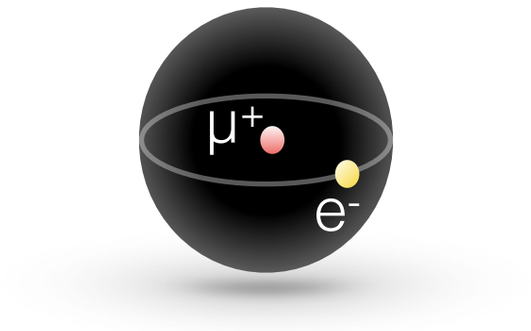
The Development of a High Brightness Muonium Beam

Narongrit Ritjoho

on behalf of Muonium collaboration

What is Muonium ?



- Muonium is a bound state of an antimuon and an electron
- Hydrogen-like atom
- Unstable atom with lifetime 2.2 μs
- Pure leptonic system (1st and 2nd generations)
- No finite size and nuclear effect

Why Muonium ?

- Gravity of antimatter and 2nd generation particle

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Trump

$9.8\ m/s^2$

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Trump

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Anti-Trump

$?\ m/s^2$

Why Muonium ?

- Gravity of antimatter and 2nd generation particle

Trump

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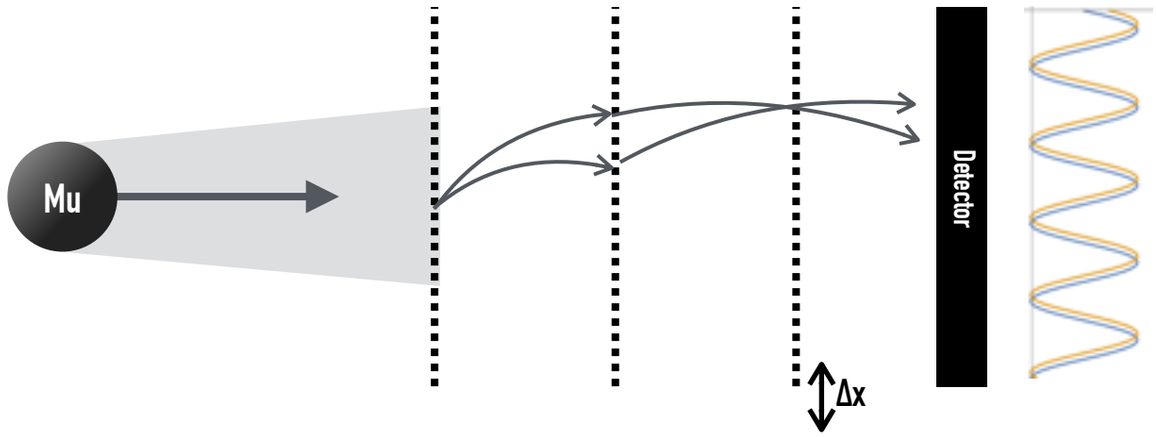
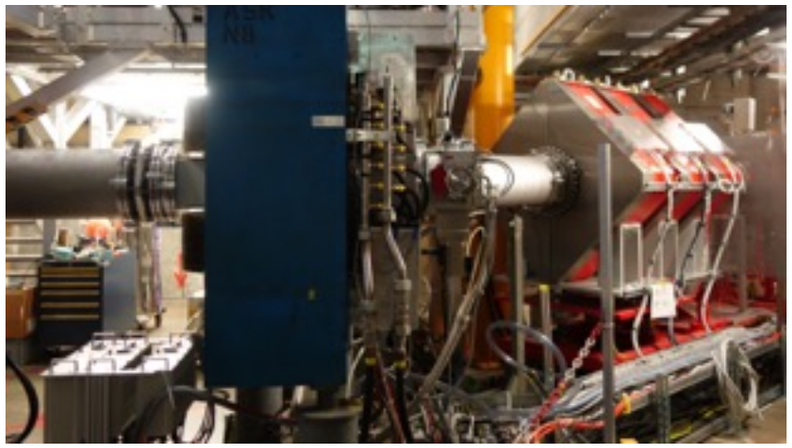
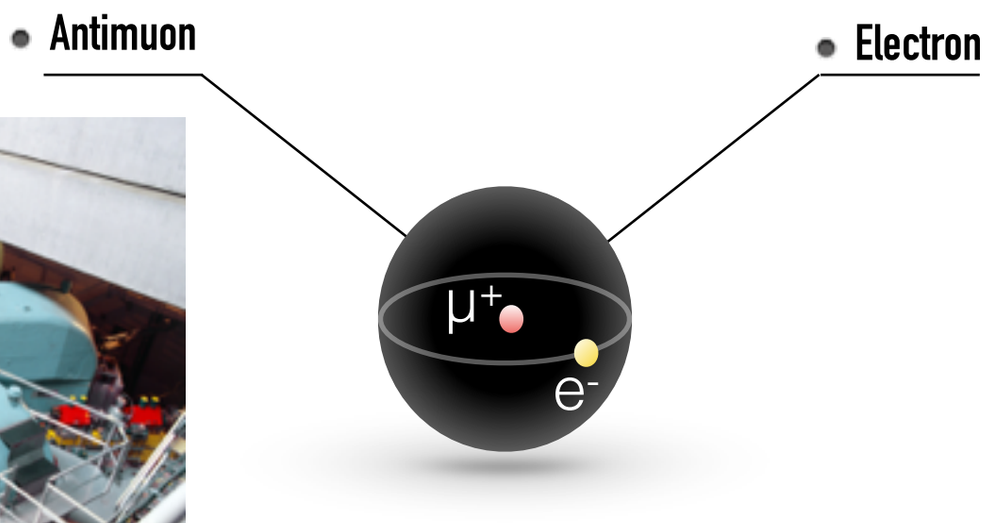
$?\ m/s^2$



