Energetic neutral and negative ion beams accelerated from spray target irradiated with ultra-short, intense laser pulses

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ELI - Extreme Light Infrastructure Science and Technology with Ultra-Intense Lasers

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laser-driven acceleration of ion is a burgeoning field of research

state-of-the-art laser systems allow to accelerate bunches of positive ions from the foil targets with unique properties:

- extreme laminarity: rms emittance < 0.002 π mm-mrad
- short duration source: ~ 1 ps *(ΔE Δt < 10-6 eV-s)*
- high energy - 60 MeV at present
- high brightness: ~1013 protons/ions (> 3 MeV)
- high current (if stripped of electrons): kA range

This work highlights another important property of laser-plasma interaction, namely the capability of acting as a source of **high energy and high brightness negative ion beams**

outline

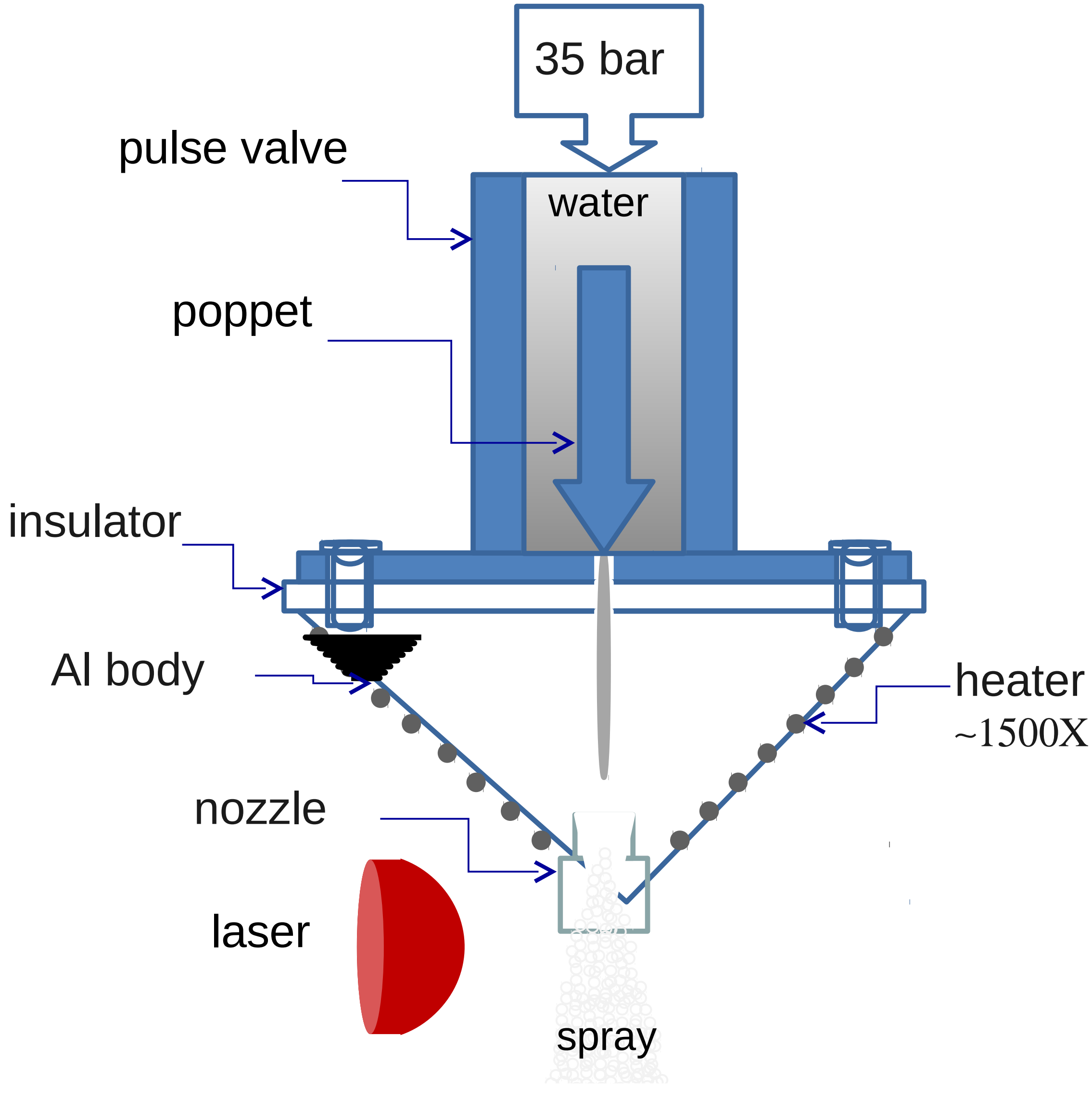
- spray target
  - charged particle acceleration from the spray: protons, heavy ions

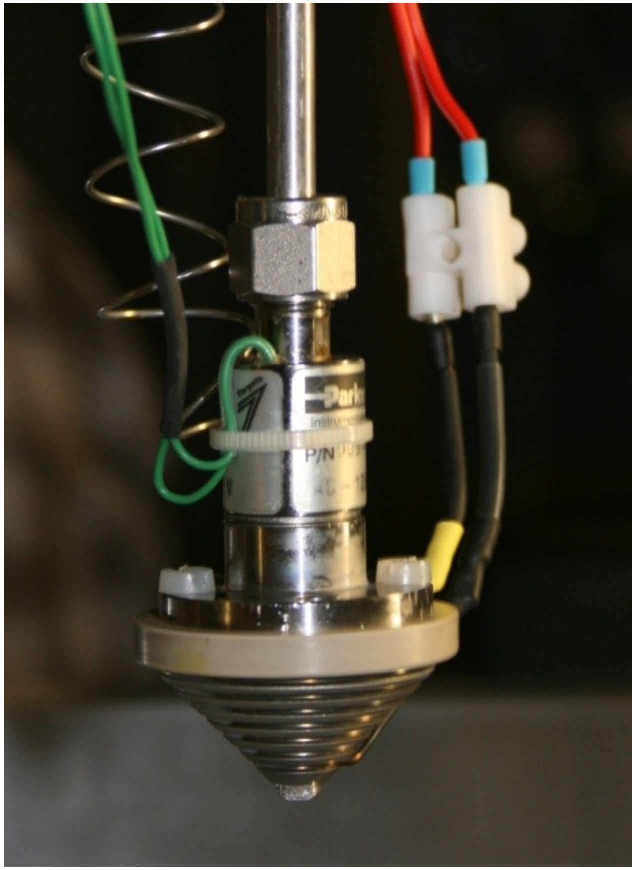
➢ main experimental evidences

- energetic negative ions
- acceleration of negative ions

- energetic neutral atoms
- heavy atoms and hydrogen

spray generator



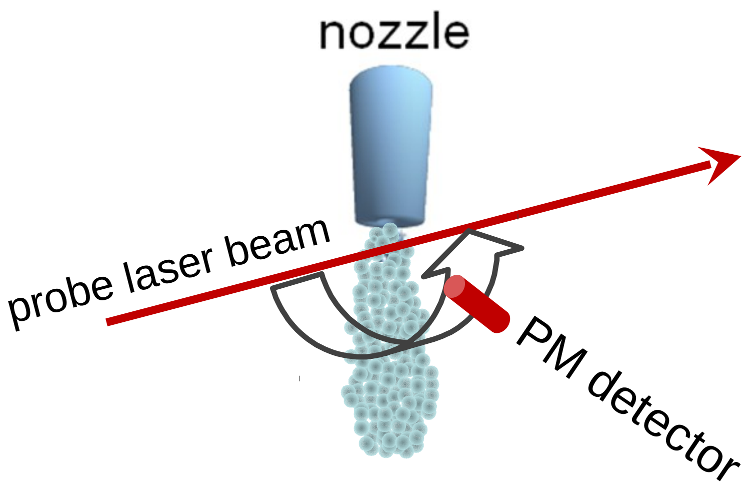


Patent; DE 102 60 376 A1 (2004) Ter-Avetisyan, Schnürer, Nickles, Device and method for the creation of droplet target

spray characterisation

The spray was characterized by employing Mie scattering and transmission measurements

measuring angular scattering pattern of the probe beam



δskin depth <ddroplet < λlaser

water (H2O)

