Coldbeams : ultra-COLD gas for Bright Electron And Monochromatic ion Source

30 Sep-3 Oct 2012 Nimes (France)

Cs$^+$ ions produced out of a laser cooled atom beam

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*The present status of a research where we apply a simple photoionization scheme to an atom beam produced by using laser cooling techniques (**cold and slow**)*

Group and funding

Nicolò Porfido (PhD student)
Simone Birindelli (undergraduate student)
Silvia Bertieri (undergraduate student)

Gholamreza Shayeganrad (freshly arrived post-doc)
Andrea Fioretti (much more expert, back to Pisa)

Nicola Puccini (technician, UHV)
Enrico Andreoni (technician, electronics)

Zhang Bao Wu (past PhD visitor)
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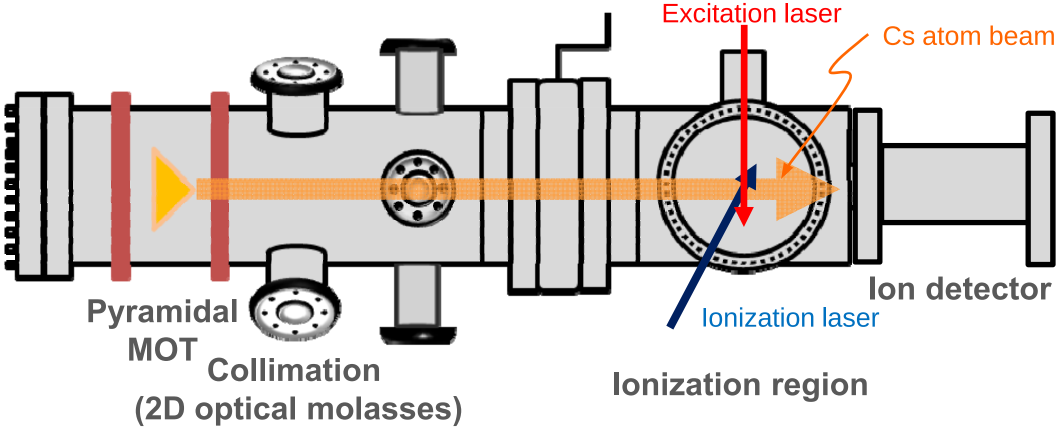
Donatella Ciampini
Maria Allegrini
Ennio Arimondo
F.F.

European Commission
PEOPLE
MARIE CURIE ACTIONS

COLDBEAMS

Basics of the approach



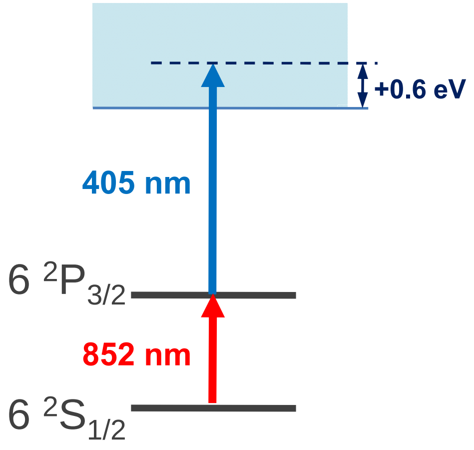
Continuous Cs atom beam:

- produced out of a **pyramidal-MOT**
- further **collimated** by a 2D transverse optical molasses

- Method originally conceived for **atom lithography**

- The beam is ***cold* and *slow***

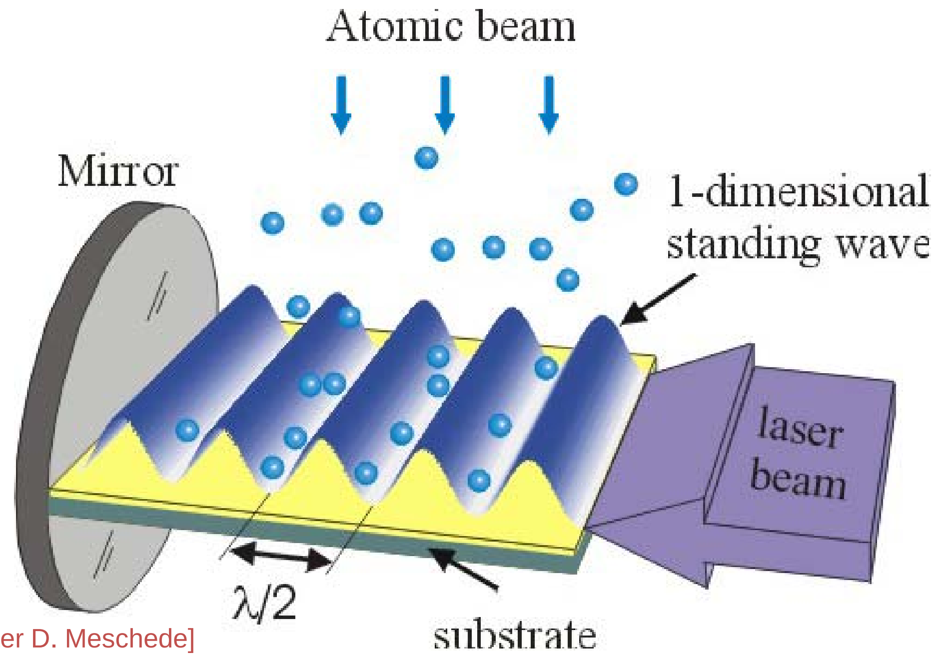
Two-photon, two-color (one resonant) photoionization scheme



Main goal:
to verify photoionization with the *most straightforward* configuration

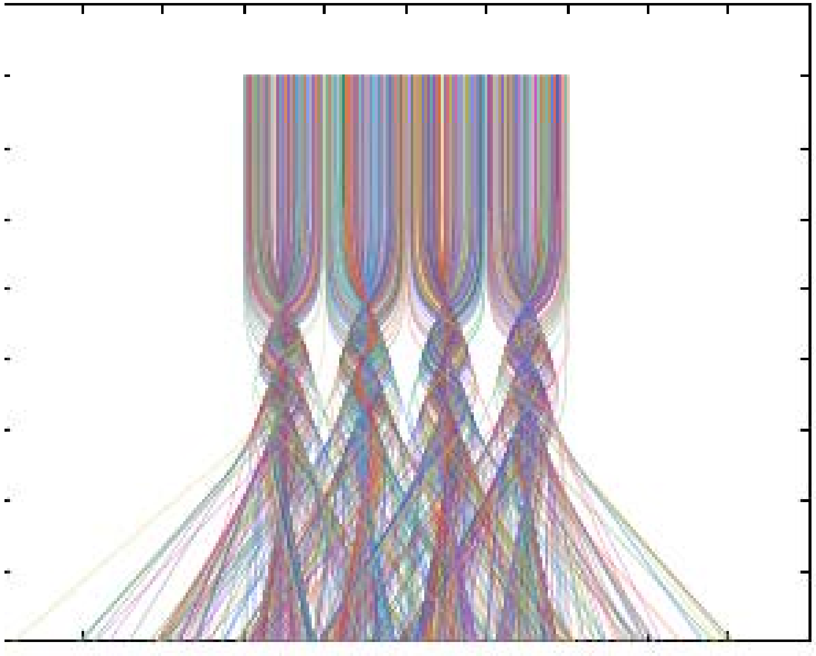
A few “hystorical” remarks

Atom lithography



[After D. Meschede]