How to produce Muonium ?





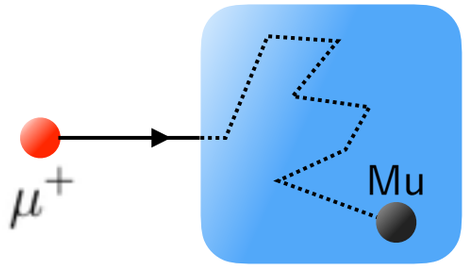
?

Pictures : https://www.psi.ch/media/the-psi-proton-accelerator

History of Muonium

1960 Ar gas

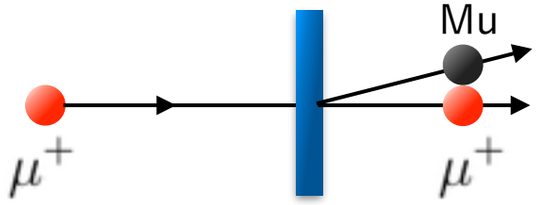
V.W.Hughes, Phys. Rev. Lett. 5, 20 (1960)



- First Mu was discovered by V.W.Hughes
- 100% Muonium yield in gas
- No vacuum yield

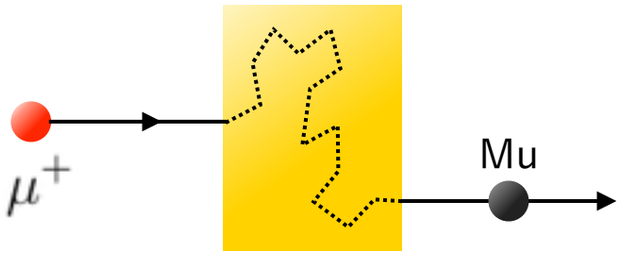
1986 Tungsten foil

A.P.Mills, Phys. Rev. Lett. 56, 14 (1986)



1986 SiO_2 powder or aerogel

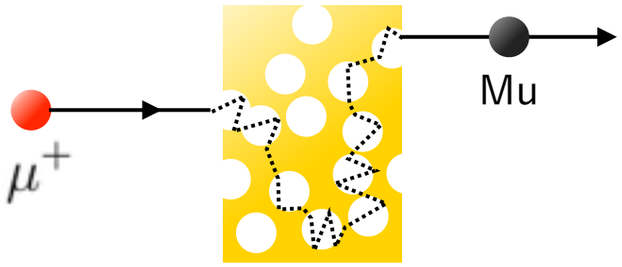
G. A. Beer, Phys. Rev. Lett. 57, 6 (1986)
G. A. Beer, Prog. Theor. Exp. Phys., 091C01 (2014)



