Experiments with ultrafast electrons: Do detectors make a difference?

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Outline

- EDET detector
  - Design
  - Experiments (with first beam)
  - Outlook
    - Electron Beam Chemistry
    - Wet Biology
- Beyond (?) EDET
  - Applications with electrons
    - Can we push the use case to challenge most demanding photon applications
    - Some science cases
- Detector Specs
  - What to revisit ?
- Beyond (!) EDET
  - Detector for mass-spectrometry

Max Planck Institute for the Structure and Dynamics of Matter

EDET team

Acknowlegements

HLL ► Ladislaw Andricek ● Martin Hensel ● Christian Koffmane ● Jelena Ninkovic ● Eduard Prinker ● Mitja Predikaka ● Rainer Richter ● Gerhard Schaller ● Martina Schnecke ● Florian Schopper ● Thomas Selle ● Johannes Treis ● Andreas Wassatsch ● Christian Zirr

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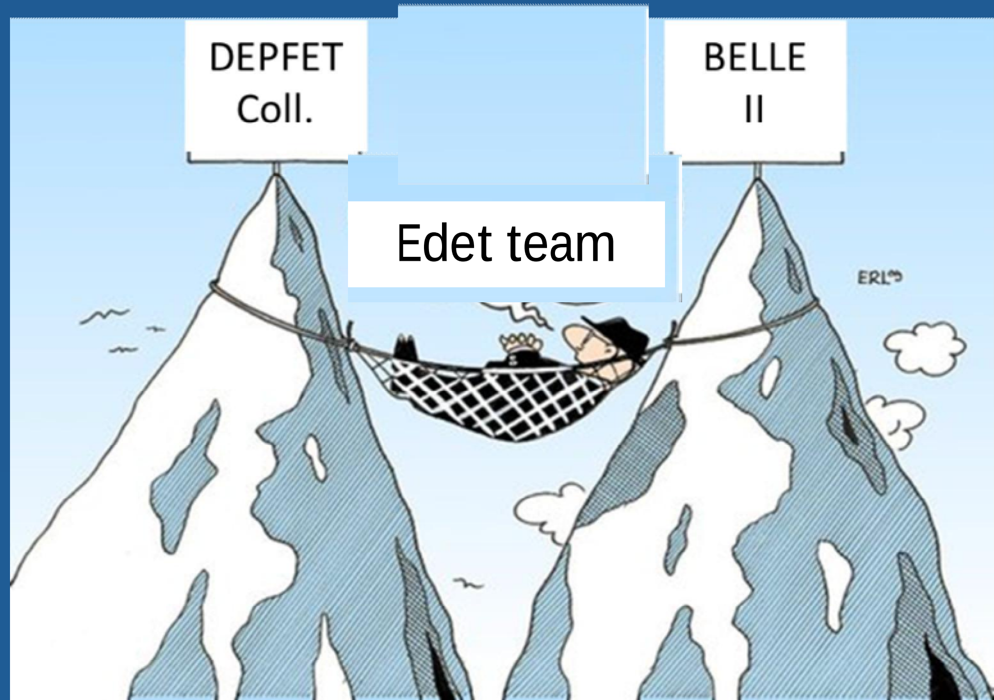
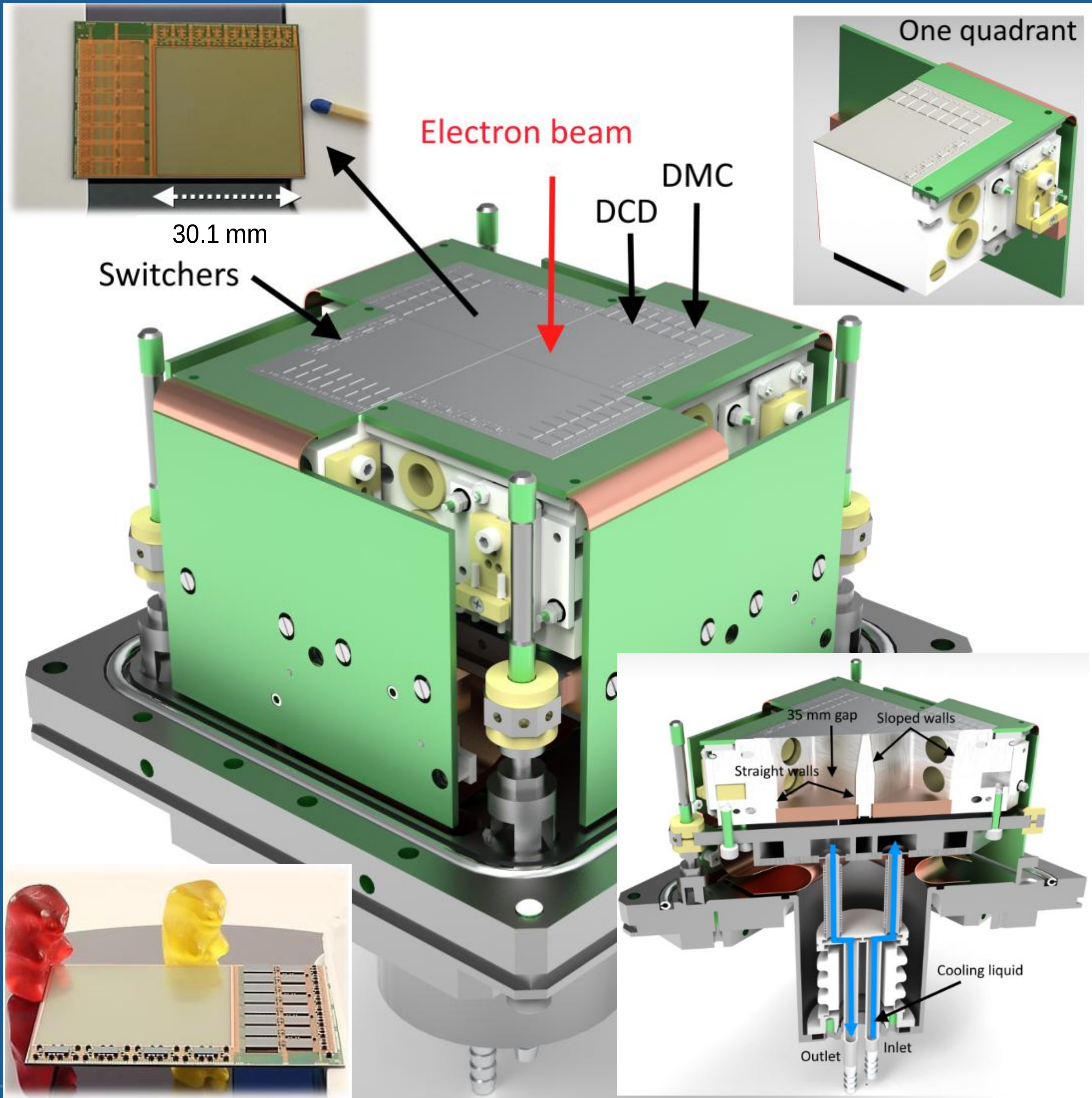
MPSD ► Ibrahym Dourki ● Djordje Gitaric ● Sascha W. Epp ● Günther Kassier ● R. J. Dwayne Miller ● Fabian Westermeier



EDET_80k
Design features

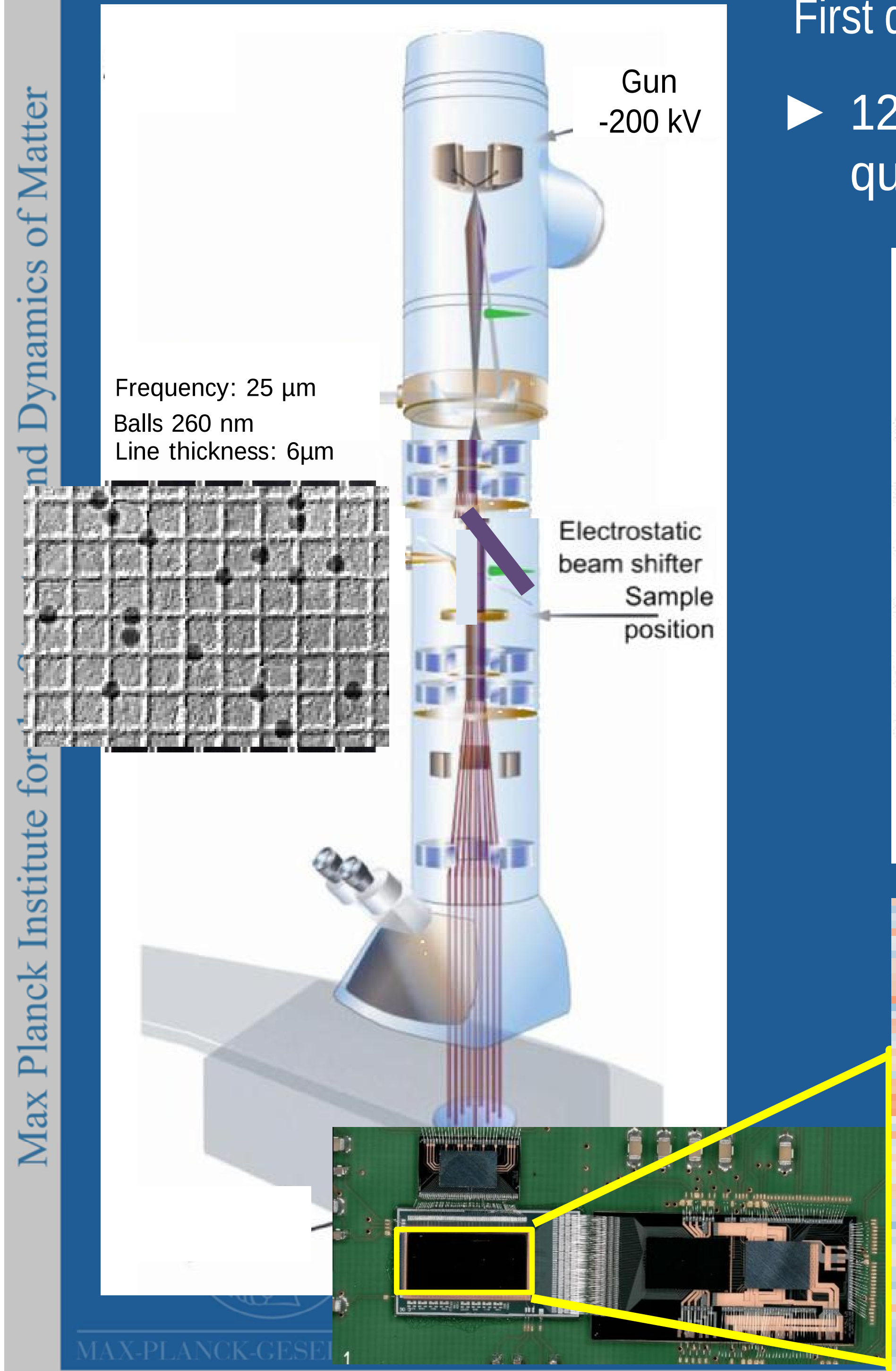


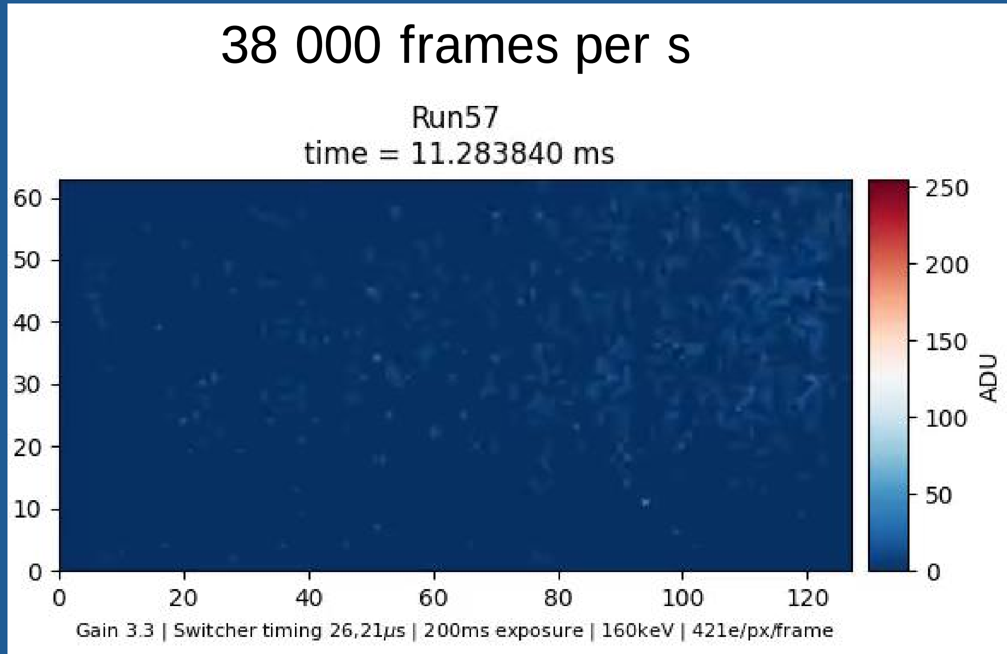
- ▶ DEPFET direct hit
- ▶ 1000 x 1000 px (4 chips)
- ▶ dead join region < 2 mm
- ▶ 60 x 60 mm^2 active area
- ▶ direct electron detection
- ▶ pixel size: 60 x 60 µm^2
- ▶ Thickness 50µm (30 µm)
- ▶ > 200 primaries of 300keV per pixel
- ▶ full frame recording at 80kHz (for 100 frames) by 4-fold rolling shutter mode [small adjustments on the way]
- ▶ 8 bit ADC (DCD)

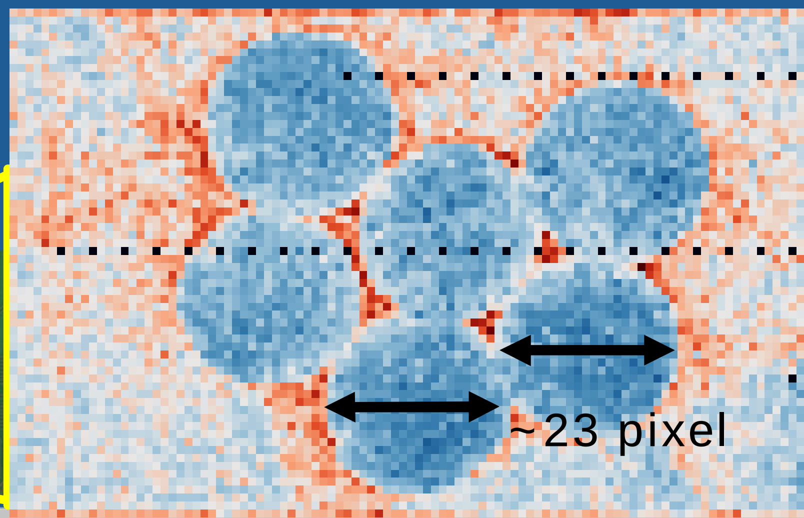
EDET_80k

First dynamic electrons

- 128 x 64 physical pixels (7.7 x 3.85 mm^2 , 1/32 of a quadrant)

