Instituto de Física
Universidade Federal do Rio de Janeiro

LASER-IF-UFRJ

Low energy hydrogen anions source for matter/antimatter precision experiments

Matrix Isolation Sublimation Technique as a H^- source

PSAS'2024

Zürich, Switzerland

Levi Azevedo – Ldeazevedo@if.ufrj.br

L. O. A. Azevedo*, R. J. S. Costa, W. Wolff, A. N. Oliveira*, R.L. Sacramento*, D.M. Silveira*, C. L. Cesar*

*ALPHA Collaboration - CERN

Ref: "Adaptable platform for trapped cold electrons, hydrogen and lithium anions and cations". *Commun Phys* 6, 112 (2023).

1

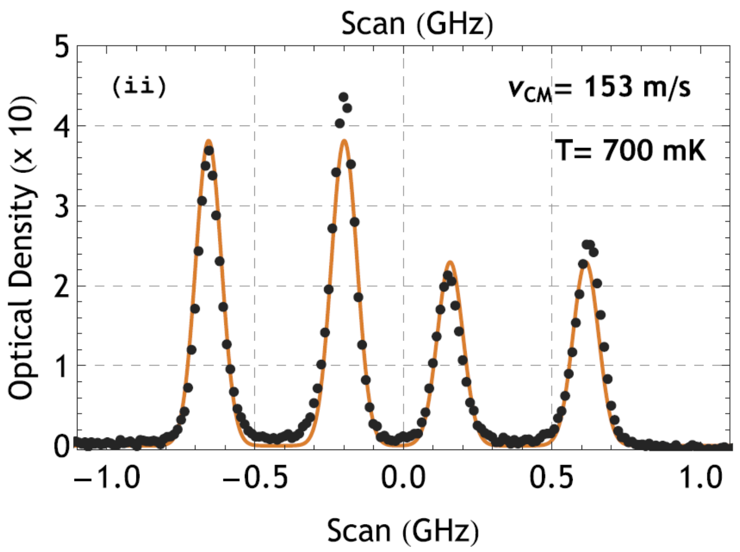
Matrix Isolation Sublimation (MISu)

› Developed at LASER-IF/UFRJ

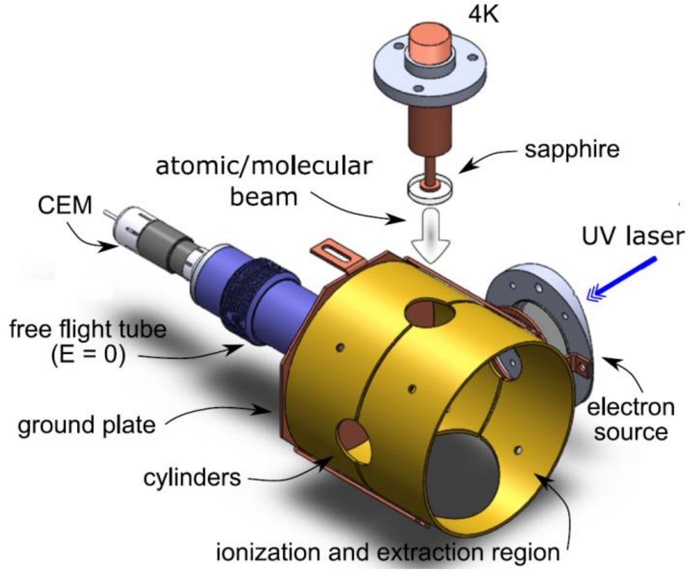
› Cold beams of Atoms and Molecules
  › Doopler Sensitive Laser spectroscopy

› Versatile to diferente species
  – Simple atomic systems to molecules

› Adaptable Technique
  – Laser Spectroscopy
  – Time of Flight Mass Spectrometer
  – Traps for confining cold particles
    › Penning-Malmberg trap
    › Magnetic trap for hydrogen (H) in a near future

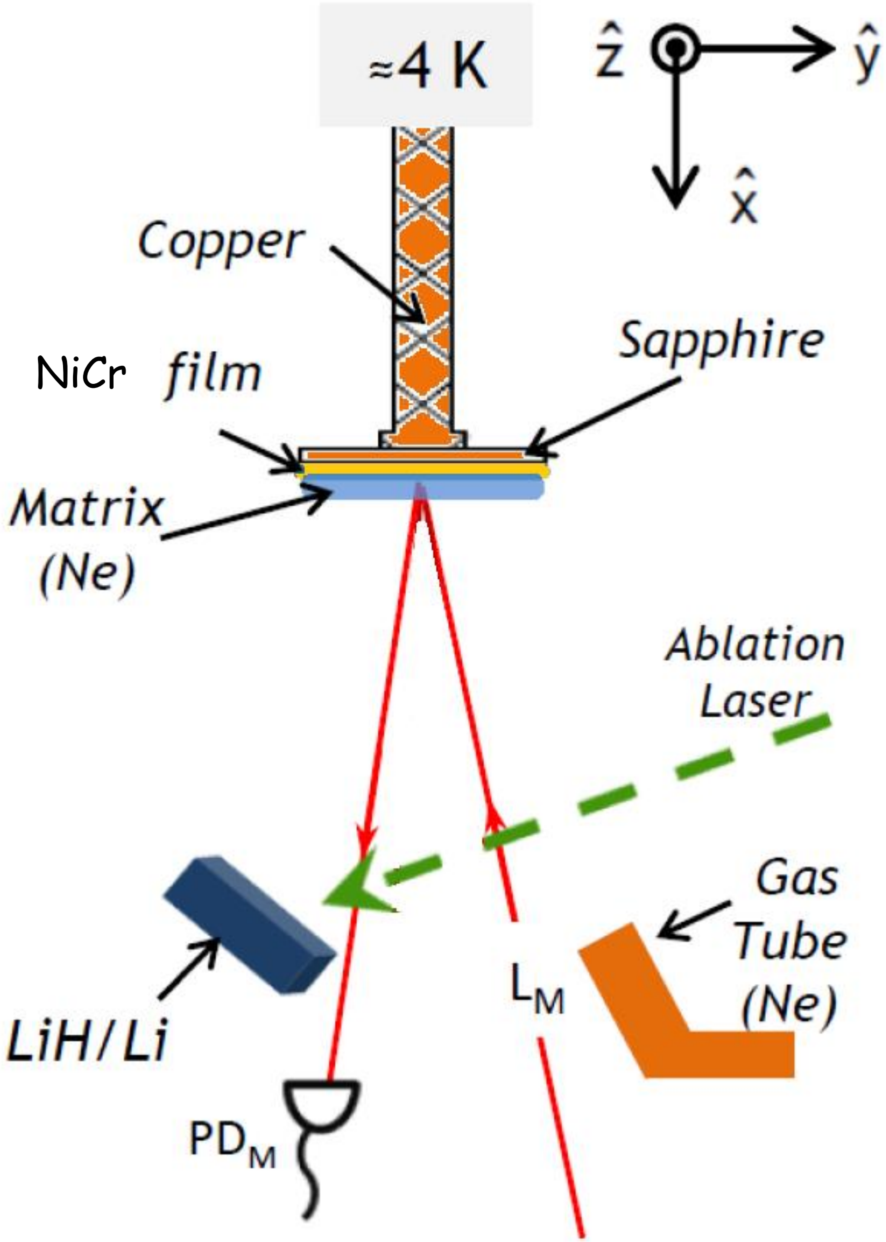


R. L. Sacramento, et al., Matrix Isolation Sublimation: an apparatus for producing cryogenic beams of atoms and molecules, Rev. Sci. Instrum. 86, 073109 (2015)

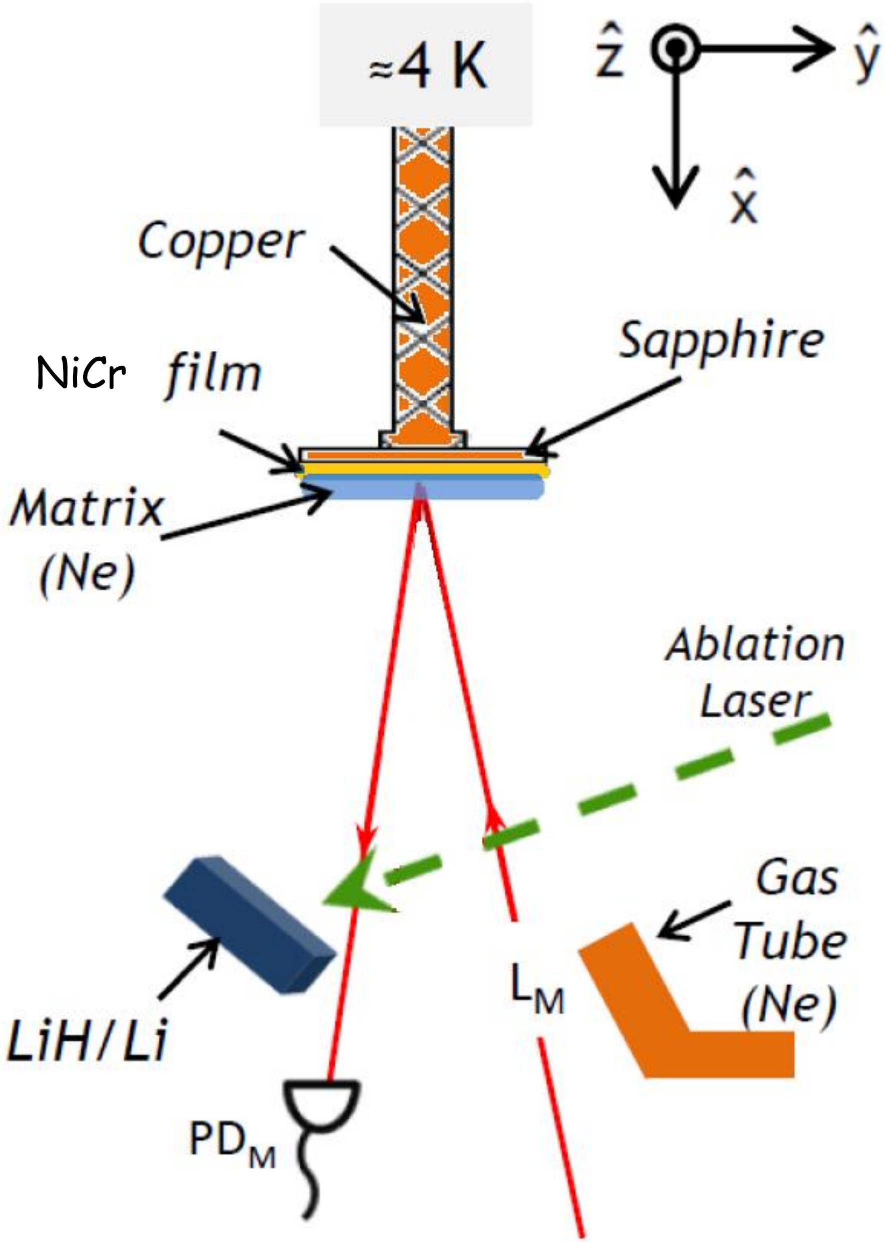


A. N. Oliveira, et al., Heteronuclear molecules from matrix isolation sublimation and atomic diffusion, J. Chem. Phys. 149, 084201 (2018)

MISu - Steps

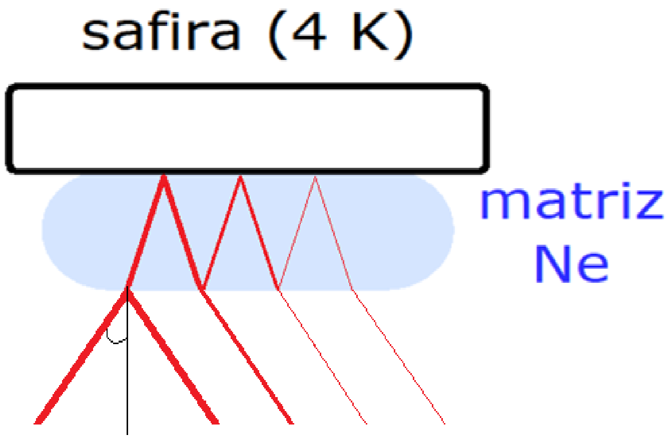

≈4 K
ẑ
ŷ
x̂
Copper
Sapphire
NiCr film
Matrix
(Ne)
Ablation
Laser
Gas
Tube
(Ne)
LiH/Li
L_M
PD_M

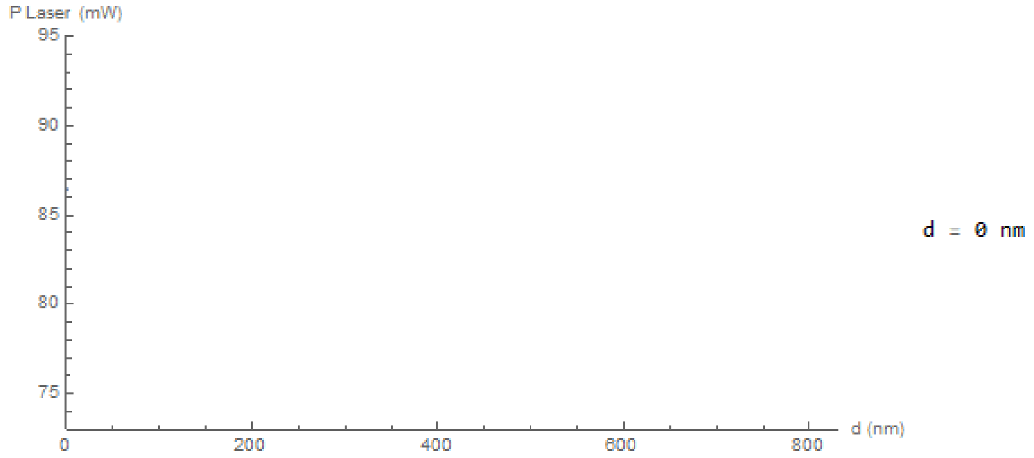
MISu - Steps



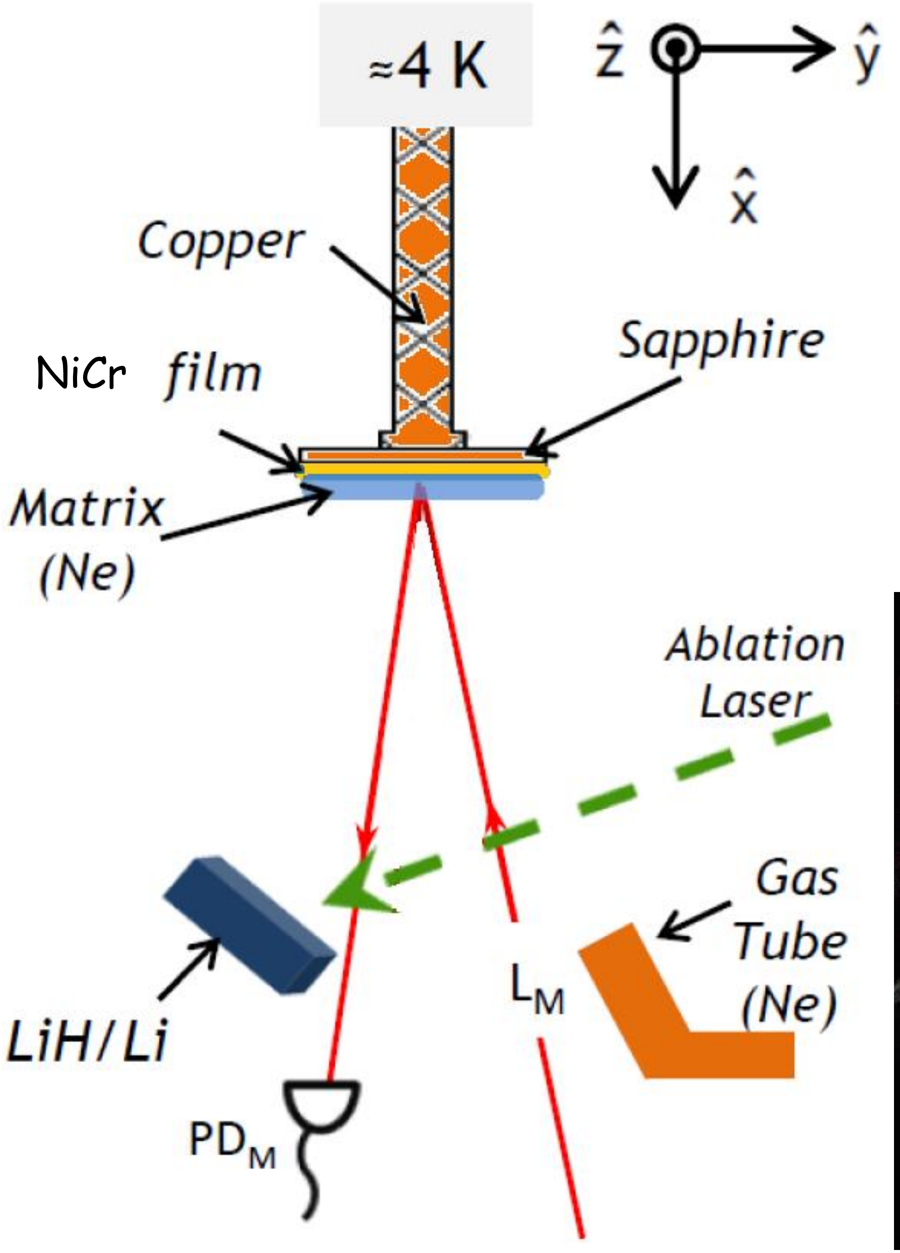
1. Growth of the Matrix
   – Inert Gas (Ne or H_2)
   – Flow Rate: 1 – 10 mmol/h
   – Solid matrices

