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Velocity Map Imaging for Electron Energy Distribution Measurements in REMPI-initiated Plasma

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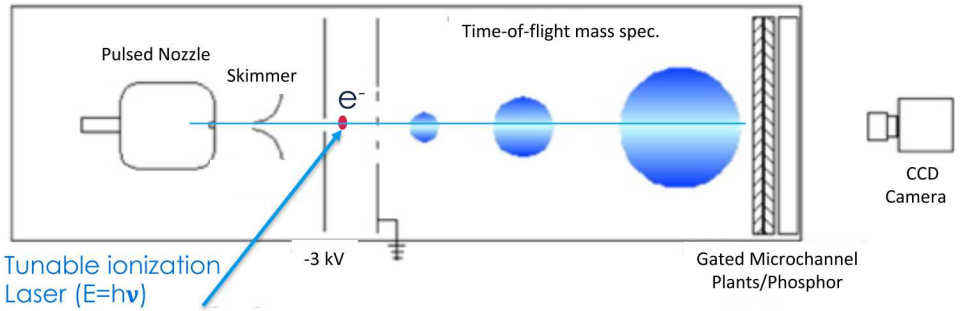

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Velocity Map Imaging and Resonance-Enhanced Multiphoton Ionization

Probe electron scattering processes, low-temperature plasma evolution, and plasma chemistry initiation using tools from chemical dynamics

- Well-controlled initial conditions away from walls
- Jet-cooled atomic/molecular beam (T~5 K) at low-pressure (10^{-6} Torr)
- Laser ionization of rare gas provides tunable narrow (<1 meV) electron energy distribution.
- Electron scattering with high energy resolution
- Generation of low-temperature plasma with well-defined initial electron energy distribution.
- Temporal evolution of EEDF can be probed over microseconds.
- Complements other work on REMPI-initiated plasmas (e.g. microwave scattering from REMPI-initiated plasmas from Princeton).

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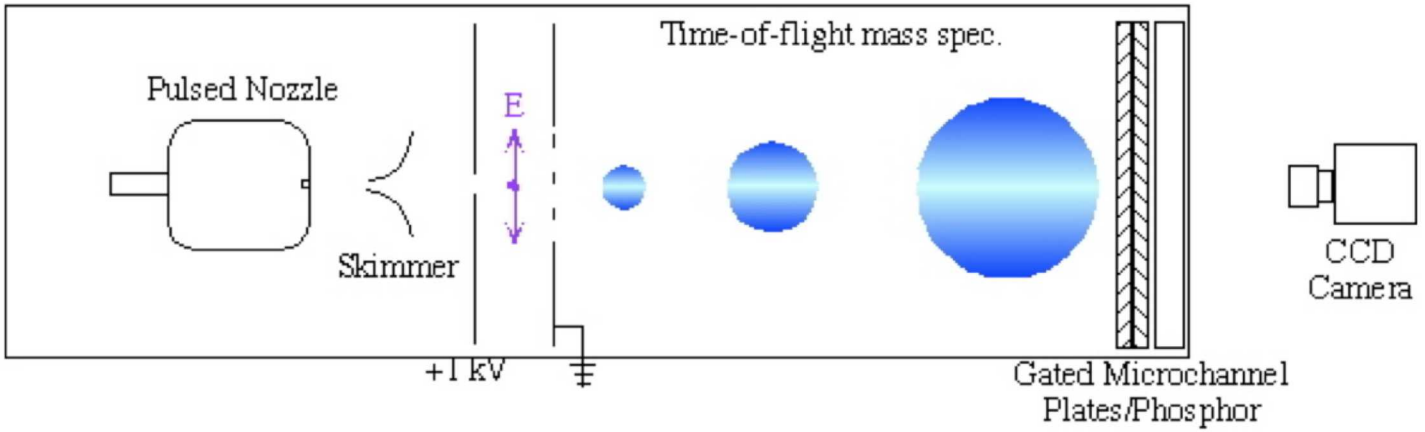
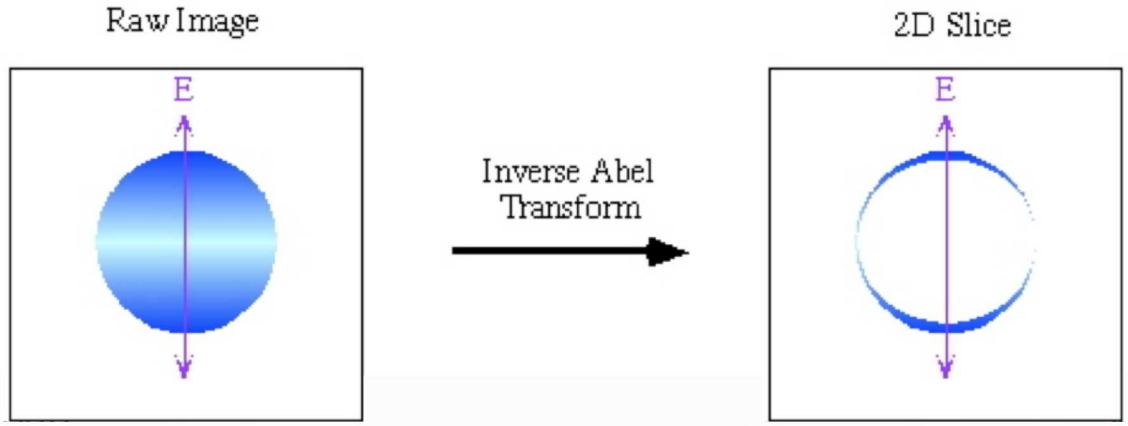
Electron/Ion Imaging

