The New IR FEL Facility at the Fritz-Haber Institute in Berlin

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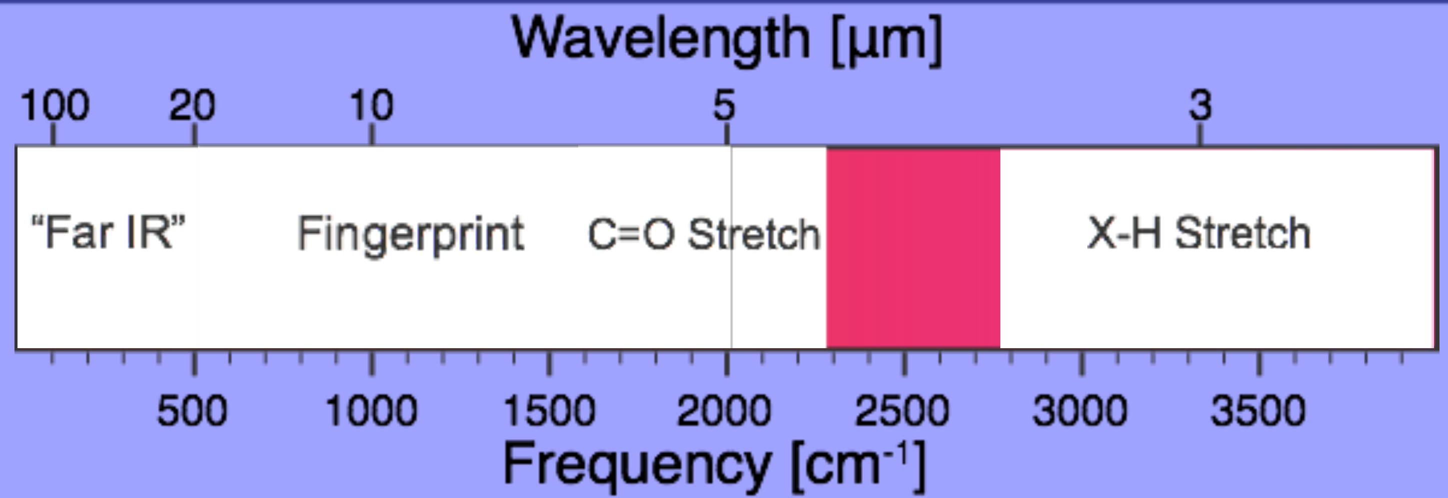
Outline

1. Design and specs of FHI FEL
2. Characterization of IR output
3. Overview of FHI FEL Facility
4. Results from user experiments
5. Outlook: Possible FIR / THz upgrade of FHI FEL

Interaction of molecules with IR light

"Far IR":
large amplitude motion / folding
metal-metal stretch
van der Waals modes
adsorbate modes on surfaces

C=O Stretch:
"Amide I" in biomolecules
C=O on surfaces



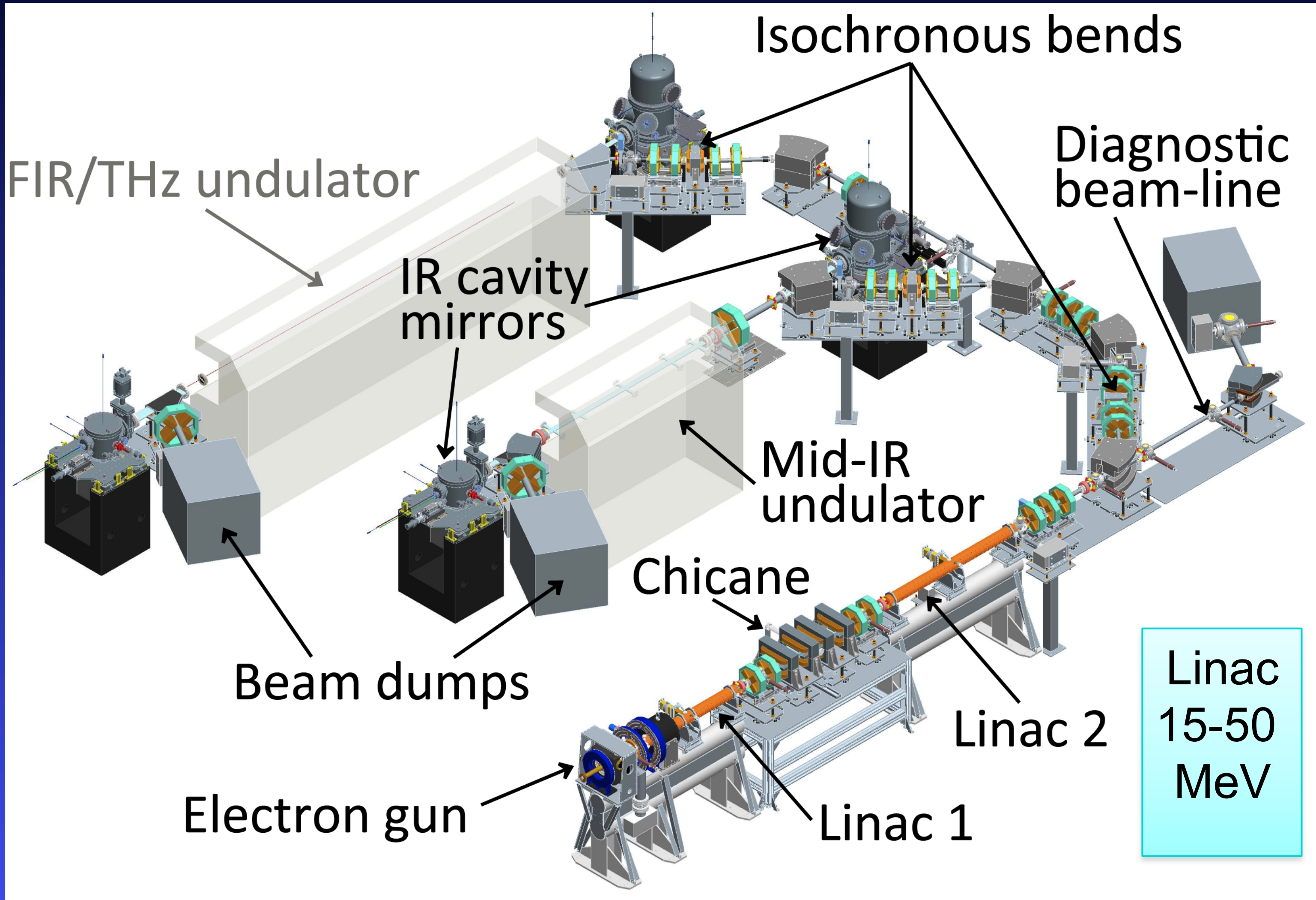
Fingerprint:
skeletal motion in molecules

X-H Stretch:
H-bonding
conformation of small biomolecules

Schematic layout of FHI FEL

Mid-IR:
4 – 50 μm

Far-IR:
40 – 500 μm



FEL 2013, WEPSO62
FEL 2012, MOOB01

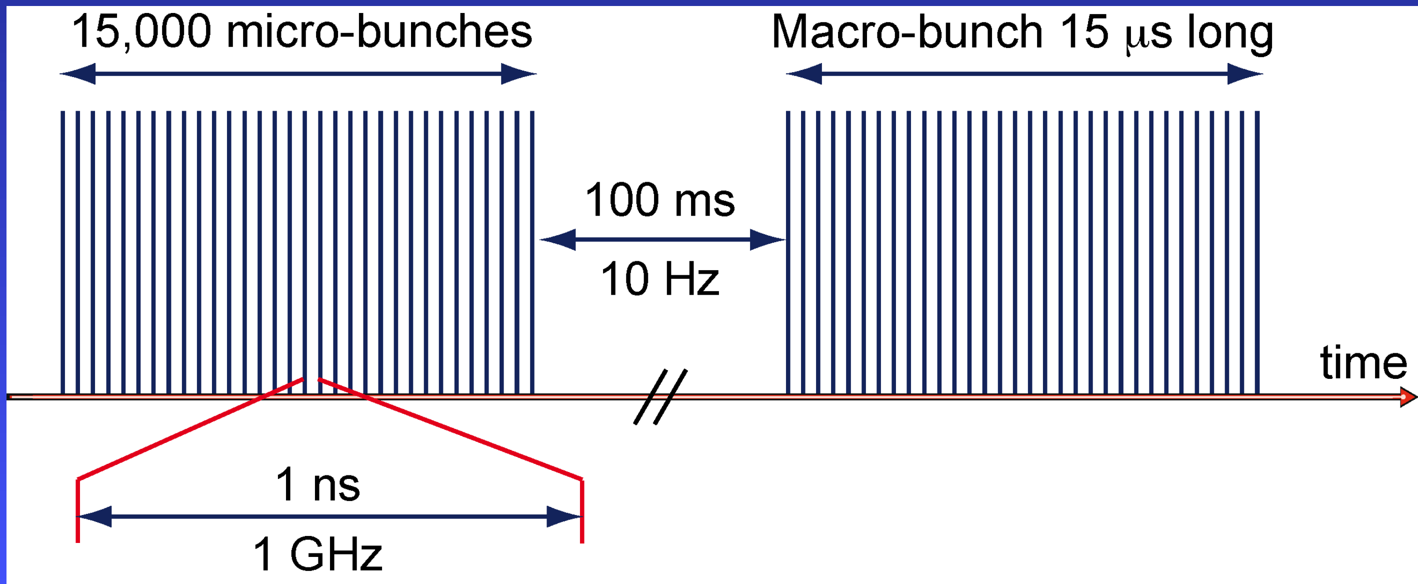
Linac and electron beamline made by Advanced Energy Systems Inc., NY, USA