   – Interference fringes signal as matrix grows

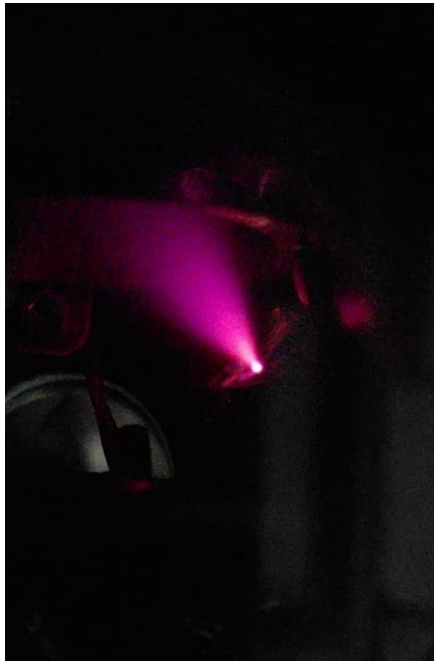


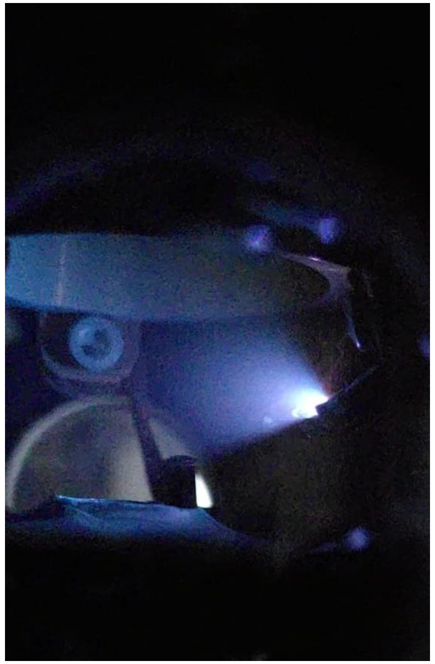


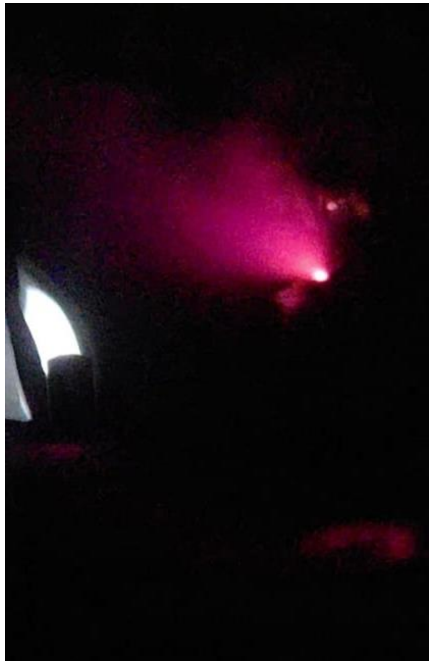
MISu - Steps



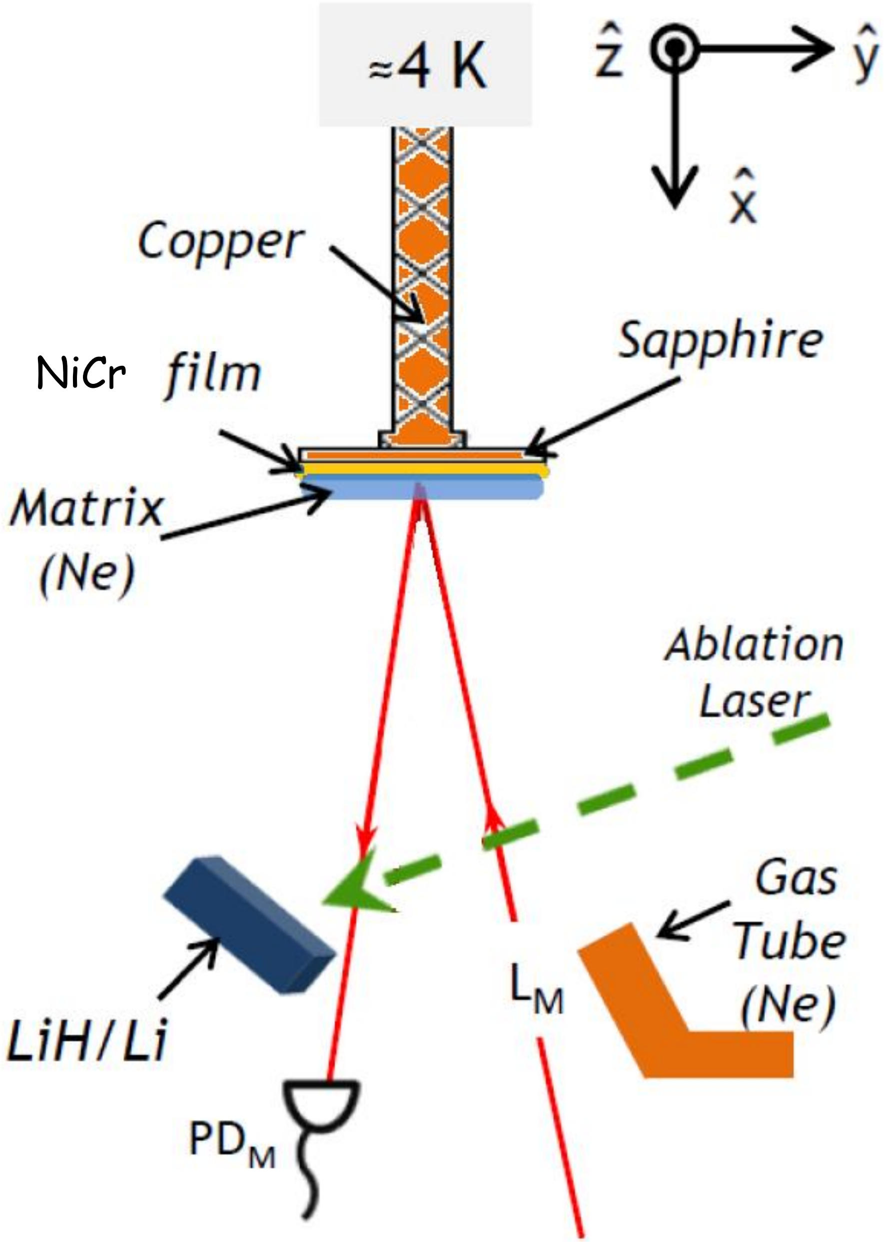
2. Laser Ablation
   - Pulsed Laser of 5 ns pulses
   - Typical energy: 1 mJ
   - ND: YAG (1064 nm or 532 nm)
   - Solid Targets (LiH, TiH_2 and Li – Applicable to other targes)





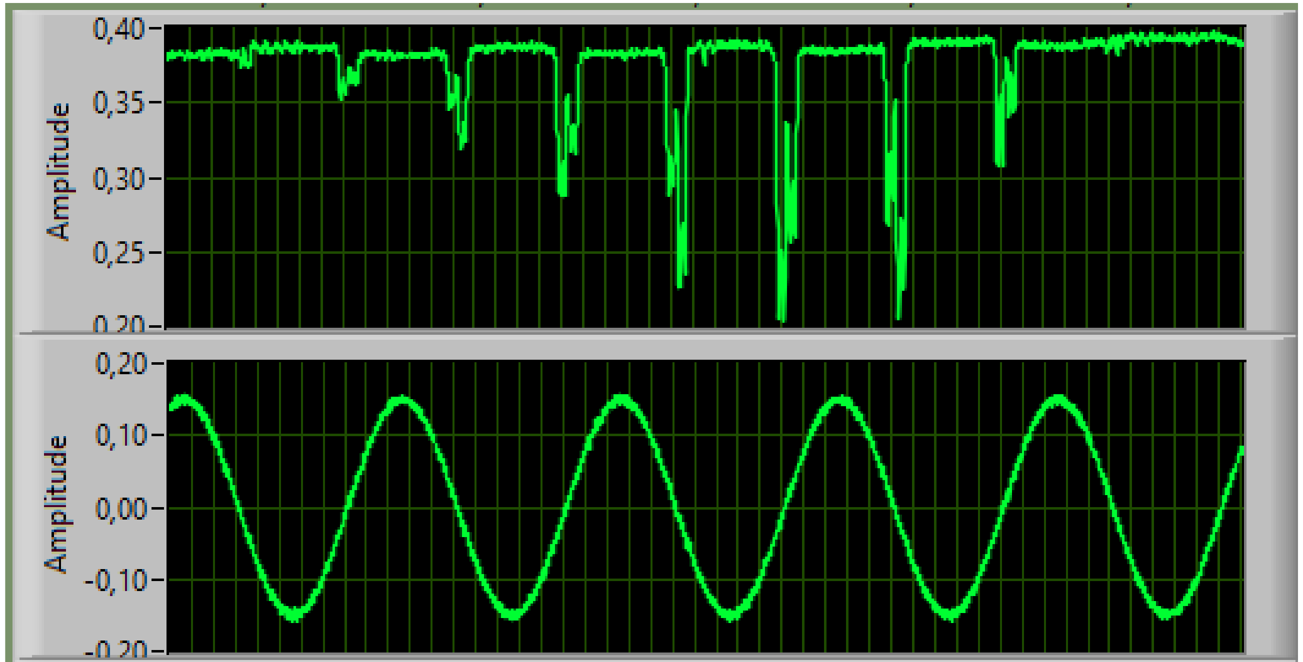


MISu - Steps

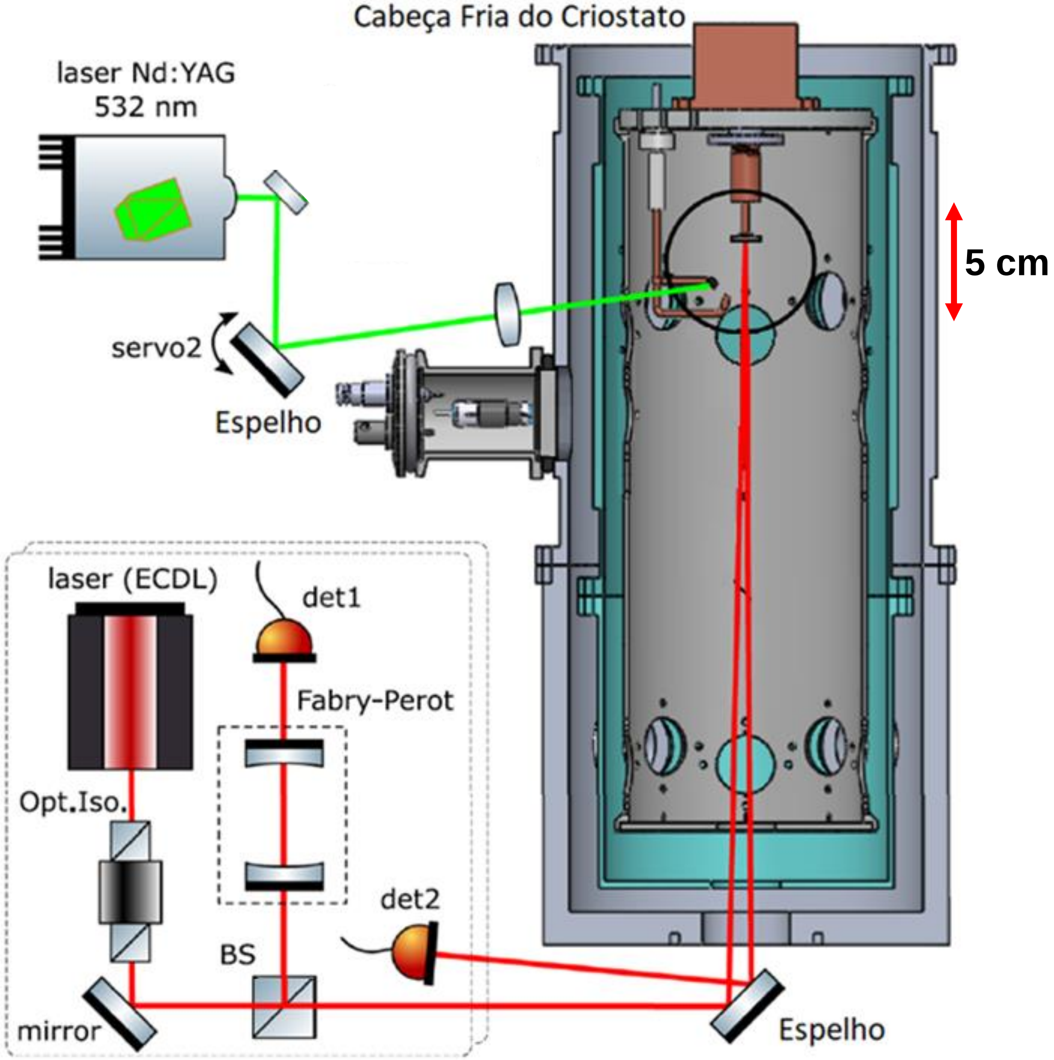


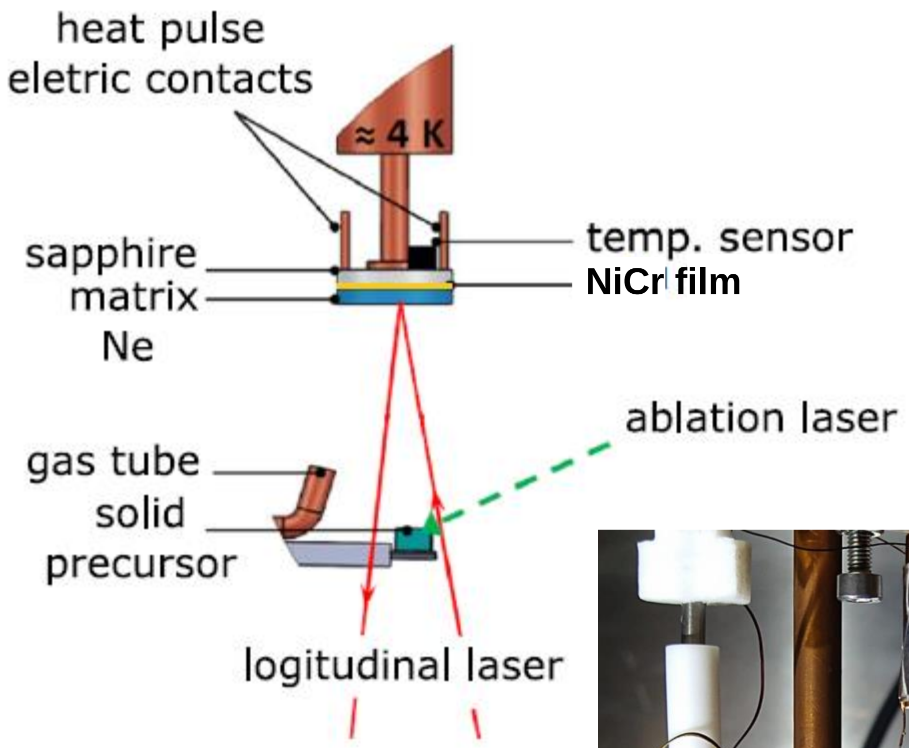
3. Sublimation

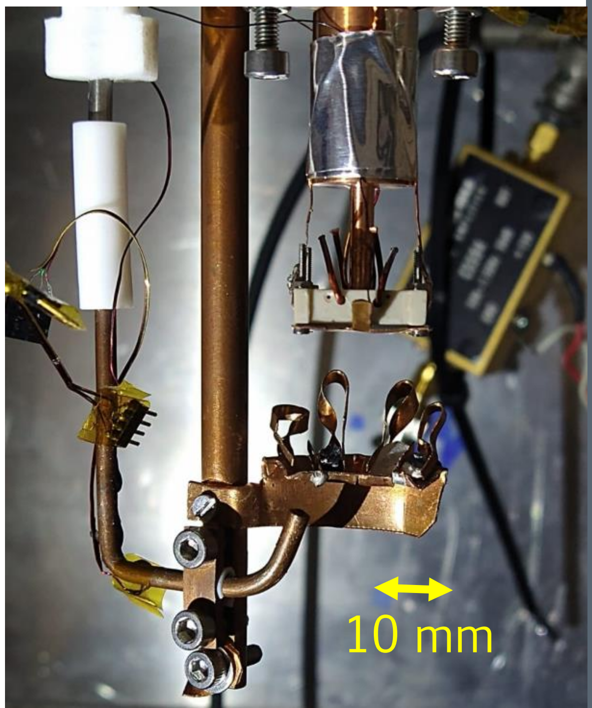
– Heat pulse to the Sapphire
  › Sublimation plume
  › Cold beams
– Spectroscopy
  › Longitudinal Laser (L_M)



