Ultrafast Dynamics in Dense Hydrogen Explored at FLASH

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on behalf of the TS team within the Peak Brightness Collaboration

HELMHOLTZ | ASSOCIATION

New Science Opportunities at FLASH

DESY Hamburg, Germany, October 12th – 14th , 2011

DESY

The Team

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- **DESY, Hamburg**

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Structure of the Talk

- XUV Thomson Scattering to diagnose Dense Plasmas
- Innovative Instrumentation at FLASH
- XUV-pump XUV-probe experiments
- IR-pump XUV-probe experiments
- Additional Diagnostics: TOF and “fs imaging system”
- Summary

Warm Dense Matter

Condensed Matter <> **Warm Dense Matter** <> Ideal Plasma

$E_{therm} \sim E_{Fermi}$

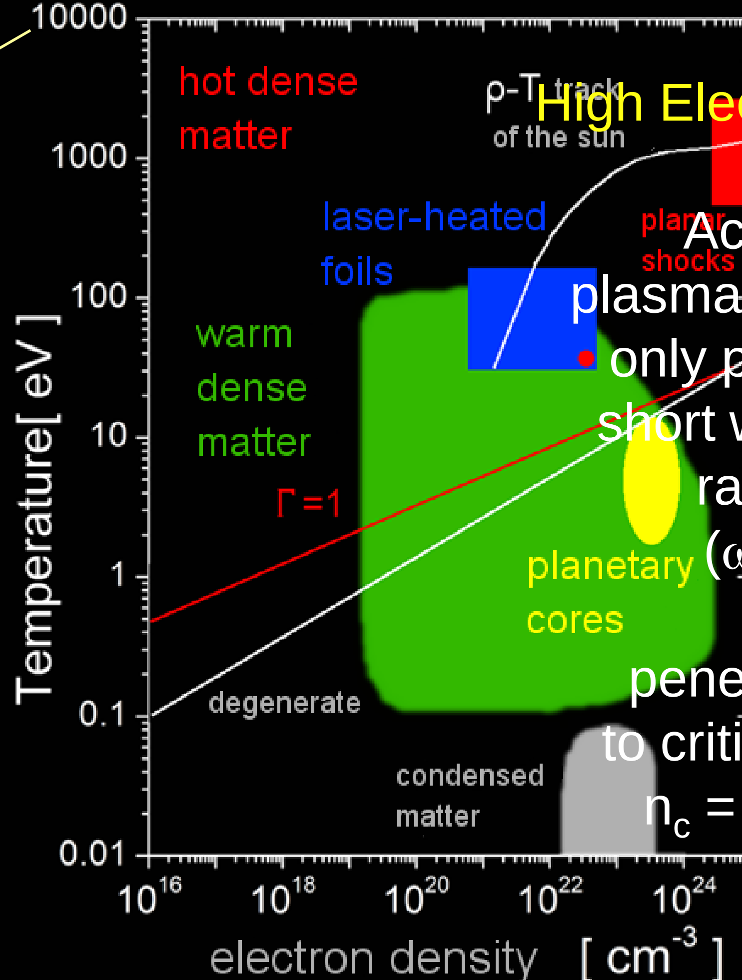
1..100 eV

$\rho_{WDM} \approx \rho_{solid}$

strong coupling

$\Gamma \geq 1$

$E_{coulomb} \sim E_{therm}$



High Electron Density:

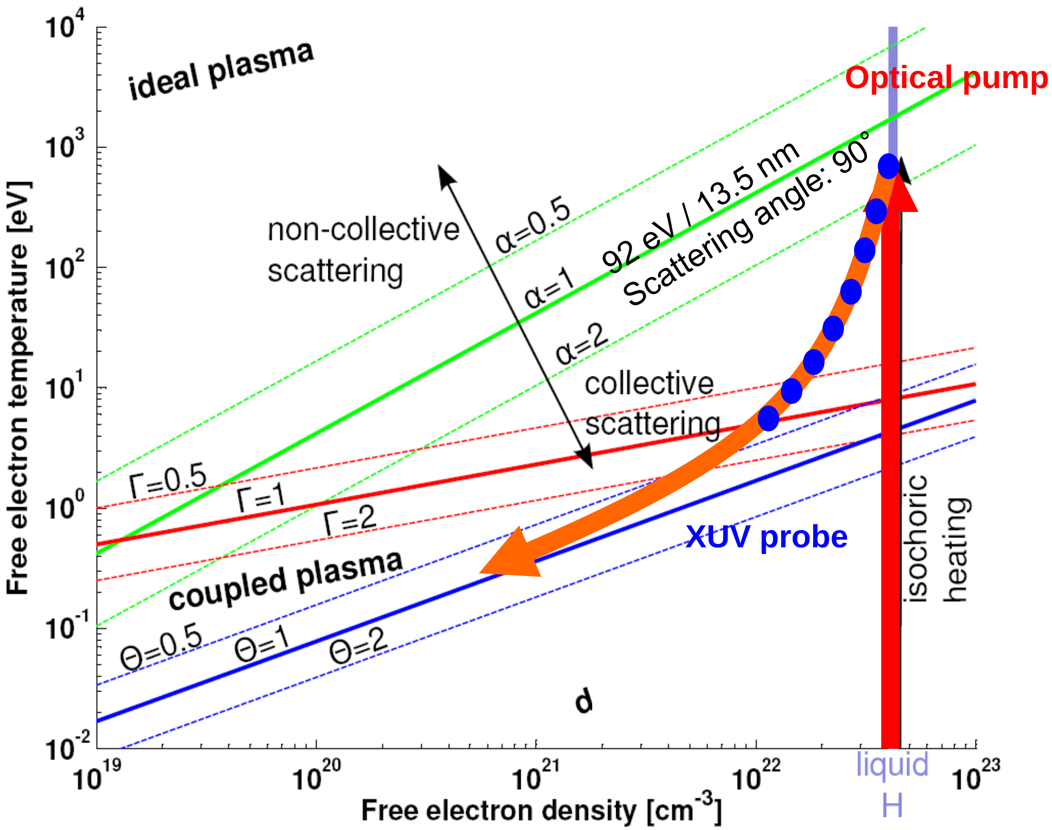
Access of plasma parameters only possible by short wavelength radiation ($\omega > \omega_P$)

penetration up to critical density $n_c = \omega^2 \varepsilon_0 m/e^2$

after R.W. Lee

Prepare and Investigate Warm Dense Matter (WDM)