- single droplet size 150 ± 10 nm
- droplet density 1011 cm-3
- average spray density 1018 cm-3

ethanol (C2H5OH)

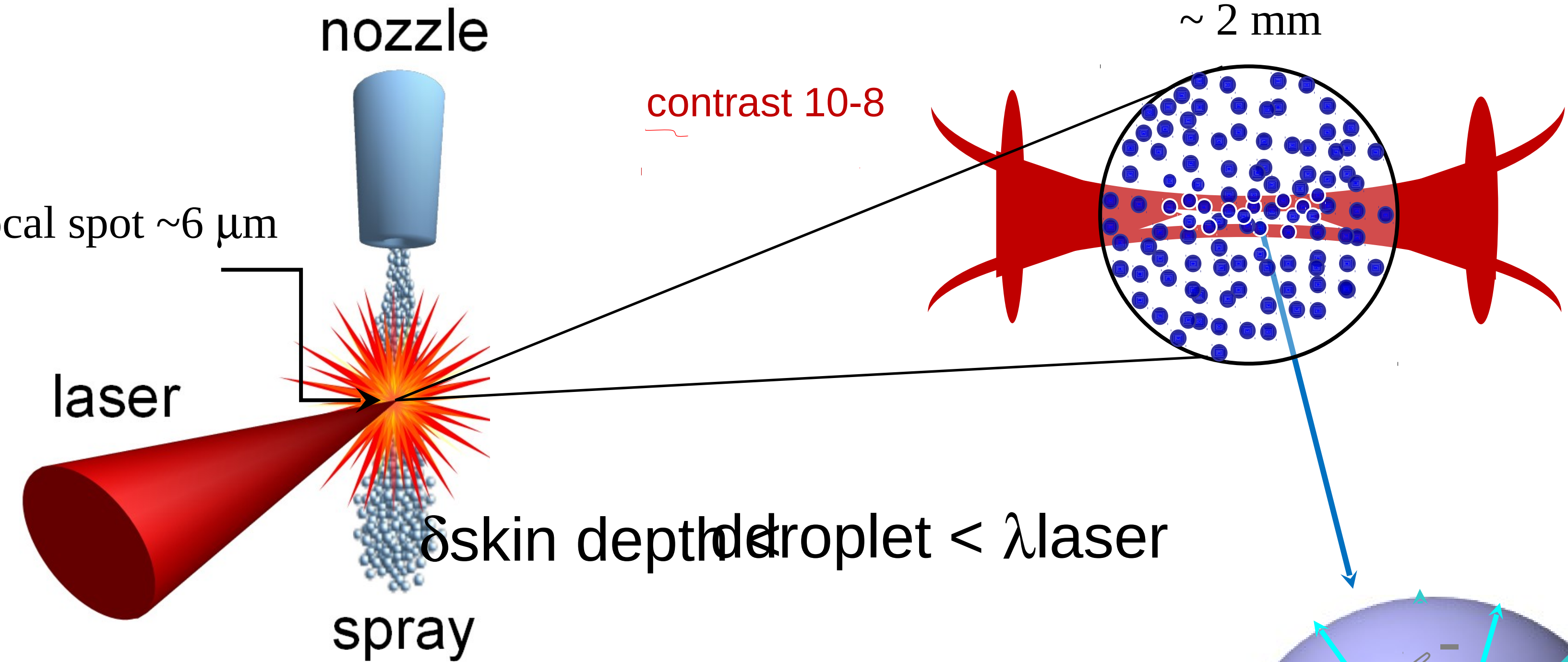
- single droplet size 180 ± 10 nm
- droplet density 5×1011 cm-3
- average spray density ~1019 χμ–3

S. Ter-Avetisyan et.al., J. Phys. D: 36, 2421 (2003), R. Prasad et al., RSI ,

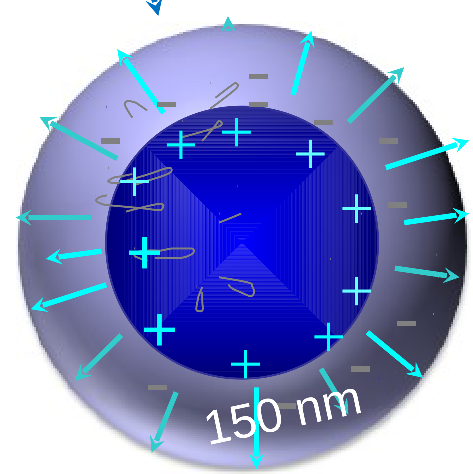
ion acceleration from the droplets

5×1019 W/cm2

contrast 10-8



$\delta_{skin\ depth} < d_{droplet} < \lambda_{laser}$

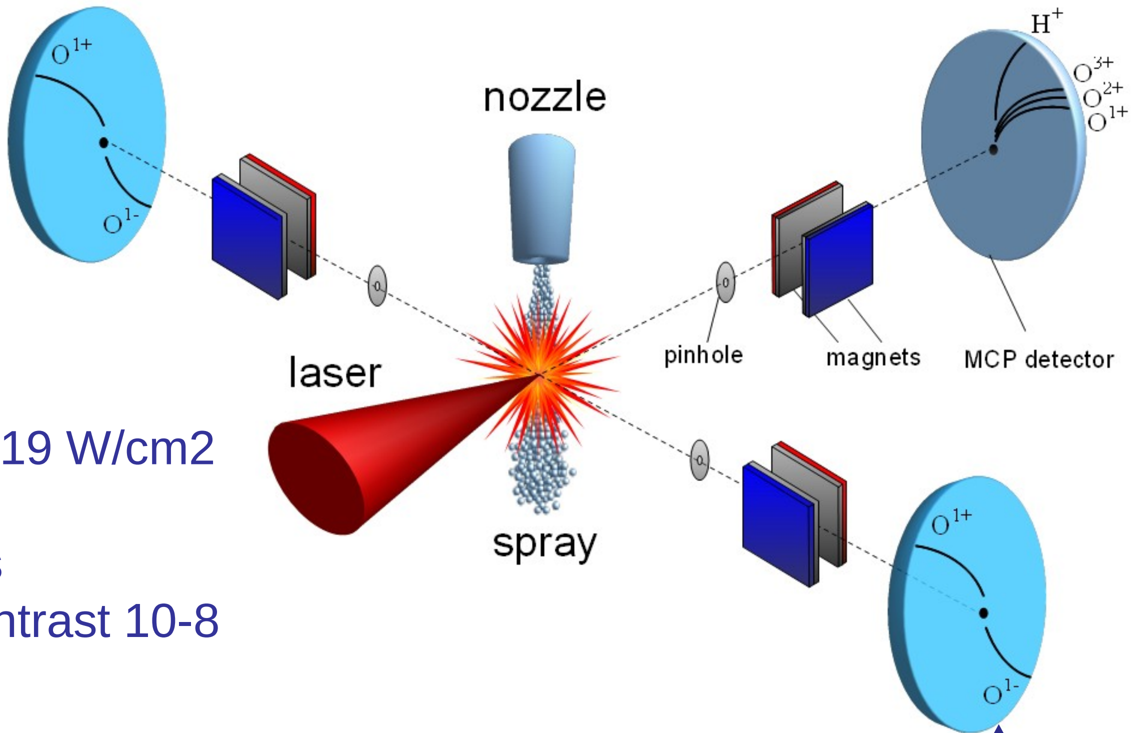


- by pre-evaporation of the droplets, its diameter is reduced
- outer shell (~10 – 15 nm) is ionized to high degree
- cold core remains
- “iso-Coulomb-potential” accelerates ions to high energies

