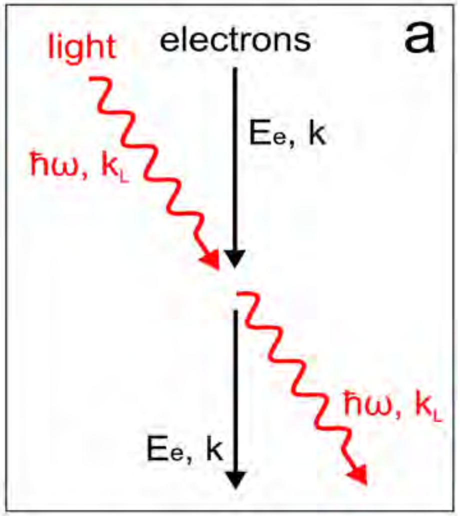
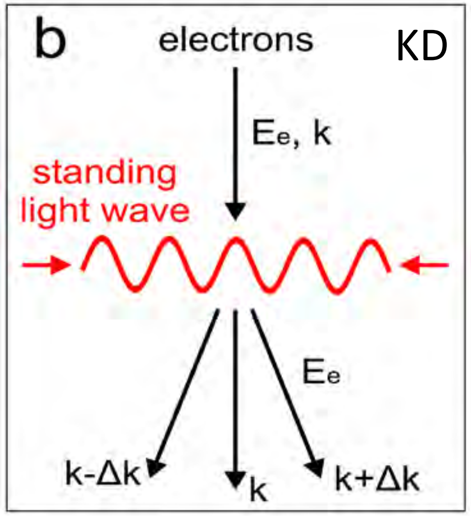
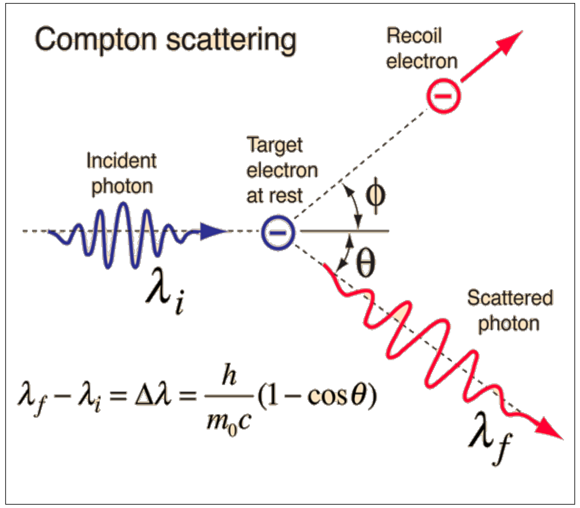
Coherent control of light electrons interaction

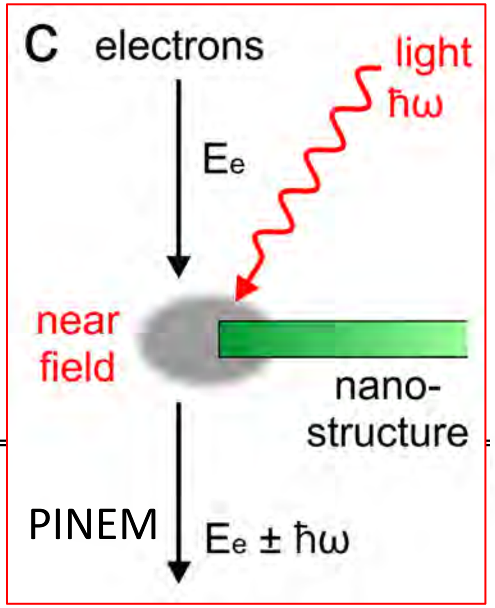
How can light and e⁻ interact?

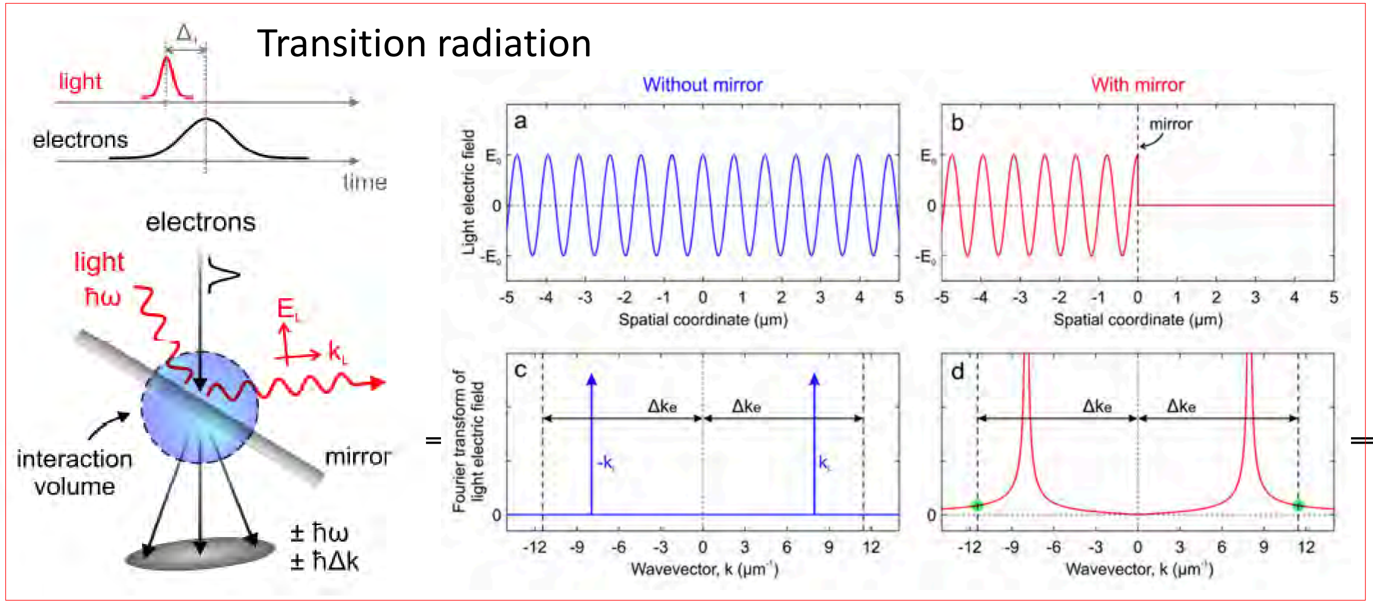






See in the lab

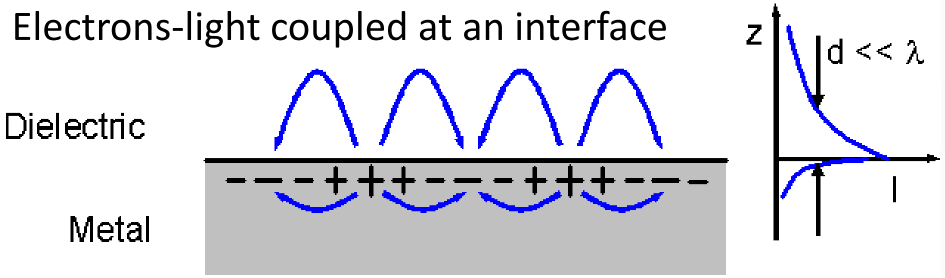


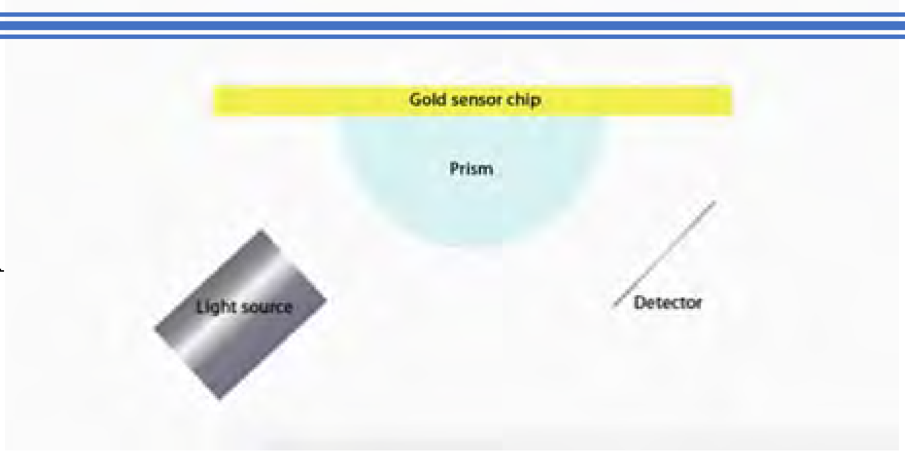


LUMES

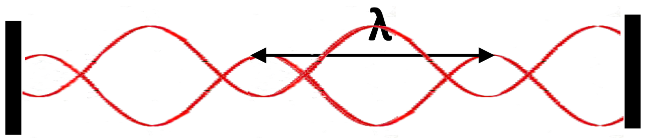
Surface plasmons polaritons and plasma resonances

Surface plasmon:
Electrons-light coupled at an interface

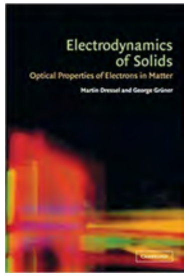




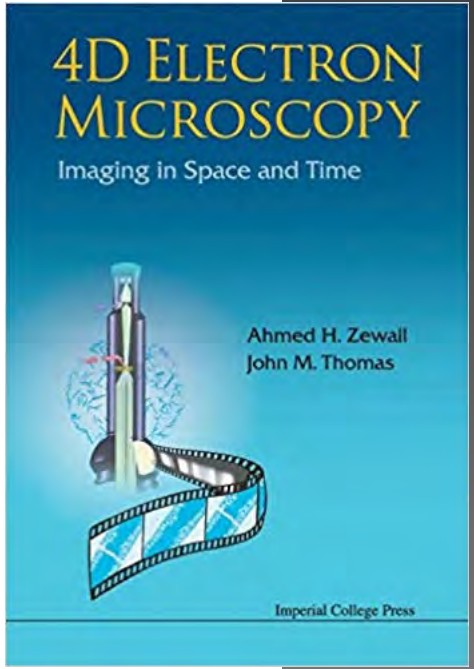
Plasma resonance



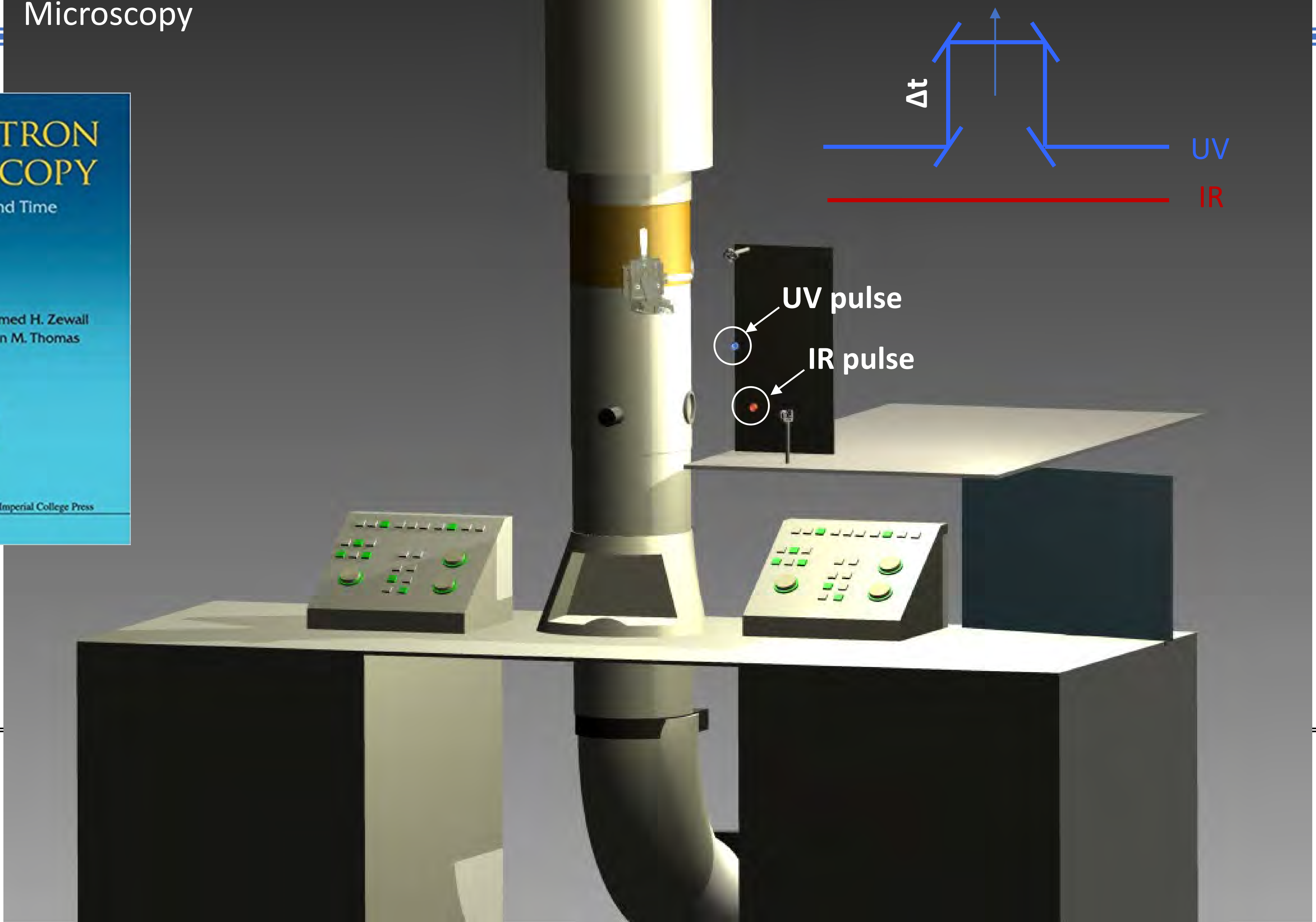
Suggested reading: Dressel, “Electrodynamics of solids”



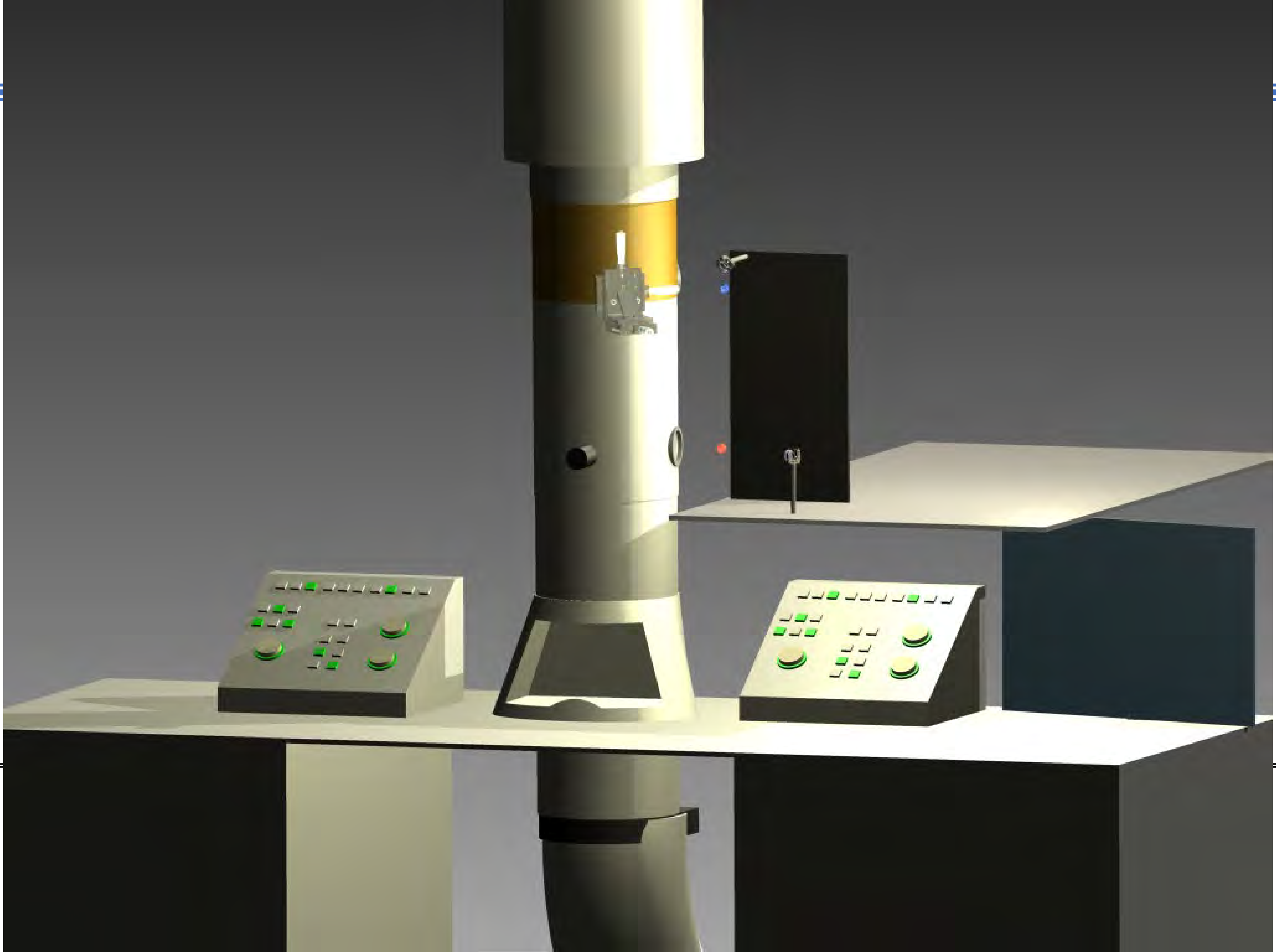
Ultrafast Transmission Electron Microscopy

