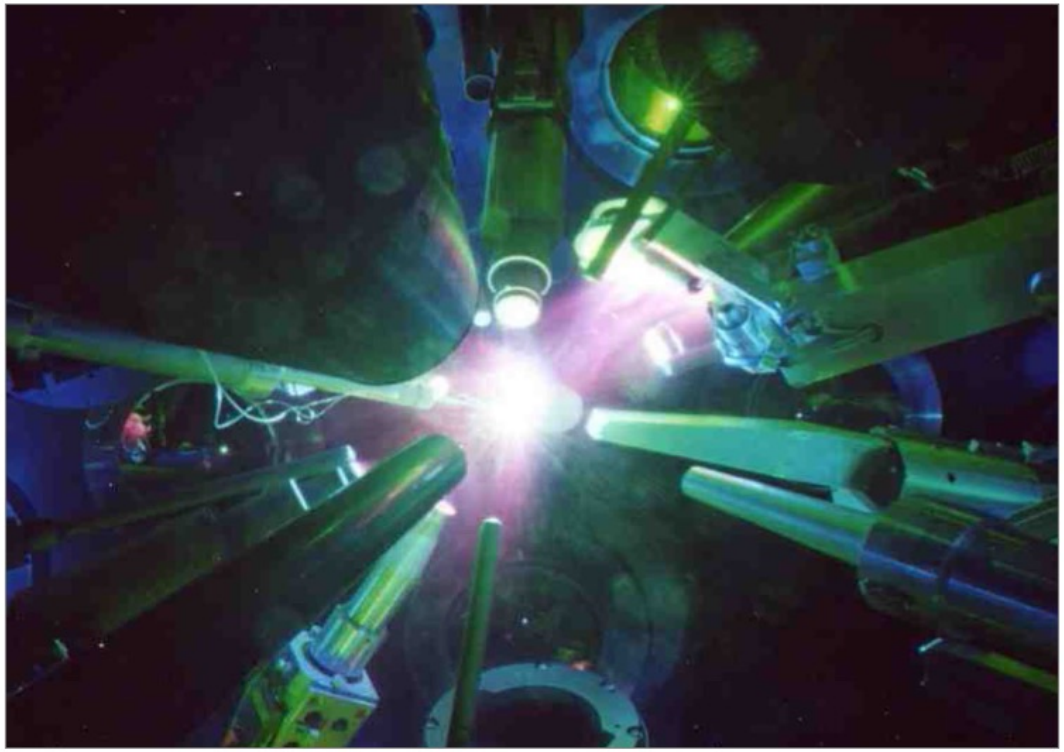
Research Needs

- ***Equation of state***: Measurement of temperature is essential but has proven to be extremely difficult
- ***Material structure***: Measurements of ionic and electronic structures provide significant insight and are necessary to understand the phase of the material and its transport and mechanical properties
- ***Transport properties***: A critical need is to develop measurements of transport properties, such as electrical and thermal conductivity.



- ***Approach to equilibrium***: Definitive time-dependent information is lacking, and successful collection of relevant data would represent a major breakthrough.
- *and more…*

A major hurdle in understanding HED matter is the lack of single-state data

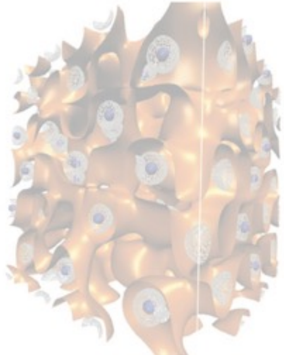


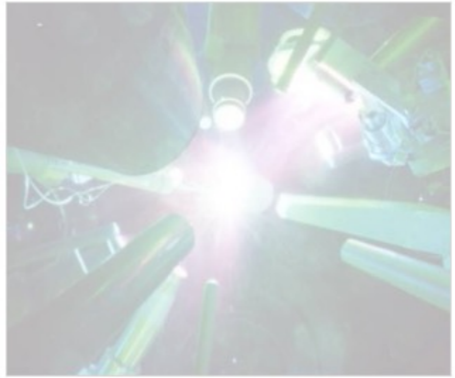
- **Short-living, Fast-varying:** Laboratory HED matter tends to be *non-uniform* due to hydrodynamic expansion at extreme pressure. Properties measured on non-uniform or *multi-state* systems can only be compared with theory through code simulations that includes modeling of *gradient effects*

Experimental requirement :
Ultrafast and Intense Light Sources

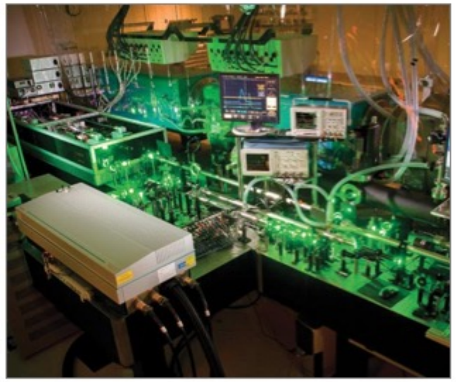
Contents

- **What is HEDP?**

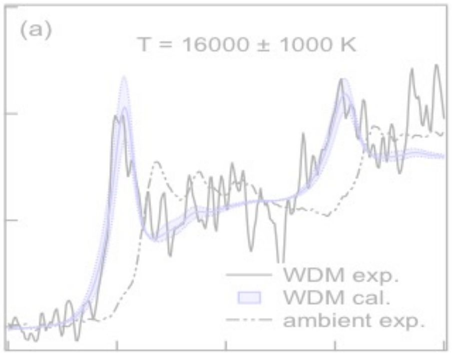


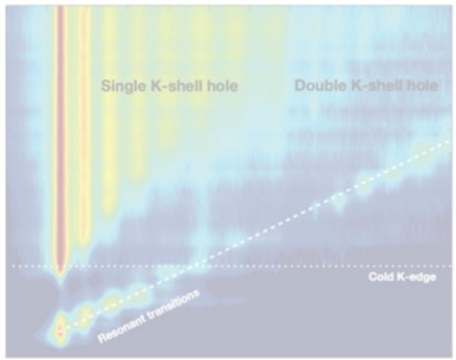


- **Extreme Light :**
  X-ray Free electron laser & High power laser



- **Ultrafast X-ray spectroscopies**
  for IPD, x-ray transmission,
  el-ph coupling of HED matters, etc



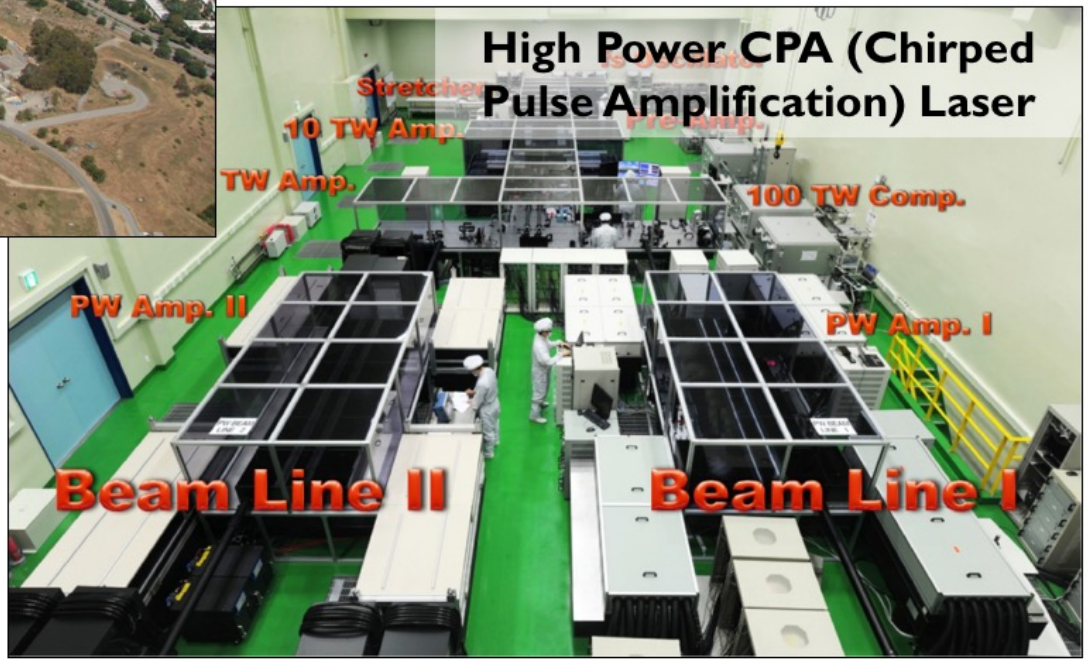


Unprecedantly extreme power & brightness at optical and x-ray regime in femtosecond time scales


X-ray Free Electron Laser (XFEL)

PW laser @ GIST

- λ: 0.8 μm
- pulse length: 35 fs
- pulse energy : > 40 J
- focusing to achieve IR intensities $>10^{21}$ Wcm^{-2}

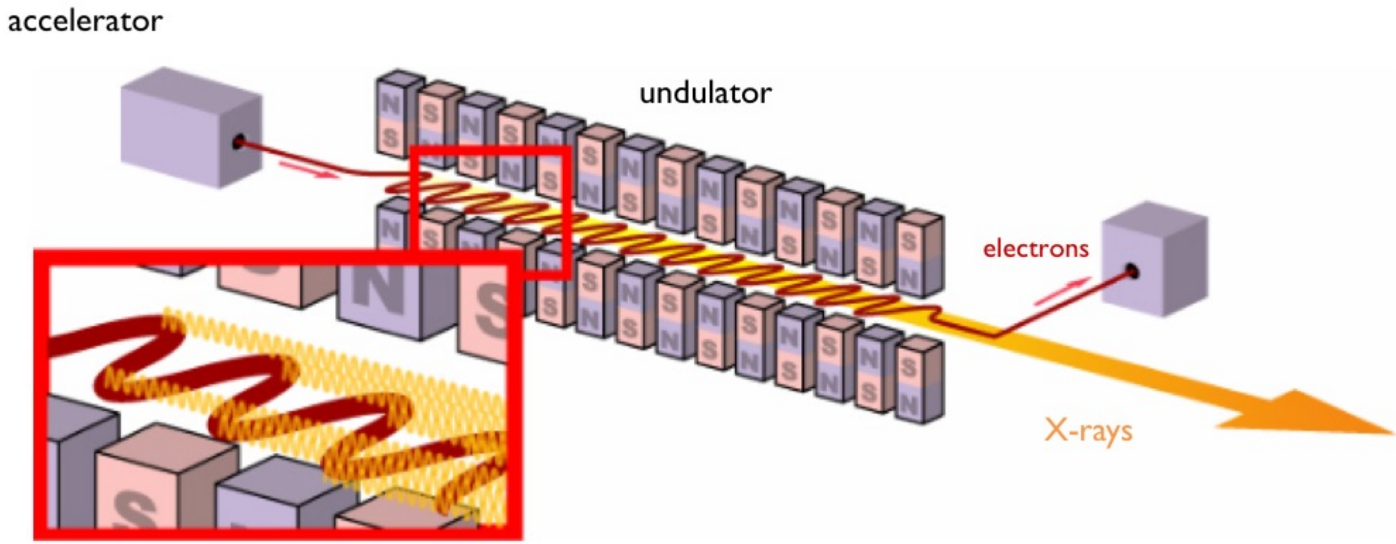


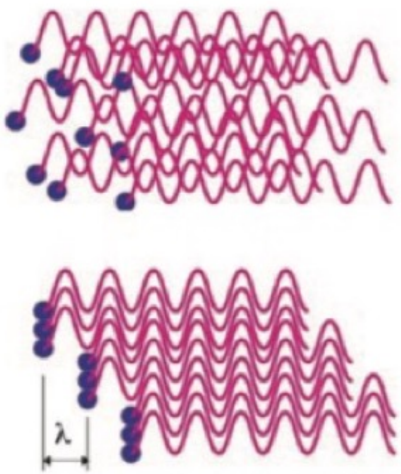
High Power CPA (Chirped Pulse Amplification) Laser

LCLS @ SLAC

- hv : 250 eV – 10.5 keV
- pulse length: <5 fs - 500 fs
- pulse energy : < 4.7 mJ
- focusing to achieve X-ray intensities $>10^{18}$ Wcm^{-2}

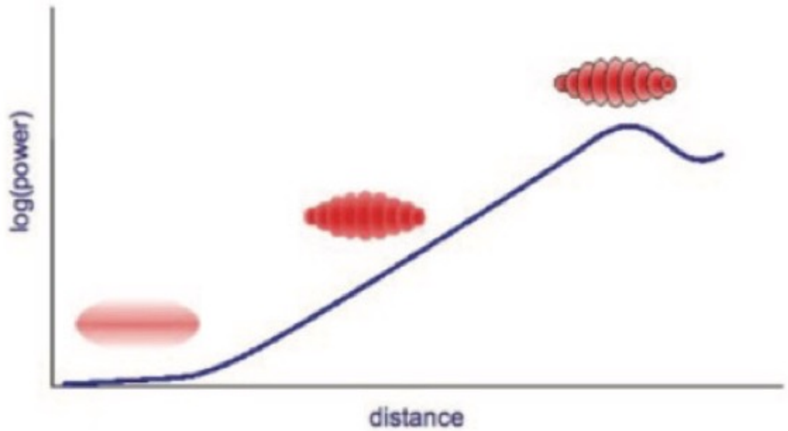
What is X-ray Free Electron Laser (XFEL) ?