MISu - Main setup

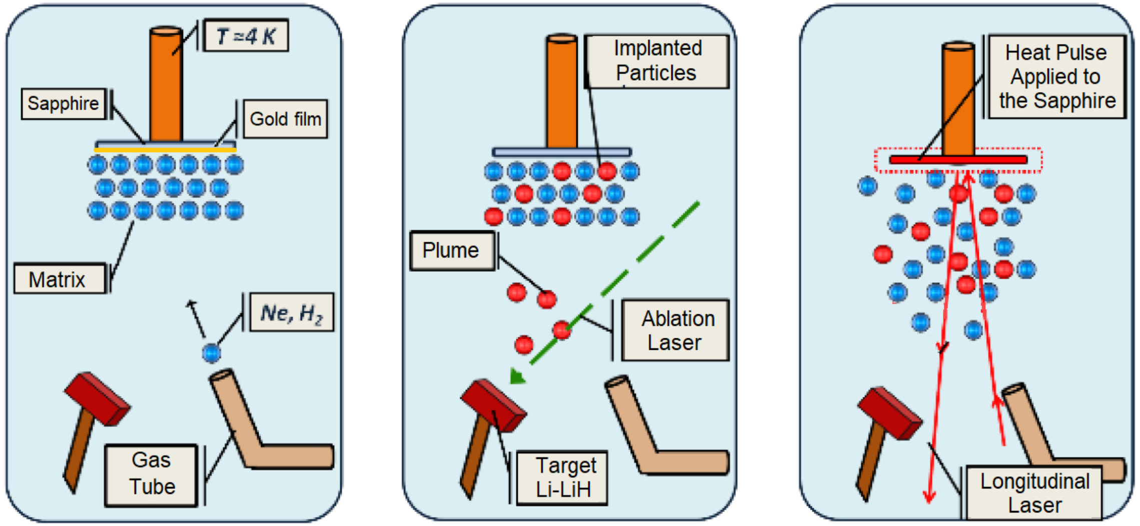




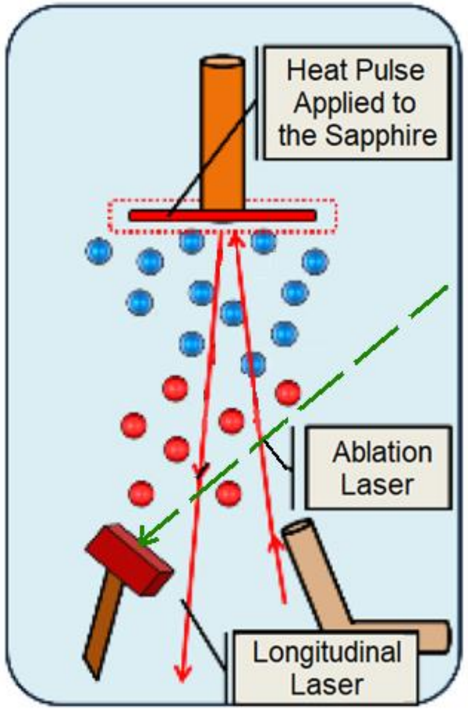


MISu - Variant

› Typical MISu cycle
1. Growth
2. Ablation during or after growth
3. Sublimation

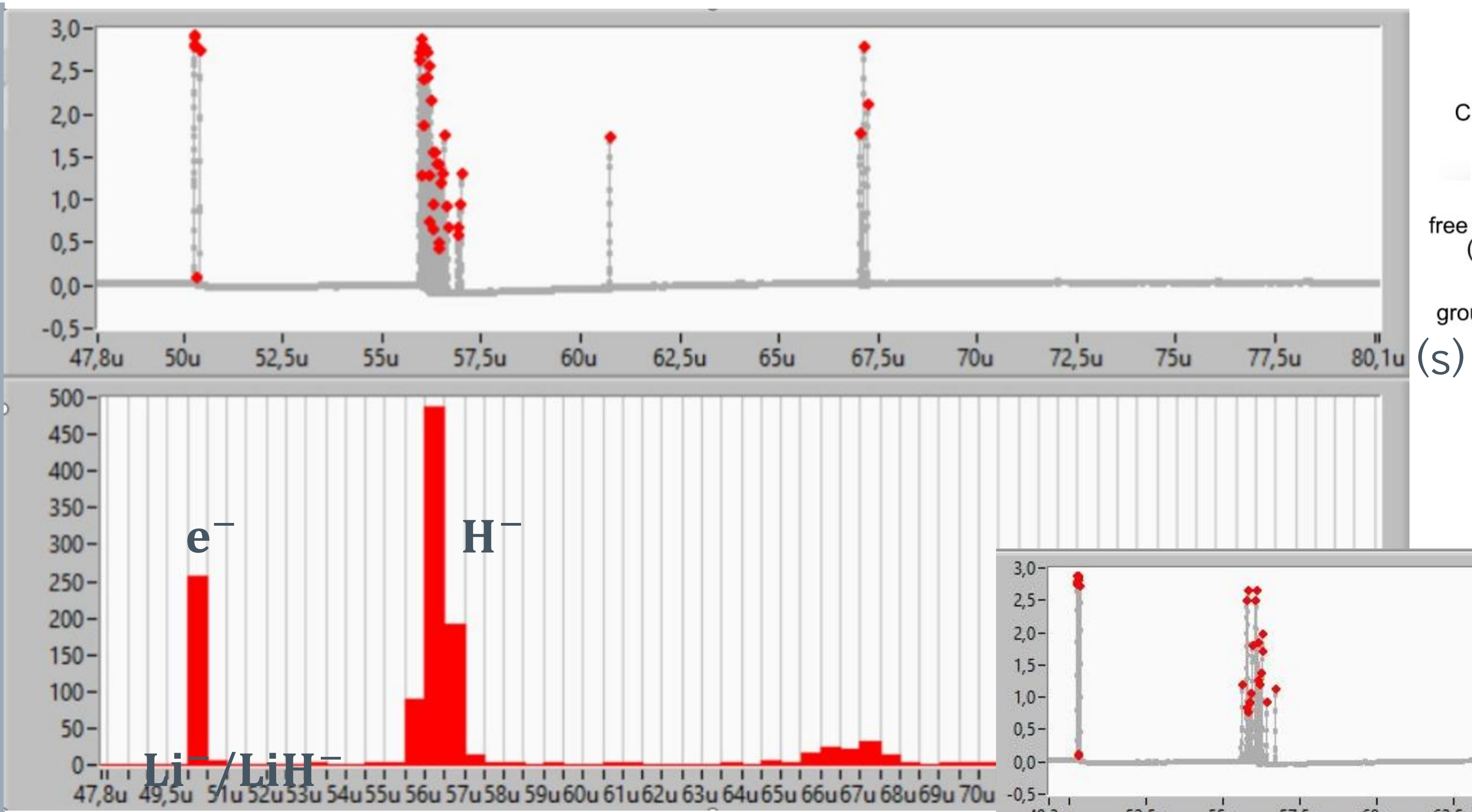


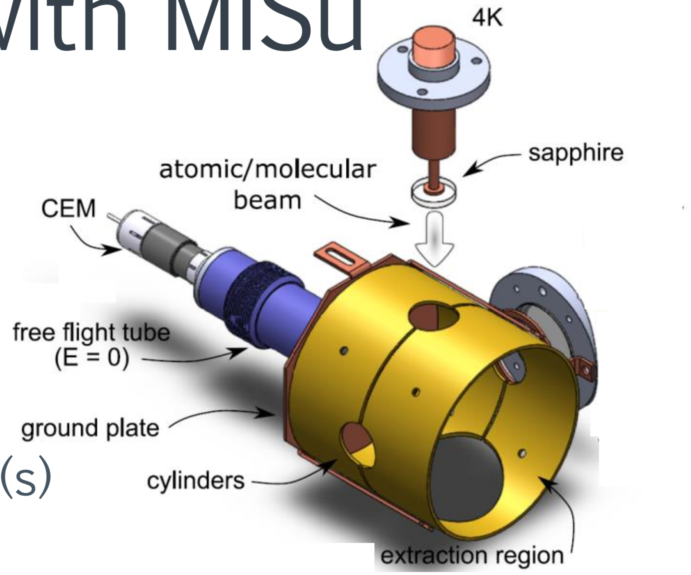
› MISu variant (New-MISu)
1. Growth
2. Ablation followed by a partial or total sublimation

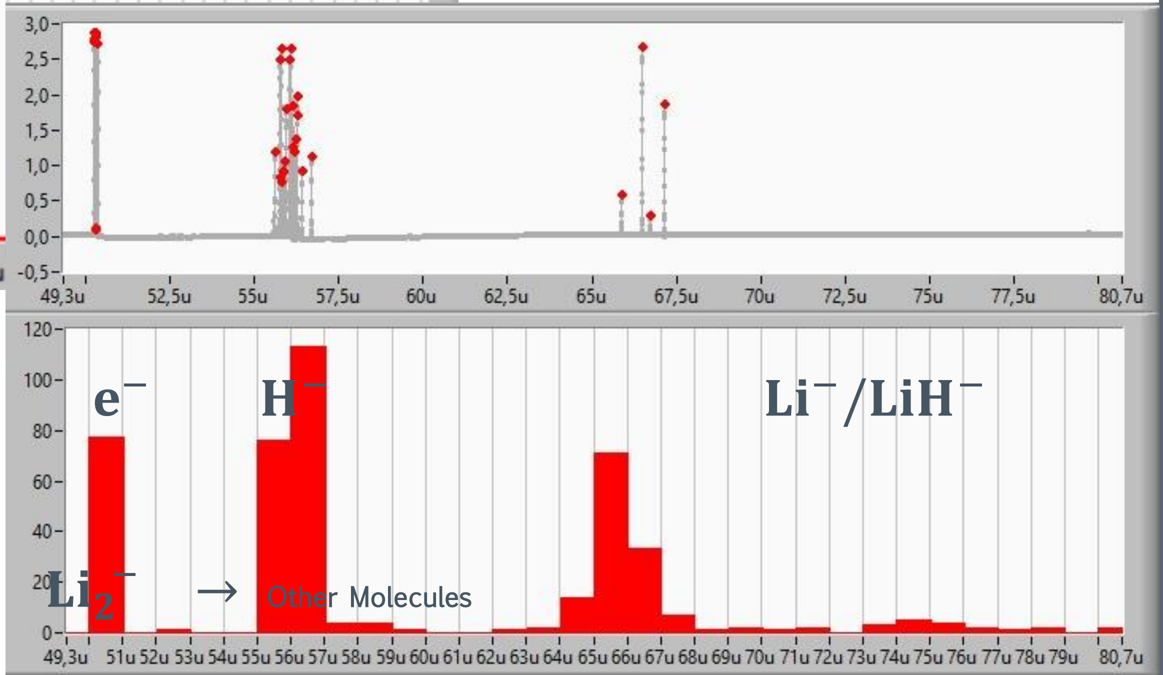


– Produced particles stay shorter times inside matrix
– Depending on delay – Ions are "deflected" by the sublimation cloud

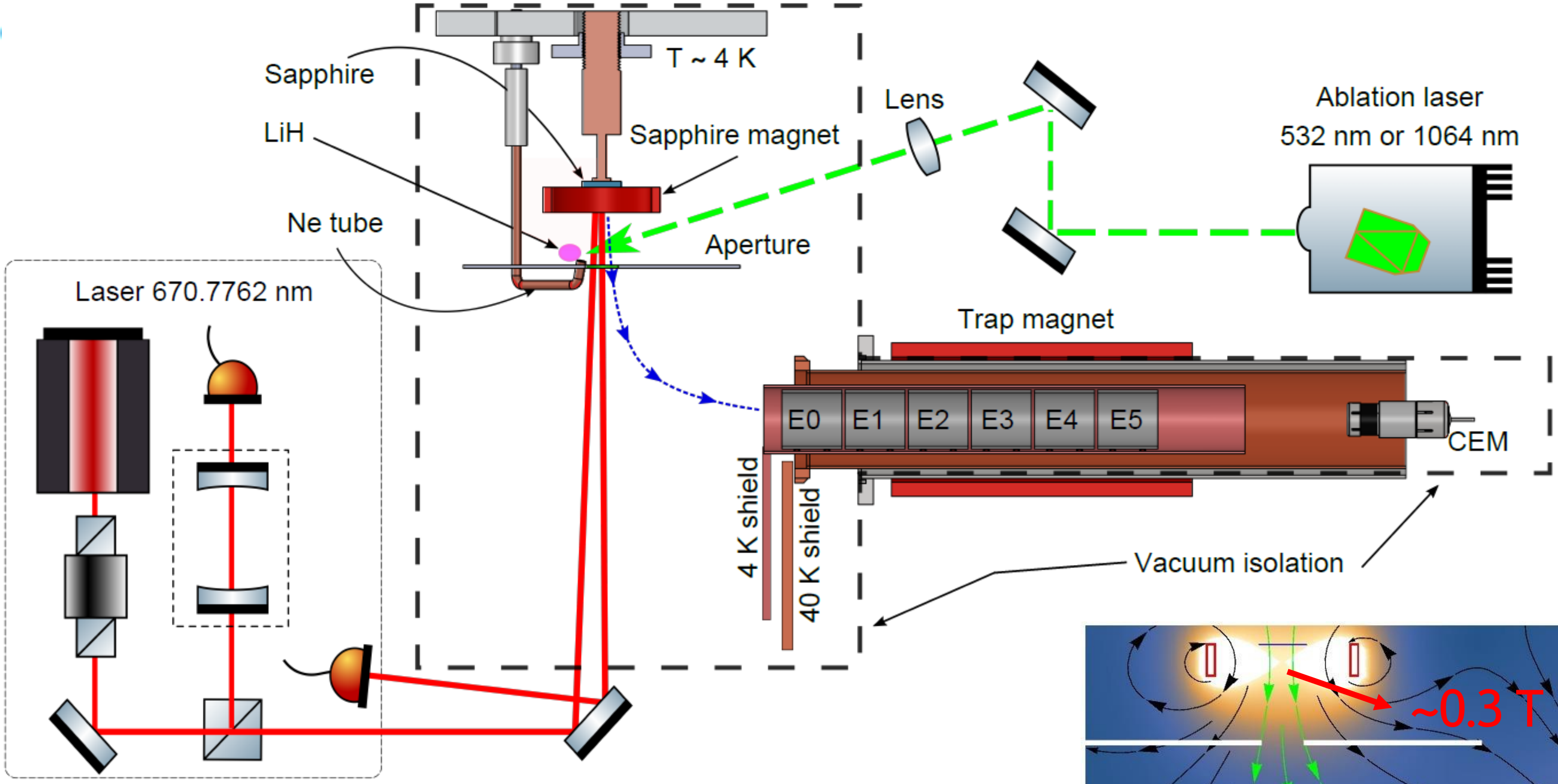
Time of Flight – Anions produced with MISu