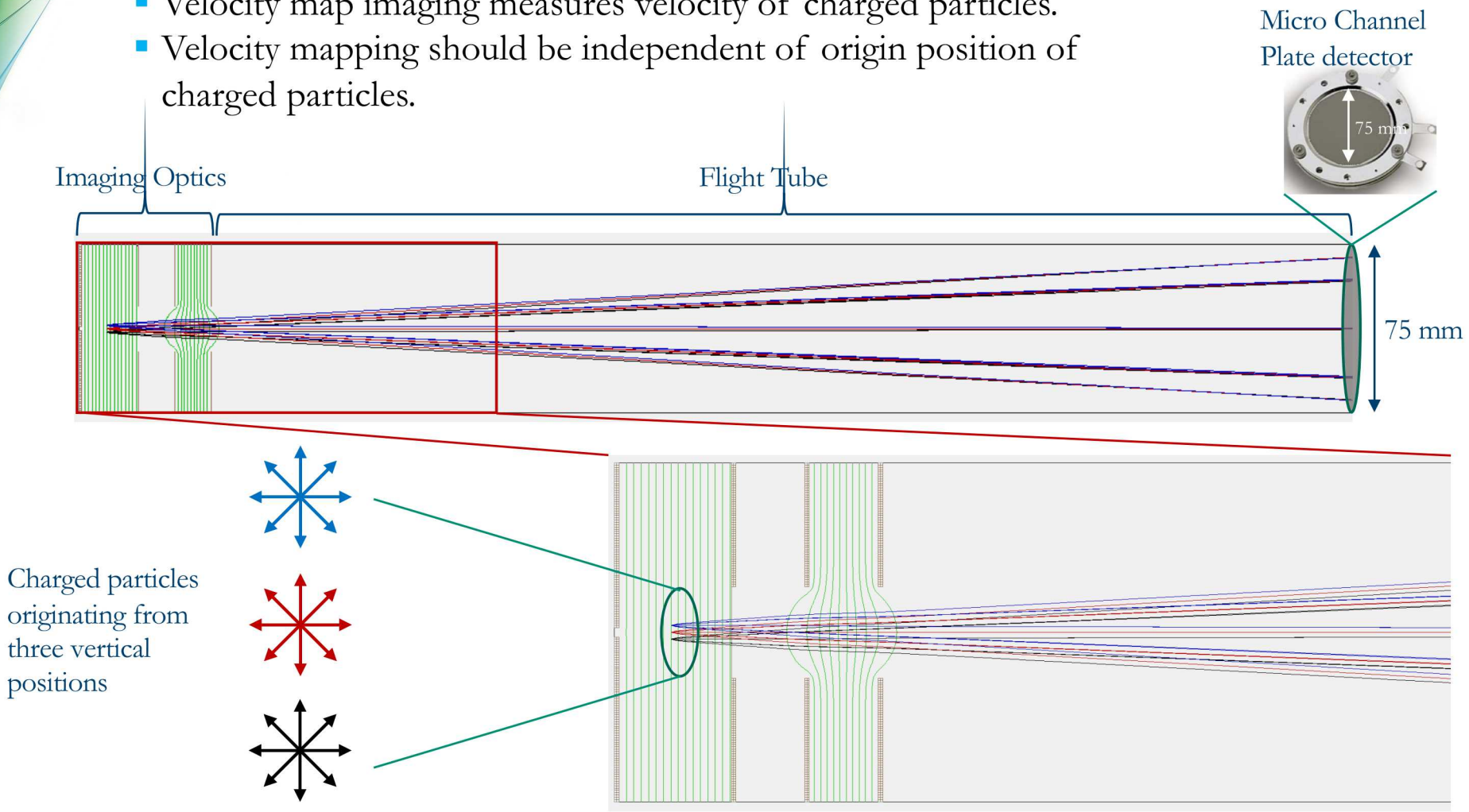




Recorded image is a 2-D projection of 3-D distribution of electrons/ions from which 3-D velocity distribution can be obtained

Velocity Mapping

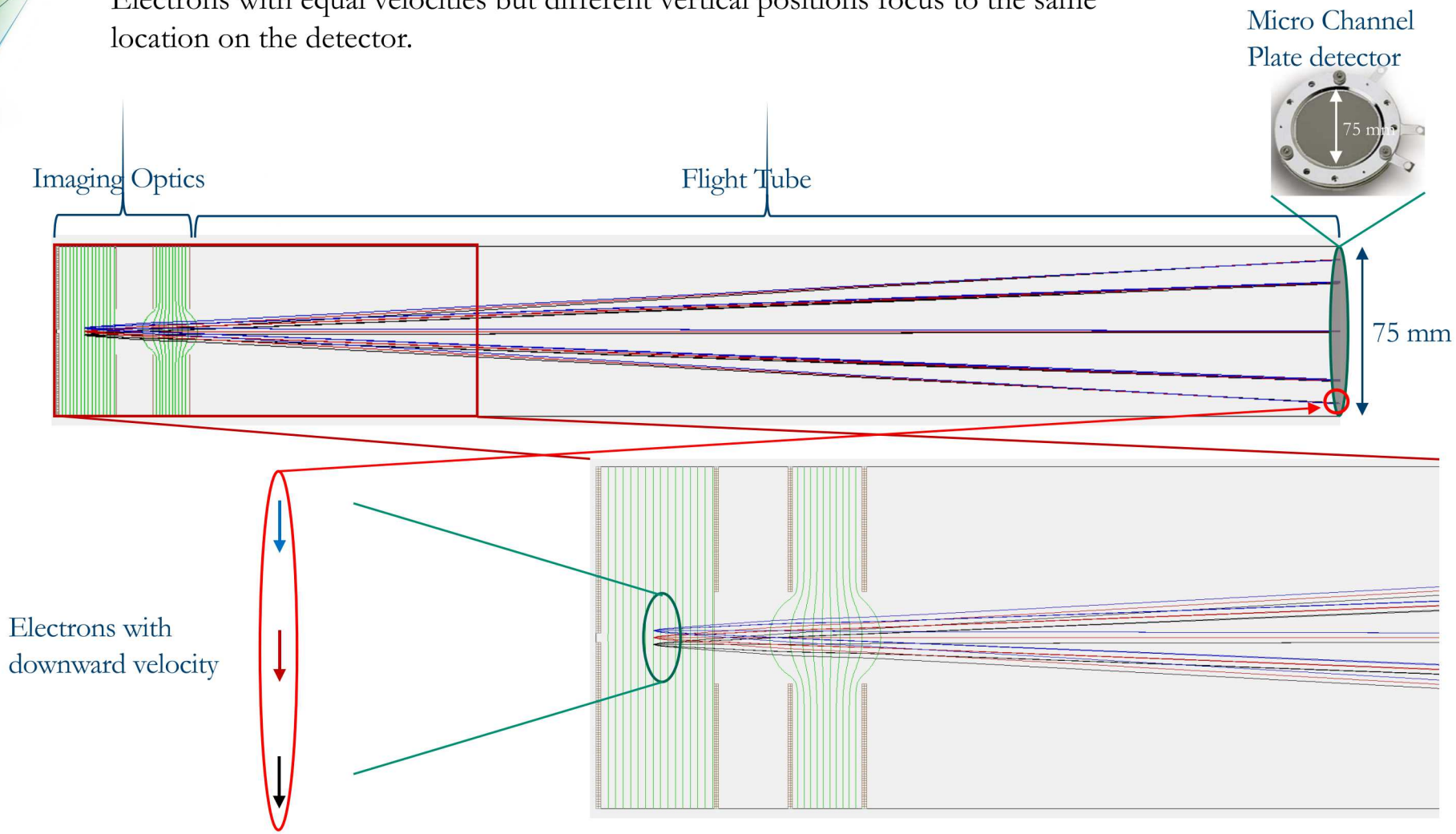
- Velocity map imaging measures velocity of charged particles.
- Velocity mapping should be independent of origin position of charged particles.