Simulation of atom trajectories

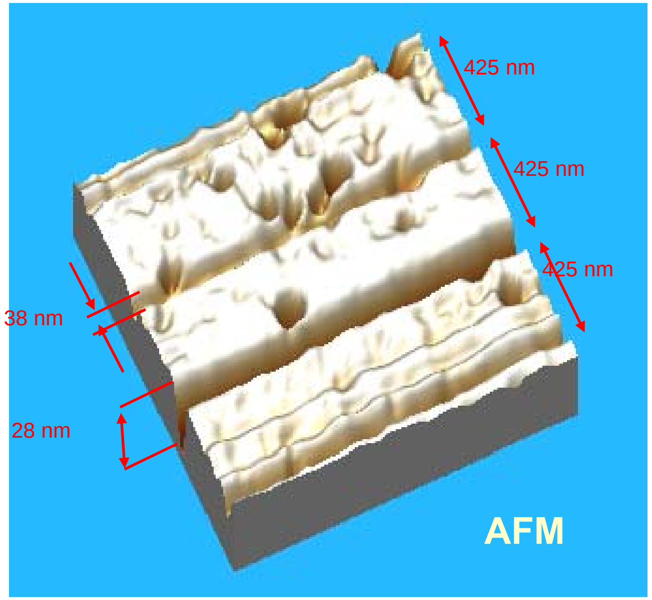


Strong collimation of the atom beam was a pre-requisite for atom lithograpaphy (*cold* beam)

Moreover, we used a *slow* beam to increase the interaction time

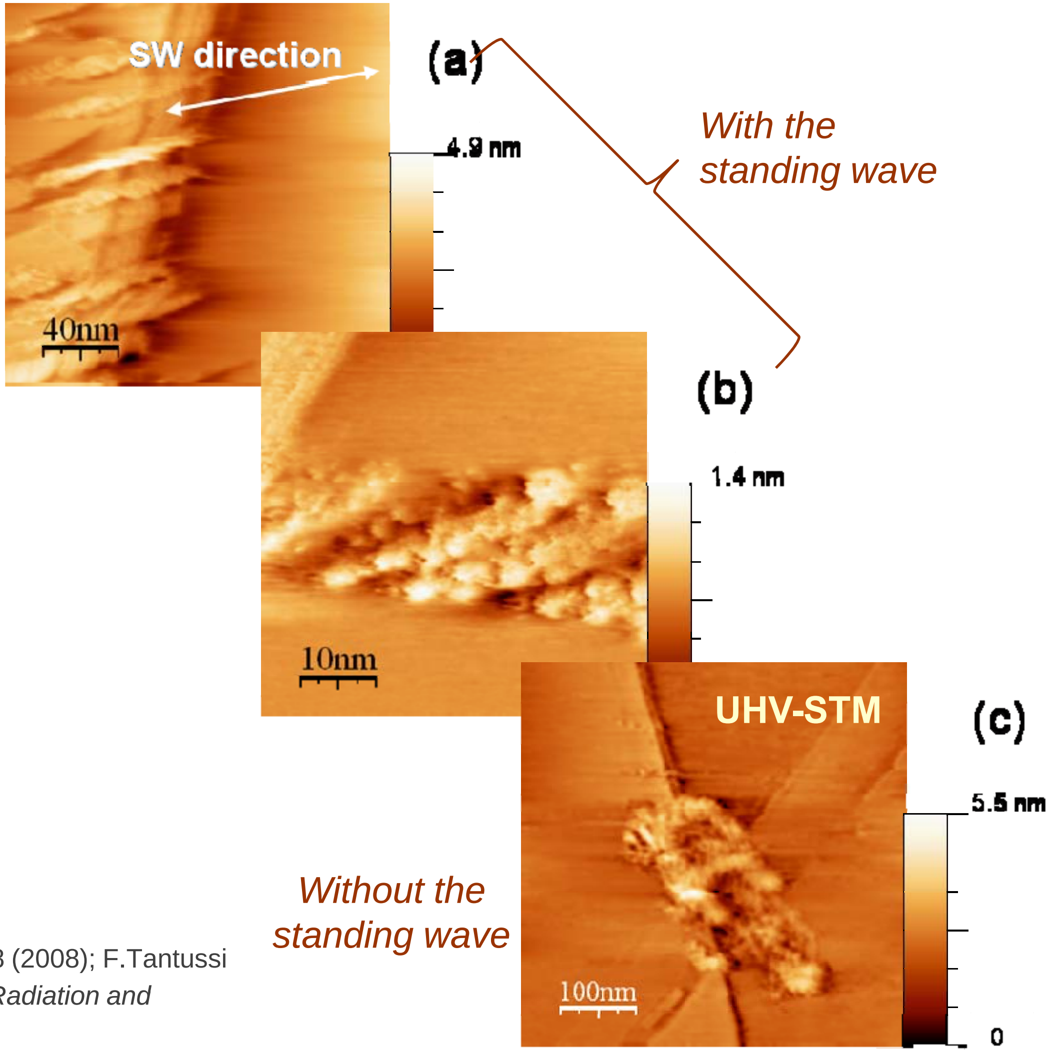
A few “hystorical” remarks

Resist-assisted
(trenches on gold)



[C. O’Dwyer, et al., *Nanotechnology* **16** 1536 (2005)]

Direct deposition
(many different morphologies found)



With the standing wave

Without the standing wave

[F. Tantussi, et al., *Mat. Sci. Eng. C* **27** 1418 (2008); F.Tantussi et al., pag.65 in *Highlights on Synchrotron Radiation and Nanostructures* (World Sci. Publ., 2009)]

A few “hystorical” remarks

Strong collimation of the atom beam was a pre-requisite for atom lithograpaphy (*cold* beam)

Moreover, we used a *slow* beam to increase the interaction time

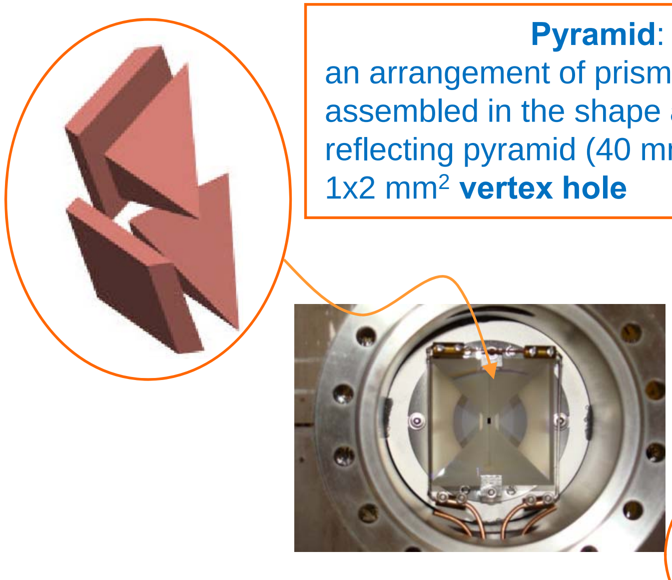
Might the specific dynamical properties of a so-conceived atom beam be useful in the frame of ion beam production?