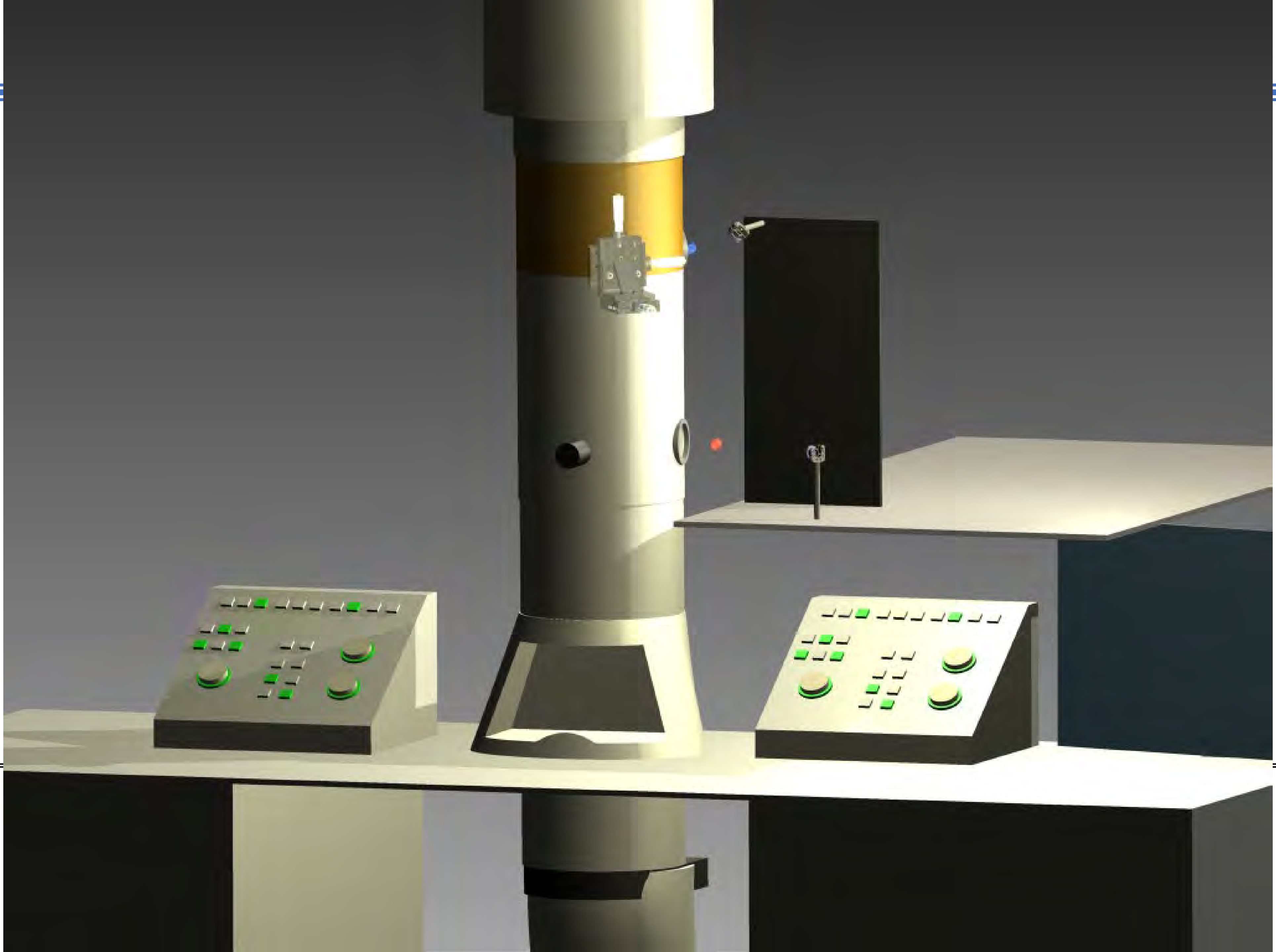


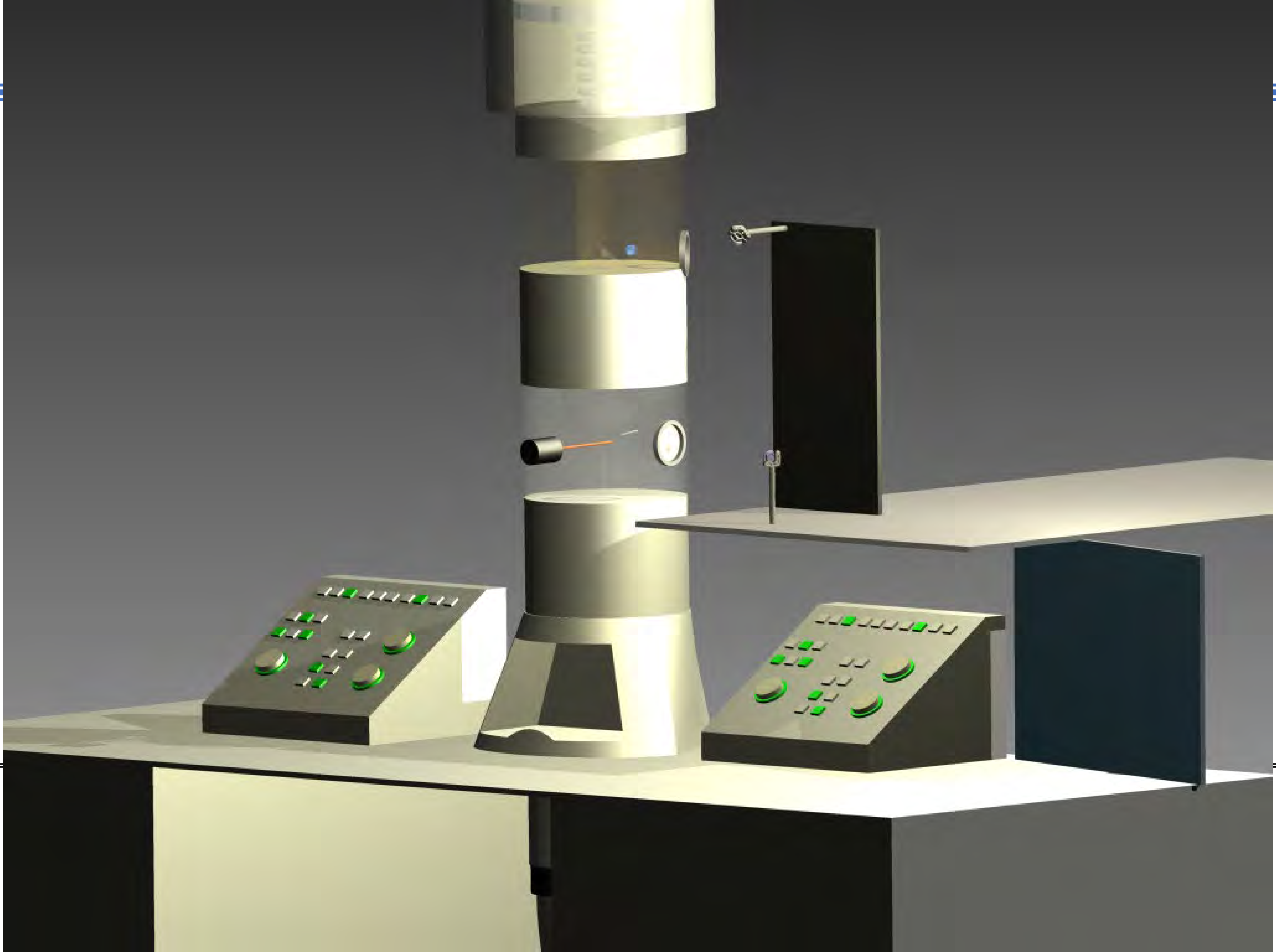
Delay between IR and UV photons

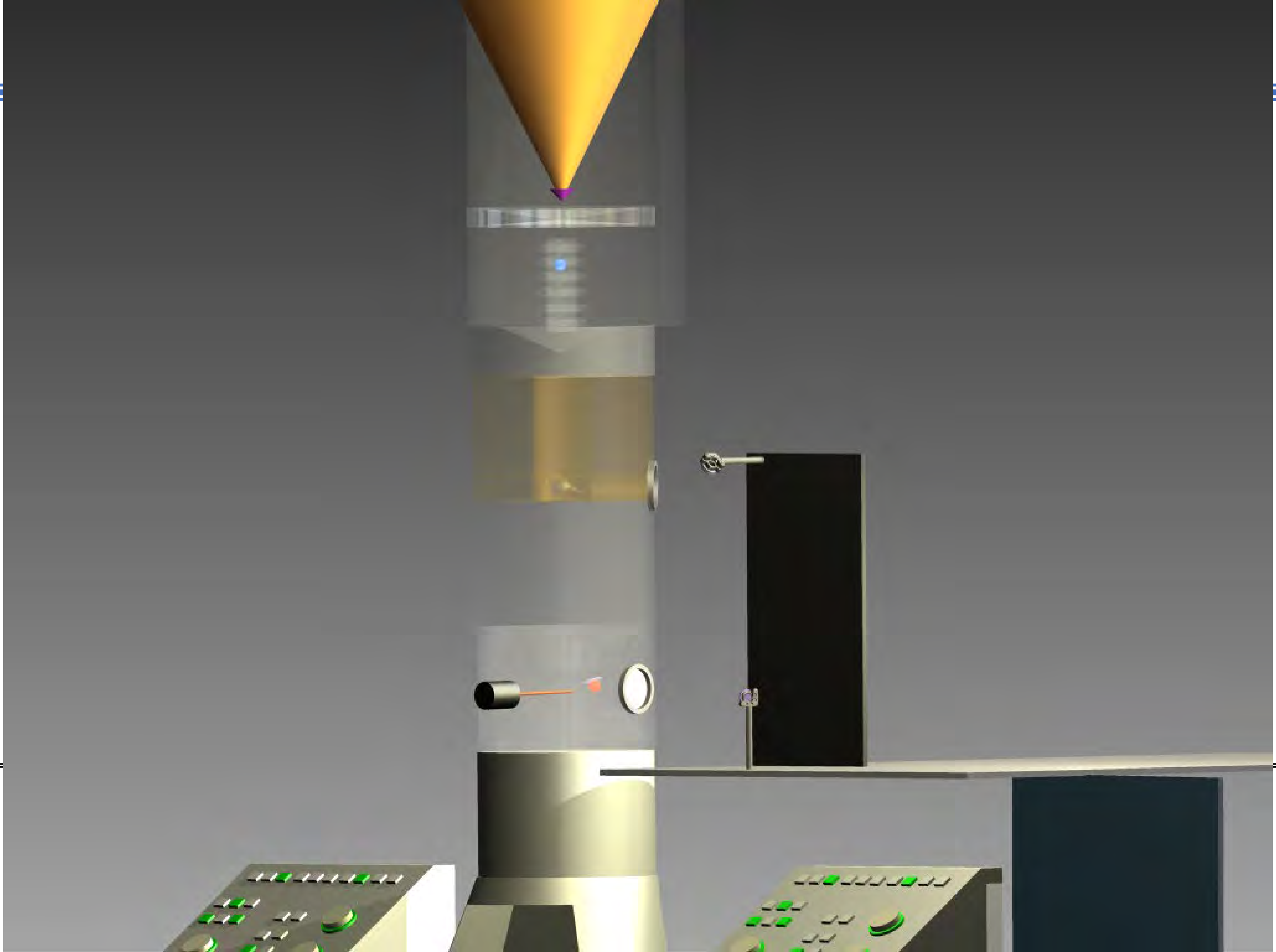


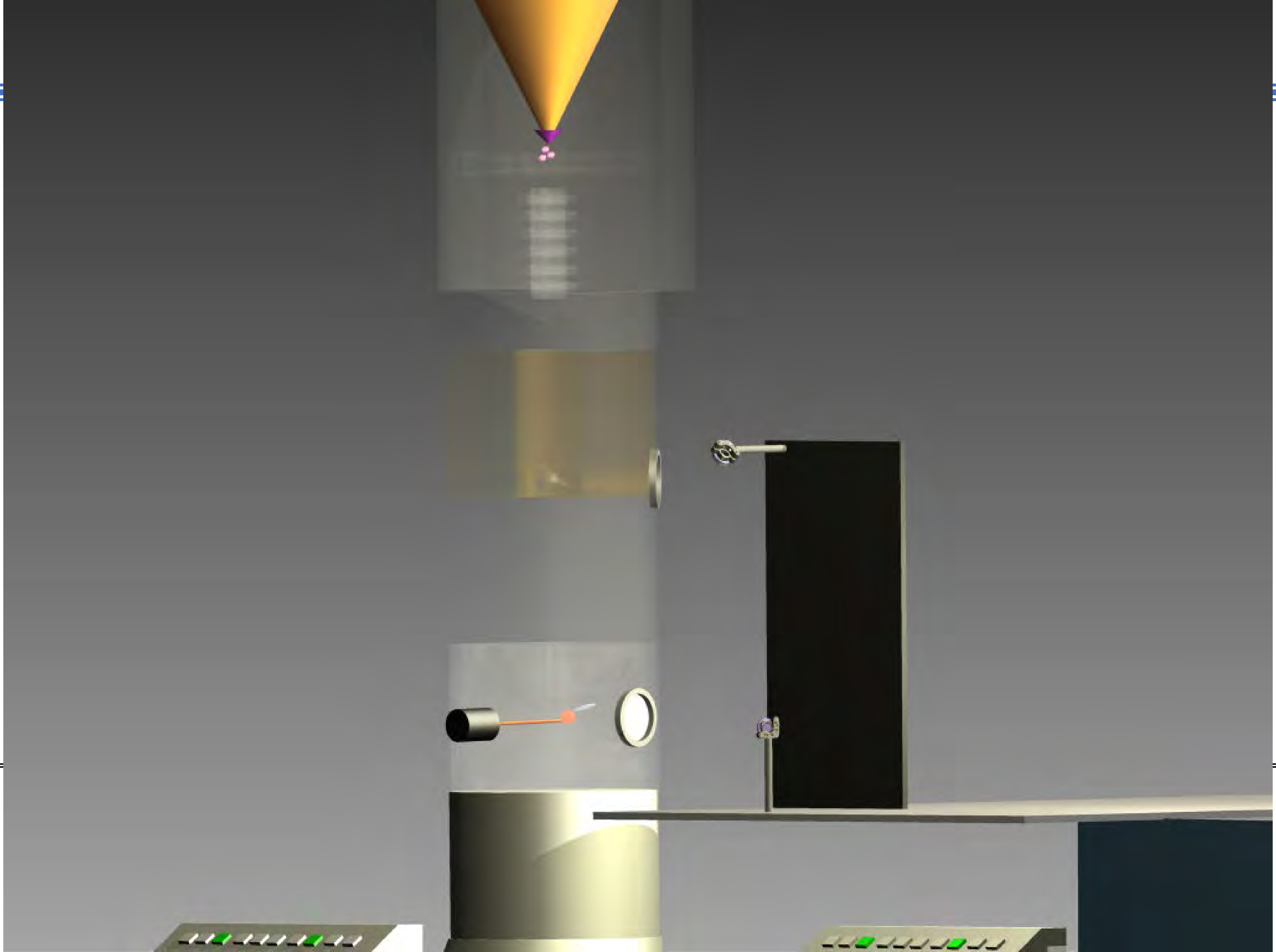
LUMES

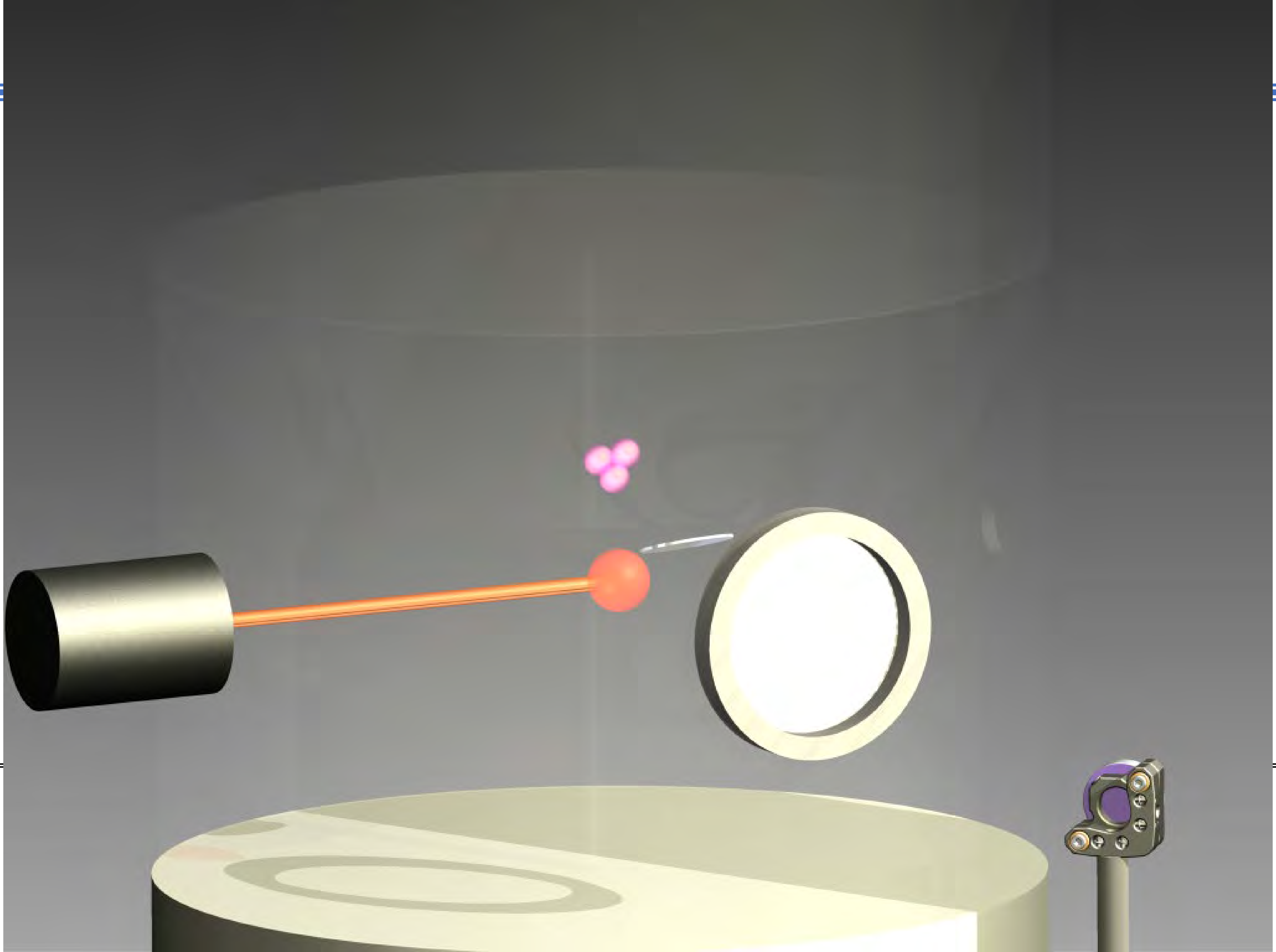


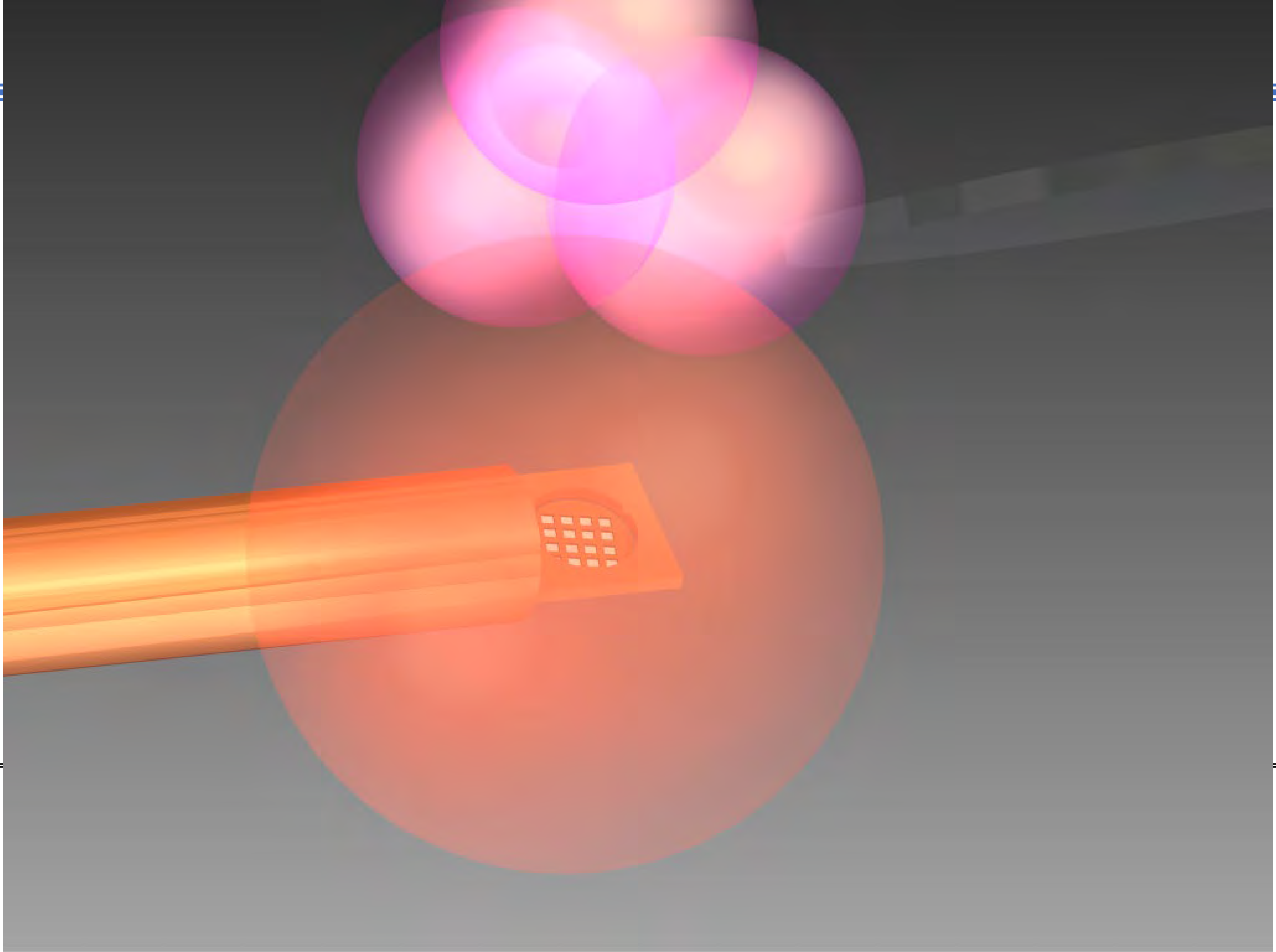


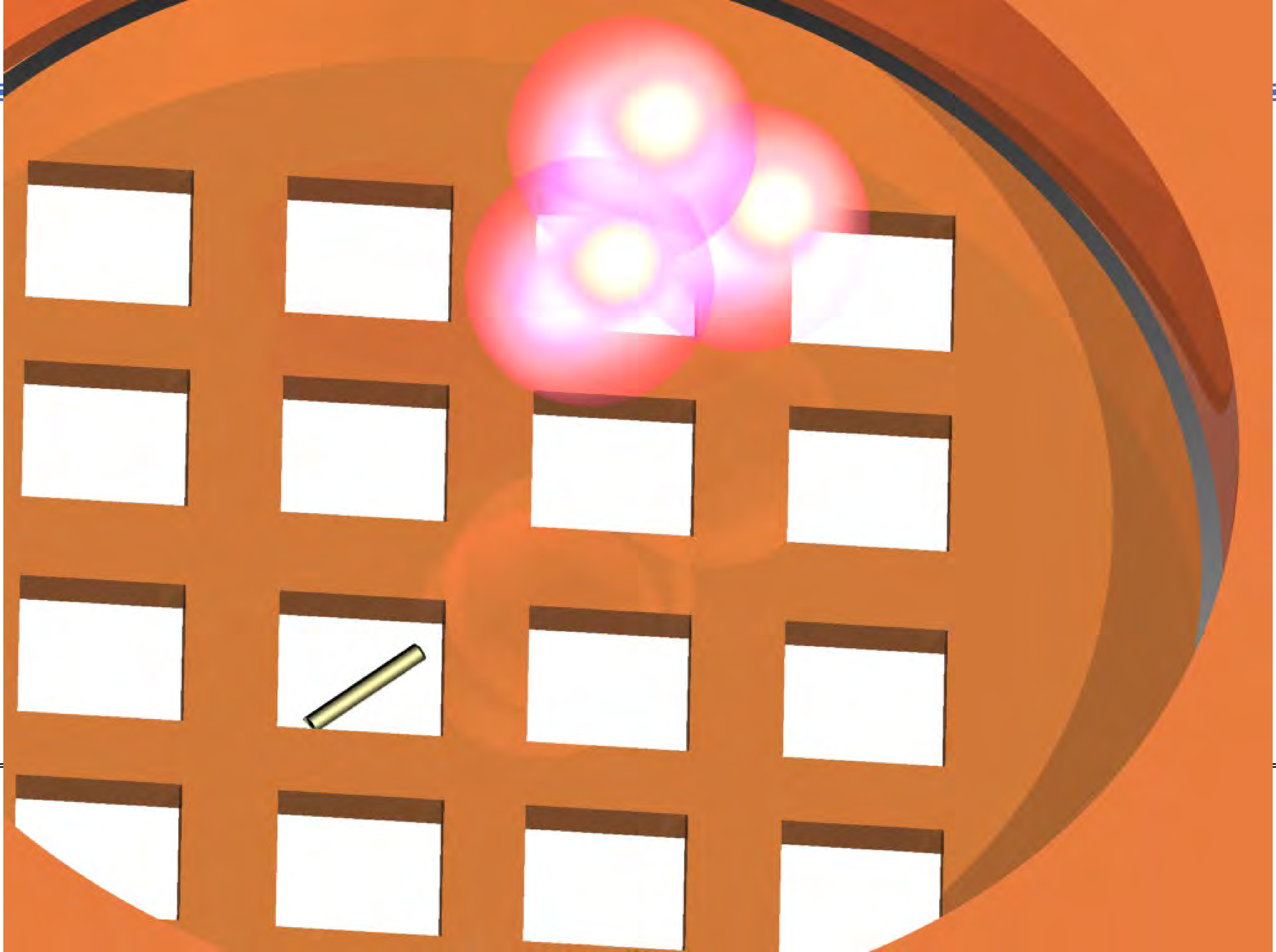


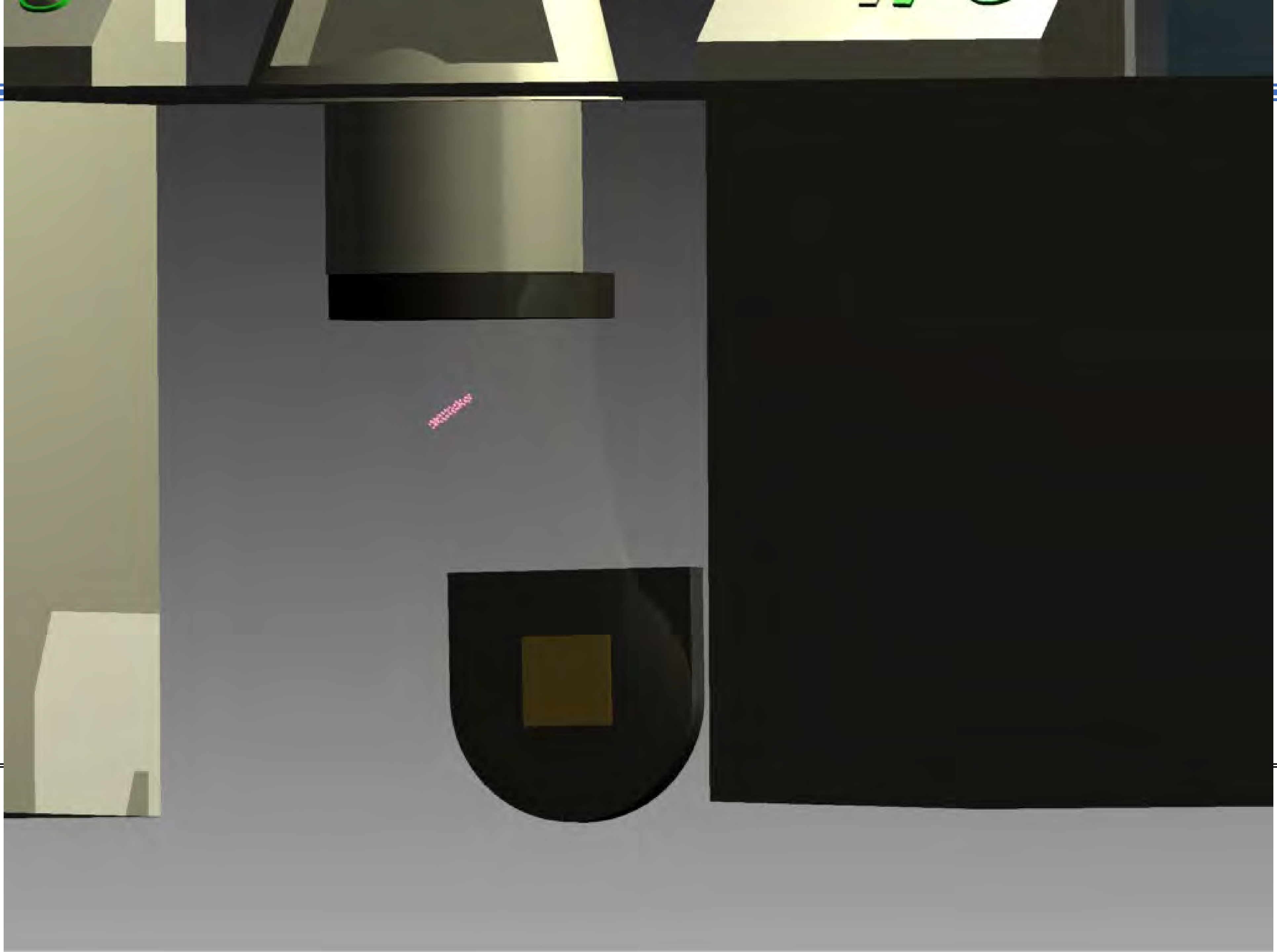