Hydrogen **Temperature - Density** Phase Diagram



Pump-Probe Thomson scattering experiment

Collective Thomson Scattering → T_e, n_e

Temperature asymmetry via "detailed balance" relation:

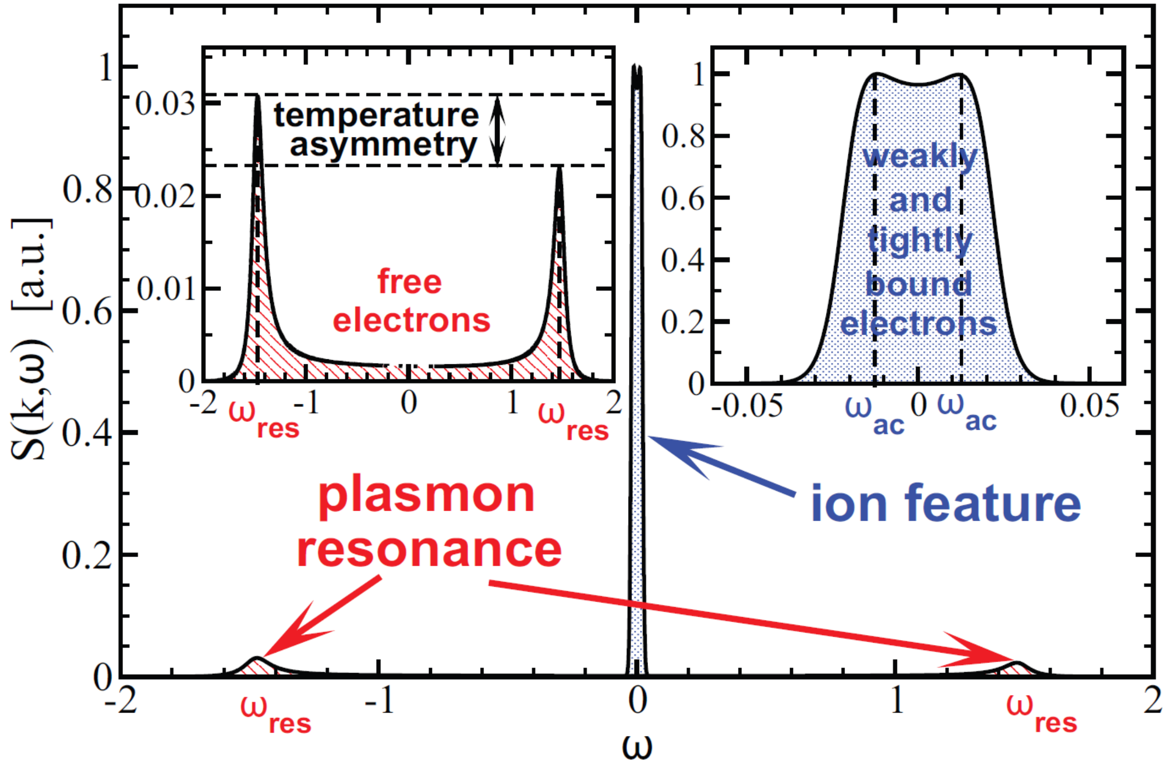
$$\frac{S(k,\omega)}{S(-k,-\omega)} = e^{-\hbar\omega/k_B T_e}$$

S(±k, ±ω): Structure factor

(applies only in case of a *Maxwell-Boltzmann* equilibrium plasma)

*A. Höll et al., HEDP **3**, 120-130 (2007)*

*S. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625–1663 (2009)*



Free-electron density via plasmon position by classical Gross-Bohm dispersion:

$$\omega_{res}^2(k) \approx \omega_{pe}^2 + \frac{3k_B T_e}{m_e}k^2$$

*Generalized Gross-Bohm: R. Thiele et al., Phys. Rev. **E 78**, 026411 (2008)*
Local field corrections: Fortmann et al., PRE (2010); Neumayer at al., PRL (2010)

FLASH after upgrade

Free electron LASer Hamburg

■ Photon energy	30-300 eV
→ Penetrates dense plasmas	
■ Pulse duration	~ 30-250 fs
→ Ultrafast processes	
■ Bandwidth	~ 1 %
■ Max. pulse energy	~500 µJ
→ Scattering diagnostic	
■ Repetition rate	10 Hz
→ Accumulate events	

