The role of low energy seeded FELs in x-ray science: Fermi@Elettra

(a view biased towards atomic and molecular science)

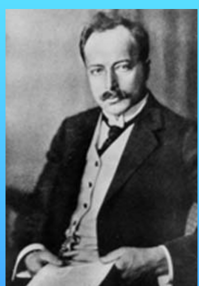
K.C. Prince
Sincrotrone Trieste S.c.p.A.,
Trieste, Italy.

Outline.
History of x-rays.
Characteristics of Fermi
Which experiments?
Future

A short history of x-rays

"Each time history repeats itself, the price goes up."

1895. Wilhelm Röntgen, first description of x-rays. Nobel Prize, 1901.
Cold cathode tubes.



1914. Max von Laue,
diffraction of x-rays by crystals.
Nobel prize.

1915. W. H. and W. L. Bragg, crystal structure analysis. Nobel prize.

1917. Charles Barkla, characteristic
emission spectrum of gases. Nobel prize.

1924. Manne Siegbahn, x-ray spectroscopy. Nobel prize.

The first quarter of the 20th century: x-rays went from being "just discovered" to a routine medical and crystallographic tool.

There were few major developments in sources for another half century or so.

1944. Ivananko and Pomeranchuk predict synchrotron radiation.

1947. Observation of synchrotron radiation.

1950s. Parasitic use of synchrotron radiation (first generation).

1980s. Purpose built synchrotron radiation sources (second generation – "dedicated".)

(1981. Kai Siegbahn, electron spectroscopy. Nobel prize. No more prizes for "x-rays", but Prizes for their application, as in electron spectroscopy.)

1990s. Low emittance, insertion device based synchrotron radiation sources (third generation)

2000. Lasing at FLASH (TTF)
2005. FLASH FEL starts operation.
2006. First lasing, SCSS FEL, SPring-8.
2009. LCLS FEL starts operation.

...and then there is harmonic generation.....

The discovery of x-rays was followed by three decades of outstanding applications and breakthroughs.

“Conventional” sources initially developed, then showed modest improvements.

From the middle of the 20th century, synchrotron light sources developed., culminating in third generation , undulator based, sources. Unprecedented brightness, tunability, polarization control. Useful time structure.

In the first decade of this century, FELs began operation. Unprecedented brightness, peak power and time structure.

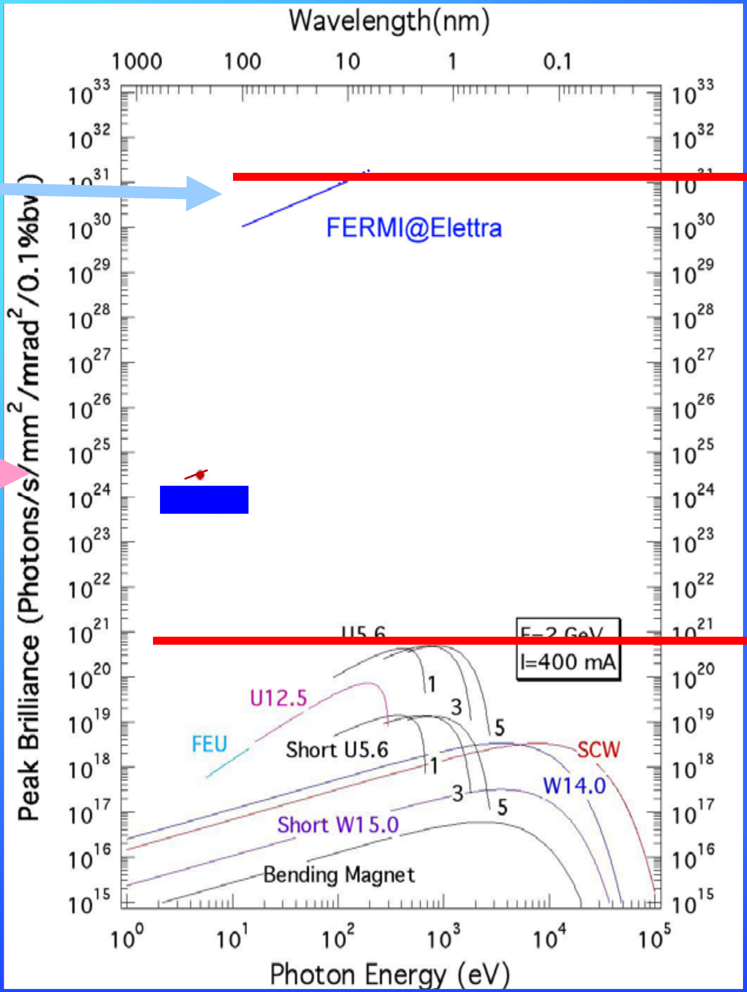
The word “free” in Free Electron Laser is a subtle joke: they are far from free.

“Each time history repeats itself, the price goes up.”

Why build FELs?