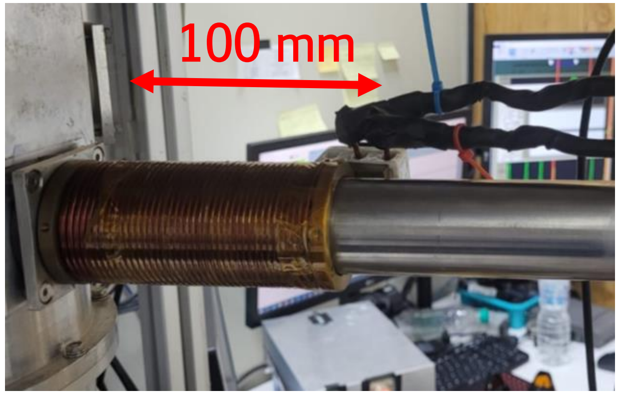


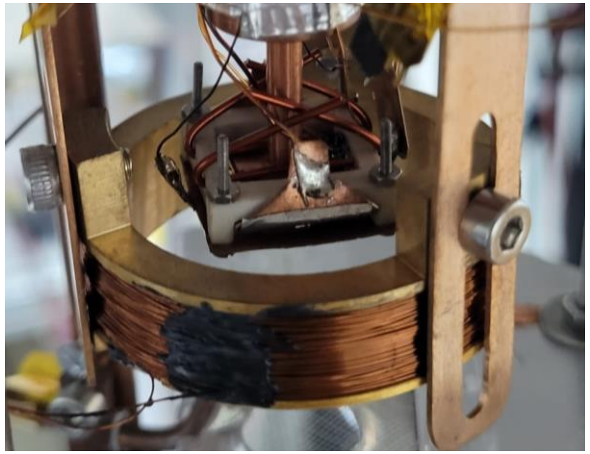


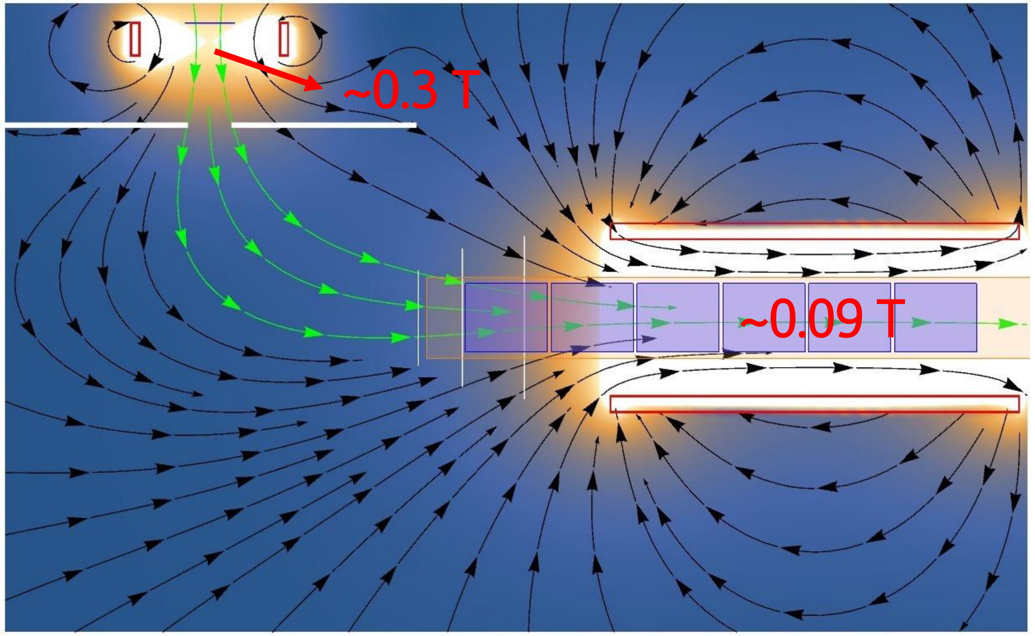


MISu Setup – With Penning-Malmberg Trap



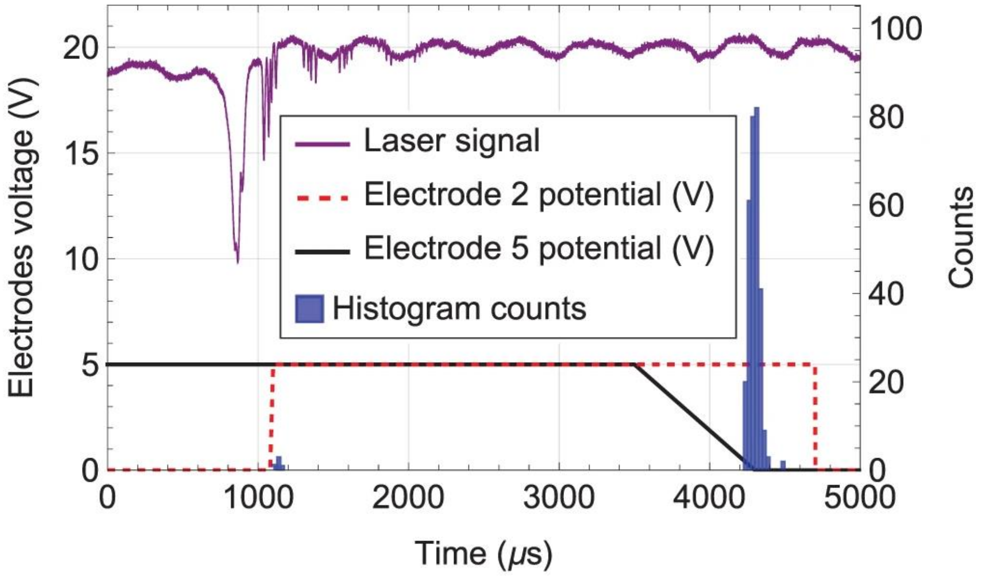


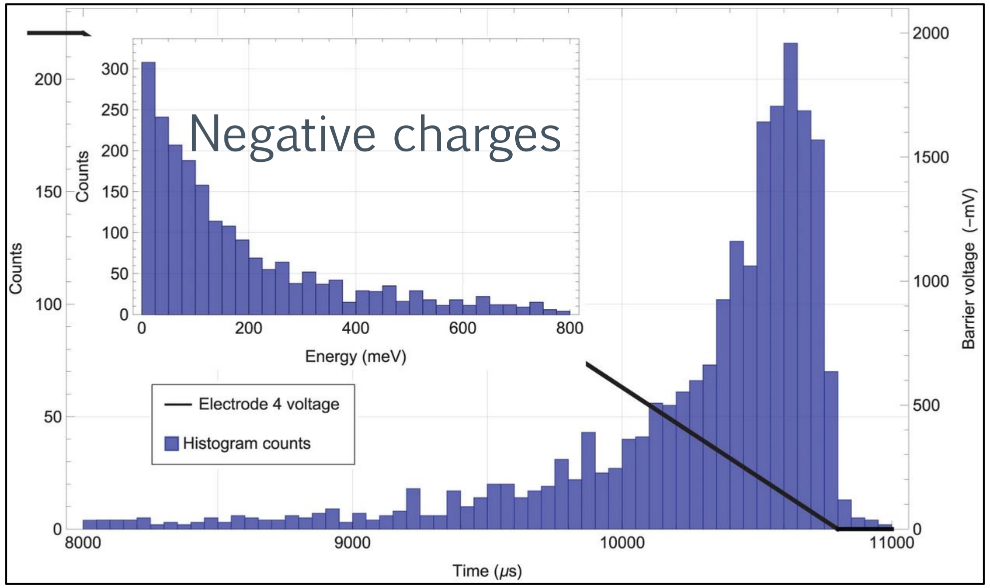


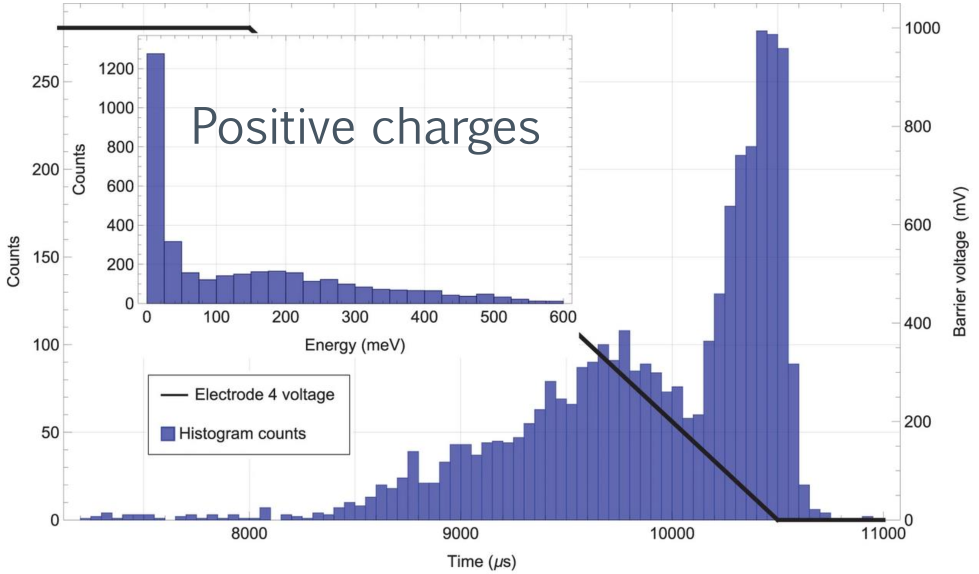


Experimental cycle

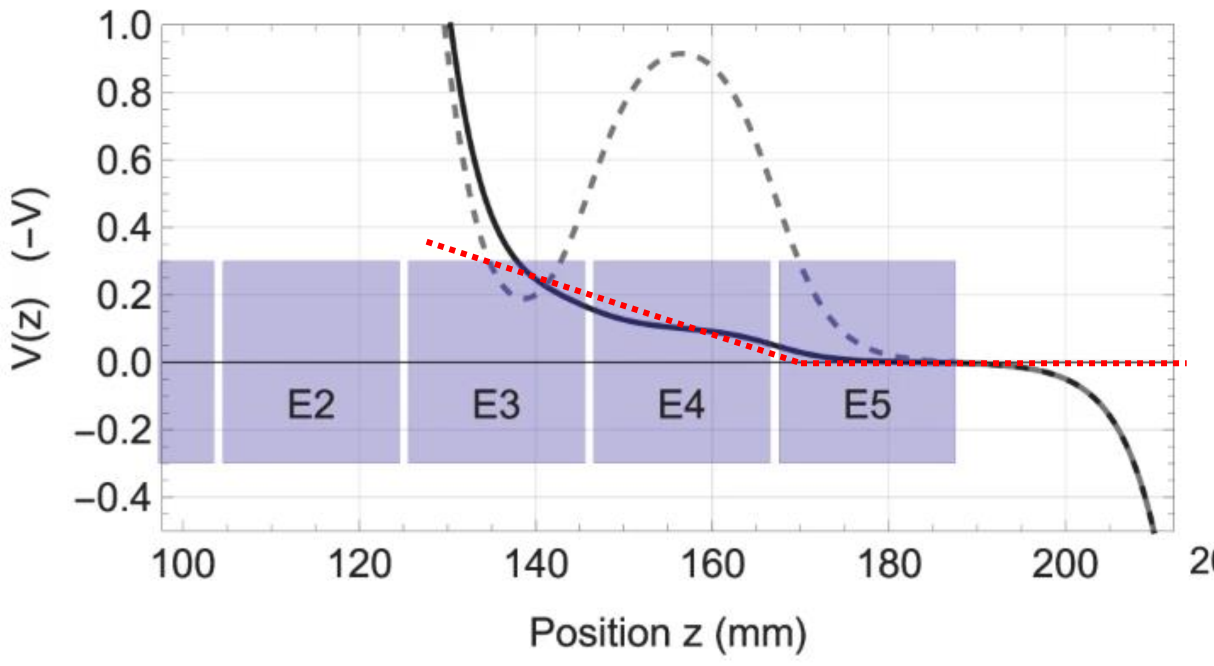
- Few seconds production cycle
- +5000 of particles trapped per pulse
  - Can be improved
    - Higher ablation energy
    - Stronger guiding magnetic field
    - Adding more coils for guiding charged particles
    - Stronger trapping magnetic field
    - Increasing the size of aperture
    - Trapping on axis (Sapphire axis)



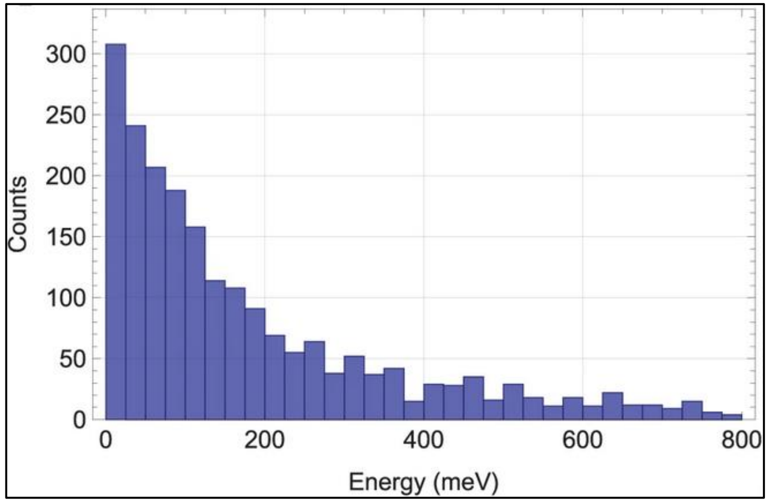


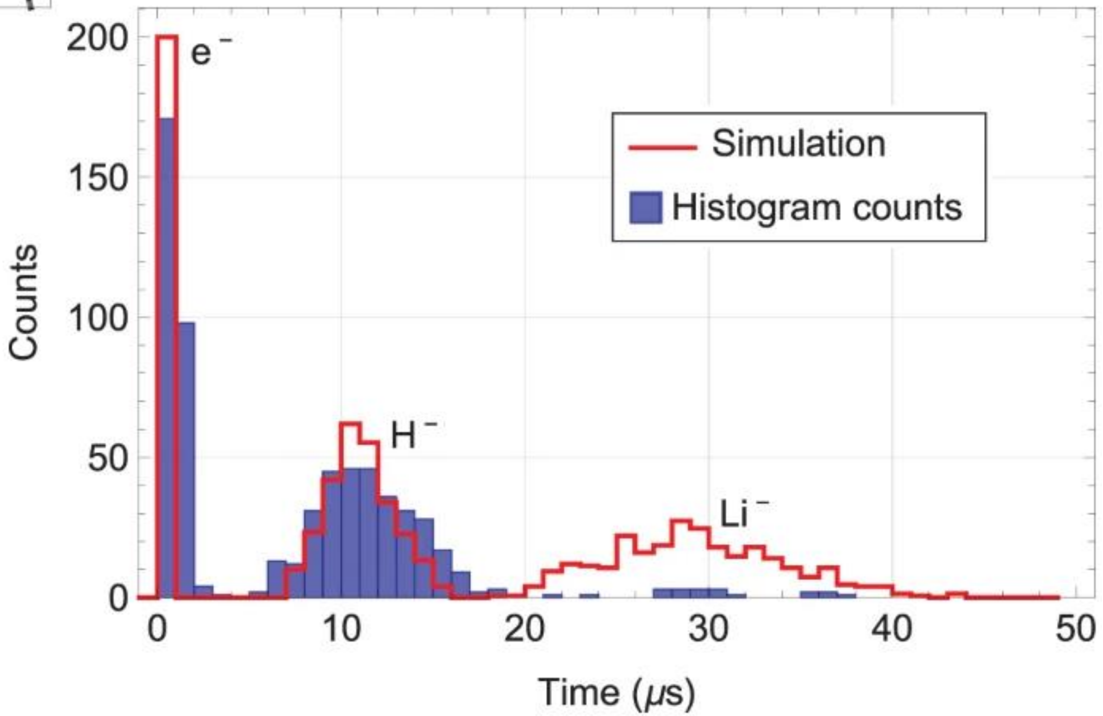


Time of Flight Mass Discriminator (ToF-MD)



$$t_{ToF-MD} = \int_{z_0}^{z_f} \frac{1}{\sqrt{\frac{2}{m}\{\epsilon - q\,V_{ToF-MD}(z)\}}}\Delta z$$





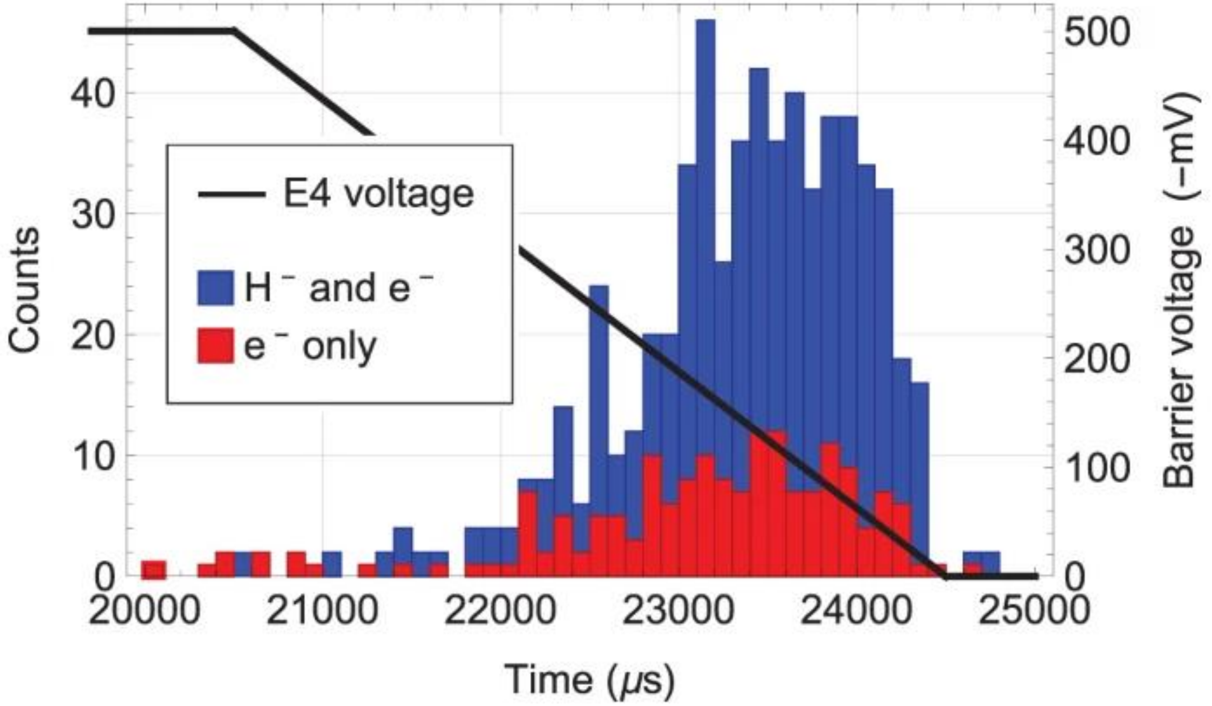
H^- to e^- proportion

- Trap instability

$$\omega_c > \sqrt{2}\,\omega_z \quad \rightarrow \quad \omega_c = \frac{q\,B}{m} \quad \& \quad \omega_z \propto \frac{1}{\sqrt{m}}$$

- Controling trapping potentials
  - "Squeezed" trap
    - Trap particles (regular trap)
    - Morph to squeezed trap
      -10V / 10V / -10V
      Higher ω_z
    - Morph to regular trap
    - Dump

    - H^- becomes unstable but not e^-

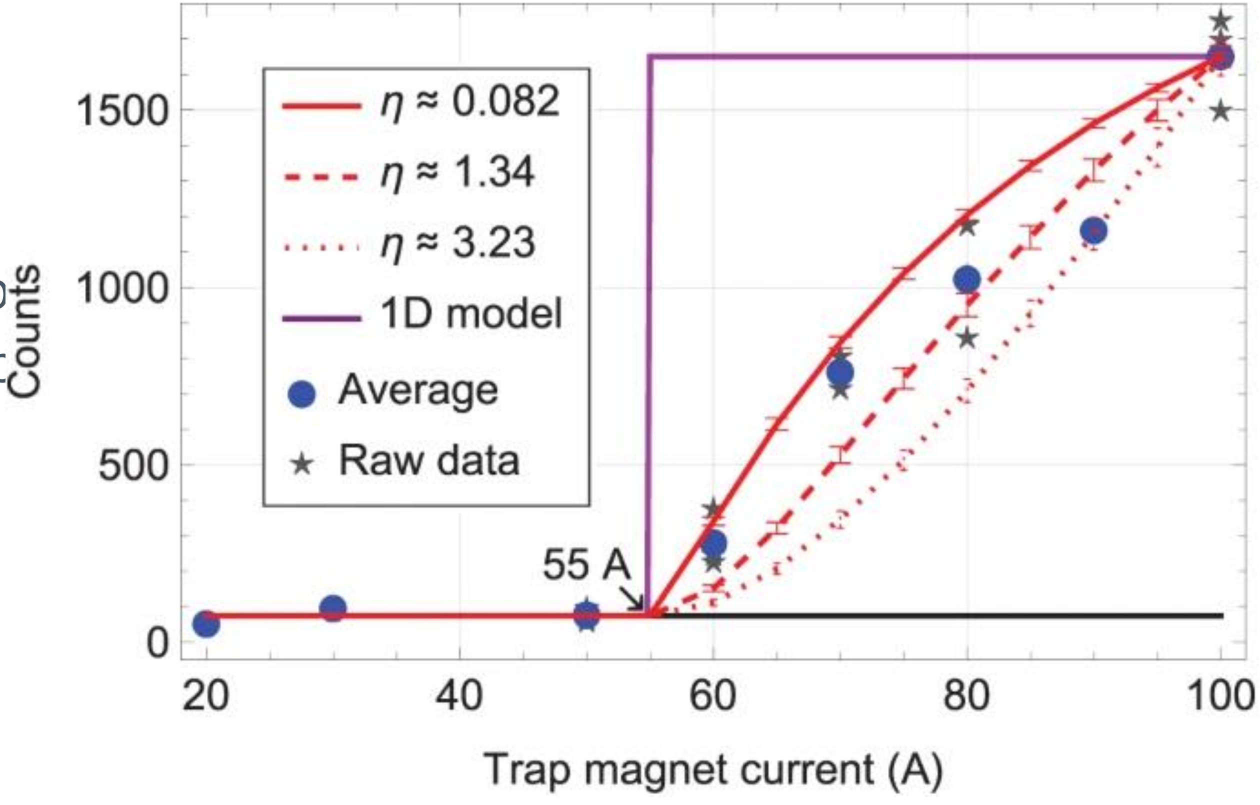


H^- to e^- proportion

- Controling magnetic field
  - Weaker Guiding field & Weaker trap magnetic field
    - Guide particles with weaker magnetic field
    - Trap particles (regular trap)
      - Trap with low B-field

        Lower ω_c
    - Dump

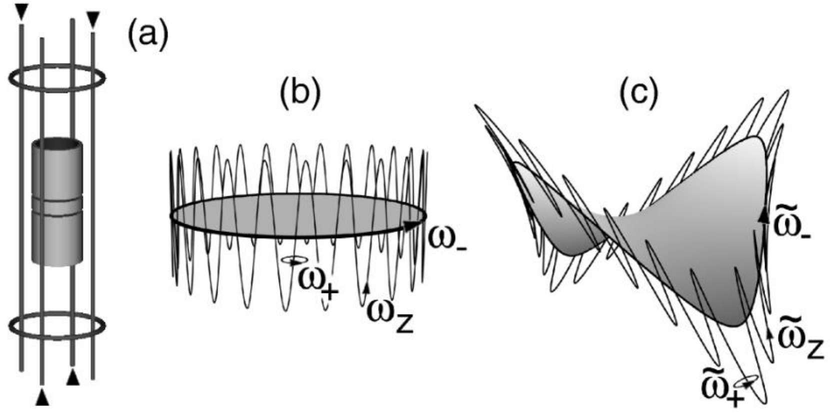
    - H^- are not guided into the trap
    - e^- are still guided into the trap