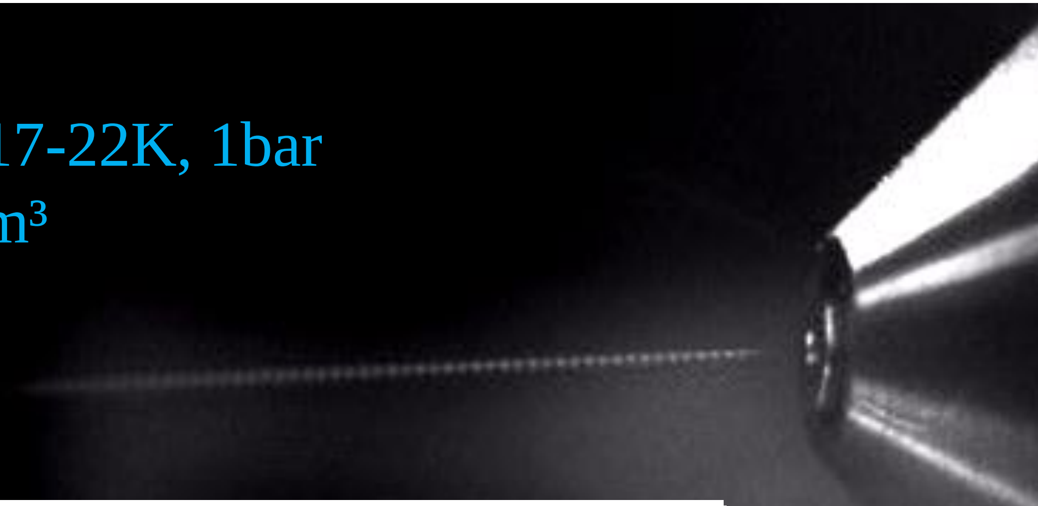
HIDRA Optical Laser

■ Energy	20 mJ
■ Pulse duration	50 fs
■ Repetition rate	10 Hz

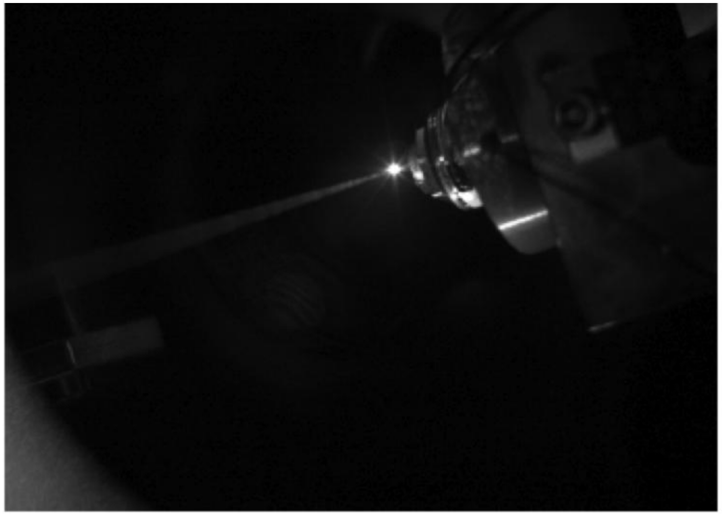
Ackermann et al., Nature Photonics 1, 336 (2007)

Liquid Hydrogen Beam

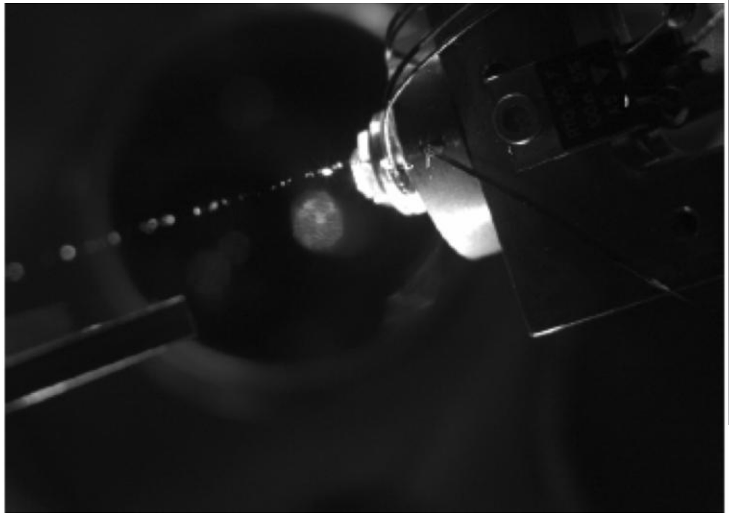
- He cooled cryostat
- 5 and 10µm droplets @ 17-22K, 1bar
- Solid density: 4.2 $10^{22}/cm^3$