FERMI@Elettra FEL

ELETTRA
Storage Ring FEL

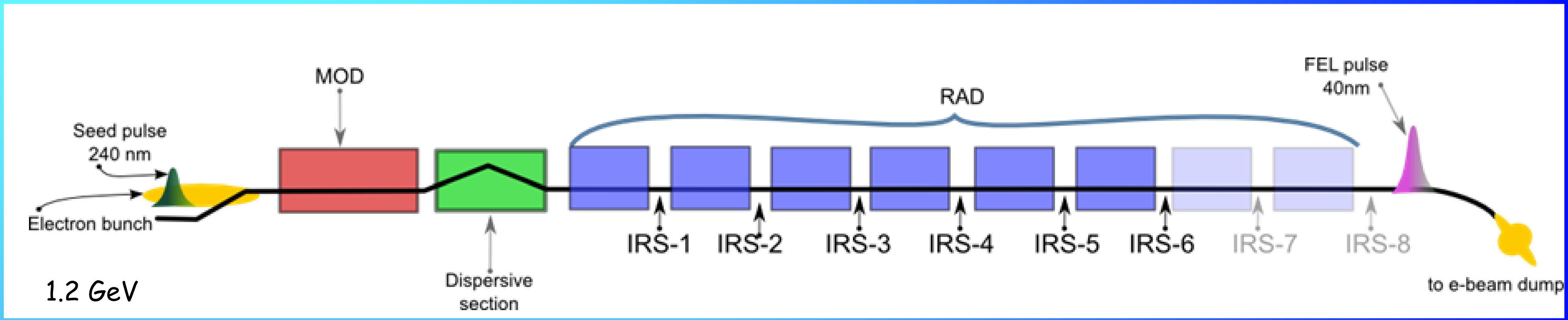


$P \sim N_e^2$

10^{10} Increase

$P \sim N_e$

FERMI I layout



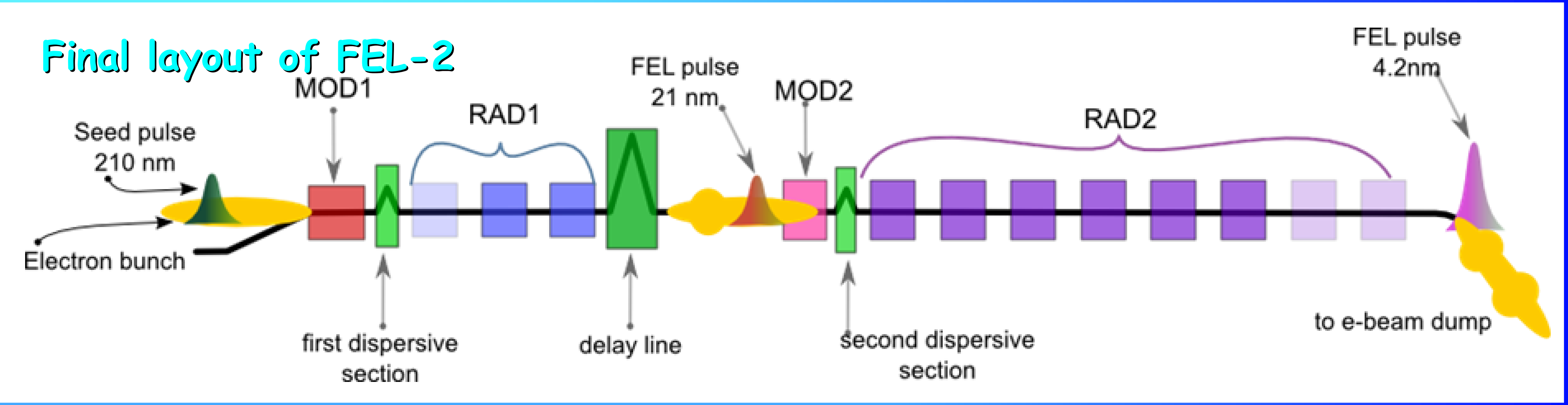
A 240 nm pulse (100-150 MW) co-propagates with the electrons in the modulator, modulating their energy.
The dispersive section converts energy variation to spatial dispersion: micro bunching.
In the radiator (55 mm period, 3.6 m), the electrons radiate.

Advantage of seeding over SASE: greater wavelength stability, coherence.
Quick switching of polarization –vertical, or horizontal linear, left or right circular.

Specifications: 30-100 fs pulse, 100-20 nm, (12-62 eV), stable to within bandwidth of 20-40 meV.
$2 \cdot 10^{14}$ photons/pulse @ 100 nm, $4.5.10^{13}$ @ 20 nm, 1-5 GW peak power.
Rep rate: 10 to 50 Hz.

Thanks to Enrico Allaria.

FERMI II layout



FEL2 works in cascade. A short radiator produces a 21 nm pulse that then repeats the scheme of FEL1 (modulator, dispersion section, radiator).

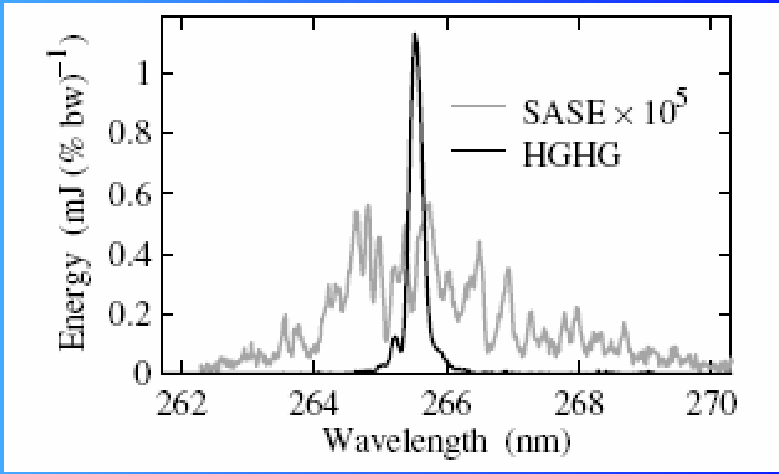
RAD1 undulators are 55 mm period, RAD2 35 mm.

Specifications: < 100 fs pulse length, 20-3 nm (62-413 eV), stable to within bandwidth of 20-40 meV
peak power 1 GW, 1×10^{13} ph/pulse (120 eV), 7×10^{12} ph/pulse (240 eV)
Rep. rate 10-50 Hz.

Why is seeding useful?

Compared with SASE,
the photons arrive in a narrower, more stable, more coherent bandwidth.

"Nearly transform limited."



Yu et al, PRL 91 (2003) 074801.

FERMI is being developed as it is being built:
initial specification for FEL II was up to 126 eV – now it is 413 eV
machine physicists investigating chirped pulses, increasing or suppressing third harmonic, coherence with first harmonic.