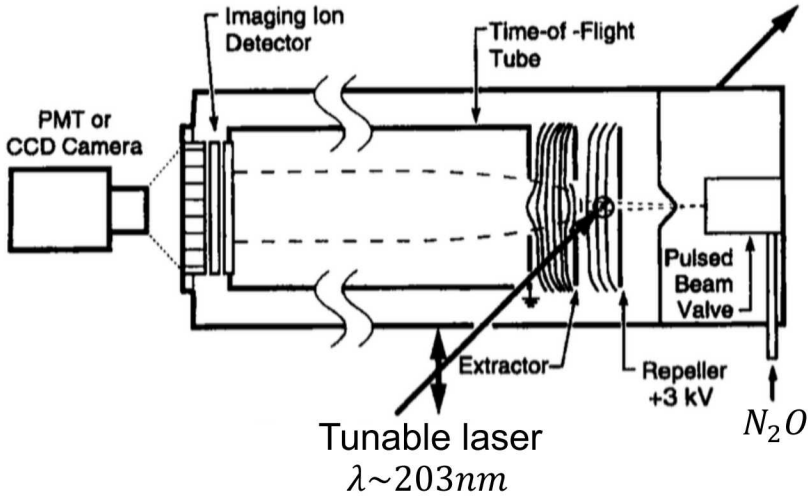
Eppink, Parker, Rev. Sci. Instrum. 68, 3477 (1997)

Velocity Mapping

Electrons with equal velocities but different vertical positions focus to the same location on the detector.

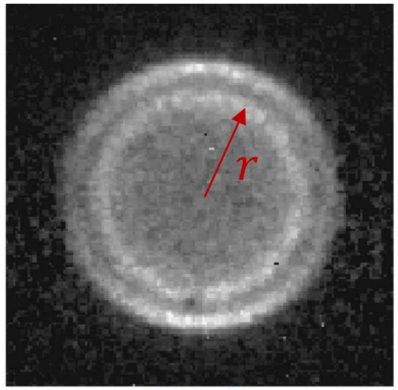


VMI Traditionally Used to Study Chemical Dynamics For Example: Photodissociation Dynamics of N_2O



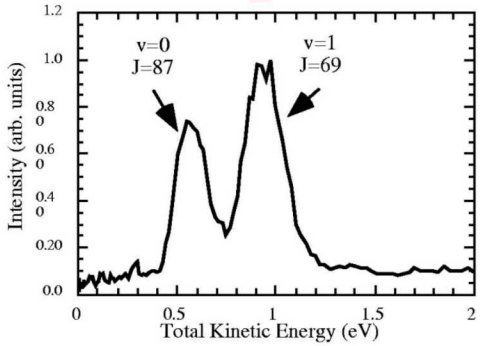
$$N_2O + h\nu \rightarrow N_2(v,J) + O(^1D)$$

Velocity Map Image of N_2 photofragments by 2+1 REMPI to form N_2^+ ion



$$u \propto r$$

$$E_T = \frac{1}{2}mu^2$$



- State-selected detection of translational energy (E_T) of dissociation products
- Calculate available internal energy using measured E_T
- Angular distribution of product recoil trajectories
- Time-of-flight discriminates different mass-to-charge ratios (*m/z*)

Neyer, Heck, Chandler, J. Chem. Phys. 110, 3411 (1999)

Velocity Map Imaging Extended To Dissociative Electron Attachment Using Electron Gun

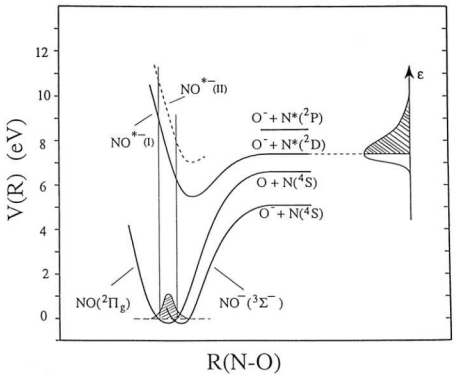
Imaging of O^- ions provides insights into dependence of DEA pathways for NO on electron energy.

$$e^- + NO \rightarrow NO^{-*} \rightarrow \begin{cases} O^-(^2P) + N(^4S)\ (E_{th}\ 5.0\ eV) \\ O^-(^2P) + N(^2D)\ (E_{th}\ 7.4\ eV) \\ O^-(^2P) + N(^2P)\ (E_{th}\ 8.6\ eV) \end{cases}$$