Ter-Avetisyan, et al., Phys.Plasmas (2012), R,amakrishna et al., Phys.Plasmas 17 083113 (2010) , Ter-Avetisyan, et al., Phys.Plasmas 16 043101 (2009)

set-up to measure ion yield from the spray

for calibration and quantitative analyses



I ~ 5×1019 W/cm2

τ ~ 40 fs

laser contrast 10-8

for calibration of detector response MCP was substituted with CR39

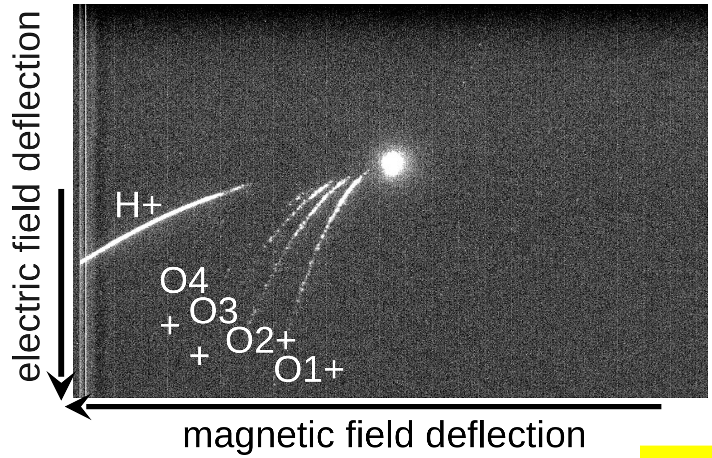
Ion yield was characterised

- 

- changing the delay between laser and spray pulse

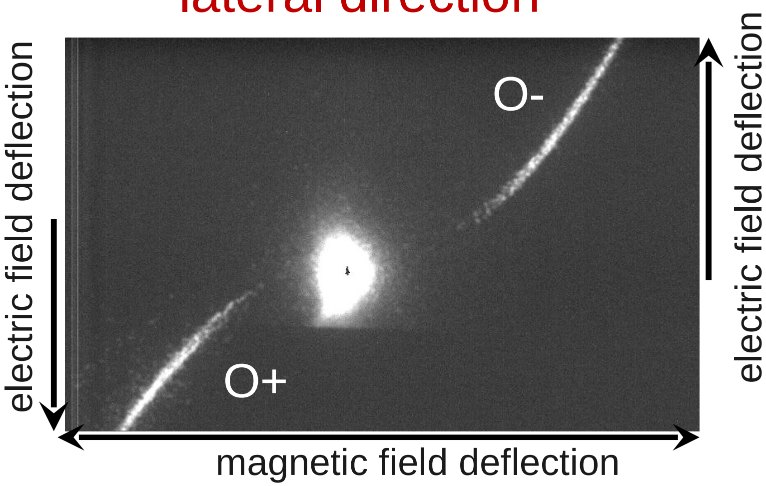
negative ion acceleration in water spray

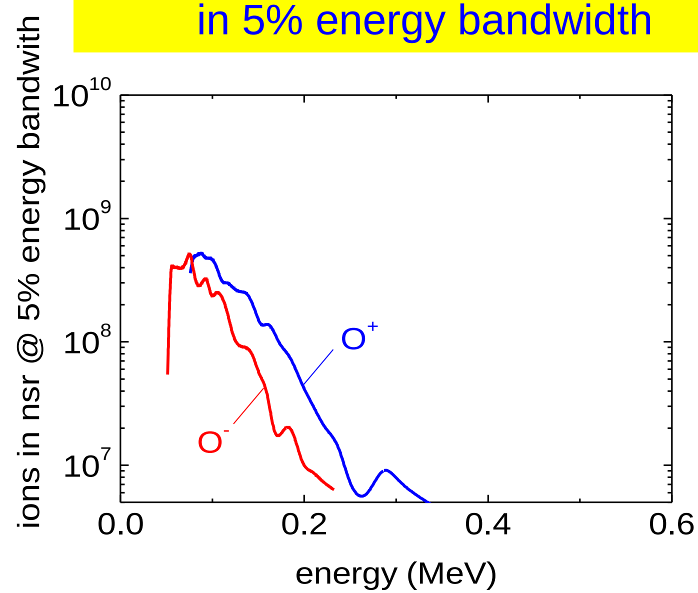
laser propagation direction



~109 negative ions per steradian
in 5% energy bandwidth

lateral direction





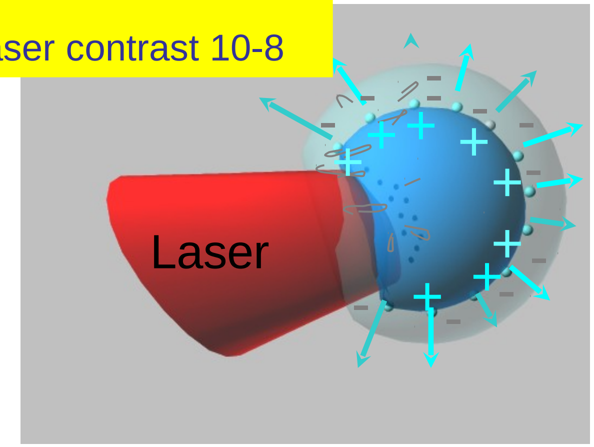
S. Ter-Avetisyan et al., Appl. Phys. Lett. ***99****, 051501 (2011)*