Linac specs summary

Normal-conducting S-band accelerator:

electron energy:	15 - 50 MeV	(18, 26, or 38 MeV)
RF frequency:	3 GHz	
bunch rep. rate:	1 GHz	
bunch charge:	> 200 pC	(220 pC)
bunch length:	1 - 5 ps	
macro-bunch length:	8 μs / 15 μs	(10 μs)
macro-bunch rep. rate:	10 Hz	(5 Hz)

Macro-bunch temporal structure



Specs of FHI FEL

Mid-IR:

installed and commissioned

IR wavelength: ~4 – ~50 μm
IR cavity length: 5.4 m
IR waveguide: none

Undulator: planar hybrid, NdFeB

period:	40 mm
number of periods:	50
length:	2 m
rms-K:	0.5 – 1.6

Far-IR:

projected

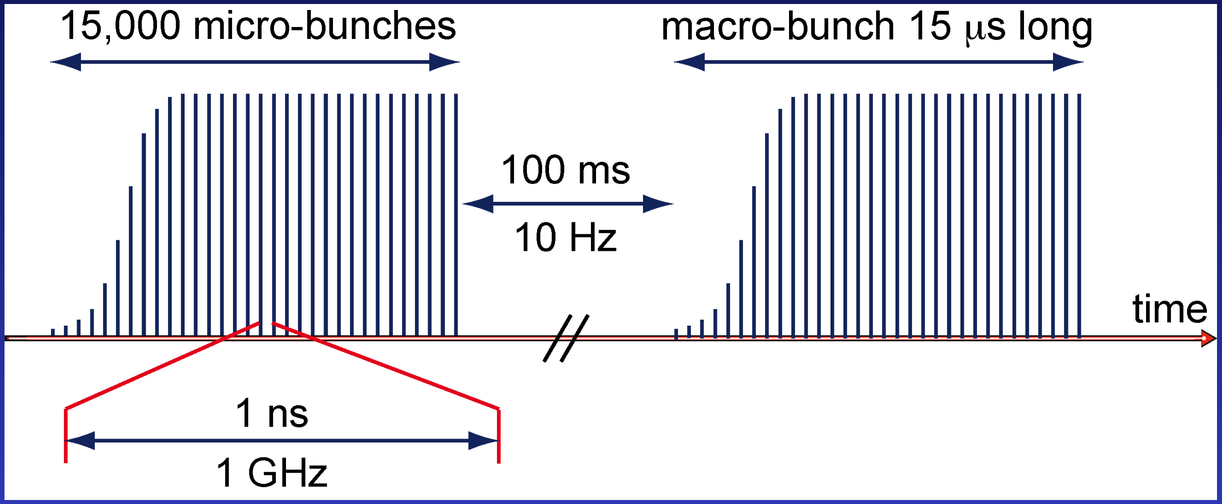
IR cavity length: 7.2 m
IR wavelength: ~30 – ~500 μm
IR waveguide: 1-dim. 10 mm height