- Muonium emitted into vacuum

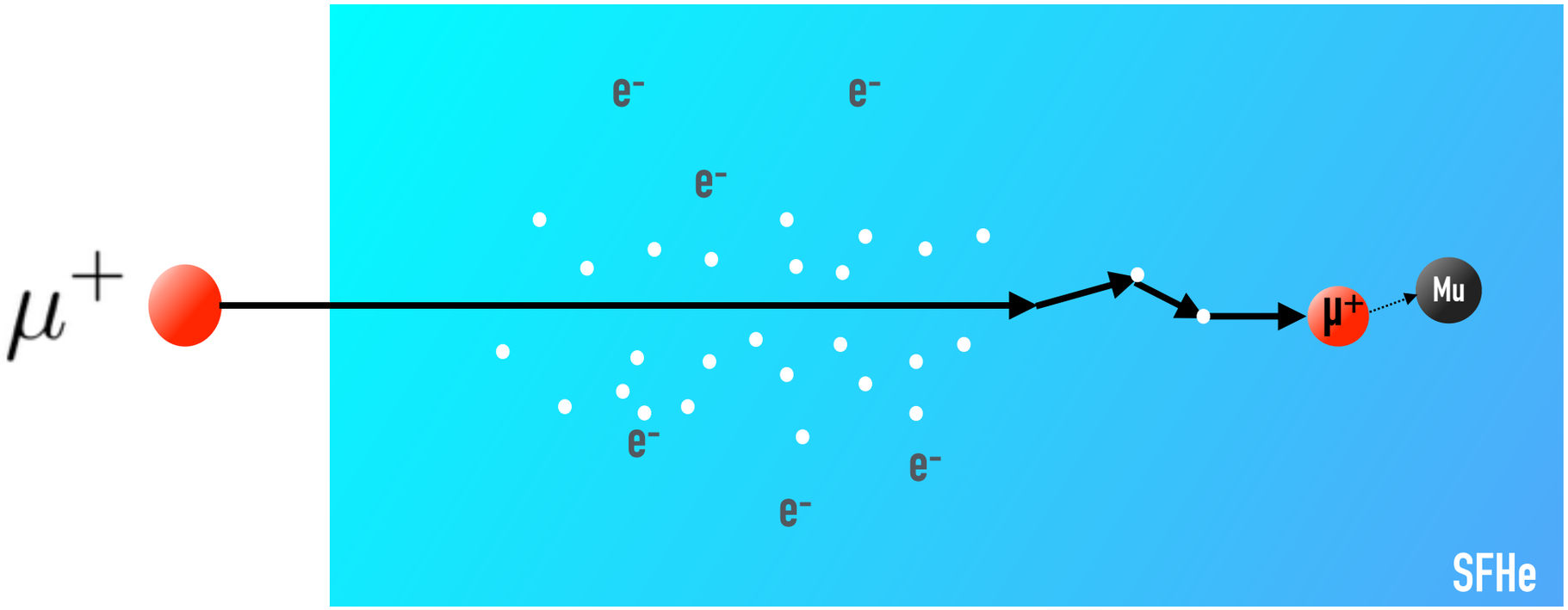
2012 SiO_2 mesoporous thin film

A.Antognini, Phys. Rev. Lett. 108, 14 (2012)