Active for Excited State NO

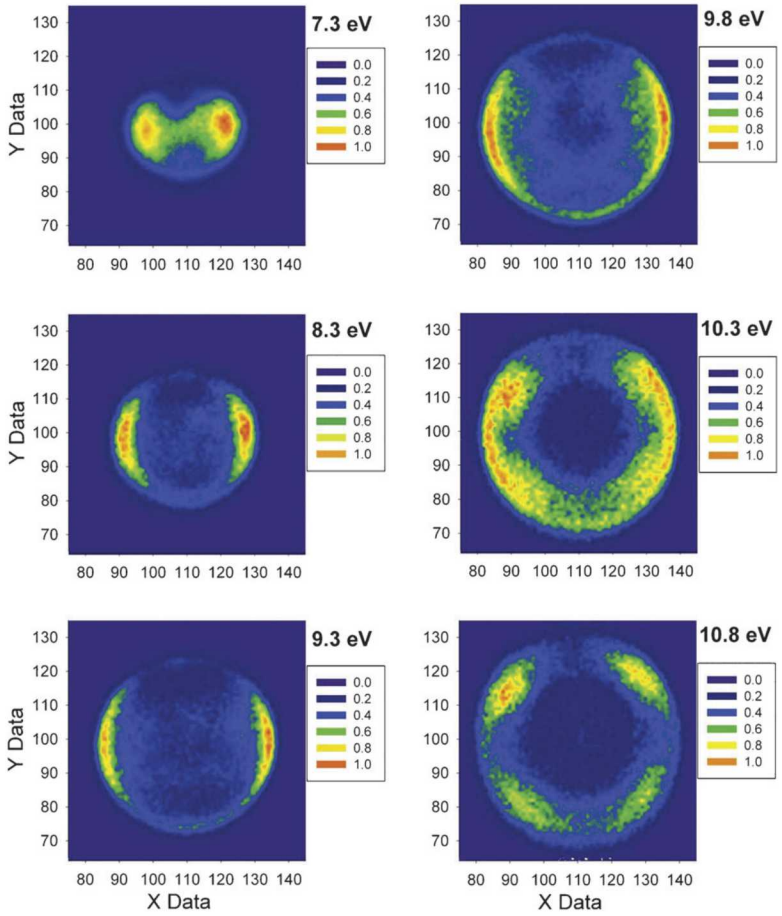
Dominant for Ground State NO

$$E_{th} = Threshold\ Energy$$



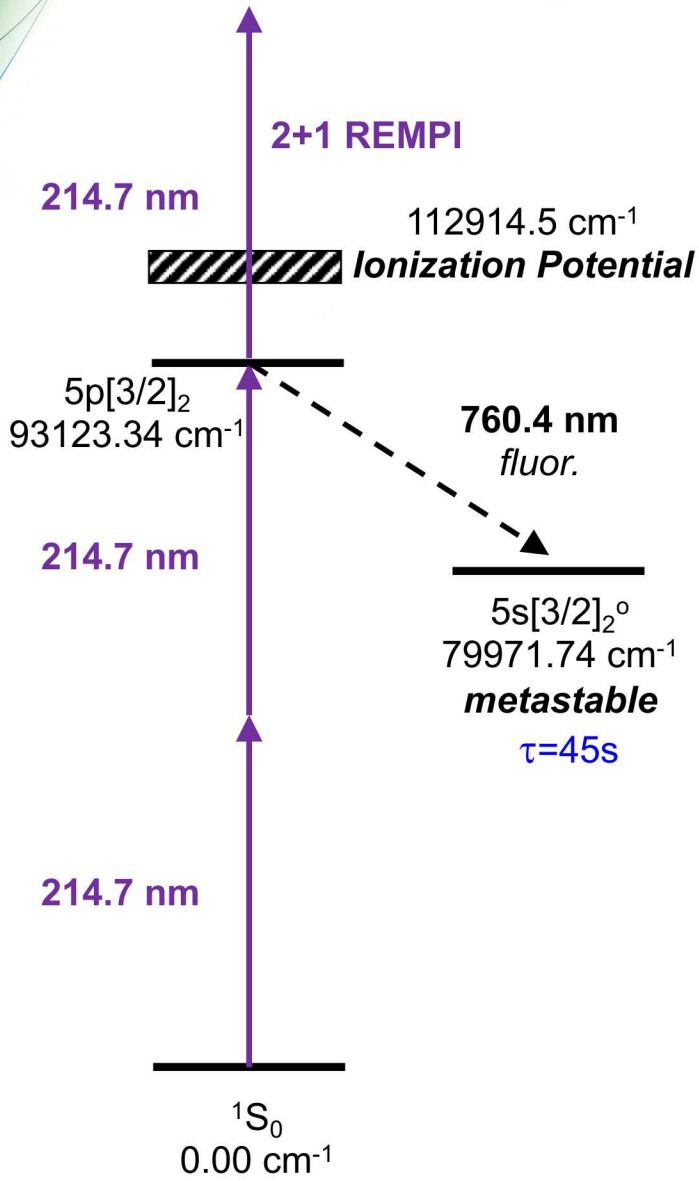
Denifl, *Chem. Phys. Lett.* (1998)

Velocity images of O^- ions from NO at different electron energies



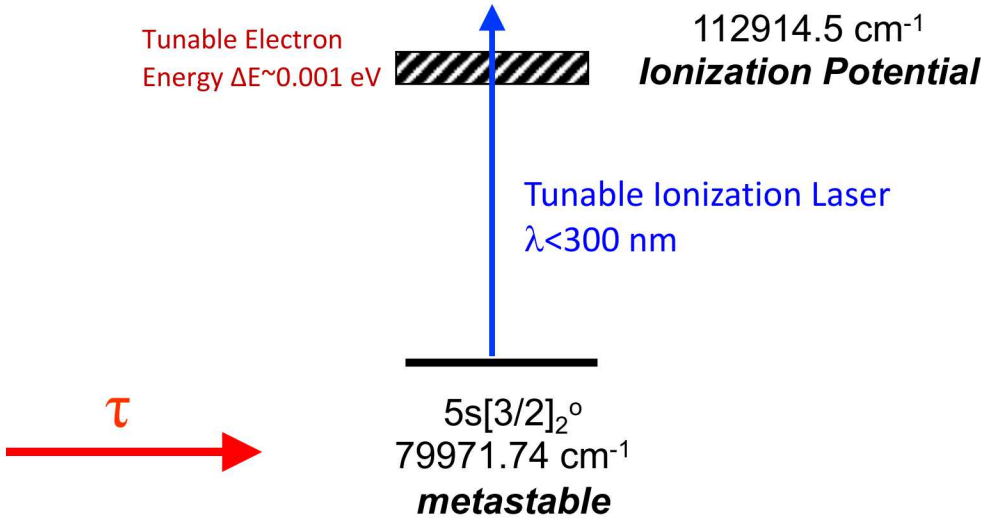
Nandi, Prabhudesai, Nestmann, Krishnakumar, Phys. Chem. Chem. Phys., 13, 1542 (2011)