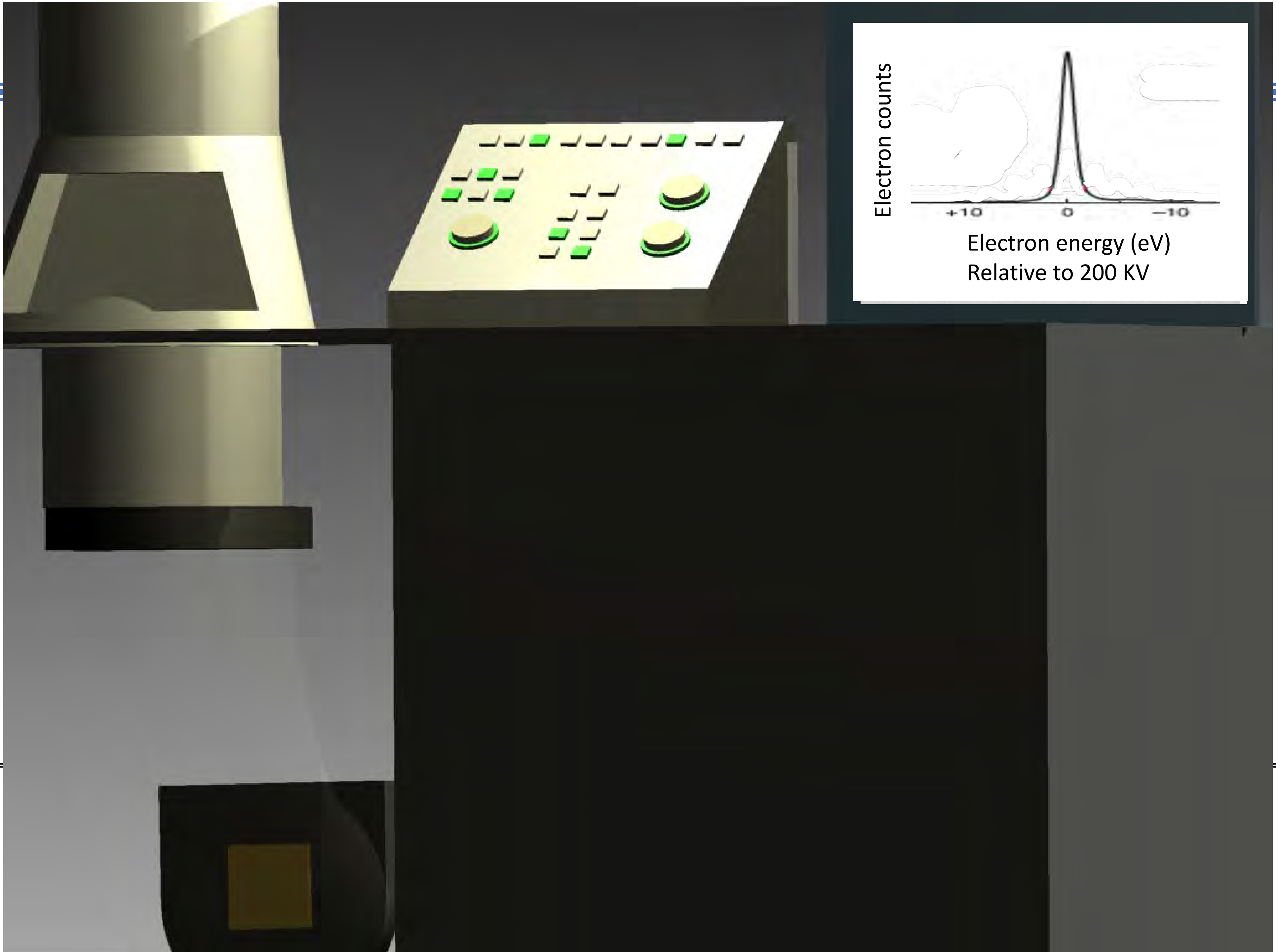


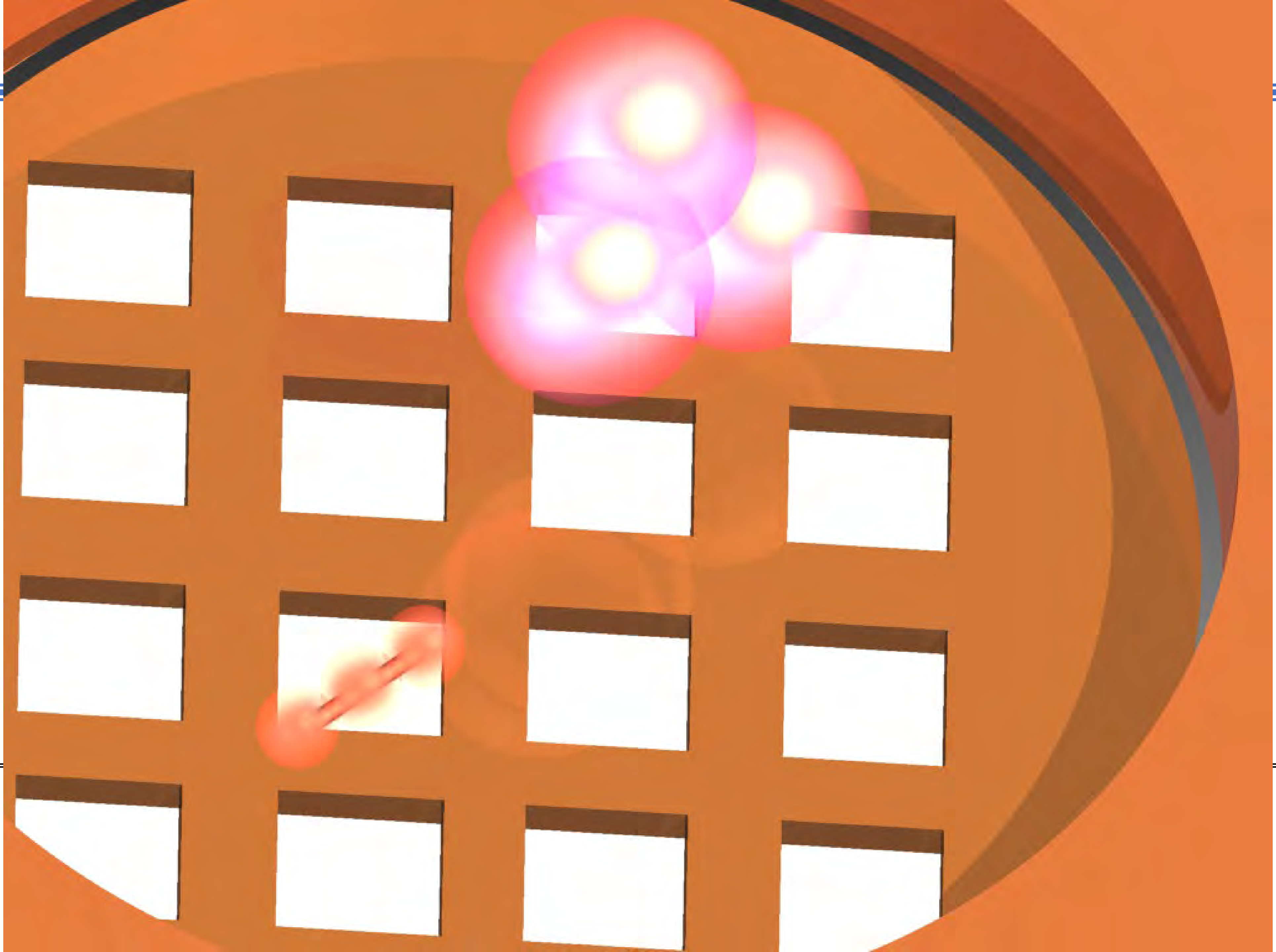


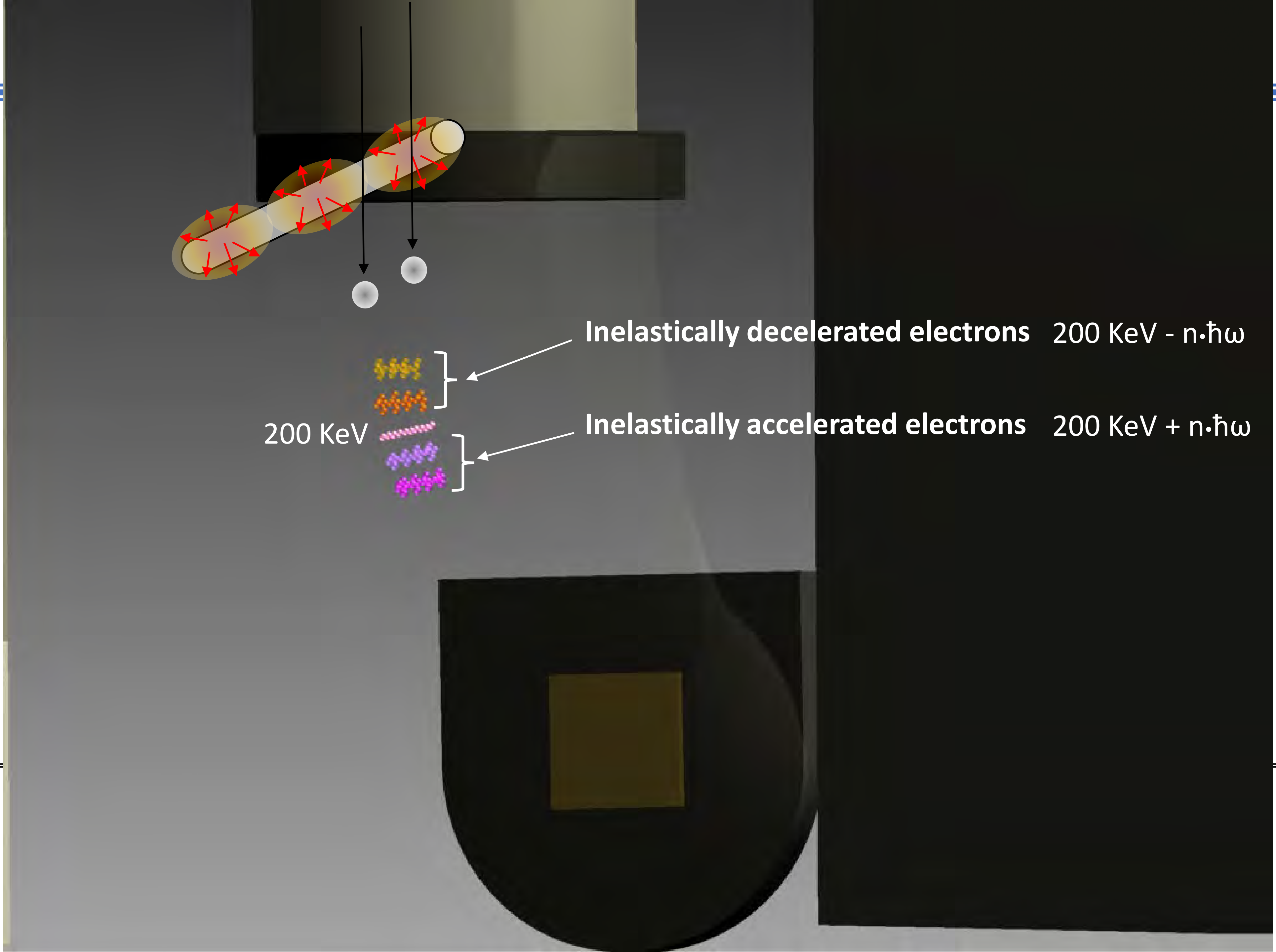


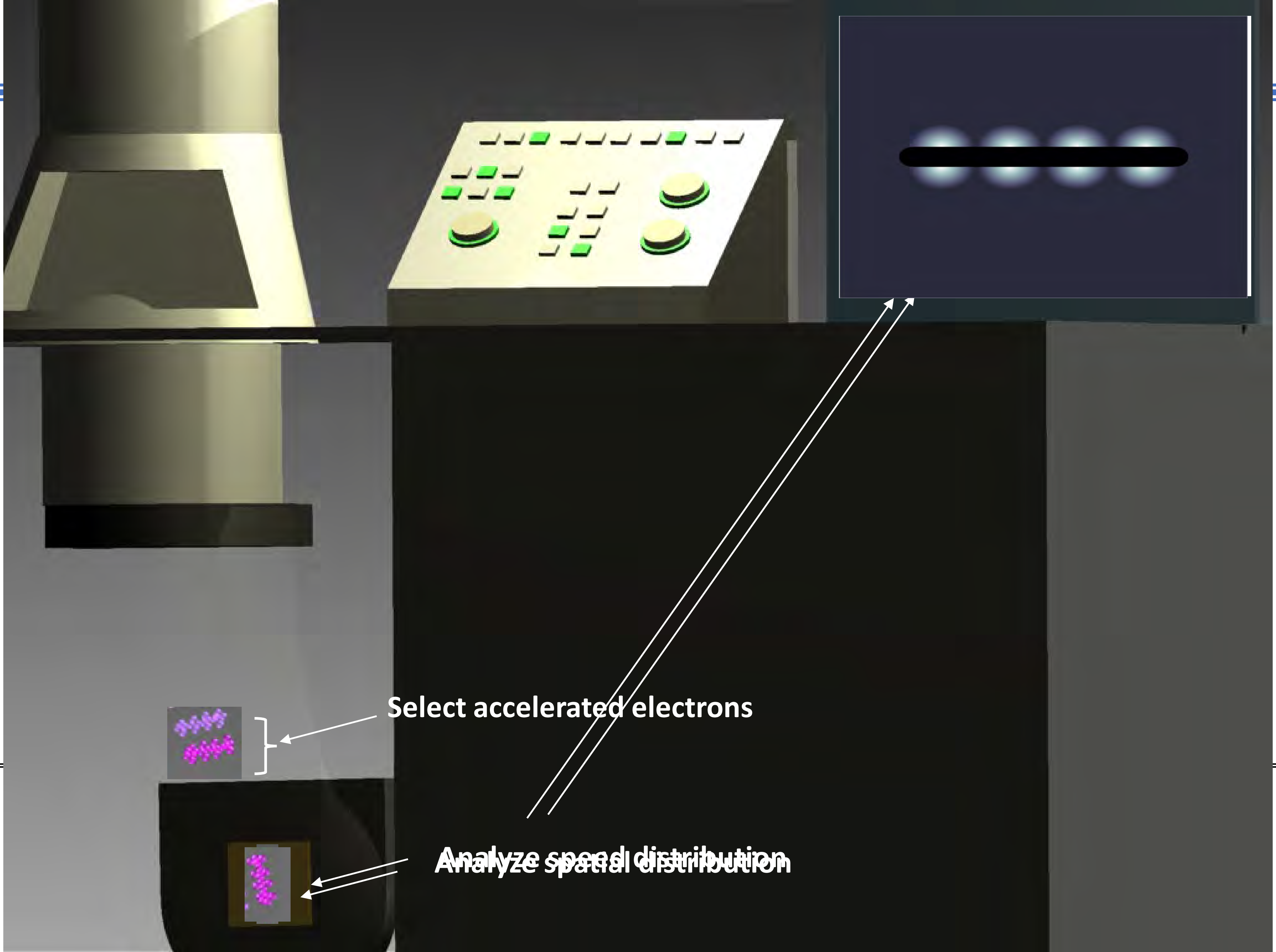


LUMES


Electron counts
+10
0
−10
Electron energy (eV)
Relative to 200 KV



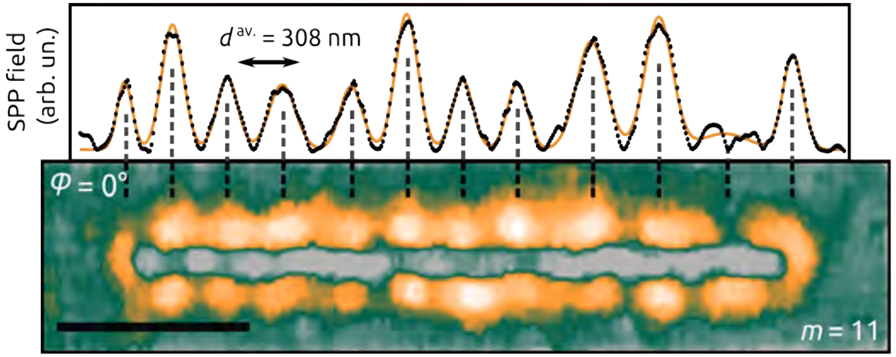

Inelastically decelerated electrons
200 KeV - n·ħω
200 KeV
Inelastically accelerated electrons
200 KeV + n·ħω