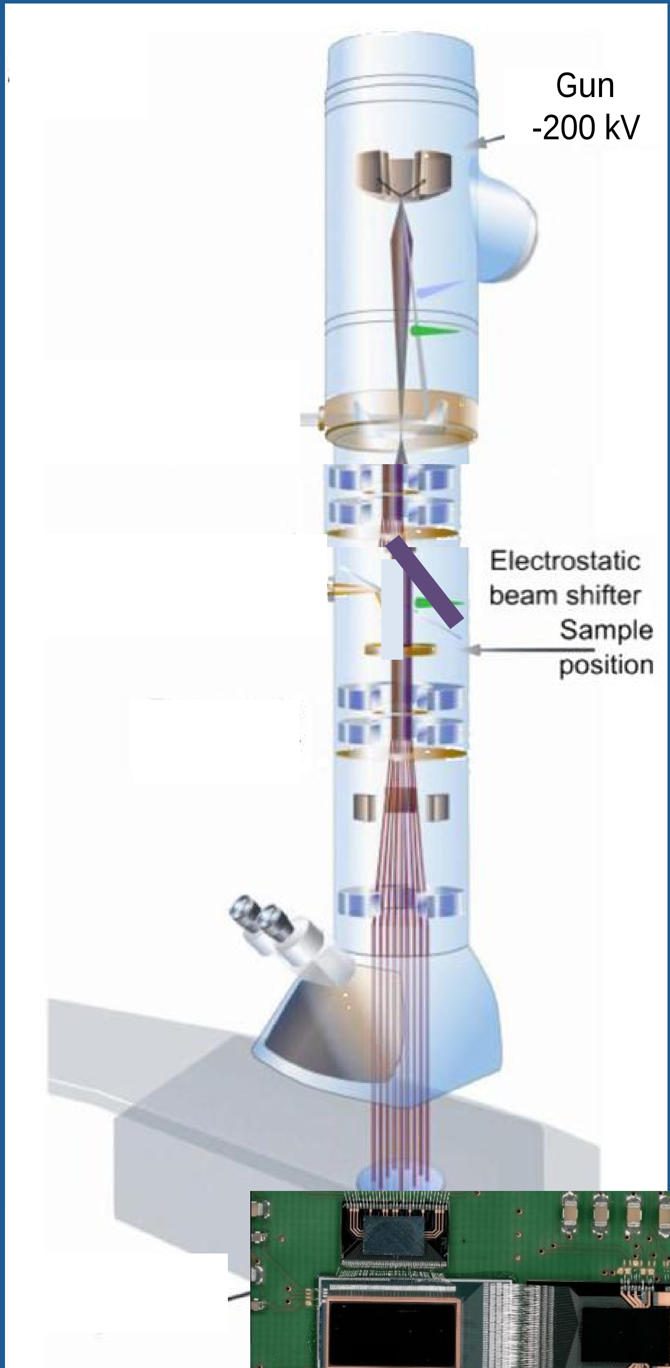




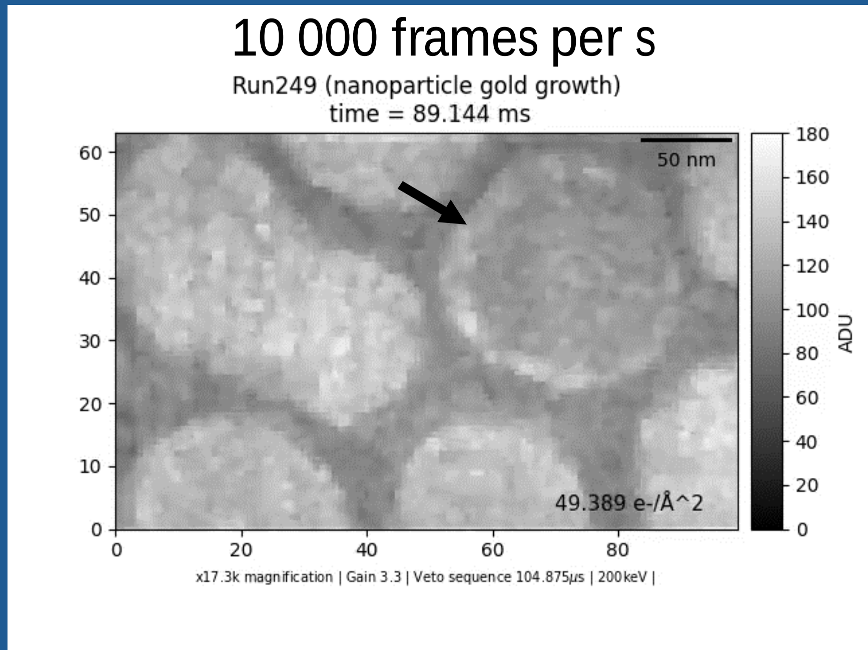


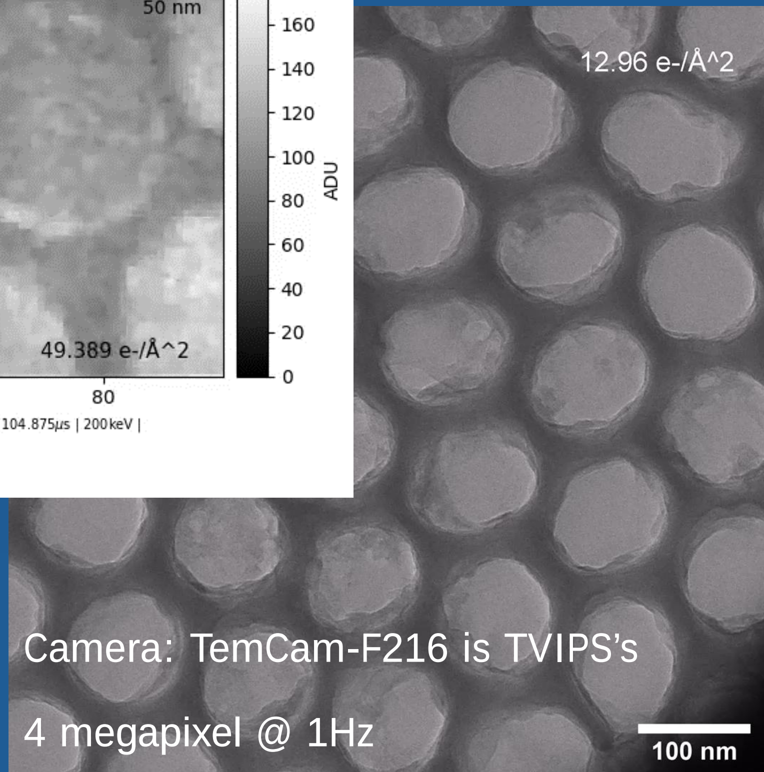
EDET_80k

Nanoparticel gold growth



- 128 x 64 physical pixels (7.7 x 3.85 mm^2 , 1/32 of a quadrant)
- Probe = Trigger, very nice condition for experimental control and initial experiments
- Fastest continuous detector ever employed in a TEM ? I guess!

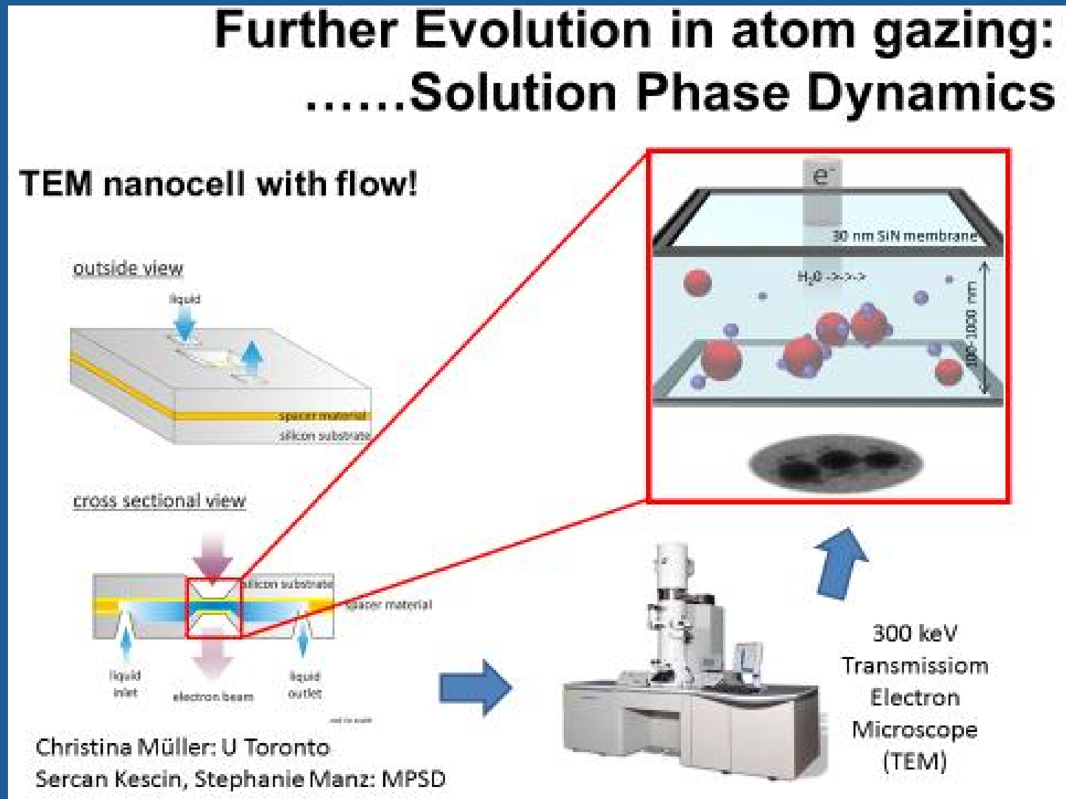




EDET_80k
Electron Beam Driven Chemistry

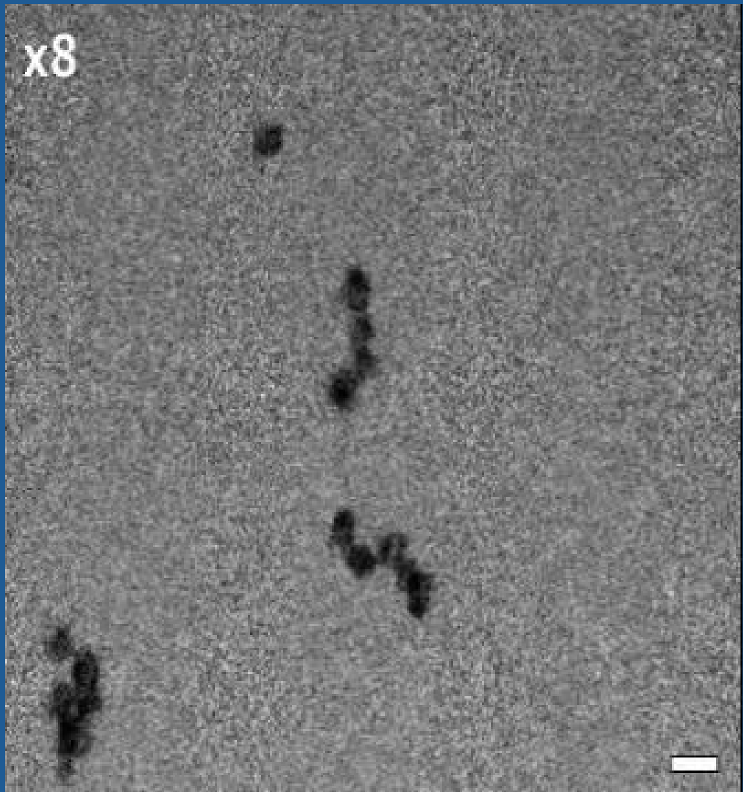
- Employed since the 1940's on the industrial scale. (2G€ annually)
- Opens the door to a entire world where yet nobody can measure at 80 000 frames per second.

- Liquid and gas phase
- Nanoparticles are employed in a multiptude of aplications: Medical, environmental to basic science
- How does shape, structure affect function
- What makes them harmful ? Can this interation be attributed to some exposed morphology?

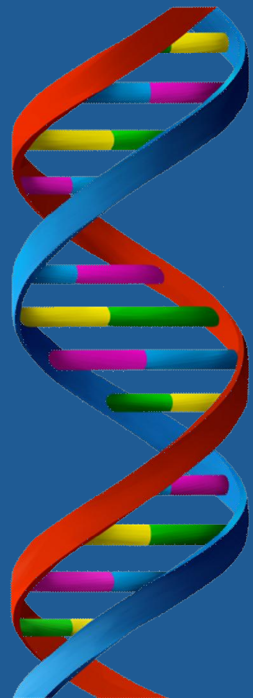


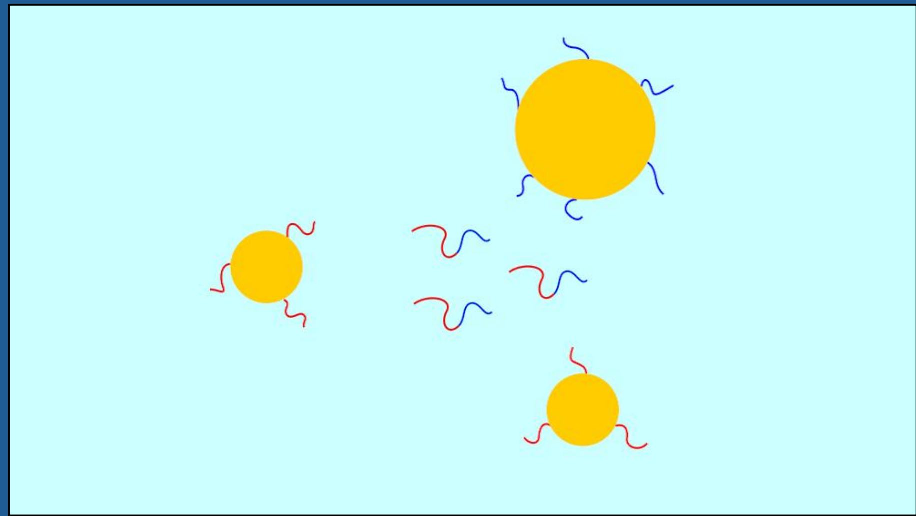
EDET_80k

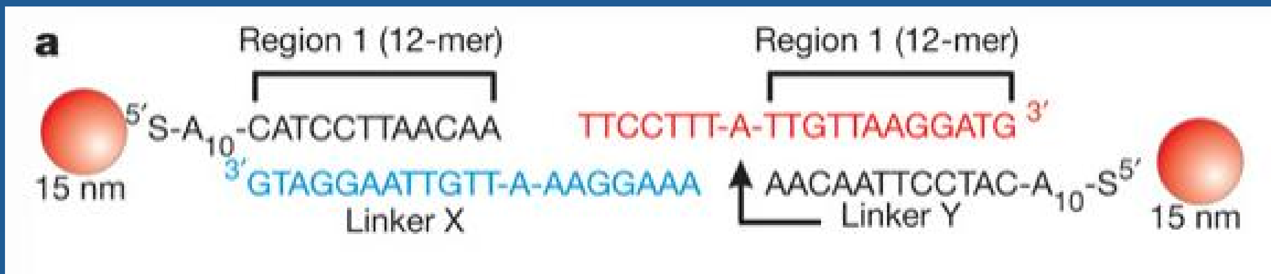
base-pairing dynamics and ubiquitous nature of DNA interactions



- 200 nm







- ► DNA origami
- ► Drug delivery
- ► DNA based electronic dev.

► From 1 Hz frame rate we want to go 80 000 Hz frame rate.