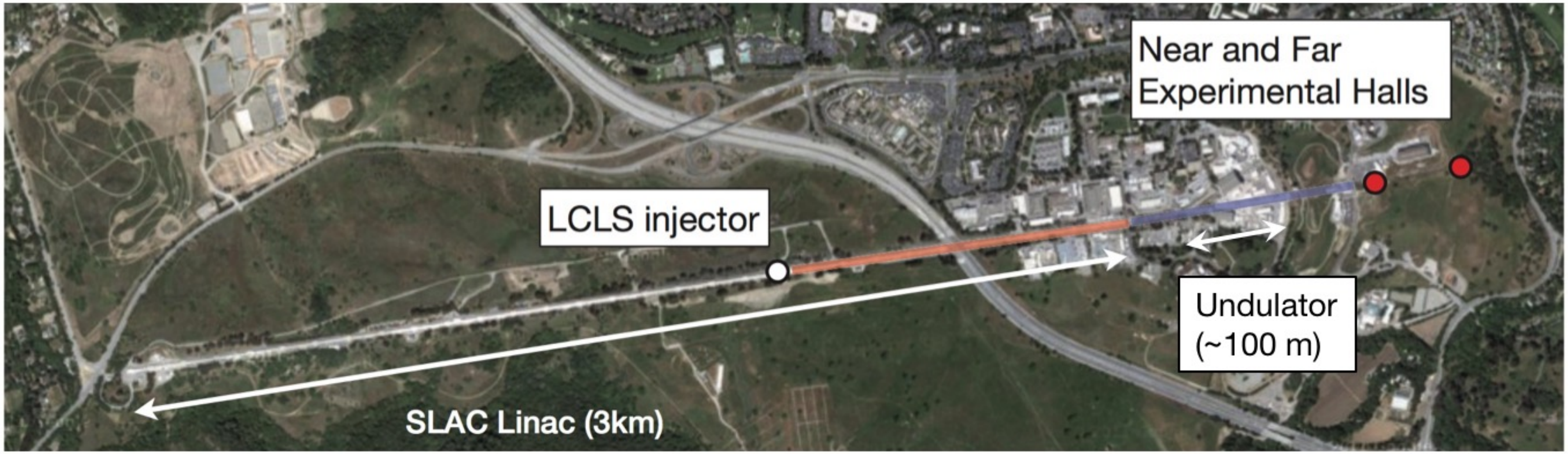


$$P = N\,P_1$$

$$E = N\,E_1$$
$$P = N^2\,P_1$$

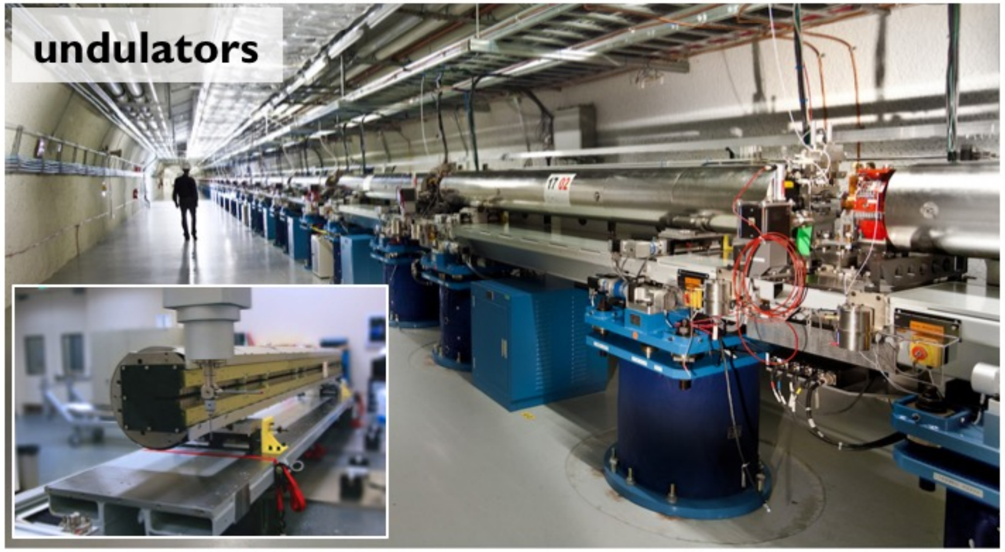


Linac Coherent Light Source (LCLS) @ Stanford Linear Accelerator Center (SLAC)



World's first XFEL

- tunable photon energy range: 250 eV – 10.5 keV (2.4 – 15.4 GeV e-beam)
- pulse repetition rate: 120 Hz
- pulse energy: < 4.7 mJ
- bandwidth: 0.3%
- variable pulse length: <5 fs - 500 fs
- focusing to achieve X-ray intensities $>10^{18}$ Wcm^{-2}



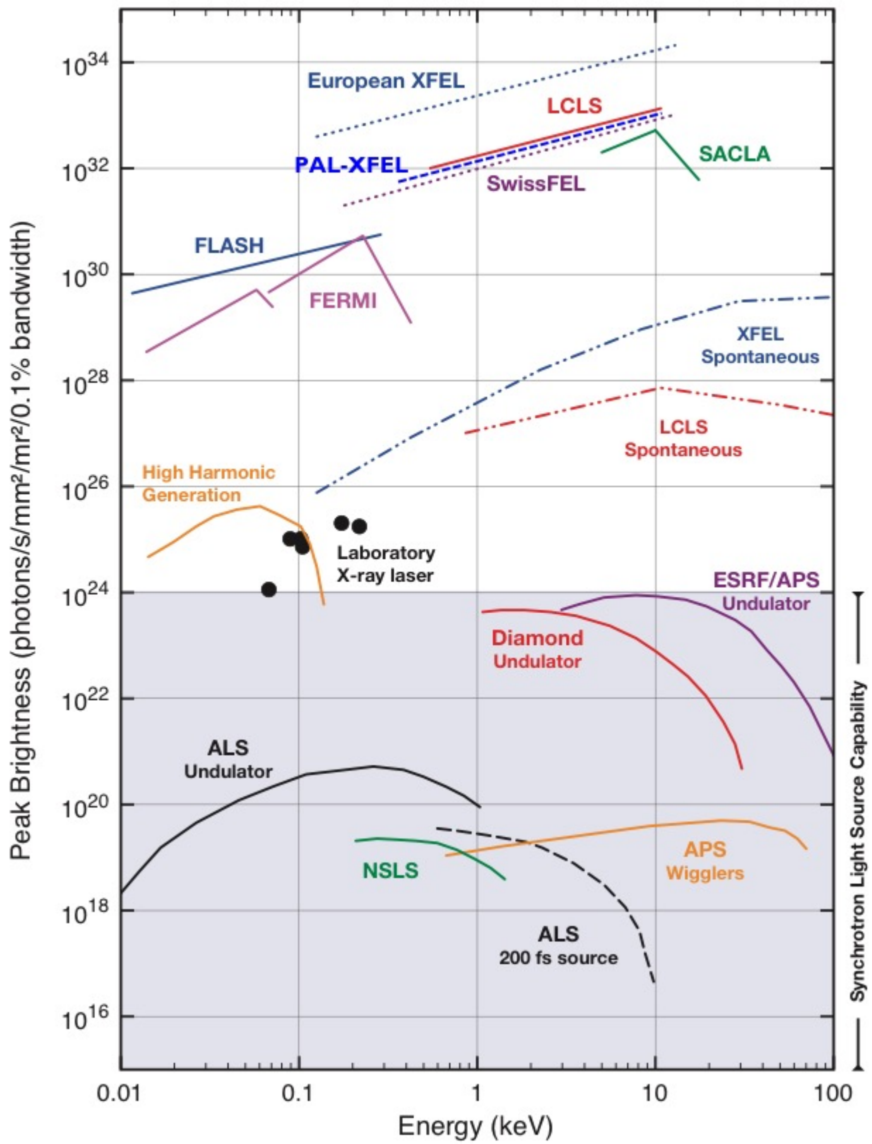
XFEL provides tremendous possibilities for HEDP

Peak brightness 9 orders of magnitude higher than 3rd gen. sources

- Short pulse duration (1–100 fs)
- Full transverse coherence
- High repetition rate
- Tunable
- High # of photons / bunch ($\geq 10^{12}$)

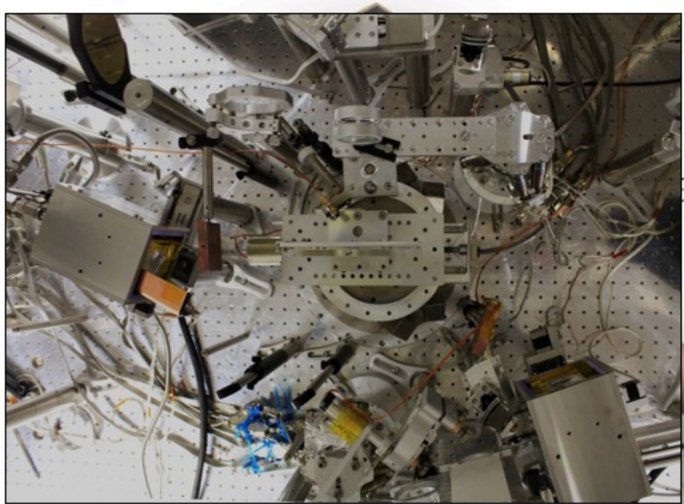
X-ray FELs worldwide

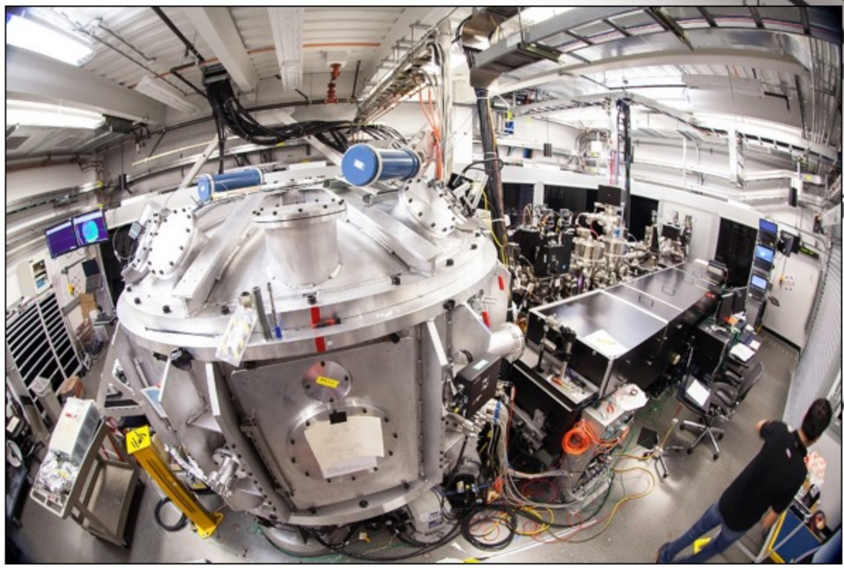
- LCLS, USA : 0.12 ~ 2.5 nm
- SACLA, Japan : 0.1 ~ 3.6 nm
- PAL-XFEL, Korea : 0.06 ~ 4.5 nm
- Euro X-FEL, Germany : 0.1 ~ 6 nm
- Swiss-FEL, Swiss : 0.1 ~ 7 nm