High Resolution Electron Generation by Photoionization of Krypton

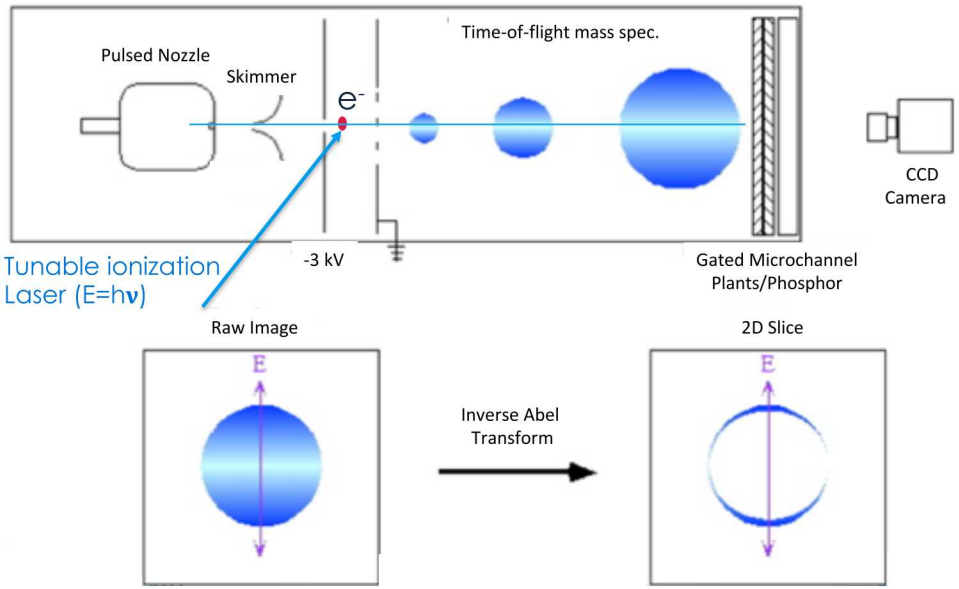


Tunable Low-Energy Electrons from Photoionization

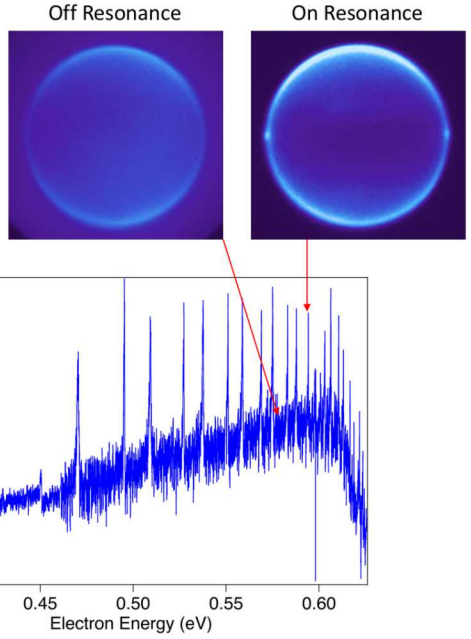
Energy resolution determined by laser linewidth and velocity spread



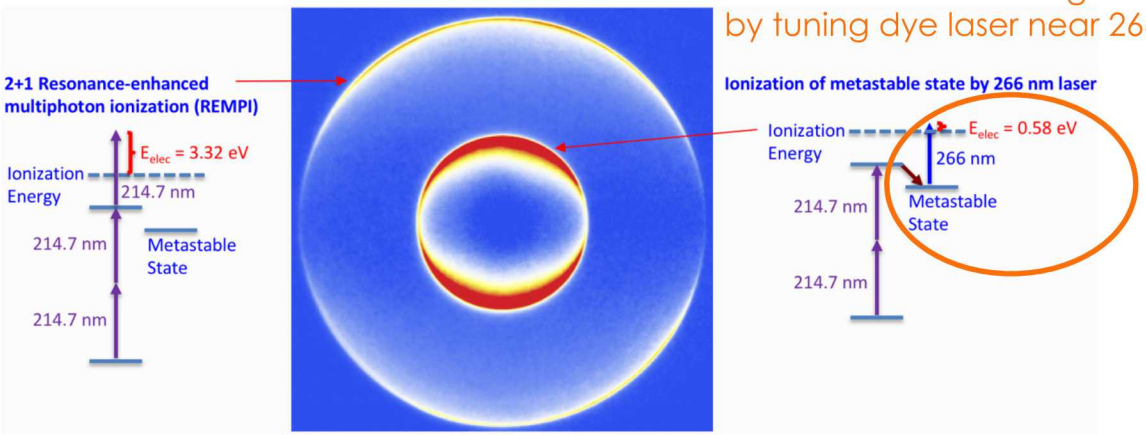
Velocity Map Imaging with Tunable Electron Energies



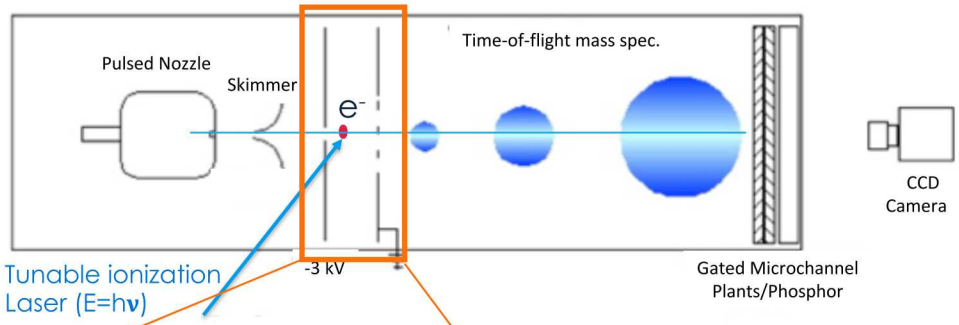
High resolution spectrum resolves Rydberg states of krypton



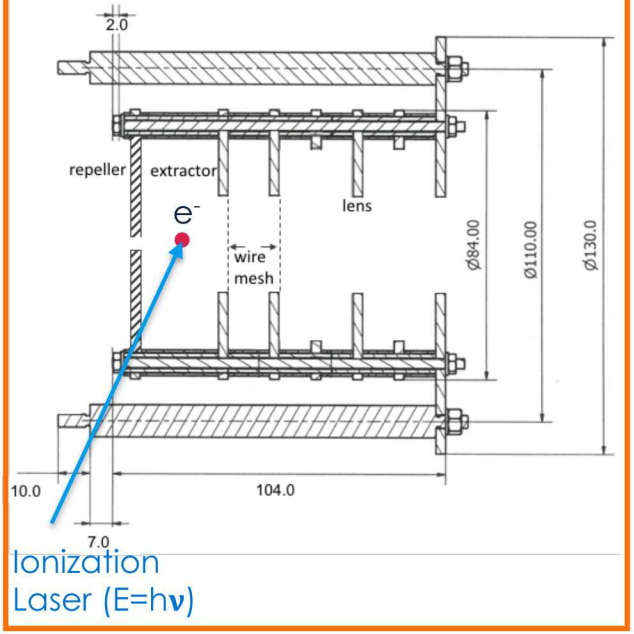
Tunable electron energies by tuning dye laser near 266 nm



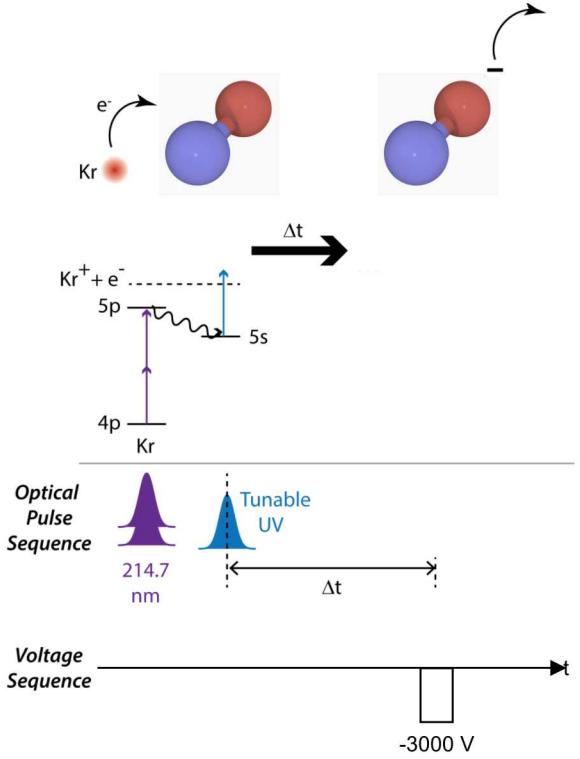
Electron Optics for Pulsed Velocity Map Imaging