FEL alignment Laser



Focused optical laser



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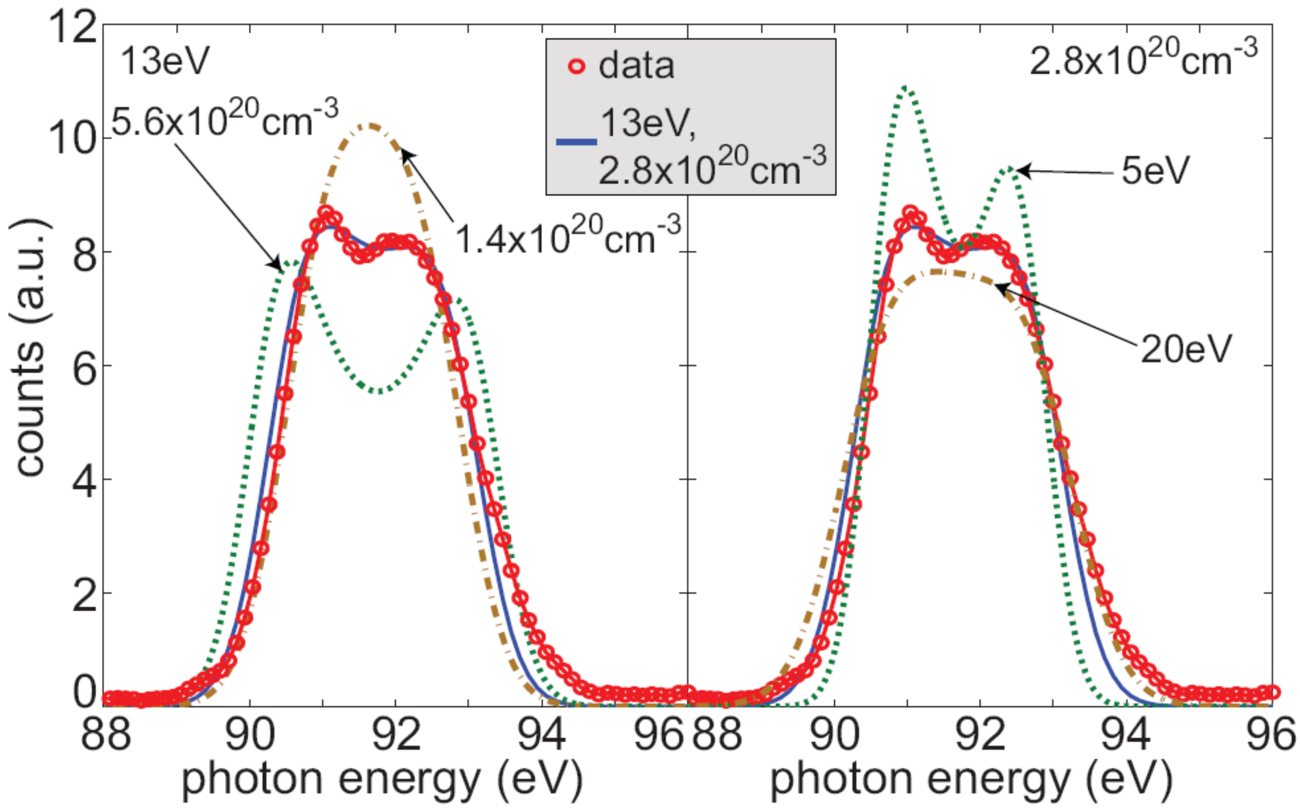
Former published Results – “Self” Thomson Scattering

FEL: ~$8 \cdot 10^{13}$ W/cm² heats and scatters during the FEL pulse

$S_{ii}(k) \sim 0$ – cold ions, warm free electrons

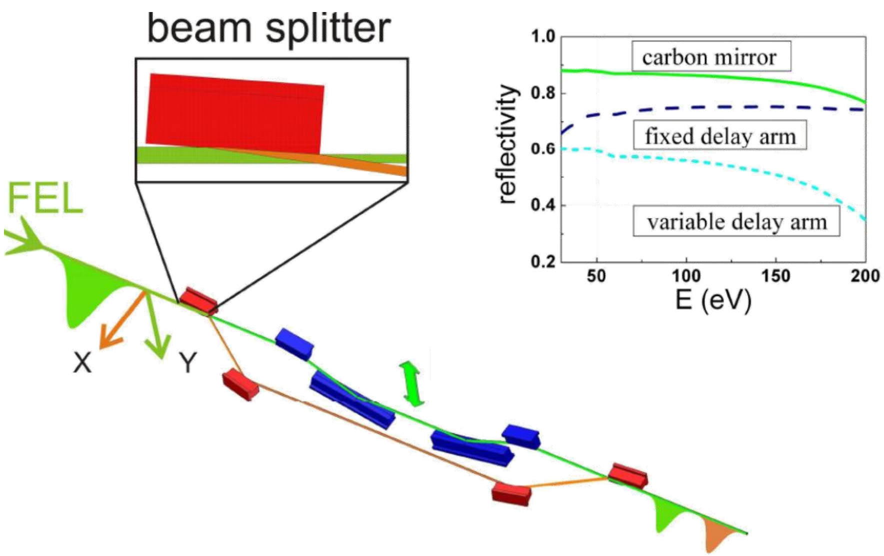


R. Fäustlin et al., Phys. Rev. Lett. ***104****, 125002 (2010)*

Next step : realize pump probe experiments to study dynamic of Warm Dense Hydrogen

First results : FEL pump / FEL probe

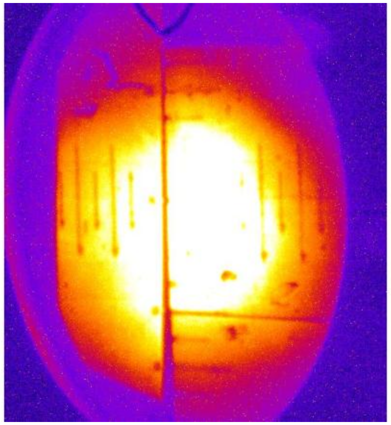
Thanks to operators B. Siemer and M. Woestmann, U Münster



R. Mitzner et al., Opt. Express ***16****, 19909 (2008)*

Beam on the Ce-Yag screen before the interaction chamber

ratio confirmed to be 1:1



- Delay : -1 to 5ps
- Overlap adjusted at -1, 0, 1, 2, 3, 4, 5 ps and interpolated in between