Keskin et al. J. Phys. Chem. Lett. 2015, 6, 4487−4492

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Structural Dynamics

The small & the fast

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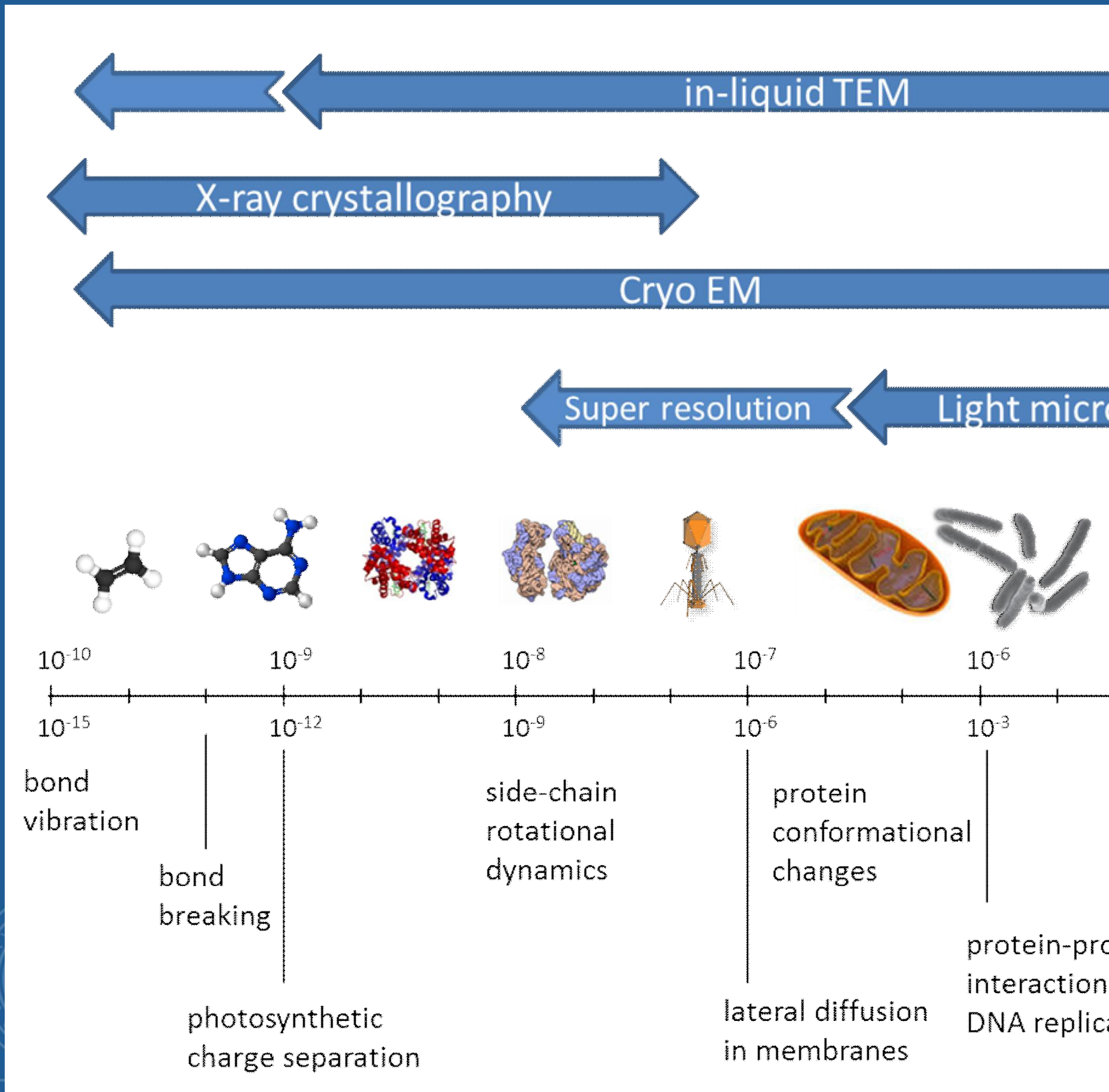
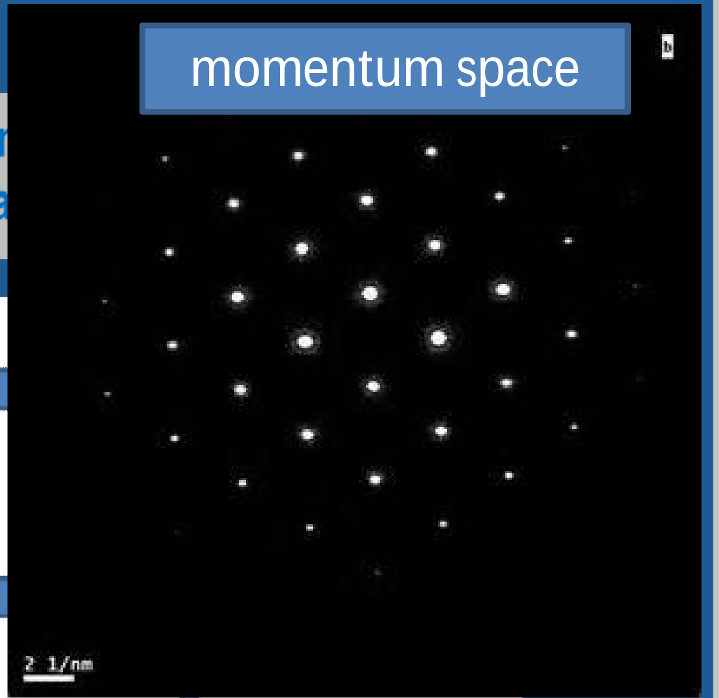
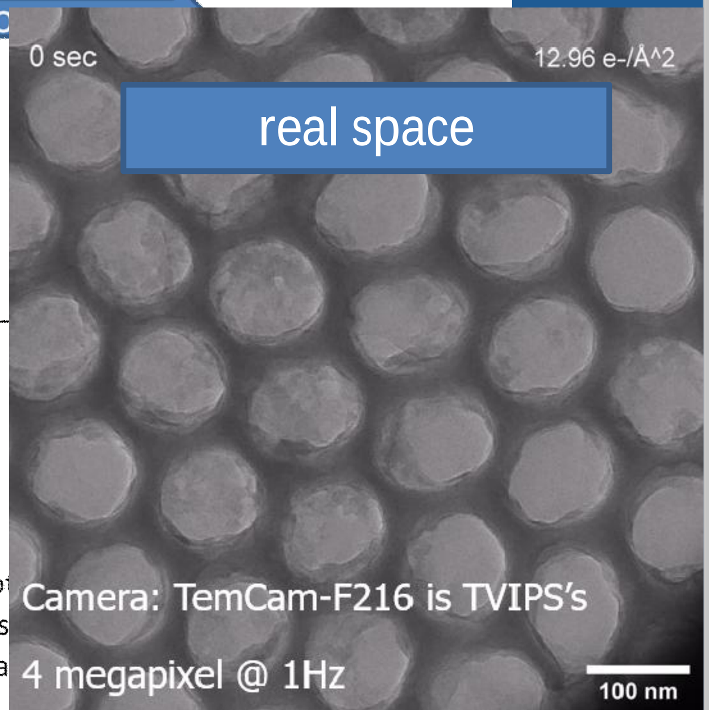
▶ **Mission statement: Visualization of the electronic and geor
time and space of chemical, biological, and condensed-ma**

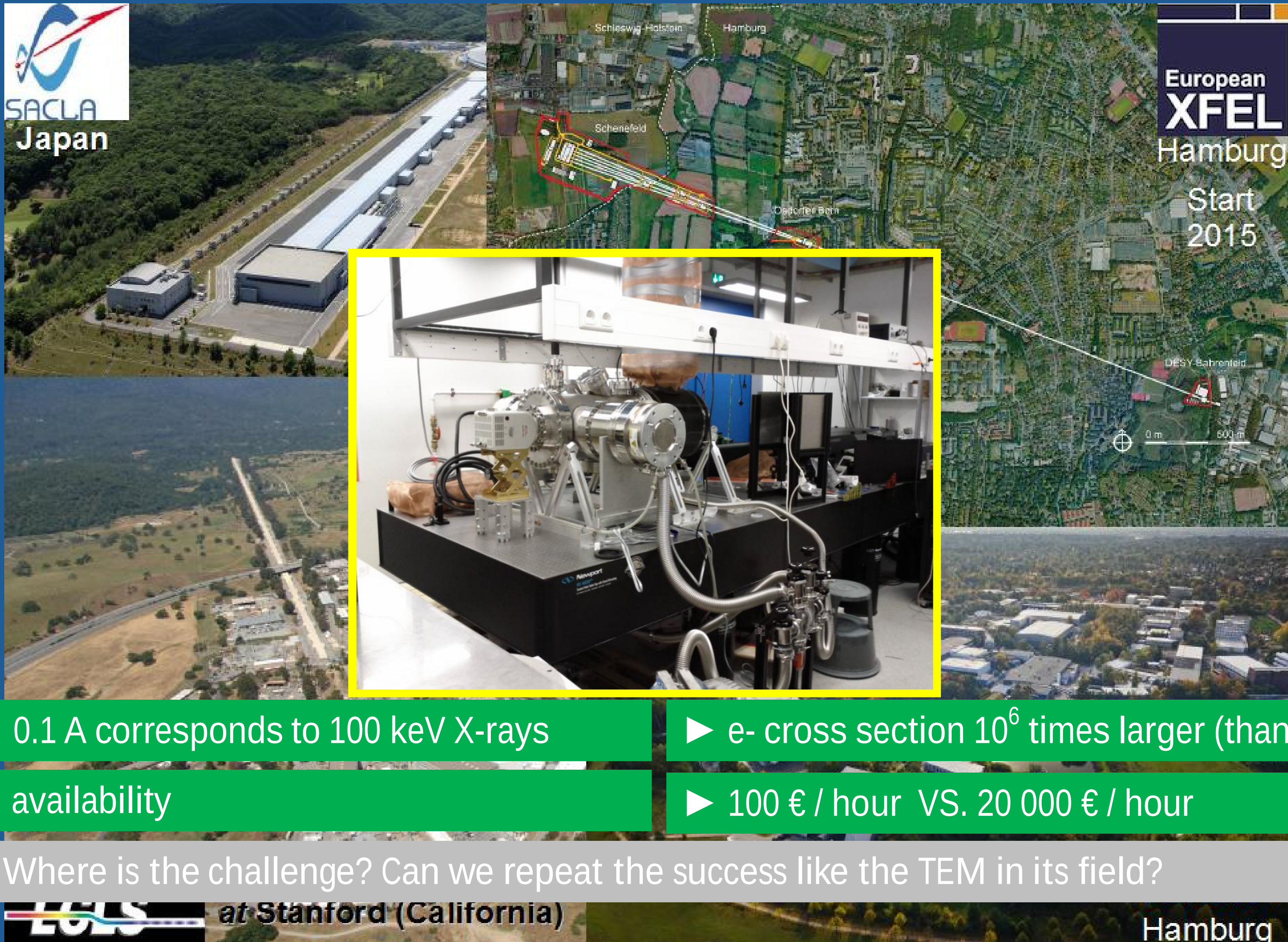






Experiments

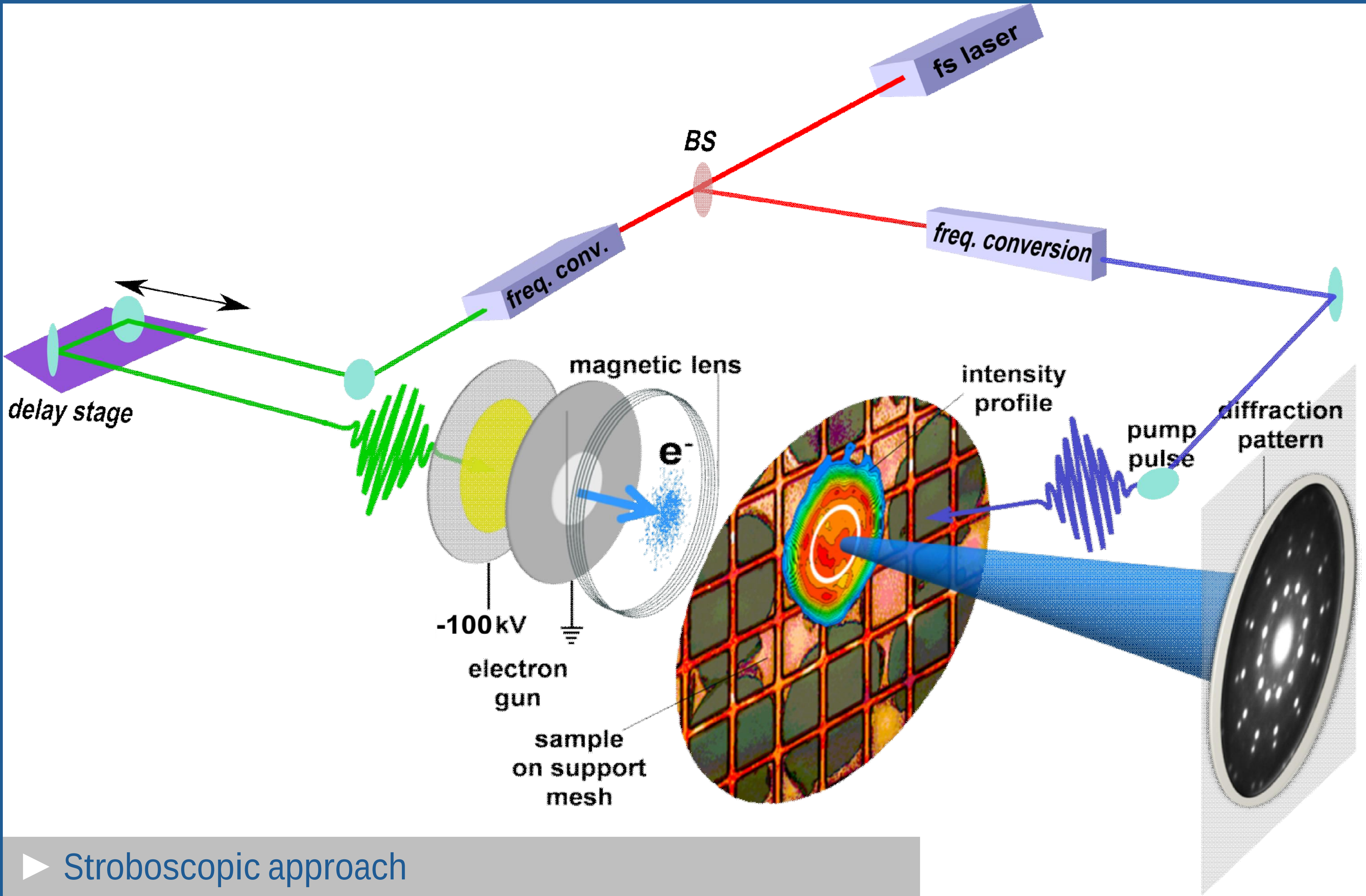
Large scale & small scale



- ► 0.1 A corresponds to 100 keV X-rays
- ► e- cross section 10^6 times larger (than g)
- ► availability
- ► 100 € / hour VS. 20 000 € / hour
- ► Where is the challenge? Can we repeat the success like the TEM in its field?

Femtosecond electron diffraction

The principle

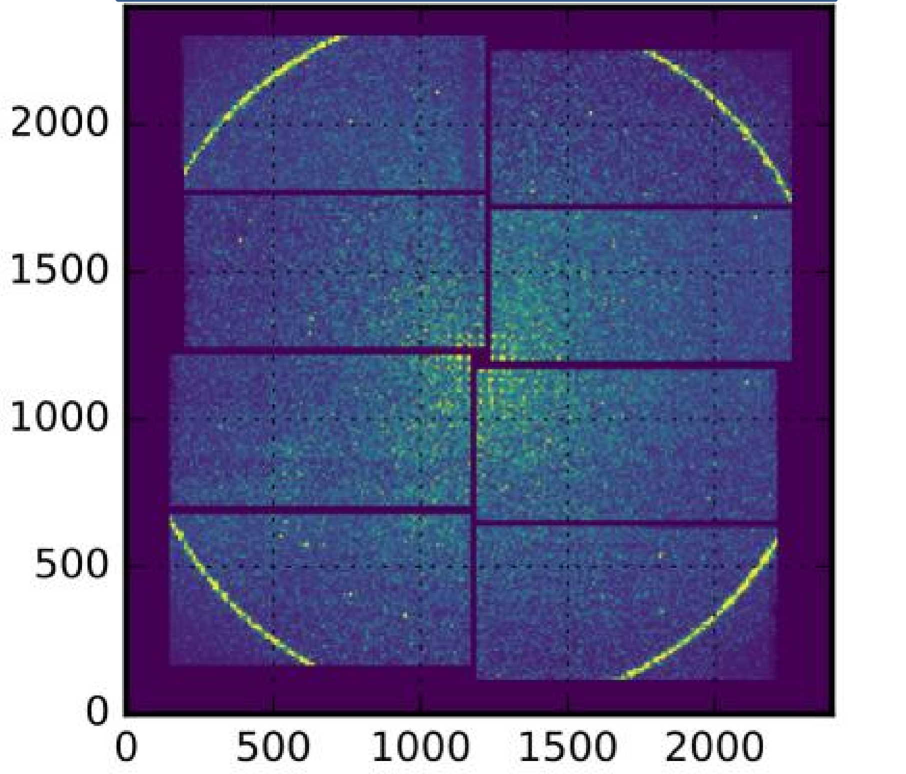


▶ Stroboscopic approach

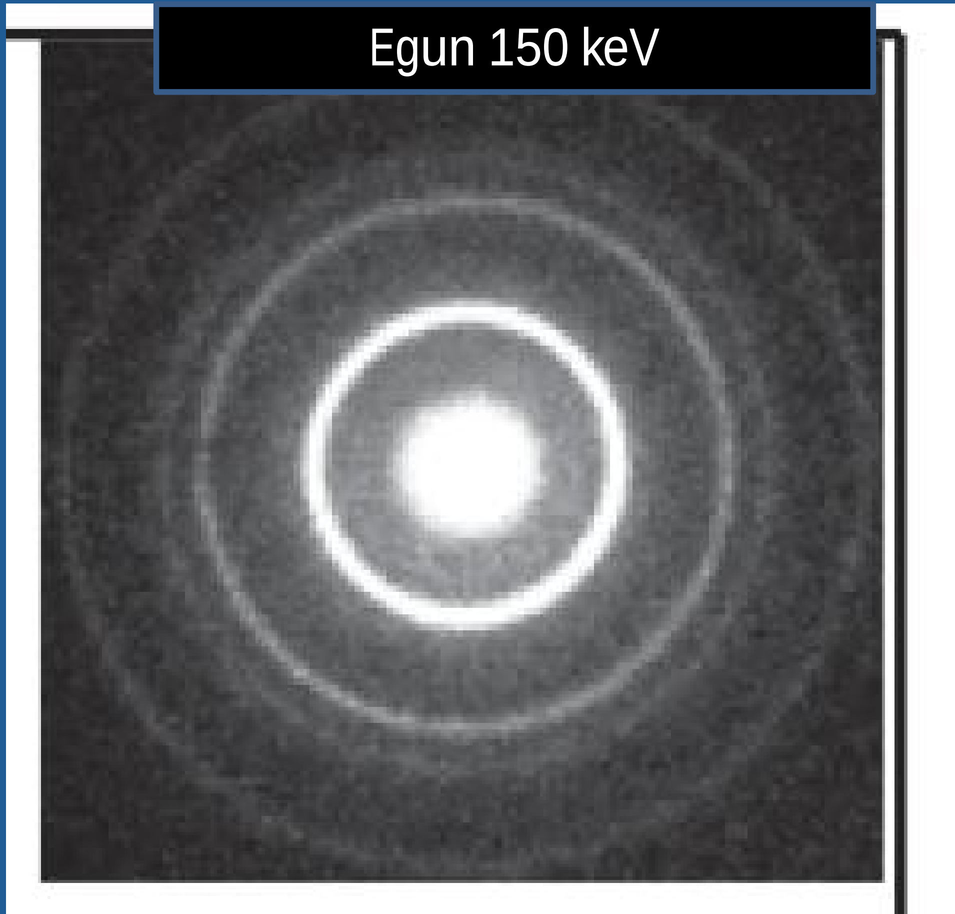
Femtosecond electron diffraction

Access the same physics with different data

SACLA XFEL 1.24 A



Egun 150 keV



- Similar poly-crystalline Bi sample: data is not identical, generally richer with electrons
- Xrays interact with electron shell, ultrafast electrons interact with the positive cores
- Electrons can be more suscesible to certain effects e.g. Spin and magnetic contributions
- Photon sensor interaction “cleaner” than electron sensor interaction (can anything be done)