Select accelerated electrons
Analyze speed distribution
Analyze spatial distribution

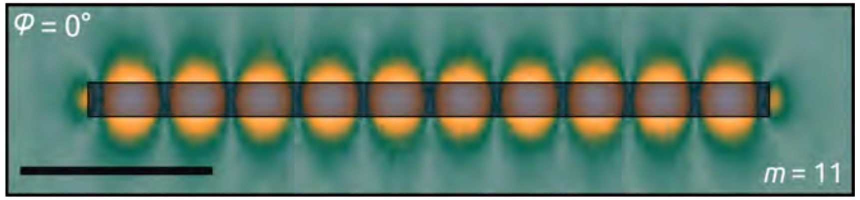
LUMES

Filming plasma resonances

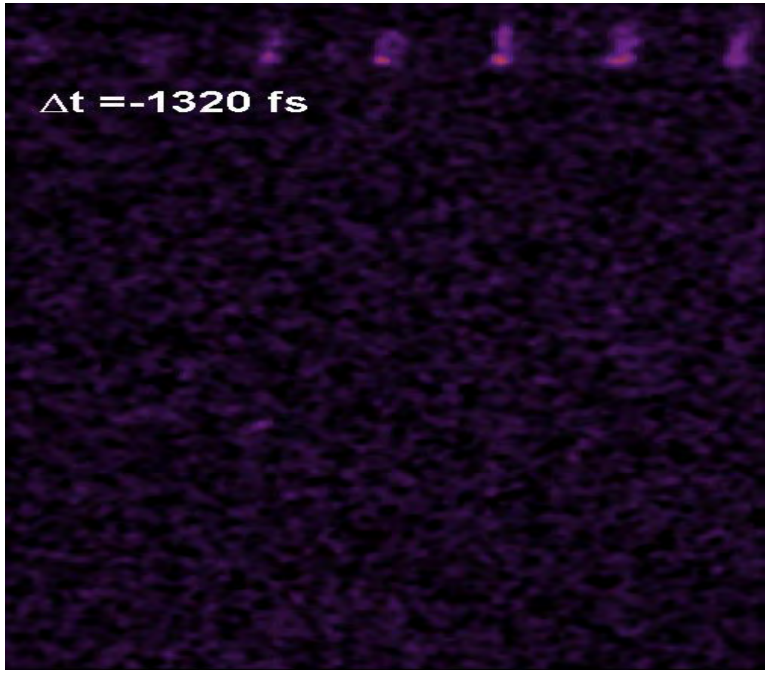


Experiment

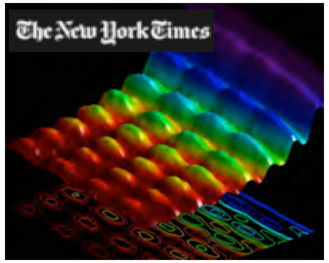
Polarization ⟷



Simulation



LUMES



Piazza et al., **Nat. Comm.** 6 6407 (2015)

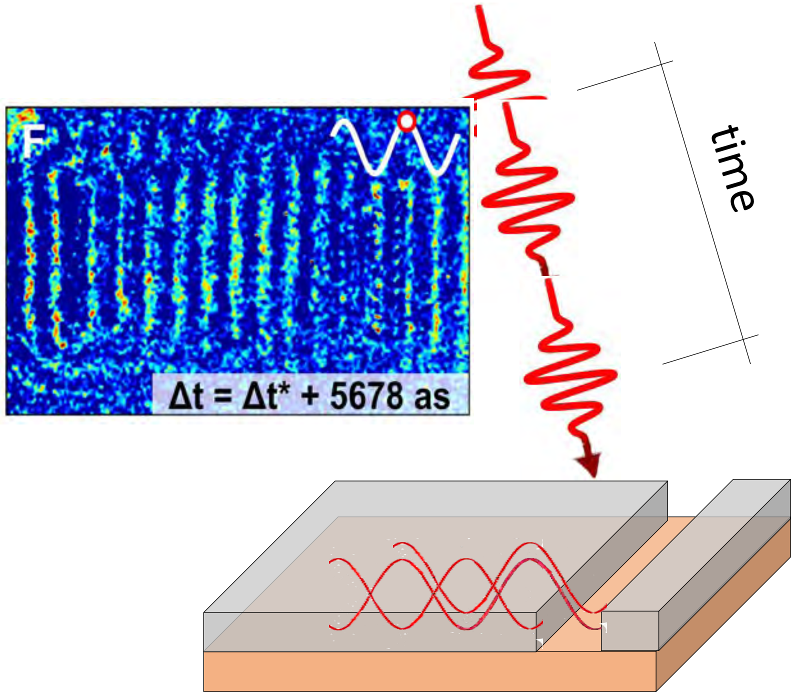
Most cited article in Nat Comm since 2015

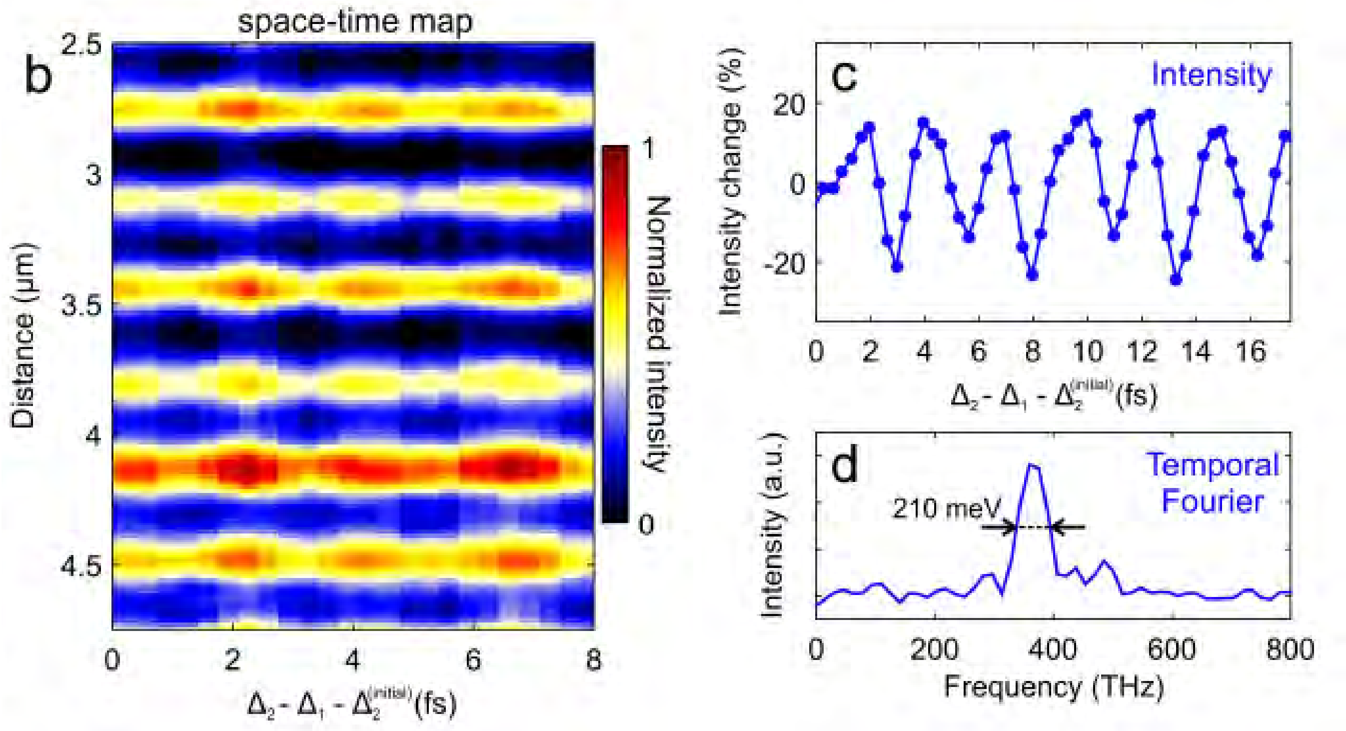
Now product manager at Dectris, Zurich

Lummen et al., **Nat. Comm.** 7 13156 (2016)

Now senior scientist at ETHZ

Coherent control of plasma resonances

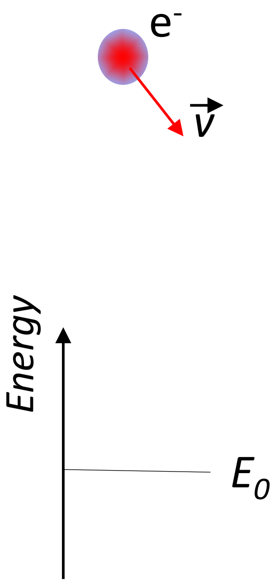


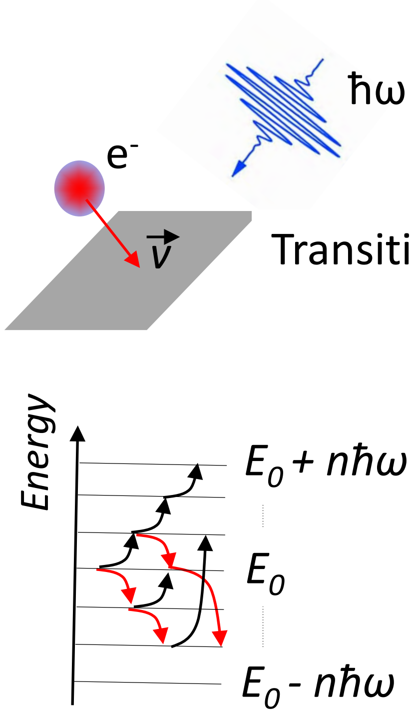


Vanacore, et al. **Nat. Comm** 9 2694 (2018)

Now tenure track professor at the University of Milan Bicocca

What about the e^- after these interactions?

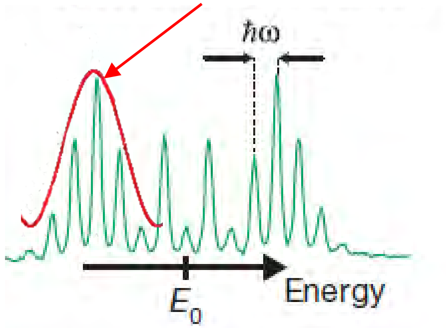




Transition radiation

e^- wavefunction split in a multilevel quantum ladder

Levels population depends on quantum interference between paths: Rabi oscillations



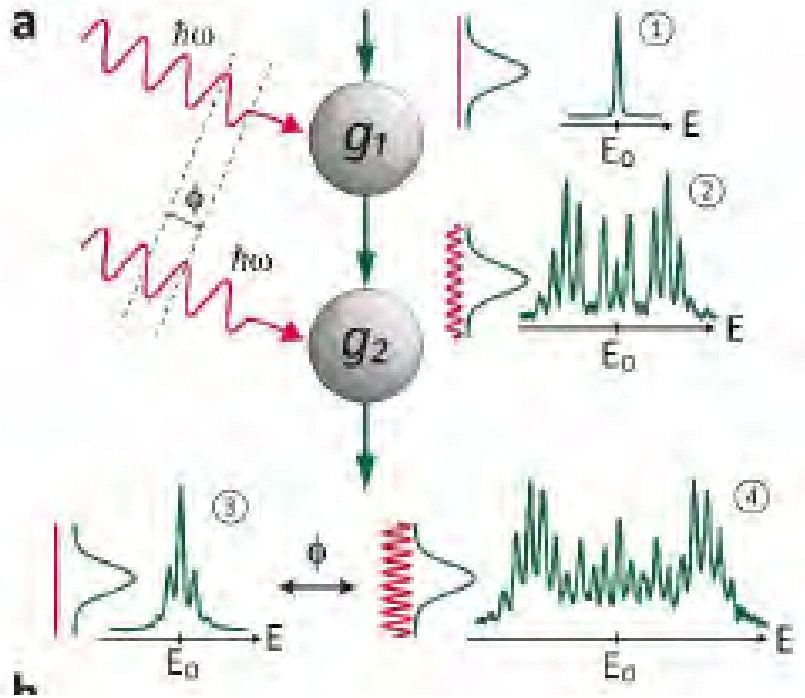
See in the lab

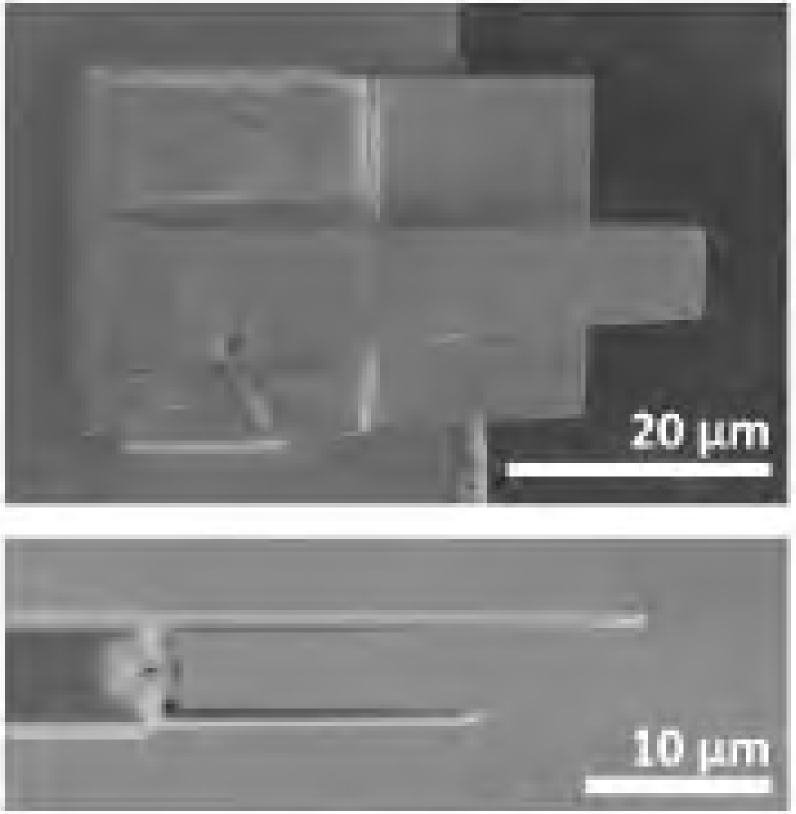
Park *et al.*, **New J. Phys.** 12, 123028 (2010)

García de Abajo *et al.*, **Nano Lett.** 10, 1859 (2010)

Feist *et al.*, **Nature** 521, 14463 (2015)

Coherent control of the longitudinal electron wavefunction by plasma resonances





Echternkamp et al. 12 1000 **Nat. Phys.** (2016)

What about the e⁻ after these interactions?

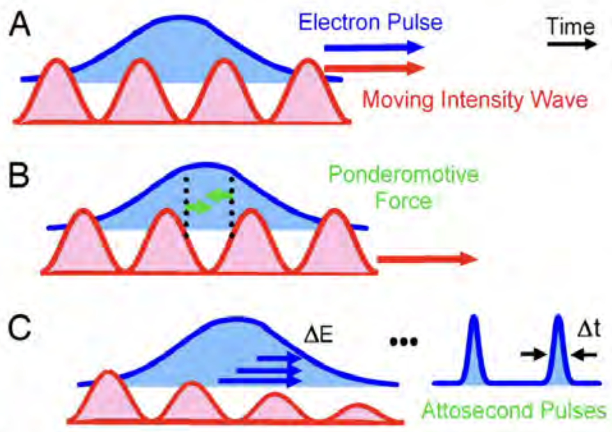


Fig. 2. Concept of optical compression in a moving intensity grating. (*A*) An electron packet (blue) copropagates at a velocity of less than the speed of light with the maxima and minima of a moving intensity wave (red), synthesized from two counterpropagating laser pulses of different frequencies (see text). (*B*) The ponderomotive forces (green arrows) push electrons out of regions with high intensity. Within every optical cycle, the parts of the electron packets that are located at a falling slope are accelerated (left green arrow) and the parts located at a rising slope are retarded (right green arrow). (*C*) The resultant momentum and velocity distribution Δ*p* leads into self-compression to the final attosecond duration (Δ*t*) within every optical cycle (see text).

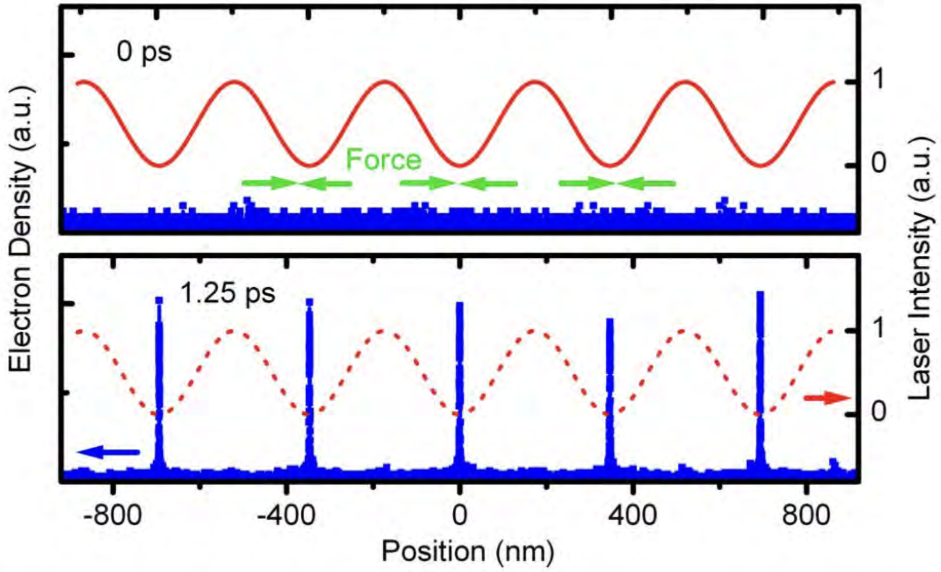
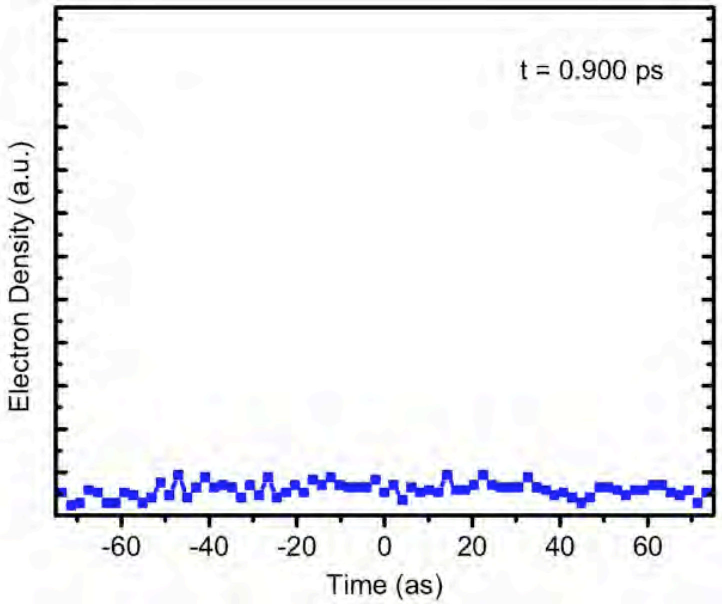


Fig. 4. Trajectory calculations showing the compression. (*Upper*) A long electron packet (blue) is overlapped with a moving intensity wave (red wave). Over time, the ponderomotive force (green arrows) accumulates and initiates self-compression. (*Lower*) At later times, when the intensity wave has faded (red, dotted wave), the electron density shows marked peaks of attosecond duration, which are located at the minima of the intensity wave. Note that the position scale is relative to the electron packet center.



Attosecond electron pulses for 4D diffraction and microscopy

Peter Baum and Ahmed H. Zewail*

Physical Biology Center for Ultrafast Science and Technology, Arthur Amos Noyes Laboratory of Chemical Physics, California Institute of Technology, Pasadena, CA 91125

Contributed by Ahmed H. Zewail, September 27, 2007 (sent for review September 12, 2007)

LUMES

But what if an electron interacts with **incoherent** light?