Undulator: planar PPM or hybrid, SmCo or NdFeB

period:	110 mm
number of periods:	40
length:	4.4 m
rms-K:	1 – 3

Specs of FHI FEL

Time structure of IR output given by electrons: micro-pulses and macro-pulses

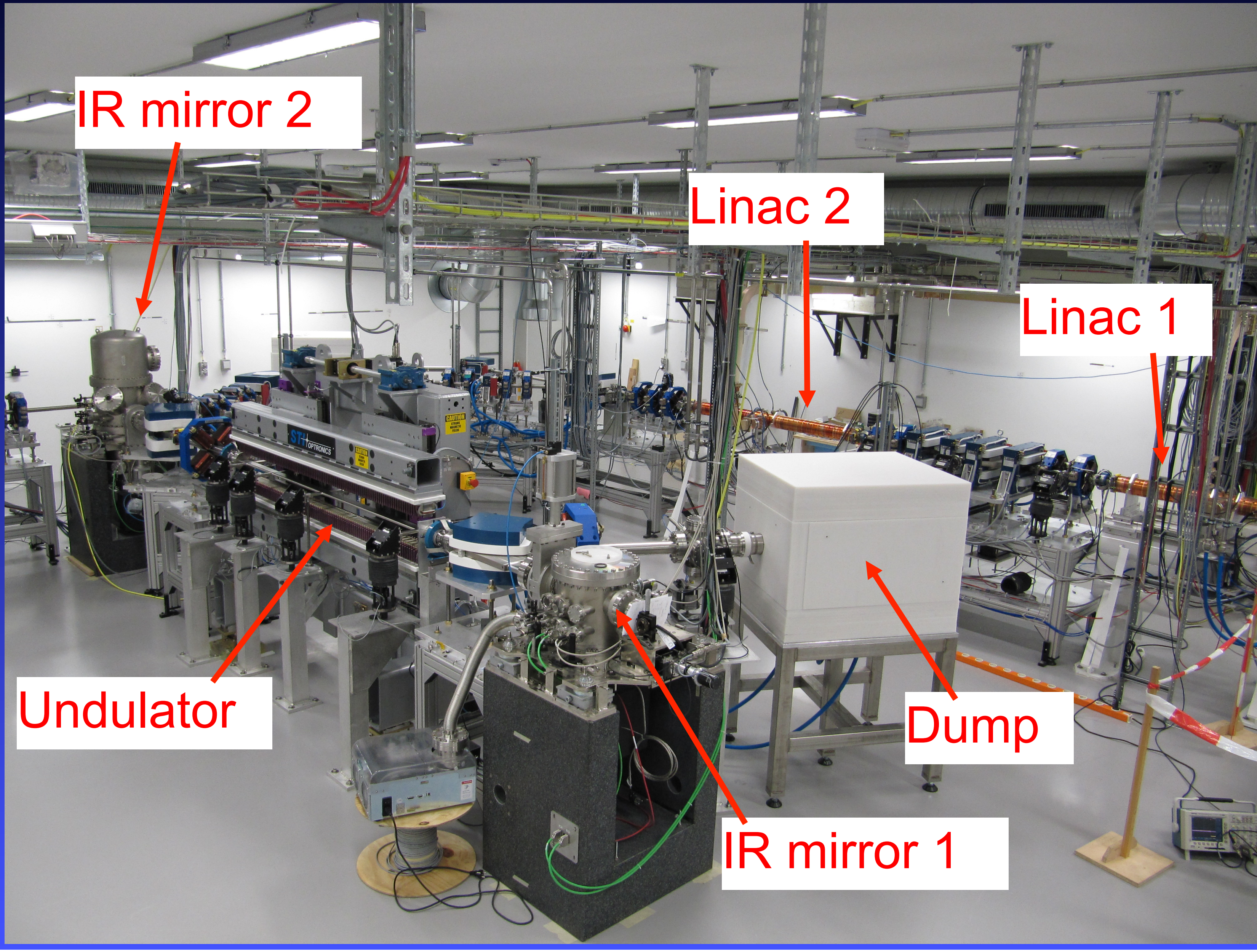


<u>IR output:</u>

- macro-pulse length > 10 µs
- ≈ 100 mJ / macro-pulse
- 10 – 20 µJ / micro-pulse

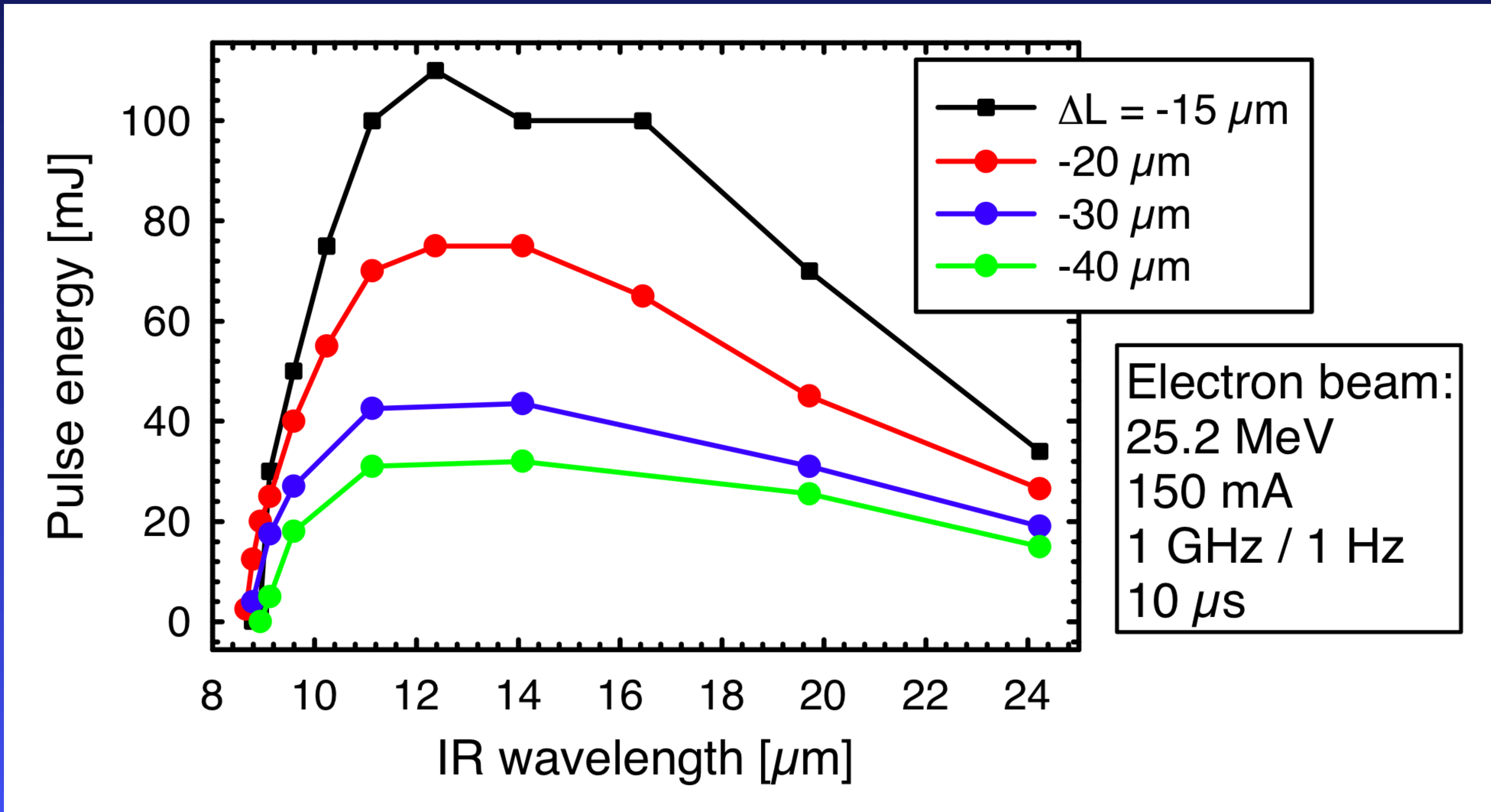
- micro-pulse length 0.3 – >5 ps
- FT-limited bandwidth: 0.3 – 5% of central frequency

Photograph of FHI FEL



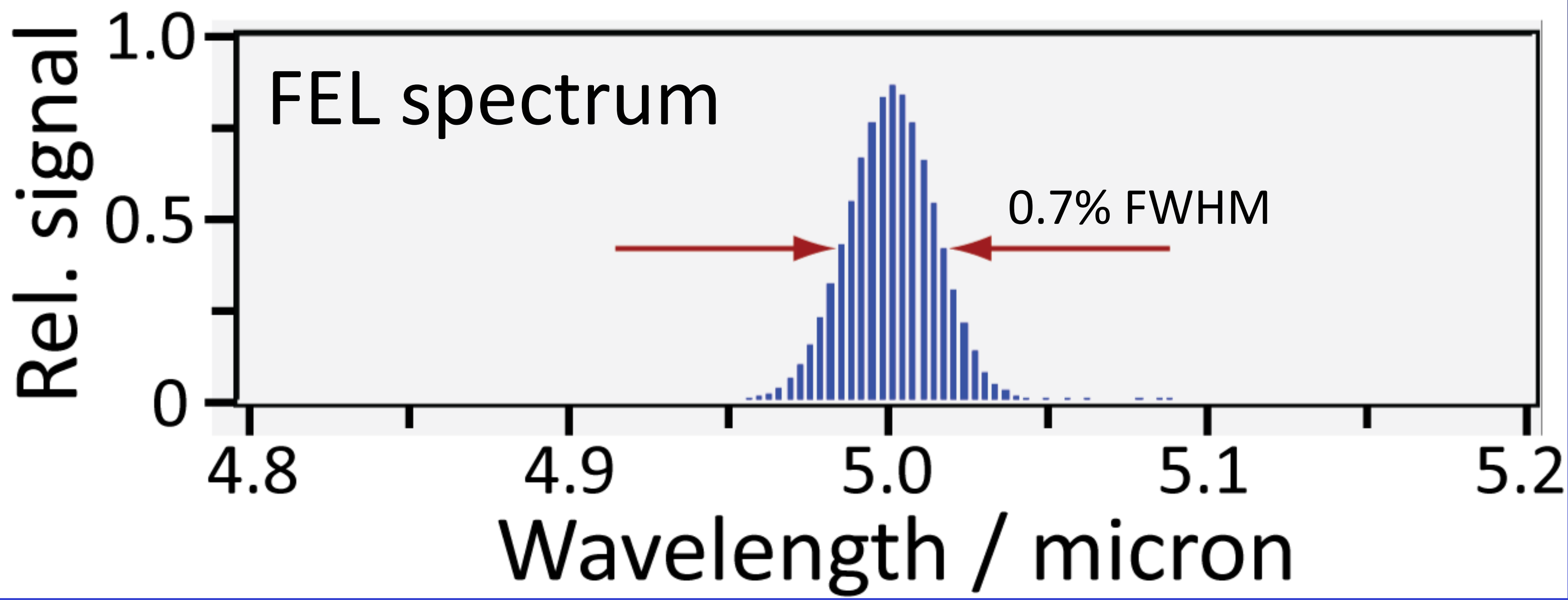
Wavelength scan by undulator gap change

4 undulator gap scans at slightly different cavity lengths



FHI FEL Spectrum

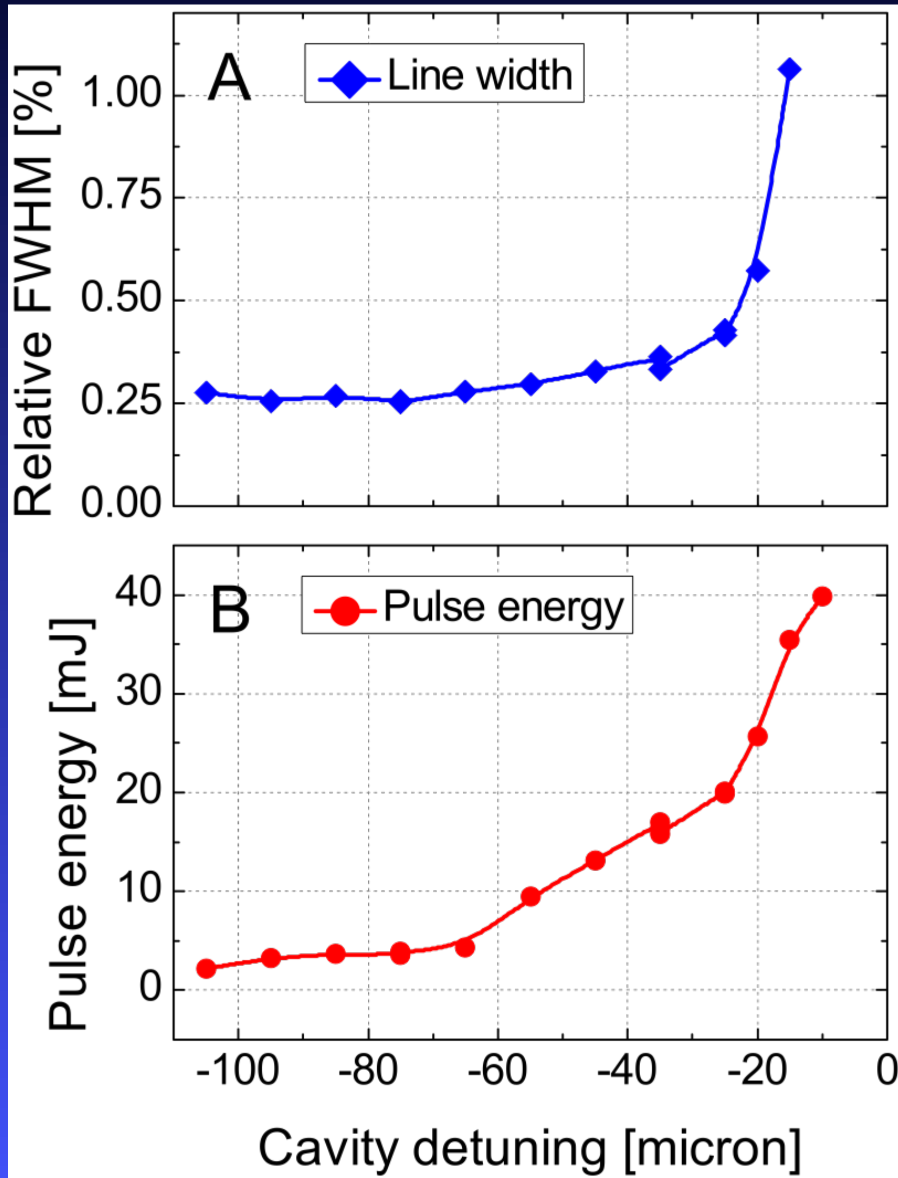
Line spectrum measured with a grating spectrometer (Acton, 75 g / mm)