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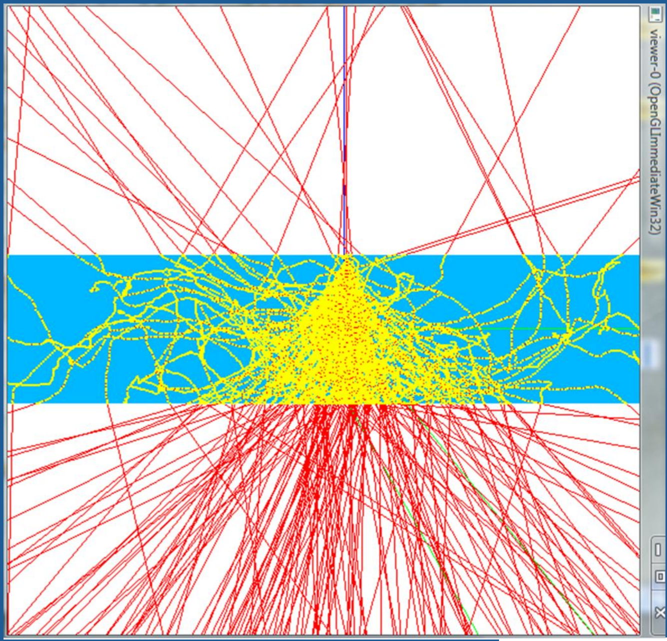
Detector Statistics



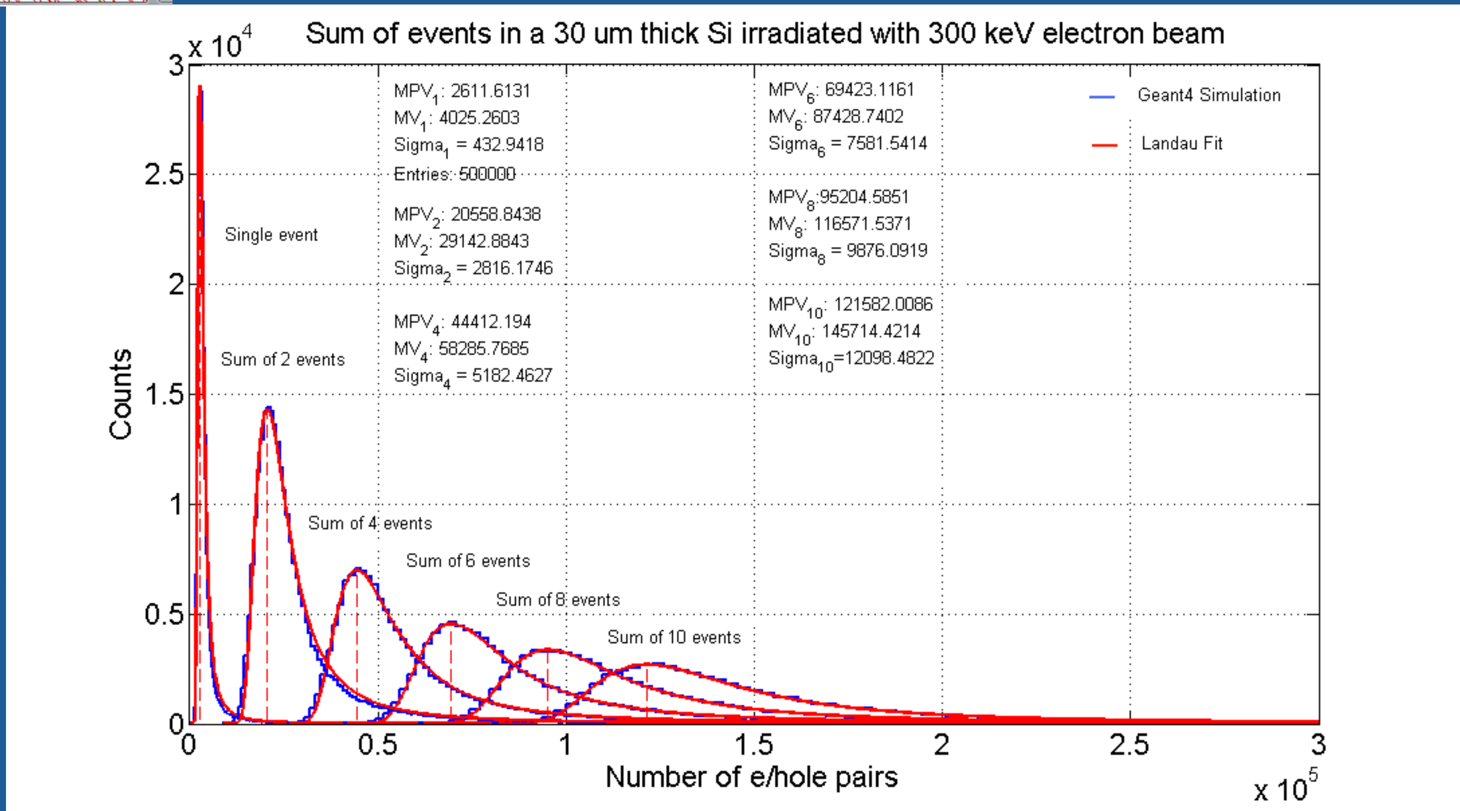
Uphill battle for electrons

- Photons create electron-hole pairs according to Fano statistics
- Sigma is about 10% of the mean value

- Electrons produce e-h pairs according to Landau statistics
- Sigma not constant > 20% of the mean value
- Electrons produce a straggling track

- 300 keV primary electron generates ≃ 8000 eh-pairs in 50µm Si and 80 000 eh-pairs in thick (500µm) Si.

- Most Probable Value gives useful statistics



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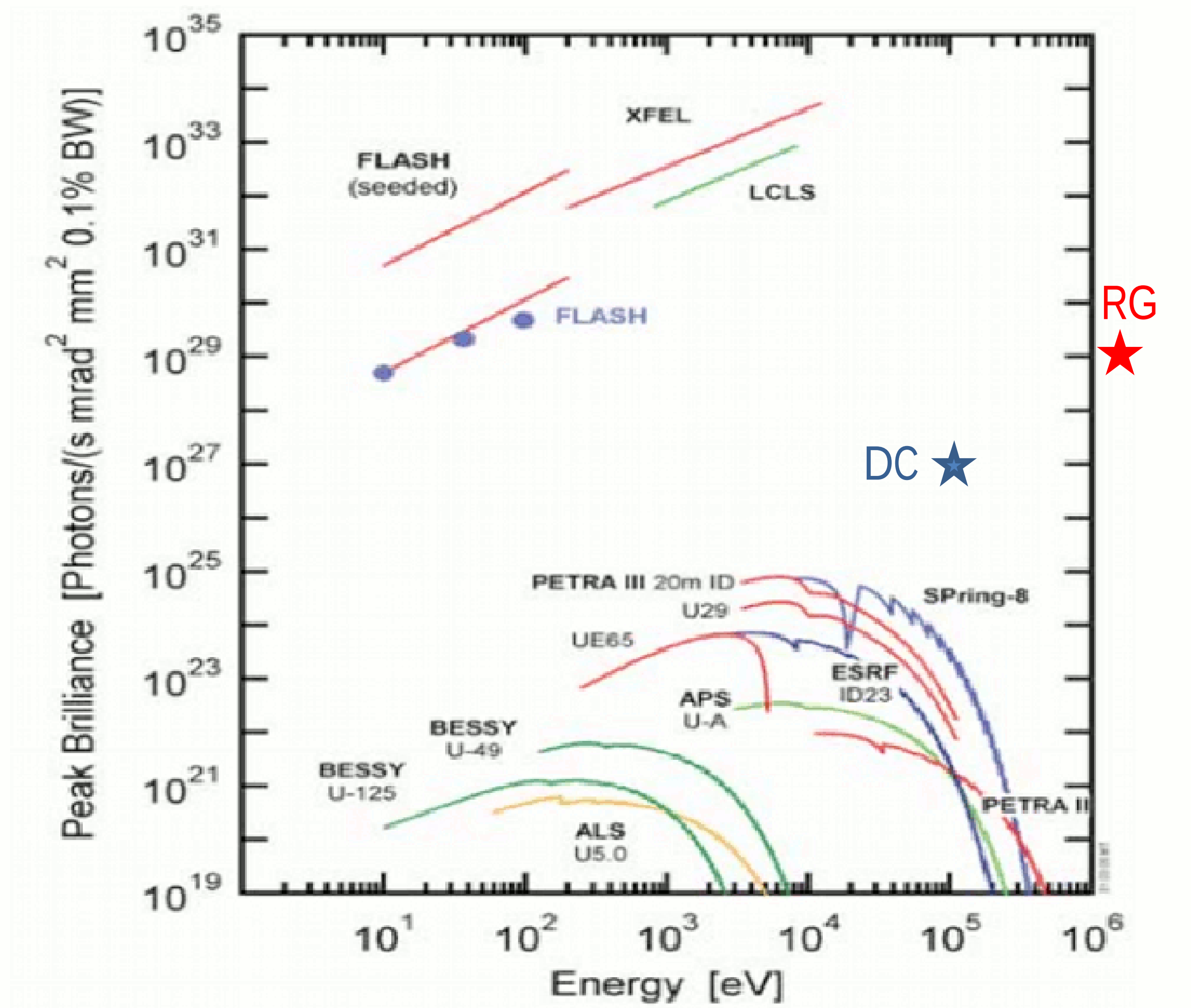
MAX-PLANCK-GESELLSCHAFT

XFEL: Xray Free-Electron Laser

Brilliance

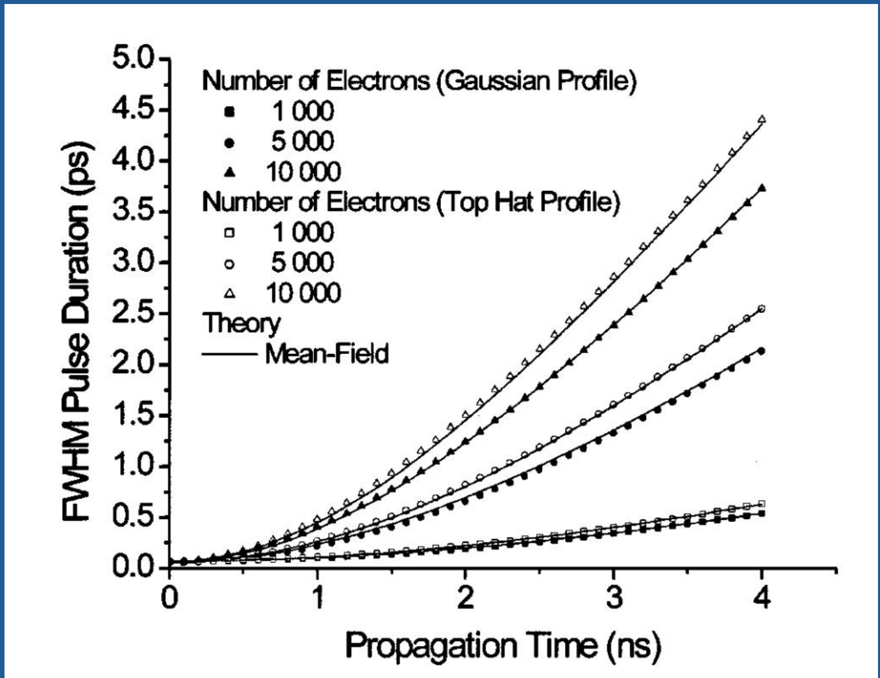


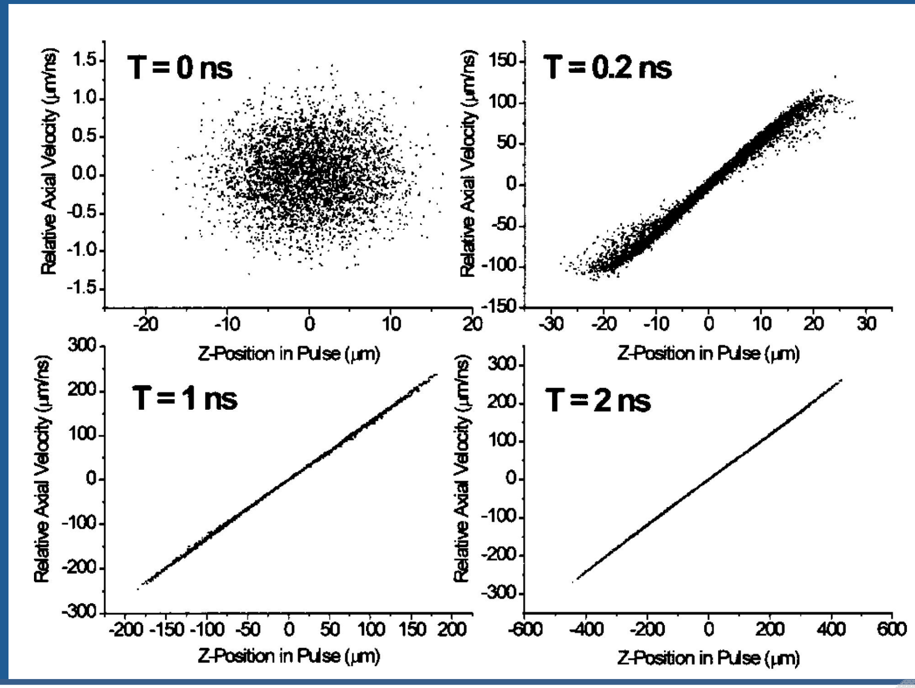
- DC gun:
  - 100 keV
  - 100 fs
  - 50k e-/shot
  - 0.02 mm mrad
- REGAE
  - 3 MeV
  - 10 fs
  - 100 k e-/shot
  - 0.01 Pi mm mrad
- Photons
  = #e- * 1e6 (C.S.)