- Coherent light can be easily described as a wave (in the high intensity limit)
- Incoherent light needs a quantum description of its noise distribution

Science

Current Issue   First release papers

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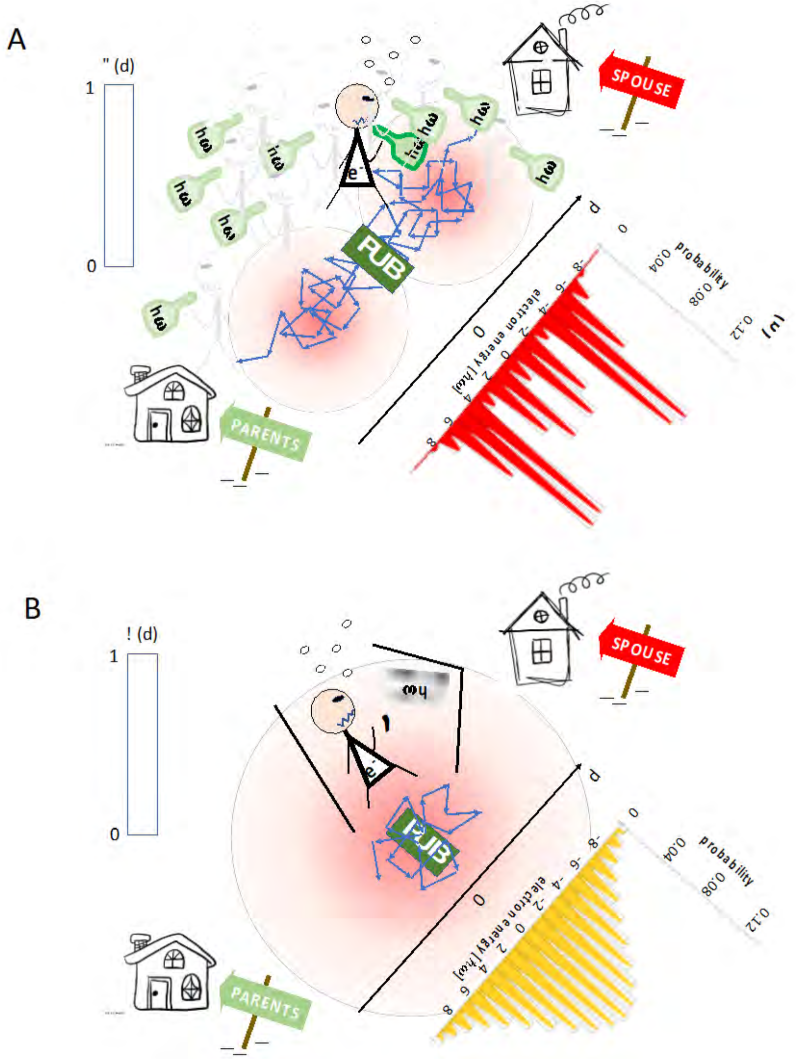
PERSPECTIVE | QUANTUM OPTICS

An electron walks into a quantum bar...

FABRIZIO CARBONE

SCIENCE • 16 Sep 2021 • Vol 373, Issue 6561 • pp. 1309-1310 • DOI: 10.1126/science.abl6366

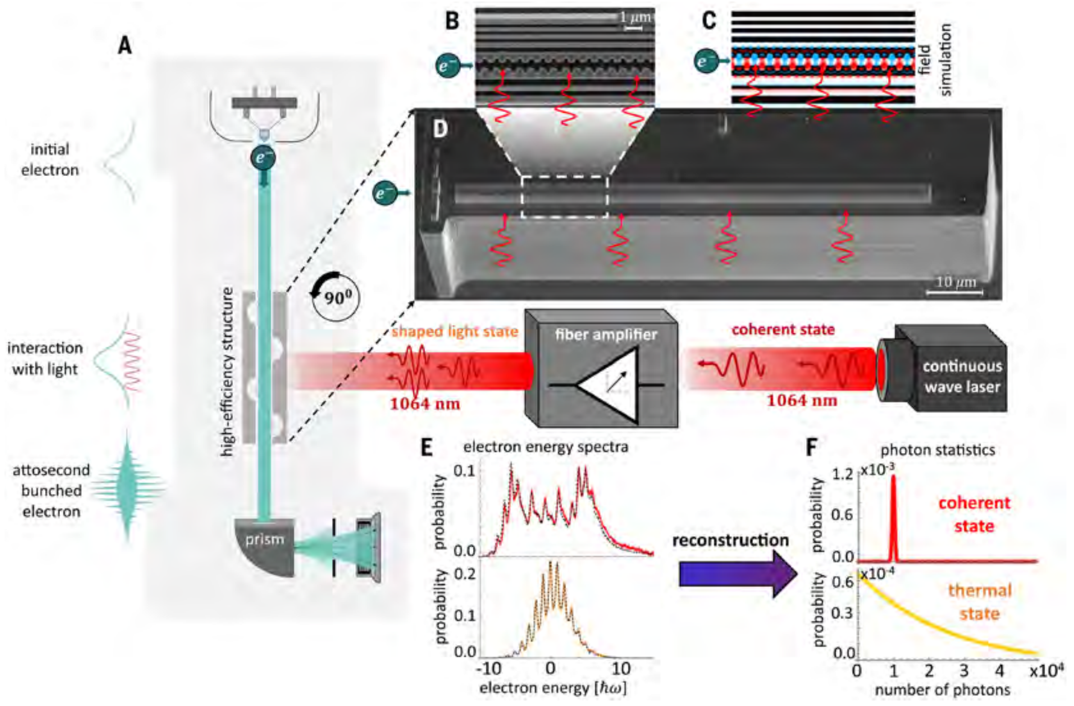


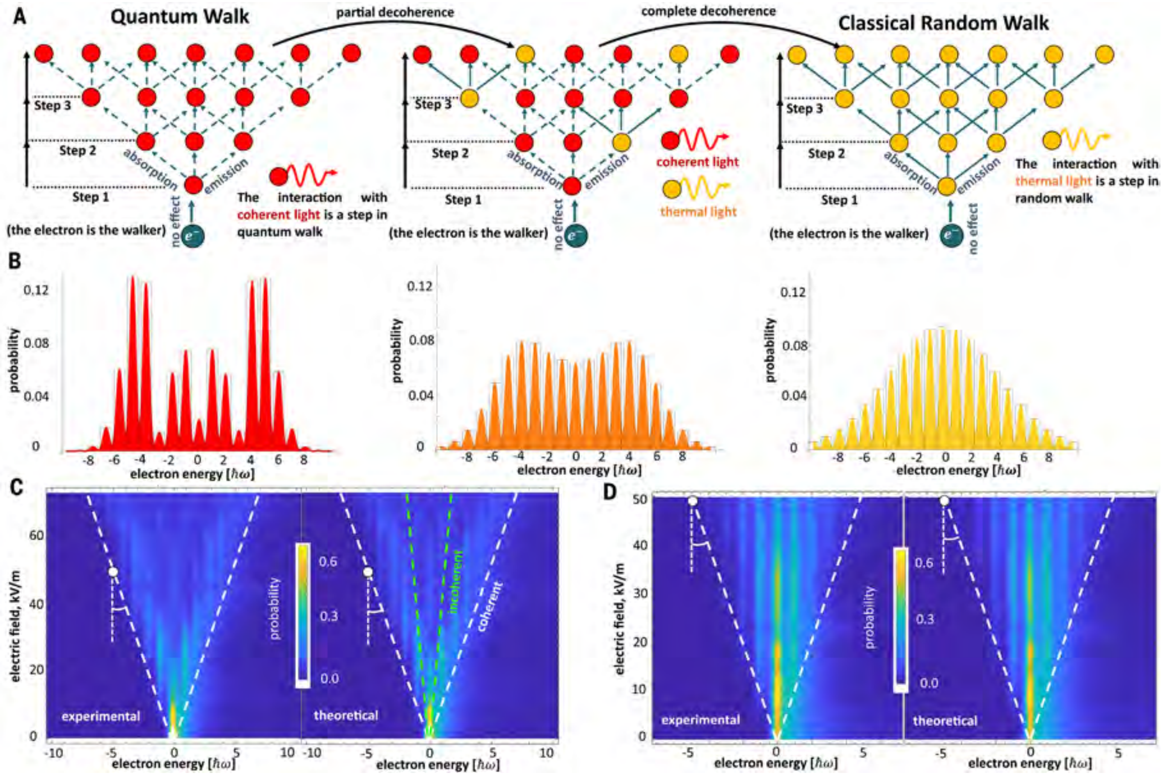
R. Dahan et al., *Science* **373**, eabj7128 (2021).

But what if an electron interacts with **incoherent** light?

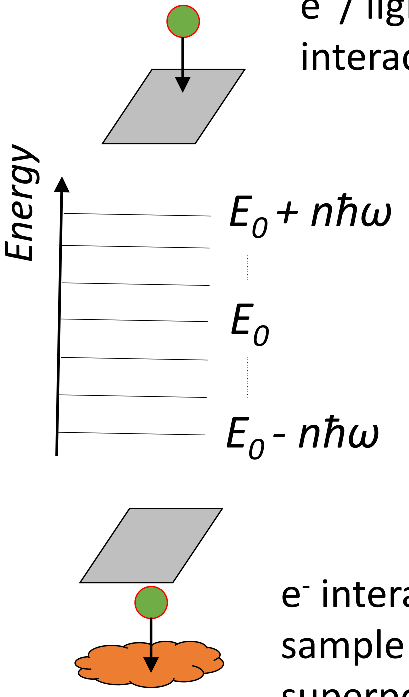
R. Dahan et al., *Science* **373**, eabj7128 (2021).

See in the lab





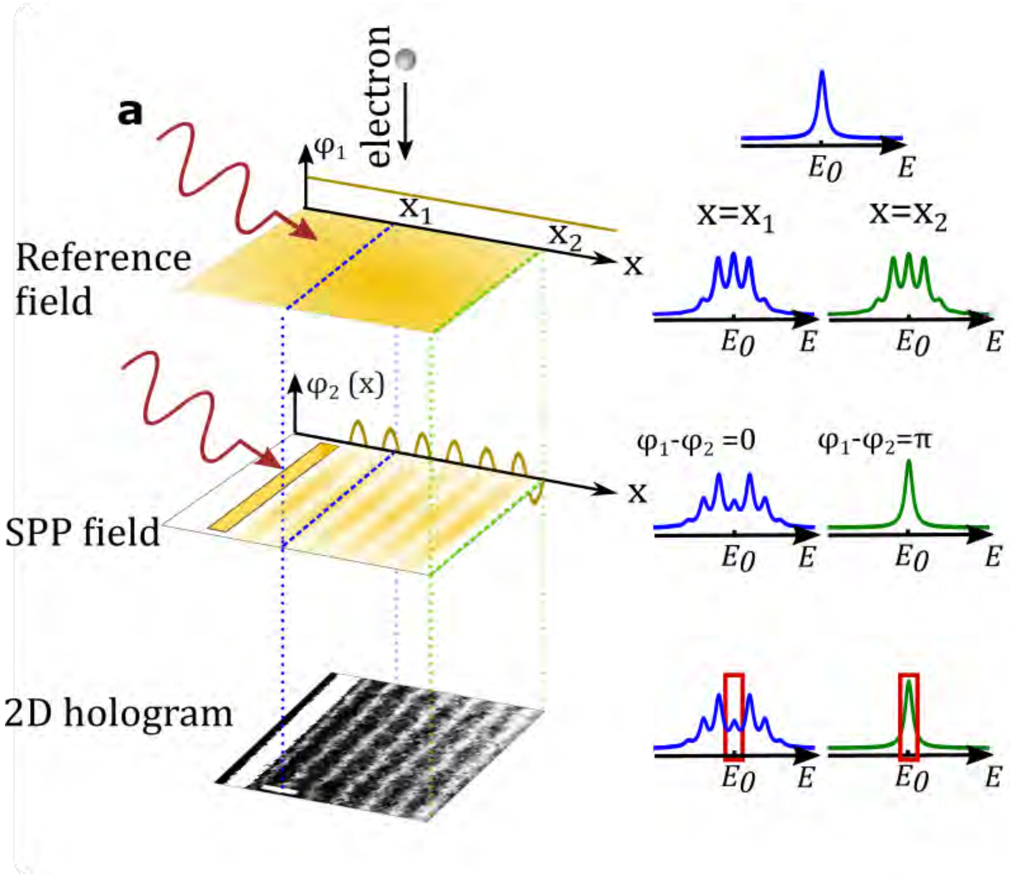
Quantum holography



e^- / light field interaction

e^- WF split in a quantum ladder

e^- interacts with sample while in a superposition of states



Vary dt between the two interactions

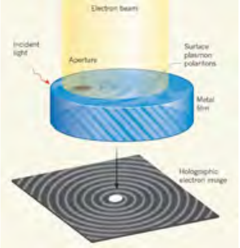
LUMES

Madan et al, **Science Advances** 6 eaav8358 (2019)

News and Views article: Ropers, **Nature** 571, 331 (2019)

https://actu.epfl.ch/news/new-holographic-technique-opens-the-way-for-quantu/

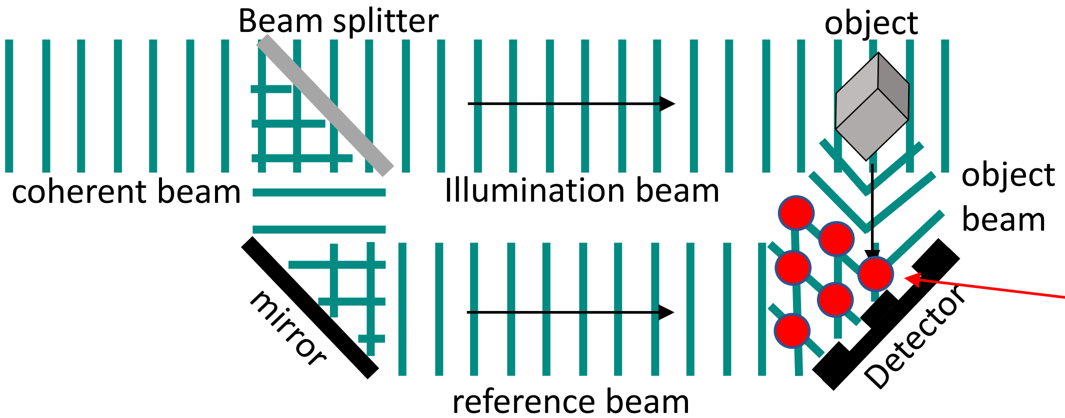
https://www.youtube.com/watch?v=s2iiBbTuZn4&feature=emb_logo



Holographic imaging of electromagnetic fields via electron-light quantum interference

SCIENCE ADVANCES | RESEARCH ARTICLE

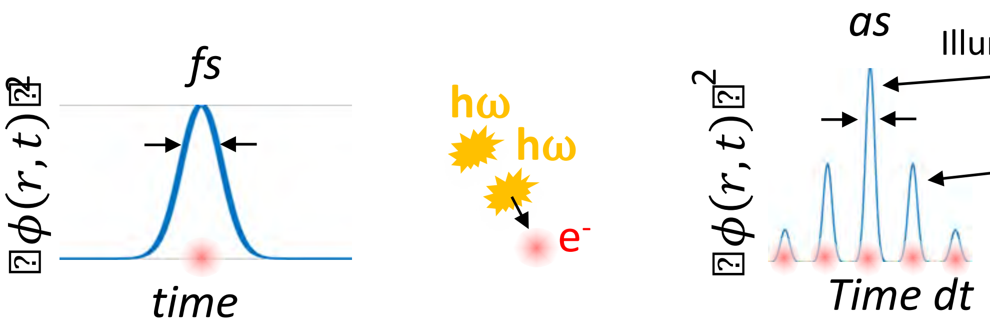
Madan *et al.*, *Sci. Adv.* 2019;**5**:eaav8358 3 May 2019



Conventional holography:
two **coherent** beams are separated in space to provide signal and reference

Count interferences
deduce depth information

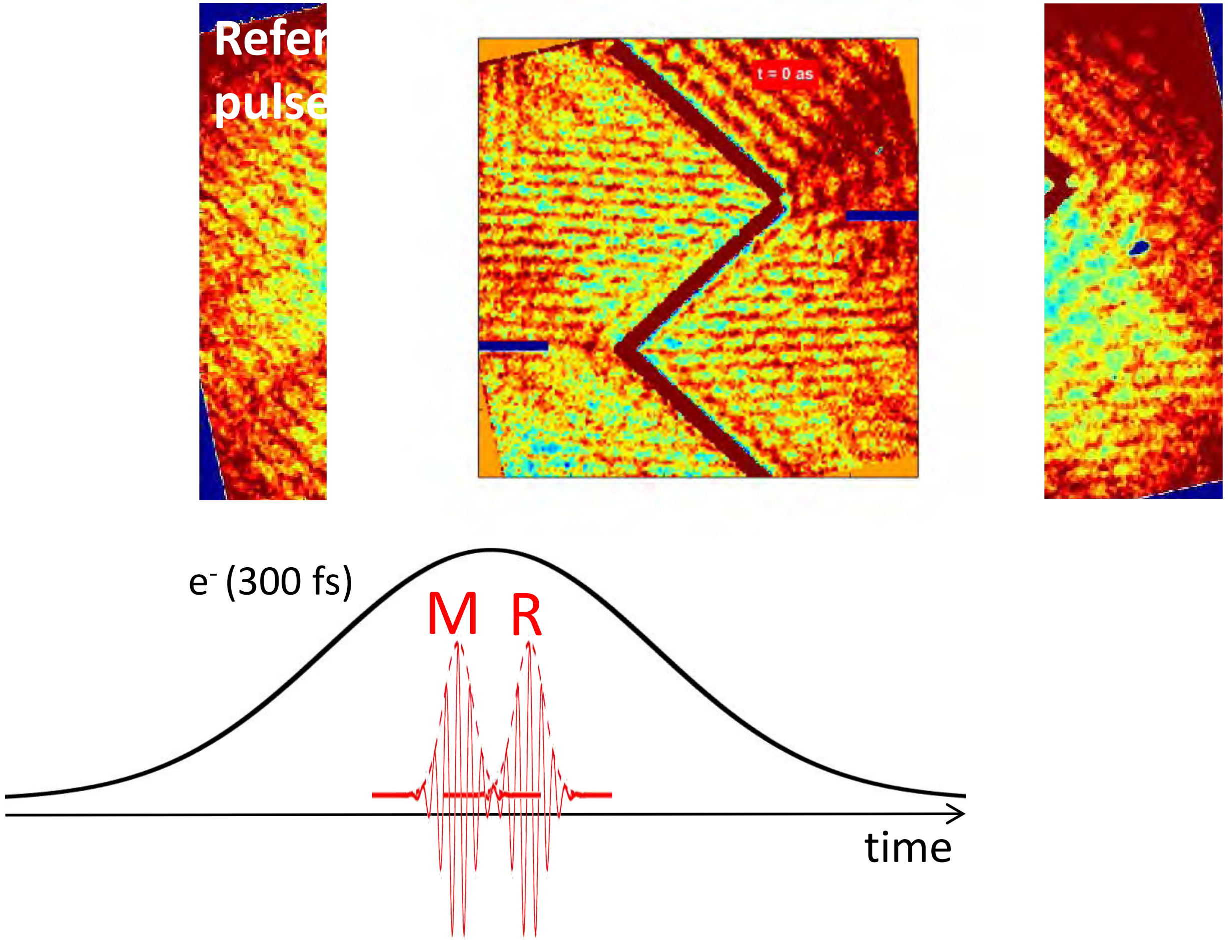
Quantum holography: two beams (made of **one e⁻**) are separated in time to provide as-resolved signal and references

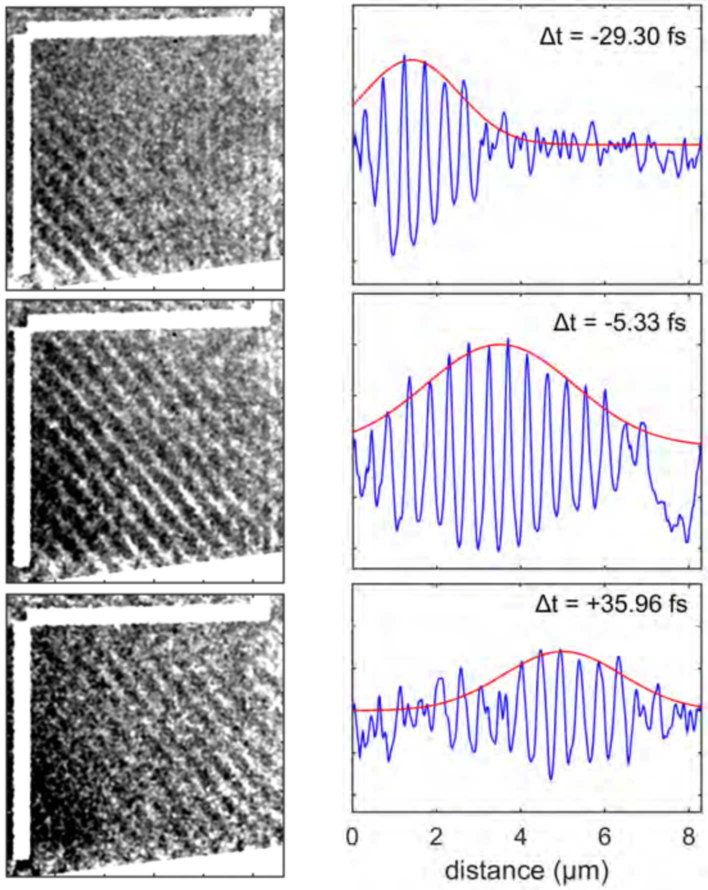


nature NEWS & VIEWS
Light scatters electrons to make holograms
CLAUS ROPERS

as-nm microscopic **quantum holography** of guided light in a nanostructure
Image the sample with WF-manipulated e⁻

Holography of plasma resonance



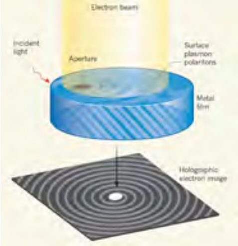


- Attosecond mapping of plasmon propagation
- Direct measurement of group and phase velocity

LUMES

Madan et al, **Science Advances** 6 eaav8358 (2019)
News and Views article: Ropers, **Nature** 571, 331 (2019)

https://actu.epfl.ch/news/new-holographic-technique-opens-the-way-for-quantu/
https://www.youtube.com/watch?v=s2iiBbTuZn4&feature=emb_logo



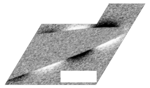
Article

Attosecond electron microscopy of sub-cycle optical dynamics

https://doi.org/10.1038/s41586-023-06074-9
Received: 12 October 2022
Accepted: 12 April 2023
Published online: 31 May 2023
Check for updates

David Nabben[1,2], Joel Kuttruff[1,2], Levin Stolz[1], Andrey Ryabov[1]✉ & Peter Baum[1]✉

The primary step of almost any interaction between light and materials is the electrodynamic response of the electrons to the optical cycles of the impinging light wave on sub-wavelength and sub-cycle dimensions[1]. Understanding and controlling the electromagnetic responses of a material[2–11] is therefore essential for modern optics and nanophotonics[12–19]. Although the small de Broglie wavelength of electron beams should allow access to attosecond and ångström dimensions[20], the time resolution of ultrafast electron microscopy[21] and diffraction[22] has so far been limited to the femtosecond domain[16–18], which is insufficient for recording fundamental material responses on the scale of the cycles of light[1,2,10]. Here we advance transmission electron microscopy to attosecond time resolution of optical responses within one cycle of excitation light[23]. We apply a continuous-wave laser[24] to modulate the electron wave function into a rapid sequence of electron pulses, and use an energy filter to resolve electromagnetic near-fields in and around a material as a movie in space and time. Experiments on nanostructured needle tips, dielectric resonators and metamaterial antennas reveal a directional launch of chiral surface waves, a delay between dipole and quadrupole dynamics, a subluminal buried waveguide field and a symmetry-broken multi-antenna response. These results signify the value of combining electron microscopy and attosecond laser science to understand light–matter interactions in terms of their fundamental dimensions in space and time.



lved with nanometre and attosecond precision. Black arrows and white line indicate the space–time propagation. Scale bar, 500 nm. ΔI is electron current change. See Supplementary Video 1 for full data.