negative ion emission from single droplet

I ~ 5×1019 W/cm2

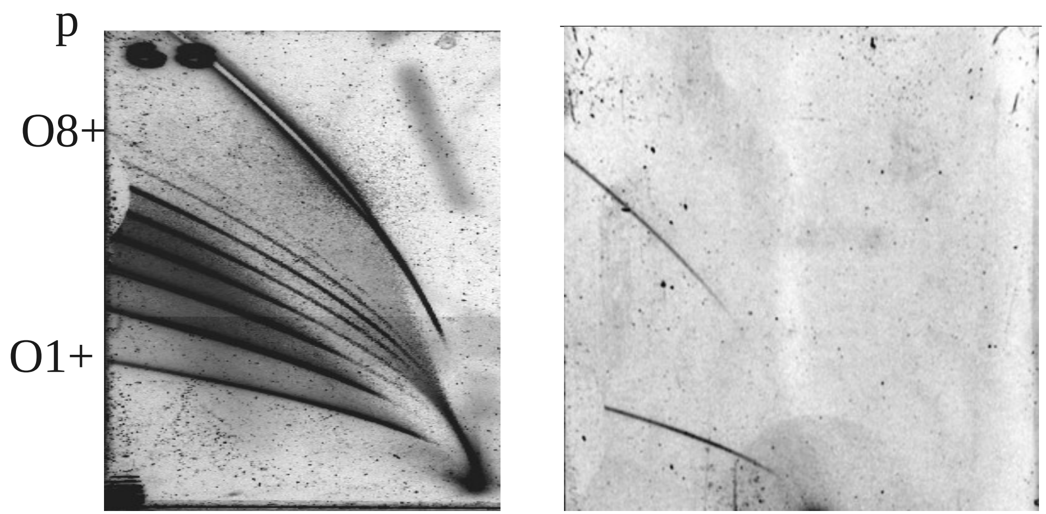
pulse duration 40 fs

laser contrast 10-8

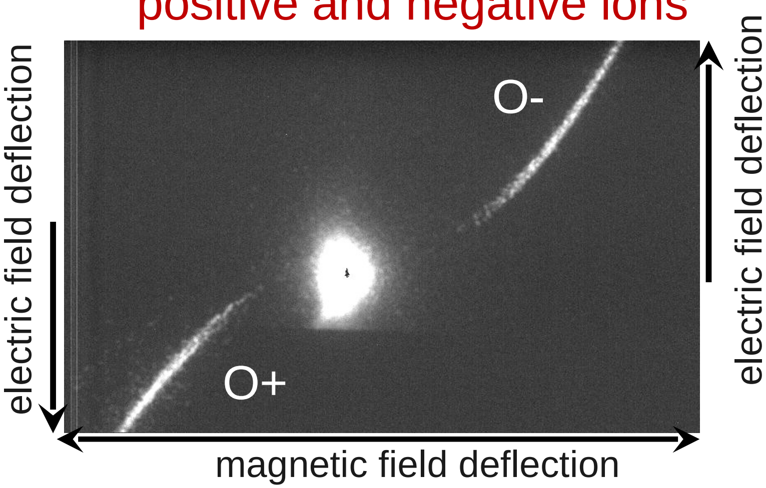


droplet size 20 µm

Ion spectra from H2O and D2O exploded droples



positive and negative ions



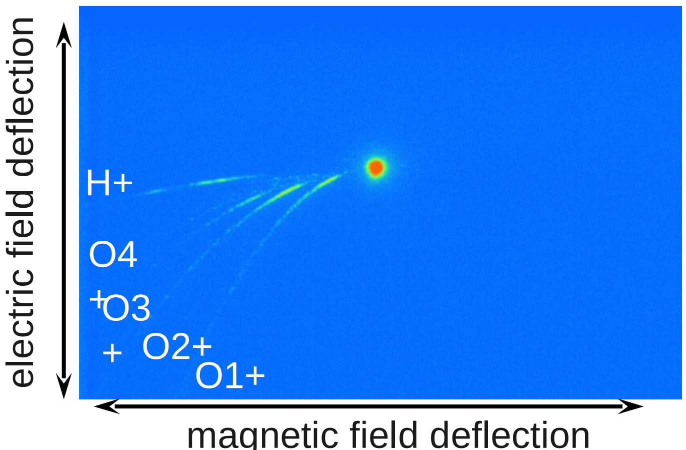
up to 104 shot accumulation

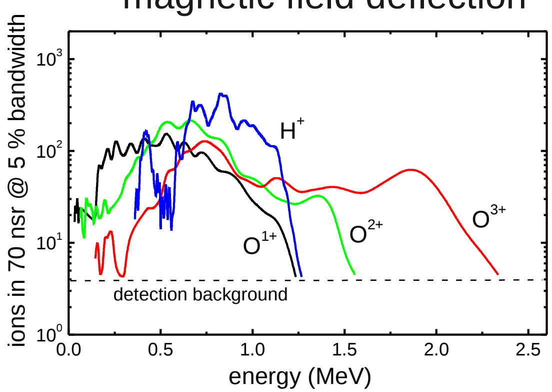
S. Ter-Avetisyan et.al., J. Phys. B: 37, 3633 (2004),

asymmetry of negative ions emission

laser pulse is at the rising edge of the spray density

laser propagation direction

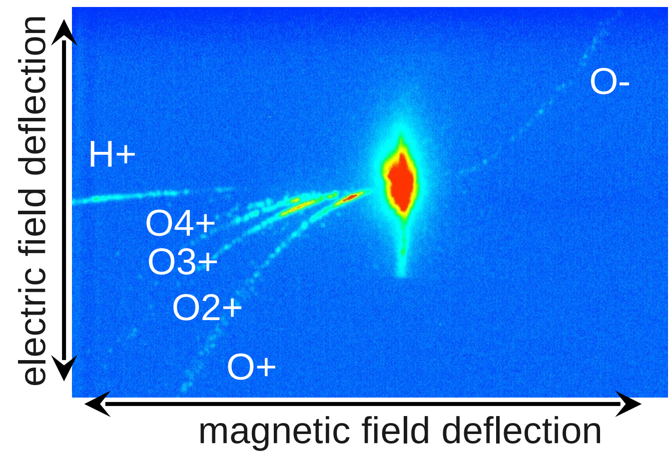


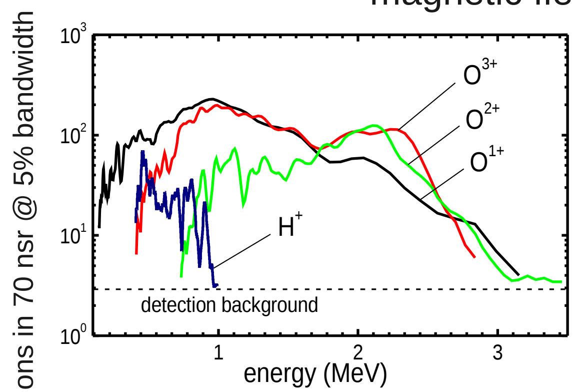


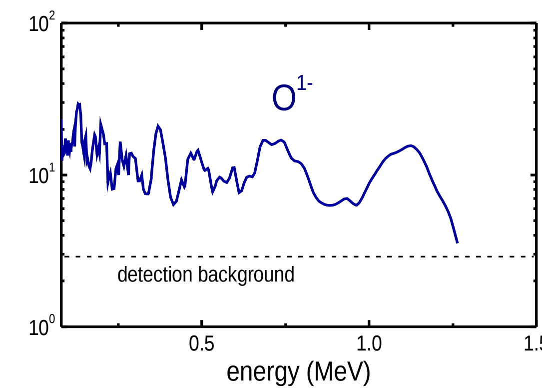
Ion max. energy increase with charge state

O+ ~ 1.25 MeV

lateral direction







all ions have similar (~ 3 MeV) max. energy

O- ~ 1.25 MeV

S. Ter-Avetisyan et al., A.P.L. **99**, 051501 (2011)

no negative hydrogen has been observed from water spray

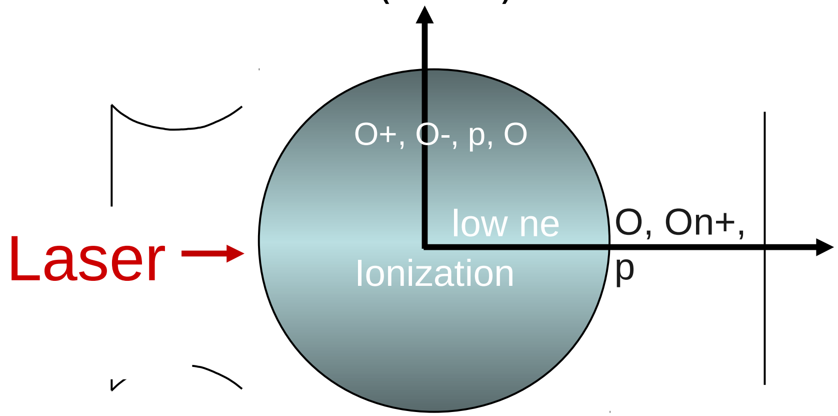
negative ion formation in charge-exchange

- spray density distribution is modified by the laser pulse

  in forward direction a low density channel is created by ionizing and heating the medium