100 A → 0.092 T at trap center

Loading a neutral trap

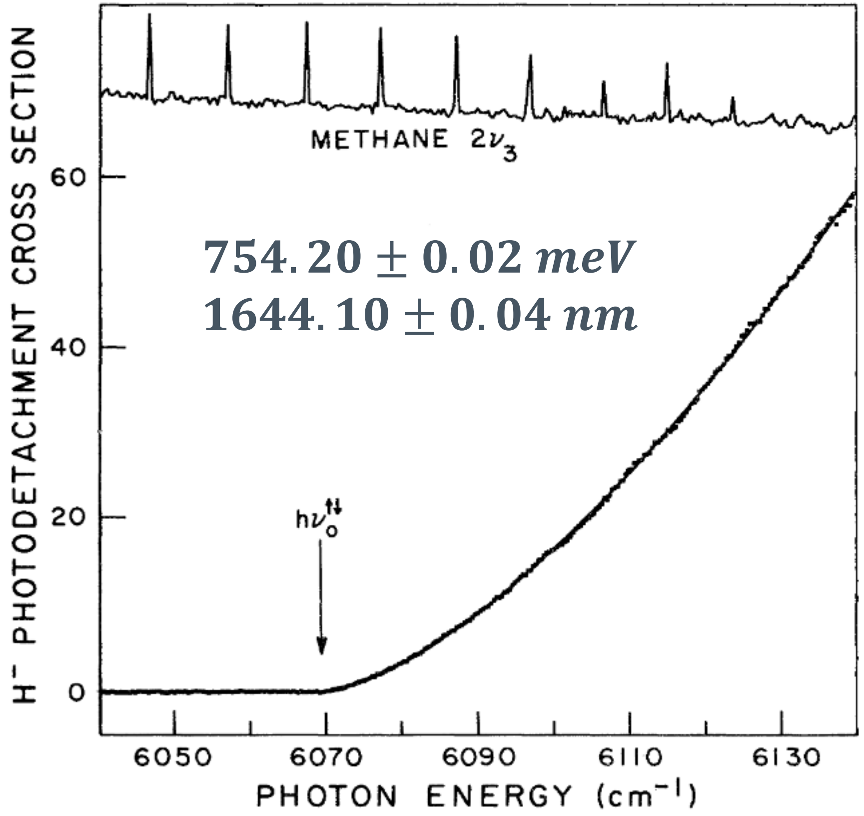
- Trapping the H^- and e^- in a Penning-Ioffe-Pritchard*
  - Cyclotron cooling of e^- - Sympathetic cooling of H^-
  - Near threshold Photodetachment of H^-
    - Low recoil energy given to the remaining H



Squires, T. M., Yesley, P., & Gabrielse, G. (2001). *Stability of a Charged Particle in a Combined Penning-Ioffe Trap. Physical Review Letters, 86(23), 5266–5269.*

$$\sigma \propto k^{2l+1} \quad \text{or} \quad \sigma \propto \Delta E^{l+1/2}$$

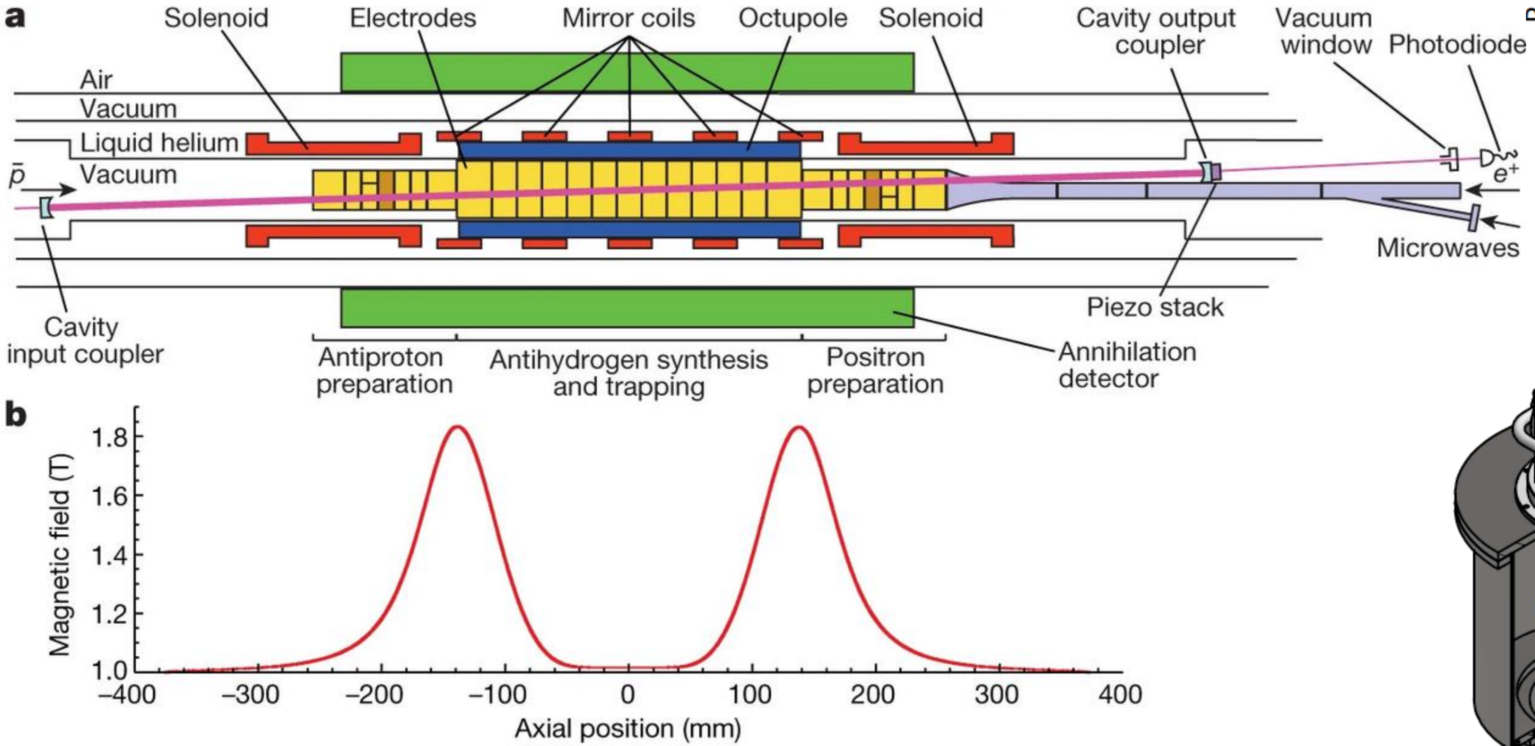
Wigner, E. P. (1948). *On the Behavior of Cross Sections Near Thresholds. Physical Review, 73(9), 1002–1009.*



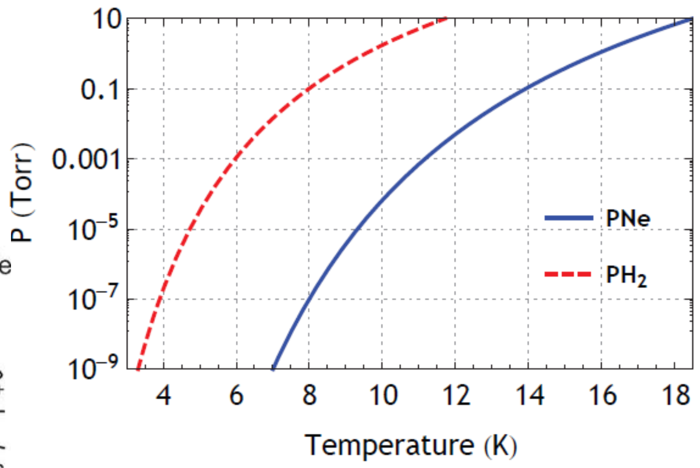
Lykke, K. R., Murray, K. K., & Lineberger, W. C. (1991). *Threshold photodetachment ofH–. Physical Review A, 43(11), 6104–6107.*

ALPHA - CERN

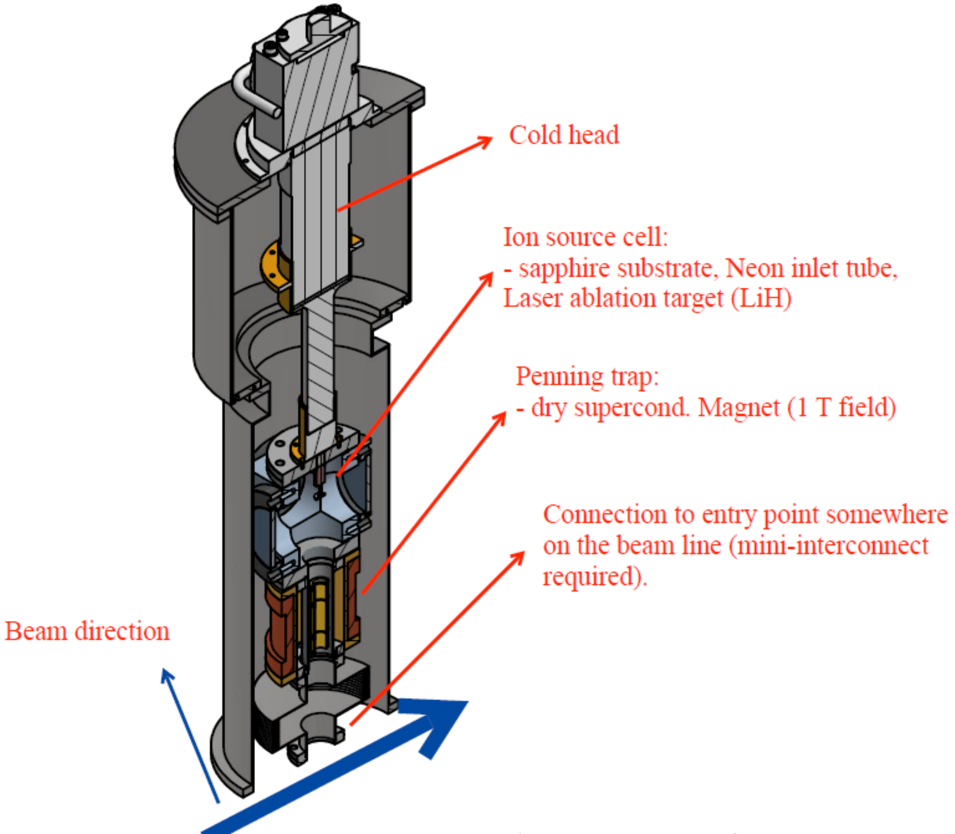
› ALPHA experiment apparatus



Ahmadi, M., Alves, B.X.R., Baker, C.J. *et al.* Characterization of the 1S–2S transition in antihydrogen. *Nature* **557**, 71–75 (2018)



Adapted MISu Source



- Electron cooling
- Near threshold photodetachment
- Hydrogen laser cooling (Lyman-α source)
- 1s-2s spectroscopy on Hydrogen
  - Detection: Ion recapture / Lyman-α detection

Claudio Lenz Cesar 2016 *J. Phys. B: At. Mol. Opt. Phys.* **49** 074001

Conclusions

Azevedo, L.O.A. *et al.* Adaptable platform for trapped cold electrons, hydrogen and lithium anions and cations. *Commun Phys* **6**, 112 (2023).

- Low energy H^- production
    - Other sources produce it at energies > 5 keV
  - Scalability
    - Improving B-fields and ablation power
    - Possible to stack
  - Electron cyclotron sympathetic cooling
  - Evaporative cooling
- Production of H
  - Near threshold photodetachment
    - Low recoil energy
    - Trappable Hydrogen production
  - Spectroscopy of magnetically trapped Hydrogen
- Antimatter research
  - Spectroscopy in same Gravitational&Magnetic enviroment
    - Reduce of systematic uncertainties
    - Possibility of reaching precision in the comparision of 10^{-16} (Relative precision)

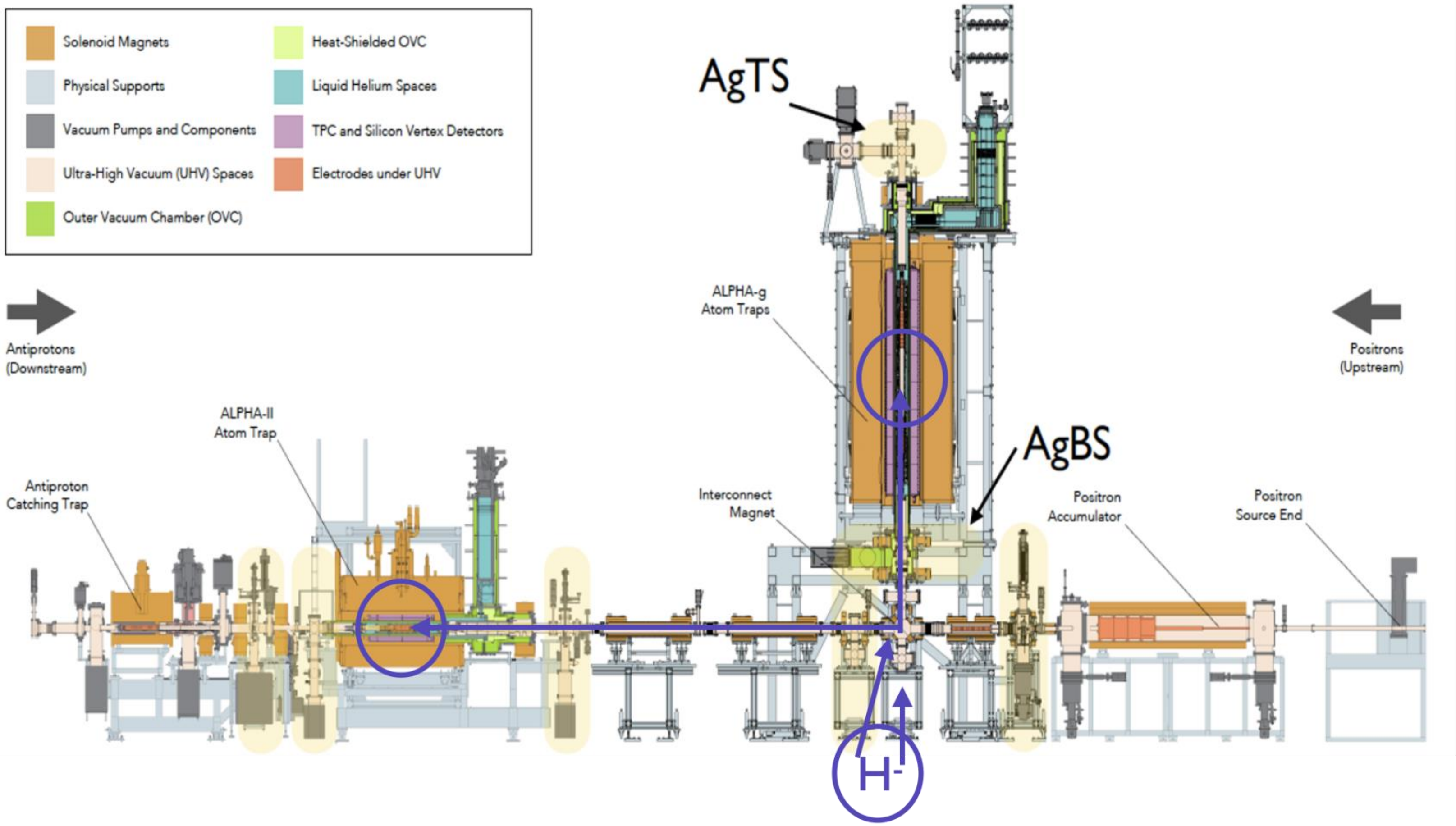
Thank you!