LETTERS
https://doi.org/10.1038/s41567-017-0007-6
nature physics

Diffraction and microscopy with attosecond electron pulse trains

Yuya Morimoto[1,2] and Peter Baum[1,2]*

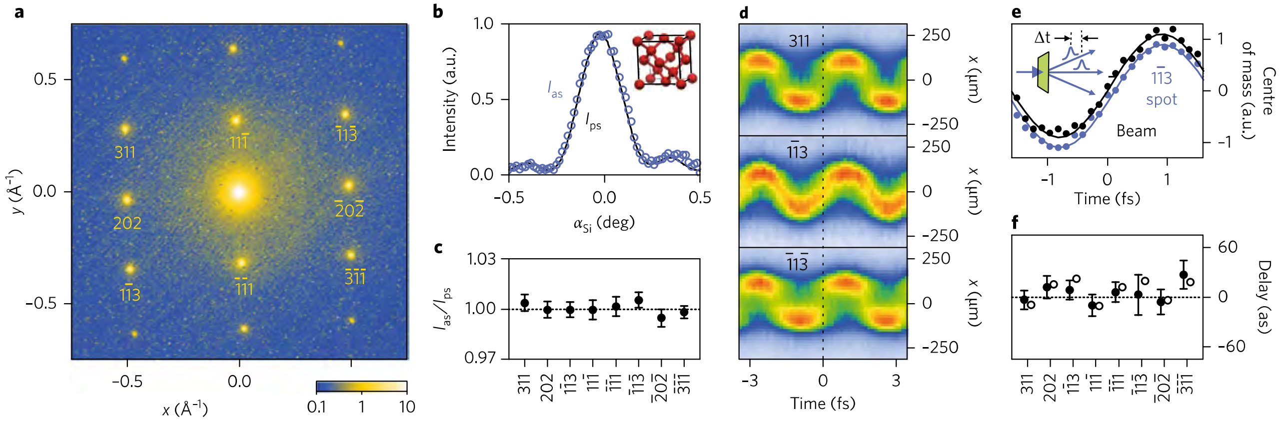
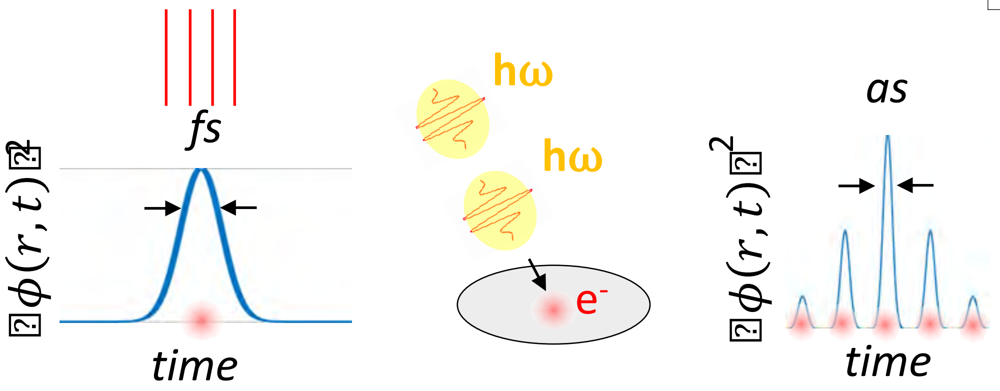


Fig. 3 | Atomic diffraction with attosecond electron pulses. a, Diffraction pattern of single-crystalline silicon, taken with the attosecond electron pulse train. The non-labelled Bragg spots are forbidden but visible via multiple scattering. **b**, Rocking curve of the $1\bar{1}3$ spot for picosecond pulses in comparison with the attosecond electron pulse train. Inset, crystal structure of silicon. **c**, Absolute intensity of all Bragg spots, measured with the attosecond pulses and normalized to the picosecond case. The error bars denote the shot noise of the measurement (~140 s integration). **d**, Streaking deflectograms of three example Bragg spots; all of them behave similarly. **e**, Centre-of-mass of the deflectogram of the $1\bar{1}3$ spot versus the direct beam for delay analysis. Inset, illustration of delays in Bragg spot emission. **f**, Measured attosecond-level delay of different Bragg spot emissions with respect to the direct beam. The filled and open circles are the results of centre-of-mass analysis and deflectogram fitting, respectively. The error bars represent standard deviation. The average delay is (4.6 ± 5.4) as.

$$\phi(r,t) = e^{(ikr-\omega t)}$$

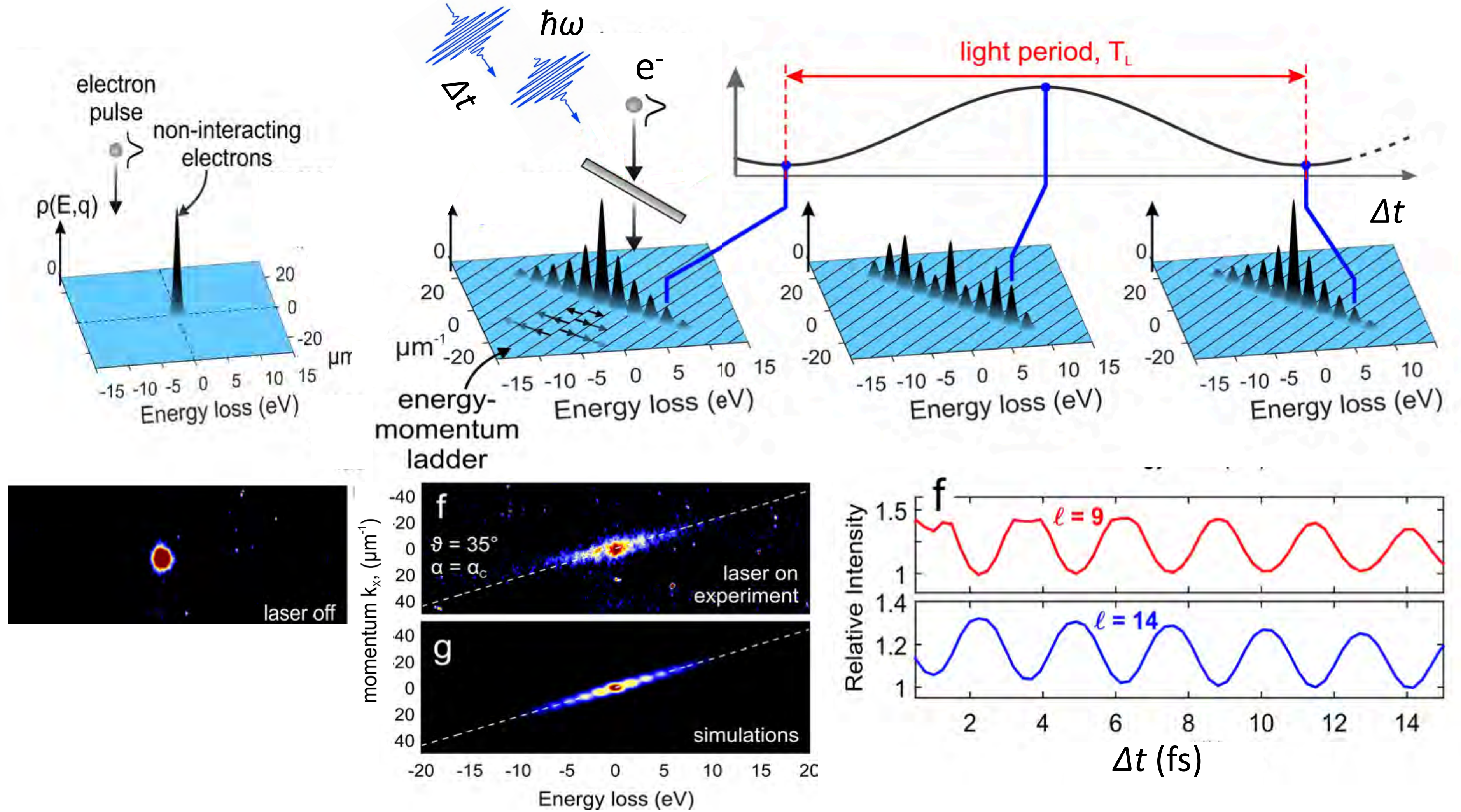
$$\phi(\mathbf{r},t) = \phi_0(\mathbf{r}-\mathbf{v}t)\sum_{\ell=-\infty}^{\infty} J_\ell(2|\beta|)\mathrm{e}^{\mathrm{i}\ell\arg\{-\beta\}+\mathrm{i}\ell\omega(z/v-t)}$$



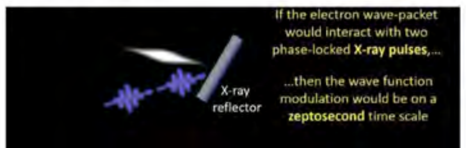
Temporal Tomography of the e⁻ wavefunction

Image electrons

Coherent control of the longitudinal electron wavefunction by transition radiation



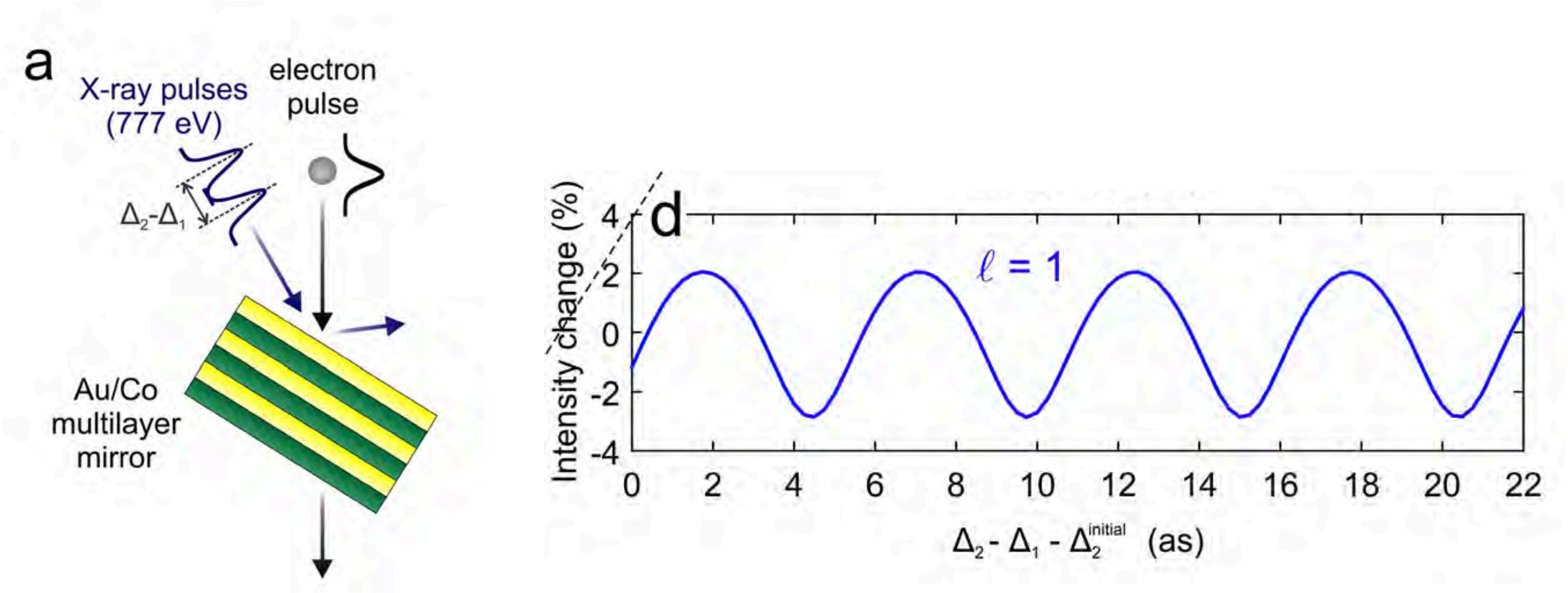
Can ultrashort electron flashes help harvest nuclear energy?



Vanacore, et al **Nat. Comm** 9 2694 (2018)

https://phys.org/news/2018-07-ultrashort-electron-harvest-nuclear-energy.html

Zeptoseconds (10^{-21}) electron pulses



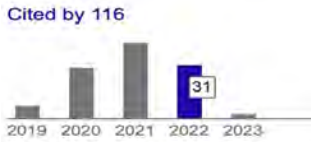
Zeptosecond physics:

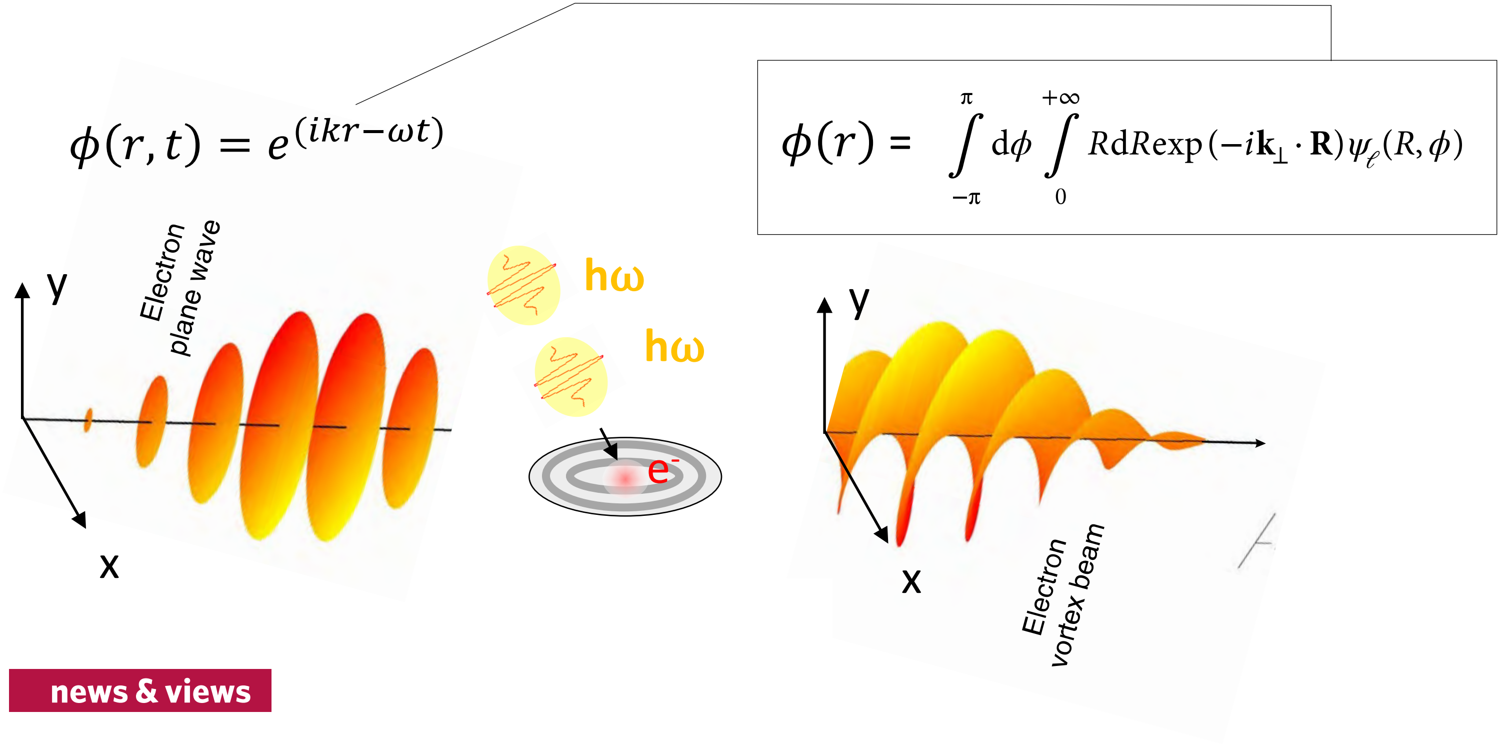
- Nuclear processes (electron capture, core-level photoemission)
- Intramolecular processes (charge transfer)

Ultrafast generation and control of an electron vortex beam via chiral plasmonic near fields

nature materials

Vanacore et al., **18** 573 (2019)





news & views

PHOTONICS

Vorticity induced by chiral plasmonic fields

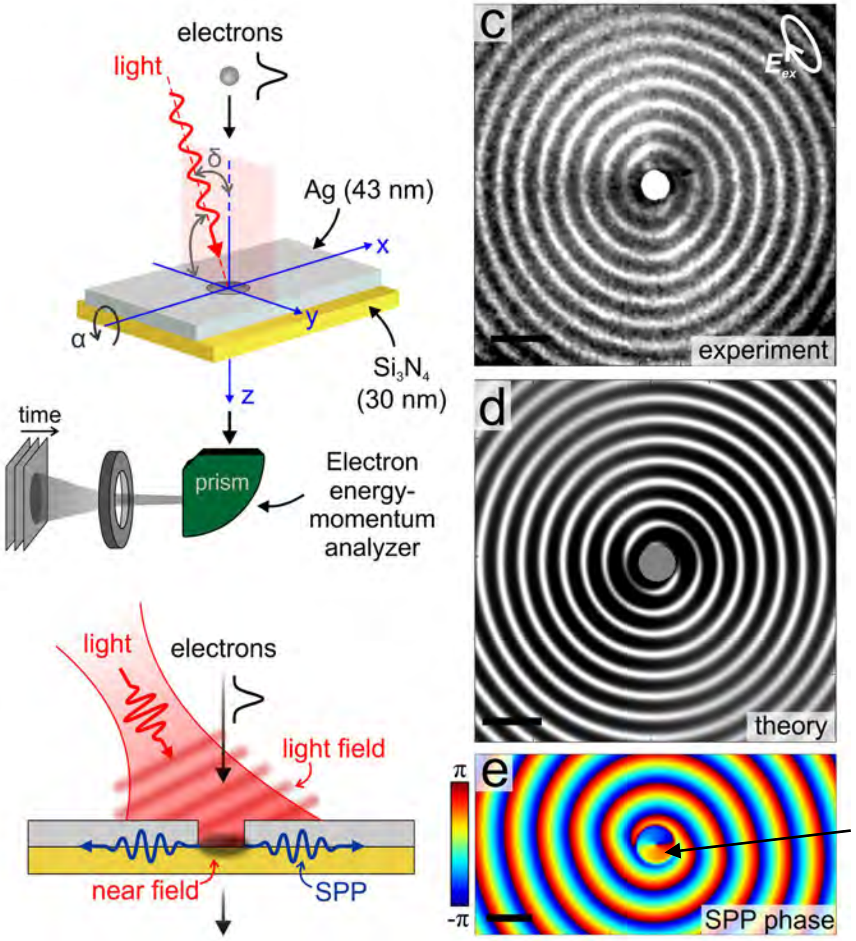
Coherent shaping of matter waves in temporal and spatial domains by photon-induced near fields opens up new possibilities for the quantum control of matter.