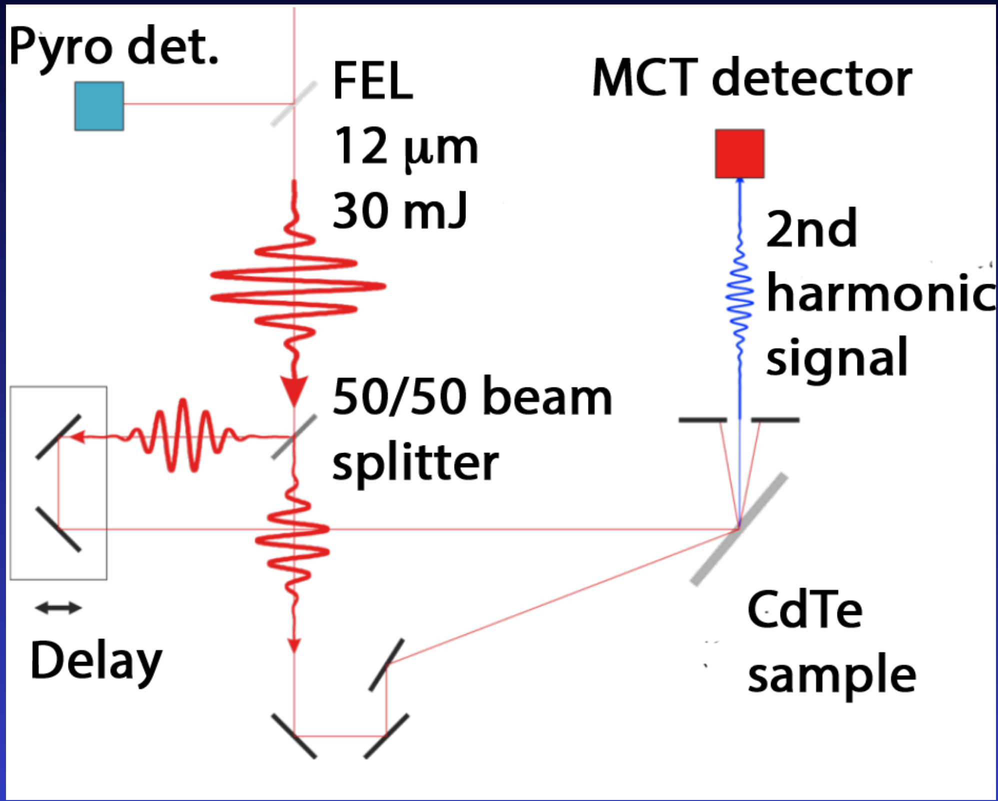
Nowadays adjusted to typically 0.4 ... 0.5% for IR spectroscopic user experiments

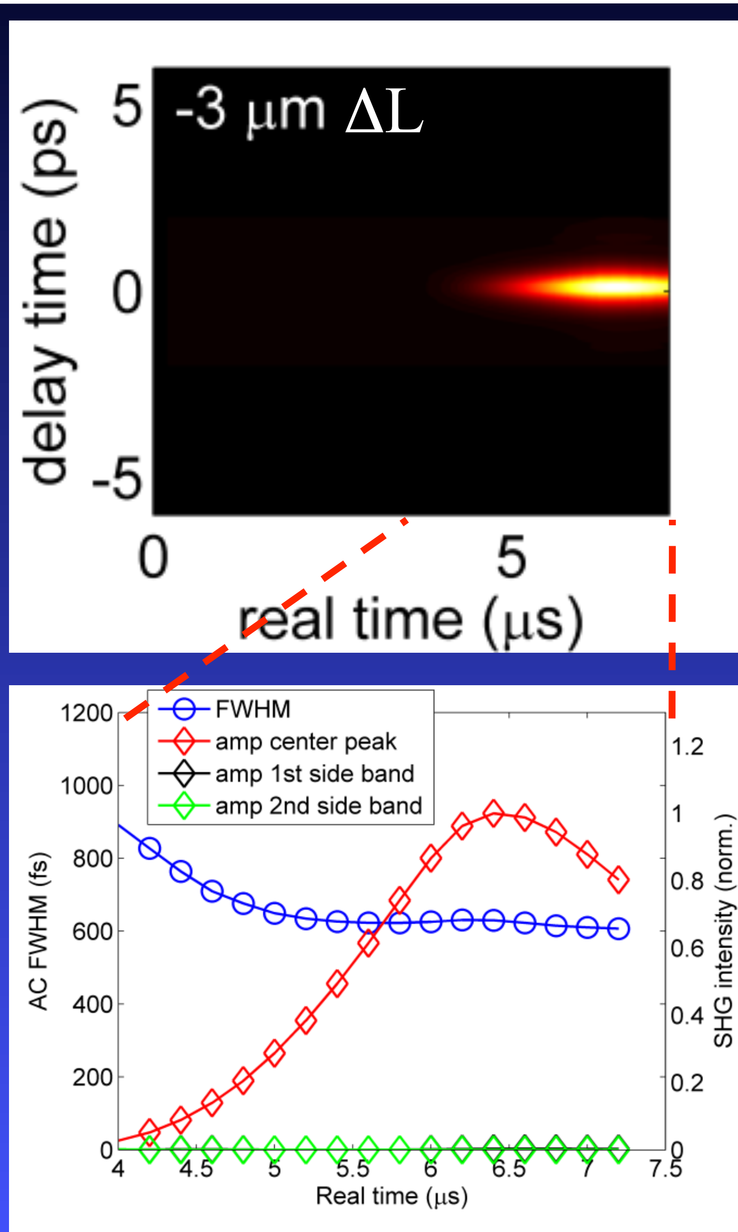
Pulse energies and line widths

Pulse energy and line width can be varied by cavity detuning:
Reducing the cavity length (5.4 m) by a few wavelengths (~ tens of micron) leads to narrower line and less power.