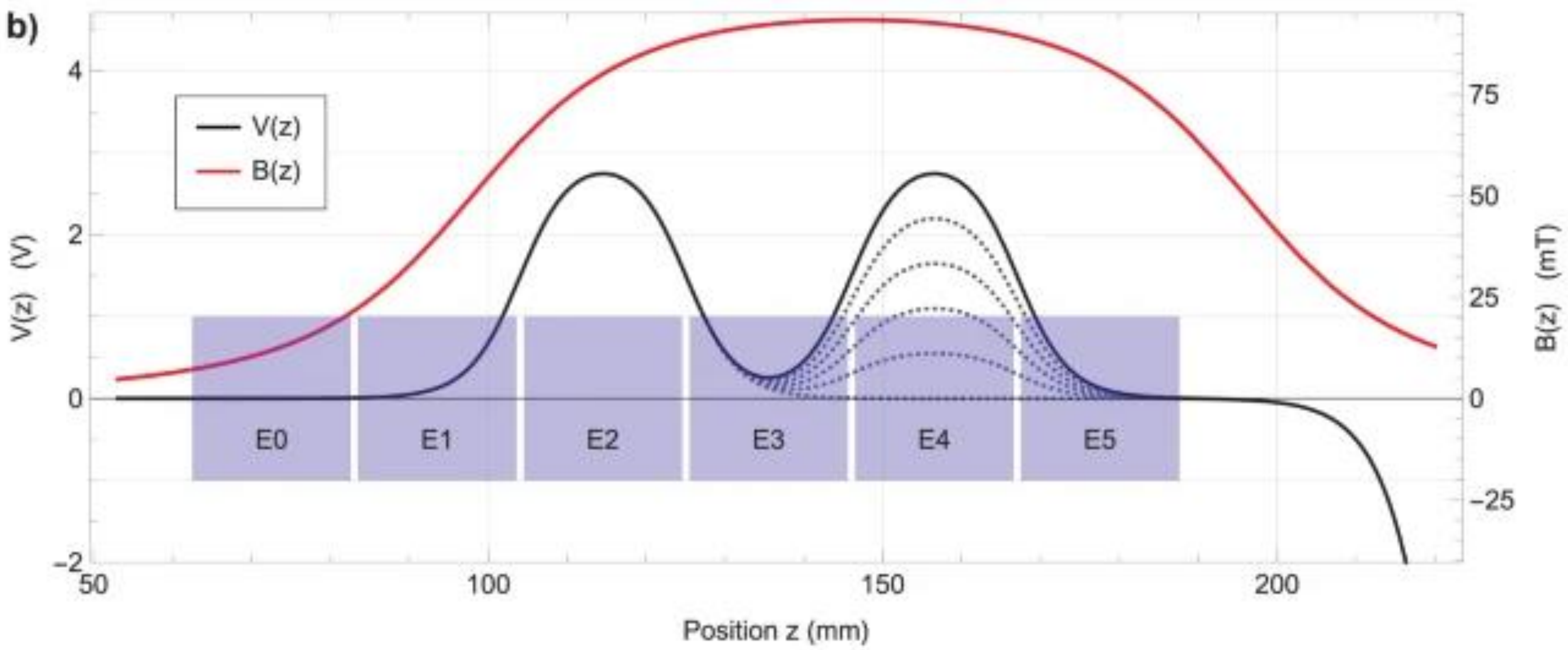
Instituto de Física

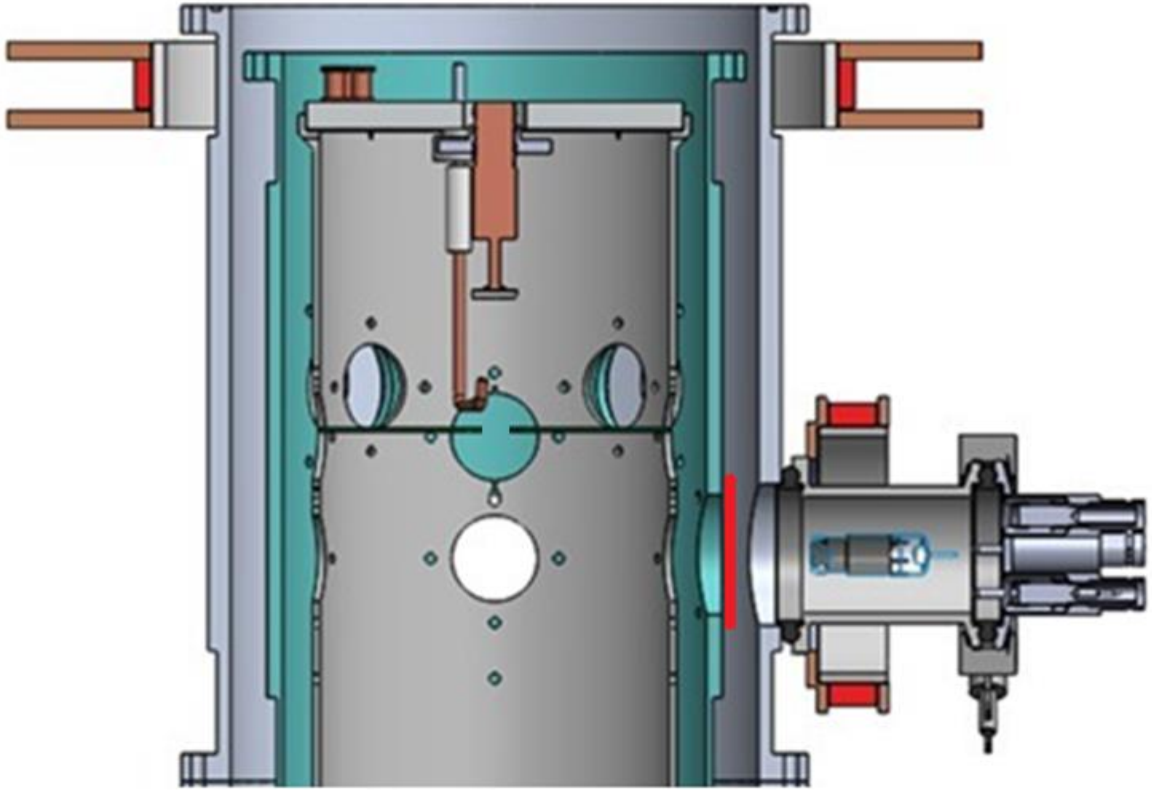
Universidade Federal do Rio de Janeiro

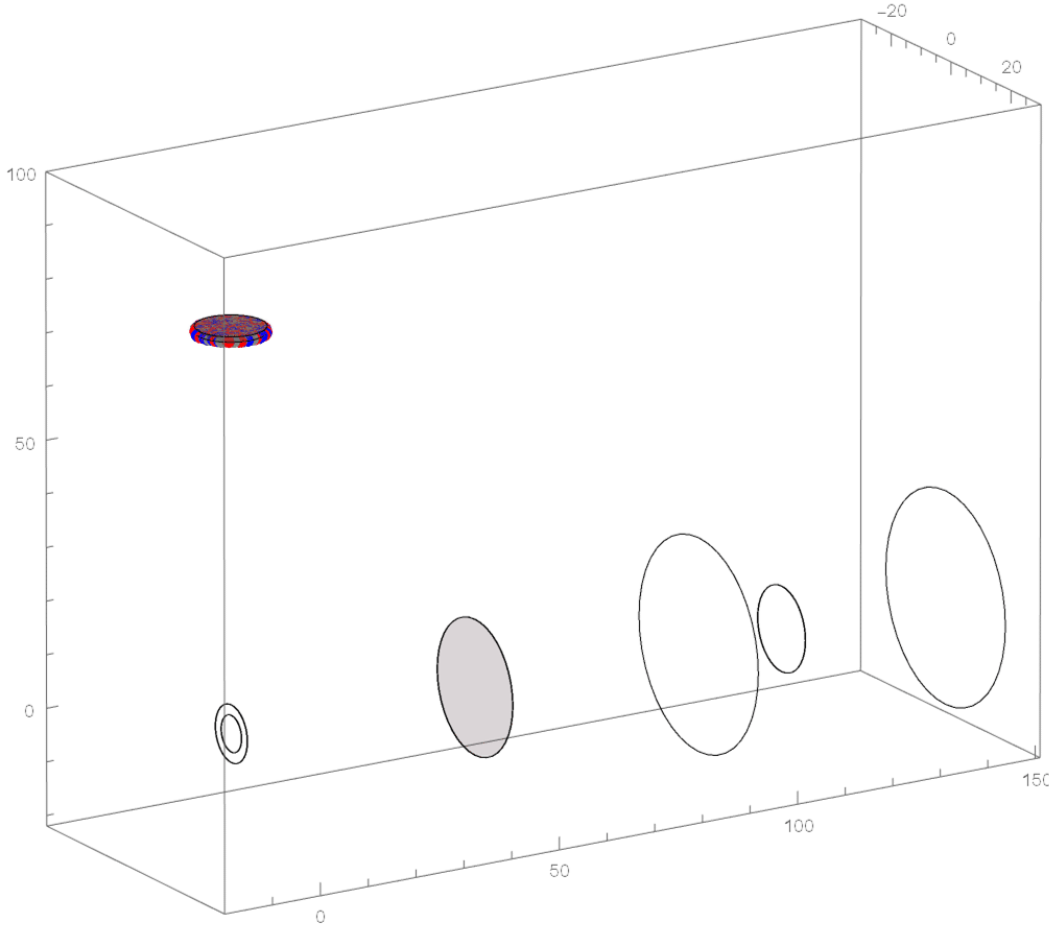
LASER-IF-UFRJ

Matrix Isolation Sublimation (MISu): (PRELIMINARY) proposal: H^- for ALPHA Hbar trap




b)
V(z)
B(z)
V(z) (V)
B(z) (mT)
E0
E1
E2
E3
E4
E5
4
2
0
−2
75
50
25
0
−25
50
100
150
200
Position z (mm)





-20
0
20
100
50
0
0
50
100
150

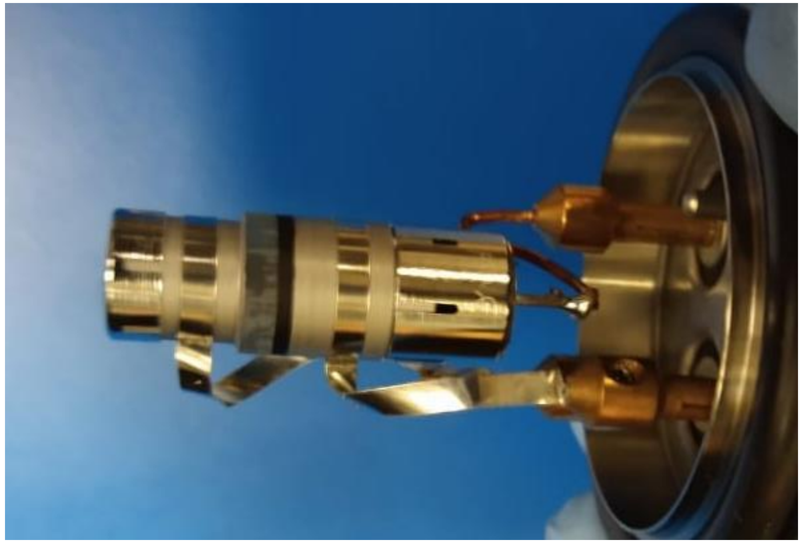
Software

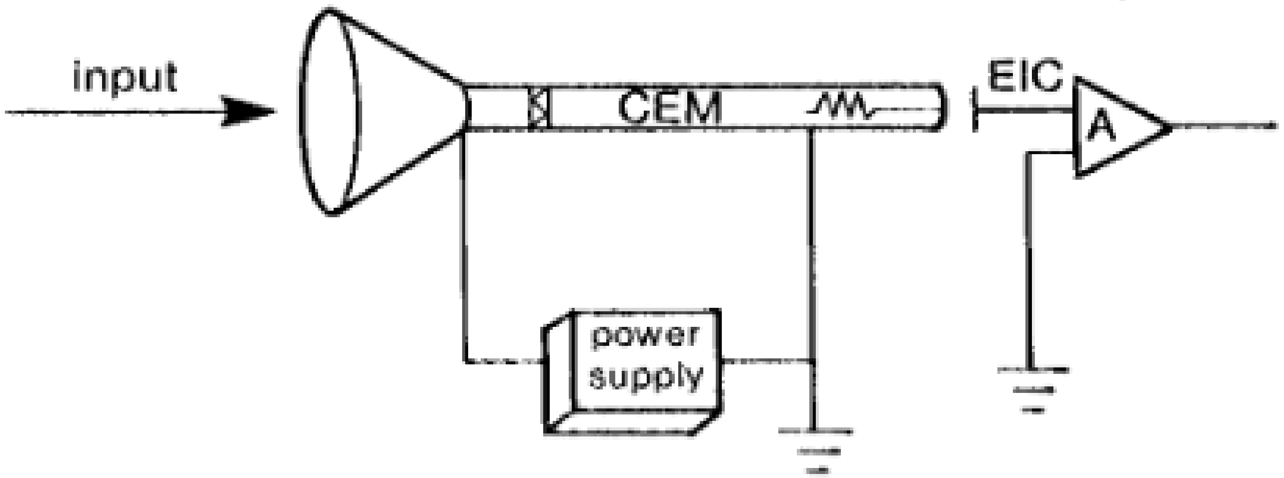
PITANGA_v5.vi
ERROR
reset osc
config osc
done
0
RUN
SHOW PARAMETERS
HV INTERLOCK
clear
mirror - Ablation
shutter - CLOSED
ON
Pulse Laser Continuosly
N
344
mean
65,4591
standard deviation
0,0000
size(s)
0
time (ms)
0
HISTOGRAM
STOP MATRIX
event
Principal
Cooldown
Matriz/Ablação
Pulso de Calor
Visualização
DAQmx & Parameters
Equipaments & Configuration
PRINT
Neônio ou H2
[0] Ne
Pressao do gas (torr)
NaN
potência laser ablação (mm)
35
Vácuo
Ne
H2
GÁS
inicial
ciclo
ablação
final
ciclos
always ON
gas (s)
flux (s)
vac. on (s)
tempo total
42,7
ABLAÇÃO
do ablation
LiH
delay (s)
number of pulses
frequency (Hz)
Q-switch (us)
Li - 670.7762 nm
Li - 670.7762 nm
Tsafira

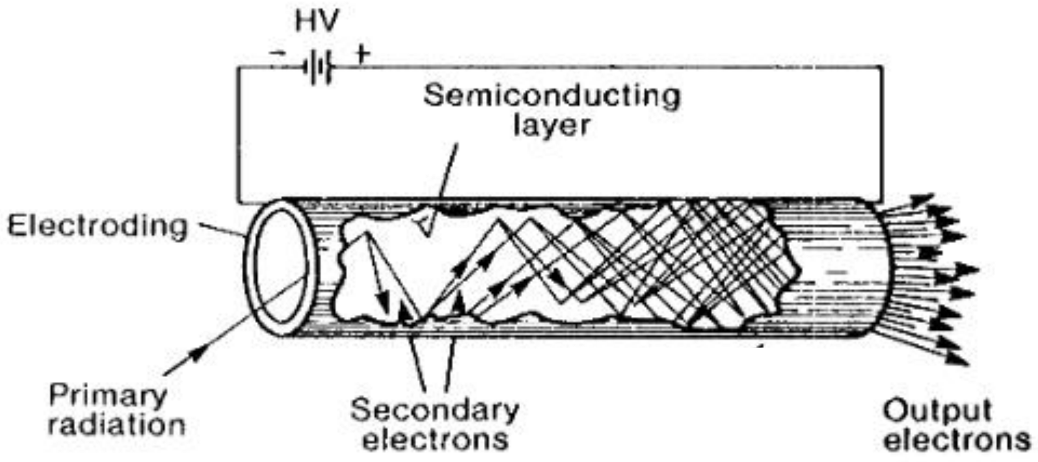
Software


PITANGA_v5.vi
reset osc
config osc
done
0
ERROR
RUN
SHOW PARAMETERS
HV INTERLOCK
clear
mirror - Ablation
shutter - CLOSED
Pulse Laser Continuosly
HISTOGRAM
STOP MATRIX
event
ON
N
746
mean
65,4591
standard deviation
0,0000
size(s)
0
time (ms)
0
Principal
Cooldown
Matriz/Ablação
Pulso de Calor
Visualização
DAQmx & Parameters
Equipaments & Configuration
Visualiza Atual
heat pulse duration (ms)
5,000
heat pulse voltage (V)
20,000
fase (graus)
0
TRIGGER
acquisition time (ms)
10
Time Of Flight
electron energy (eV)
26,0
electron pulse delay (us)
2500,0
electron intensity
210
(Q-switch)
acceleration potential (V)
5,00
acceleration delay (ns)
0
acceleration time (us)
200
Li - 670.7762 nm
FP - Li
Array
Function 1
Function 2
Channel 1
modulacao
Tsafira
extraction always ON