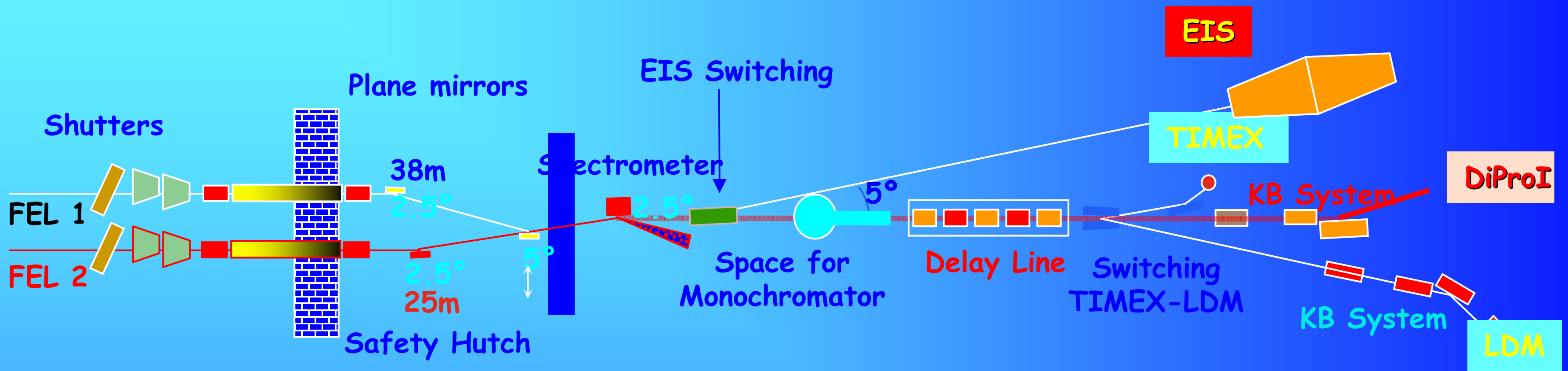
Present status: start operations at beginning of 2011.

"It is better to travel hopefully than to arrive."

http://www.elettra.trieste.it/FERMI/index.php?n=Main.Cam

18 : 40 : 08 | 6 / 08 / 2010

Fermi beamline layout



PADRES

Photon Analysis Delivery and Reduction System.

Contact Daniele Cocco.

Rev. Sci. Instrum. **80**, 113110 (2009)

Beamlines:

LDM: Low Density Matter

Diproi: Diffractive and Projective Imaging

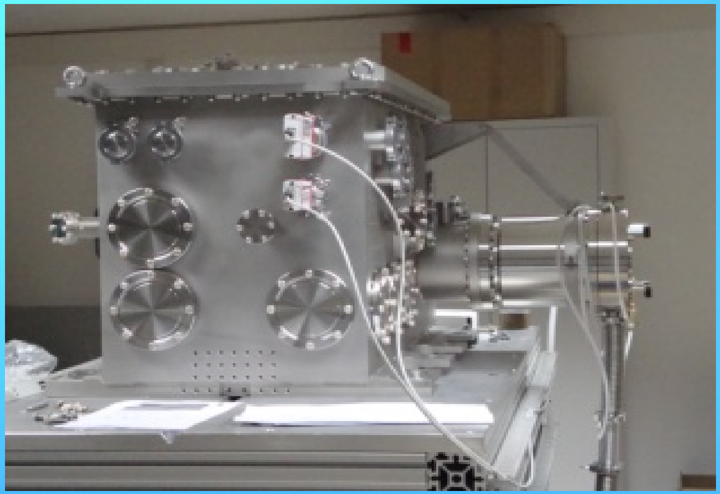
EIS (timex): Elastic and Inelastic Scattering

Shot-to-shot diagnostics, common to all beamlines:

photon energy, from a weakly diffracting grating
energy/pulse, from gas cell
beam position, from beam position monitor.