Now? Superfluid-He thin film

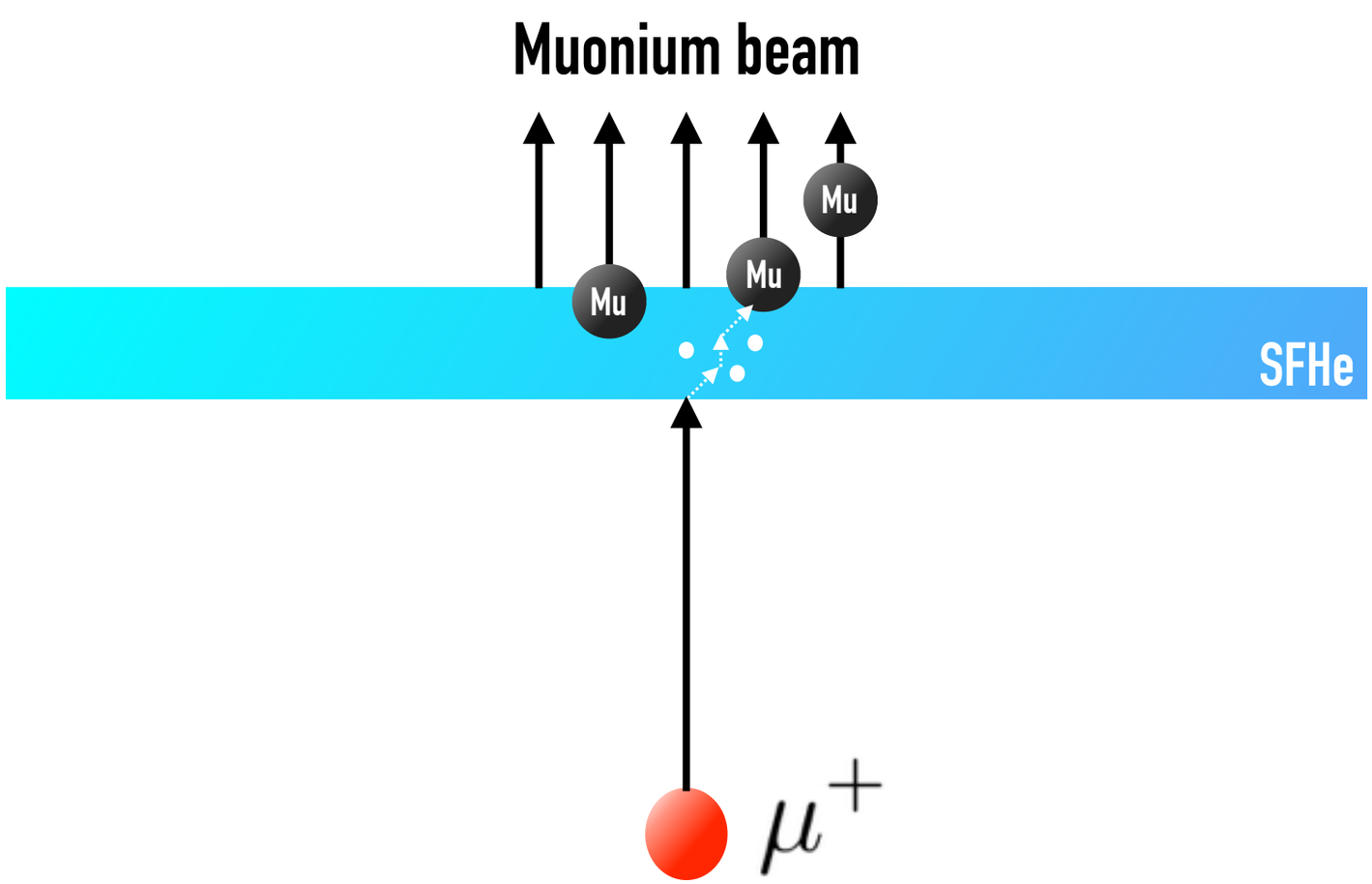
Muonium formation processes



D.G. Eshenko, Phys. Rev. B 66, 035105 (2002)

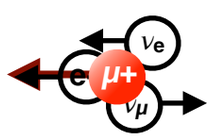
Superfluid-helium thin film target

- Mu experiences a positive chemical potential inside SFHe, $E/k_b \sim 270$ K
- Mu will be emitted out of the surface of a SFHe thin film with mono-energetic energy and narrow divergence



How to detect Muonium ?

- Muon spin rotation (muSR) technique
- $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$
- Due to parity violation of weak decay, the direction of emitted positron is distributed asymmetrically with respect to the spin of muon



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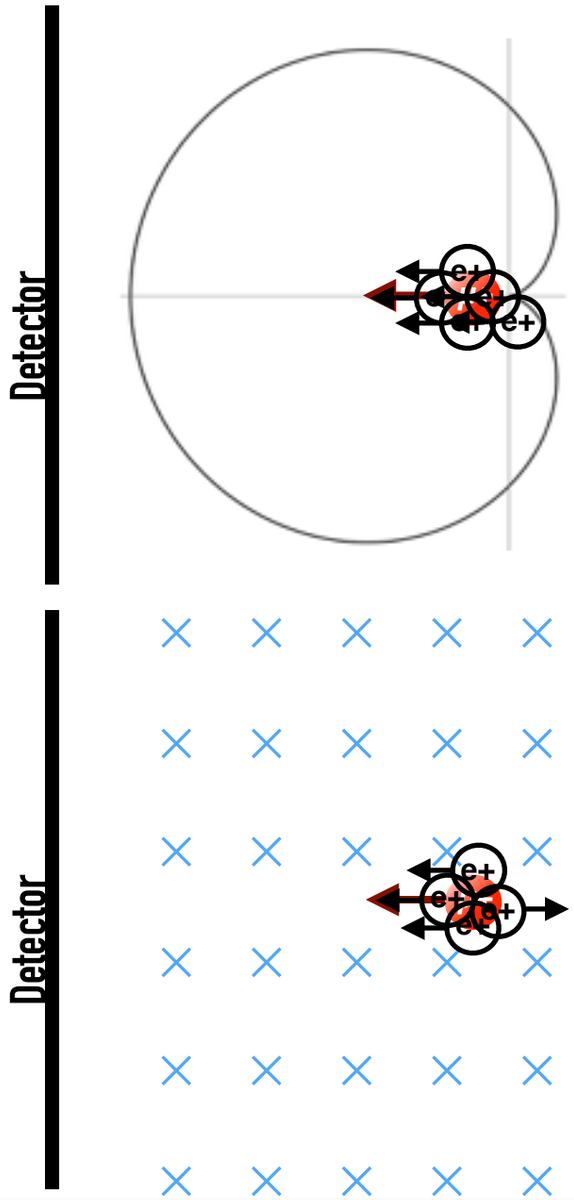