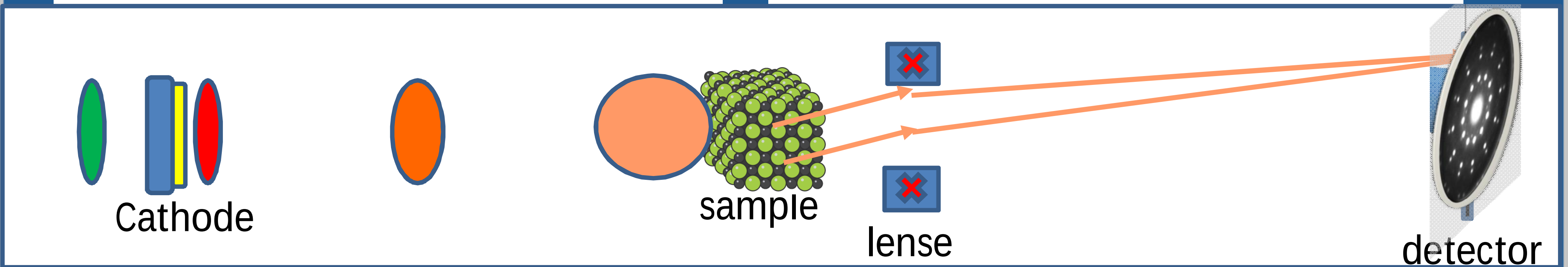
- Class of experiments: high time resolution, high spatial resolution, hight excitation (=single shot sample) = ultimate pain

Femtosecond electron diffraction

Electrons don‘t socialize

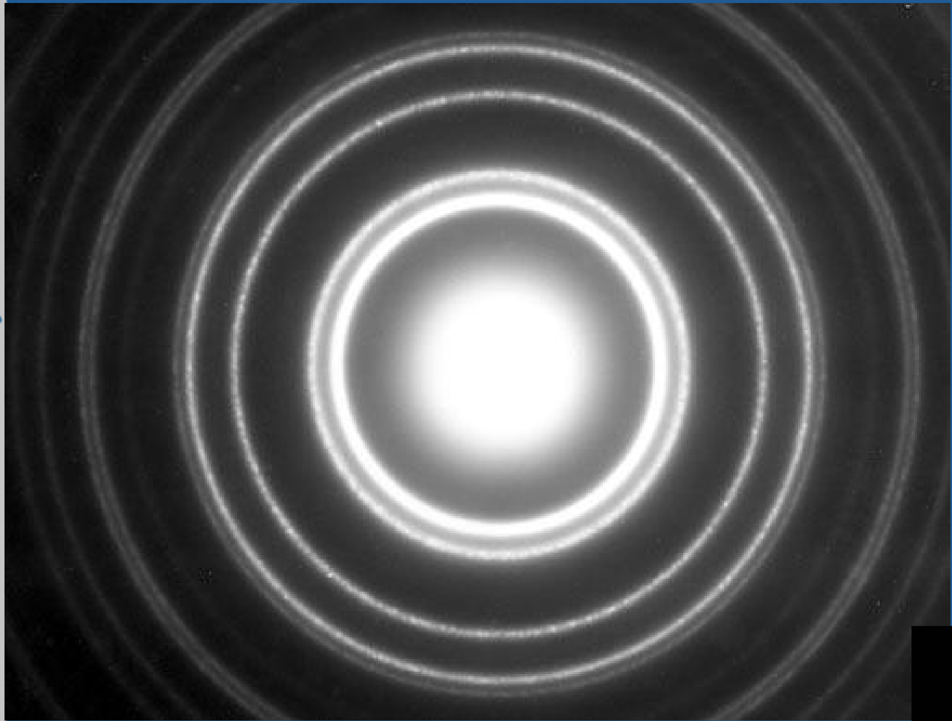


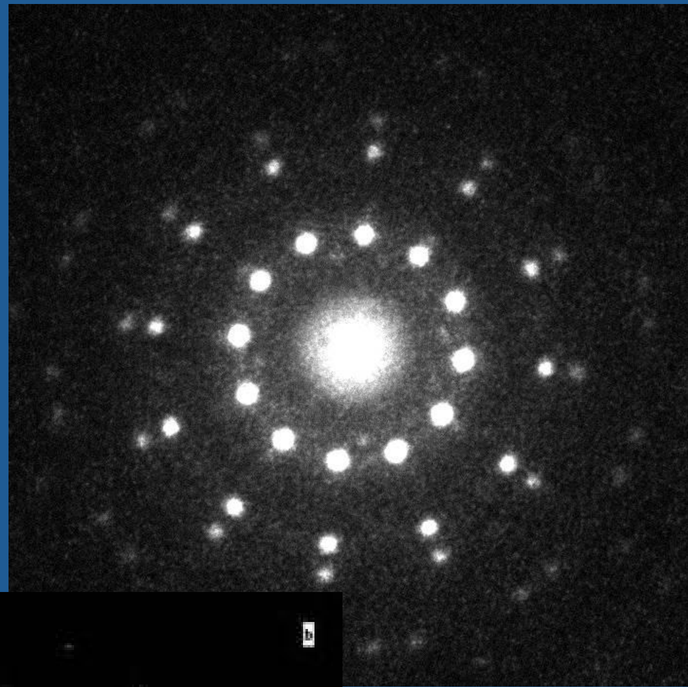




- ► Charge needs to be reduced as much as possible
- ► Production quality needs to be as high as achievable
- ► Detection quality needs to be as high as schievable

UED k-space

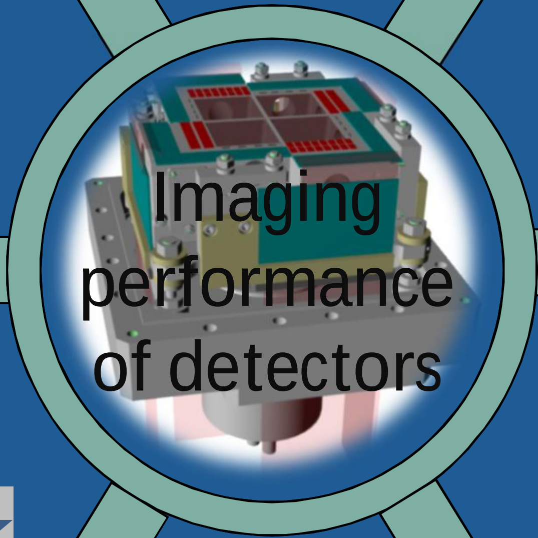




► >10,000 electrons on detector are need to attain qualitative diffraction information

► problem dependent: more electrons on detector are need to attain quantitative diffraction information

Ultrafast electrons: Do detectors make a difference



Spatial resolution:
- Pixel size and total area
- Particle sensor interaction

=> Quality of results

Temporal resolution:
- Frame rate
- Can be crucial or irrelevant

=> Quality of results

Geometric flexibility ★
- Change geometry of detection area

=> Quality of results

Usability: ★
- Radiation hardness
- Complexity of operation e.g. software, housekeeping
- Interpretability of the data

=> Quality of results

Recording Efficiency: ★
- Dynamic range
- Bit depth
- Charge handling capacity
- Non linear electron storage
- Sampling

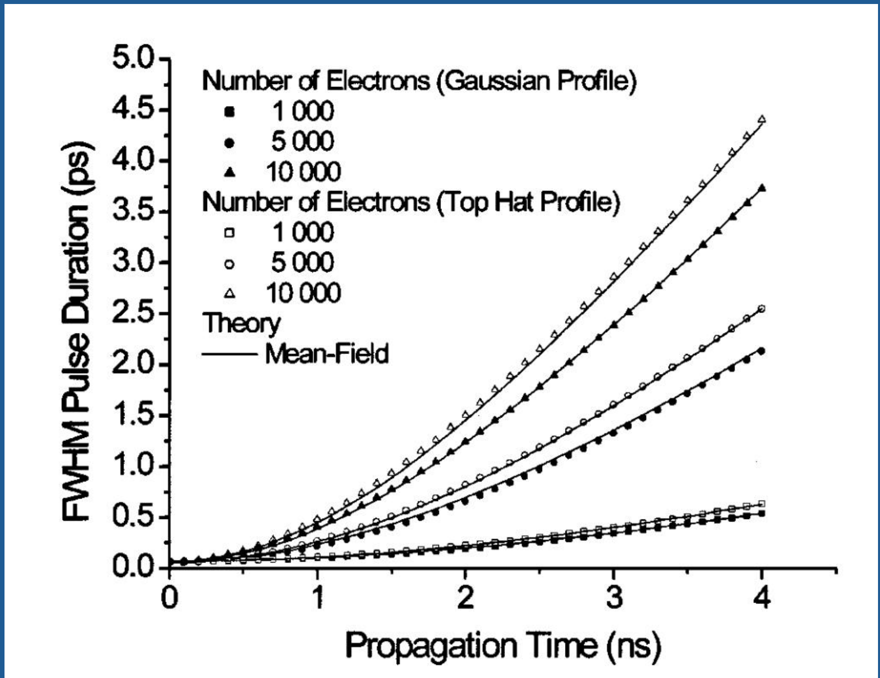
=> Quality of results

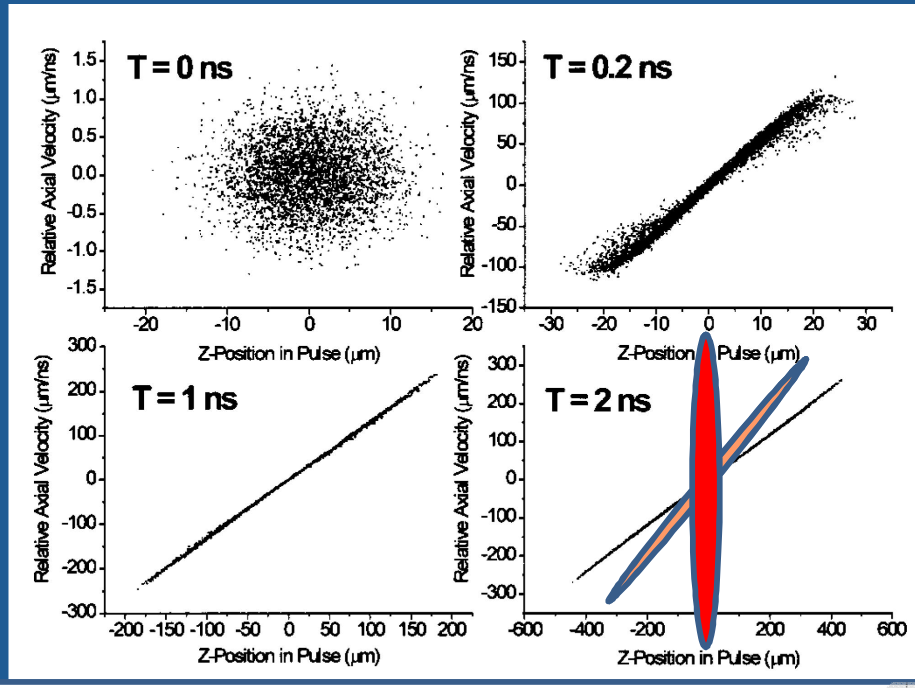
Detection efficiency ★★
- Sensor particle interaction (direct or indirect etc)
- Electronics
- Operation mode: counting integrating

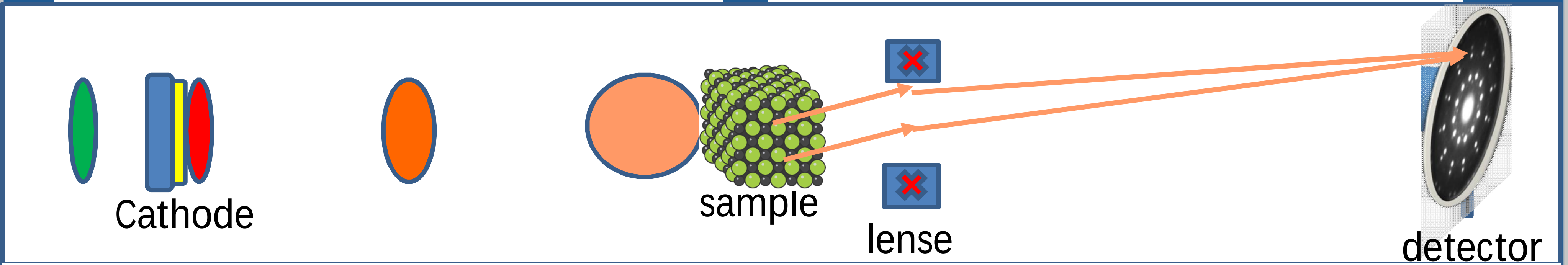
=> Feeds back to experimental parameters

Femtosecond electron diffraction

Crazy geometrical tweaks I : Refectron



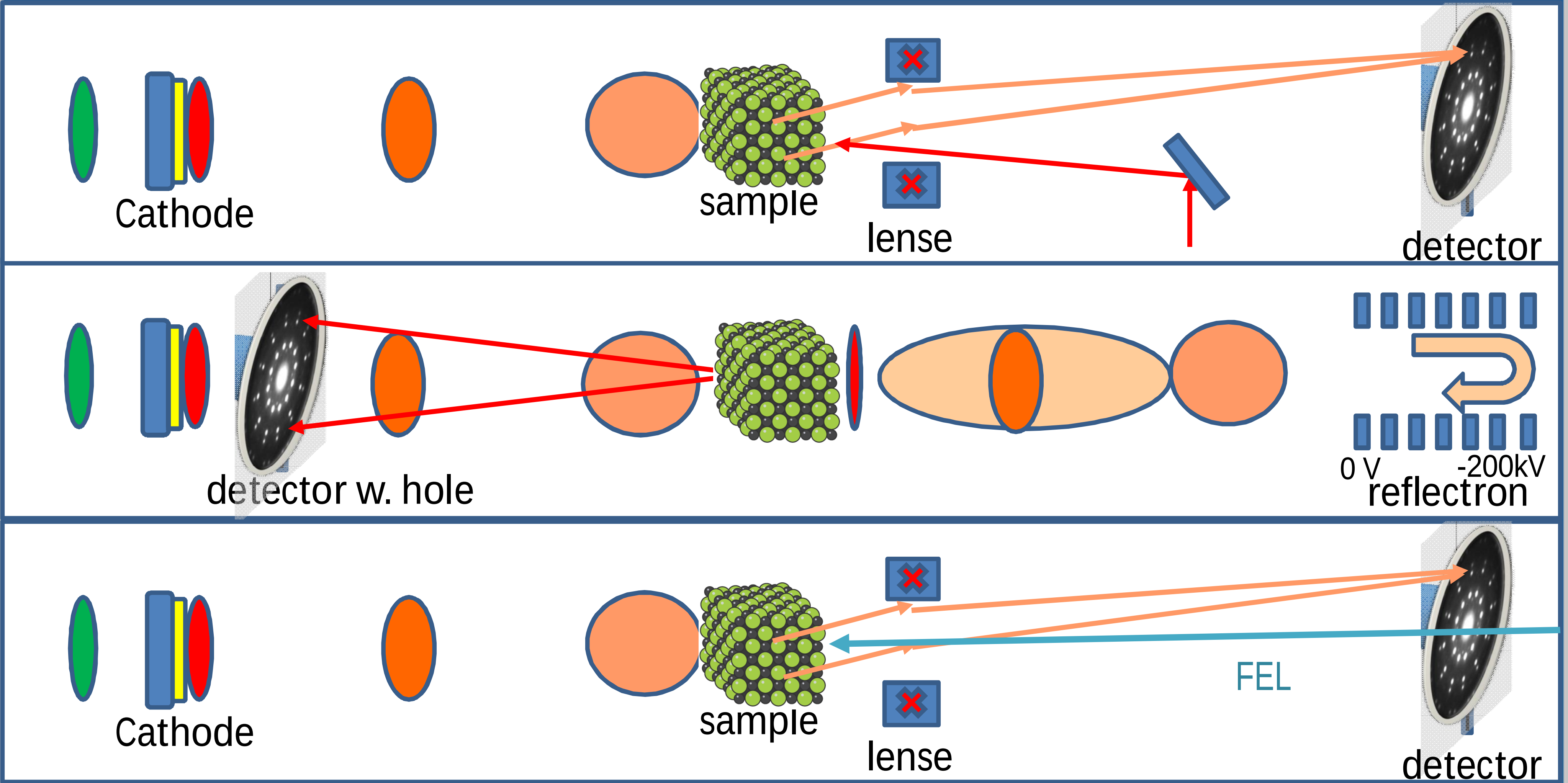




Femtosecond electron diffraction

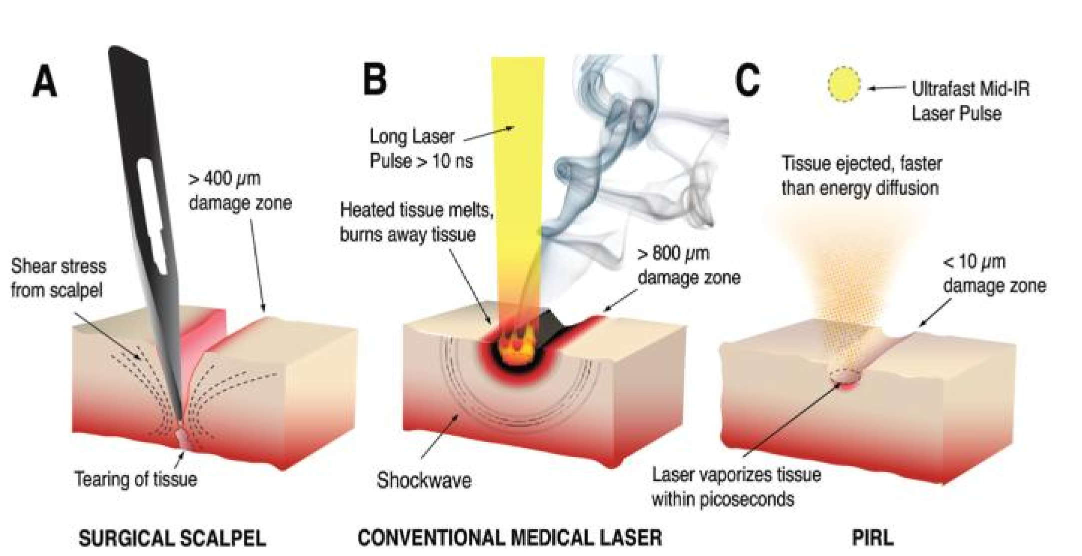
Crazy geometrical tweaks II : FEL sample pump