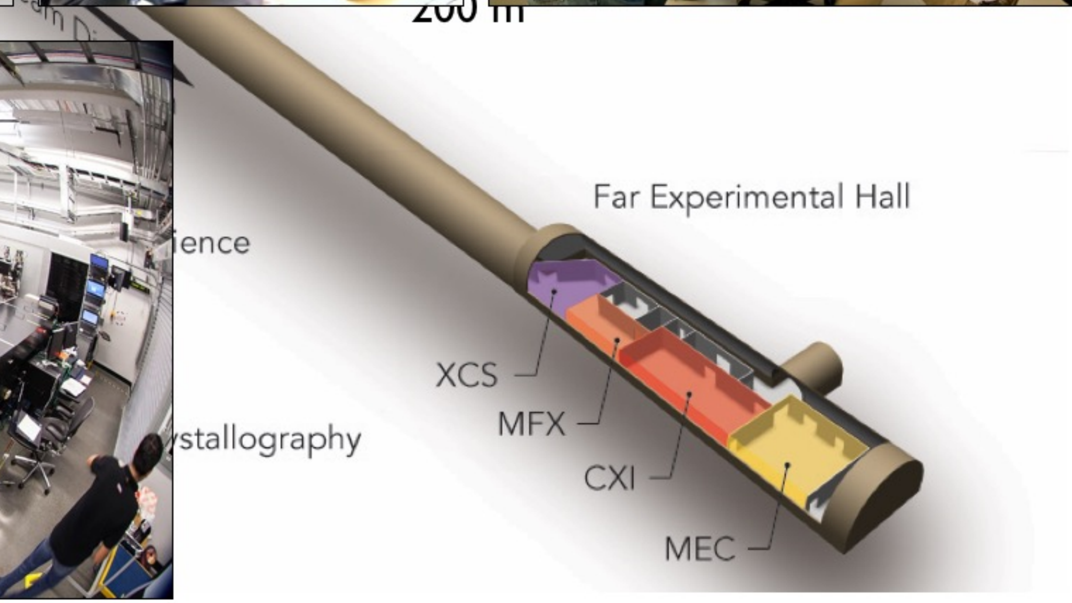


XFEL worldwide

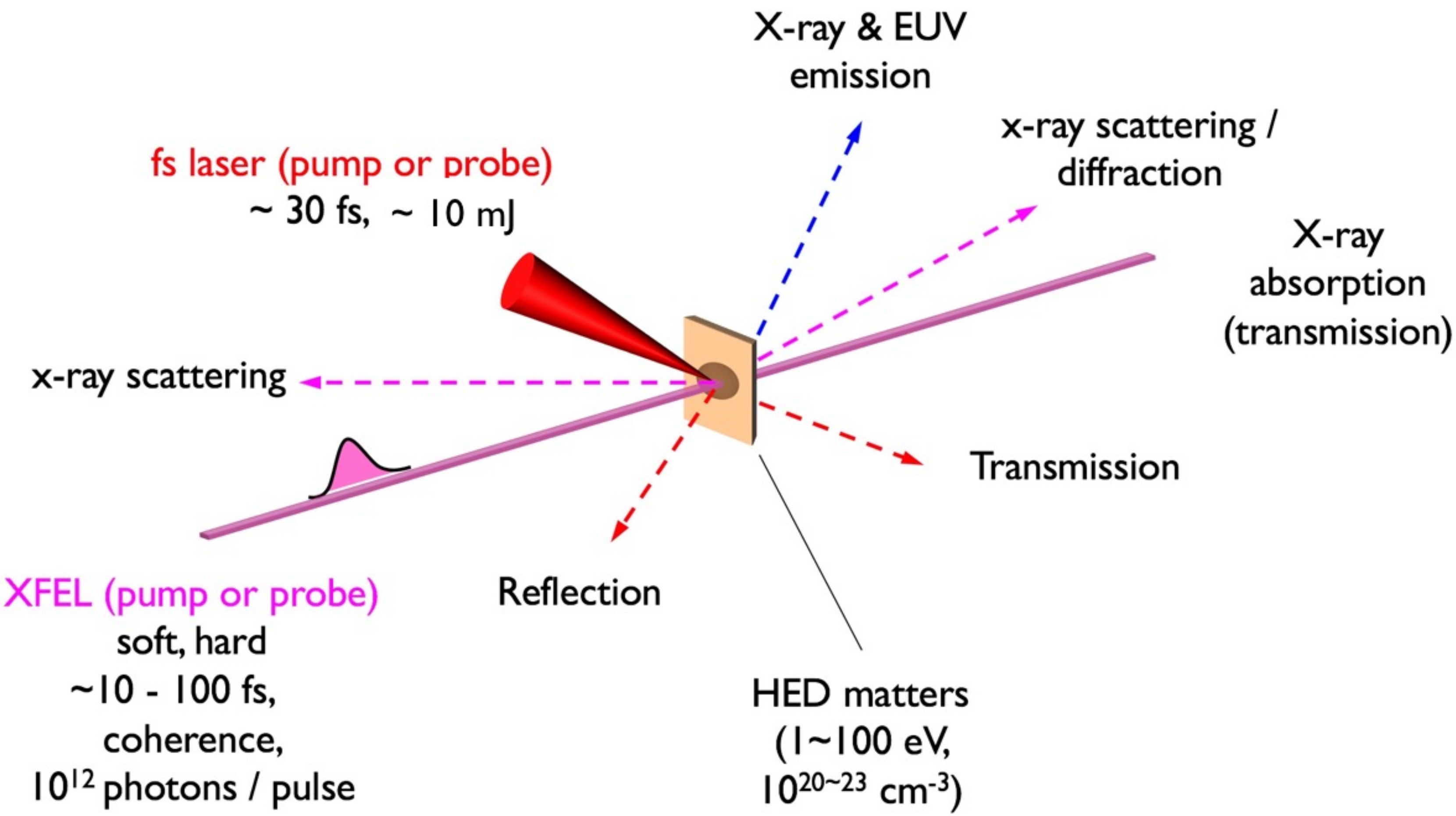
LCLS experimental hutches & control rooms





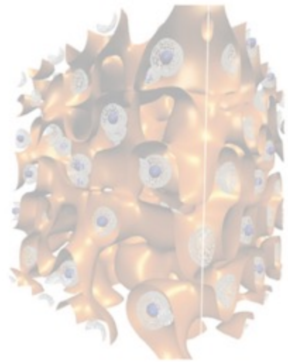


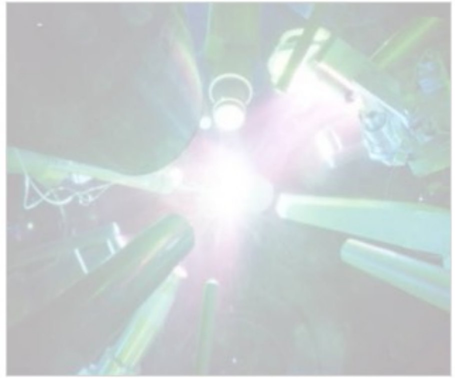
HED experiment on XFEL: Concept



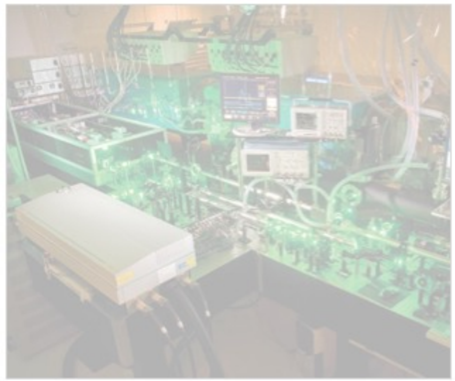
Contents

- **What is HEDP?**

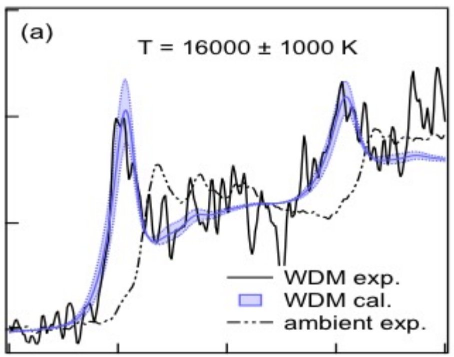


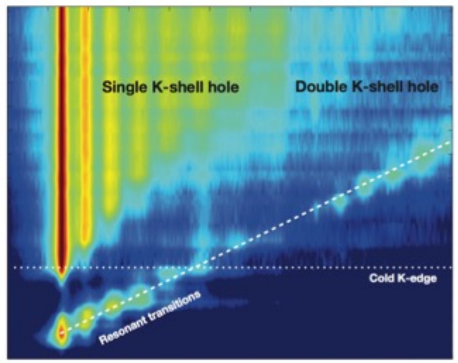


- **Extreme Light :**
  X-ray Free electron laser & High power laser



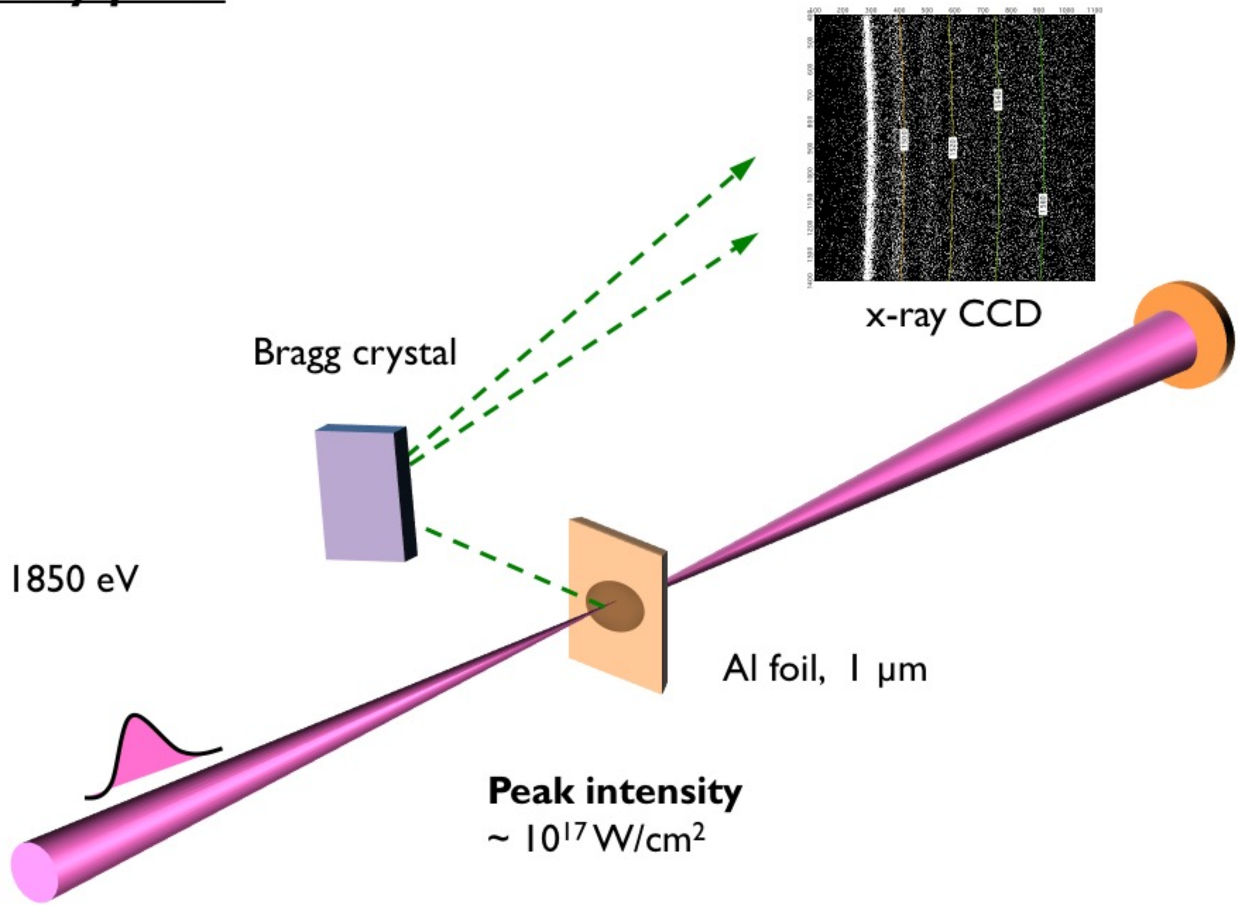
- **Ultrafast X-ray spectroscopies**
  for IPD, x-ray transmission,
  el-ph coupling of HED matters, etc





K-shell spectrosocpy of hot dense aluminum

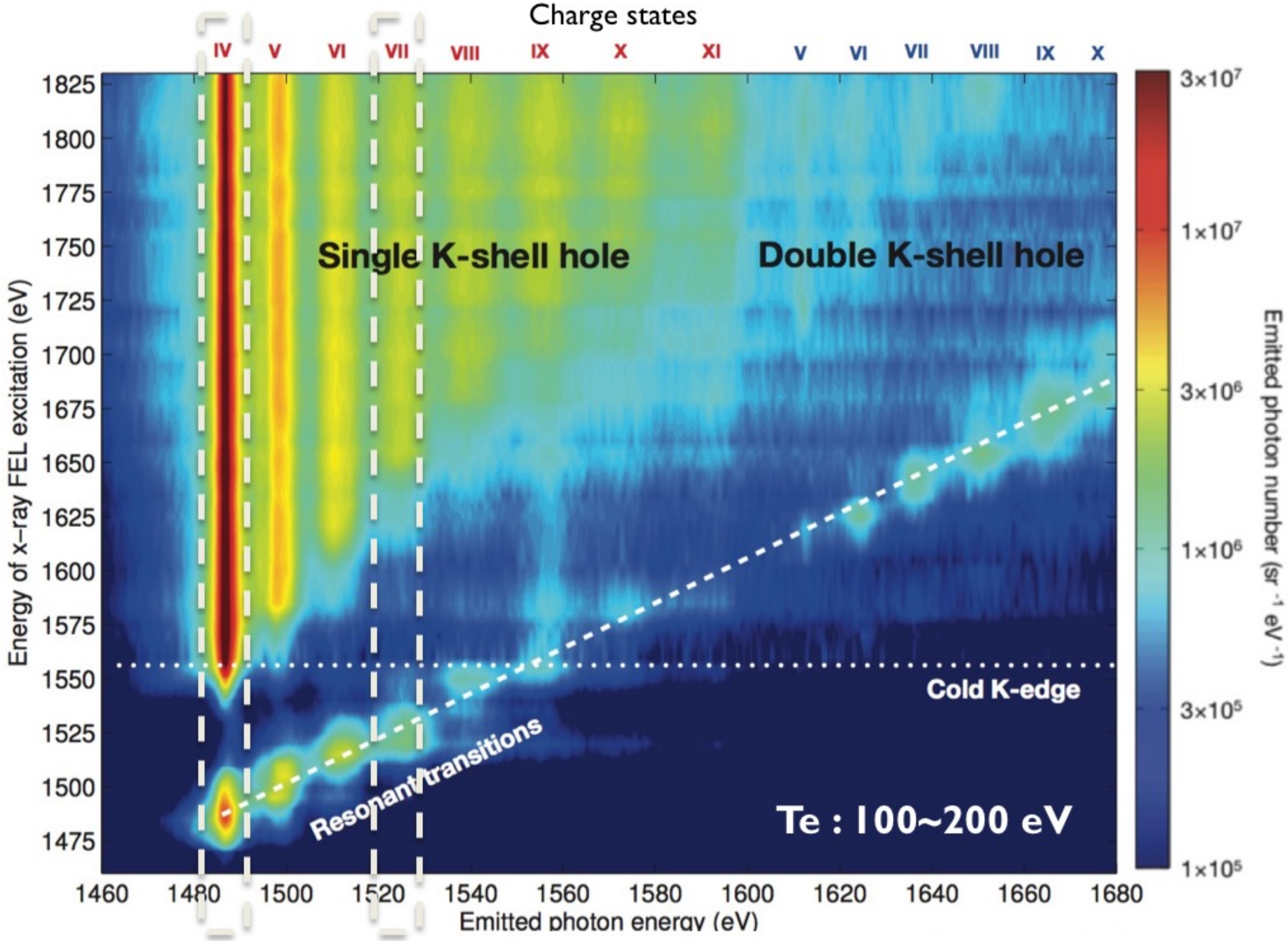
Isochoric heating of solid sample with an intense X-ray pulse