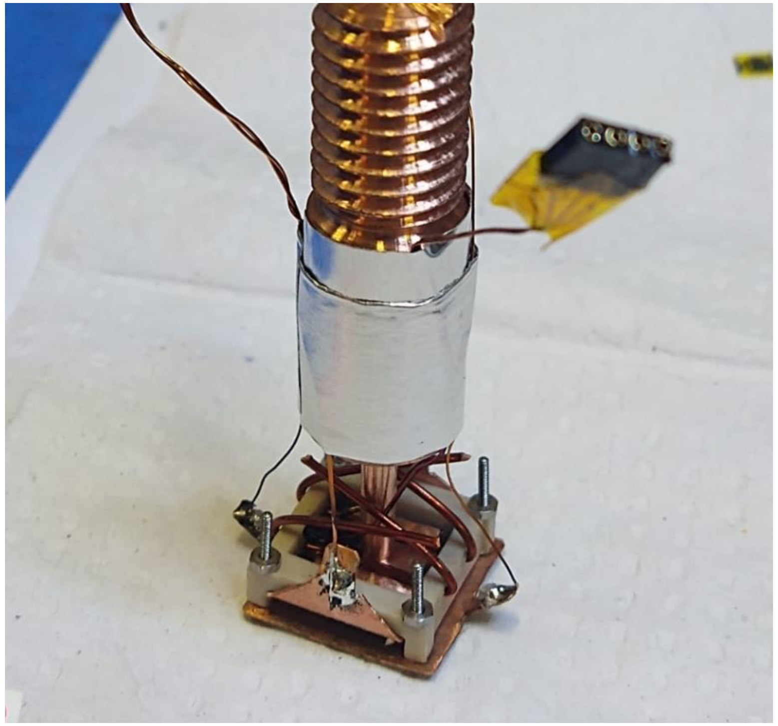
Channeltron - CEM



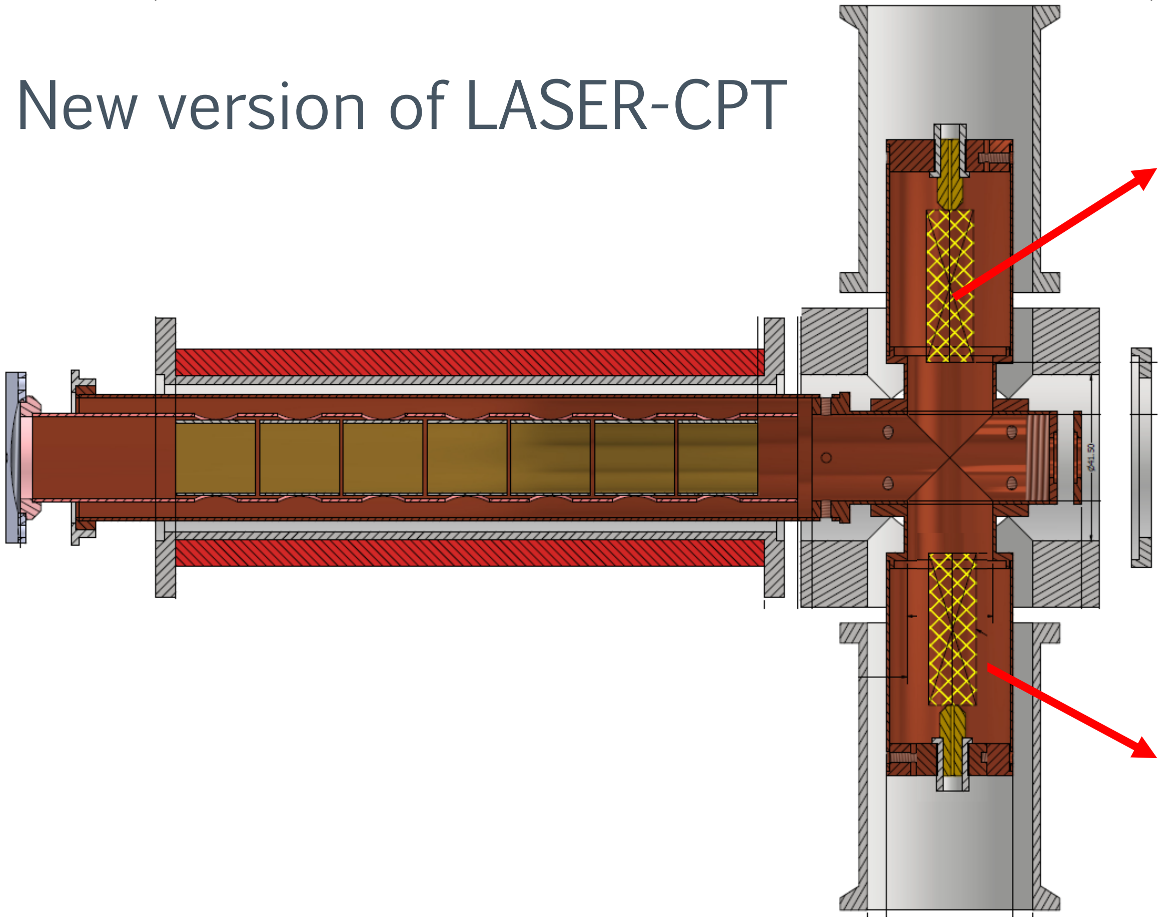




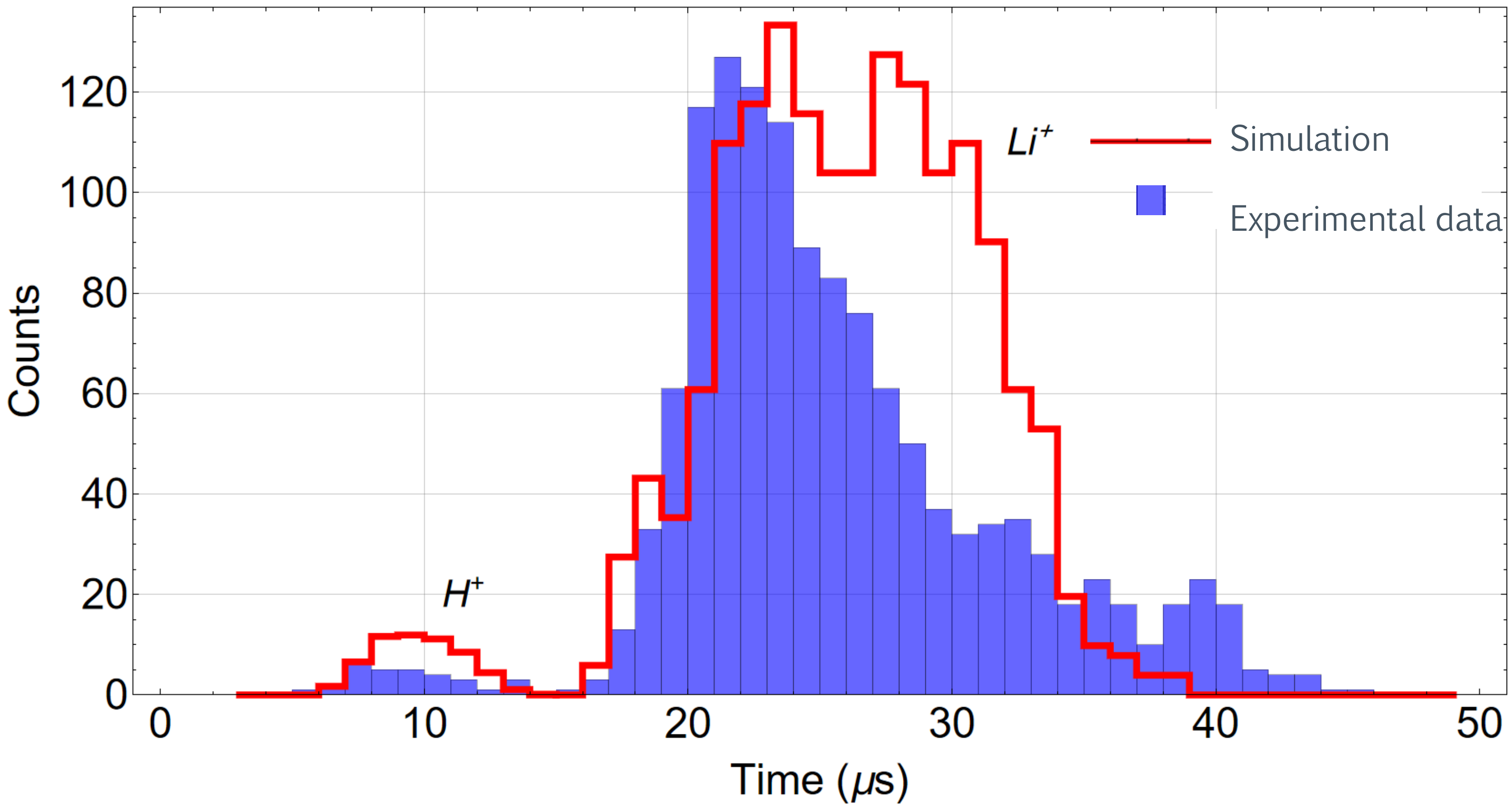
Funcionamento do Channeltron [6]



New version of LASER-CPT

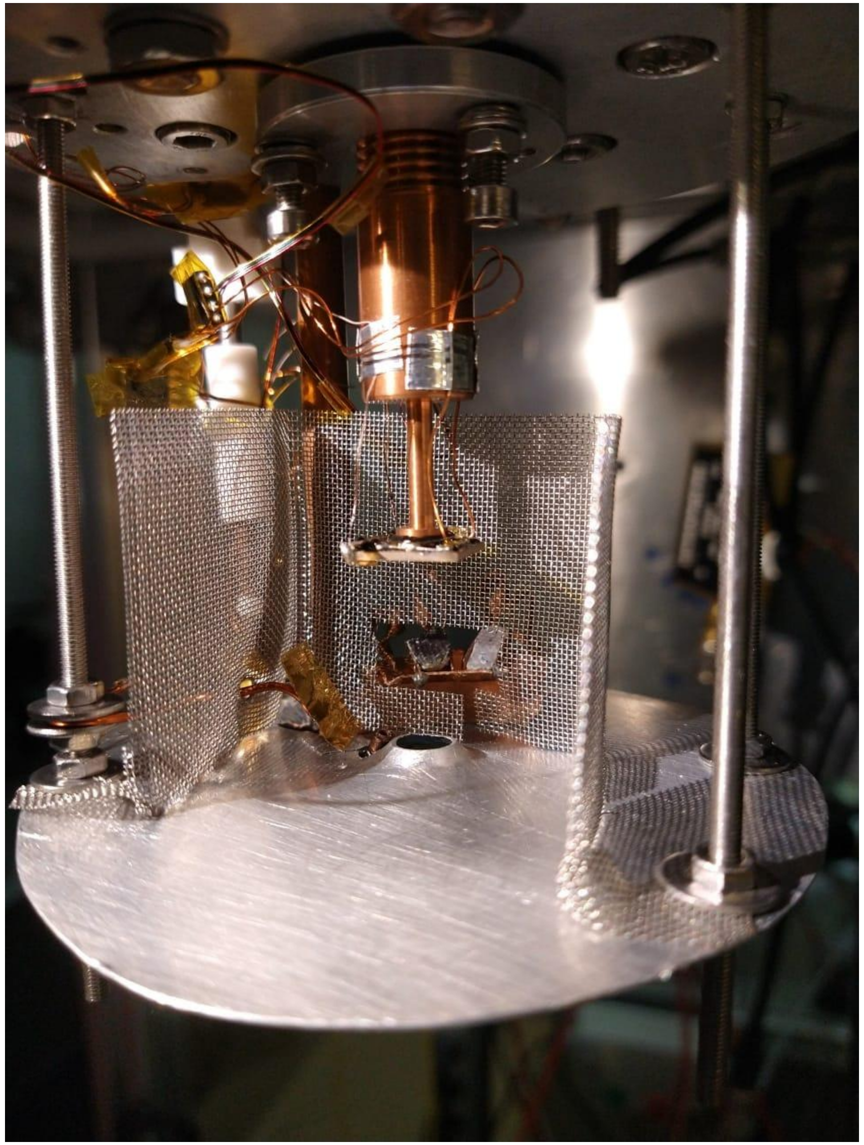


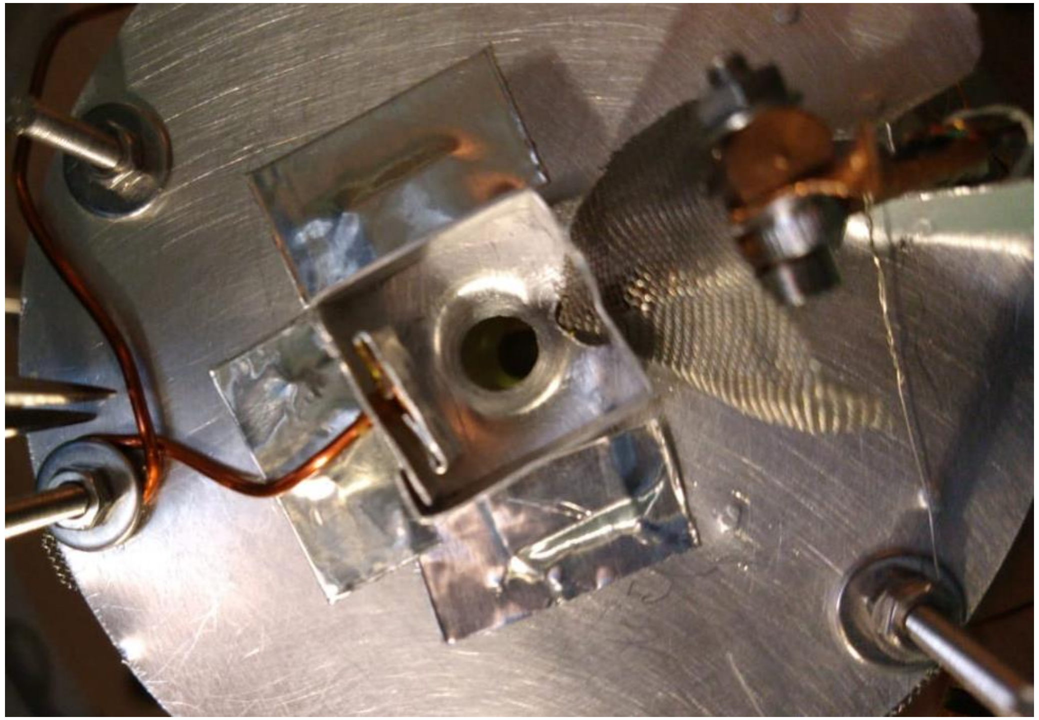
- More electrodes (possible to trap both positive and negatively charged particles)
    - Possible to stack from different pulses
    - Molecular production
- Two CEM for simultaneous detection
- More uniform magnetic field (yet still ~0.1 T)
- Optical access on axis for spectroscopy

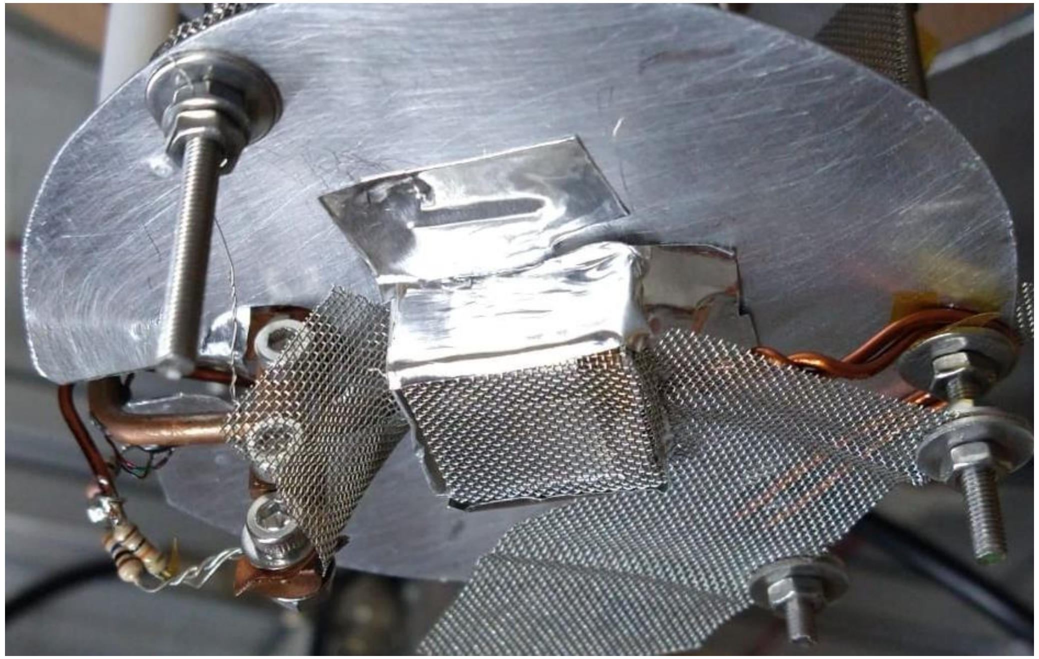


Li+
Simulation
Experimental data
H+
Counts
Time (μs)
0
20
40
60
80
100
120
0
10
20
30
40
50

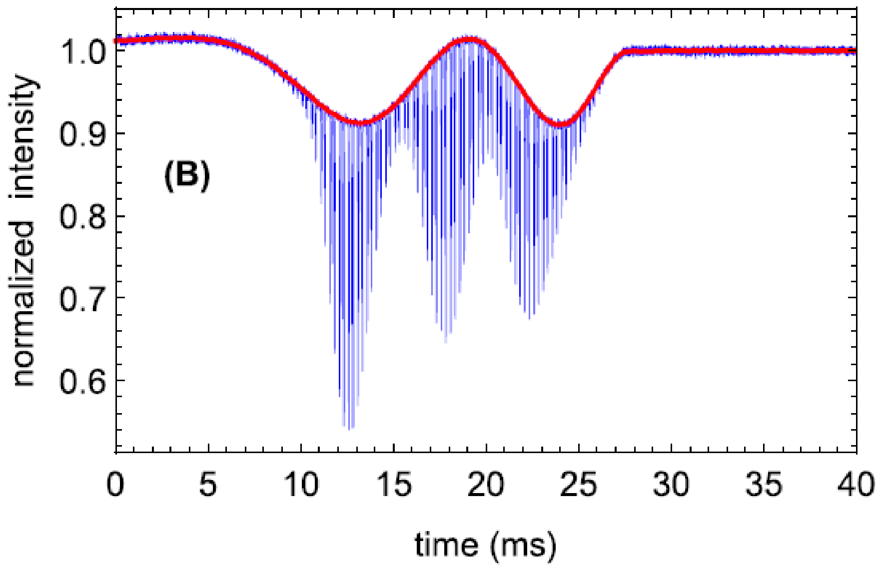
π

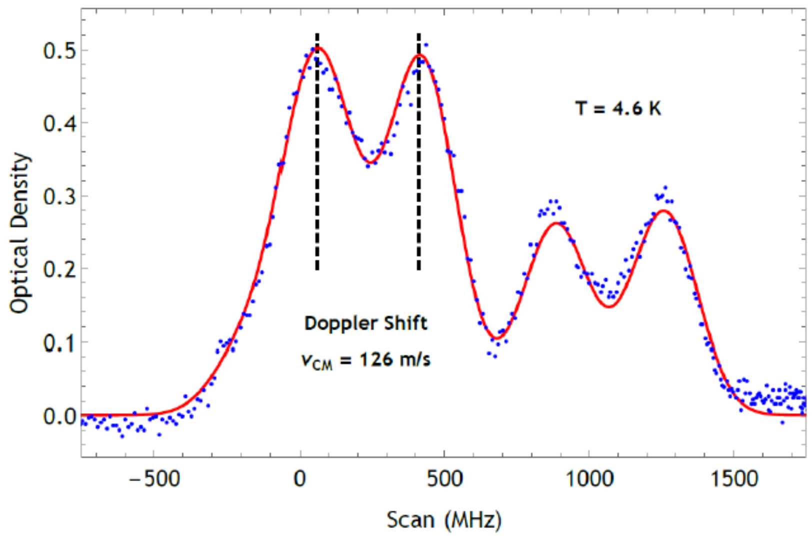


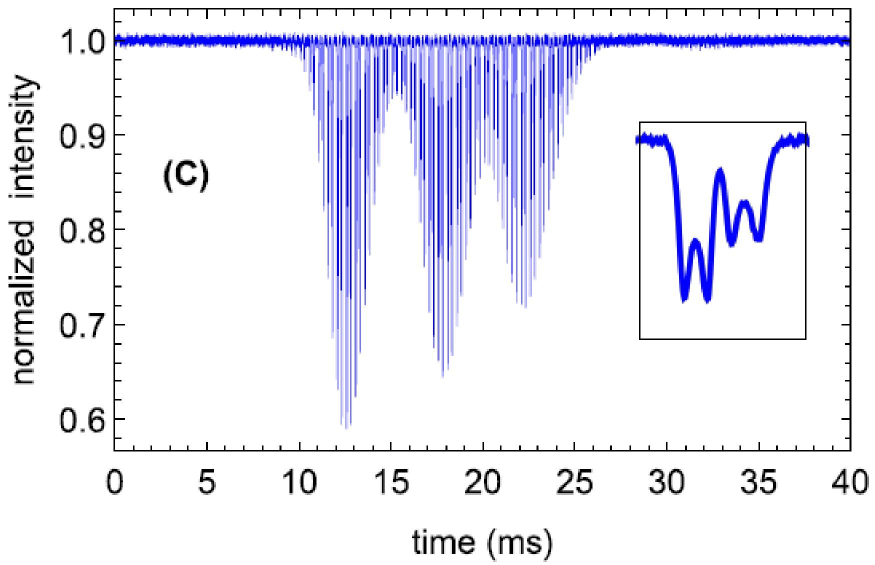


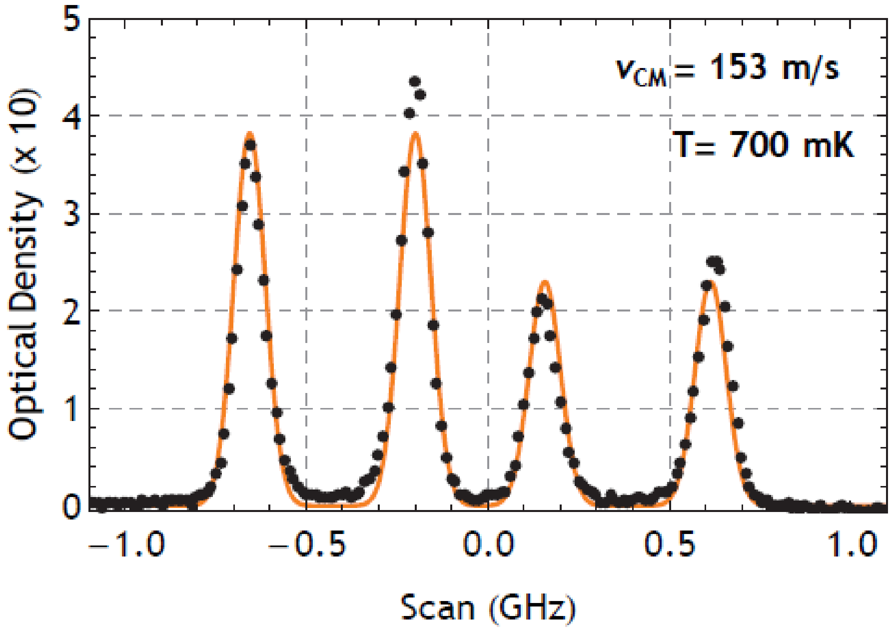


Absorption

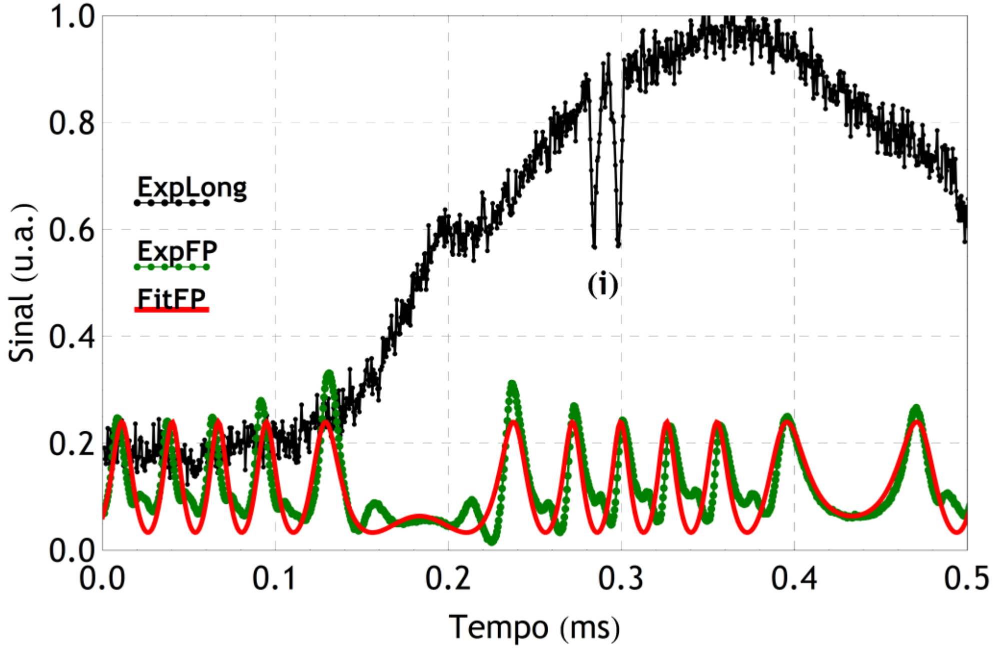

(B)
normalized intensity
1.0
0.9
0.8
0.7
0.6
0 5 10 15 20 25 30 35 40
time (ms)