Micro-pulse time structure observed by auto-correlation measurements



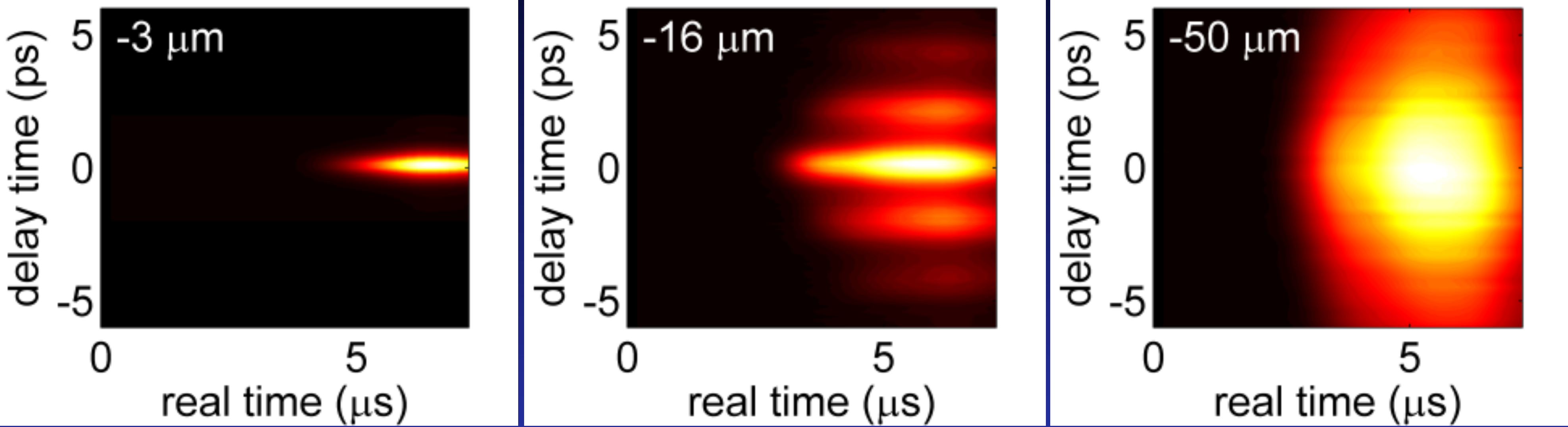


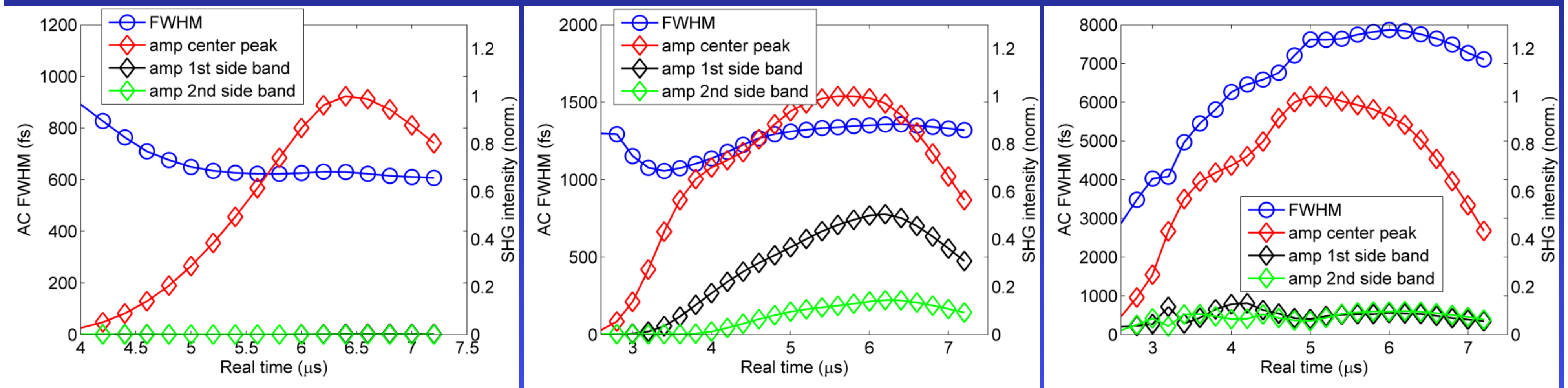
Dependence on FEL cavity-length detuning ΔL

ΔL = -3 μm → 0.6 ps FWHM

Results of Alex Paarmann (FHI, Dept. PC)

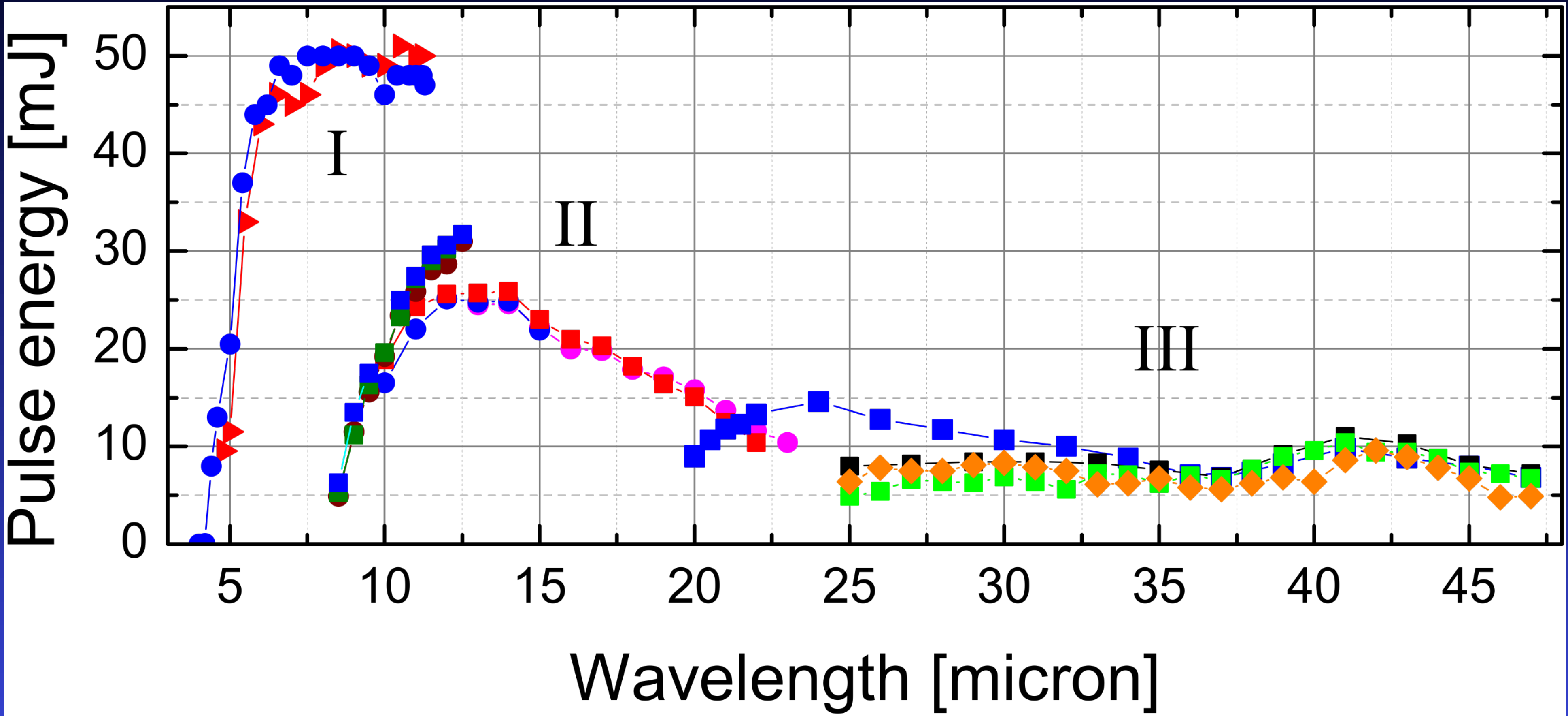
Micro-pulse time structure dependence on FEL cavity length





c.f. Knippels et al. *Formation of multiple subpulses in a free-electron laser operating in the limit-cycle mode*. Phys. Rev. E, **53** 2778, 1996.