LCLS pulse
Photon energy : 1480 ~ 1850 eV
Pulse length < 100 fs
Pulse energy ~ 2 mJ
Bandwidth ~ 0.3 %

K-shell spectrosocpy of hot dense aluminum

XFEL pumping : 10^{12} photons, 10^{17} W/cm^2

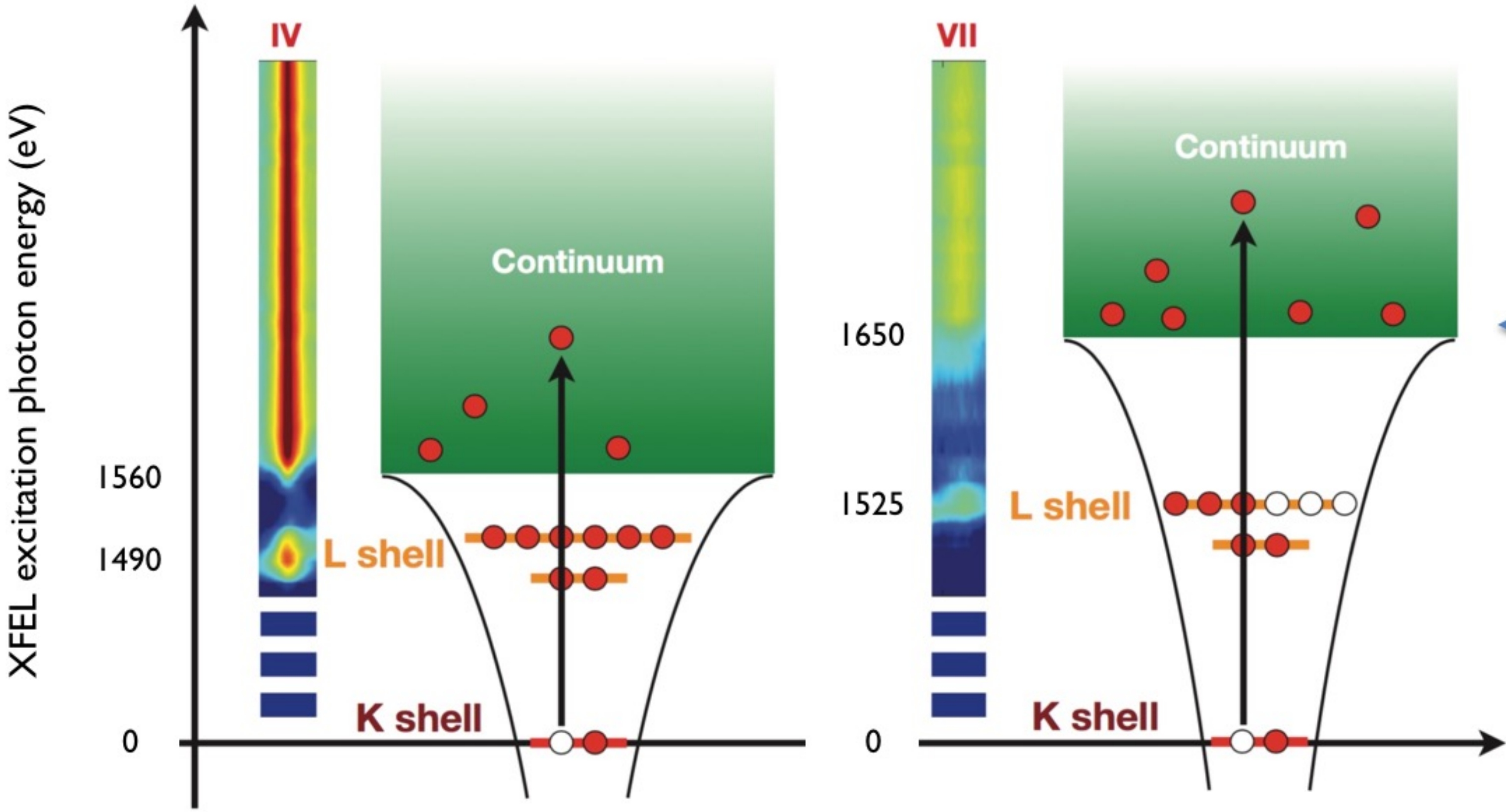


Byoung-ick Cho, bicho@gist.ac.kr

Vinko et al, Nature (2012), Ciricosta et al PRL (2012), Cho et al PRL (2012), Rackstraw et al, HEDP (2014), Rackstraw et al, PRL (2015), Vinko et al, Nat. Comm (2015), Ciricosta et al, (submitted), Cho et al, (submitted)

K-shell emission spectra represent energy levels of ionized aluminum in hot dense conditions

Absorption thresholds is observed

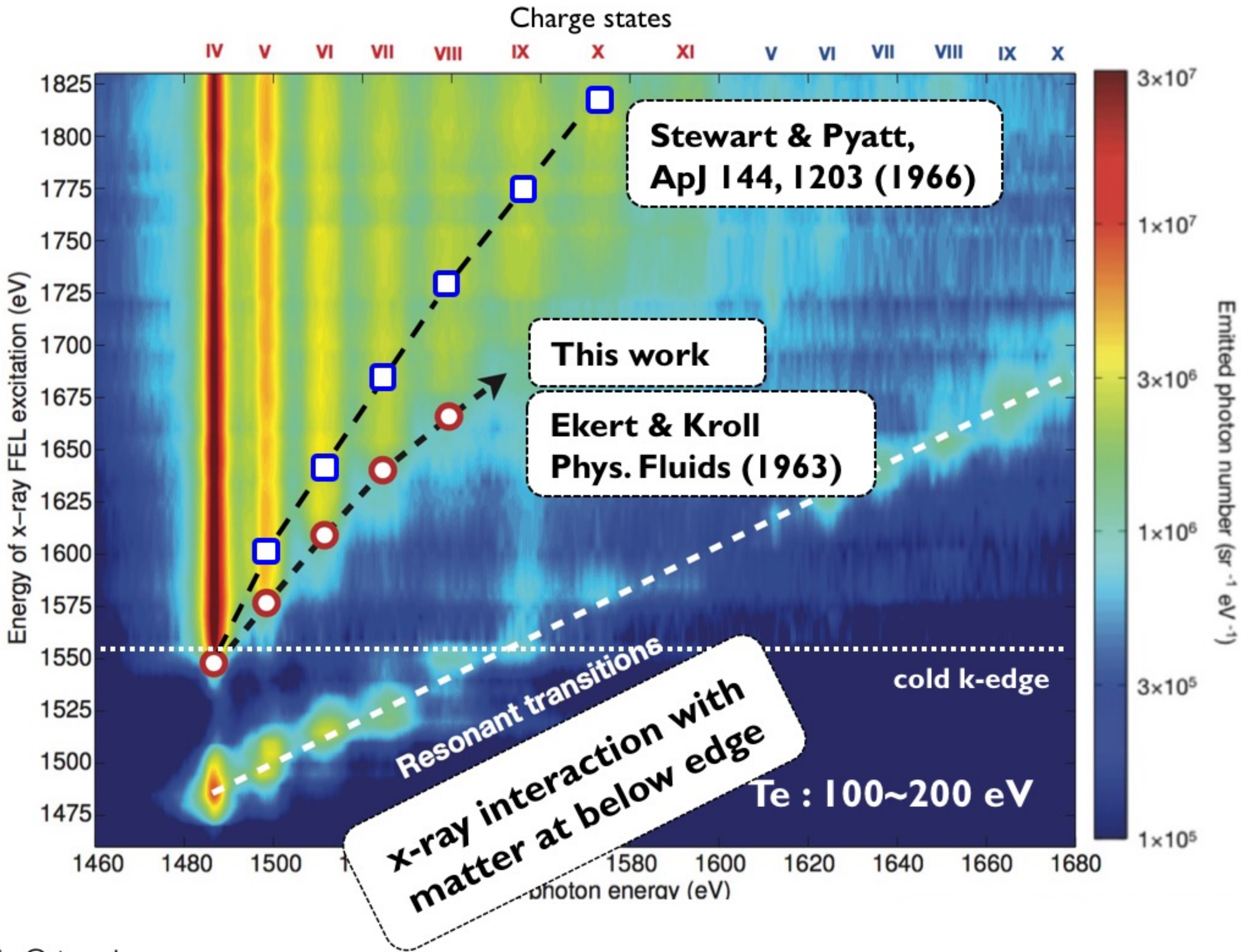


Absoroption edge measurement

Experimental IPD = Atomic edge - Measured edge

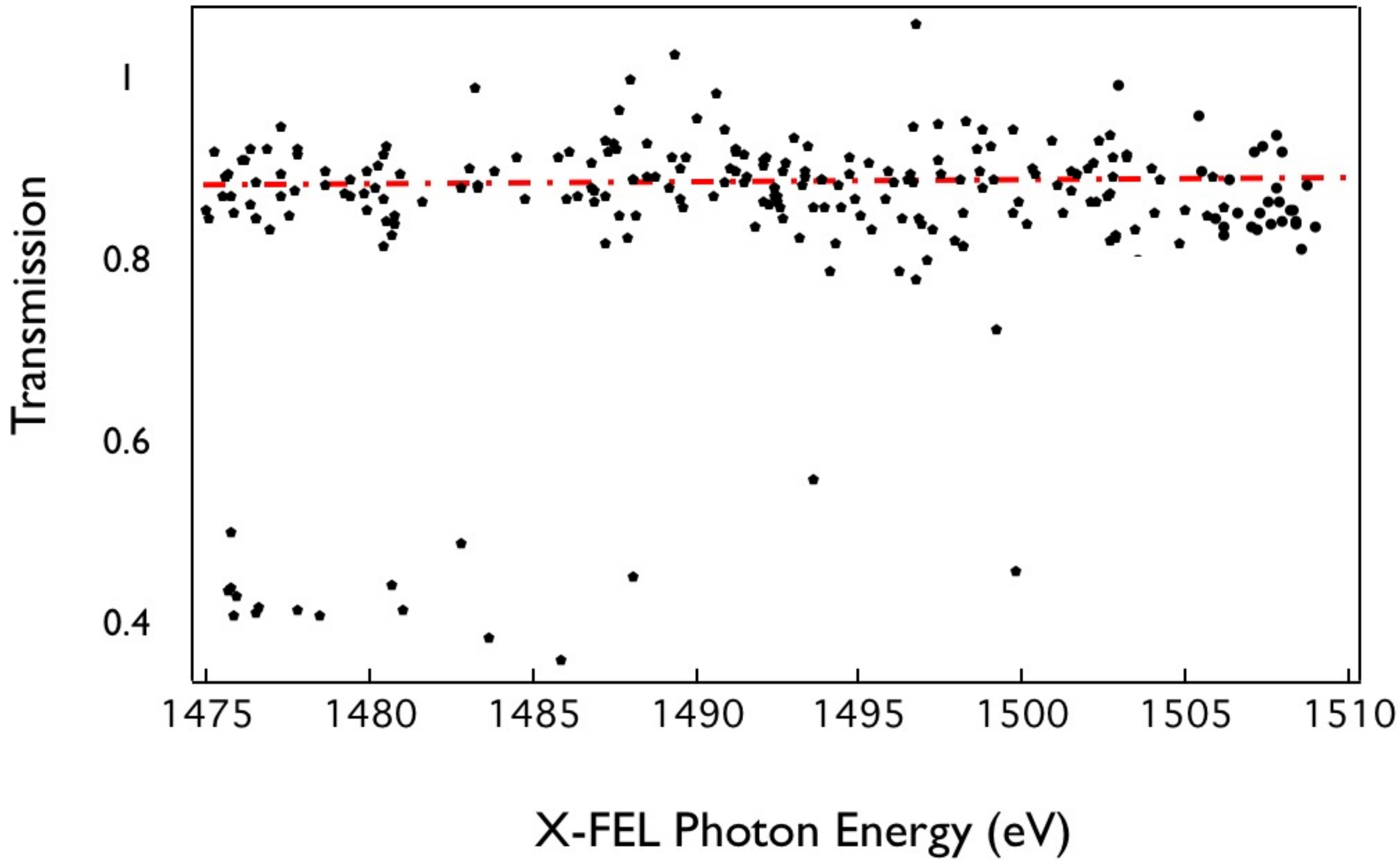
Experimental benchmarks for IPD theories