[At the expenses of a limited particle density (limited brilliance)
→ proof of principle rather than a system able to replace conventional sources]

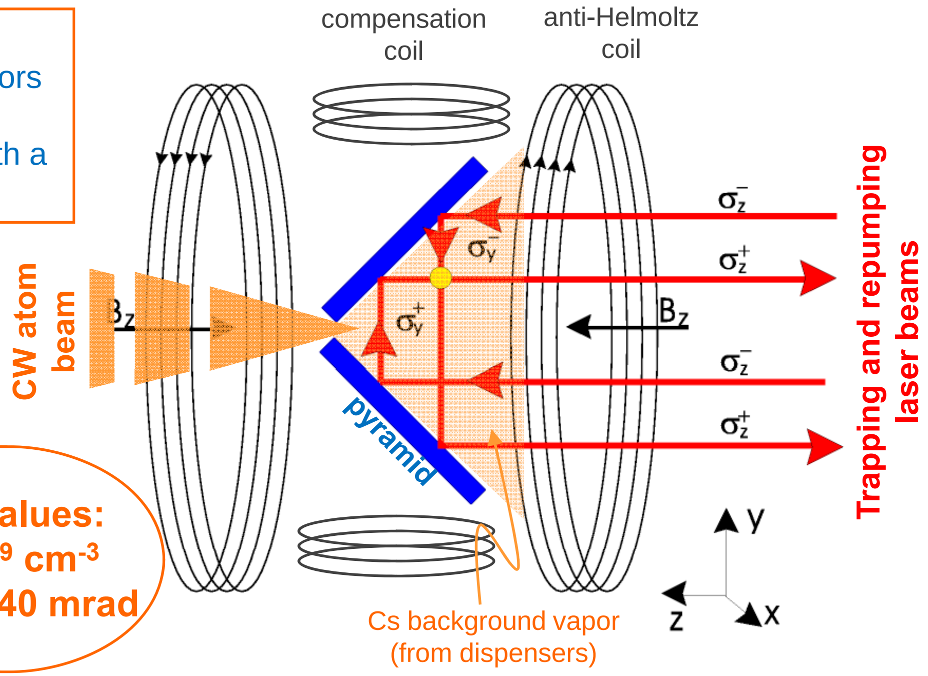
Joined with all predicted appealing features of ion beams coming from laser manipulated atoms such as:

- Small divergence and large area (negligible space charge effects);
- Relatively wide range of species ;
- Ionization and accelaration ideally decoupled
- …

Basics of the approach



Pyramid:
an arrangement of prisms and mirrors assembled in the shape a hollow reflecting pyramid (40 mm side) with a 1x2 mm^2 **vertex hole**



Typ. values:
n **~ 10^9 cm^{-3}**
div. ~ 40 mrad

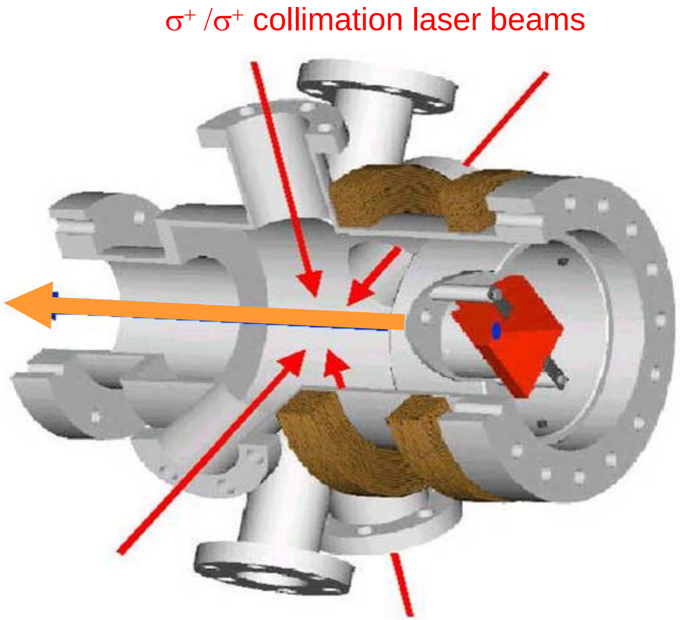
- ✓ By shining a single, large dia (35 mm) laser beam onto the pyramid, the optical configuration of a MOT is achieved
- ✓ Unbalance in radiation pressure along the pyramid axis pushes Cs atoms out of the pyramid hole

Typical operating parameters:
- Trapping radiation: $F = 4 \rightarrow F' = 5$ of the D2 Cs transition (852 nm), red detuned by ~2 Γ; I ~ 5 mW/cm^2
- Repumping radiation: $F = 3 \rightarrow F' = 4$ of the D2 Cs transition (852 nm), resonant; I ~ 0.2 mW/cm^2
- Quadrupole magnetic field gradient ~ 5-10 G/cm

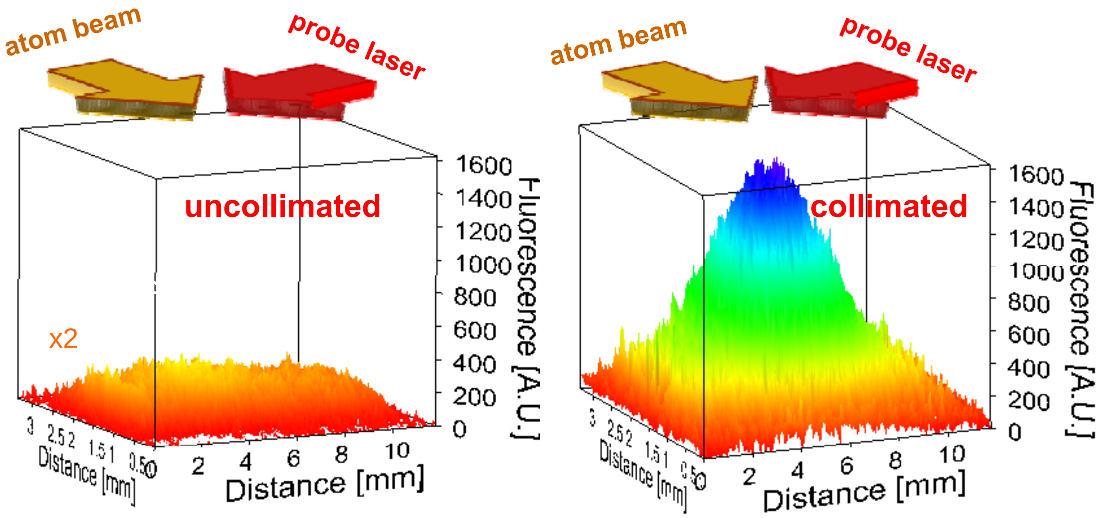
[A. Camposeo, et al., *Opt. Commun.* **200** 231 (2001);
A. Camposeo *Mat. Sci. Eng. C* **23** 1087 (2003)]