Gas cell: to attenuate intensity, filter higher orders

DiProI:
multipurpose experimental station

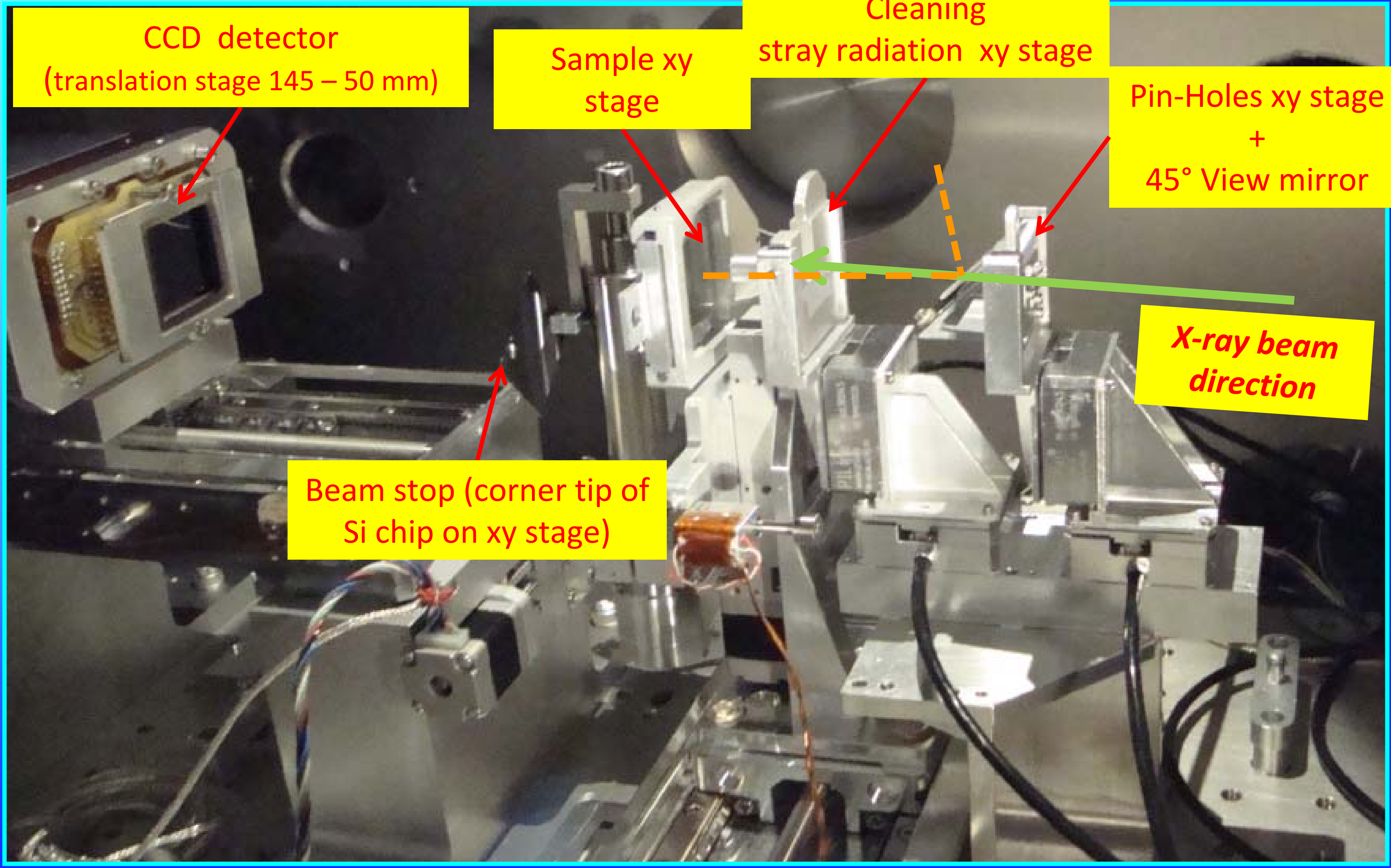


Maya Kiskinova (coordinator), Flavio Capotondi Emanuele Pedersoli, Ralf Menk, Burkhard Kaulich & Onur Mentes, Daniele Cocco et al
Partners: Henry Chapman (CFEL-DESY), Janos Hajdu(Uppsala), Mike Bogan, Mike Pivovaroff, Art Nelson (LLNL) et al

Experimental station under test at Elettra.

1. **Single-shot CDI: morphology and internal specimen structure at the nm scale resolution with 3D information for reproducible objects. tunability for optimization scattering efficiency and control radiation damage!**
2. **Resonant CDI: 'chemical' and 'magnetic' imaging exploring multiple polarization!**
3. Single-shot dynamic CDI of non-repetitive phenomena where radiation-induced damage (e.g. non-thermal melting or ablation) or intrinsic specimen fluctuations prevent the repeated accumulation of data.
4. Transient nanoscale dynamics of materials: condensed phase dynamics such as structural deformation, magnetic domain dynamics, phase separation and nucleation, complex rearrangements of constituents in cells etc.

SR Detector Configuration



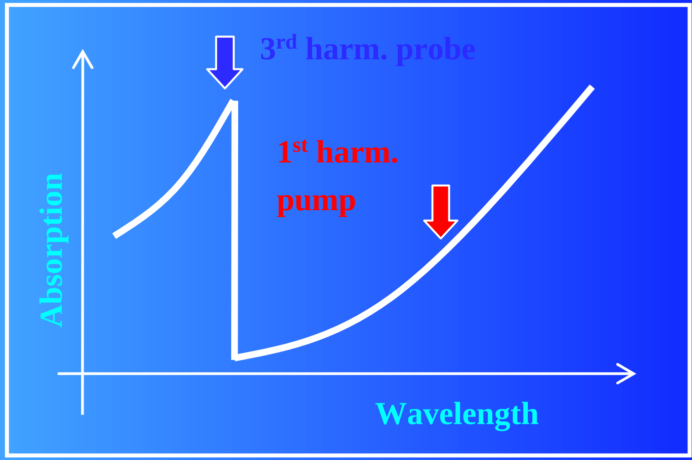
EIS beamline (TIMEX)

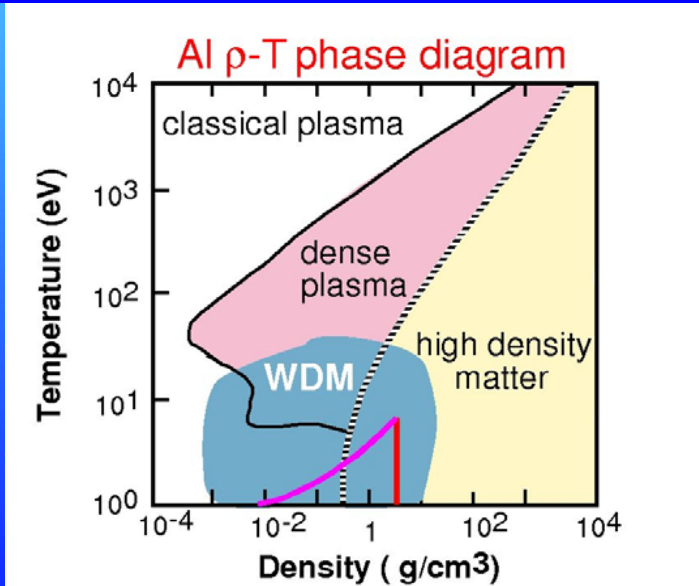
EIS team: C. Masciovecchio, F. Bencivenga, R. Cucini (TIMER), F. D'Amico (TIMEX) + TIMEX collaboration (A. Di Cicco et al.)

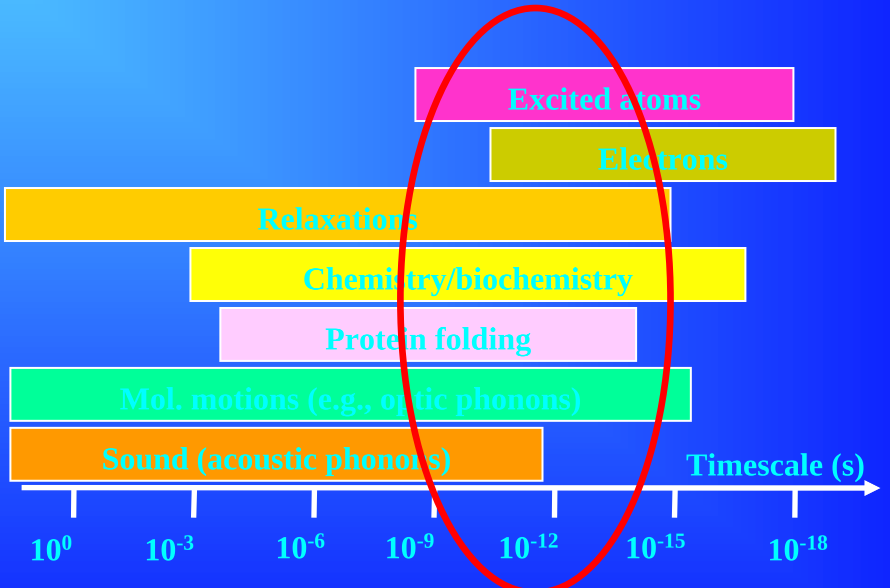
Peak power → Generation of Warm Dense Matter (WDM), metastable states, phase transitions, etc.