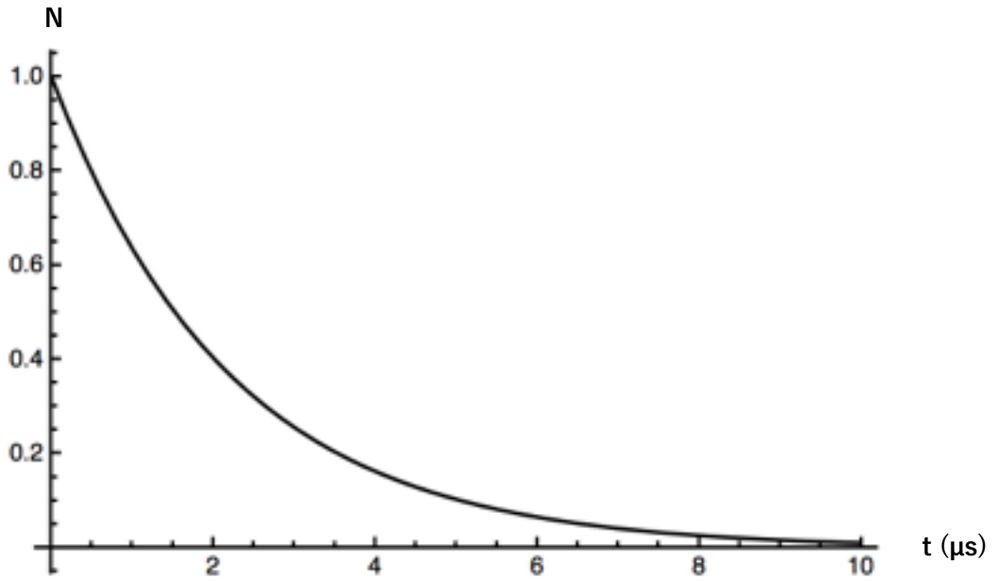

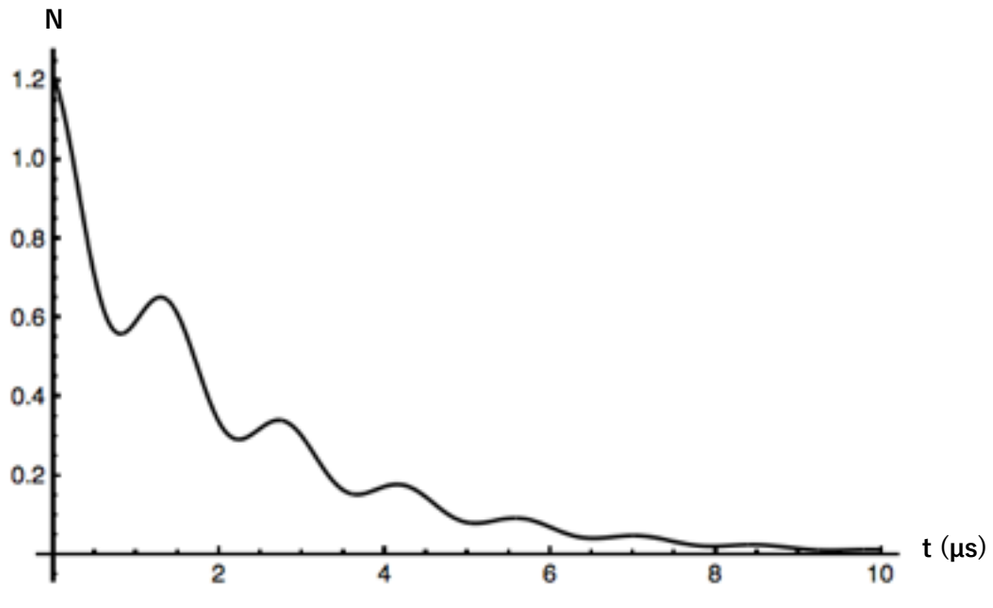

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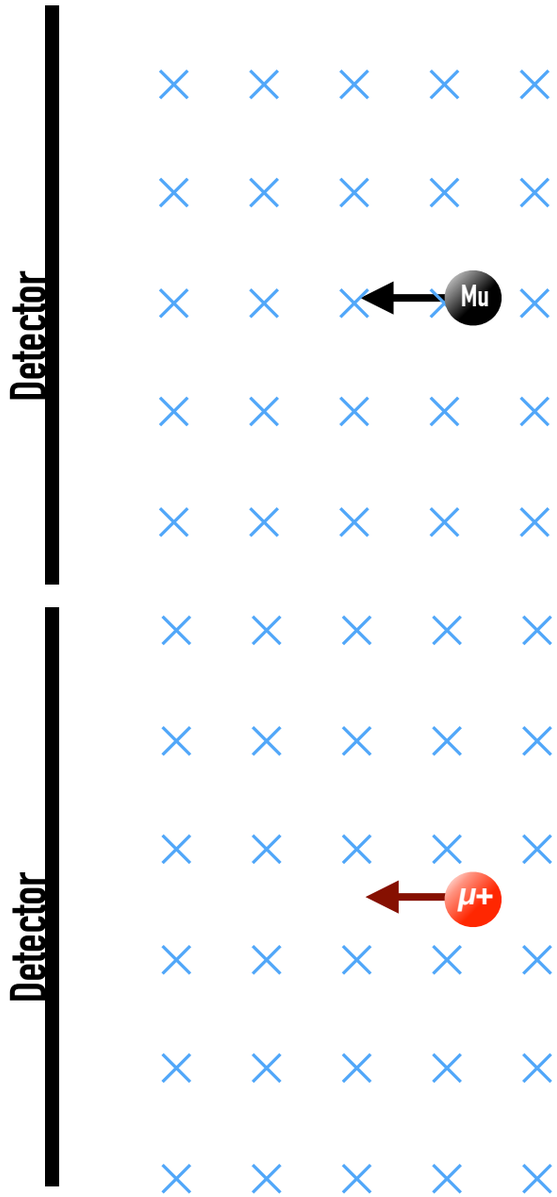