Jun Yuan

Spatial Tomography of the e^- wavefunction

Image the electrons

Coherent control of the transverse electron wavefunction



- Chiral SPP launched by elliptically polarized light
- Simulated Chiral SPP
- A chiral plasmonic field can impart a phase singularity onto the transverse component of an e⁻ wavefunction

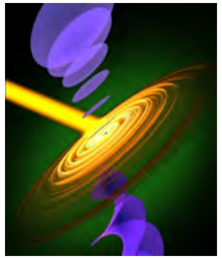
LUMES

Vanacore et al., **Nature Materials** 18, 573 (2019)

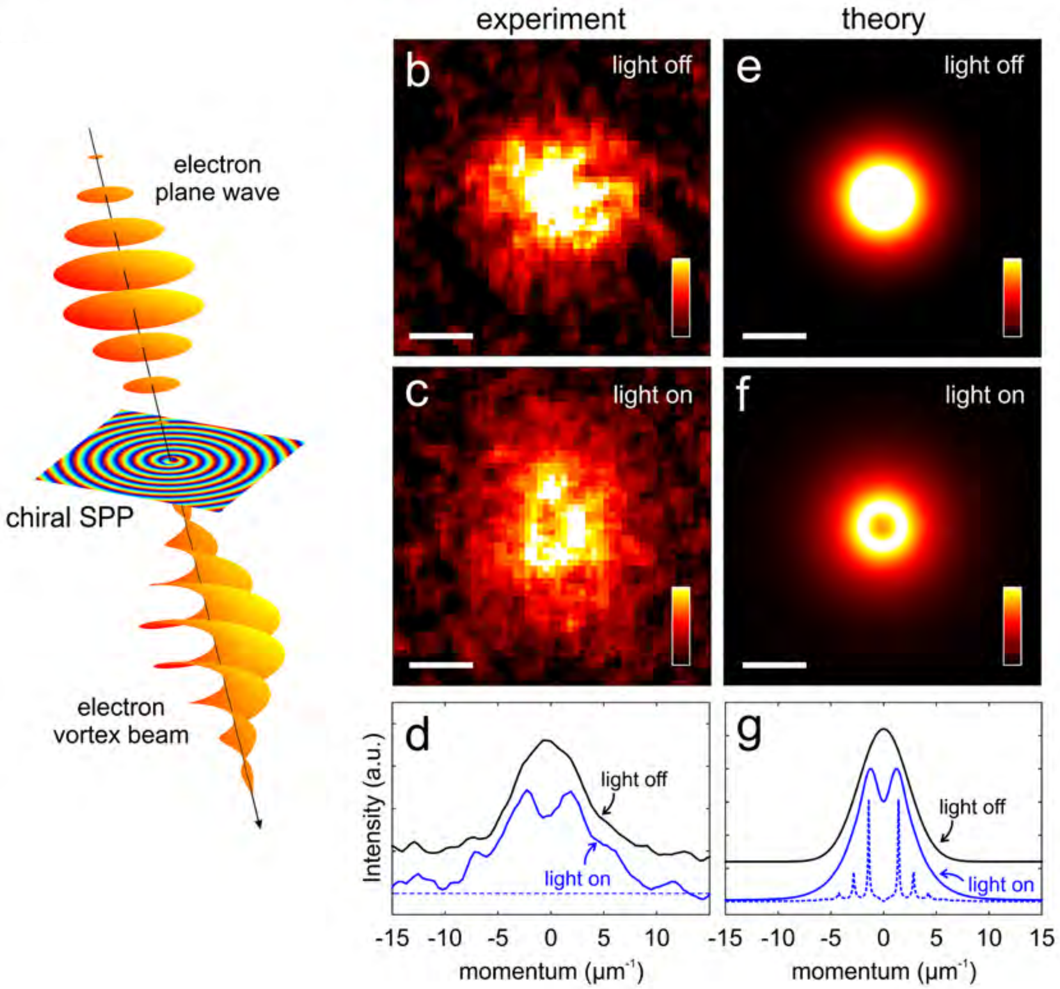
New and Views article: Jun Yuan **Nature Materials** 18, 533 (2019)

https://actu.epfl.ch/news/twisting-whirlpools-of-electrons/

https://www.youtube.com/watch?time_continue=5&v=TIJ-mlh2LSI&feature=emb_logo



Generation of electron vortex beams

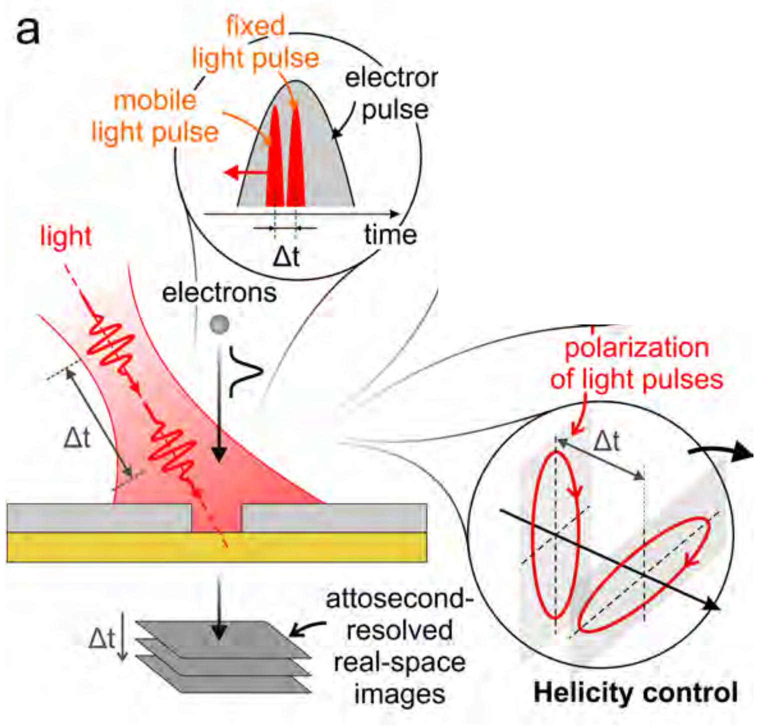


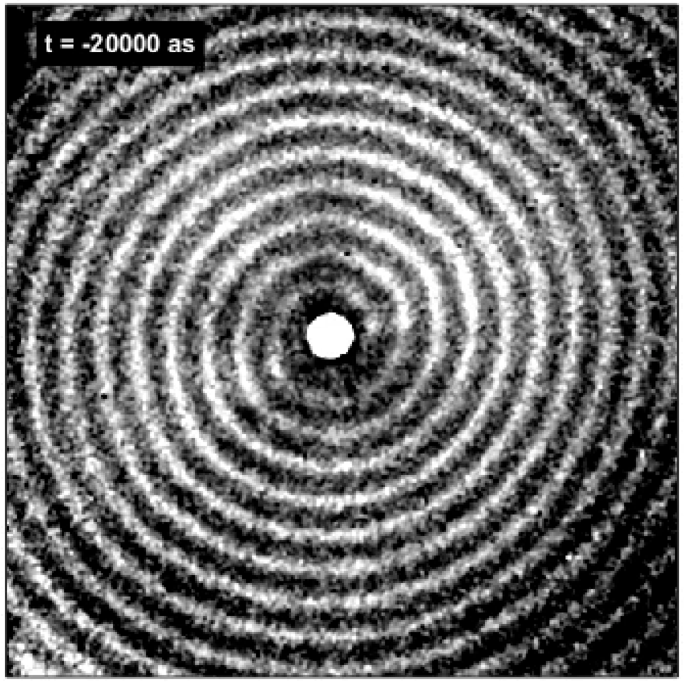
Electron wavefunction microscopy
in momentum space

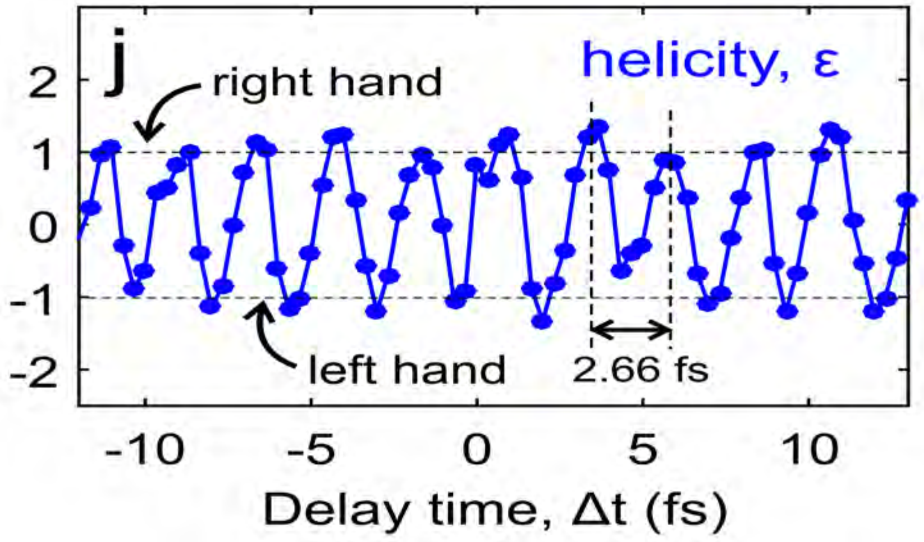
Vanacore et al., **Nature Materials** 18, 573 (2019)

LUMES

Coherent control of vortex beams







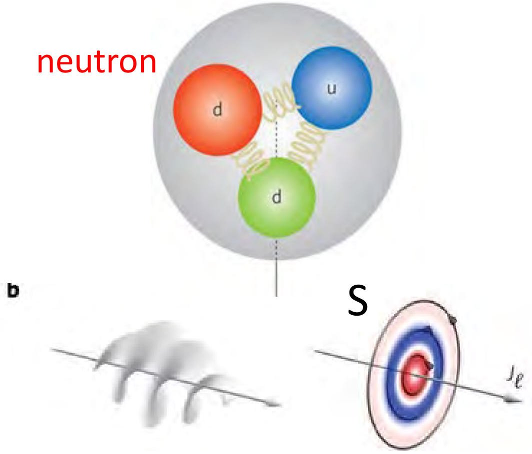
Three pulses experiment: attosecond control of the topological charge of an e^- wavefunction between +1 and. -1

Vanacore et al., **Nature Materials** 18, 573 (2019)

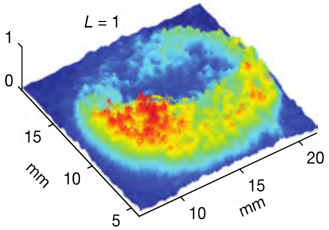
LUMES

Application of vortex beams

Twisted neutrons



Neutron orbital angular momentum



Make a particle with a fine structure spiral reveals its inner structure

- Can we twist protons as well?
- Can we twist atoms and ions?
- Exploit the different radiation/matter interaction for selective tissue ablation (ongoing project with ADAM and CERN)

Vortex beams, magnetic sensing

- Spin-polarized TEM does not exist yet
- Left handed/right handed vortex beams are sensitive to magnetization orientation
- Transfer topological charge from e^- vortex beam to spins in materials

LUMES

Clark et al., Nature 525, 504 (2015)

Laroque et al., Nat. Phys. 14 1 (2018)

Manipulating the element transmutation

Dreamt of: 1600
Observed and used: 1950s to now
Controlled: **not yet**

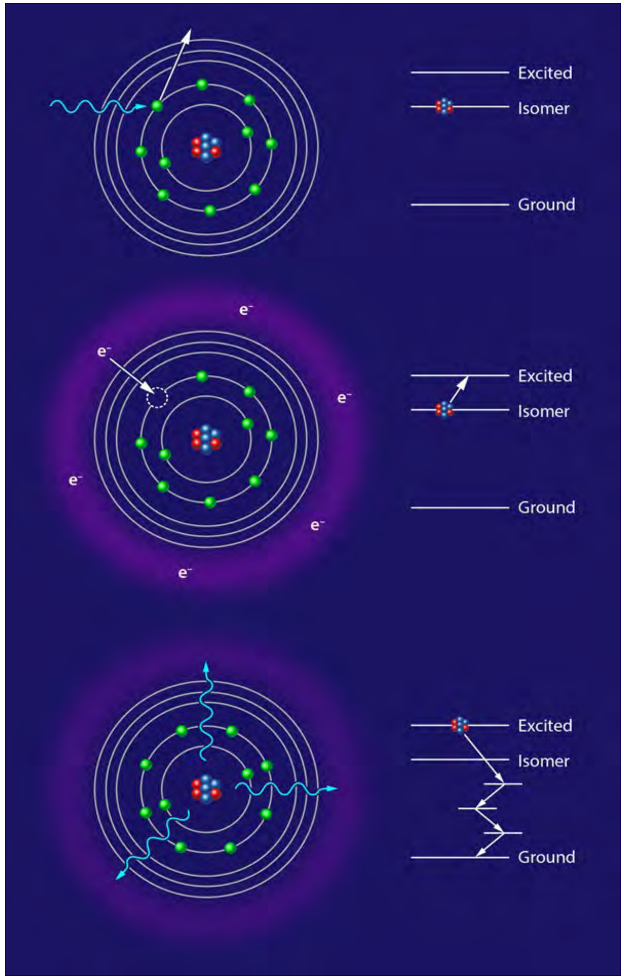
Orbital electron capture

Ionized atom captures a free e^-
Instead of Auger recombination with gamma ray emission
the atomic nucleus is excited

Nuclear isomer:
metastable atomic nucleus made of one or more of its nucleons (protons or neutrons) in an excited state.
Half-lives 100 to 1000 times longer (ns) than other excited nuclear states (ps or less)

Create metastable isomers: high energy process
The metastable state is not necessarily the most convenient for EC

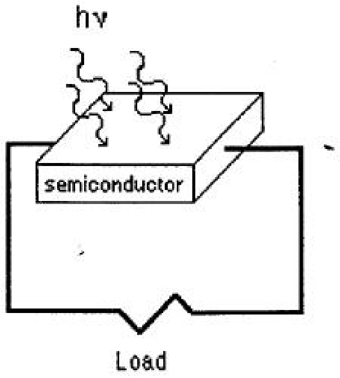
Sample short-lived states: impossible until now
Expand parameter space from which to study NEEC



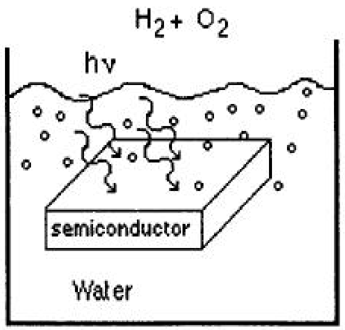
LUMES

Chiara et al., Nature 554, 216 (2018)

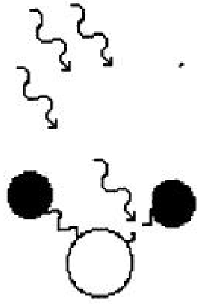
Nuclear batteries



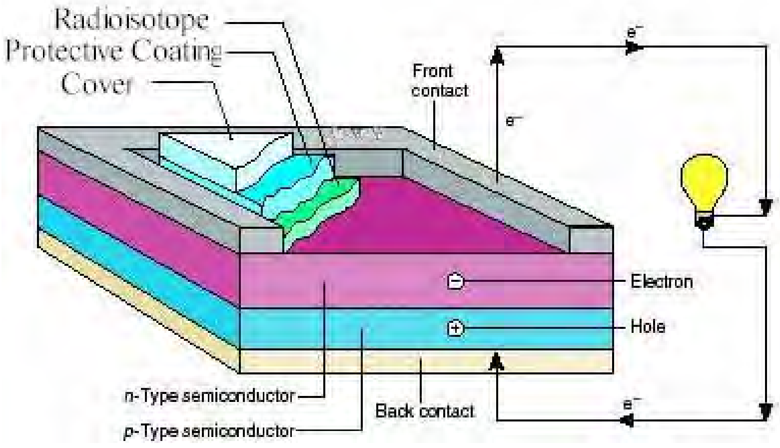
Photovoltaic



Photoelctrochemical



Photochemical



Nuclear

Major plus

- 4-5 orders of magnitude higher **energy** density
- Long-lasting (even 100s of years, use in satellites)

Major minus

- Low **power** density (slow energy release process)
- Dangerous/poisonous materials (not eco-friendly)
- Low nuclear to electric energy conversion efficiency

Solutions:

- Control decay-rates: control power delivery
- Transiently induce radioactivity in stable elements: reduce environmental hazard, cost, danger
- Electrons and light technology can be integrated. Common nuclear technology cannot

LUMES

https://physicsworld.com/a/nuclear-excitation-by-electron-capture-seen-at-long-last/

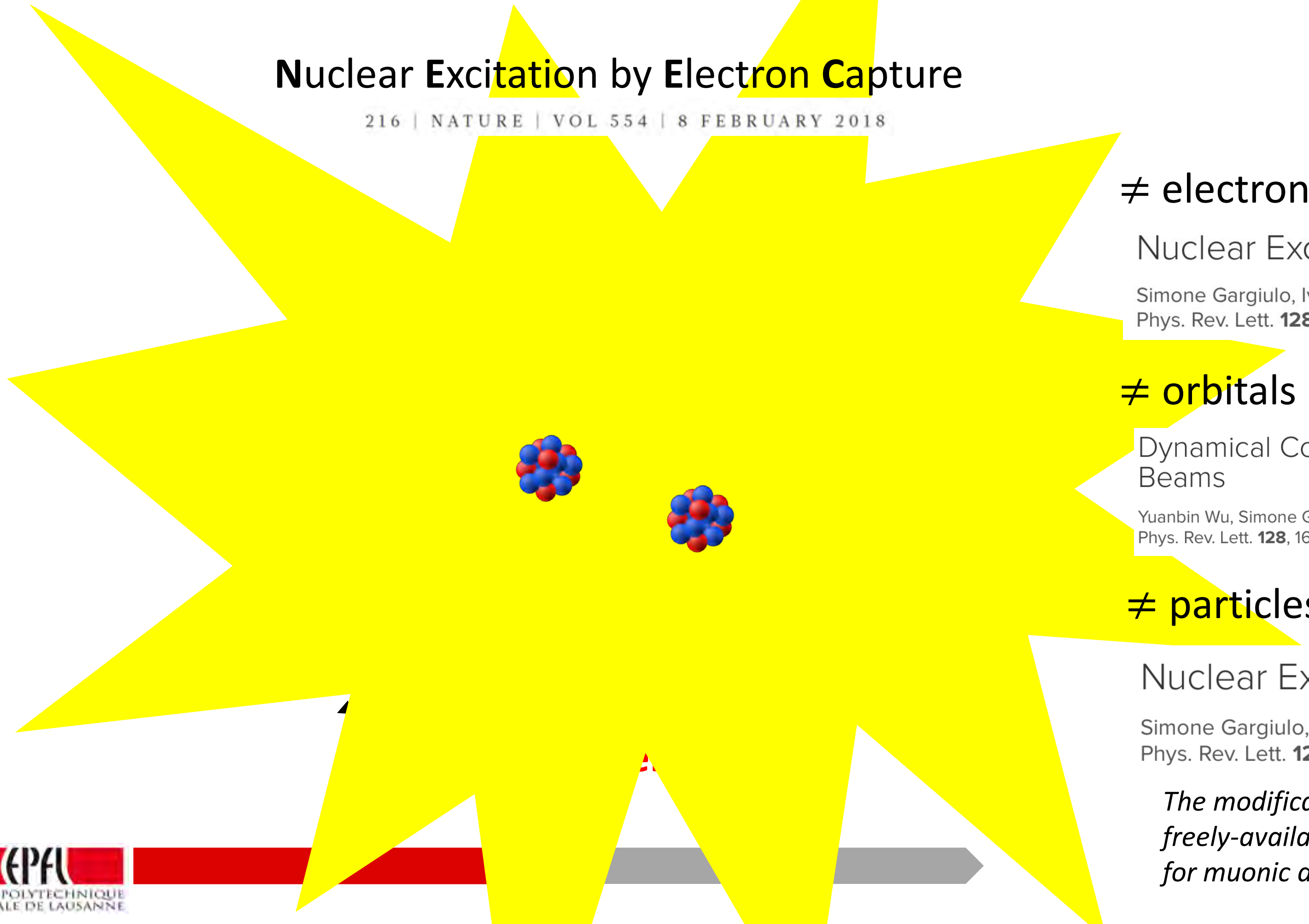
Coherent control of nuclei

Can we use out of equilibrium methods to control the release of nuclear energy?

- Speed up the decay of nuclear waste
- Engineer long-lasting/high power nuclear batteries
- Induce radioactivity on demand in stable atoms

Nuclear **E**xcitation by **E**lectron **C**apture

216 | NATURE | VOL 554 | 8 FEBRUARY 2018



≠ electronic configurations ≠ channels available

Nuclear Excitation by Electron Capture in Excited Ions

Simone Gargiulo, Ivan Madan, and Fabrizio Carbone
Phys. Rev. Lett. **128**, 212502 – Published 27 May 2022

≠ orbitals ≠ cross section (10^6 higher!)