Short pulses → Time resolution (dynamics)

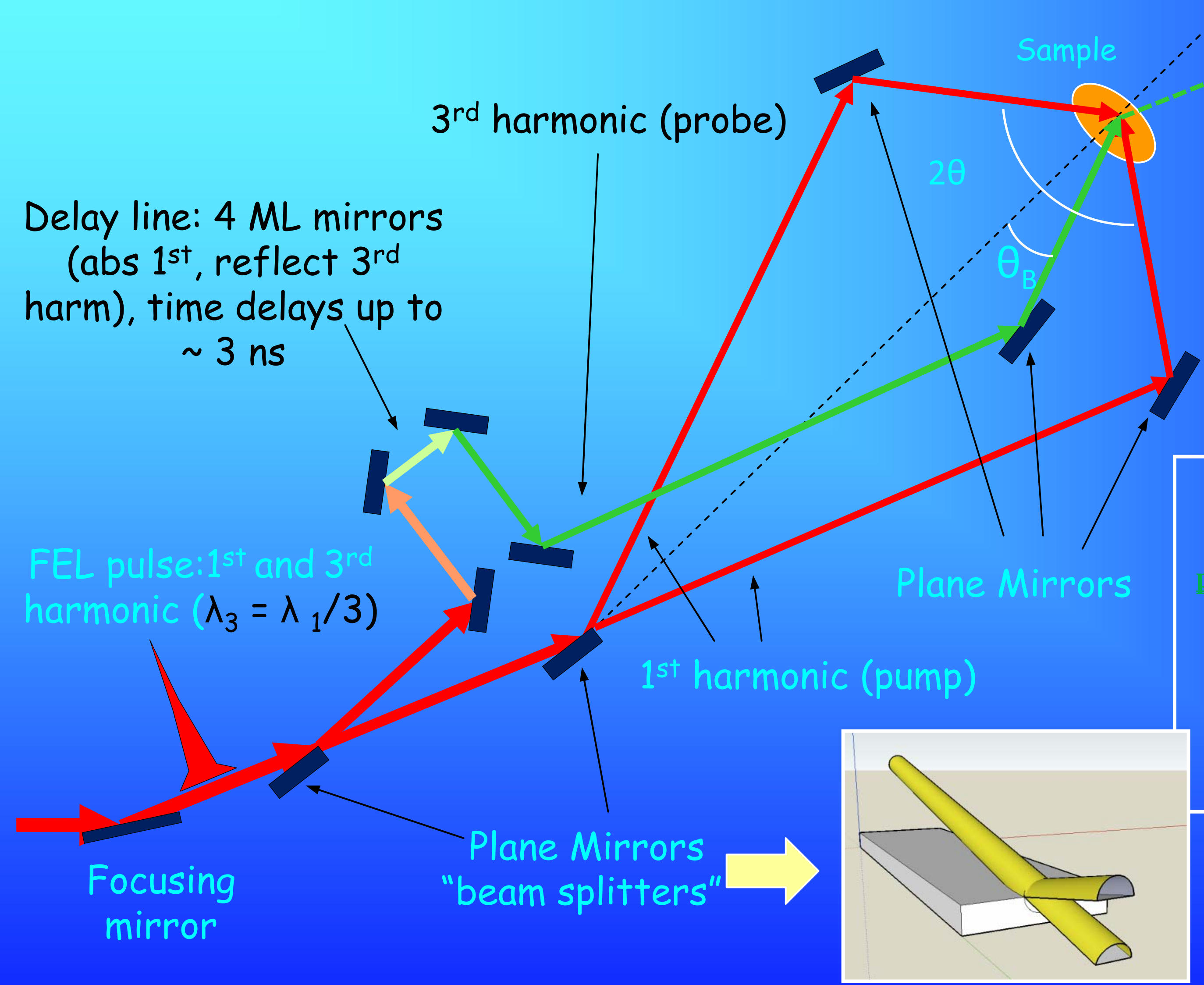
$1^{st}+3^{rd}$ harmonic (or FEL+laser) → Two colors pump-probe experiments (e.g., XAS)

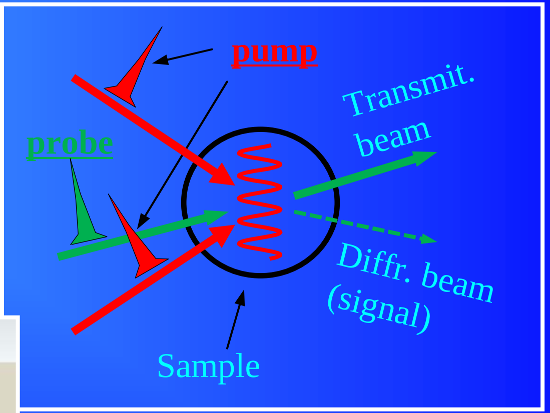






Beamline layout (TIMER)