Ionization Potential Measurement in Hot Dense Matter



X-FEL transmission *below* K-edge: Experiment

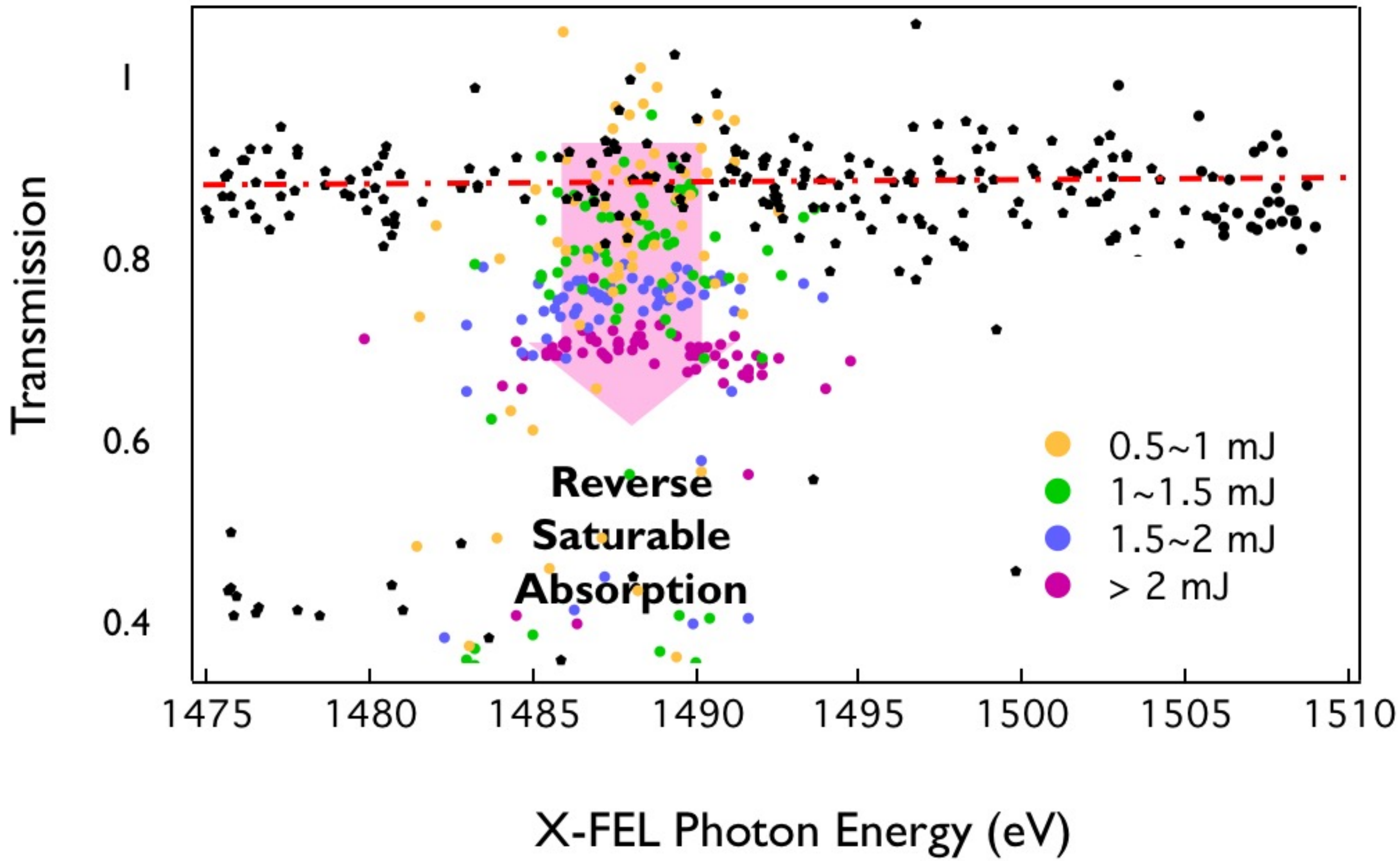
Peak intensity < 10^{16} W/cm^2 Pulse length < 100 fs
Photon energy : 1470 ~ 1510 eV Aluminum foil : 1.4 μm



X-FEL transmission *below* K-edge: Experiment

Peak intensity ~ $10^{16\sim17}$ W/cm^2
Photon energy : ~ 1487 eV

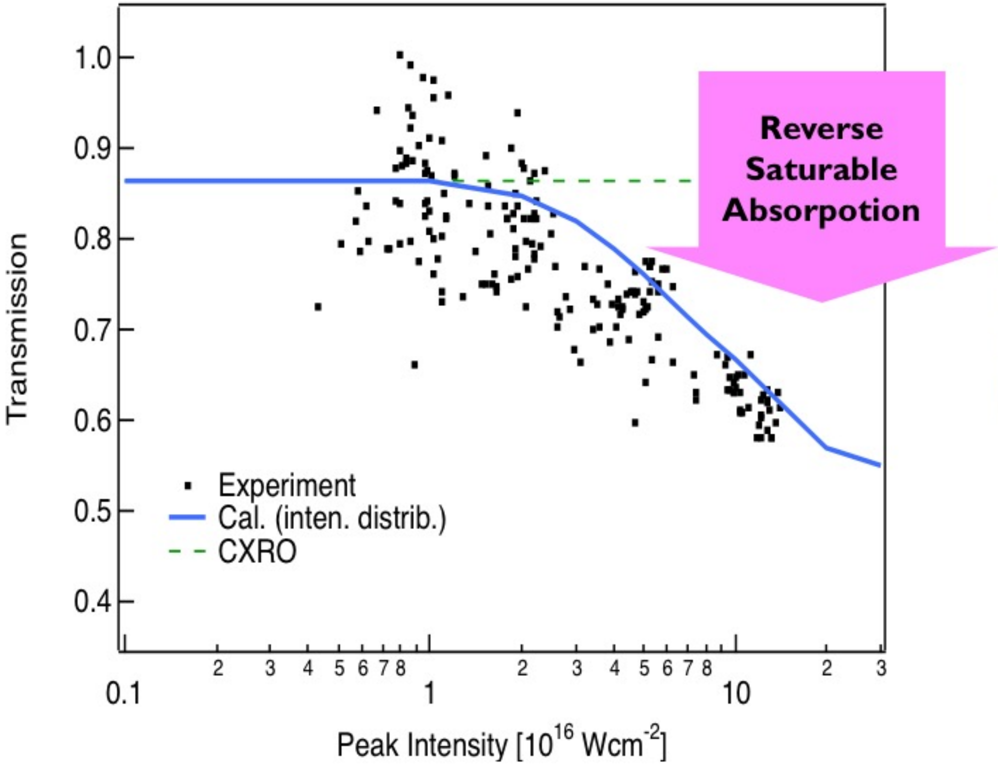
Pulse length < 100 fs
Aluminum foil : 1.4 μm



Byoung-ick Cho, bicho@gist.ac.kr

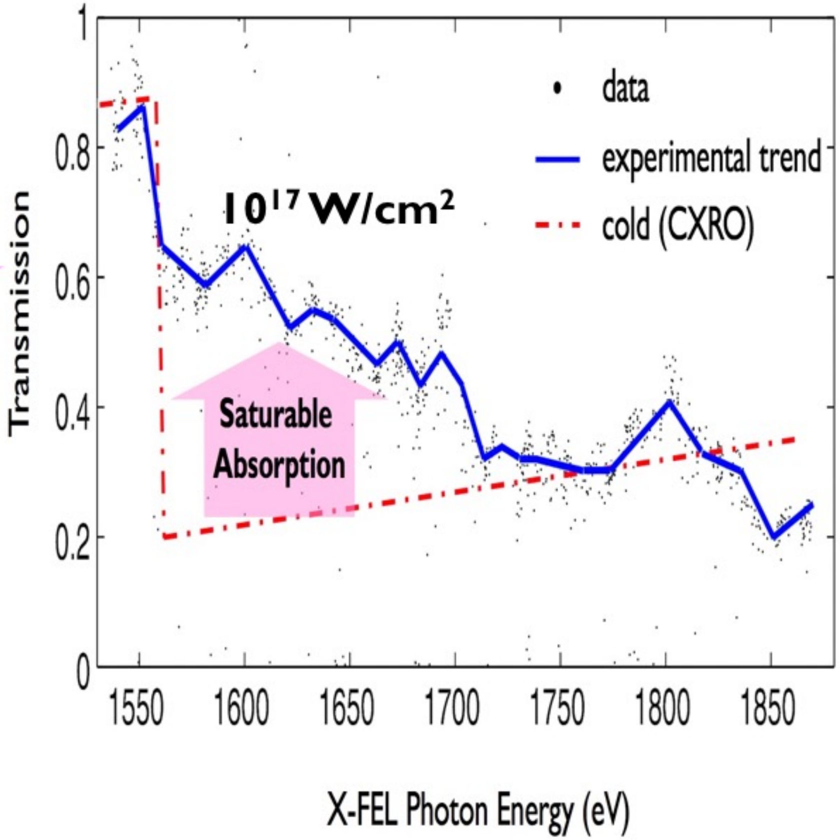
Intensity dependent x-ray transmission of hot dense aluminum

Transmission vs Intensity



Cho et al, - submitted

Transmission vs photon energy



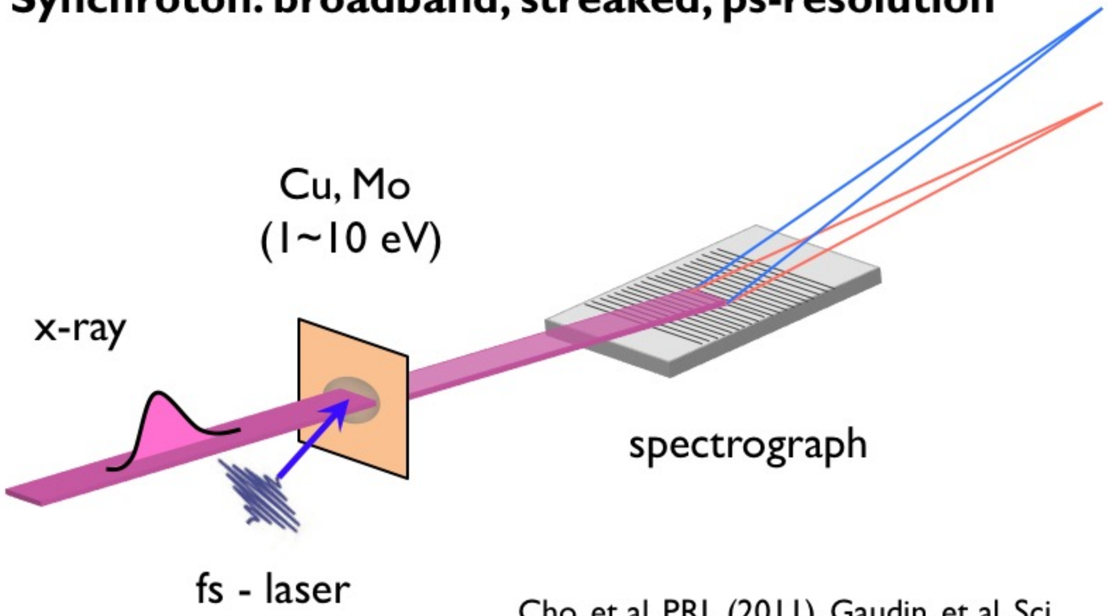
Rackstraw et al, PRL (2015)

Oppacity & energy transport via radiation in HED matters

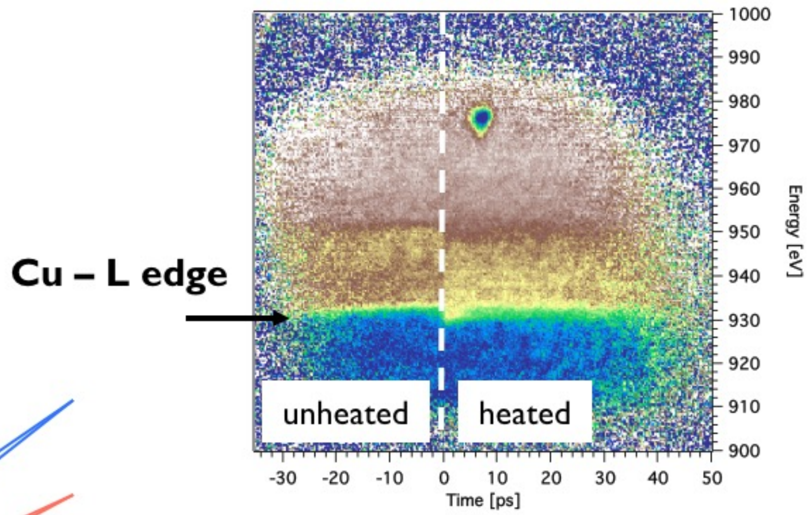
Time resolved x-ray absorption spectroscopy for super heated metals