New Design of Electron Imaging Optics

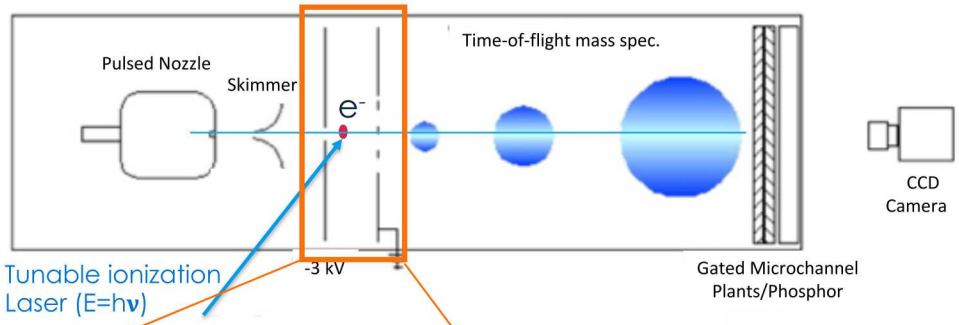


Time delayed extraction of electrons



- Field-free interaction region with grounded mesh
- Pulsed extraction of electrons by ns pulse applied to repeller plate

Electron Optics for Pulsed Velocity Map Imaging



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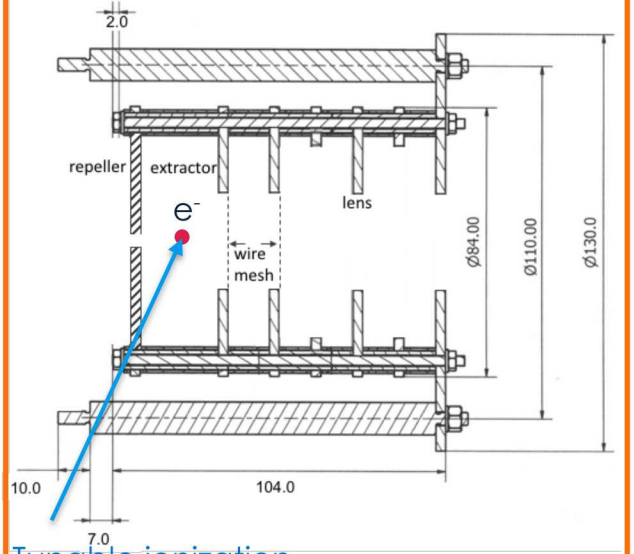
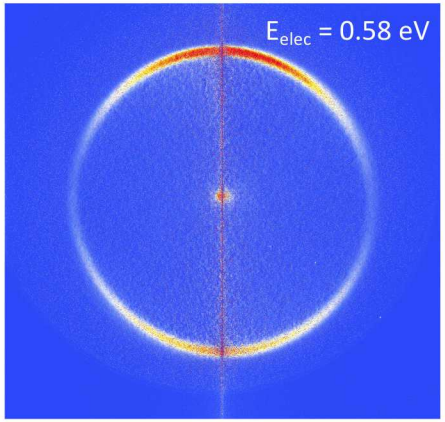
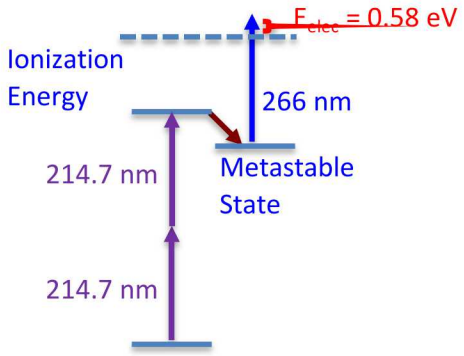
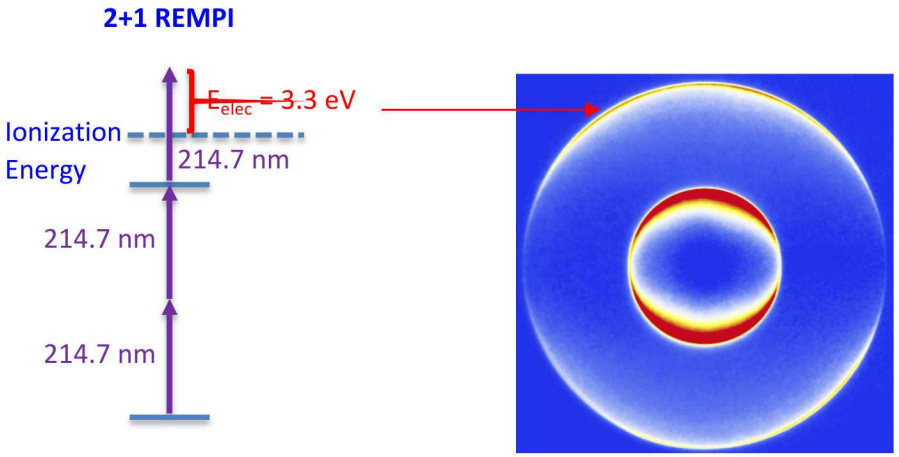




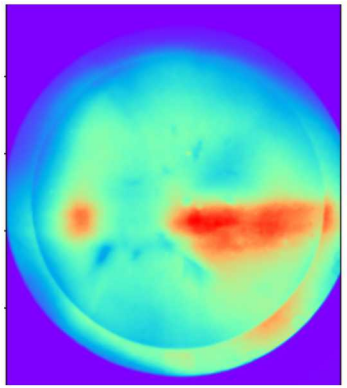


At High Laser Fluences REMPI Electrons Produce Broad Electron Velocity Distribution Instead of Distinct Ring