Dynamical Control of Nuclear Isomer Depletion via Electron Vortex Beams

Yuanbin Wu, Simone Gargiulo, Fabrizio Carbone, Christoph H. Keitel, and Adriana Pálffy
Phys. Rev. Lett. **128**, 162501 – Published 22 April 2022

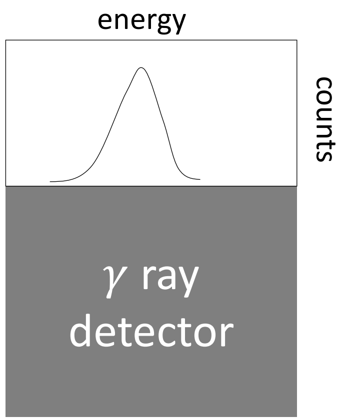
≠ particles ≠ effect (induced fission)

Nuclear Excitation by Free Muon Capture

Simone Gargiulo, Ming Feng Gu, Fabrizio Carbone, and Ivan Madan
Phys. Rev. Lett. **129**, 142501 – Published 27 September 2022

The modifications of the FAC code made it the only freely-available online tool that can solve the Dirac equations for muonic atoms

Experimental Implementation

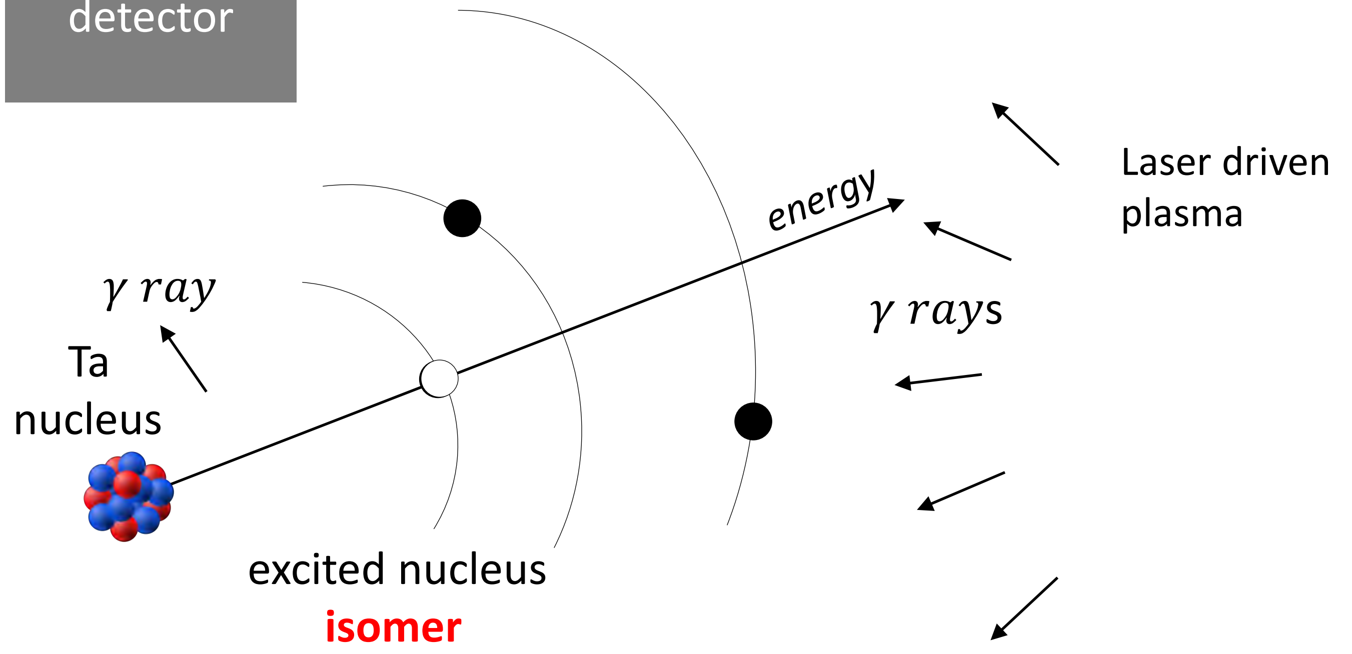


Logic:

- Induce vacancies with laser in the correct orbital
- Provide engineered electrons for the capture

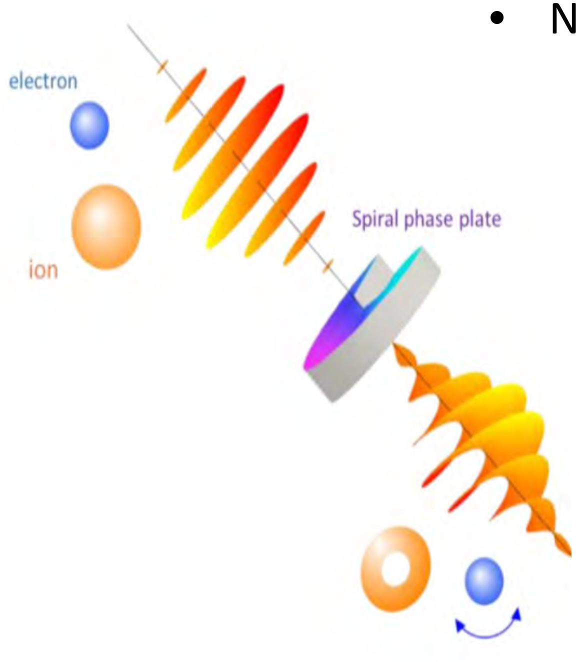
Step number 1:

- Test the idea first by doing direct excitation of the nucleus (never observed from laser-induced plasma)

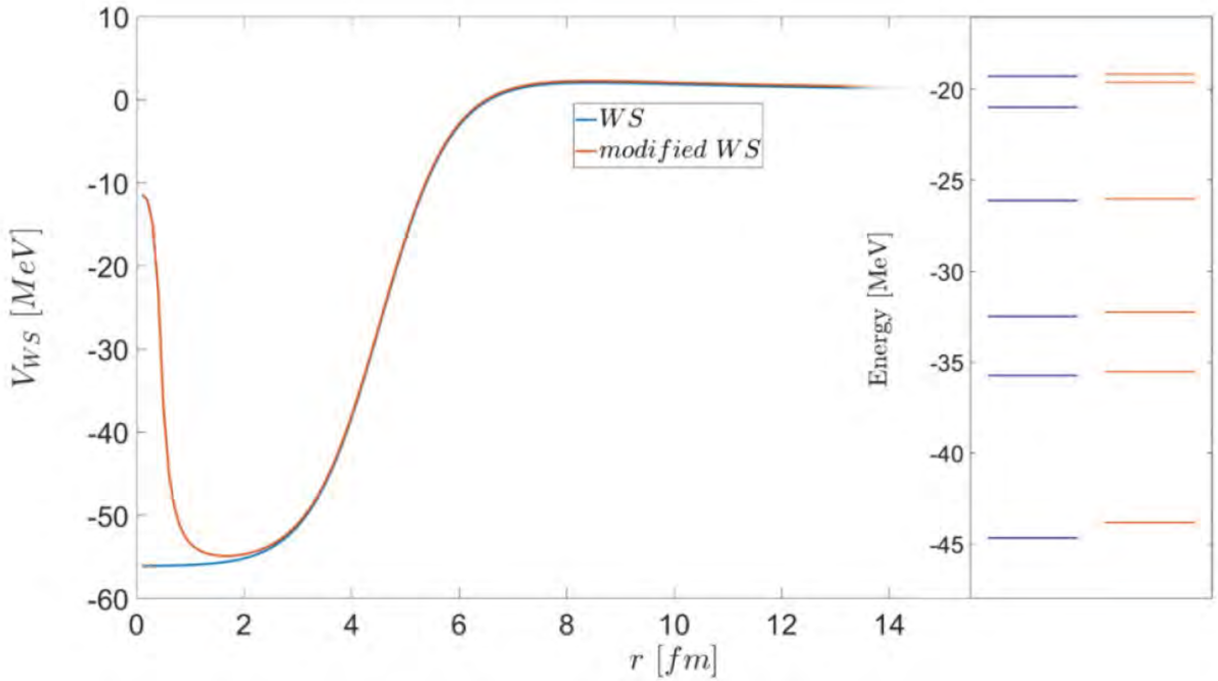


Nuclear physics with vortex beams

- Twisting ions WF modifies nuclear excitations spectrum
- Vortex e^- can be captured in higher l-shells, created ad hoc
- NEEC **σ** up to 6 orders of magnitude (article in preparation) **ENGINEERED NUCLEAR DECAY!!**



Nuclear excitations and nuclear Wood-Saxon potential



LUMES

EPFL

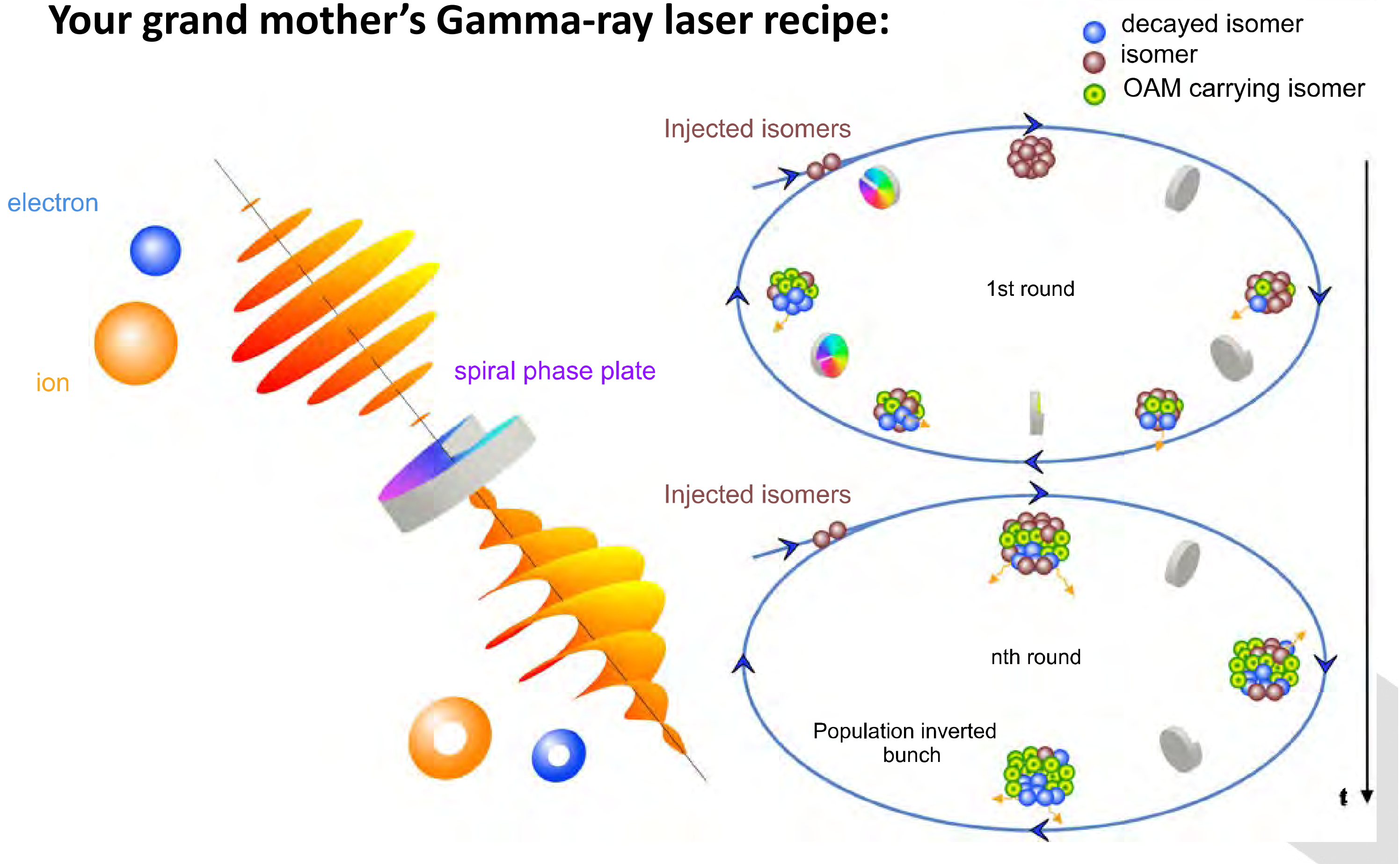
Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

The quantum future of microscopy: Wave function engineering of electrons, ions, and nuclei

Cite as: Appl. Phys. Lett. 116, 230502 (2020); doi: 10.1063/1.5143008
Submitted: 19 December 2019 · Accepted: 29 May 2020 ·
Published Online: 11 June 2020

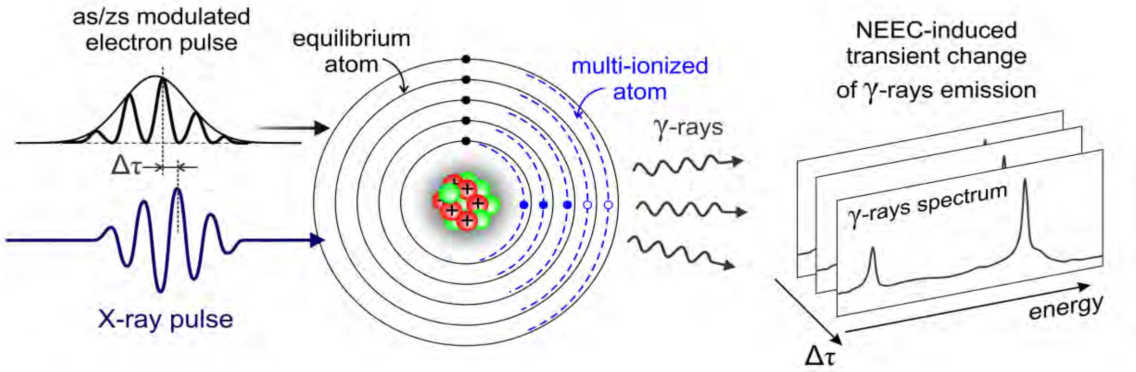
I. Madan, G. M. Vanacore, S. Gargiulo, T. LaGrange, and F. Carbone[a]

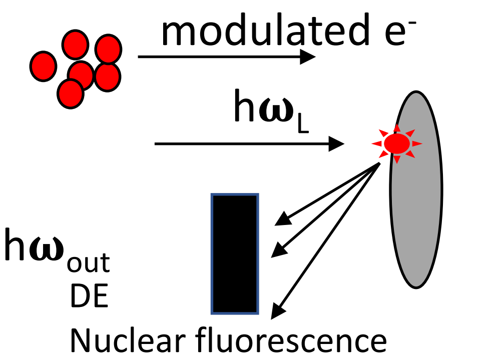
Your grand mother's Gamma-ray laser recipe:



Thank you!

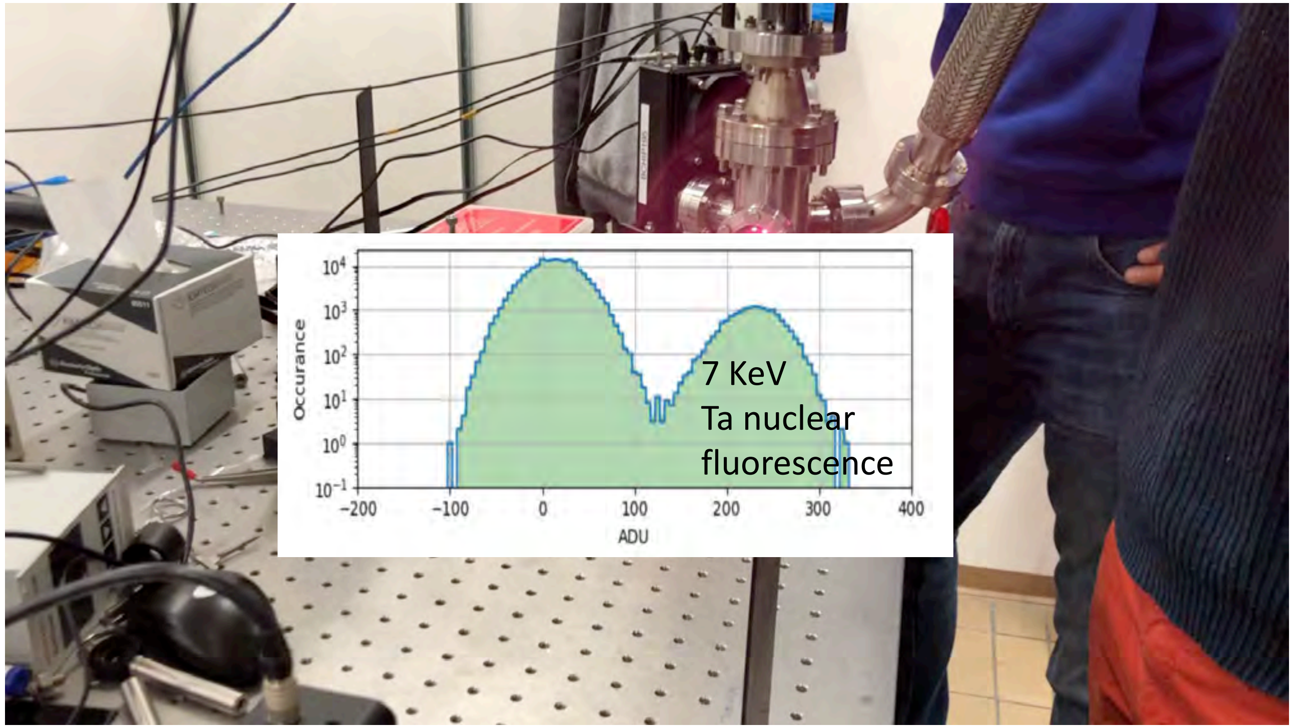
Experimental concept and implementation





Same energy! Different time…….

New medipix detector:
Energy-resolution +
ns time resolution



We don't have an FEL: Use light induced plasma to generate the needed X-rays for direct photoexcitation

LUMES

Rudek et al., Nat. Phot. 6 858 (2012)

Vanacore, et al., Nat. Comm 9 2694 (2018)

Gargiulo et al (submitted to PRL, http://arxiv.org/abs/2102.05718)

Out of equilibrium nuclear physics:

Observed NEEC **σ** vs theoretical NEEC **σ** : 10^{11}

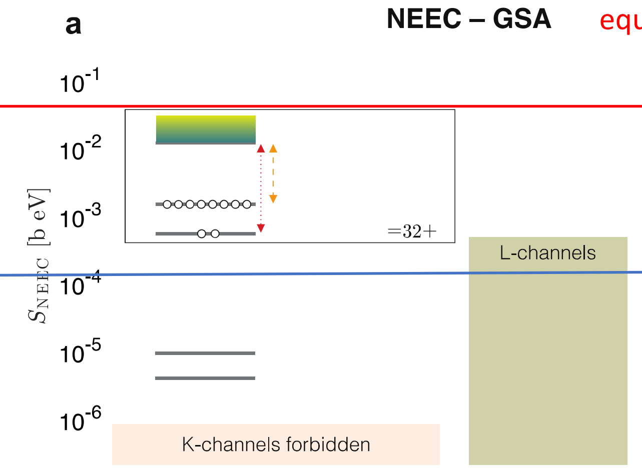
Recalculating **σ** in out of equilibrium ions: 3 orders of magnitude gained, 8 to go

Maximum cross section out of equilibrium

Maximum cross section at equilibrium

equilibrium

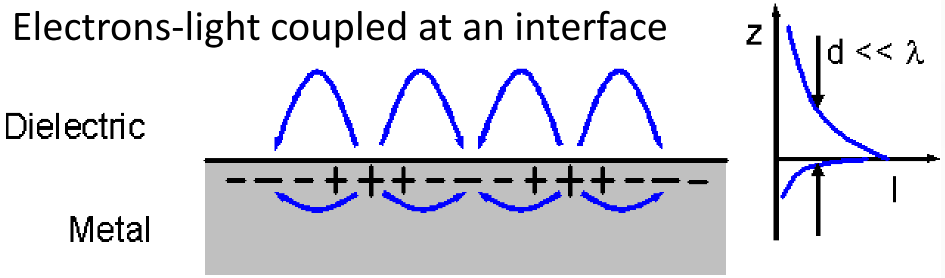
Out of Eq.

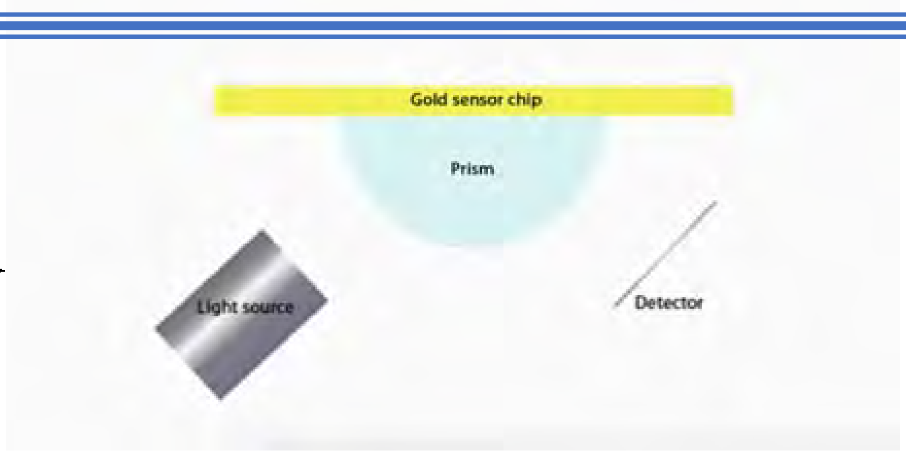


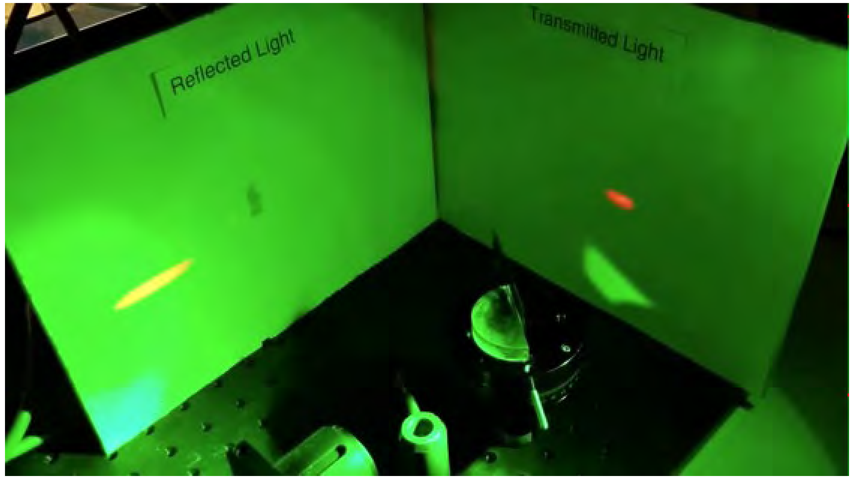
Gargiulo et al (submitted to PRL, http://arxiv.org/abs/2102.05718)

Surface plasmons polaritons and plasma resonances

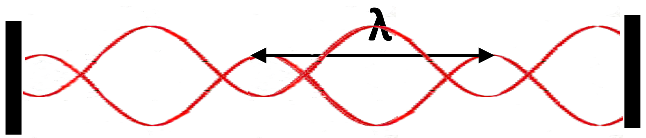
Surface plasmon:
Electrons-light coupled at an interface







Plasma resonance



Suggested reading: Dressel, “Electrodynamics of solids”