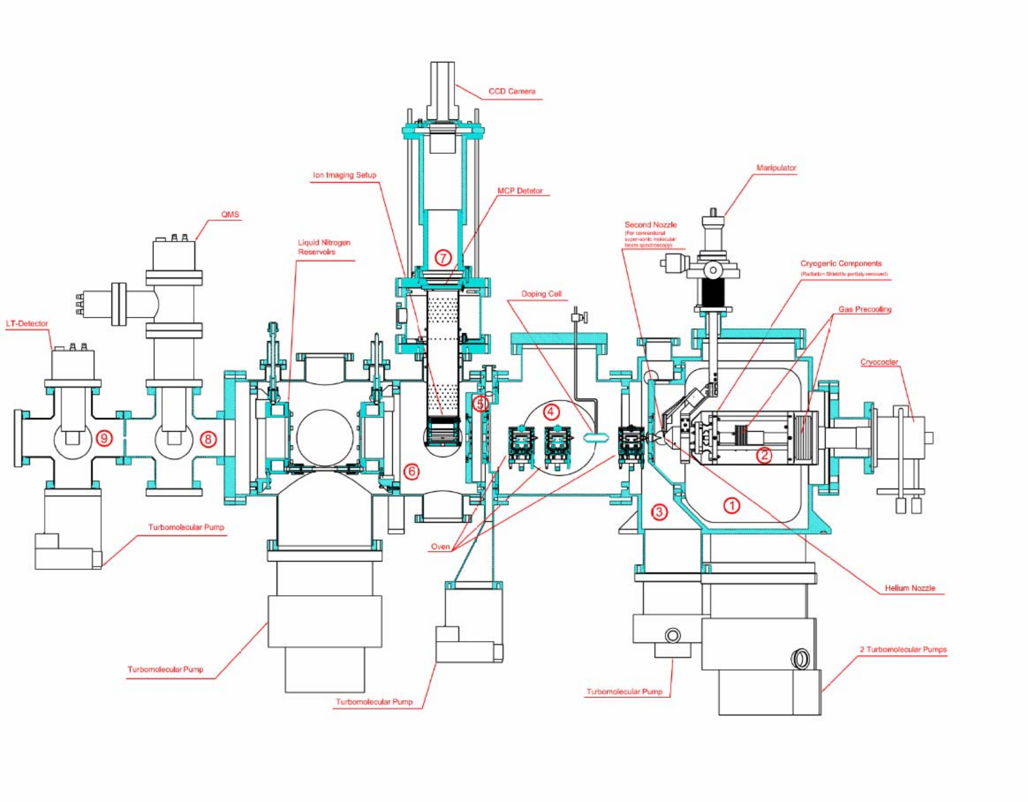


TIMER first experiment expected in **Dec. 2011**

Low Density Matter

Consortium spokespersons:
Elettra: Carlo Callegari (coordinator)
Kevin Prince
Uni Freiburg: Frank Stienkemeier
Technical Uni Berlin: Thomas Moeller
Uni Milano: Paolo Piseri
Uni Rome: Stefano Stranges

Flexible source of helium droplets, clusters (noble gas, metals, etc.) and atomic/molecular beams.
Electron, ion and photon detectors.



End-station under construction in Freiburg. Detectors under construction in Berlin. Sources of clusters and radicals under construction.

When will all this be ready?

Schedule:
lasing in December 2010/Jan 2010
Beamlines installed April 2011
Installation of beamline pump laser, FEL beam splitter during 2011.
2011: commissioning and test experiments
Then open to user proposals.
2012: FEL2

Which experiments?

- High number of photons: very low density targets.

Helium droplets: biomolecules, clusters, radicals

Clusters of refractory metals, oxides etc.

- High power:

non-linear optics: two photon absorption, sequential and non-sequential

adjustment of the Keldysh parameter

field effects such as AC Stark, Autler-Townes, electromagnetically induced transparency.

- Fast pulses – dynamics via pump-probe, double (shallow) core holes

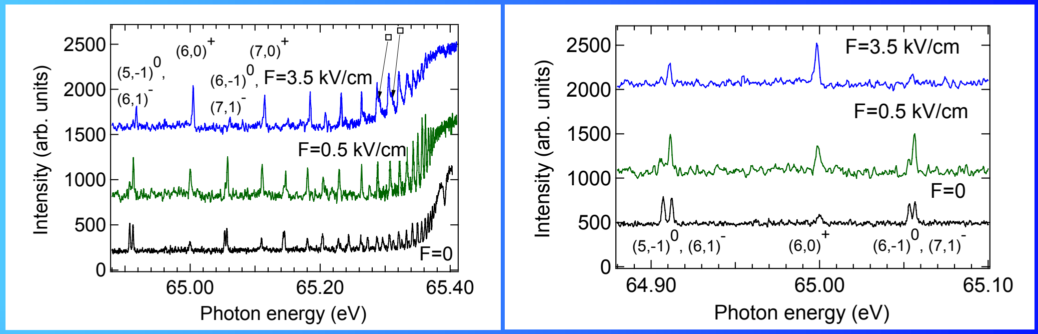
All this with polarization control and wavelength stability.

Example: two photon excitation of He

Much has been done at FLASH,
much has been calculated.
We can contribute angle resolved photoemission,

Single photon absorption: Δl=1.
Two photon absorption: Δl=0, 2.

Even states are also visible via the Stark effect: (PRL 96 (2006) 093001).
Only resonant states observed.

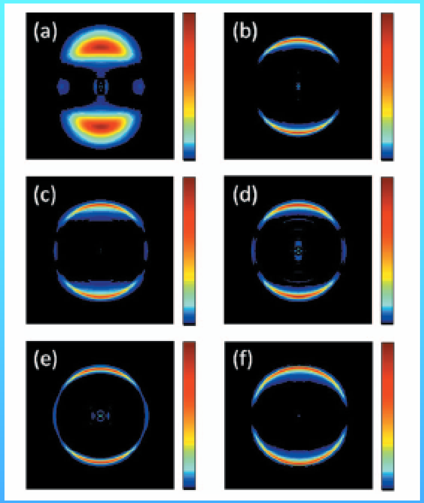


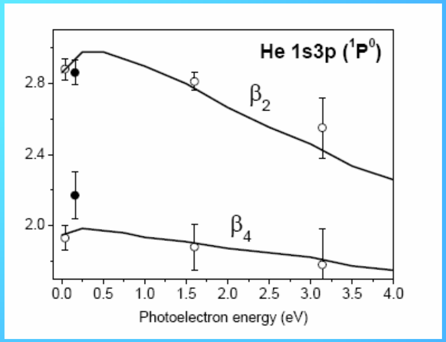
Work done at FLASH

T. Laarmann et al, Phys. Rev. A **72** (2005) 023409; Phys. Rev. A **74**, 037402.
A. Maquet et al, Phys. Rev. A. **74**, 027401 (2006).
D. Charalambidis et al, Phys. Rev. A **74**, 037401 (2006).
R. B. de Castro et al, Phys. Rev. A **74**, 027402 (2006).
L. A. A. Nikolopoulos and P. Lambropoulos, Phys. Rev. A **74**, 063410 (2006).
M. Nagasono et al, Phys. Rev. A **75**, 051406(R) (2007).