Lower Laser Energy



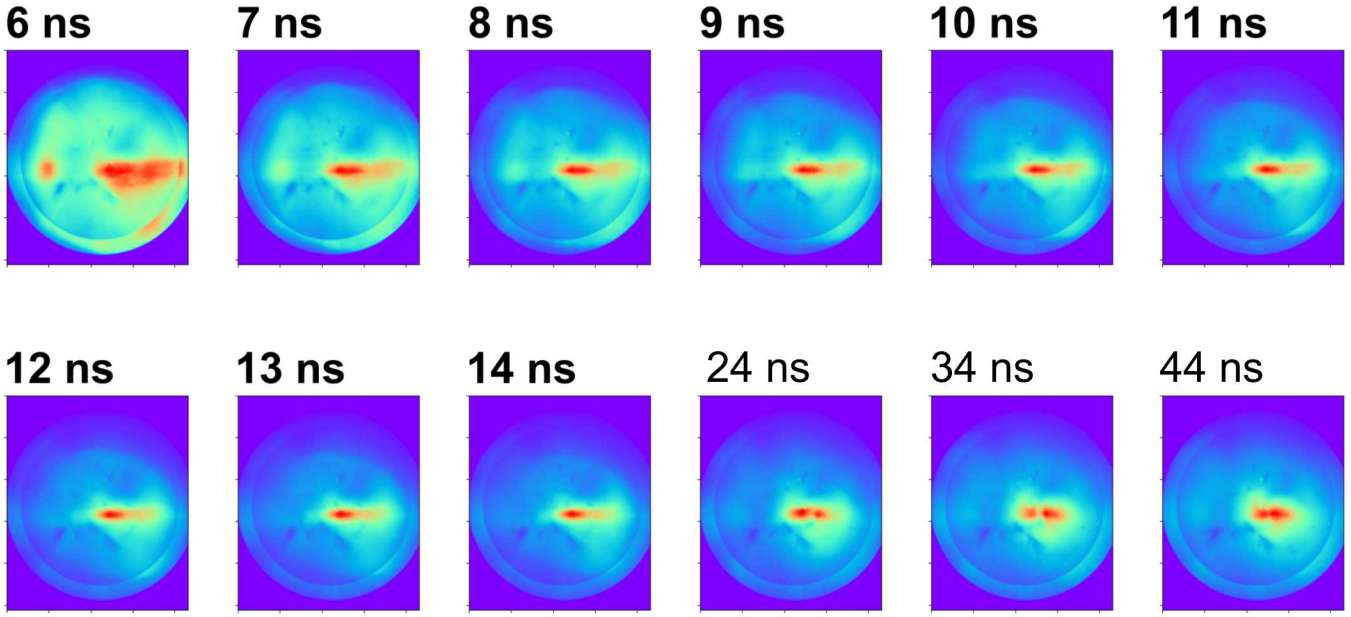
Higher Laser Energy (50 µJ/pulse)



Laser Propagation Direction

Evolution of REMPI-Generated Electrons Imaged with Nanosecond Resolution

Velocity map images of electrons at different time delays between ionization laser pulse and repeller voltage pulse



Speed of initial 3.3 eV photoelectrons = 1.1mm/ns

Microsecond Evolution of REMPI-Initiated Plasma

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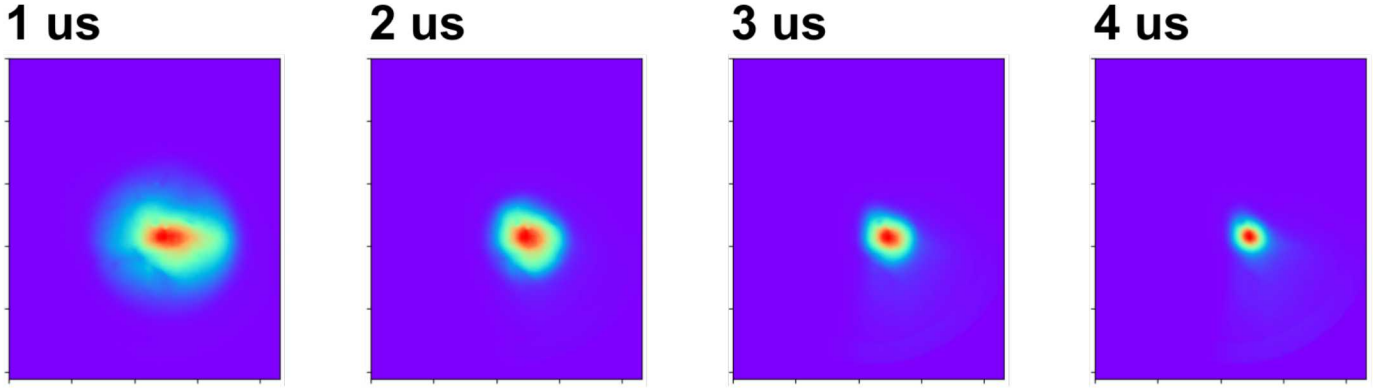
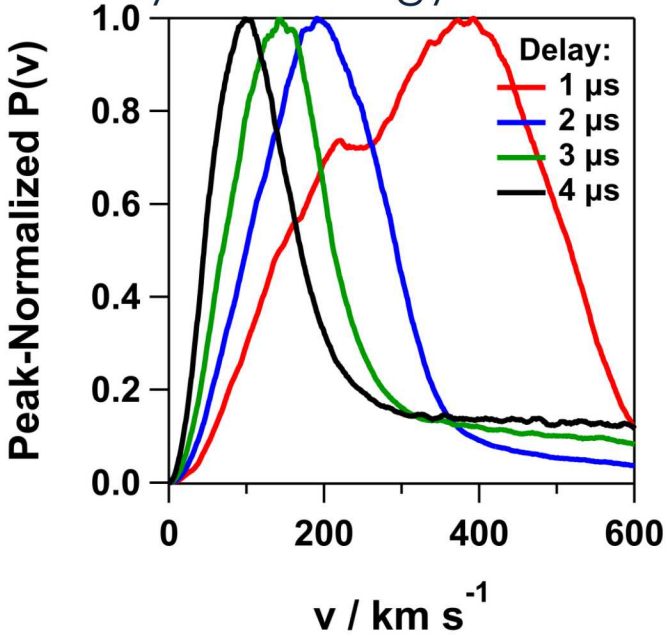
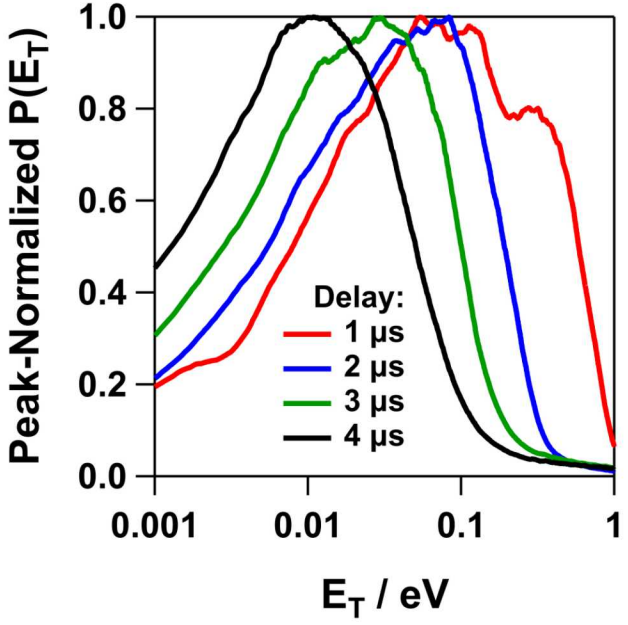