- **<u>Femtosecond laser pulse</u>**
  ~ 10 mJ / pulse
  heating sample above the damage threshold
  Te: 1~10 eV

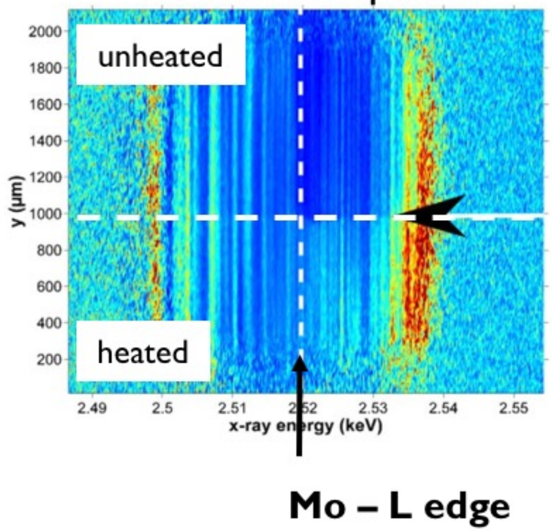
- **<u>X-rays</u>**
  FEL: SASE, fs-resolution
  Synchroton: broadband, streaked, ps-resolution



streaked spectrum of
70 ps x-ray pulse



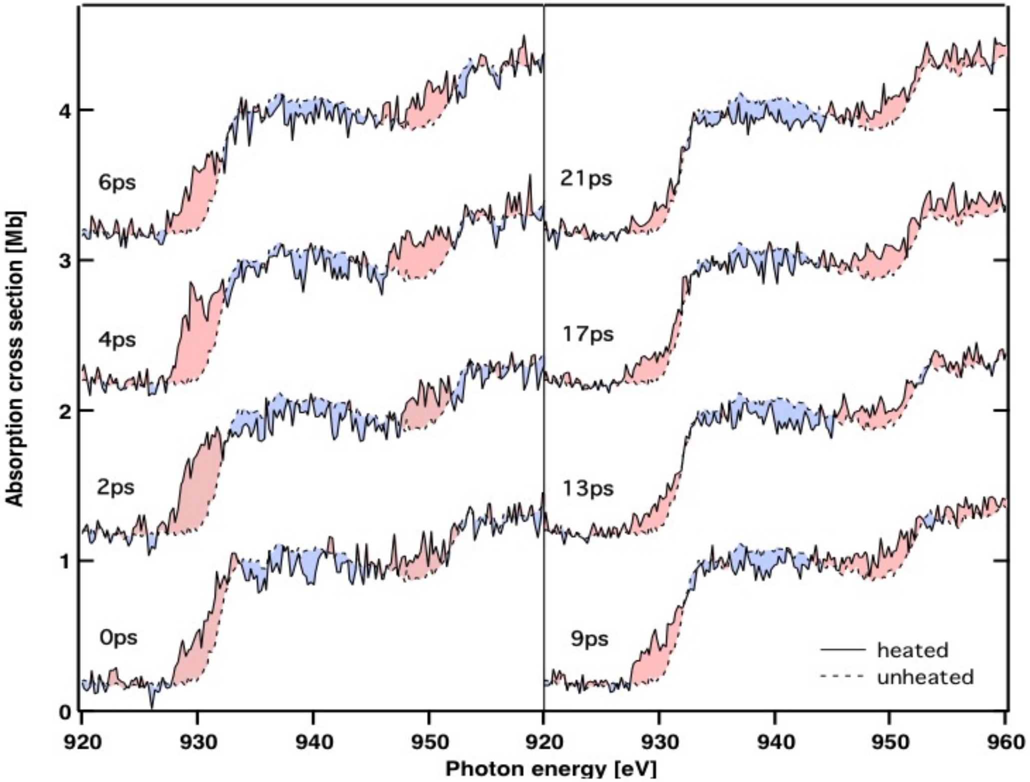
80 fs XFEL spectra



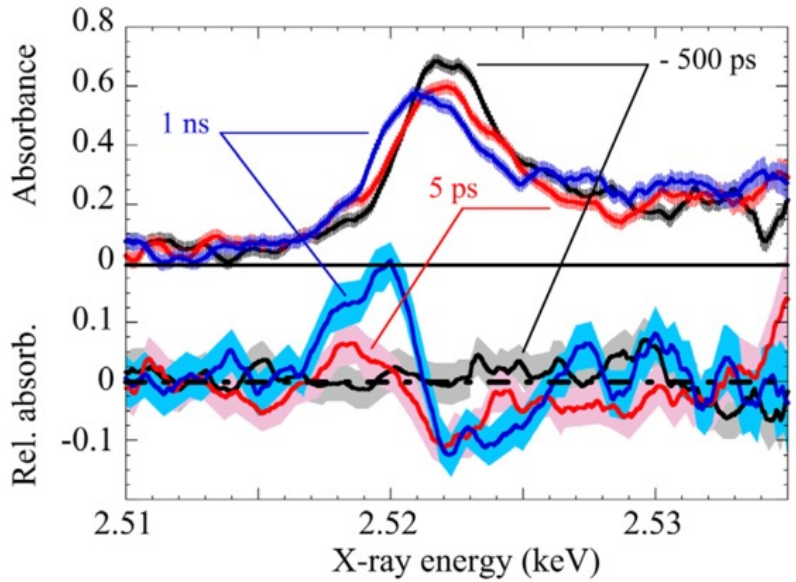
Cho, et al, PRL (2011), Gaudin, et al, Sci Rep. (2014), Dorchies et al, PRB (2015), Cho et al, Sci Rep (to be published)

Time resolved x-ray absorption spectroscopy

near L-edge of Cu



near L-edge of Mo



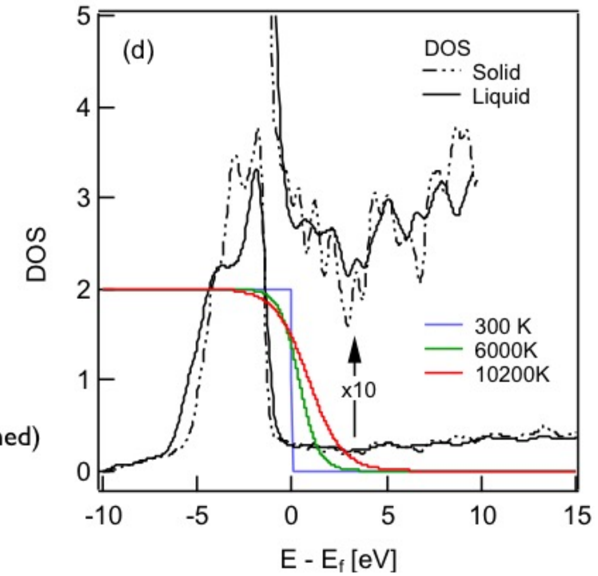
Byoung-ick Cho, bicho@gist.ac.kr

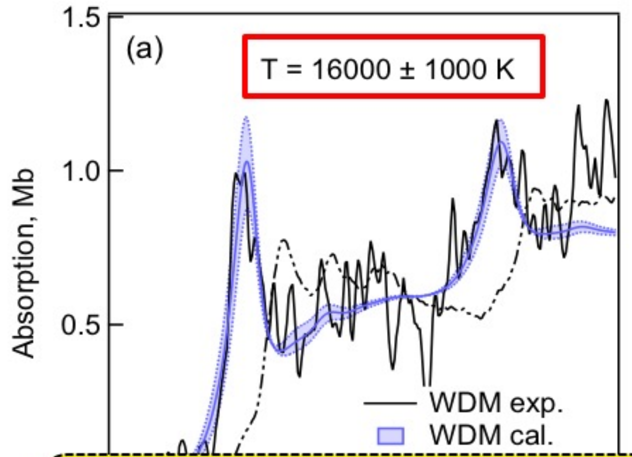
The first principle DFT-MD simulations to produce electronic DOS of HED matters

Density of states & electron distribution

XANES

Cu

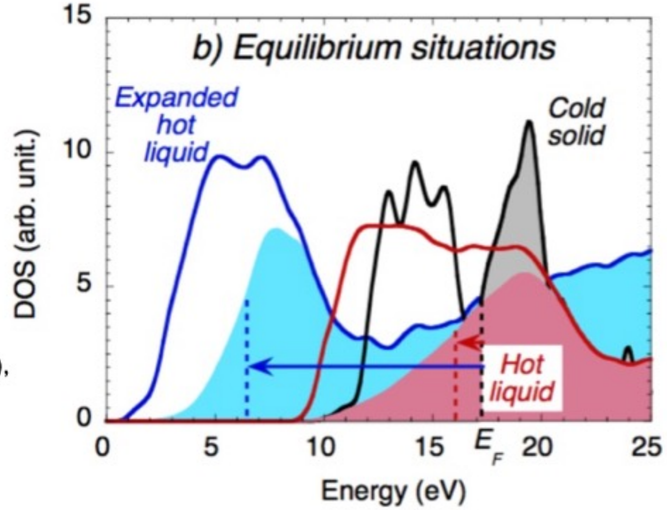


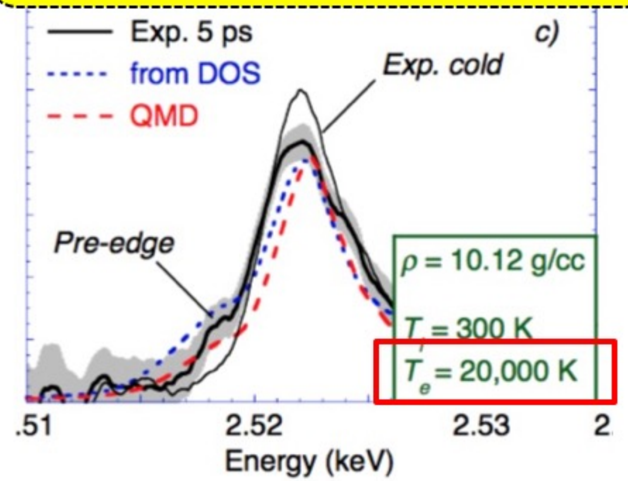


Cho, et al, PRL (2011),
Cho et al, Sci Rep (to be published)

XANES serves as an electron temperature diagnostics of HED matter

Mo

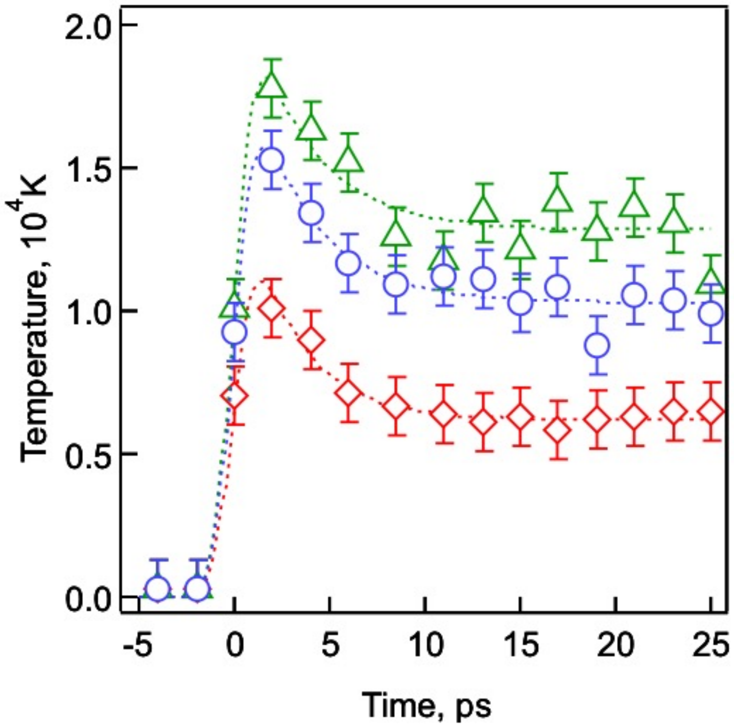




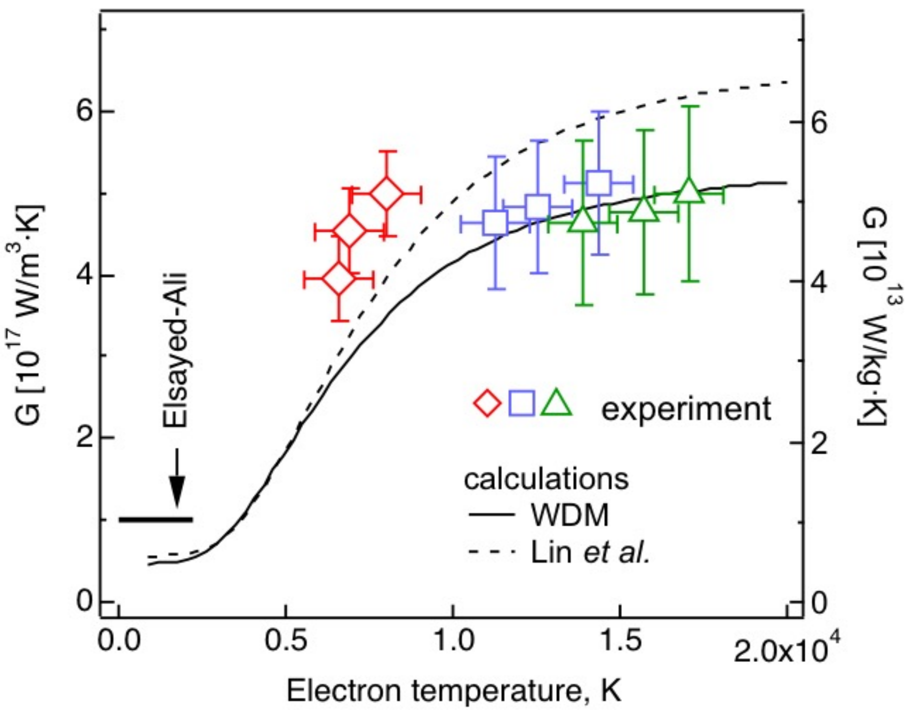
Gaudin, et al, Sci Rep. (2014),
Dorchies et al, PRB (2015)