- the propagation of ion through the cold spray medium is collisional

  for oxygen atoms L ~50 μm, for protons mean free path length: L >> dspray (~mm)



$$On+ \leftrightarrow O(n-1)+$$

- charge-exchange in a spray can explain the formation of negative ions:

  resonant process: probability is max. if vion ~ vbound el. (1MeV O1+ = 3.4×106 m/s)

$(O \rightarrow O^-)$σ0-1 ~ 1×10-16 cm2 (for 0.1–1 MeV), angular diagram is narrow (~ 1°)

electron capture and loss in the spray

competitive processes are:

electron capture A+ $\rightarrow$ A0 $\rightarrow$ A-

two electron capture A+ $\rightarrow$ A- $\rightarrow$ A0

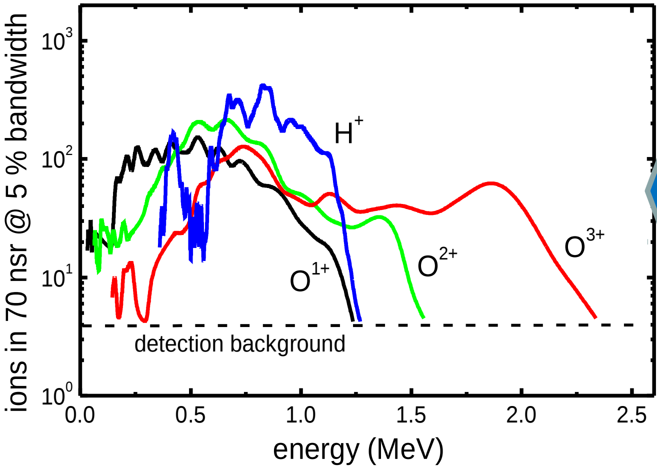
electron capture and loss A+ $\rightarrow$ A0 $\rightarrow$ A- $\rightarrow$ A0

- elastic-collisions cross-section is ×100 smaller than the charge-exchange cross-section

- inelastic-collision cross-section ~10-18 cm2:

  at spray densities ~1018 cm-3, the probability of scattering events is < 10% over the spray length of ~ 1 mm

negative ion formation in charge-exchange

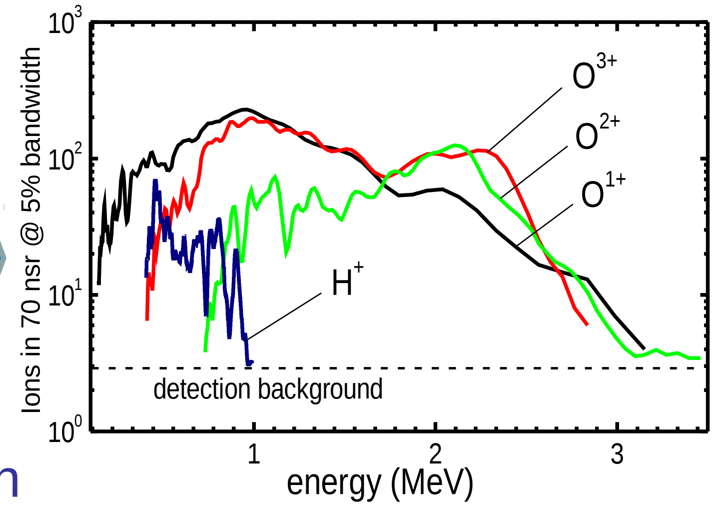


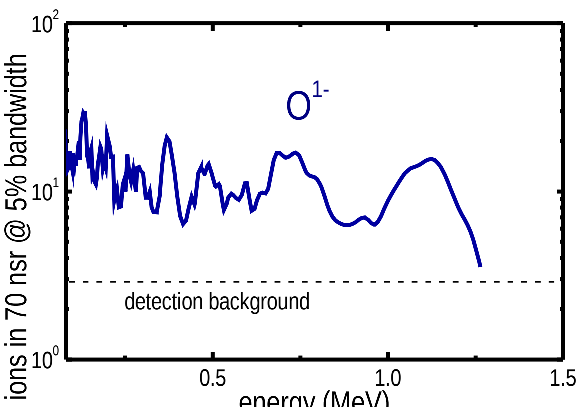
laser propagation direction

Probability of collisions is reduced:
ions spectrum defined by the acceleration process

lateral direction

Propagation is highly collisional: n0σℓ >> 1
charge-exchange is efficient; all ions have same energy





negative ion formation

The charge-exchange proceeding elastically, without energy exchange therefore the energy distributions *of the positive and negative ions should be the same:* O-, O+ ~ 1.25 MeV

B = 1.7×108 A cm-2 sr-1

This is the brightest negative ion source observed so far

ethanol spray

Ethanol (C2H5OH)

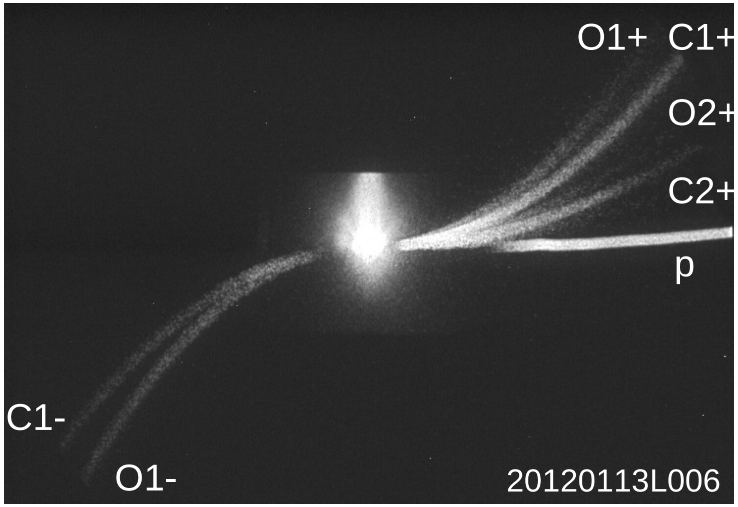
- single droplet size 180 ± 10 nm (water 150 ± 10 nm)
- droplet density 5×1011 cm-3 (water ~ 1011 γμ–3)
- average spray density ~1019 χμ–3 (ωατερ ~1018 χμ–3)

❖ is it possible to accelerate negative ions other than oxygen ?

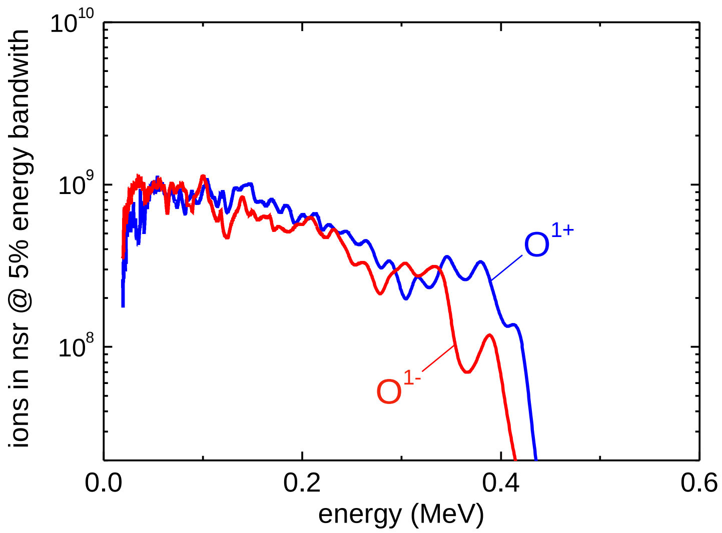
❖ what could be an effect of bigger droplets and/or high density ?