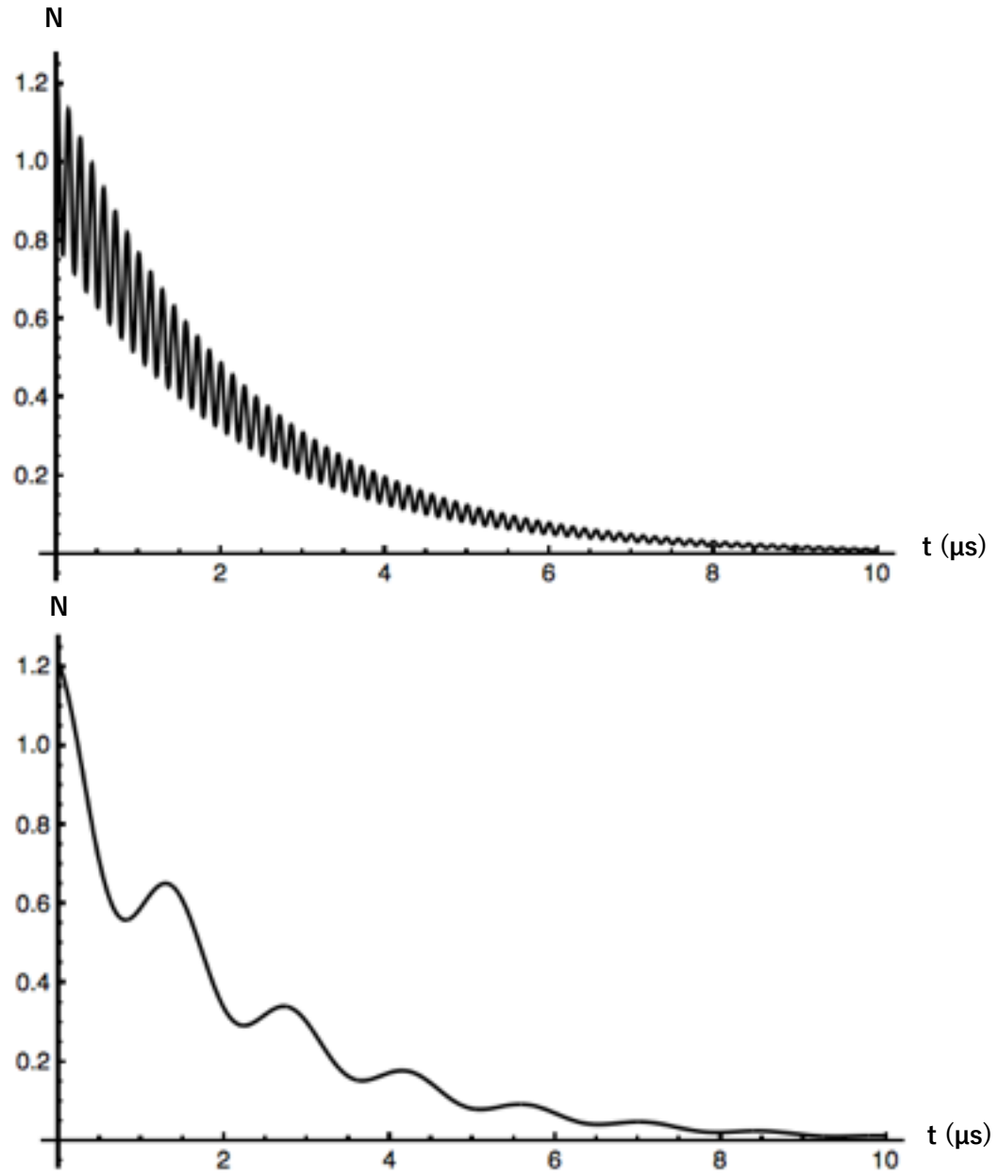
- Gyromagnetic ratio
- $\omega = \gamma \cdot B$
- $\gamma_{Mu} = 103 \cdot \gamma_\mu$