- Terra incognita: FEL pump – electron probe
- Photon equivalent would be FEL pump / FEL probe (very difficult because very different energy needed)
- Induced structure changes potentially very different from excitation with optical laser



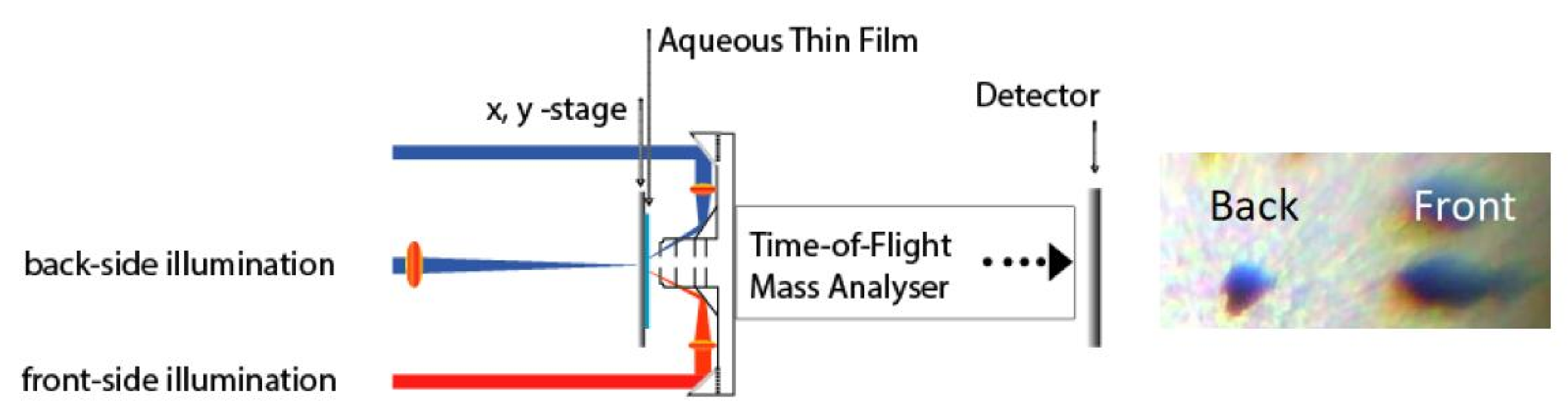
Ultrafast electrons: Do detectors make a difference

Plume dynamics



doi:10.1371/journal.pone.0013053

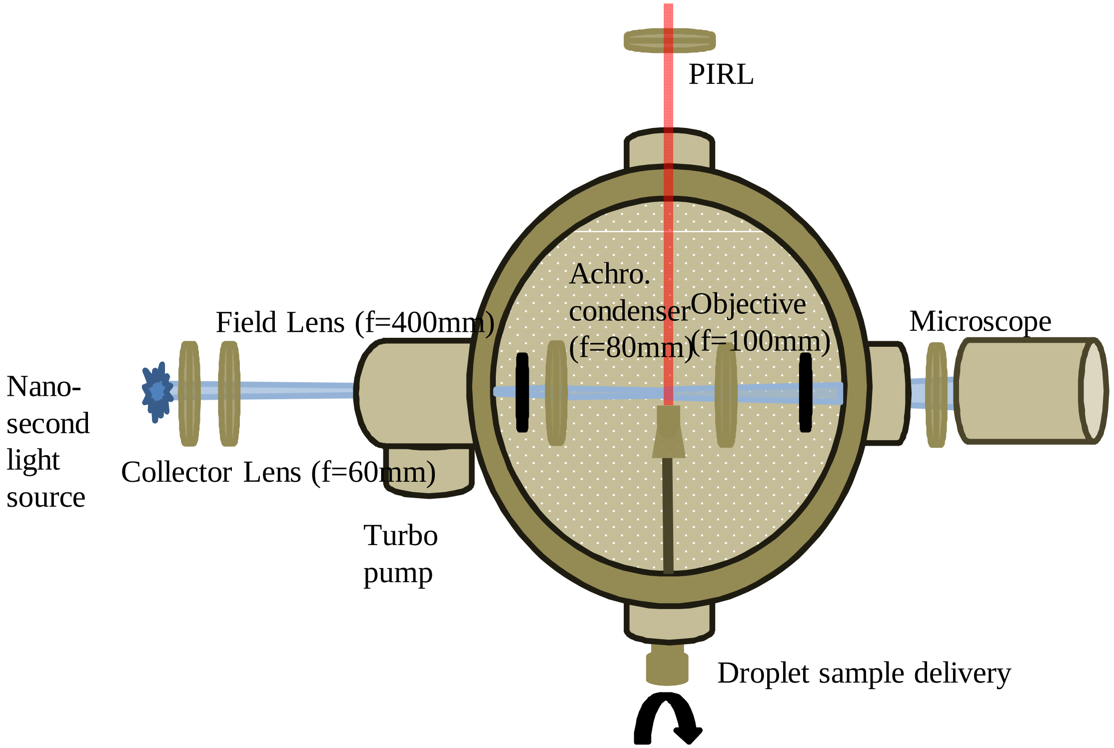
- ► Our interest started with pretty applied science and made it way back to the fundamental roots
- ► from laser surgery to mass-spectronomy to plume dynamic

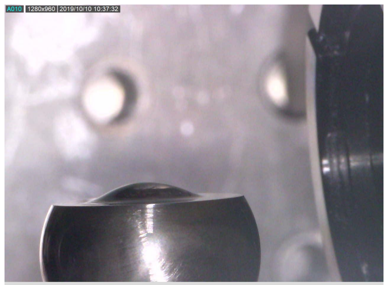


A. Krutilin, F. Busse, SWE

Plume dynamics

Setup for PIRL ablation in vacuum



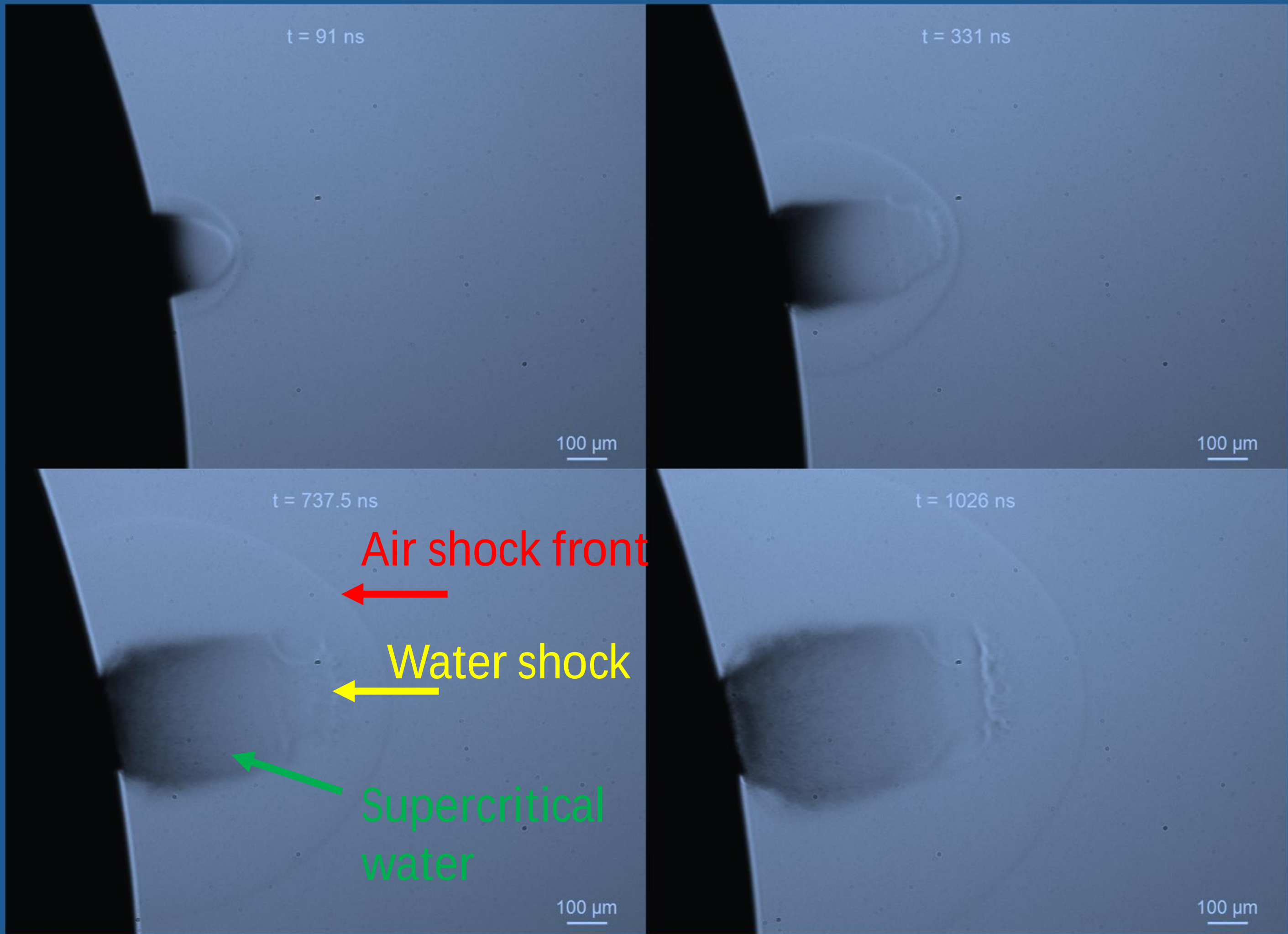


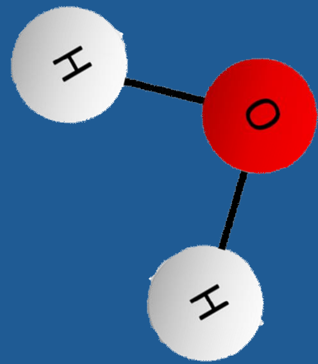
- 2950 nm laser t=400 ps
- Targets OH stretching at 2.94µm
- Absorption length very short (90 % over 2 mm)
- Creates stress-confined volume: DE >> 0; DV ≈ 0
- Vacuum vessel to set pressure between 10^{-6} and 1013 mbar

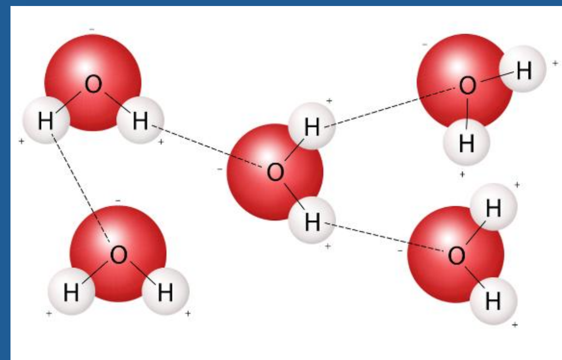
Meghanad Kayanattil, Zhipeng Huang, SWE

Plume dynamics

Ablation of liquid H2O in ambient conditions



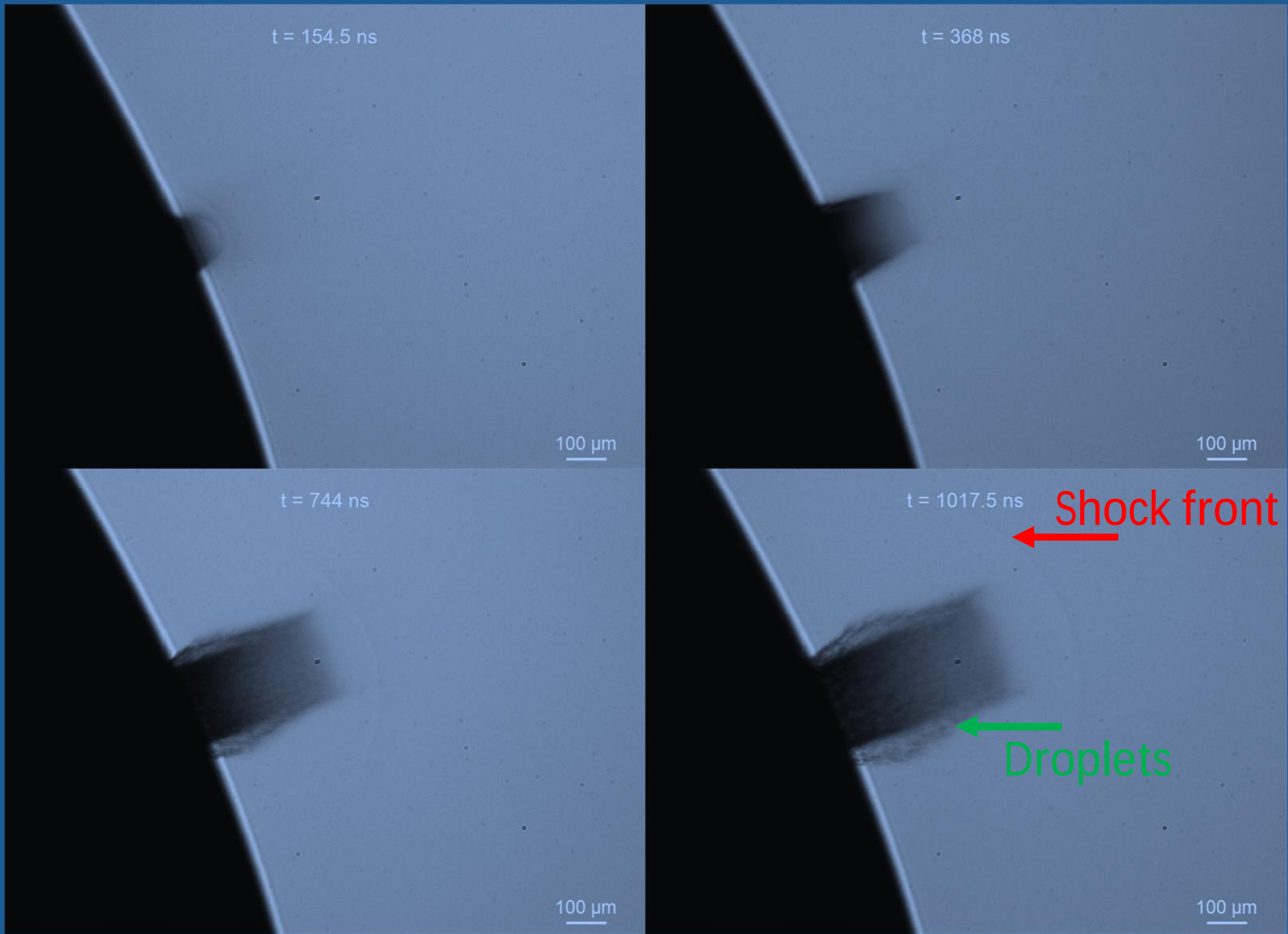


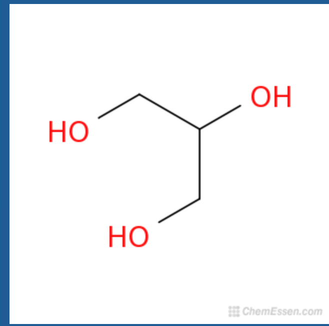


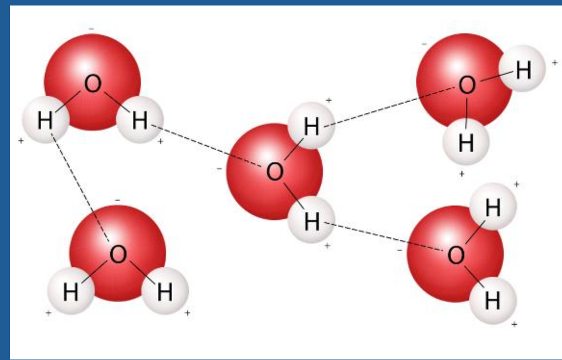
- ► Laser energy: 350 mJ / cm^2
- ► Ambient background of 1013 hPa Air
- ► Super-sonic shockwave driven by 500 000 – 1 000 000 hPa pressure