T = 4.6 K
Doppler Shift
v_{CM} = 126 m/s
Optical Density
0.5
0.4
0.3
0.2
0.1
0.0
−500 0 500 1000 1500
Scan (MHz)

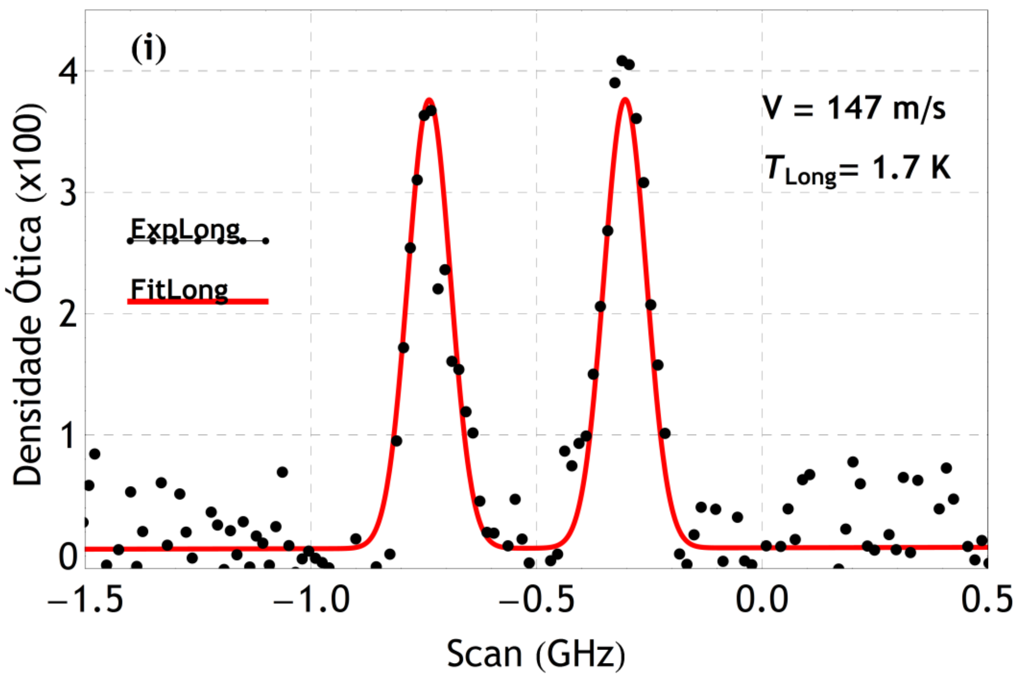

(C)
normalized intensity
1.0
0.9
0.8
0.7
0.6
0 5 10 15 20 25 30 35 40
time (ms)


v_{CM} = 153 m/s
T= 700 mK
Optical Density (x 10)
5
4
3
2
1
0
−1.0 −0.5 0.0 0.5 1.0
Scan (GHz)

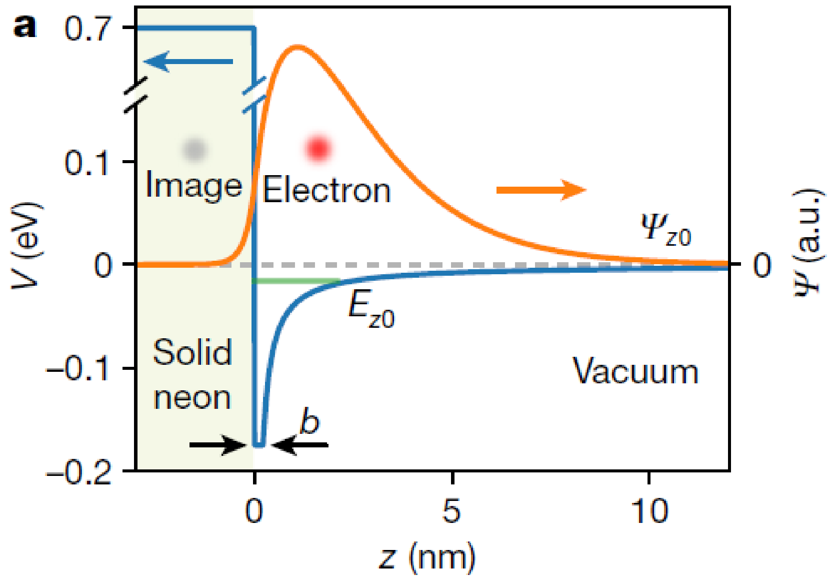
Molecules



1.0
0.8
0.6
0.4
0.2
0.0
Sinal (u.a.)
ExpLong
ExpFP
FitFP
(i)
0.0
0.1
0.2
0.3
0.4
0.5
Tempo (ms)



(i)
4
3
2
1
0
Densidade Ótica (x100)
V = 147 m/s
T_{Long}= 1.7 K
ExpLong
FitLong
−1.5
−1.0
−0.5
0.0
0.5
Scan (GHz)



$|1_z\rangle$ -3.1 meV

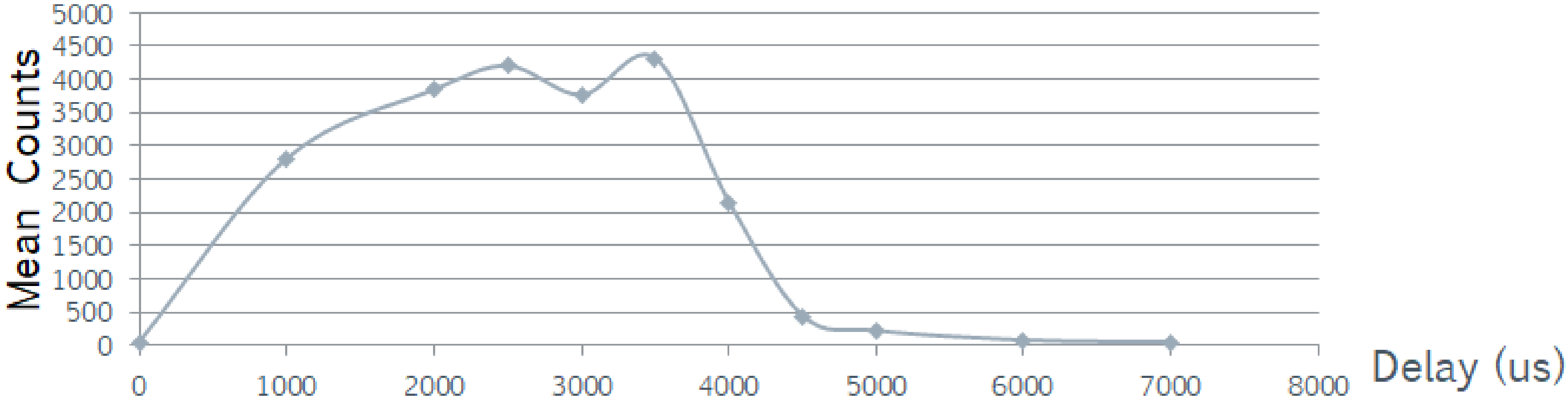
$|0_z\rangle$ -15.8 meV

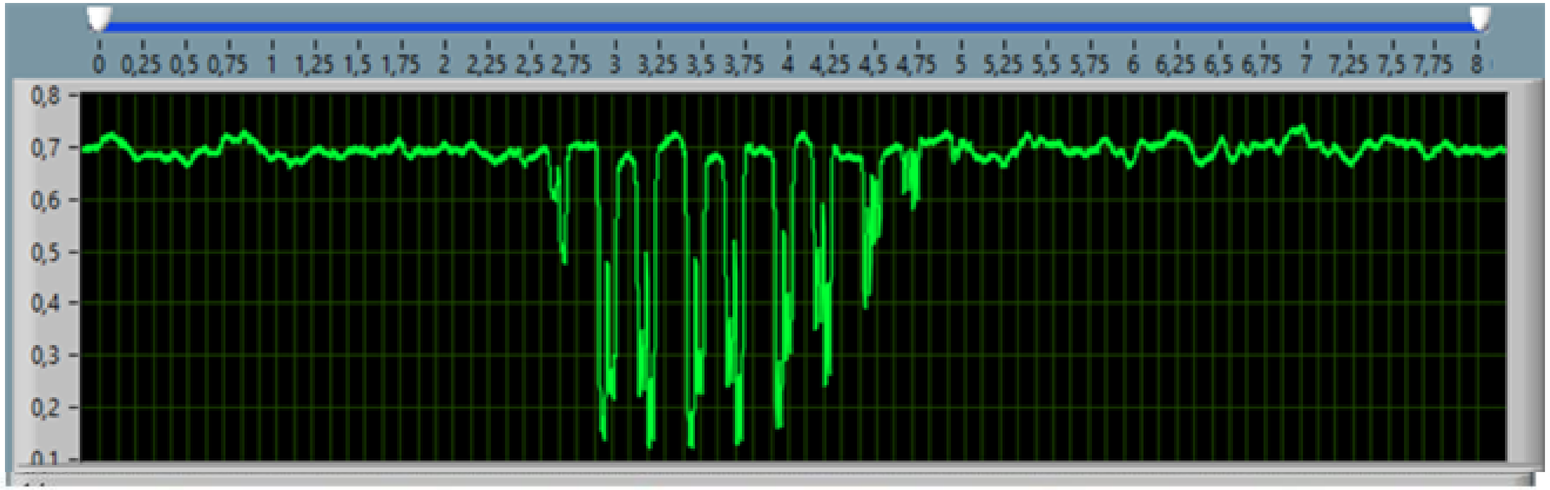
$$\Delta E_{01} = 12.7\ meV \approx 146\ K \ll 4\ K$$

Neon can accommodate a 2D electron gas with a density over $10^{10} cm^{-2}$

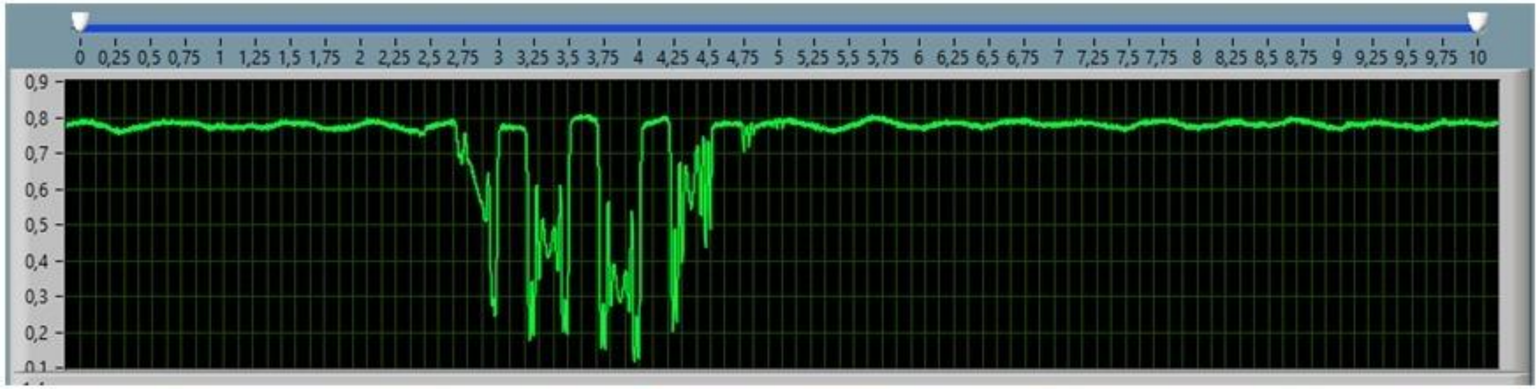
Ions and neutrals time correspondence

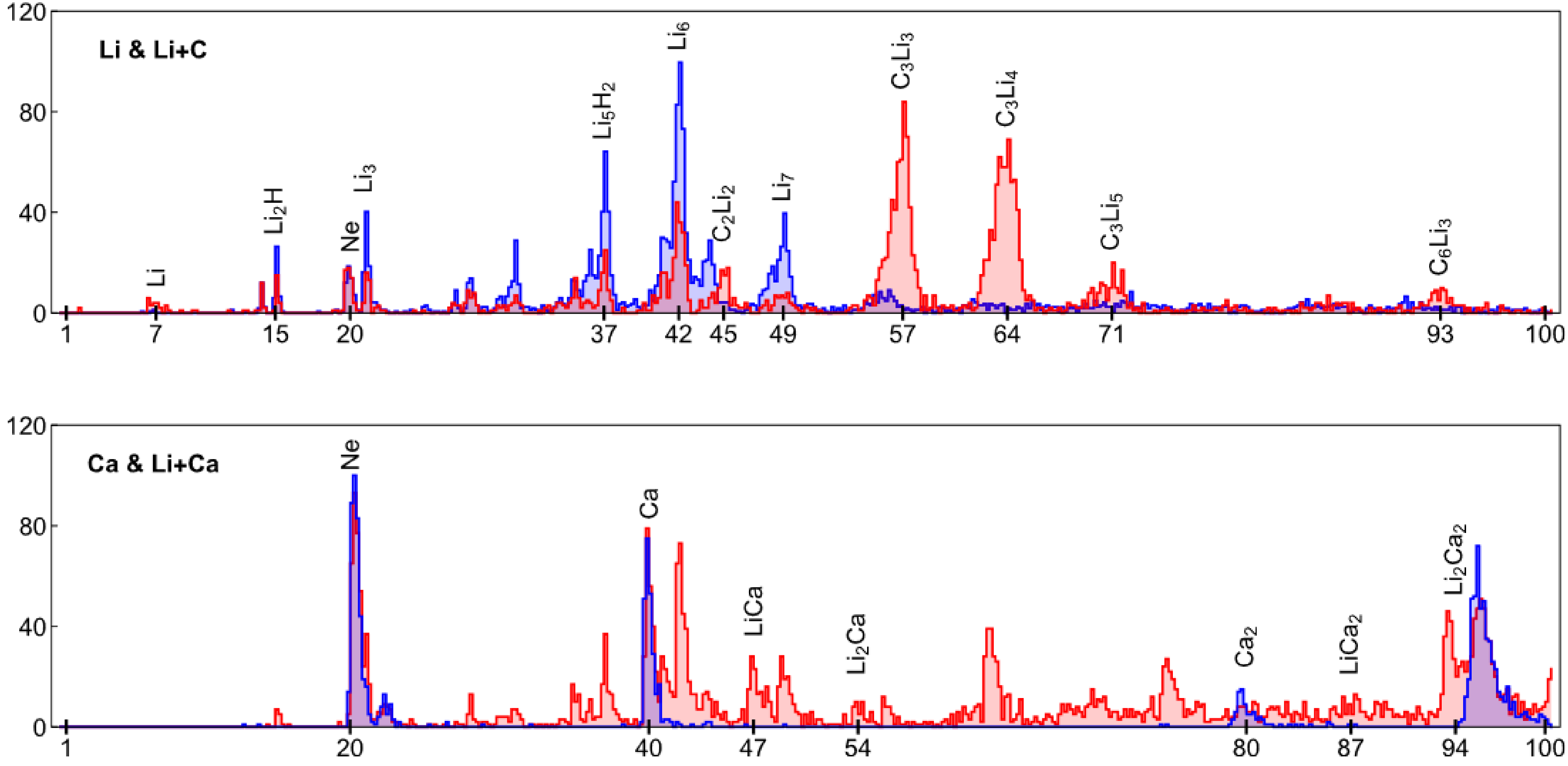
Negative charge particles detection





Ions and neutrals time correspondence




Li & Li+C
Li
Li2H
Ne
Li3
Li5H2
Li6
C2Li2
Li7
C3Li3
C3Li4
C3Li5
C6Li3
120
80
40
0
1
7
15
20
37
42
45
49
57
64
71
93
100
Ca & Li+Ca
Ne
Ca
LiCa
Li2Ca
Ca2
LiCa2
Li2Ca2
120
80
40
0
1
20
40
47
54
80
87
94
100