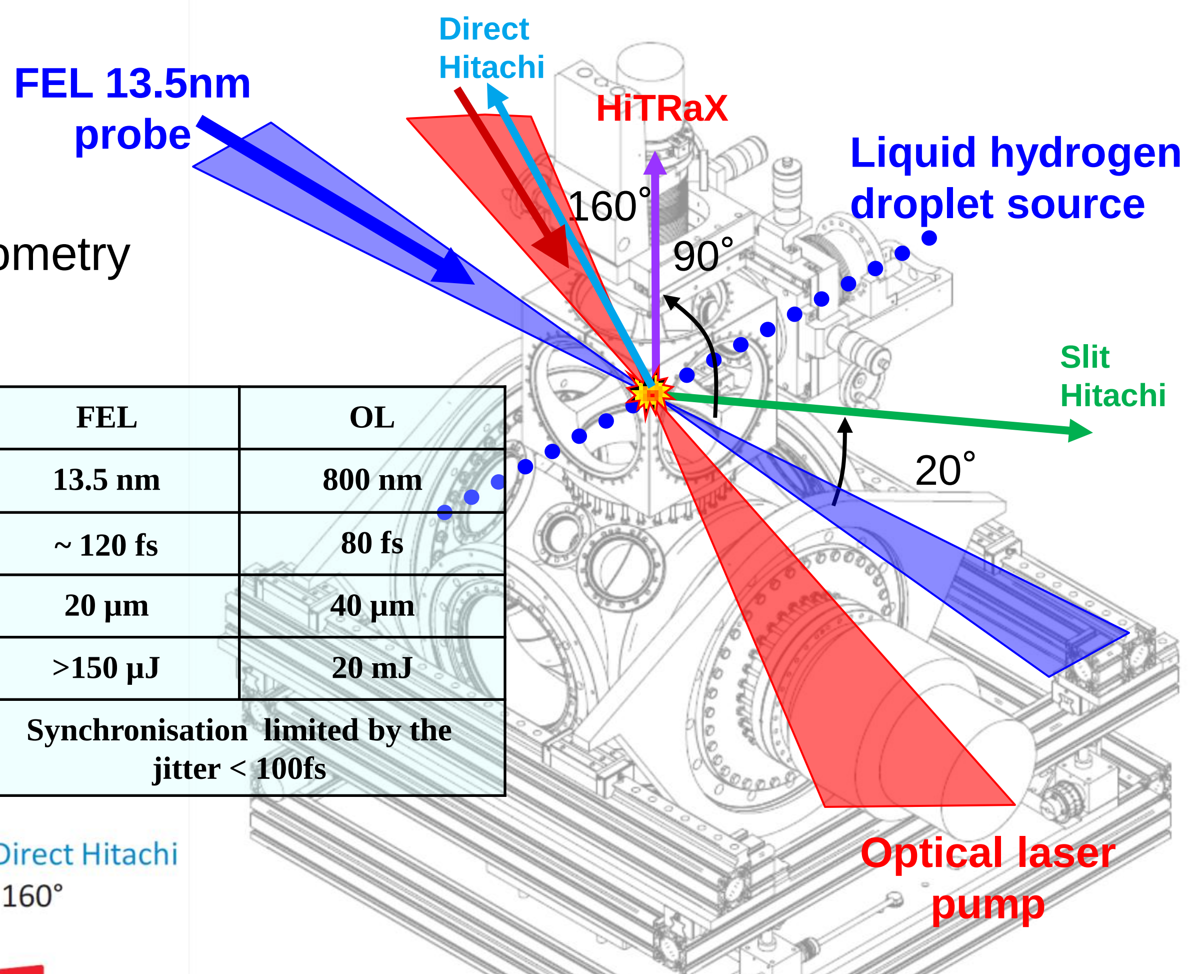
elastic (“Rayleigh”) scattering increases with pump probe delay
→ electron-ion equilibration time

New Experimental Setup (since October 2010)

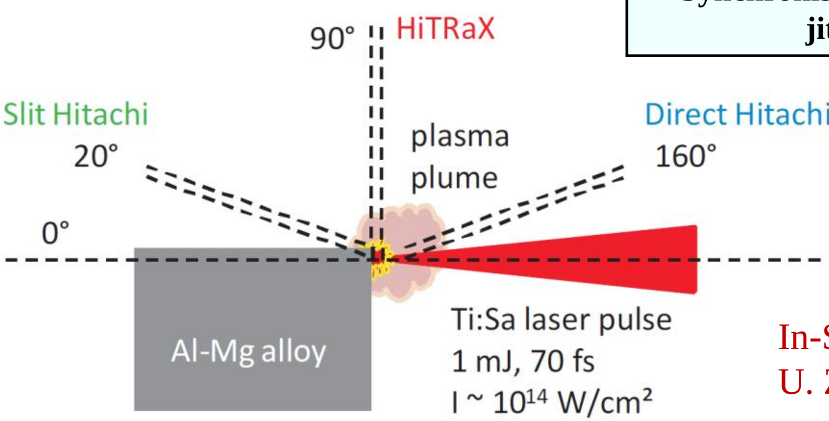
18 shifts @ FLASH in 2010/11

- Main diagnostics:
  4 XUV spectrometers to cover Θ = 20, 90, and 160°
- Non-co-linear pump-probe geometry
- Additional diagnostics:

  - ion TOF
  - long-range microscope
  - fs imaging system



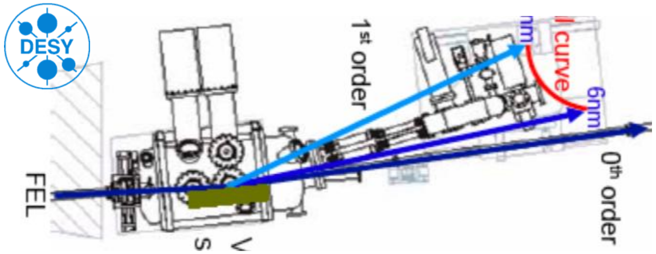
FEL	OL
13.5 nm	800 nm
~ 120 fs	80 fs
20 µm	40 µm
>150 µJ	20 mJ
Synchronisation limited by the jitter < 100fs	



In-Situ Characterization of all XUV Spectrometers:
U. Zastrau *et al.*, *JINST* **6** P10001 (2011)