Macro-pulse energies at narrow bandwidth (0.35 - 1%) at 4 to 47 μm

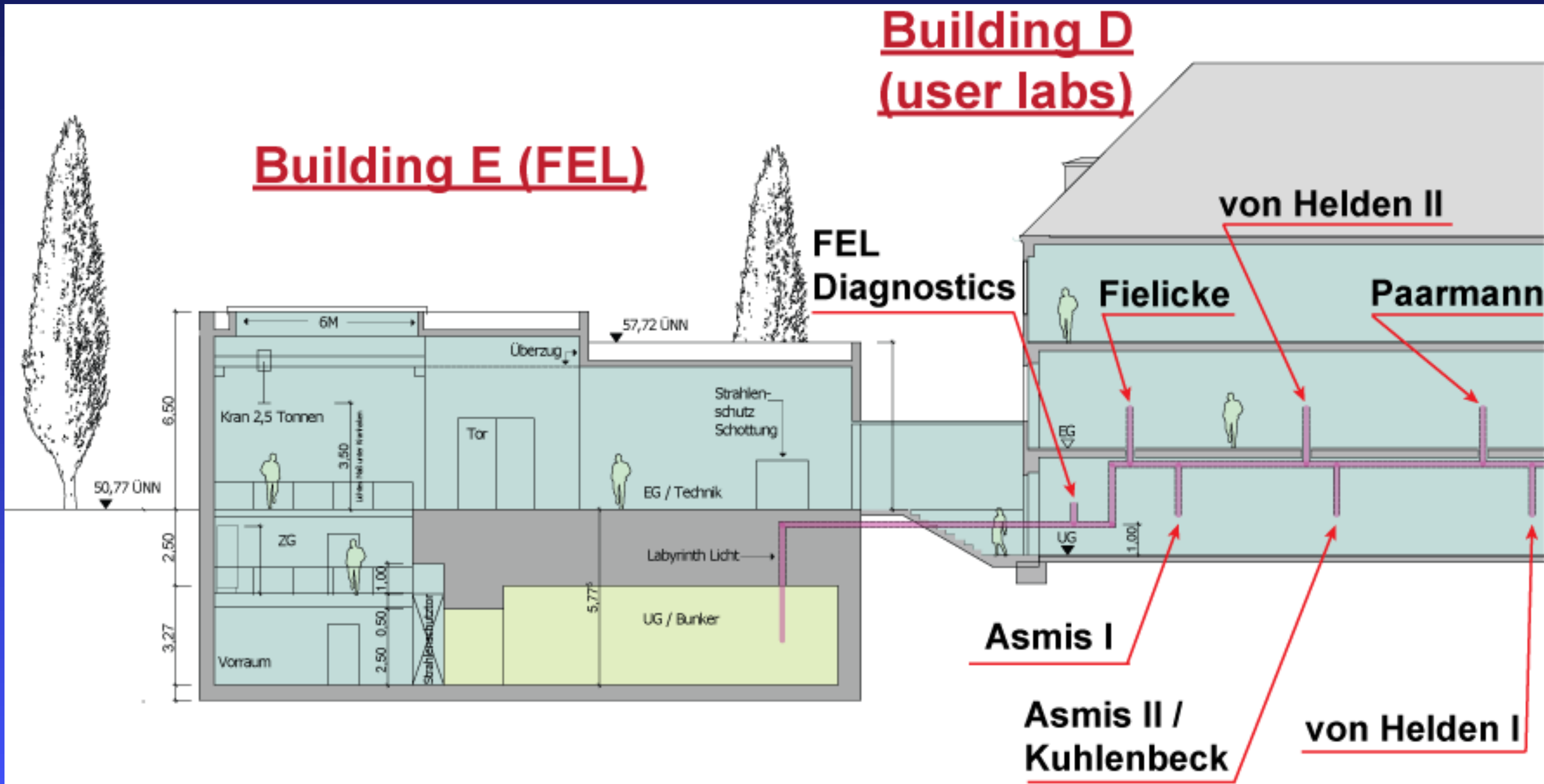


Electron energy regimes

I	II	III
38 MeV	26.5 MeV	18.5 MeV

FHI FEL Facility as of summer 2014

Regular user operation started in Nov. 2013 with 6 experimental stations



FHI FEL IR-Beamline Stations

1. André Fielicke (FHI, TU Berlin):
   Chemistry of transition metal clusters
2. Knut Asmis (FHI, U Leipzig):
   Vibrational spectroscopy of gas-phase metal-oxide clusters
3. Knut Asmis (FHI, U Leipzig):
   Vibrational spectroscopy of gas-phase clusters: ion solvation
4. Gert von Helden (FHI):
   Bio-molecules embedded in superfluid helium nano-droplets
5. Gert von Helden (FHI):
   Bio-molecules: IR spectroscopy combined with ion mobility spectrometry
6. Alexander Paarmann (FHI):
   Nonlinear spectroscopy of solids

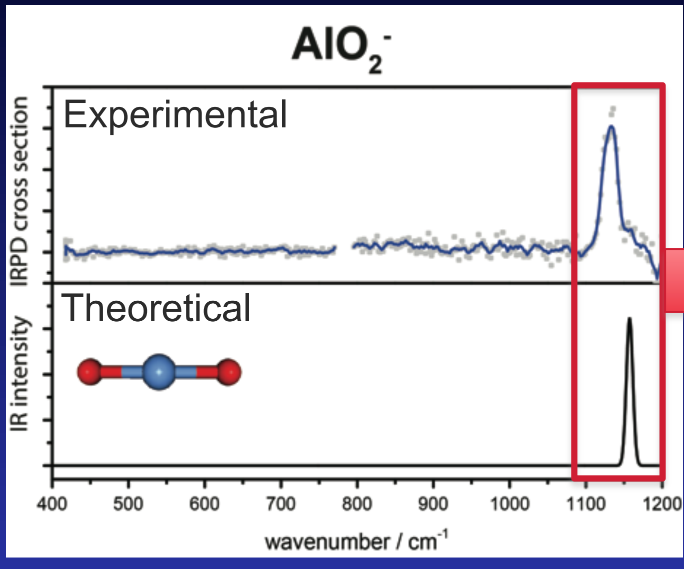
Starting fall 2014: Helmut Kuhlenbeck (FHI):
Vibrational spectroscopy of surface-deposited clusters

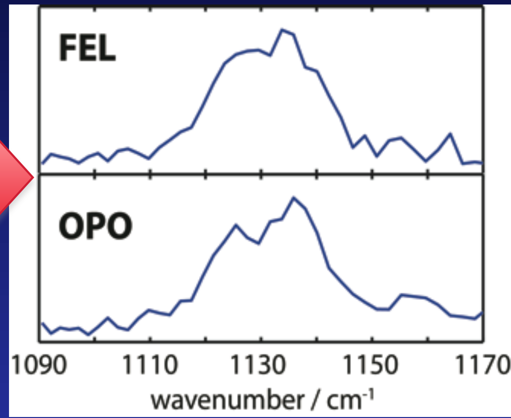
IR Spectroscopy of Aluminum Oxide Clusters

CRC 1109

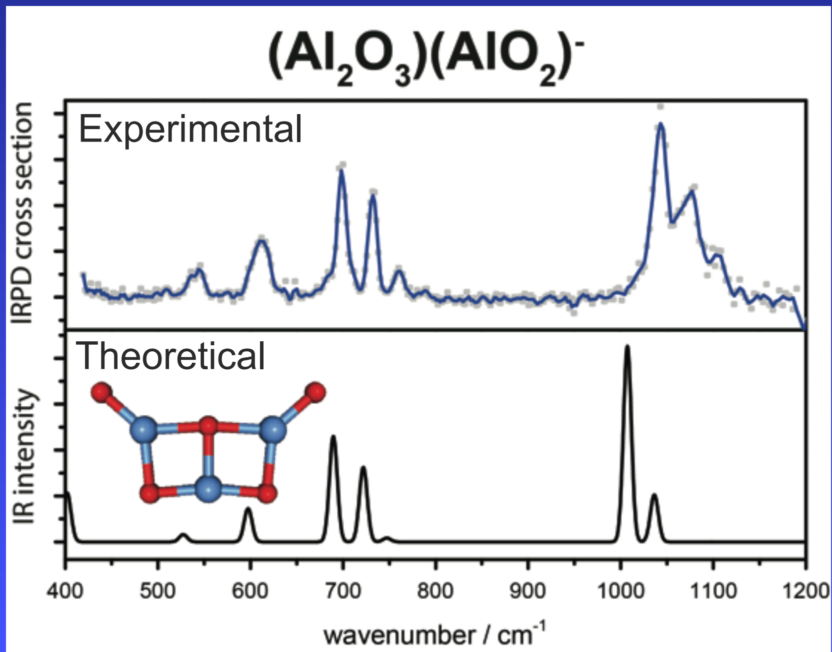
K. Asmis, M. Fagiani, X. Song, N. Heine, T. Esser, H. Knorke