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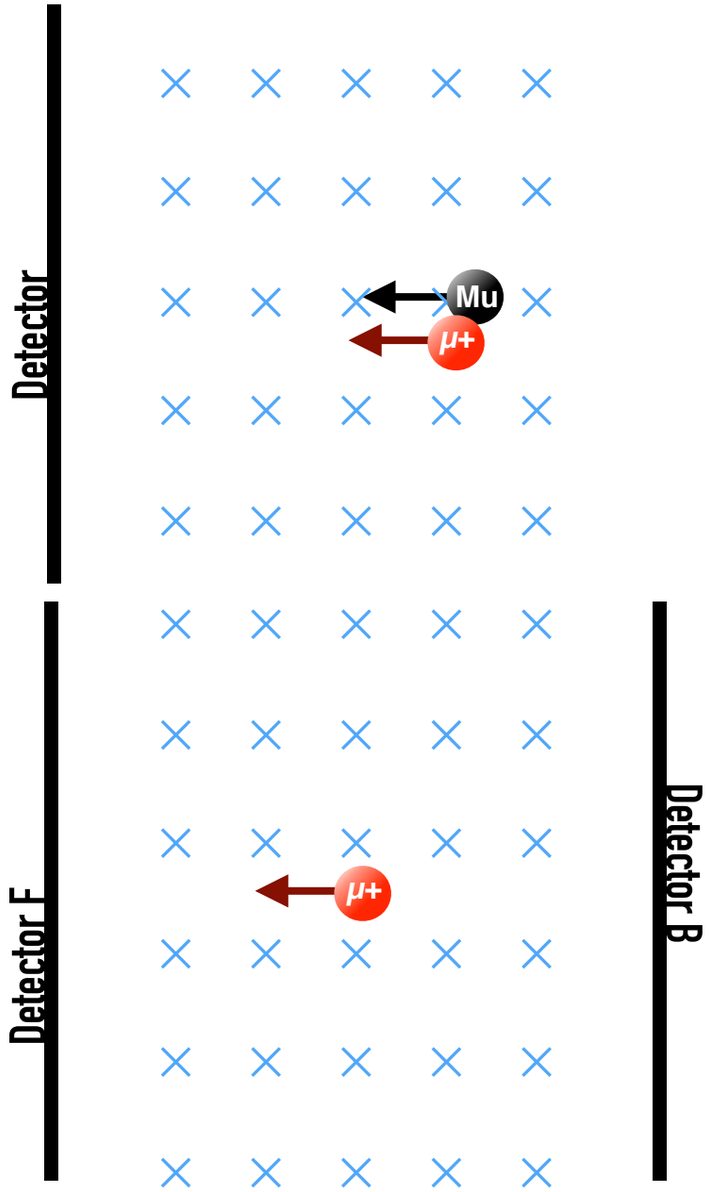
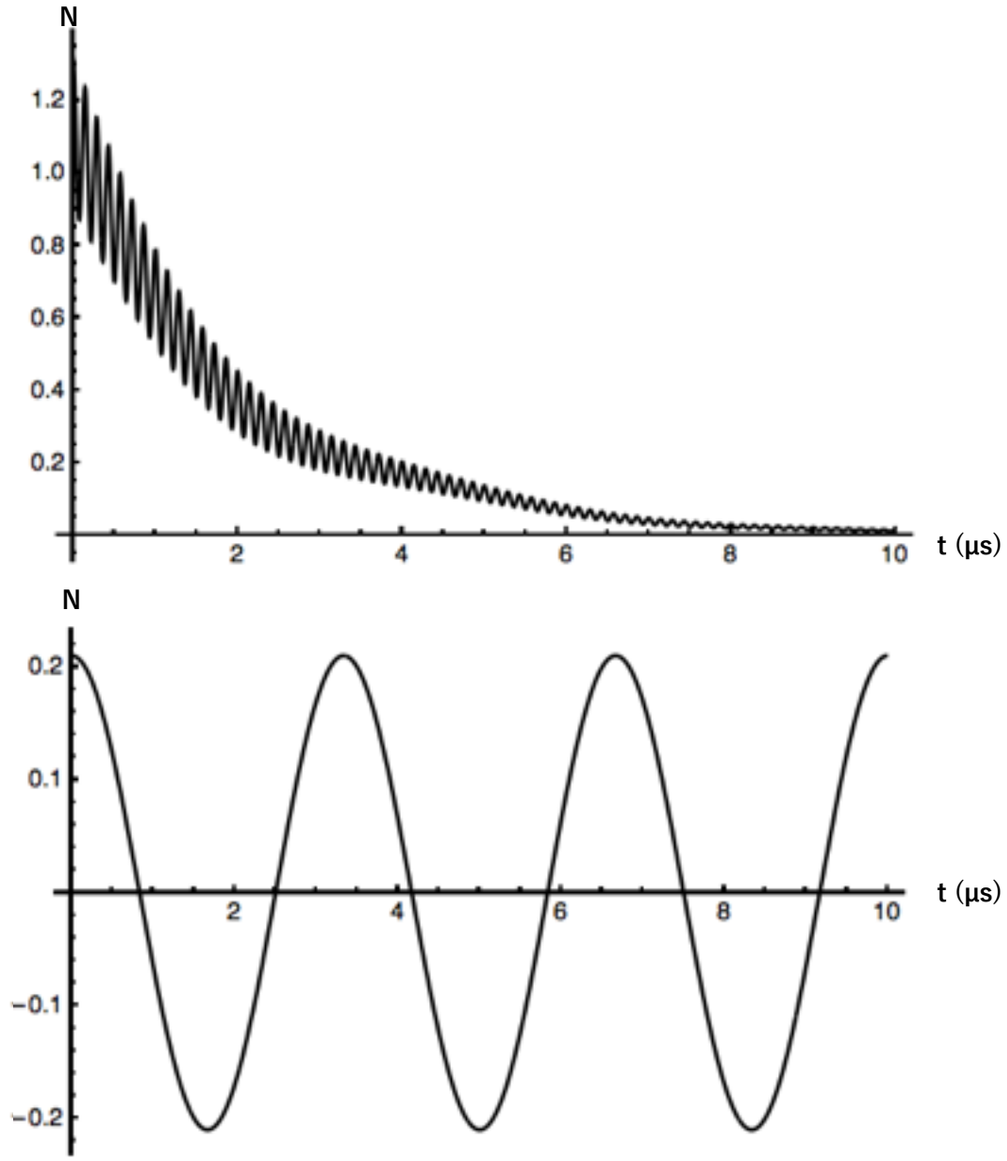