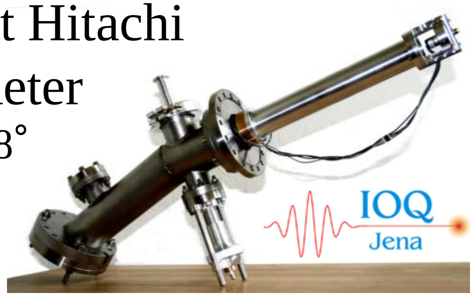
FSP 301: Innovative XUV Instrumentation for FLASH

VLS (FEL incident spectra)



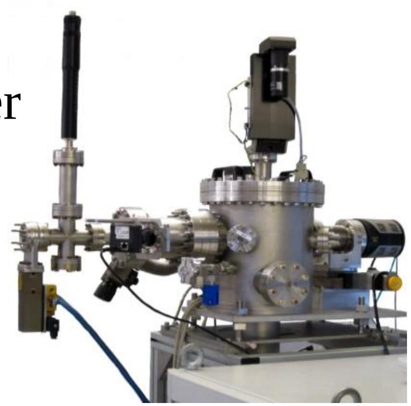
Relay-Slit Hitachi Spectrometer

angular: ±8°
spectral:
5-20nm



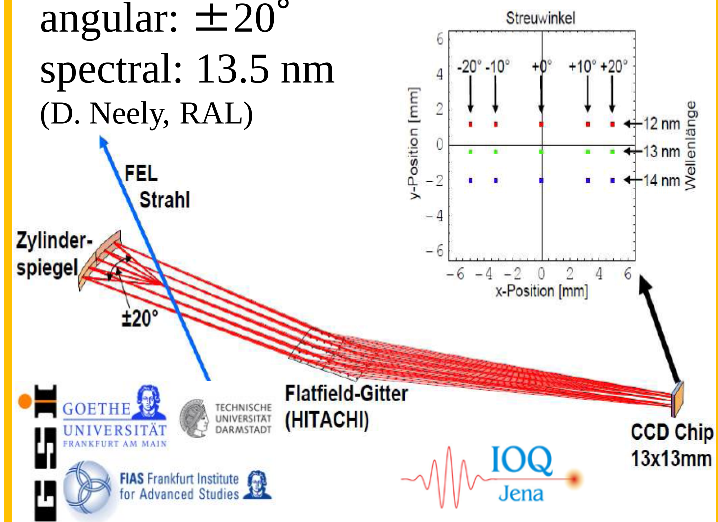
Compact Spectrometer

in transmission
behind setup



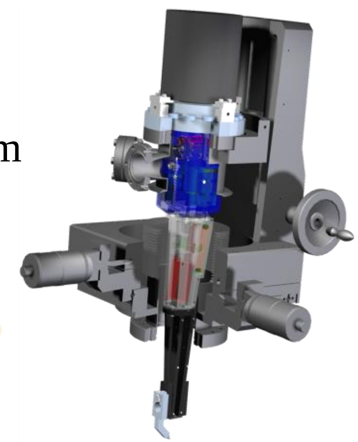
WASP Wide-angle Spectrometer

angular: ±20°
spectral: 13.5 nm
(D. Neely, RAL)



HiTRaX

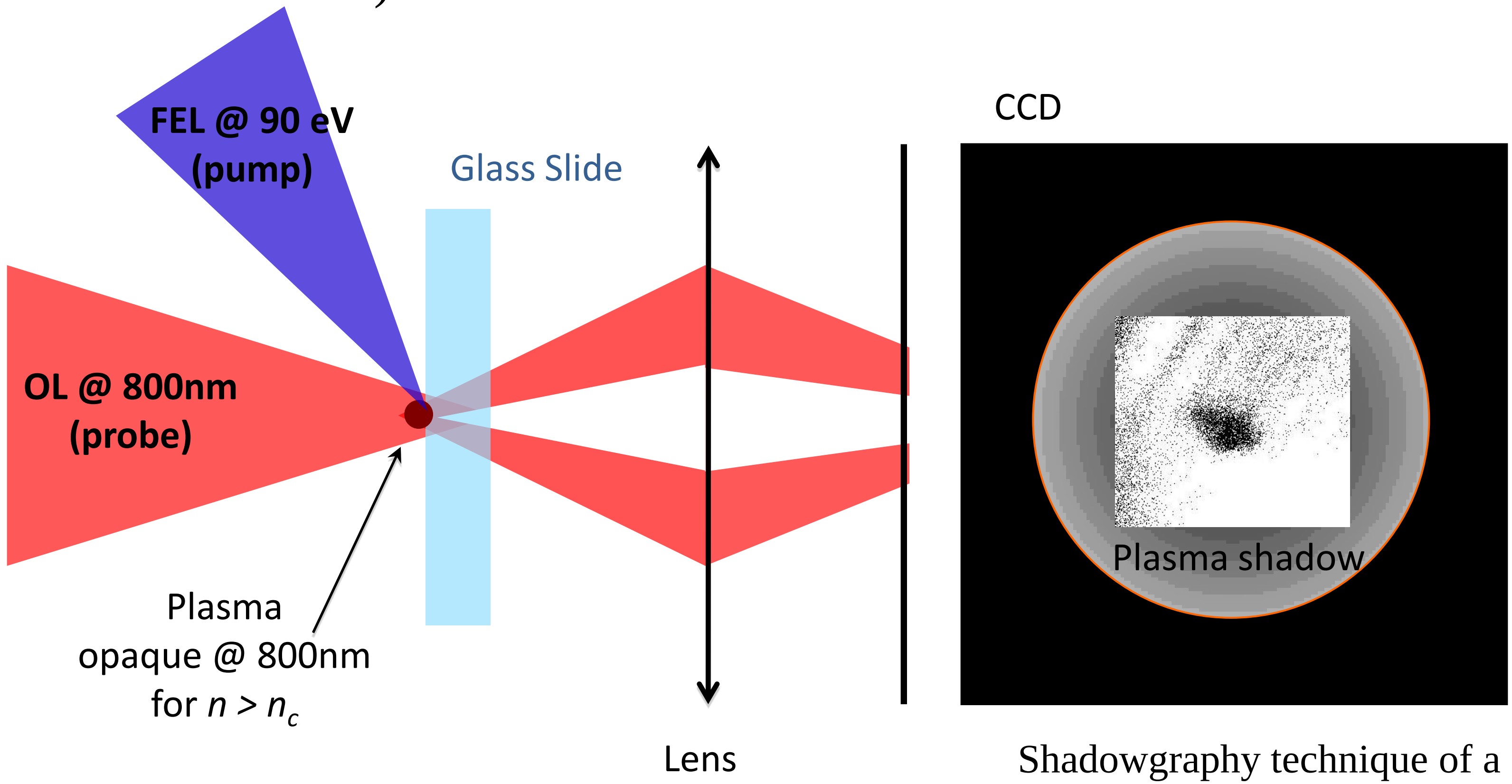
Mounted at 90°
Resolution 0.05nm
Range 7-31nm