Beam collimation (*cold* beam)

2D transverse optical molasses



Fluorescence imaging ~40 cm downward the pyramid



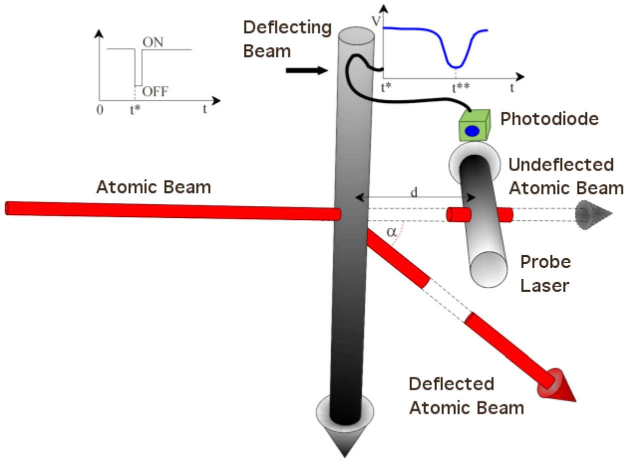
Geometrical divergence of the beam derived from fluorescence imaging at different distances from the pyramid hole

Typ. residual divergence ~ 7 mrad (full angle)

T_{trasv}~ 130 μK → *cold* atom beam

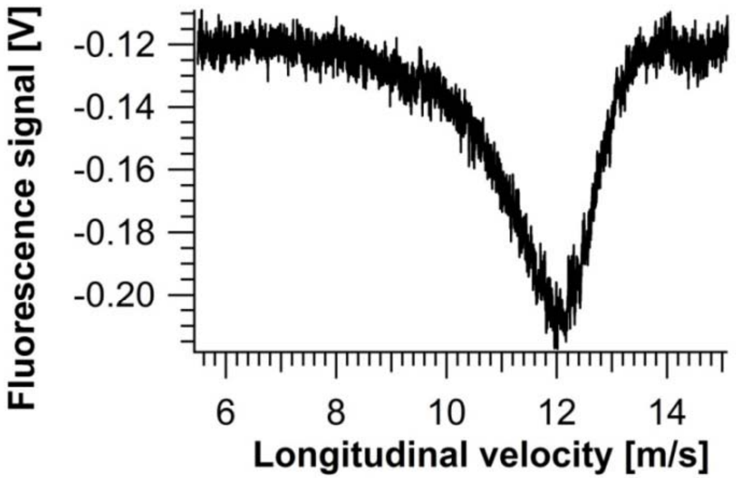
Typical collimation laser parameters:
- $F = 4 \rightarrow F' = 5$ detuned by ~4 Γ; I ~ 10 mW/cm^2
- Cigar-shaped beams (15x1 mm^2) to improve interaction time

Velocity of the *slow* beam



[A. Camposeo *Mat. Sci. Eng. C* **23** 1087 (2003)]

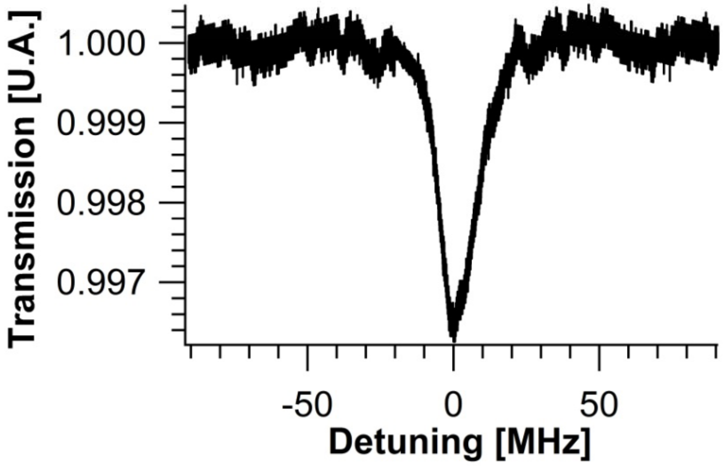
Optical time-of-flight fluorescence



Typ. longitudinal velocity ~ 12 m/s (Δ*v* ~ 1.0 m/s)