Electron - ion energy relaxation (electron-phonon coupling) of HED matters are tested

Electron temperature



Temperature dependent el-ph couplings



TTM eq.

$$C_e(T_e)\,T_e'(t) = -G\,\left[T_e(t) - T_i(t)\right] + S_L(t)$$

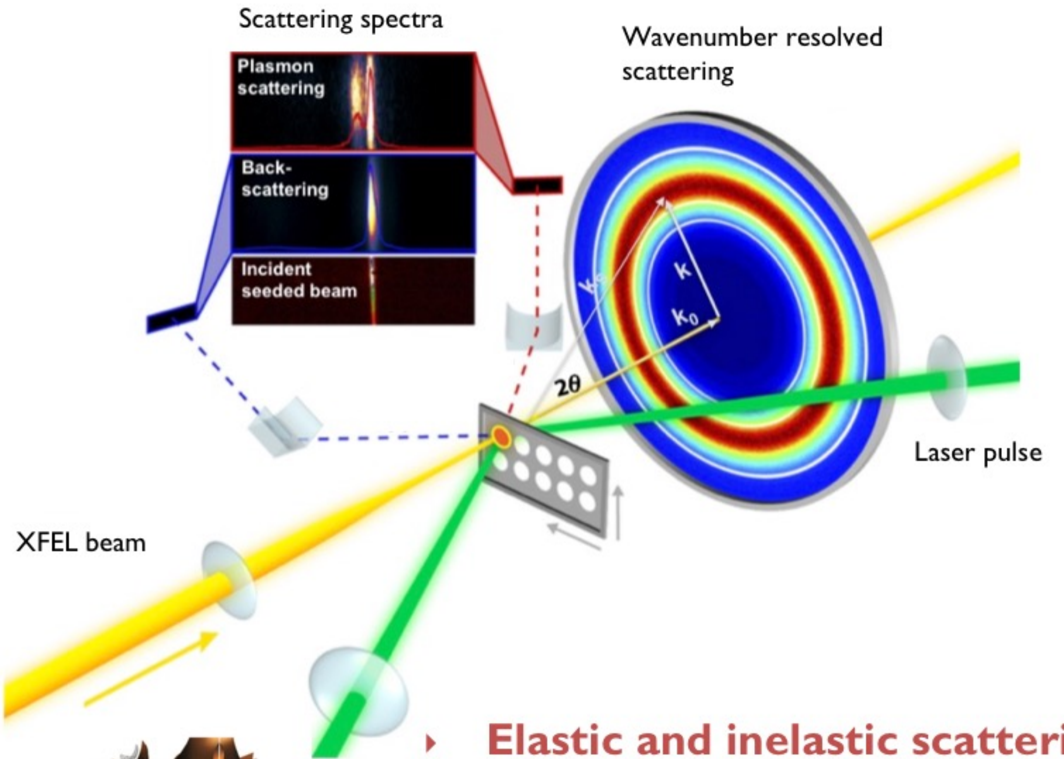
$$C_i\,T_i'(t) = G\,\left[T_e(t) - T_i(t)\right]$$

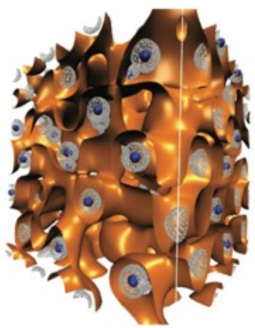
el-ph coupling

$$G(T_e) = \frac{\pi\hbar k_B \lambda\langle\omega^2\rangle}{g(\varepsilon_F)} \int_{-\infty}^{\infty} g^2(\varepsilon)\left(-\frac{\partial f}{\partial \varepsilon}\right)d\varepsilon$$

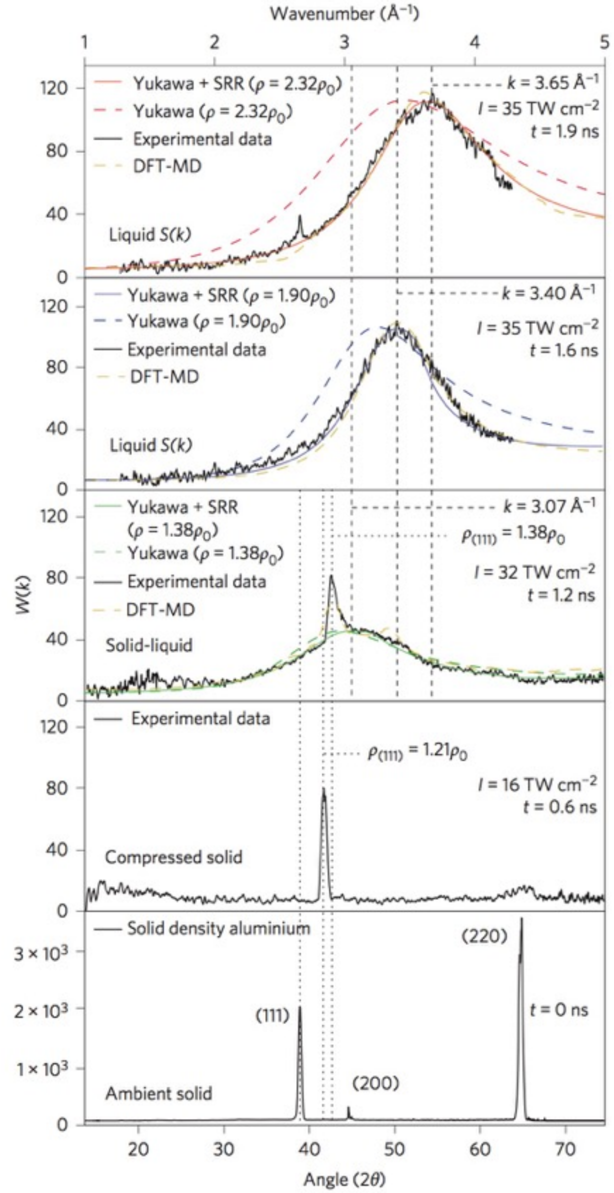
Cho, et al, Sci. Rep.

X-ray scattering :
lattice compression and melting in HED conditions





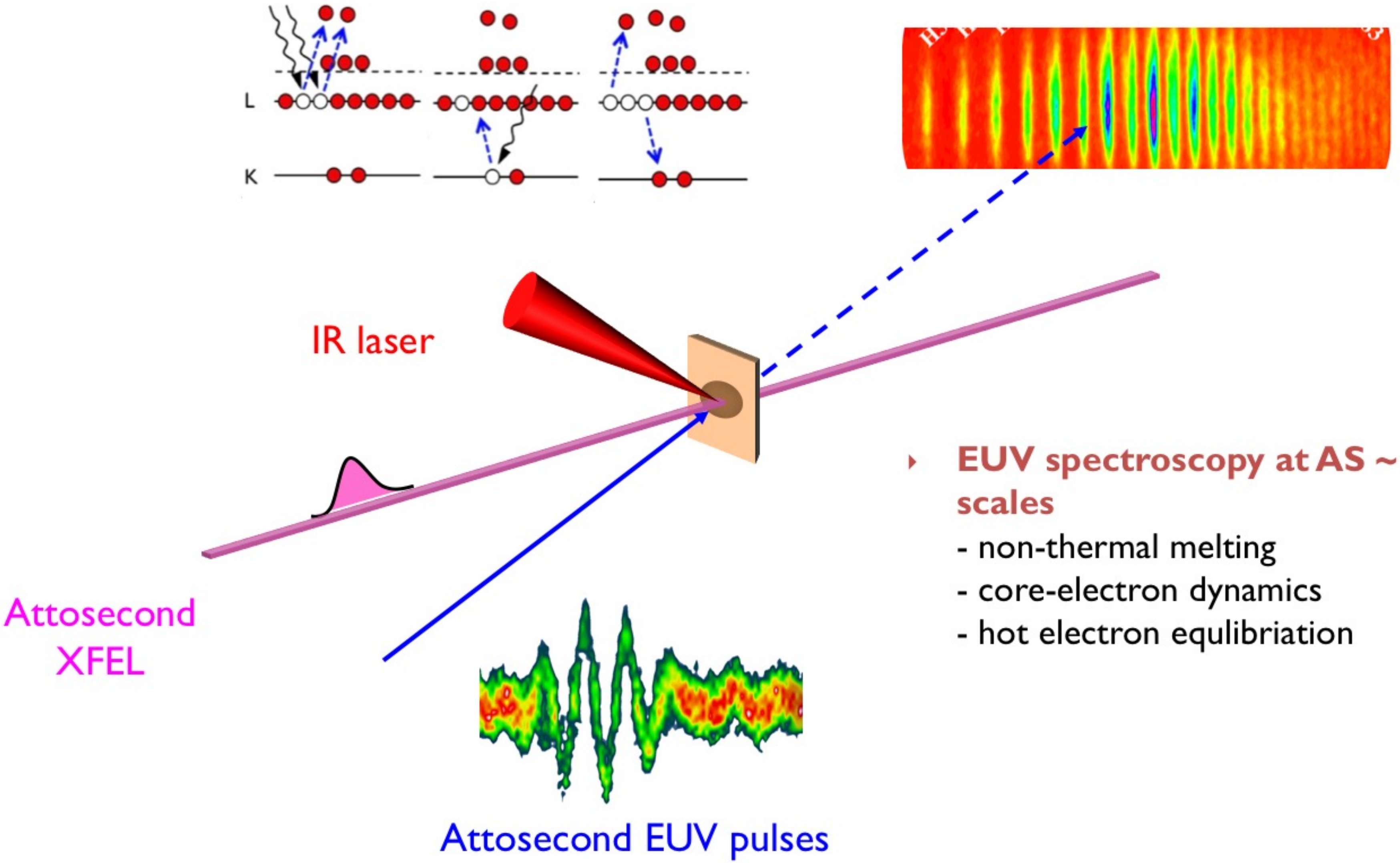
- **Elastic and inelastic scattering of x-ray from HED matter**
  - electron temperature – density & ionization states
  - ion-ion correlation
  - interatomic potentials (Comlomb/Yukawa)



Byoung-ick Cho, bicho@gist.ac.kr

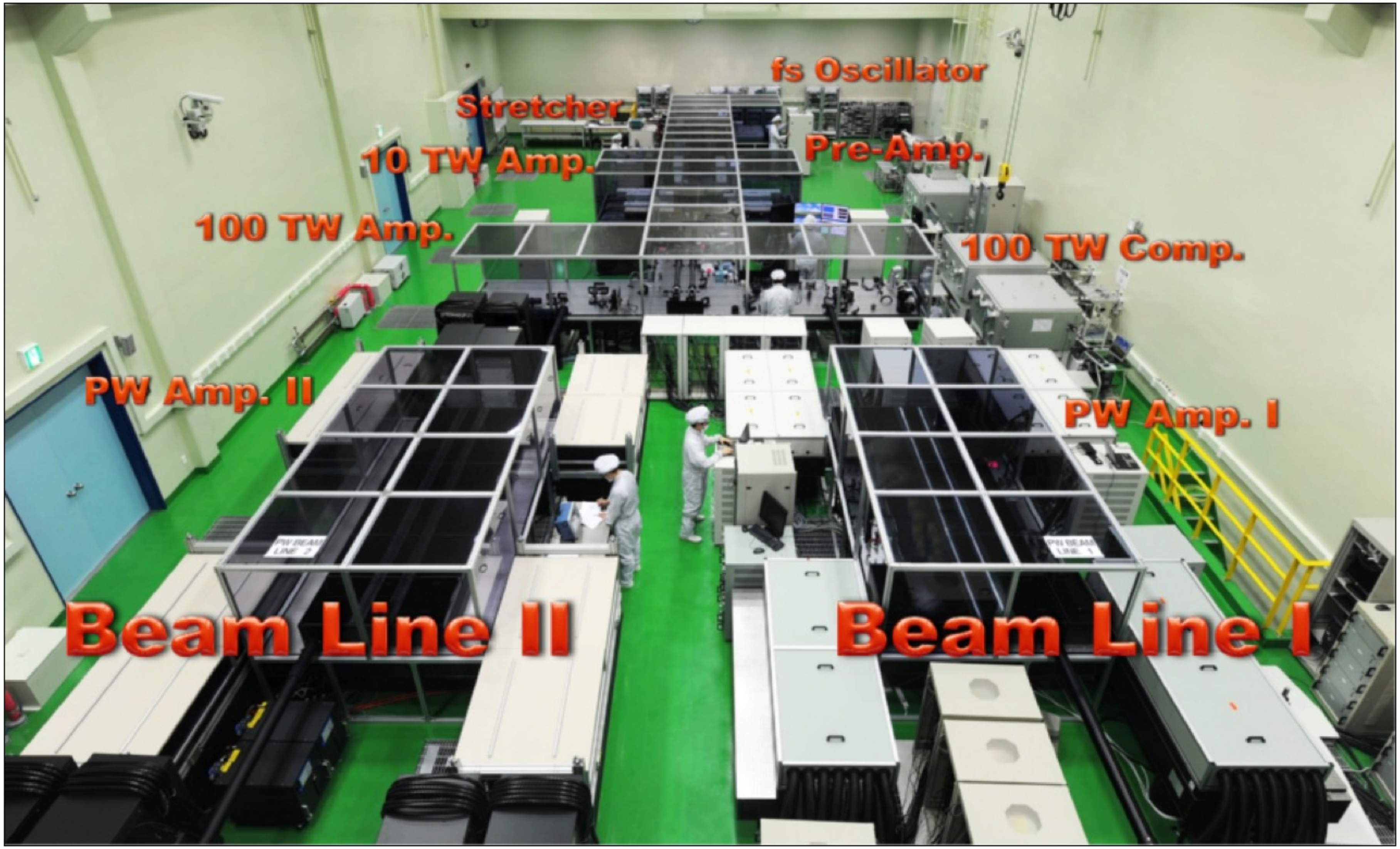
Fletcher et al, Nat. Photonics 9, 274 (2015)