R.R. Fäustlin et al., JINST 5, P02004 (2010)

OL – FEL spatial & temporal overlap

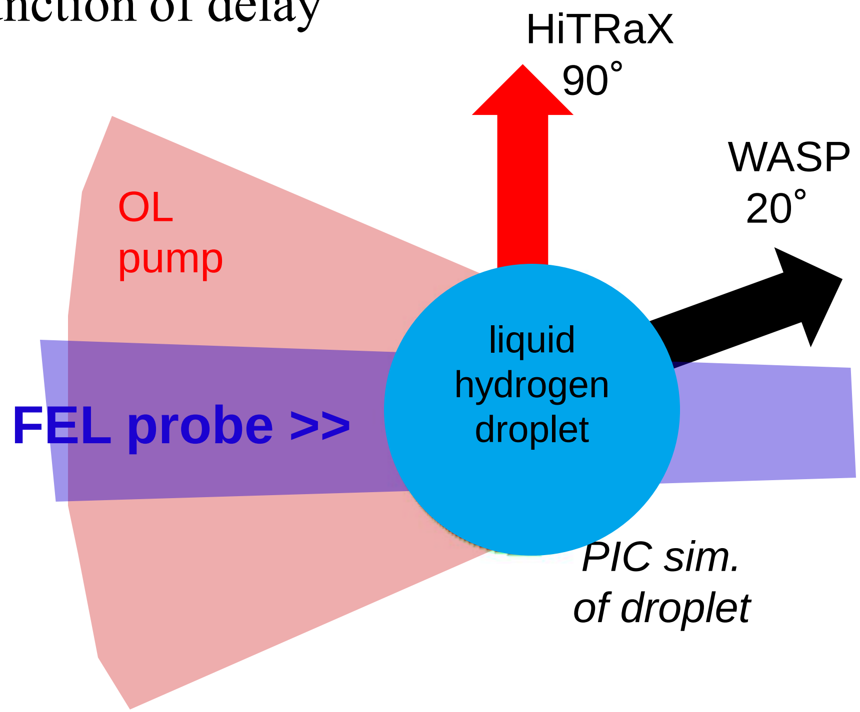
- Ce-Yag screen + Long range Microscope for coarse spatial overlap
- Fast diode for coarse time overlap (~10 ps)
- Imaging system using plasma switch method for fine temporal and spatial overlap (jitter limited ~ 100fs)