Two colour work

Resonant





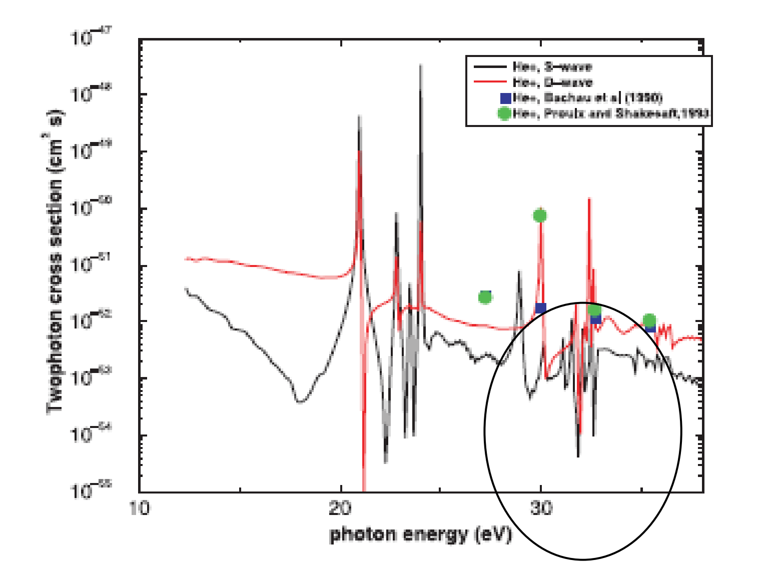
P. O'Keefe et al, J. Physics: Conf. Series 235 (2010) 012006

Haber, Doughty, Leone, PRA 79 (2009) 031401R

Non-resonant, theory

T. Laarmann et al, Phys. Rev. A **72** (2005) 023409
M. Meyer et al., Phys. Rev. A **76**, (2006) 011401R
A. Maquet et al, Phys. Rev. A. **74**, 027401 (2006).
D. Charalambidis et al, Phys. Rev. A **74**, 037401 (2006).
R. B. de Castro et al, Phys. Rev. A **74**, 027402 (2006).
T. Laarmann et al, Phys. Rev. A **74**, 037402.
L. A. A. Nikolopoulos and P. Lambropoulos, Phys. Rev. A **74**, 063410 (2006).
Mitsuru Nagasono et al, Phys. Rev. A **75**, 051406(R) (2007).

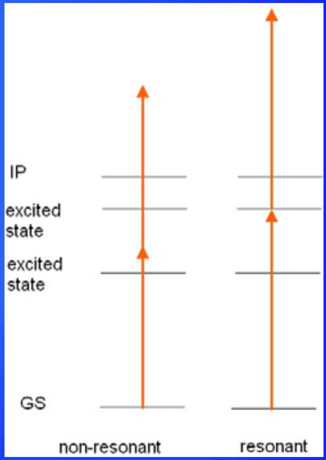
Two photon single ionization of He



He, 2 photon absorption
(L.A.A. Nikolopolous and P. Lambropolous, J. Phys. B: At. Mol. 34 (2002) 545.)

Cross-section is 10^{-50}-10^{-53} cm^4 s.

Goals: investigation of multiphoton processes
identification of doubly excited dark states



Advantages of FERMI:
wavelength stability allows fine tuning over resonances
circular polarization allows suppression of s wave (and suppression of harmonics)

What else can we do? Keldysh parameter, molecules

$\gamma \gg 1$, multi photon ionization;
$\gamma \ll 1$ indicates tunnelling ionization.

At Fermi for example, the following values can be achieved for He:

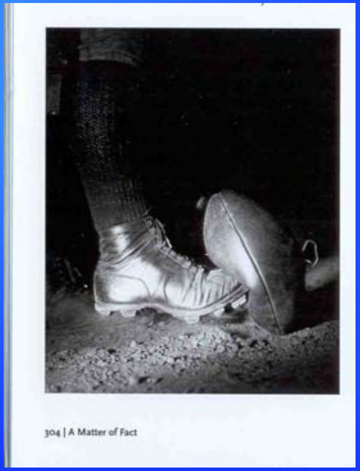
Λ (nm)	I (10^{15} W-cm^{-2})	target	Ei	γ
80	39	He	24.6	0.5
20	7.9	He	24.6	44

We can explore the transition between the two regimes.

If you can control the timing of light,
you can learn new things…

Eardweard Muybridge, 1878: do all 4 horse's hooves leave the ground at once?
A bet by Leland Stanford:
early research at Palo Alto.
Sub-second resolution.

Harold E. Edgerton, 1964. Microsecond strobe.



Or applied research, H. E. Edgerton, 1934.

Everybody wants to make a movie.

Molecular movie in the valence space (schematic)

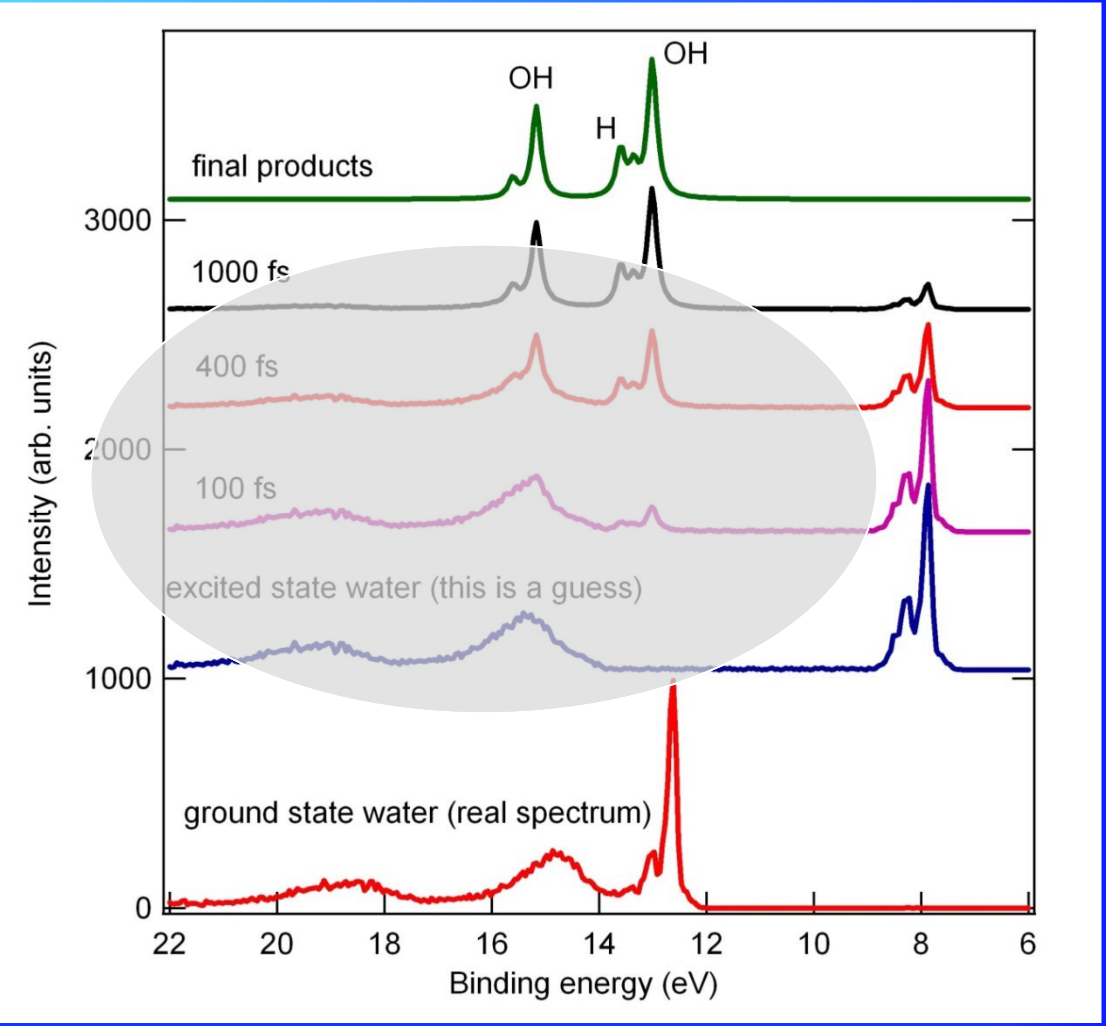
Example: H_2O (and D_2O), laser excited.
Dissociates into H + OH.
Lifetimes: 400 fs, H_2O, and 1200 fs.