→ *slow* atom beam

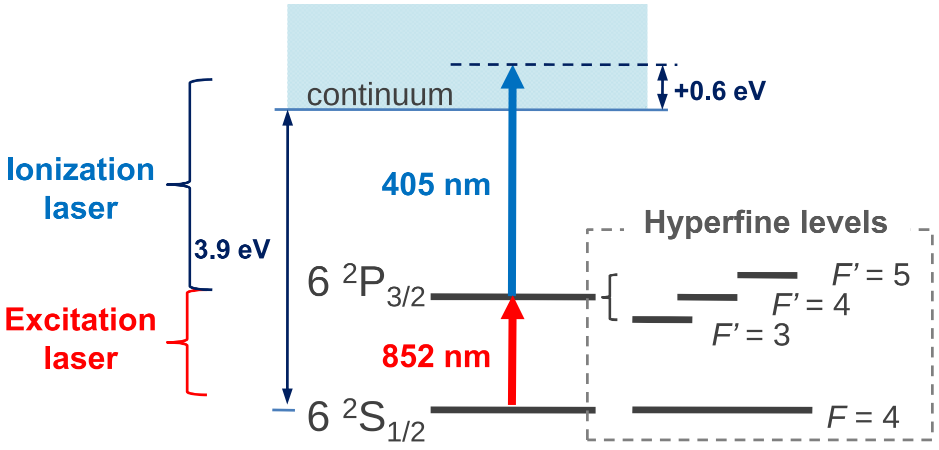
Absorption spectroscopy

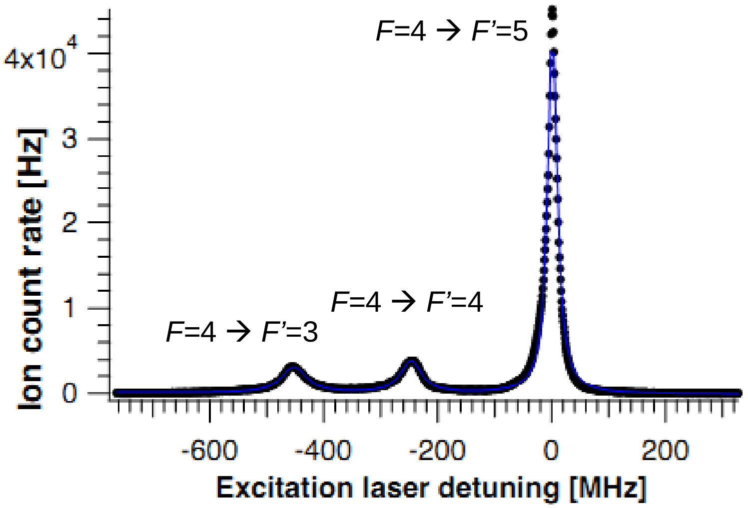


Typ. atom flux ~ 10^9 at/s
(on a ~10 mm^2 fwhm area)

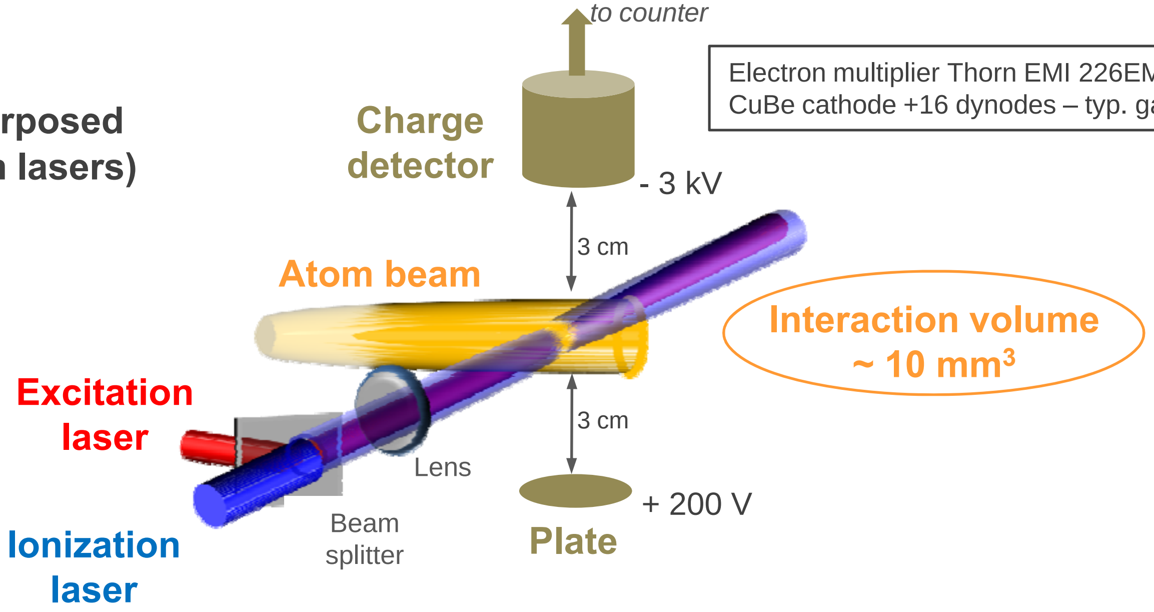
Photoionization I

Cs energy level scheme





Experimental configuration (superposed excitation + ionization lasers)

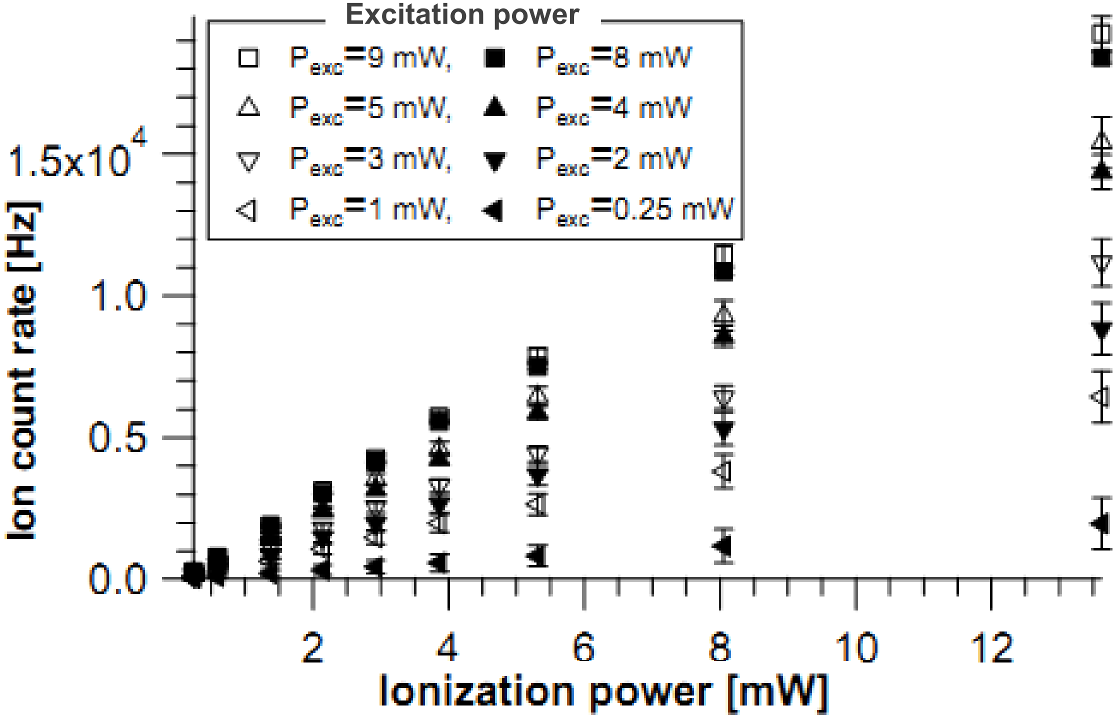


Electron multiplier Thorn EMI 226EM
CuBe cathode +16 dynodes – typ. gain 10^7

Low power (20 mW) ionization laser and weak focusing → no saturation of the ionization step

Photoionization and ionization laser power

Ion yield vs ionization power



Typical parameters:

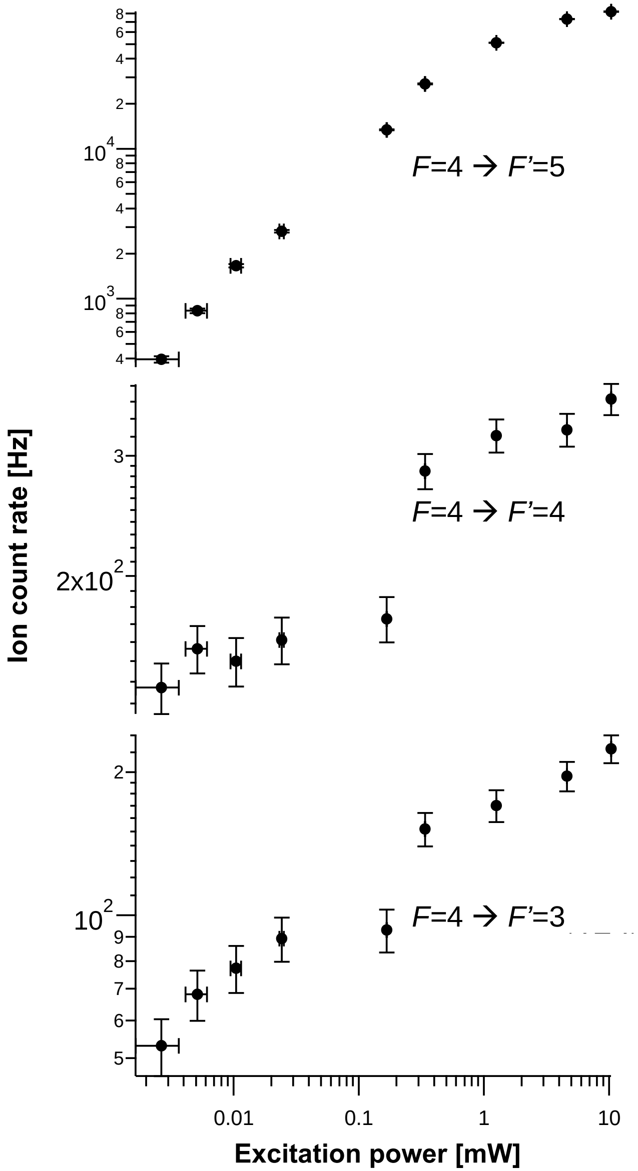
- Ionization intensity I~200 W/cm^2
- Ionization cross section σ_P=1.4x10^{-17} cm^2 (literature data)
- Charge collection and detection efficiency 1-10% (estimated)

Typ. ion current < 0.1 pA *(can easily increase by using more powerful ionization laser!)*

Linear behavior with ionization power (one photon process)

No saturation achieved in the ionization step

Photoionization and excitation laser power



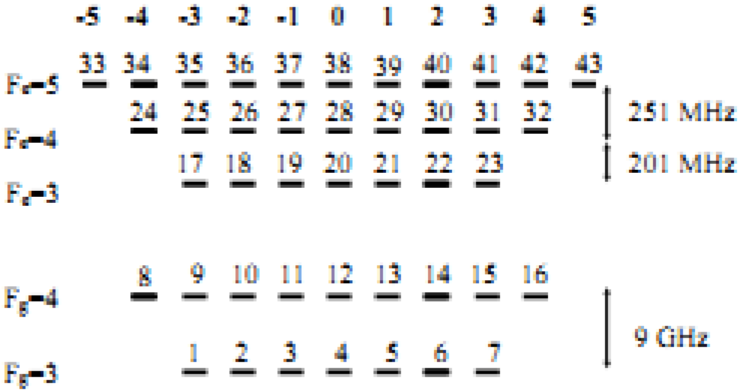
- Sublinear behavior and saturation plateaus observed when increasing the power of the excitation laser
- Remarkable differences seen for the three explored (and accessible) hyperfine transitions
- In general, data do not agree with simple predictions not accounting for the actual multi-level character of the Cs atoms

Peculiar behavior due to the *slow* character of the atom beam and the consequent relatively long interaction time in the excitation step (~ 100 μs)

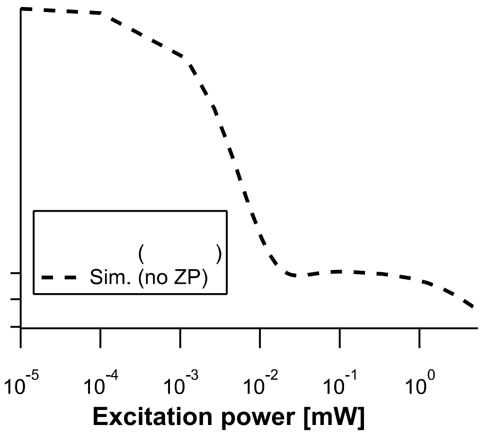
Optical pumping

- In the actual experimental conditions (large interaction time, negligible Doppler effects, small photoionization rate), the ion yield is linearly proportional to the population of the excited hyperfine state

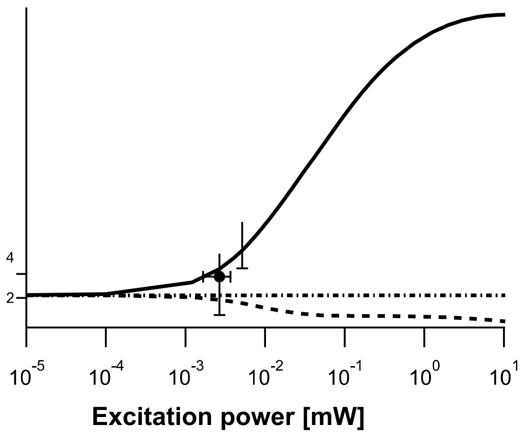
- The multi-level nature of Cs atoms makes optical pumping effects relevant in ruling population of selected Zeeman sublevels



Ratio between
***F*=4→*F'*=4 and *F*=4→*F'*=3**



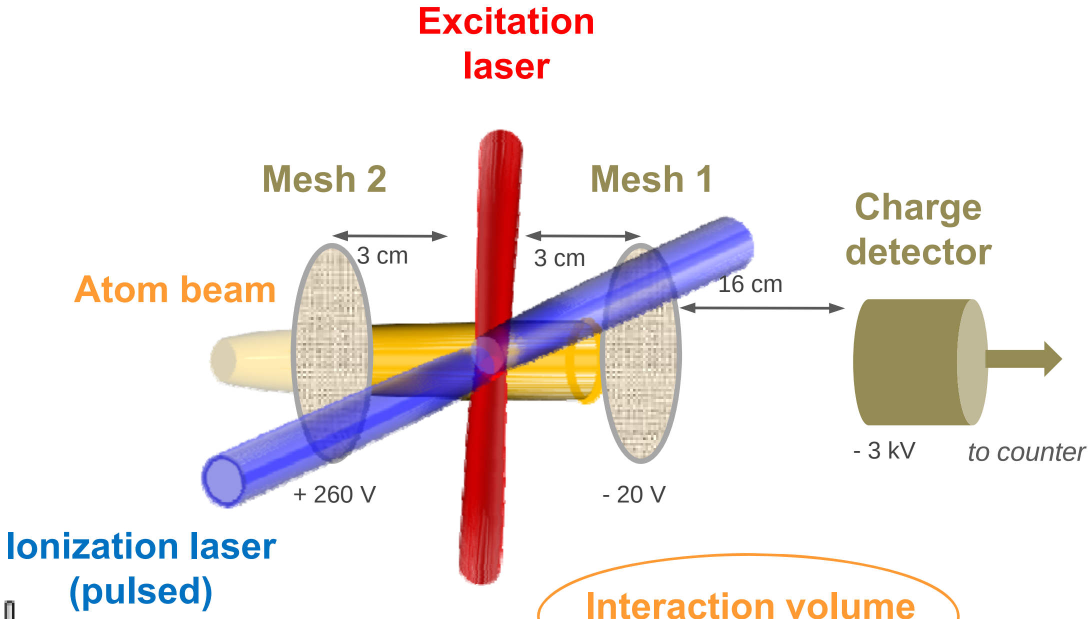
Ratio between
***F*=4→*F'*=5 and *F*=4→*F'*=4**