negative ion acceleration in ethanol spray

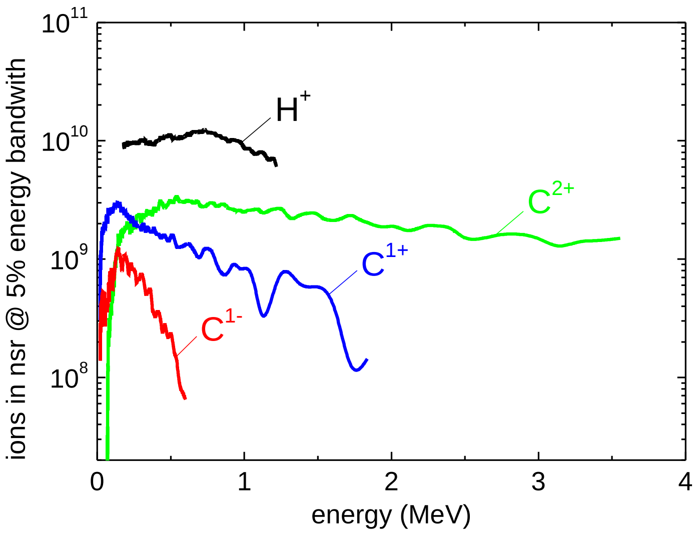
lateral direction



oxygen ion spectra

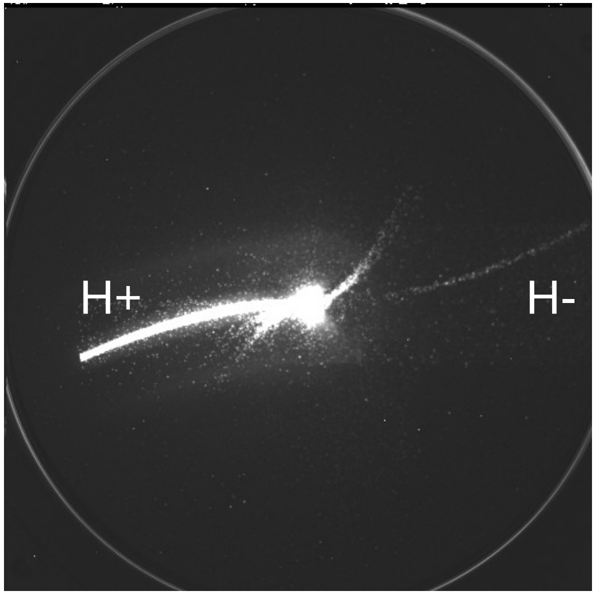


carbon and hydrogen ion spectra



negative hydrogen from ethanol spray

forward direction



lateral direction

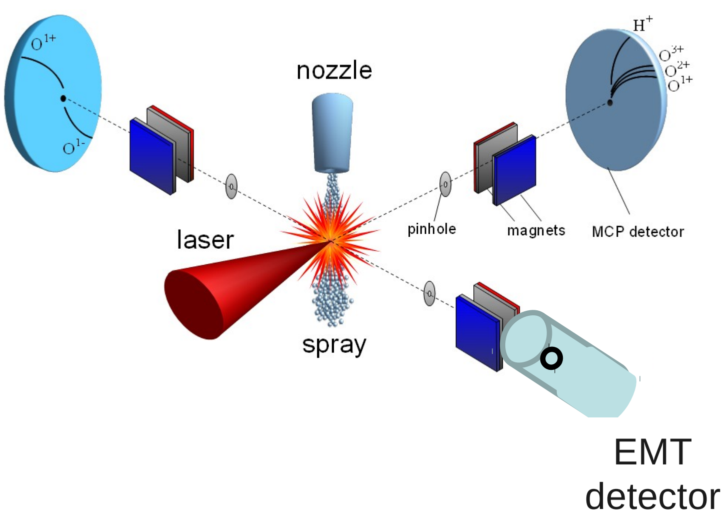
H- ~ 100 keV

we don’t see H- from water spray because it is not thick enough for the charge-exchange of hydrogen.

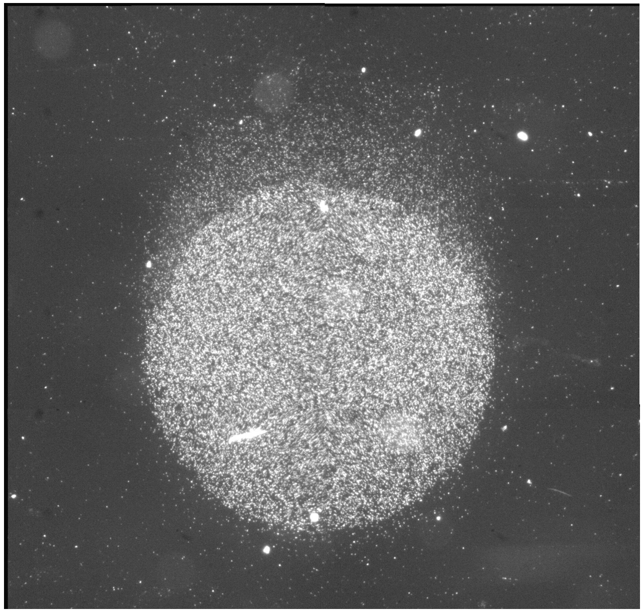
implication of the model

Our model implies the existence of a large number of fast neutrals with high energies