Shadowgraphy technique of a plasma created by the FEL

First Results : OL pump - FEL probe

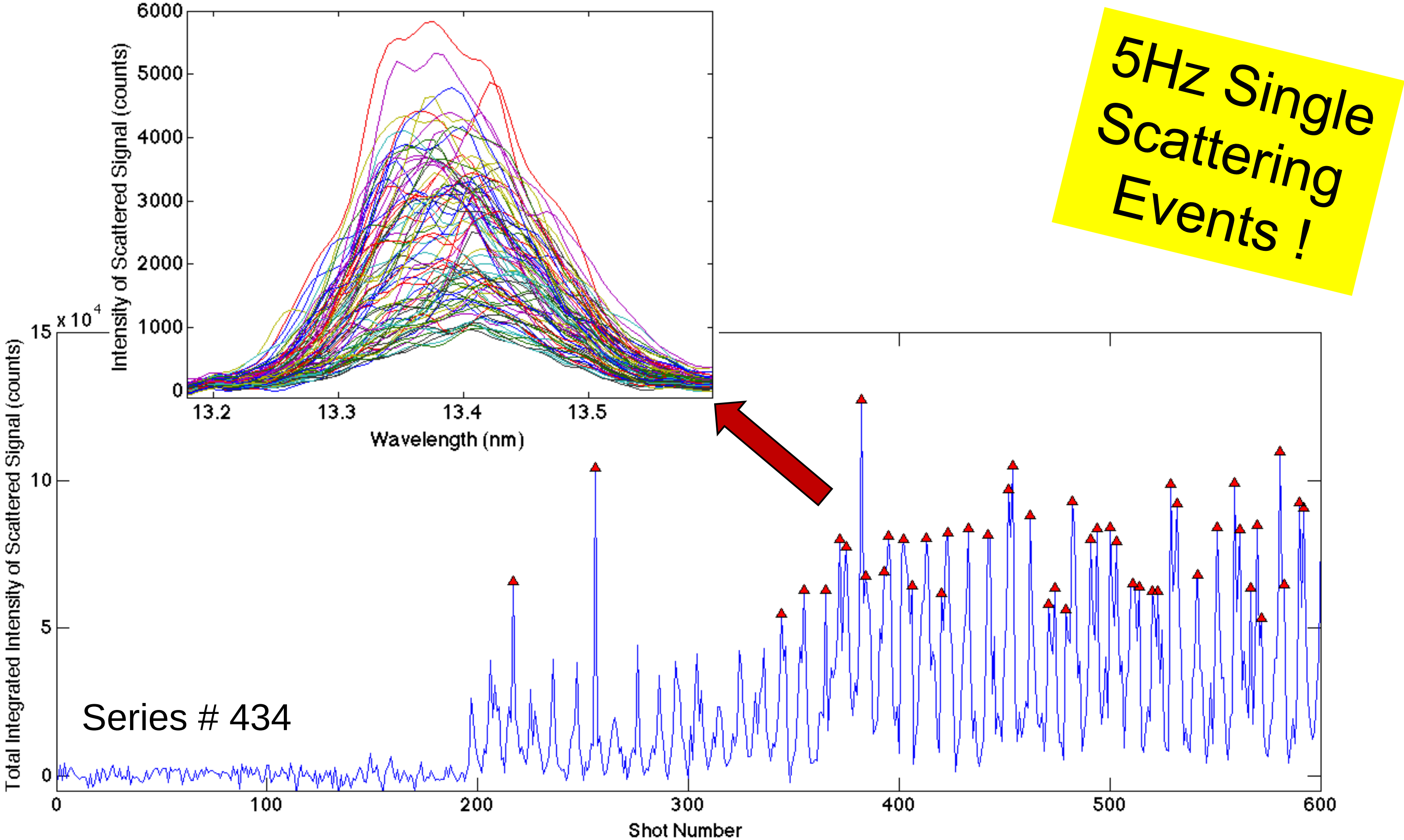
Integrated Rayleigh signal (elastic scatt.) as function of delay



- Strong pump-probe effect in the Rayleigh scattered signal
  → electron-ion equilibration
- The two spectrometer signals peak at different times after excitation (peak at ~200 fs or ~2.5 ps)
- → possible signature of **heat wave** or **strong absorption**

Approx. 500 000 single exposures: Data Analysis Scripting

The total integrated intensity over a specified scattered signal are plotted as a function of shot number → 30 best shots in the series are marked by the triangles



Courtesy of L. Fletcher, ALS Berkeley

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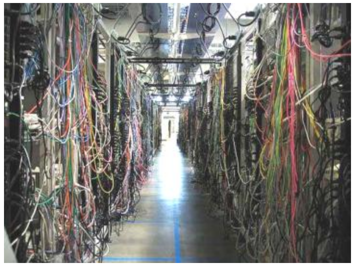
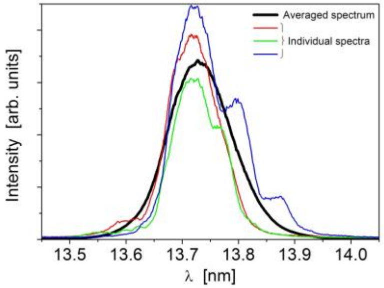
Challenges for this kind of experiments at FLASH

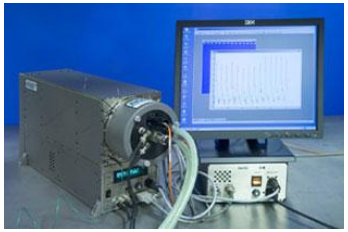


Central Data Aquisition Tool - Save all data by bunch ID

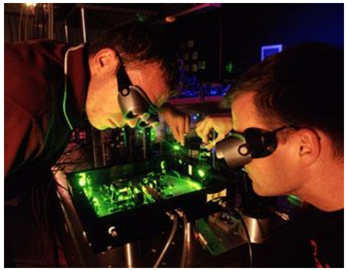
Measurement of incident FEL Spectra for every shot
with 10 Hz
→ we still observe a discrepancy between the FEL forecast and the experimental conditions
(varying bandwidth and/or pulse length)



Reliable OL – FEL drift measurement by Streak Camera
OL-FEL jitter measurement by TEO or other tool.



Powerful (pulse energy and menpower!)
optical laser facility, 10Hz



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Summary I

- We study warm dense hydrogen plasma, relevant for astrophysical phenomena, inertial fusion, and benchmark of theoretical models.
- Innovative XUV, optical, and particle diagnostics has been developed.
- Precise theoretical descriptions and powerful codes have been developed:

  - 2D-Hydro Code is under development
  - XUV absorption as function of density and temperature via DFT included
  - Rayleigh signal via Debye-Hückel description.
  → will be extended to a two-temperature HNC formalism for better time dependence.

- The experimental results are promising:

  - pump-probe measures of the scattered signal
  - for 20, 90, and 160° scattering angles
  - for various heating conditions (13.5nm, 800nm, pulse duration, energy…)

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Summary II

-electron-ion equilibration times from the rising edge of the elastic scattering
-temperature relaxation by expansion
-differences between heating by IR laser and XUV FEL (homogeneity)
-indication of inelastic scattering events

- Ion and PES TOF indicate
  OL heating: a partial explosion of droplets
  FEL heating: different oscillations in photo electron distribution.

- Analysis of 500'000 individual spectra is going on in parallel with calculations.

- Experimental Goal:

  Measure elastic ("Rayleigh") and inelastic ("Plasmon") scattering signal
  with spectral, temporal, and angular resolution.