Plume dynamics

Ablation of liquid Glycerol in ambient conditions



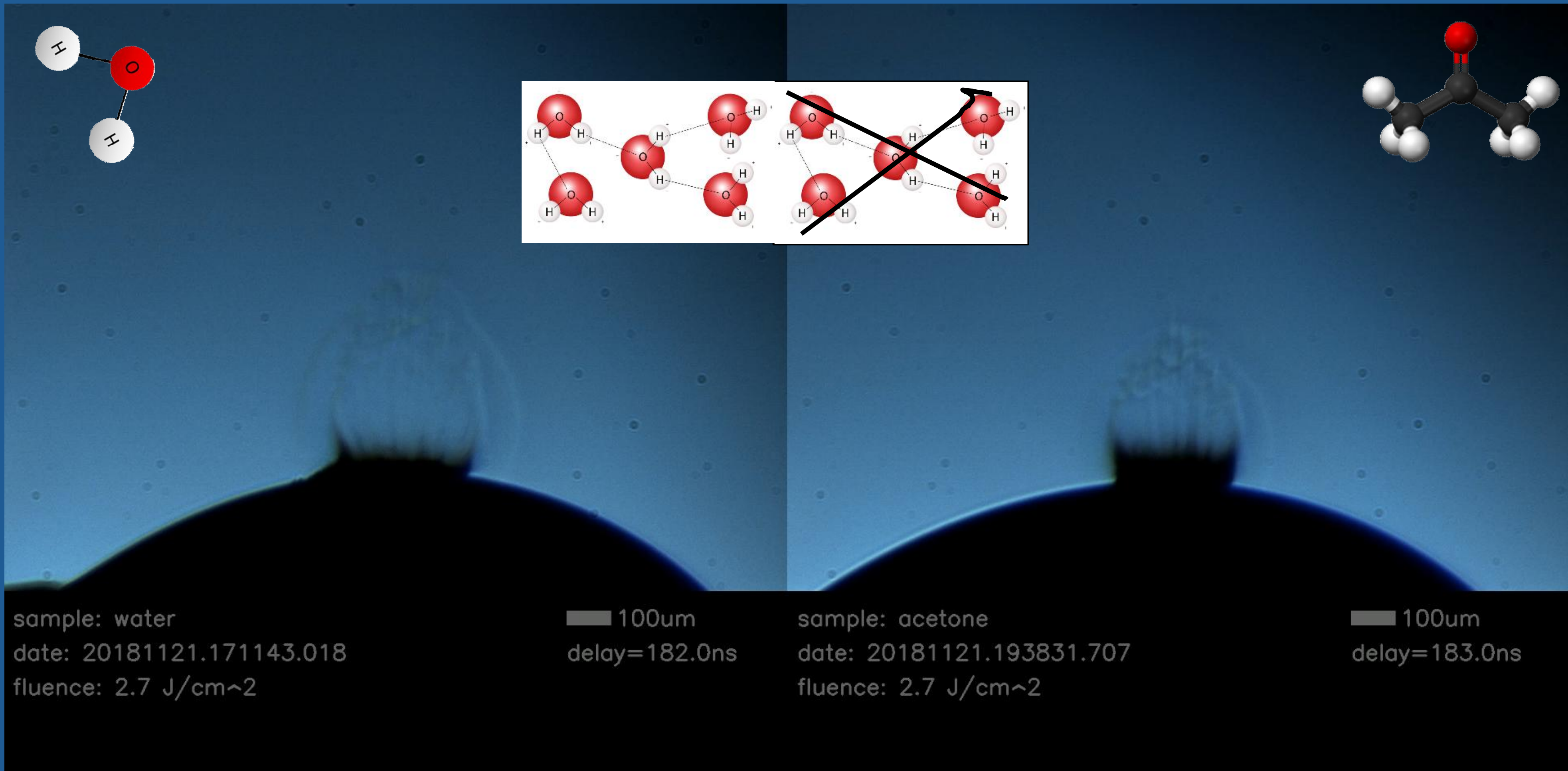




- Laser energy: 350 mJ / cm^2
- Ambient background of 1013 hPa Air
- Similar hydrogen bond network to water
- Similar absorption spectrum (slightly smaller)

Plume dynamics

Water vs Aceton



- ▶ Very similar plume dynamics
- ▶ With and w/o hydrogen bond network

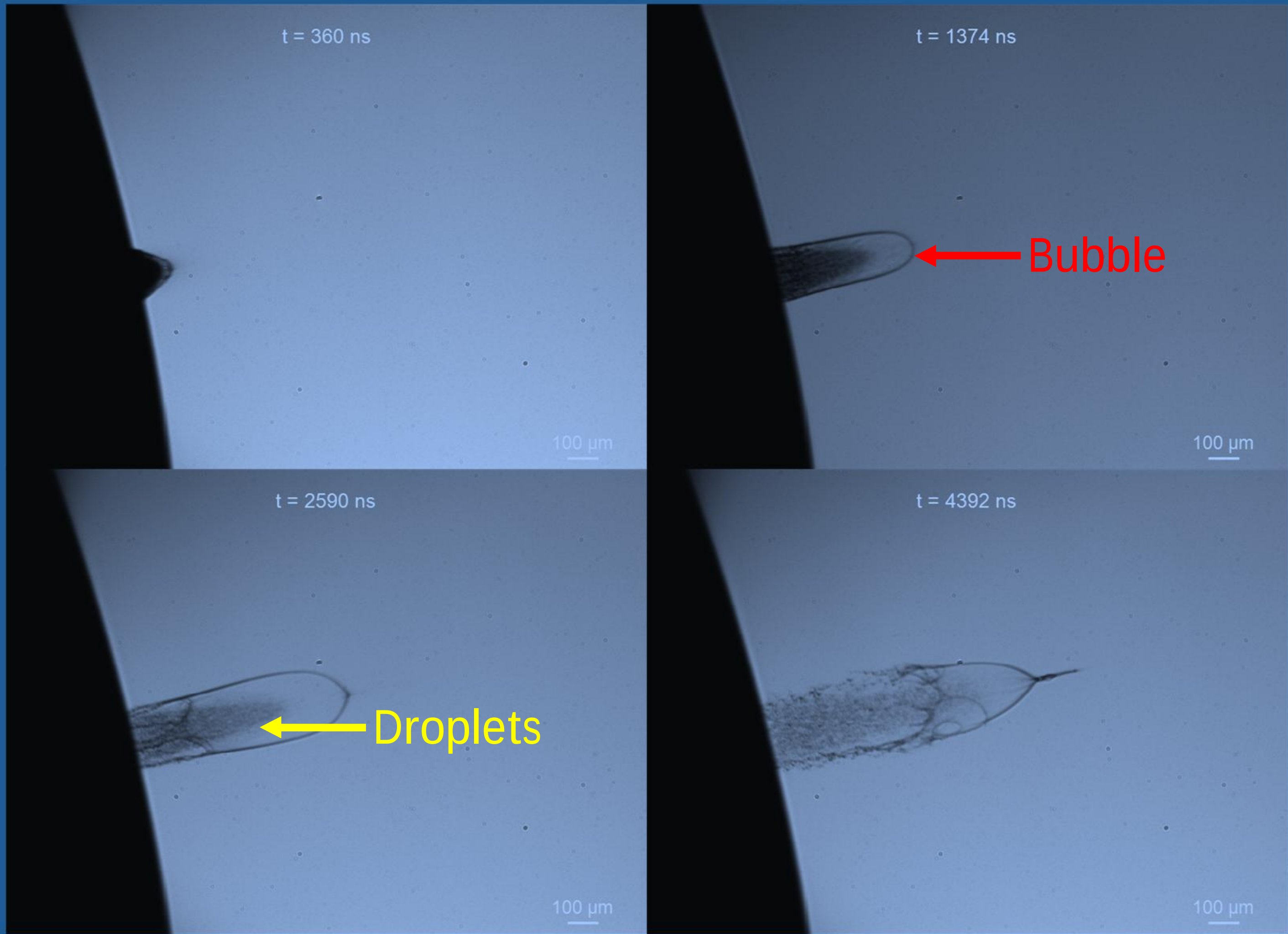
Plume dynamics

Glycerol in vacuum

- Laser energy: 160 mJ / cm^2
- Vacuum background of 10^{-5} hPa
- Formation of a shell travelling at 270 m/s
- Note: Individual images show always a different plume
- shockwave driven by 50 000 – 500 000 hPa pressure

Plume dynamics

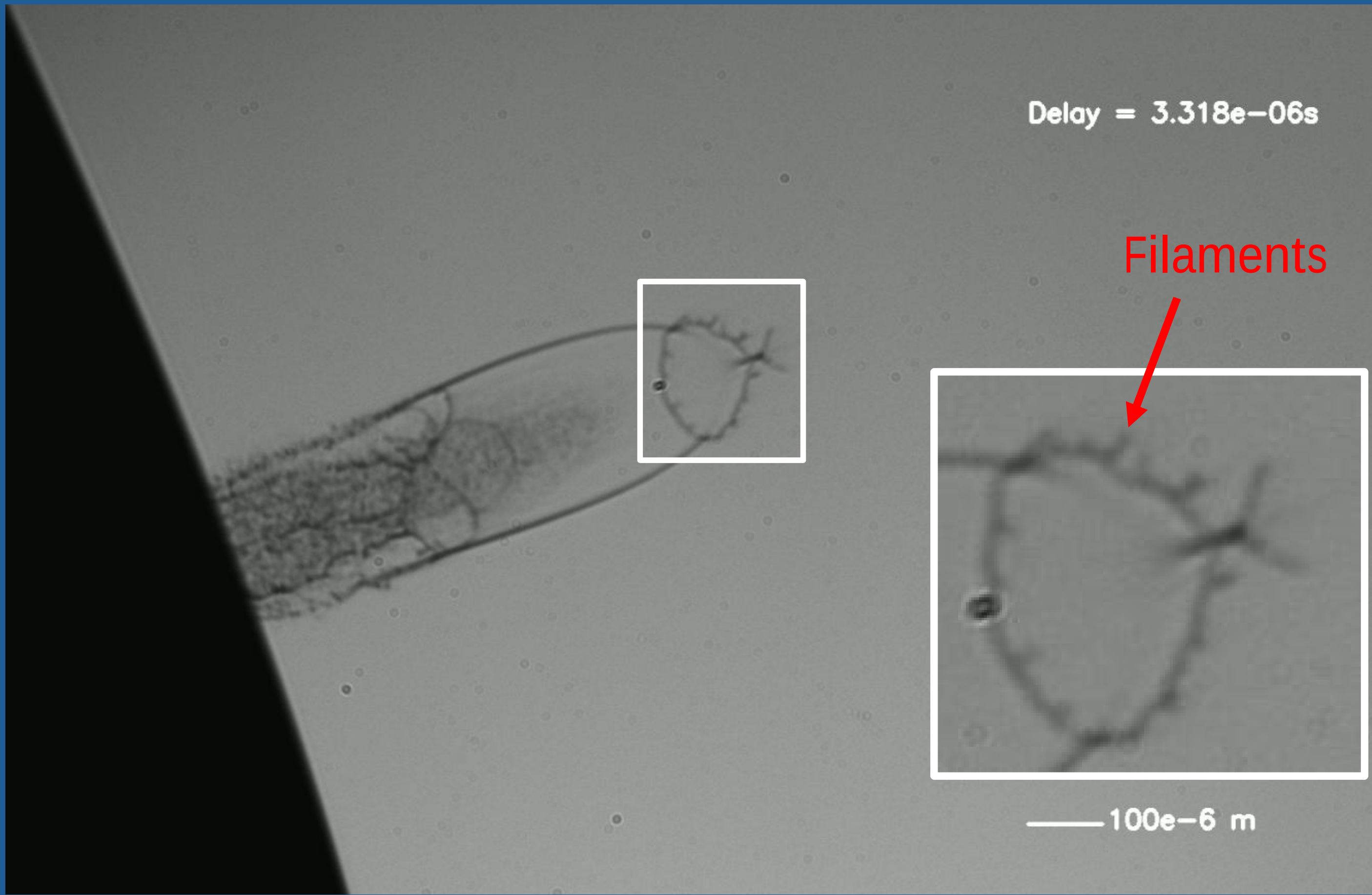
Ablation of liquid Glycerol in 1E-5 mbar vacuum (Medium fluence 160 mJ/cm^2)



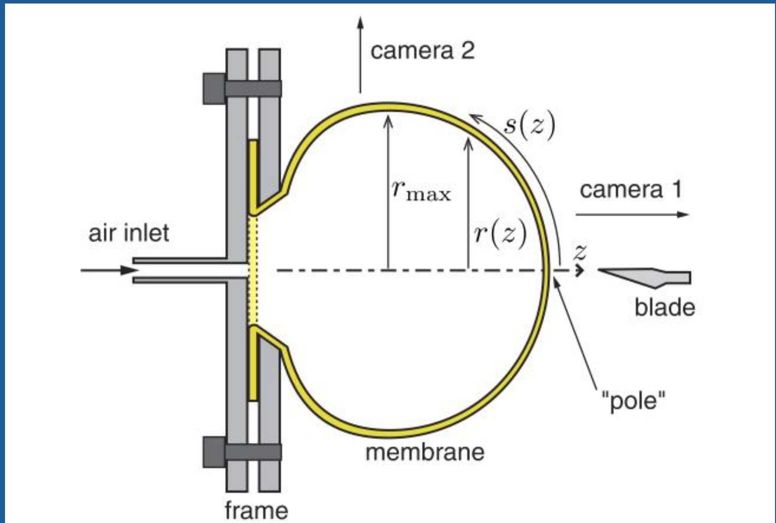
- Laser energy: 160 mJ / cm^2
- Vacuum background of 10^{-5} hPa
- Formation of a shell
- Note: Individual images show always a different plume

Plume dynamics

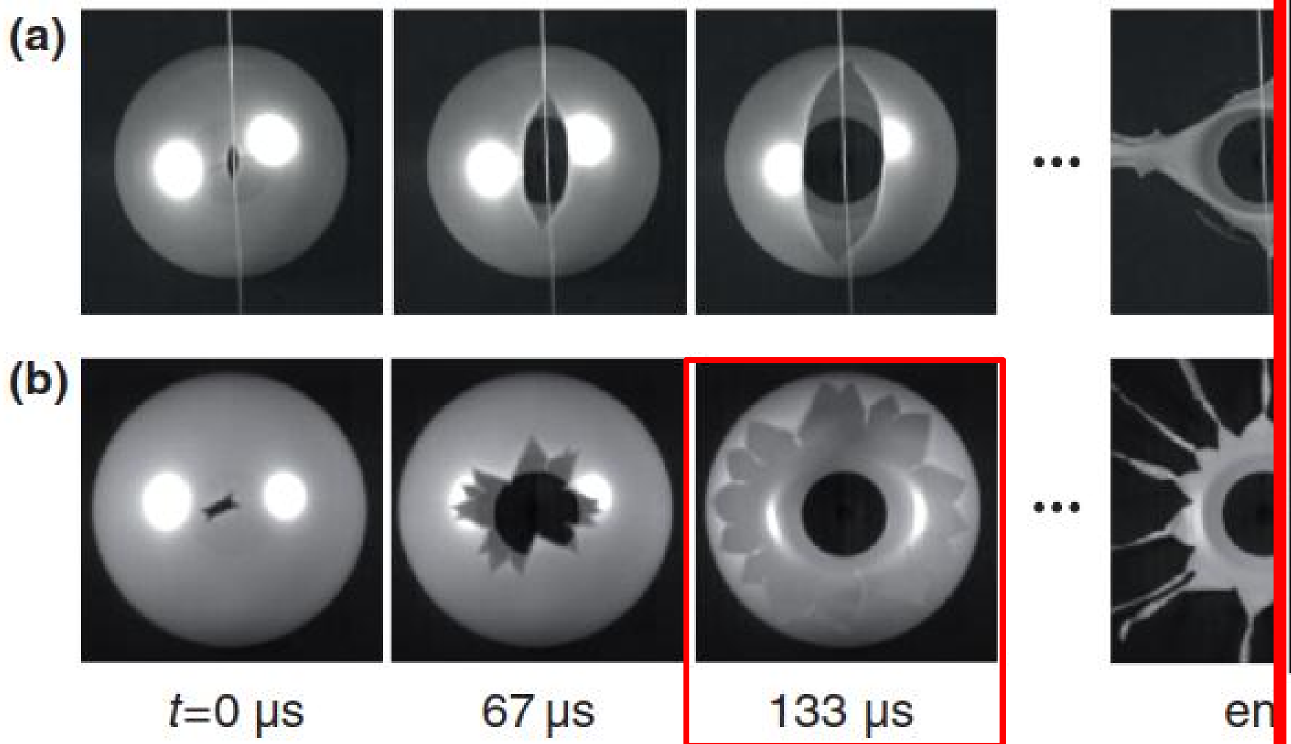
Bursting of glycerol bubble

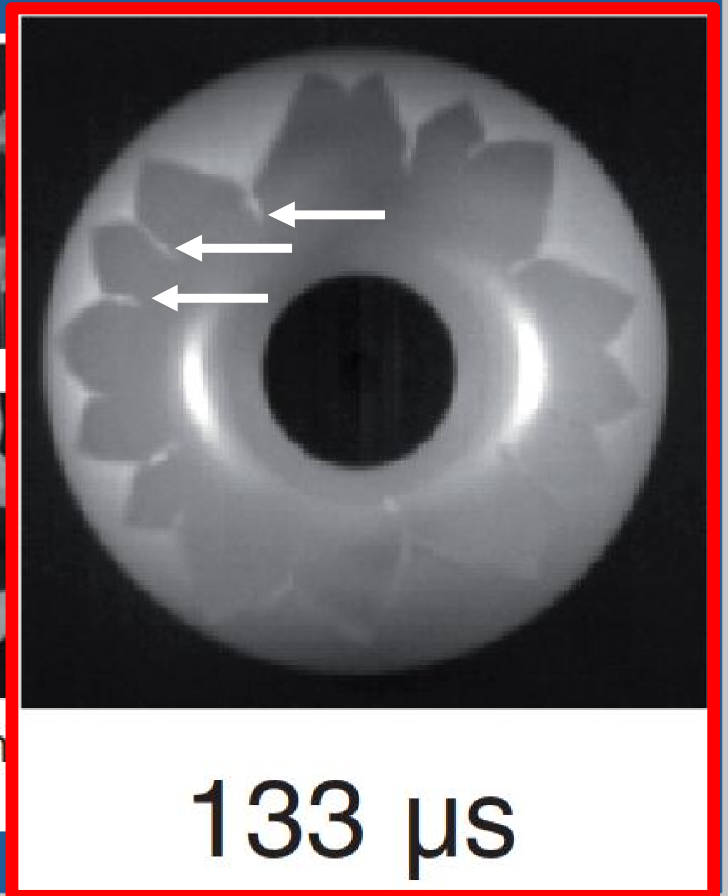


Bursting of a latex shell (balloon)