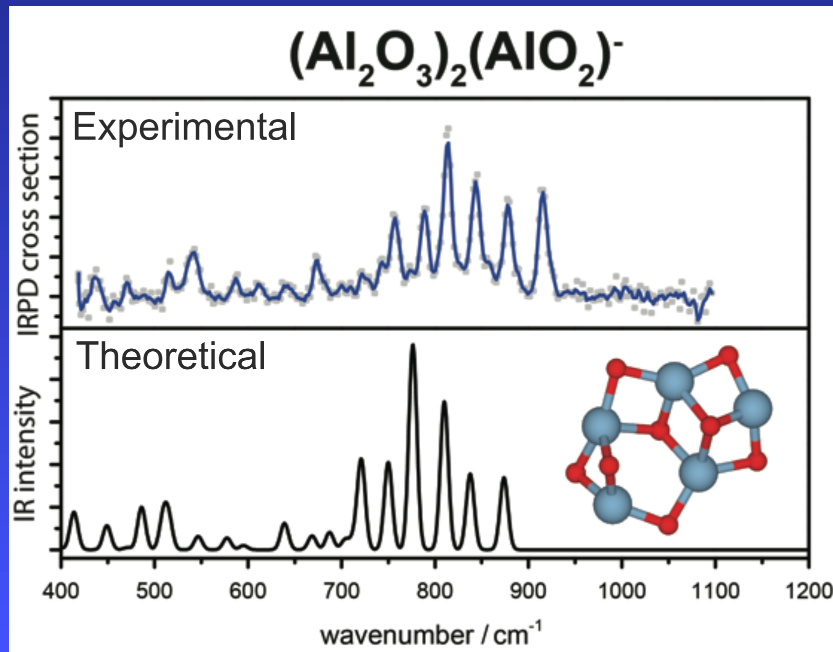
Blue-Al
Red-O





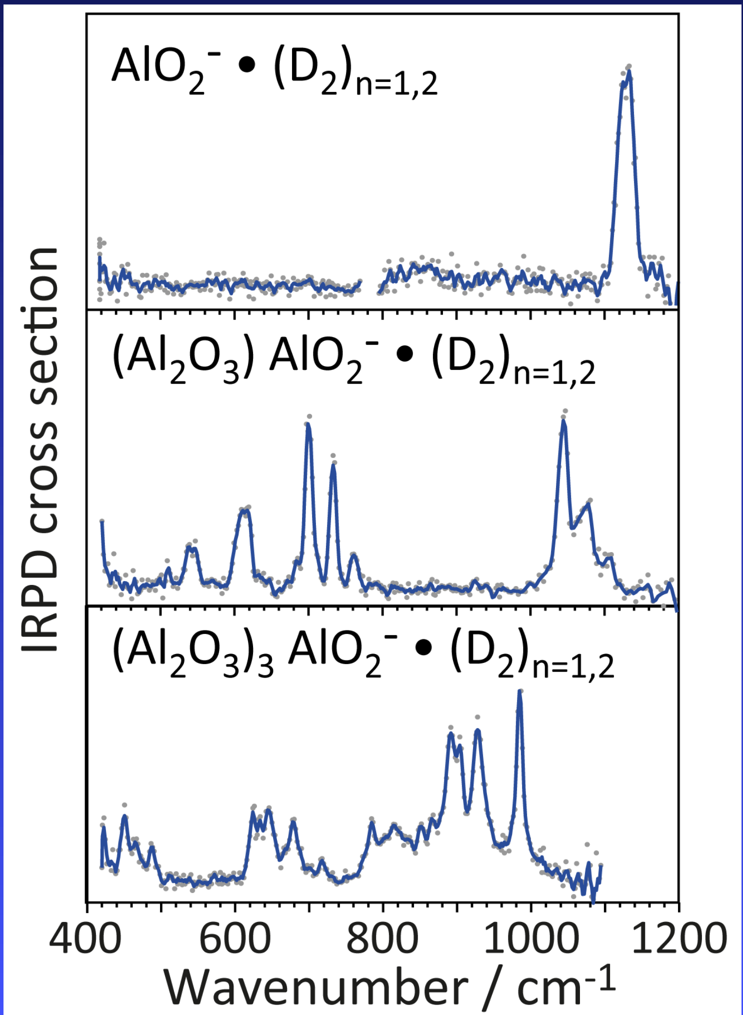
Theory:
F. Bischoff,
J. Sauer,
HU Berlin

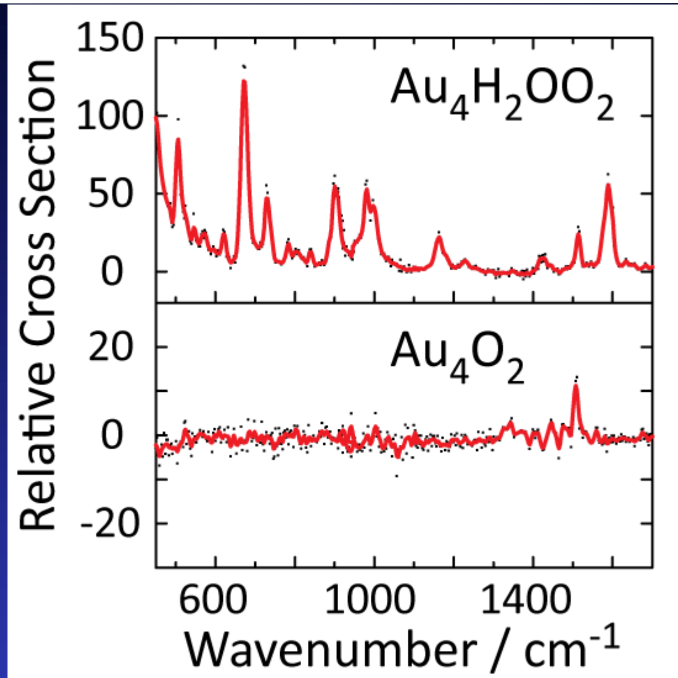




Spectroscopy of gas-phase clusters and molecules

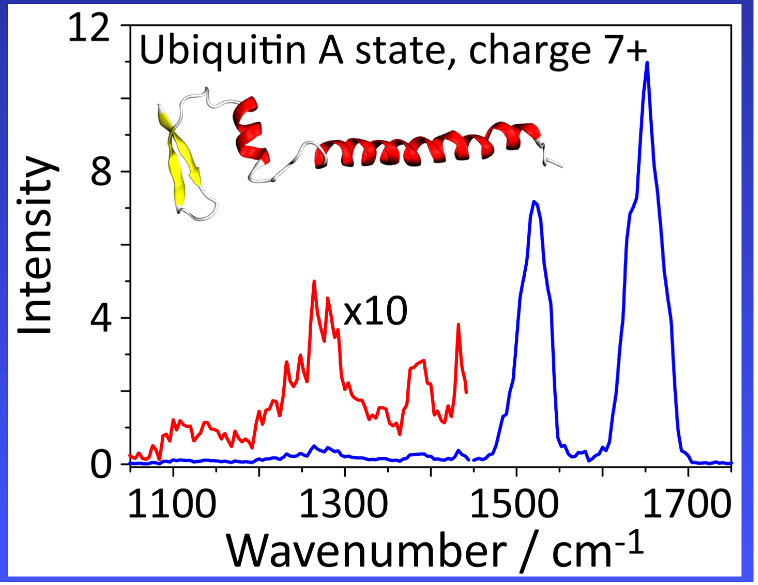
Mass-selected anionic aluminum-oxide clusters, tagged with D_2 (*Asmis & coworkers*)





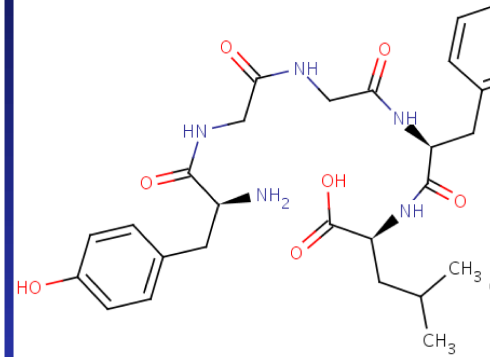
Complexes of neutral gold clusters with oxygen and water (*Fielicke & coworkers*)

Conformer-selected multiple charged Ubiquitin proteins (*von Helden & coworkers*)