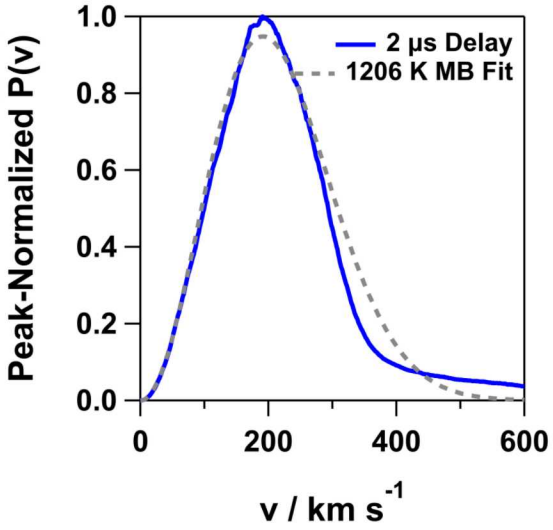
Velocity and Energy Distributions (determined after Abel inversion)

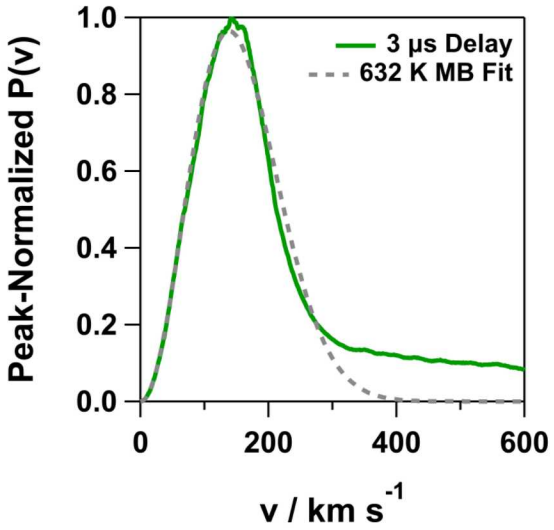


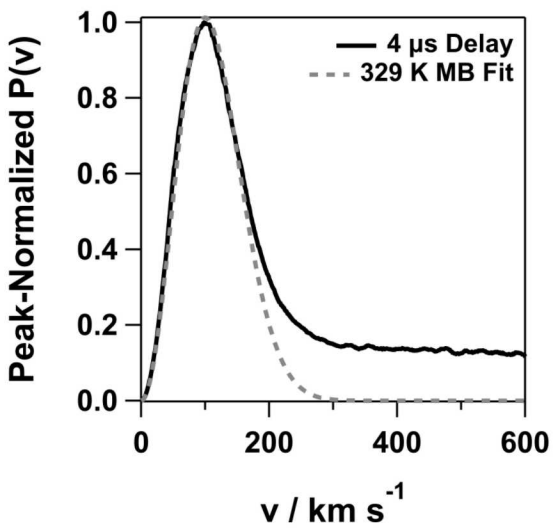


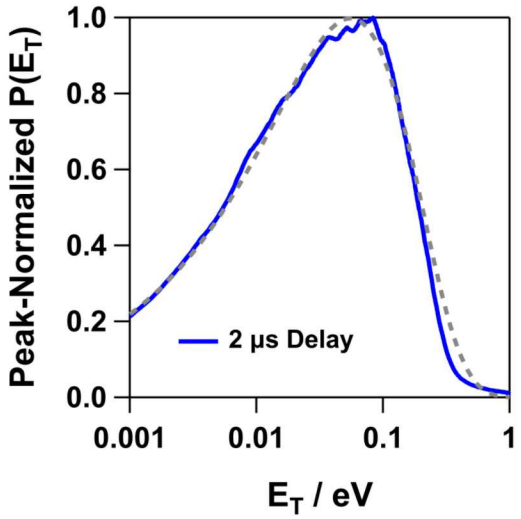
EEDF Cools and Evolves Toward M-B Distribution

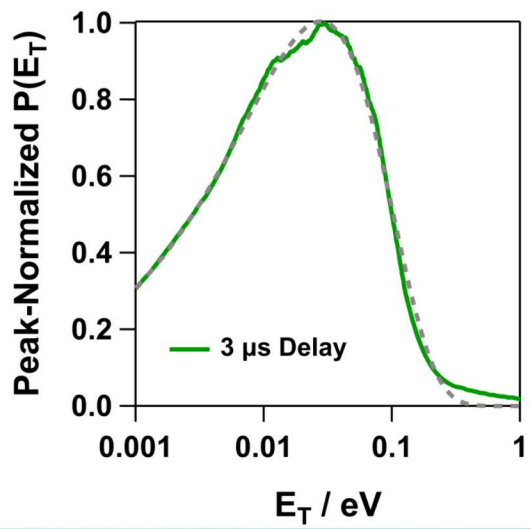
Velocity and Energy Distributions
Comparisons with Maxwell-Boltzmann Distributions

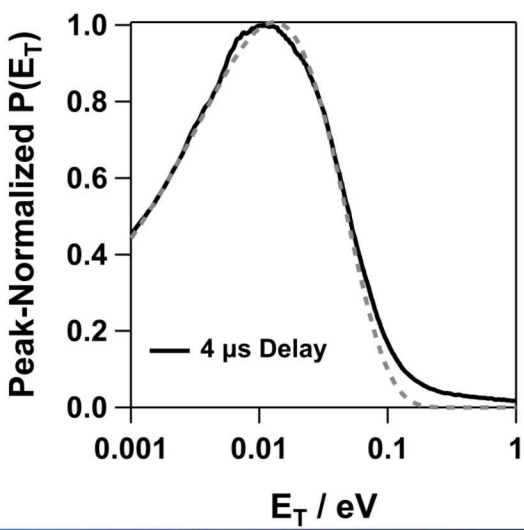












Summary

- Demonstrated EEDF measurements with velocity map imaging of REMPI—initiated plasma
- Charged particle dynamics can be studied at low pressures (10^{-6} Torr)
- Isolated in atomic beam – reduces complications of containment walls
- Charge distribution evolves in repeatable fashion starting with EEDF prescribed by laser photoionization ($E_{t0} = 3.3eV, \Delta E_{t0} < 1\ meV$)
- New platform for studying dynamics of electrons, ions, neutrals, metastables
- Study plasma chemistry by adding reactant species to atomic beam
- Constructing new multi-kHz rate VMI/REMPI system for detection of weaker processes
- Opportunities for collaborations

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