Attosecond EUV pulses:
Core electron dynamics in HED conditions

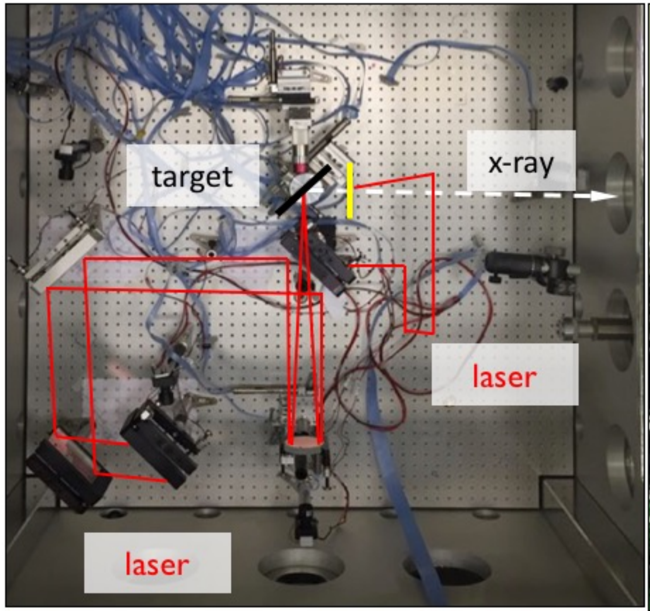


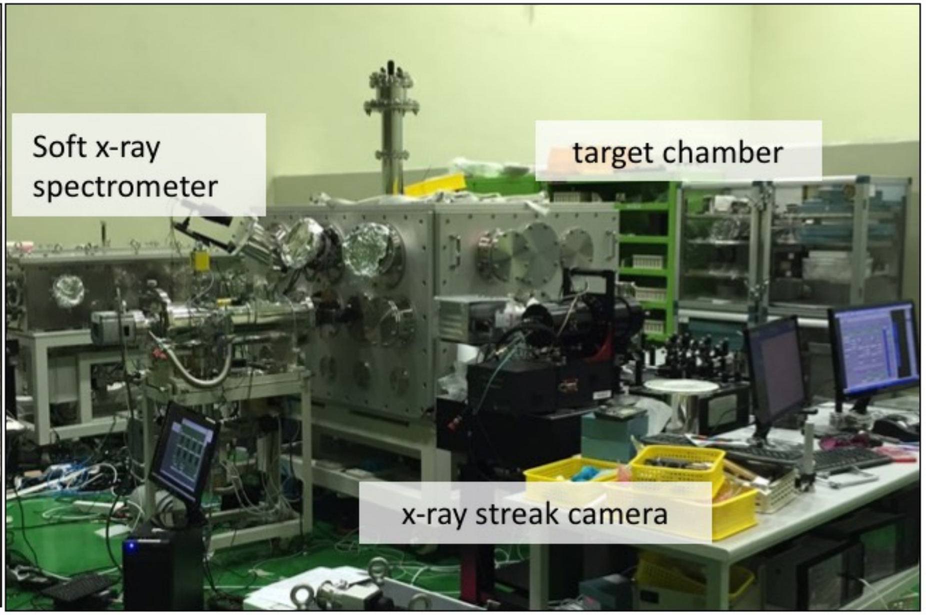
- **EUV spectroscopy at AS ~ FS scales**
  - non-thermal melting
  - core-electron dynamics
  - hot electron equlibriation

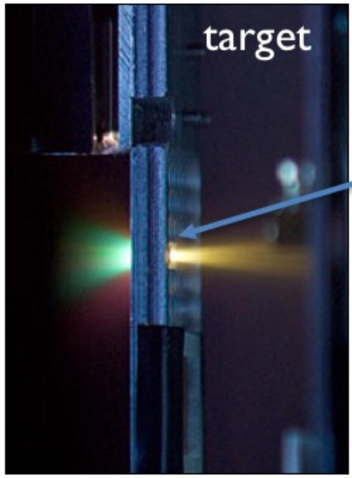
HED researches at GIST PW laser facilities



X-ray emission & absorption spectroscopy for laser plasmas

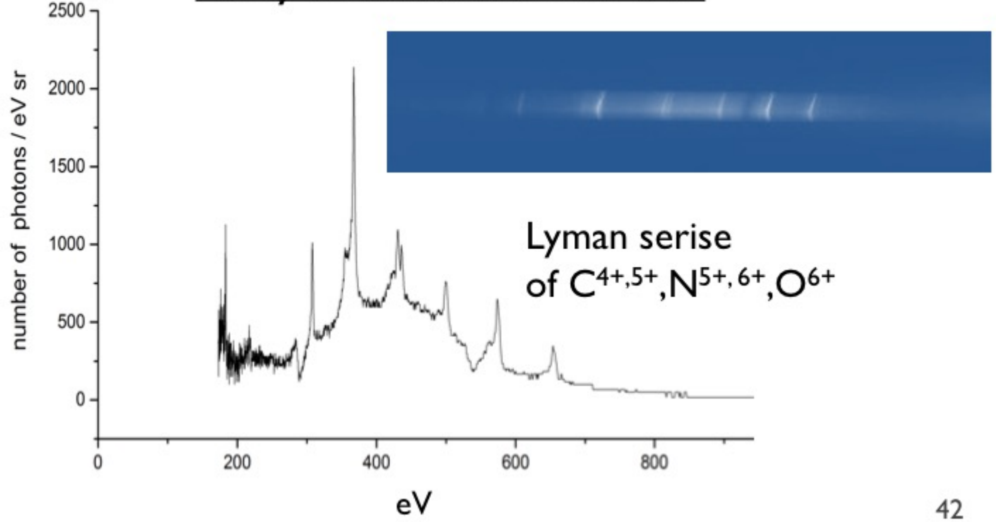






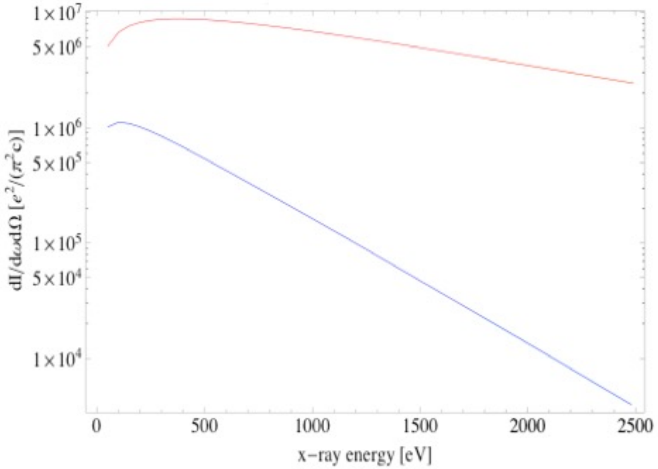
T_e ~ 10 keV
N_e ~ 10^{20} cm^3

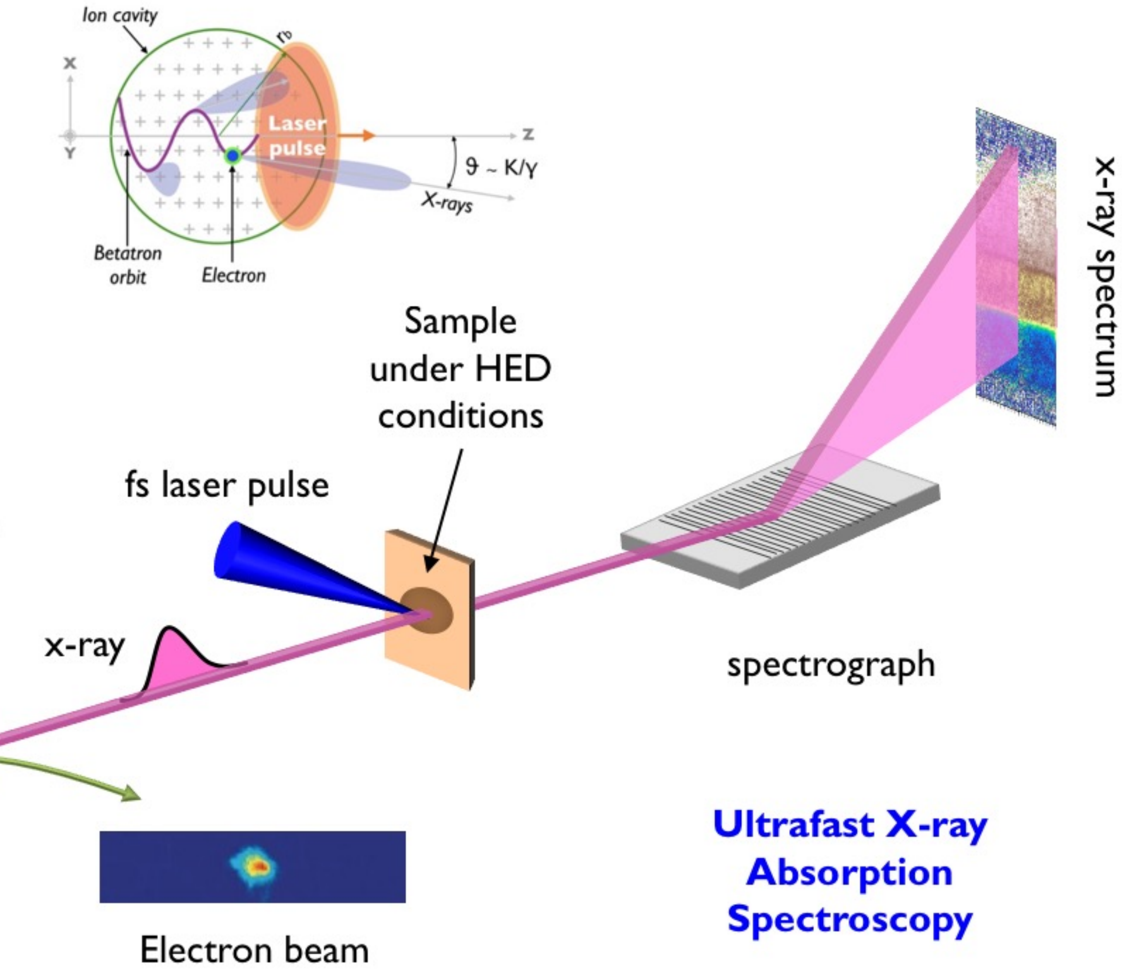
X-ray emission from PMMA



Betatron radiation from the wakefield accelerated electrons is broadband – femtosecond x-ray source

Betatron x-ray from 100 & 200 MeV e-beam





Ultrafast X-ray Absorption Spectroscopy

Ultrafast structural changes - non-thermal melting
Ultrafast electron dynamics – hot electron thermalization

Summary

- High Energy Density Physics is the study of matter at extremely high pressures and temperatures. The challenge of HEDP centers on difficulties in describing and measurement of the basic properties.

- With recent development of extreme light sources, which delivers large amount of energy in very short time scale (XFEL and PW lasers), qualitative physics experiment became feasible.

- Some fundamental properties of a few HED conditions (temperature, ionization potential, transmission, energy relaxation, etc) were experimentally measured recently, starting to provide benchmark data for theories.

- HEDP is closely related to plasma physics, condensed matter physics, optics, x-ray science, astrophysics, etc. We want to bring new experimental techniques and physical understanding from various disciplines and apply them for this new science.

High Energy Density Physics group at GIST