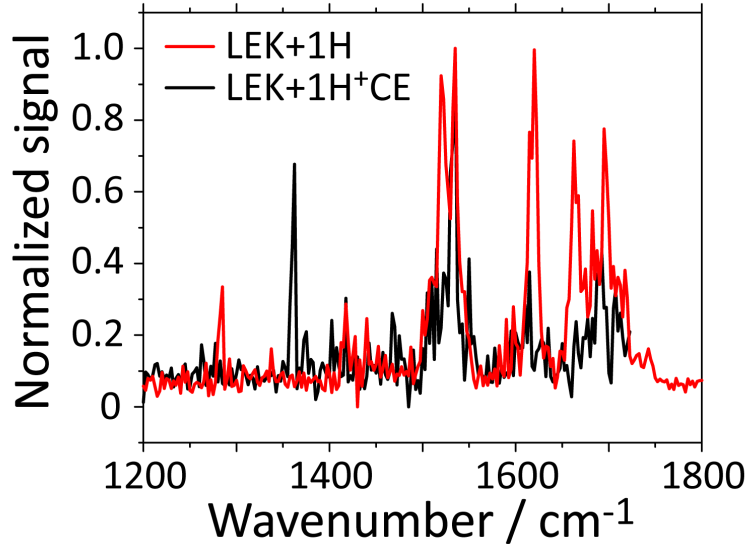


Spectroscopy in fluids, of solids and on surfaces

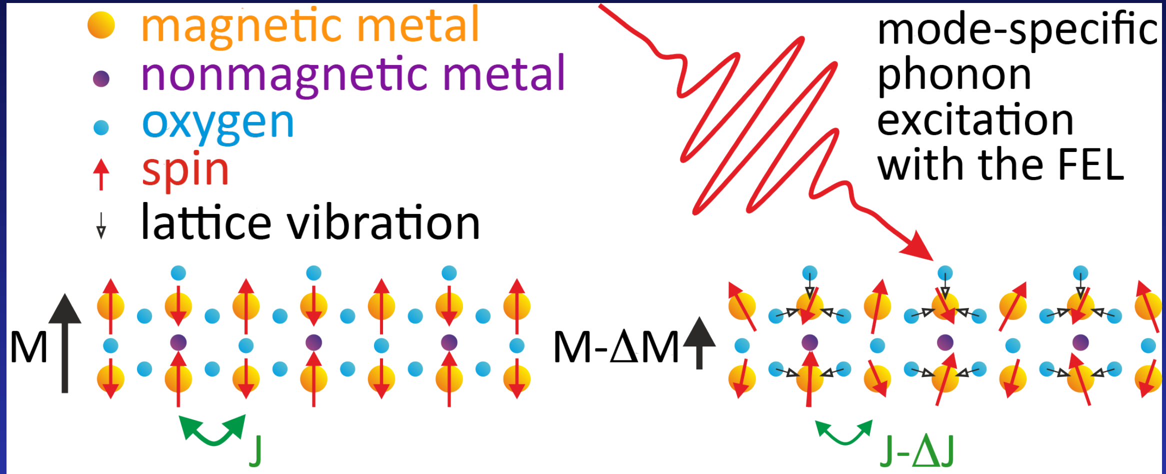
Charged pentapeptide in a superfluid (0.4 K) He nano-droplet (*von Helden & coworkers*)



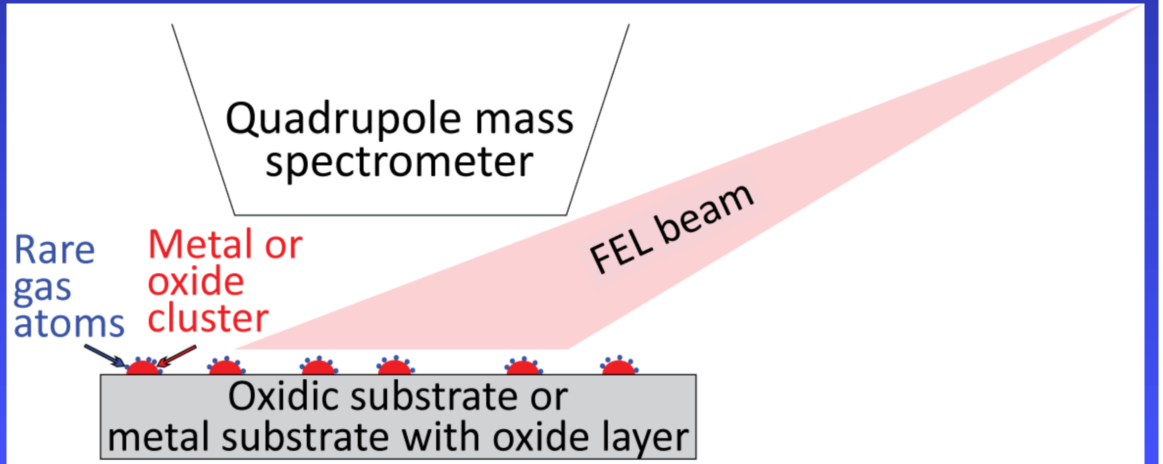
Leu-enkephalin pure and with crown ether



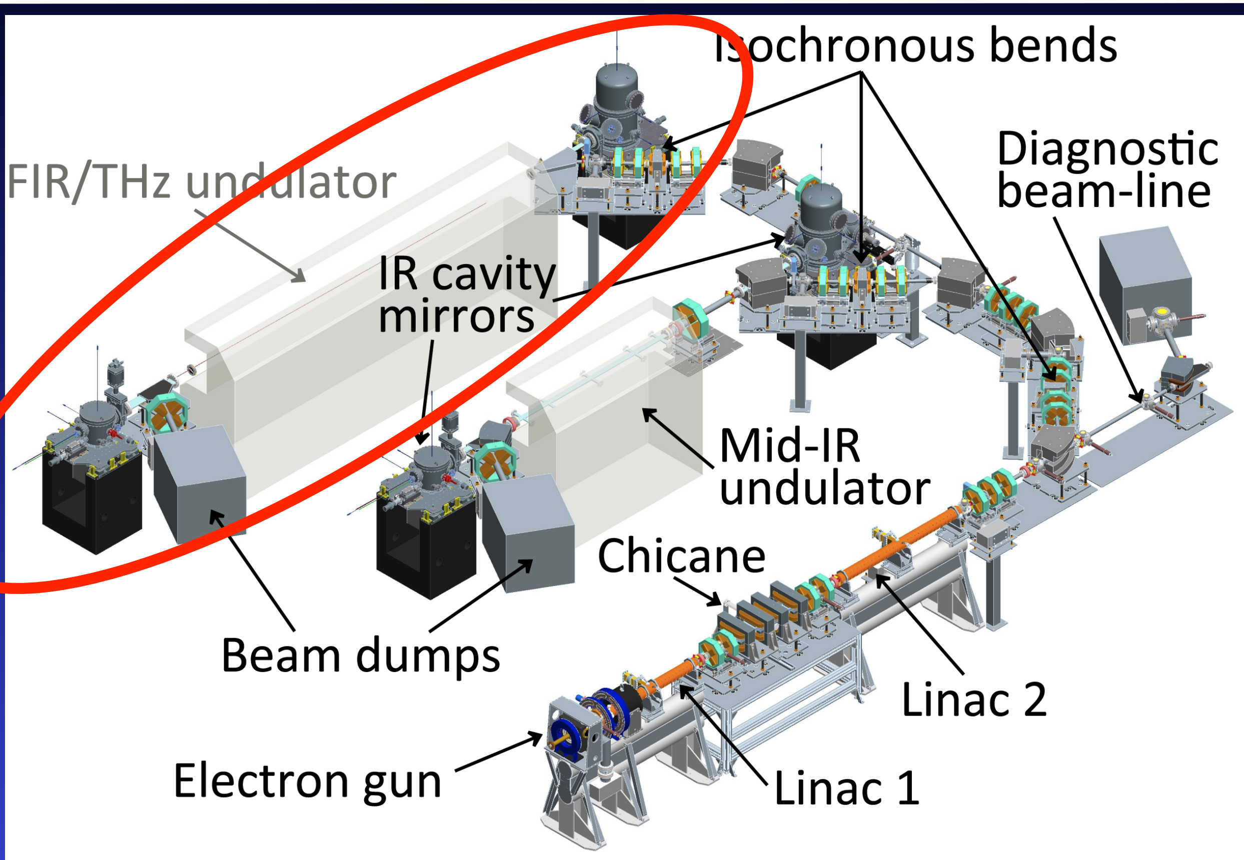
Spin-phonon coupling in a ferrimagnet (*Paarmann, Wolf & coworkers*)



Clusters deposited on a solid surface (*Kuhlenbeck, Freund & coworkers*)



Outlook
Possible FHI FEL upgrade; FIR/THz Undulator



projected

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IR cavity length: 7.2 m
IR waveguide: 1-dim. 10 mm height

Undulator:	PPM or hybrid
magnets:	SmCo or NdFeB
period:	110 mm
number of periods:	40
length:	4.4 m
rms-K:	1 – 3

The FHI FEL Team

Left to right: Sandy Gewinner, Wieland Schöllkopf, Andreas Liedke, Wolfgang Erlebach, Heinz Junkes, Gert von Helden (missing on photo)

Acknowledgment

- <u>FHI:</u>

  Alex Paarmann, Weiqing Zhang (now in Dalian), Gerard Meijer (now in Nijmegen)
- <u>FELBE (Helmholtz-Zentrum Dresden-Rossendorf):</u>

  Ulf Lehnert, Peter Michel, Wolfgang Seidel, Rudi Wünsch
- <u>AES, Inc. (electron accelerator and beamline):</u>

  Hans Bluem, Alan Todd, John Rathke, Dave Dowell, Lloyd Young, Kevin Jordan, Ralph Lange, Henrik Loos
- <u>STI Optronics, Inc (undulator):</u>

  Steve Gottschalk
- <u>FELIX (Nijmegen, NL):</u>

  Lex van der Meer
- <u>BESSY (Helmholtz-Zentrum Berlin):</u>

  Johannes Bahrdt, Andreas Gaupp, Klaus Ott, Ernst Weihreter