Numerical simulations accounting for all possible optical pumping effects lead to excellent agreement with experimental data over all the large range of power investigated

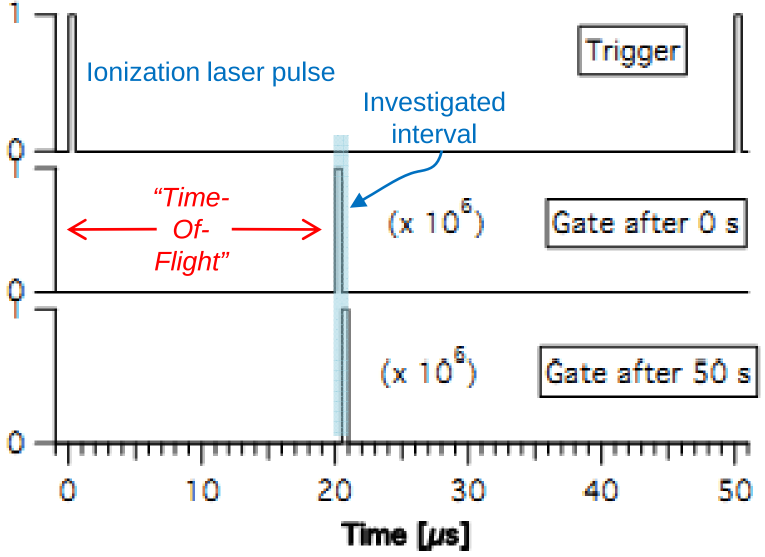
Photoionization II

Experimental configuration
(orthogonal excitation and ionization lasers)



Interaction volume ~ 1 mm^3

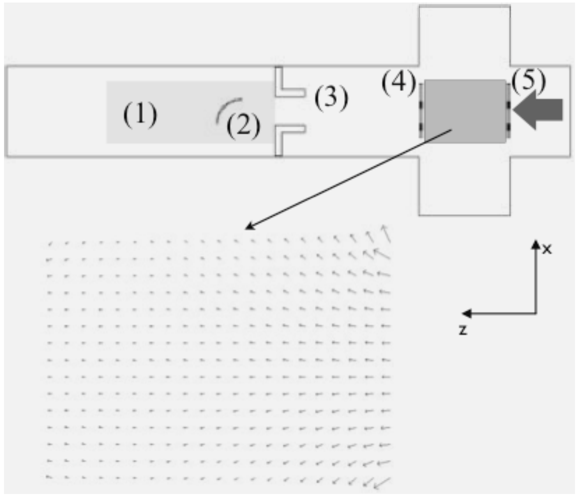
Time sequence for the gated counting meas



Main goal:
to investigate the dynamics of ion packets produced by μs ionization laser pulses through a sort of Time-Of-Flight

Collection electric field

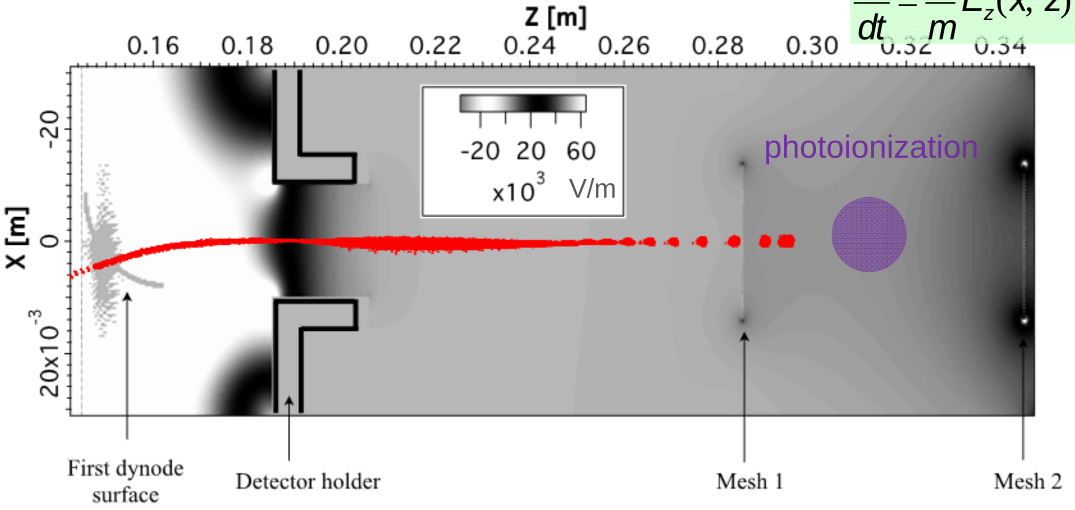
Simulated electric field (Poisson-Superfish code)