Water is pumped and probed.
At zero time delay, the spectrum of excited water is measured.
We do not know how it looks.

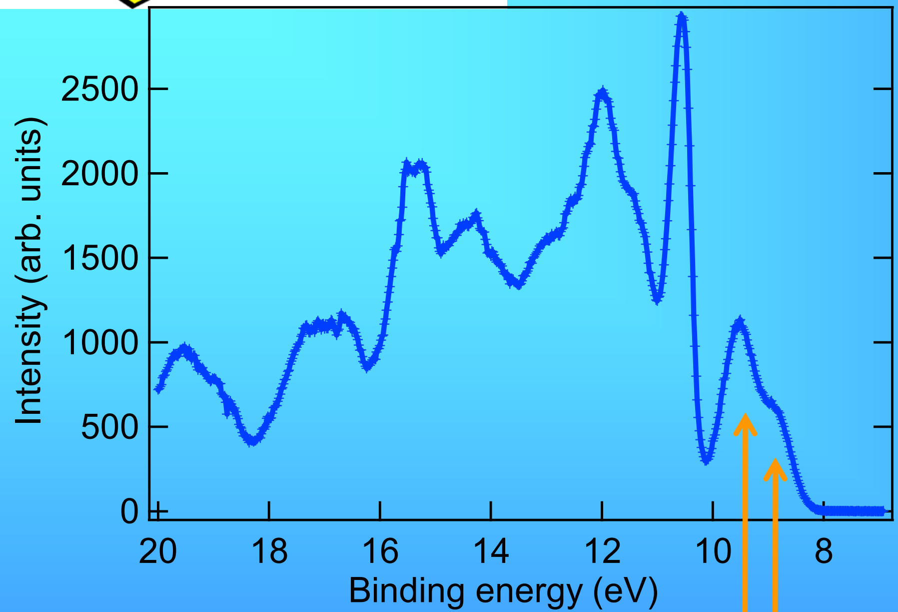
As the delay varies, excited state water disappears, and the final products appear.

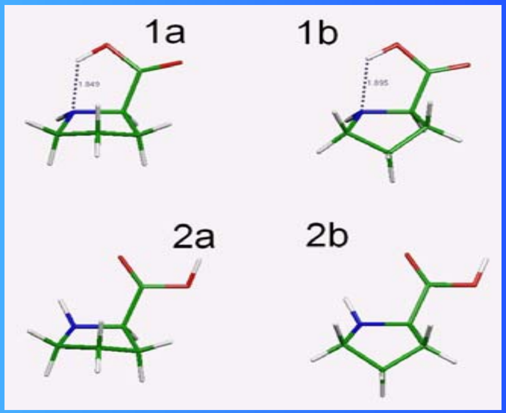
We know the spectrum of the final products.

Photon energy: > 20 eV, higher to probe 2s outer core levels .



Biomolecules. Studies of solvation in He.
For example, proline.





Proline is an amino acid which exists in four shapes (conformers) at laboratory temperatures.
Red: O Green: C Blue: N White: H.

First two peaks are HOMOs of 1a+1b and 2a+2b.
What happens on solvation? In laser spectroscopy, surprising things happen with another amino acid, protonated tryptophan.
We expect large shifts as conformation changes on solvation.

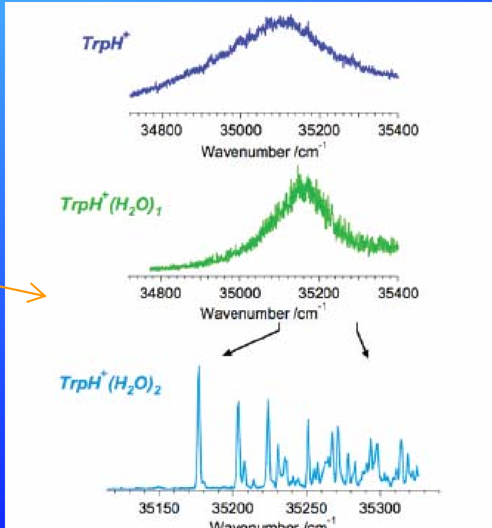


Figure 1. Electronic photofragment action spectrum of protonated tryptophan with 0, 1, and 2 attached water molecules.

Mercier et al.
JACS 128 (2006) 16938.
Very sharp spectrum for 2, but not 1, water molecules.

Photon beam requirements:
high flux.

Future work:

- Very dilute systems
-Two colour and multi photon processes
- Nuclear dynamics
-Higher energy resolution

Theoretical predictions and back-up very important.

Accelerator developments:
Multi-user facilities desirable.
Shorter pulses
More stable pulse energies


elettra
FERMI
@elettra