- ▶ Latex stores elastic energy
- ▶ Popping releases the stored energy
- ▶ Latex has a Shear module: Transverse waves can propagate

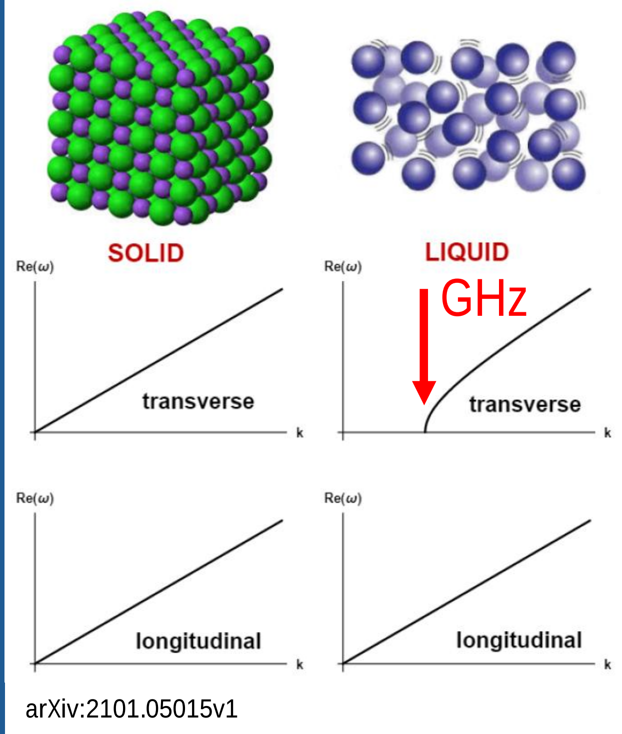


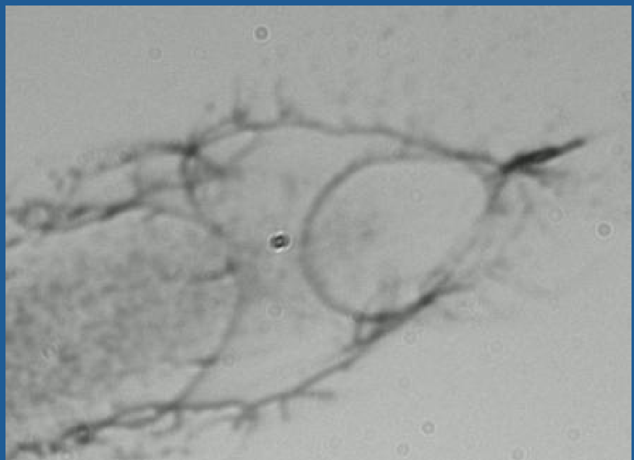


Ref: DOI: 10.1103/PhysRevLett.115.184301

Plume dynamics

We have a problem

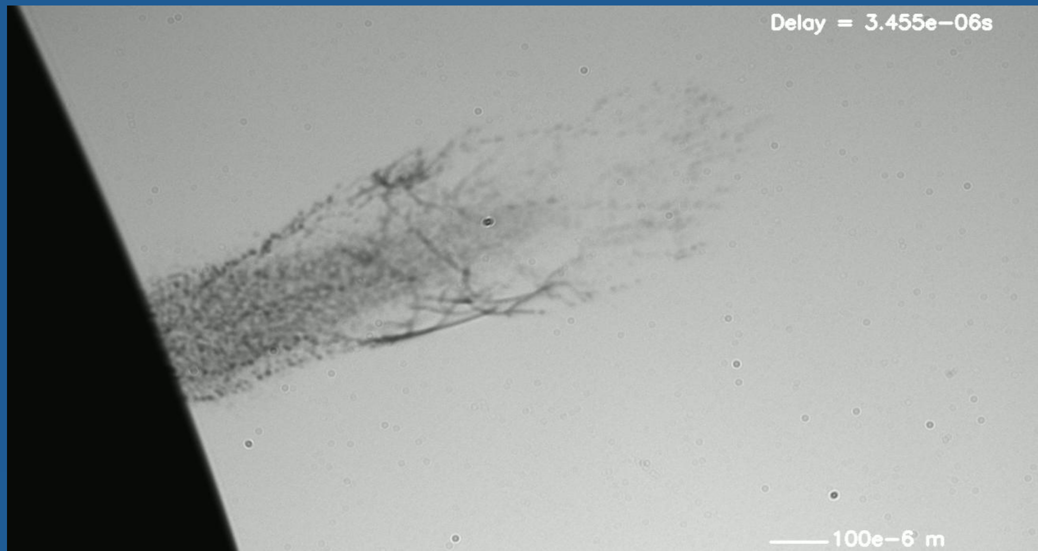




- Classical liquids do not express elasticity
- In viscous liquids the relaxation times for shear strain should be short. Water: ≈ 10 ps
- Clear indication for glycerol having a memory for mechanical forces = elasticity
  - Filaments (see latex shell)
  - Jetting (Elastic energy from the shell released at the tip)
  - Bubbles bursting earlier reach higher velocity
    - energy release cannot be stored elastically anymore but only ballistically
  - Can surface tension mimic elasticity ?

Plume dynamics

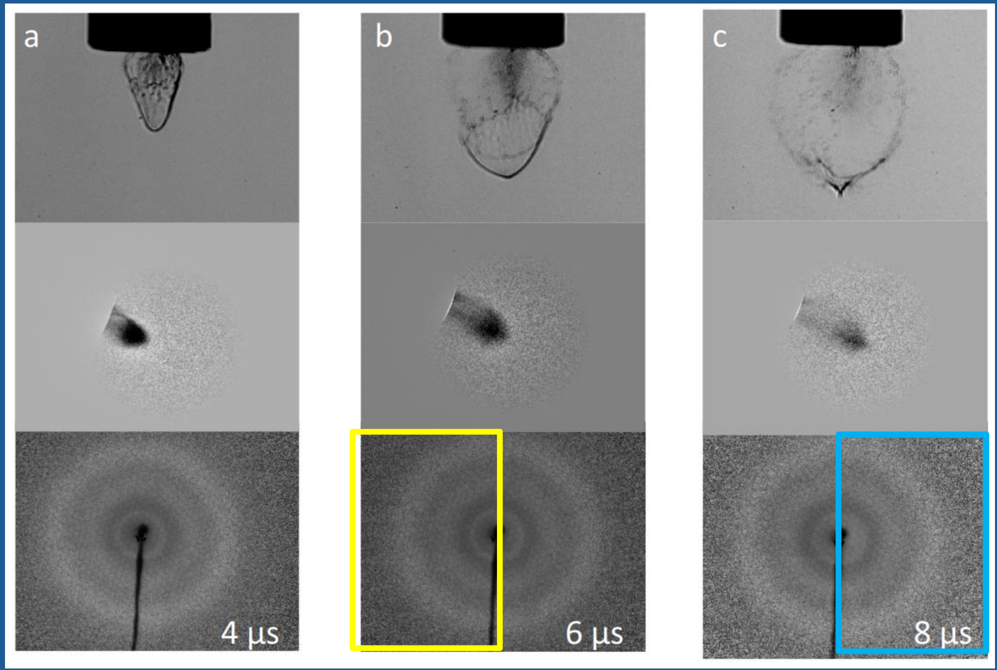
Finaly the electrons come into play



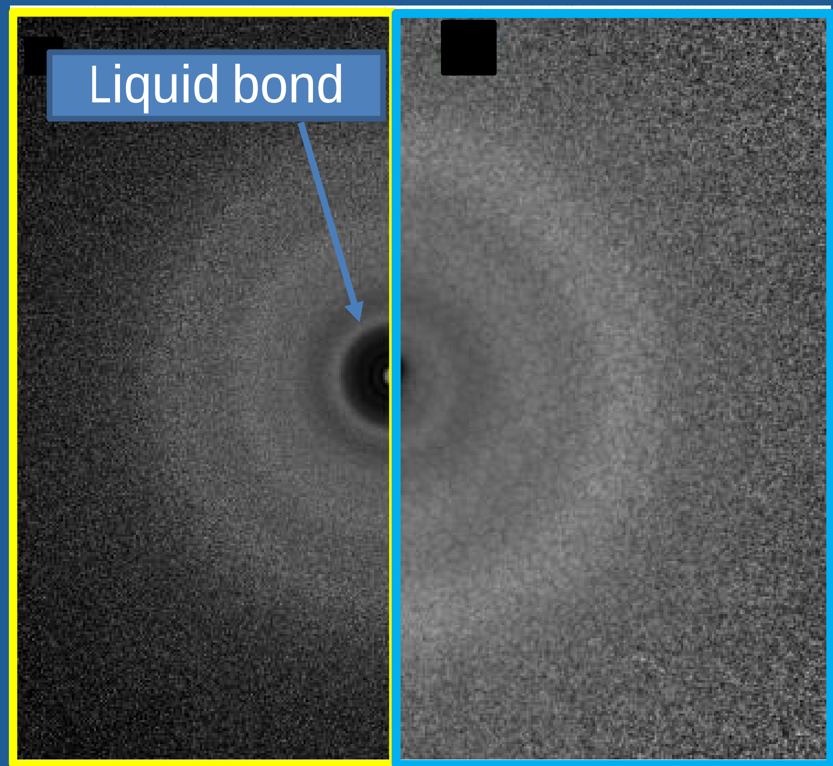
► Probe at different regions with electrons to understand the state of the mater

Electron diffraction on plumes

First results



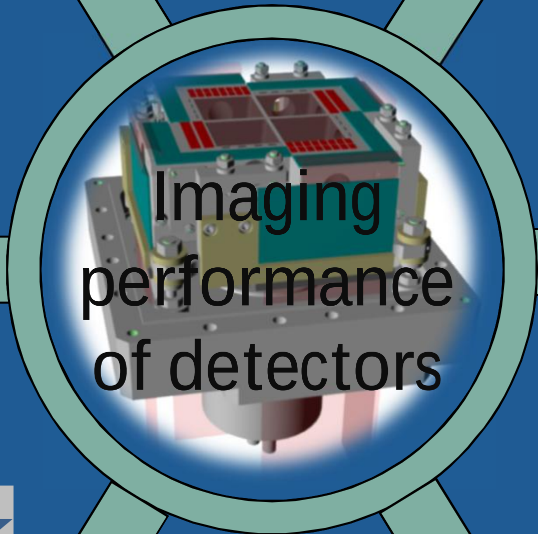
- The whole plume is hit by the electron beam
- The liquid fraction vanishes with time
- We need everything more precise (bond length) in time and space
- Typically neutron scattering (another large facility) is best used to understand typical distances in liquids



- Laser energy: 220 mJ / cm^2
- Vacuum background of 10^{-5} hPa
- Formation of a shell
- Note: Individual images show always a different plume

M. Kayanattil, Z. Huang, S. Hayes, SWE

Ultrafast electrons: Do detectors make a difference



Spatial resolution:
- Pixel size and total area
- Particle sensor interaction

=> Quality of results

Temporal resolution:
- Frame rate
- Can be crucial or irrelevant

=> Quality of results

Geometric flexibility ★
- Change geometry of detection area

=> Quality of results

Usability: ★
- Radiation hardness
- Complexity of operation e.g. software, housekeeping
- Interpretability of the data

=> Quality of results

Recording Efficiency: ★
- Dynamic range
- Bit depth
- Charge handling capacity
- Non linear electron storage
- Sampling

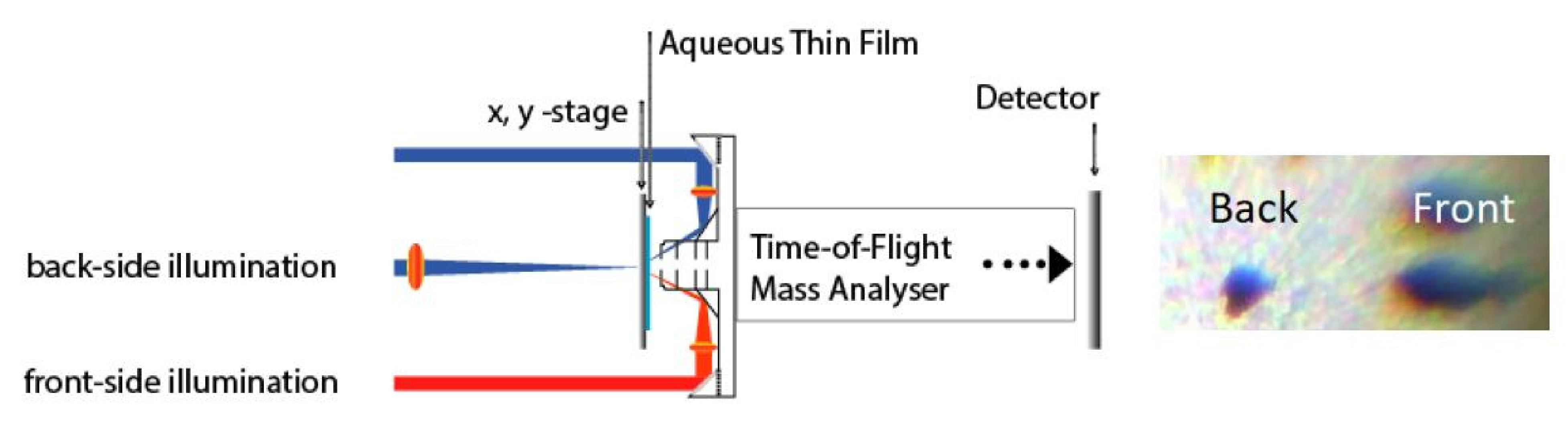
=> Quality of results

Detection efficiency ★★
- Sensor particle interaction (direct or indirect etc)
- Electronics
- Operation mode: counting integrating

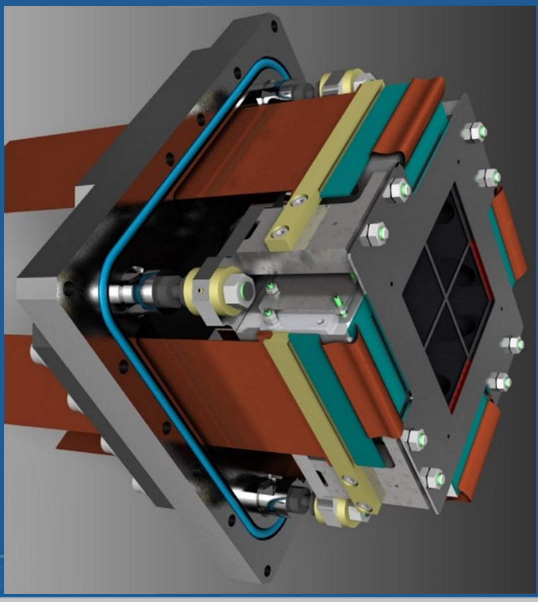
=> Feeds back to experimental parameters

Beyond (!) EDET

Ion detector



- Bio samples: High mass singly charged ions : 1000 amu … M amu; E <= 20 keV
- Detectors in mass-spec are stone age: The primary detector are micro channel plates



- mostly without spacial resolution: 1D detector
- Quantum eff. as low as 1%