Simulated ion trajectories

$$\frac{dx}{dt} = \frac{q}{m} E_x(x, z)$$

$$\frac{dz}{dt} = \frac{q}{m} E_z(x, z)$$



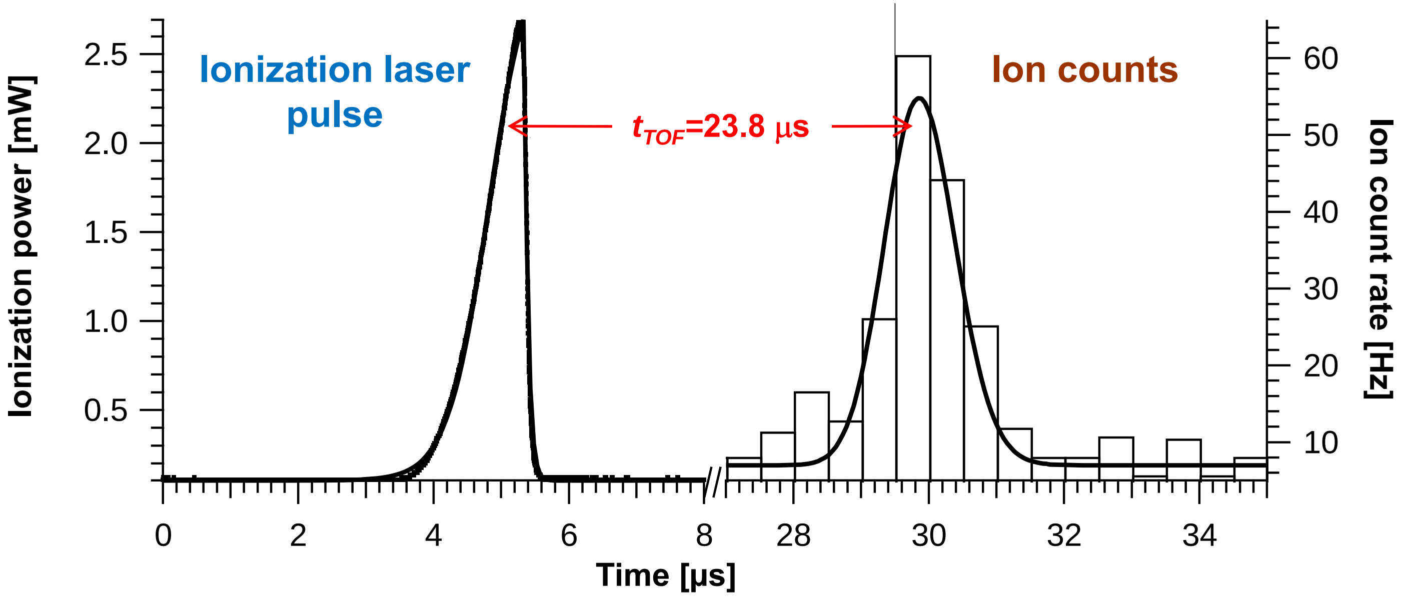
- Compromise needed between the minimum possible perturbation to the ion dynamics and sensitivity (gate duration 1 μs)

- Typically, the electric field gradient along the longitudinal direction was simulated to be around 40 V/cm (not negligible!)

Ion arrival time onto the detector

- AOM used to produce ionization laser pulses (with a large dia crystal, that explains the slow rise time of the pulse)
- Time-Of-Flight is clearly visible
- The temporal shape of the ion count hystogram is deformed and slightly broadened

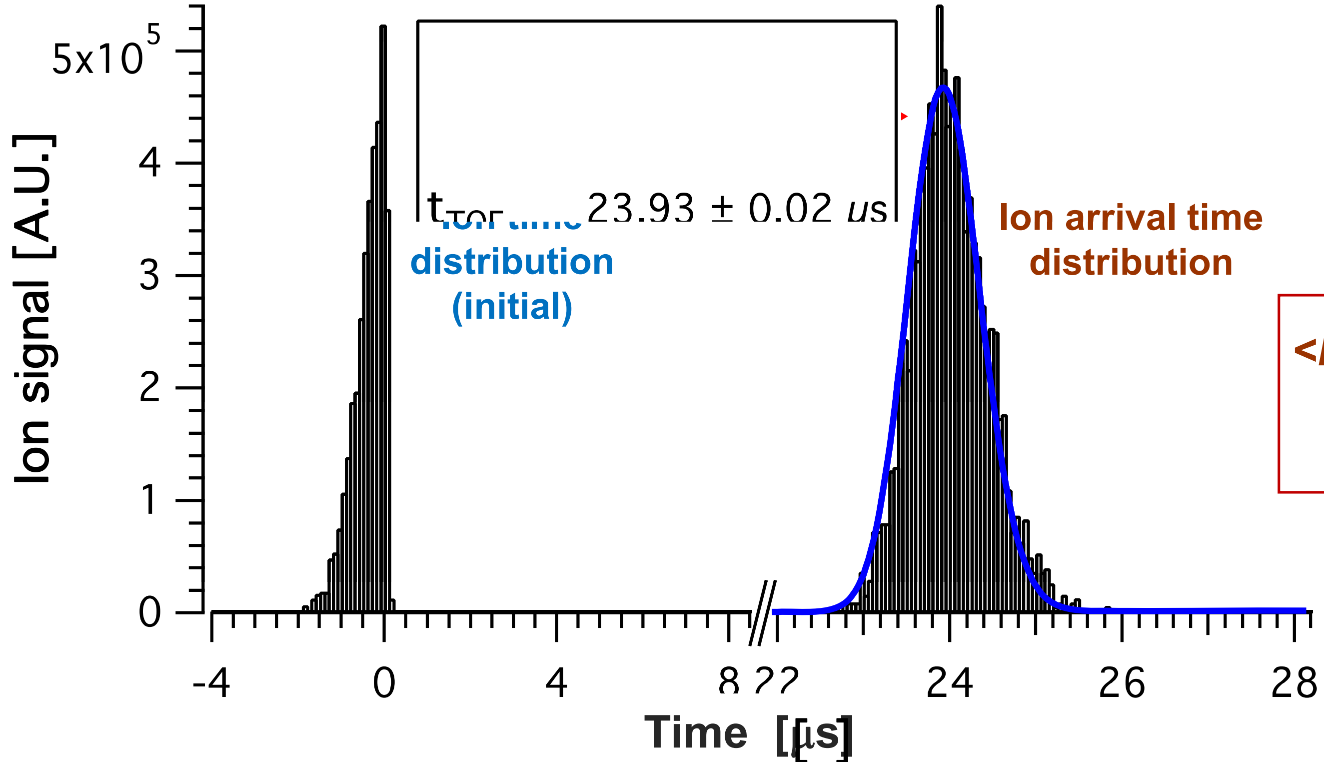
Experimental data



Simulation of ion arrival time

- ✓ Very good agreement with the experiment

Simulated ion flight



$<E_{KIN}> = 26.5 \pm 1.8$ eV

$\Delta E_{KIN} \cong 2.4$ eV

The simulation demonstrates that the relatively large kinetic energy distribution is due to:

1. **electric field gradient in the ionization volume**
2. **relatively large size of the ionization volume**

Conclusions and future directions

✓ Ions have been produced from the *cold and slow* atom beam (first objective of our research)

✓ Spectroscopy of the atom beam realized and ion beam dynamics investigation started (to be completed with, e.g., divergence measurements)

✓ Work is in progress to achieve further improvements:
- design and implement a more suited interaction region (smaller interaction volume and field gradients);
- increase the ion yield (improve ionization laser power, use a wavelength closer to ionization threshold or conceive other photoionization schemes);
- add a compression stage to the atom beam in order to improve its density

✓ In the mid-term, we will introduce and analyze laser manipulation configurations for on-demand delivery of ion packets (already tried with pushing laser beams, yet with not satisfactory results)

✓ In a longer term, we plan ion beam/surface interaction experiments and in-situ UHV-STM investigations