- Neutral oxygen and protons through 1mm pinhole, accelerated from water spray

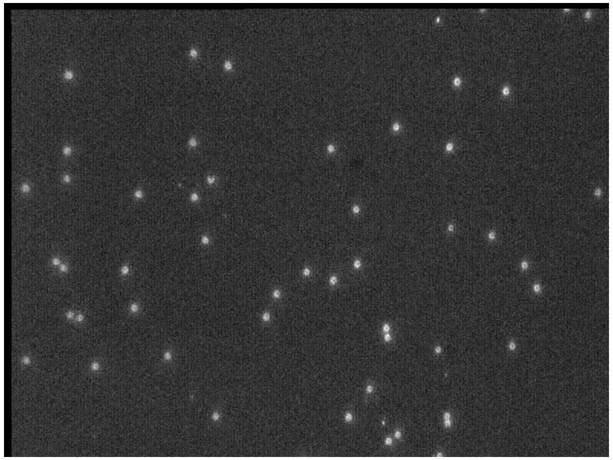


CR39 picture of the "zero" point

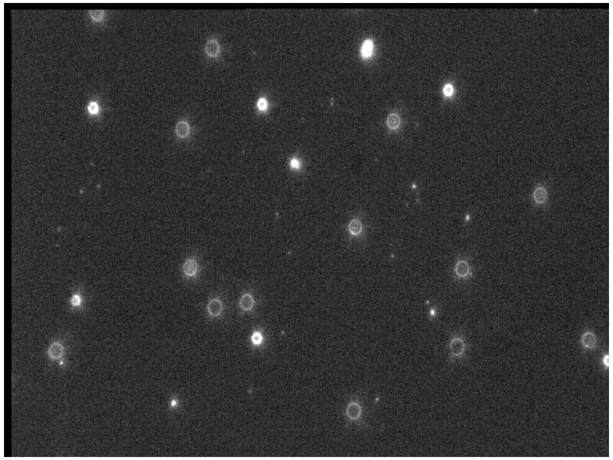


pits on CR39 crated by ion impact

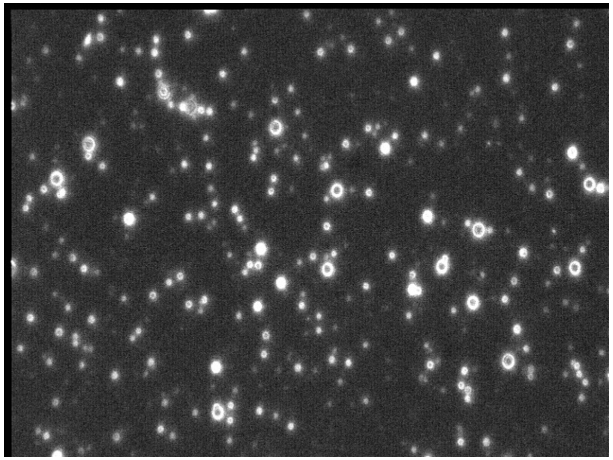
hydrogen pits



oxygen pits



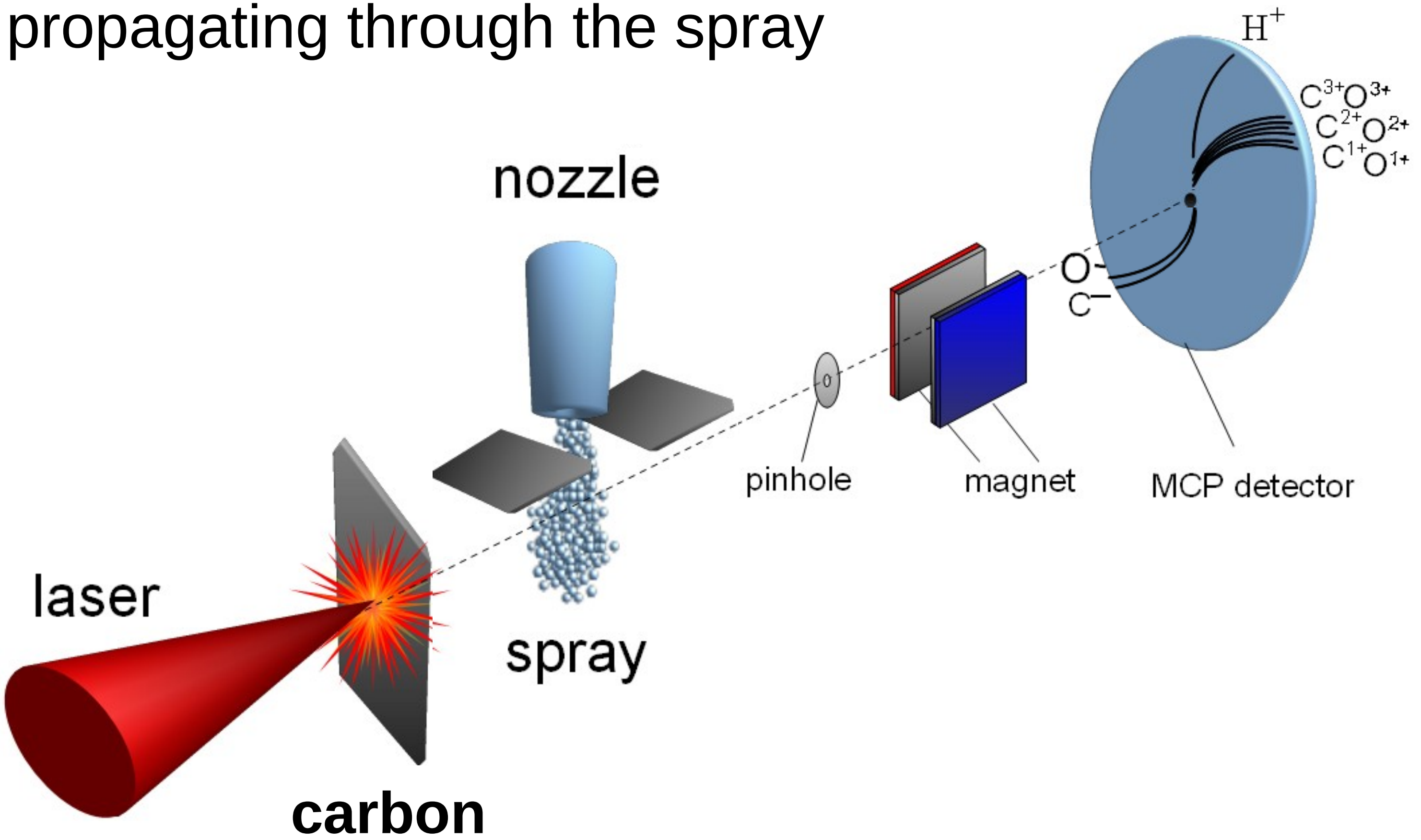
hydrogen and oxygen pits on zero point



- Number of positive and negative ions and neutrals are similar

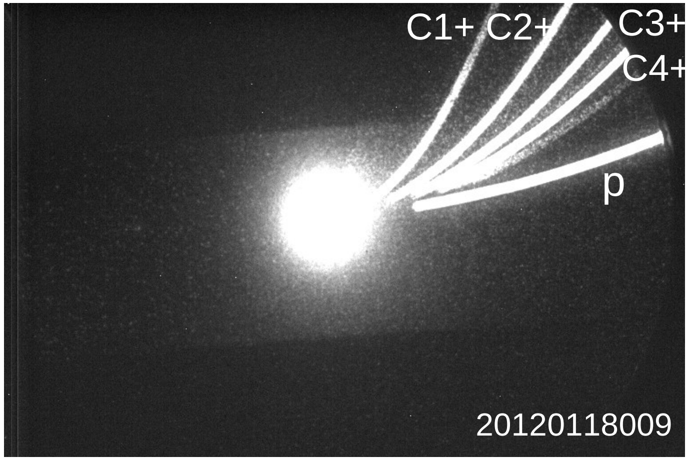
spray as secondary target

Ions accelerated from foil target
are propagating through the spray

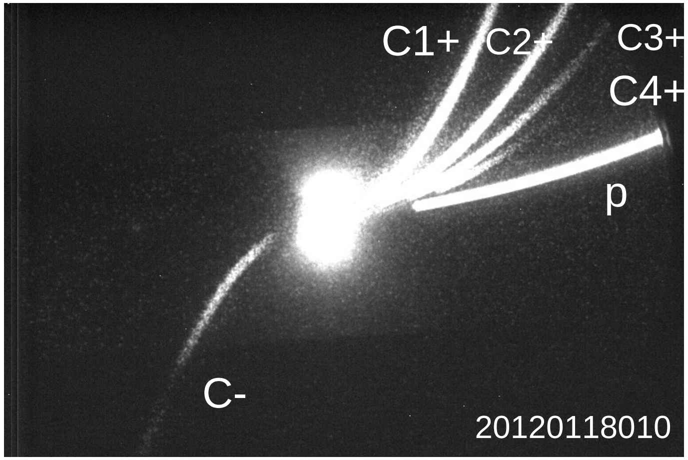


spray as secondary target

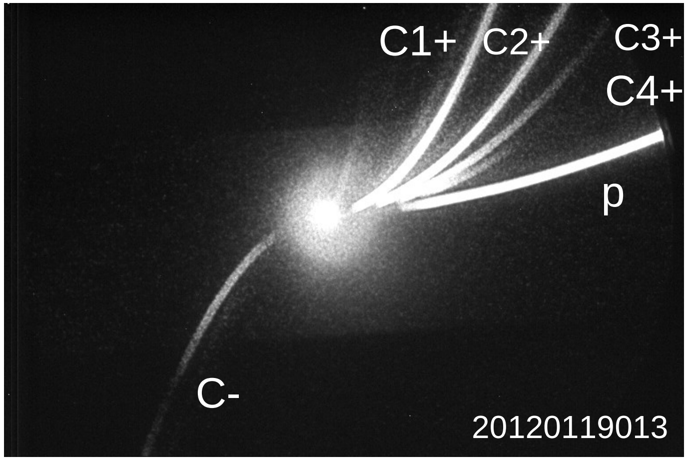
ion spectra accelerated from Ti target



through ethanol spray

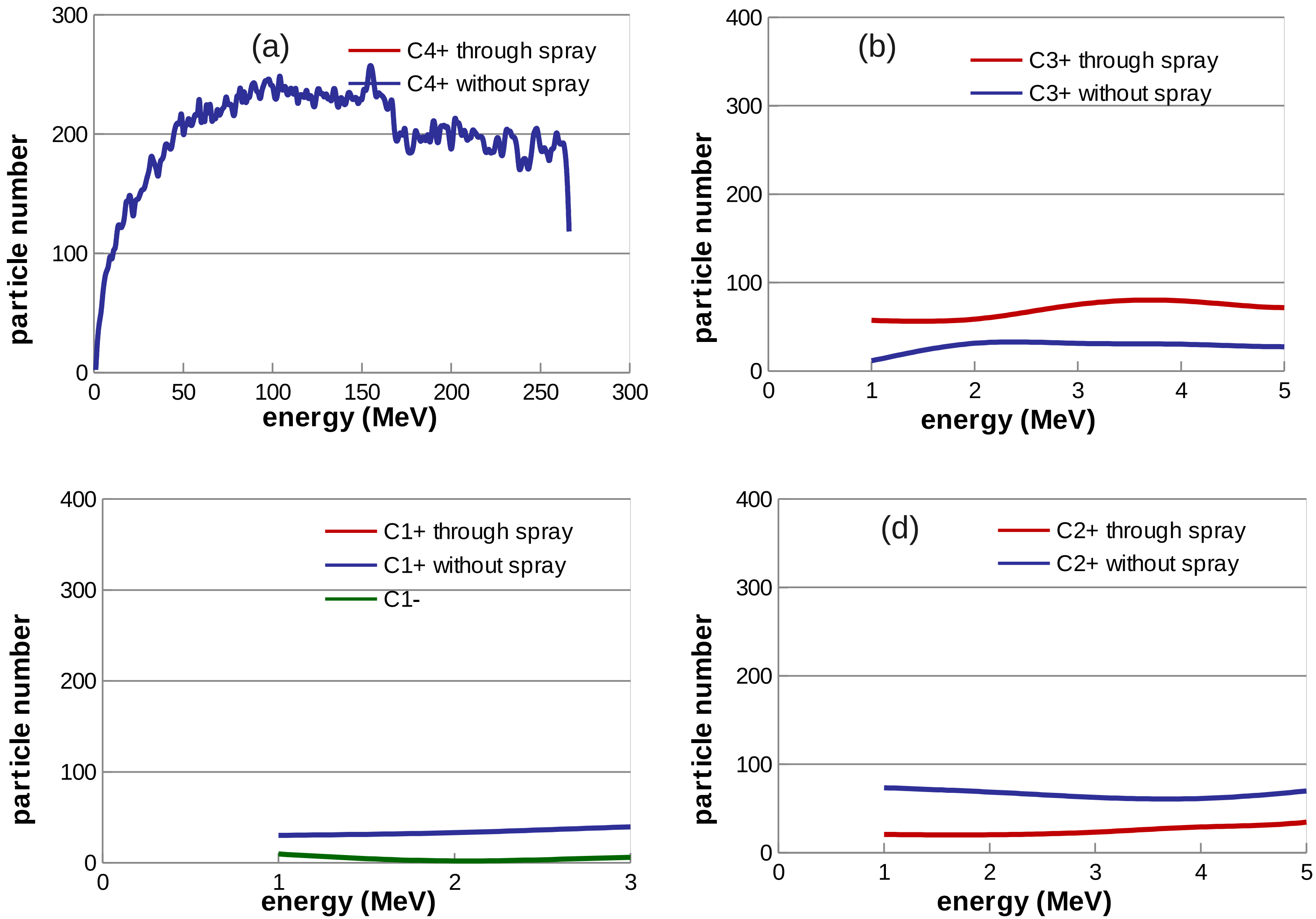


through water spray



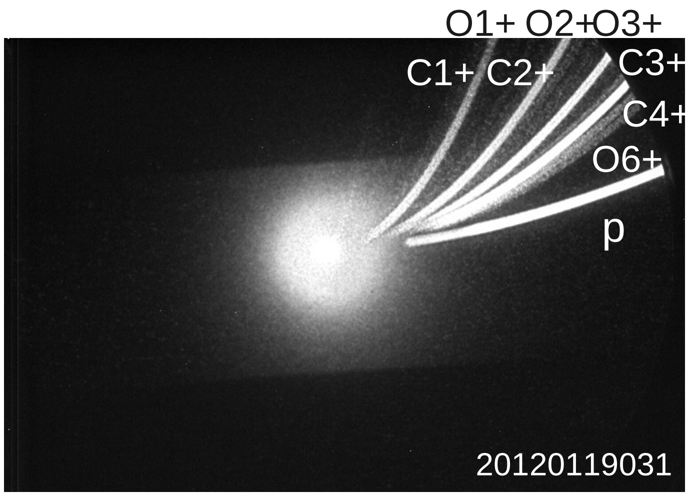
spray as secondary target

spectra of Ti ions propagating through the water spray or without spray

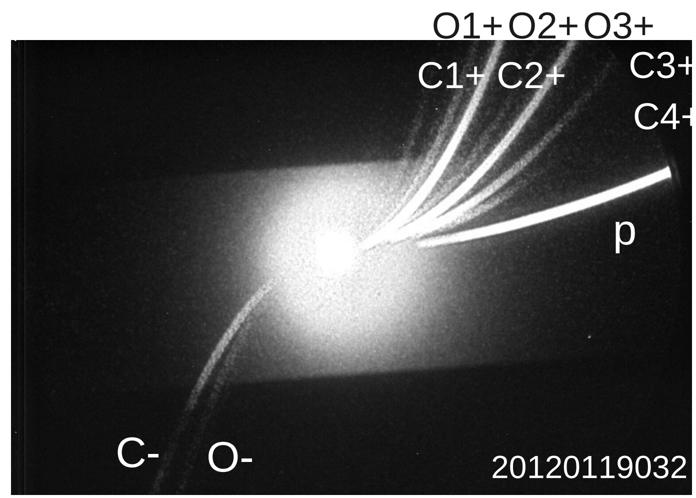


spray as secondary target

ion spectra accelerated from carbon target



accelerated ions through water spray



summary

- negative ions are generated in electron-capture and –loss processes when high-energy positive ion interacts with atoms in the spray:
  - these processes proceed
    - almost elastically without energy exchange and
    - angular diagram is very narrow:

ion that captures an electron propagates essentially in the same direction as before the collision and with the same energy.

- different positive ions species can be converted to negative in the spray environment and with high efficiency

- the brightness of negative ion source is extremely high, exceeding 108 A·cm-2sr-1

(mainly due to the ultrashort duration of the emission)

- method offers a sizeable jump (3 - 4 orders) in the achieved source brightness avoiding high costs and technological challenges typical for accelerator technology.

Why the negative ions are interesting?

- Recently negative ions have been proposed as an alternative to positive ions for heavy ion fusion drivers in inertial confinement fusion, because
  - electron accumulation would be prevented and,
  - if desired, the beams could be photo detached to neutrals.
- High brightness beams of heavy negative ions are required for
  - high current tandem accelerators
  - for ion beam microscopy and
  - lithography