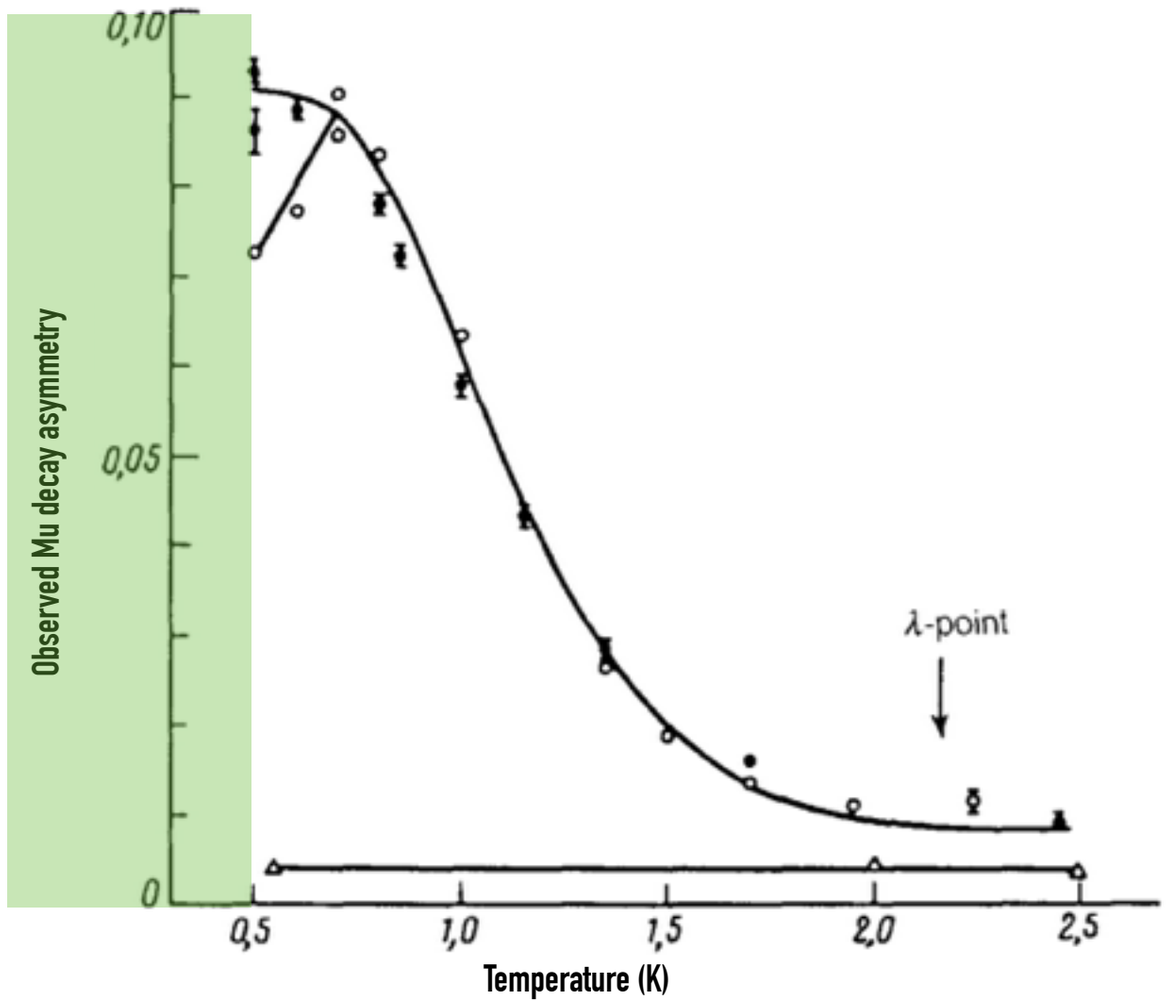
Decay asymmetry

$A = (N_F - N_B) / (N_F + N_B)$



Previous Studies of Muonium in Superfluid-Helium

- The previous study of Mu formation rate in bulk-SFHe shows a high formation rate depending on temperature(T) and mixtures of heliums
- Mu production rate depends on the mobility of muons inside the SFHe



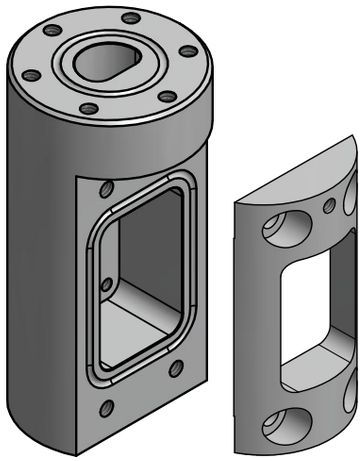
Open circles-Pure ^{4}He; filled circles-^{4}He+0.2%^{3}He; Triangle-pure ^{3}He

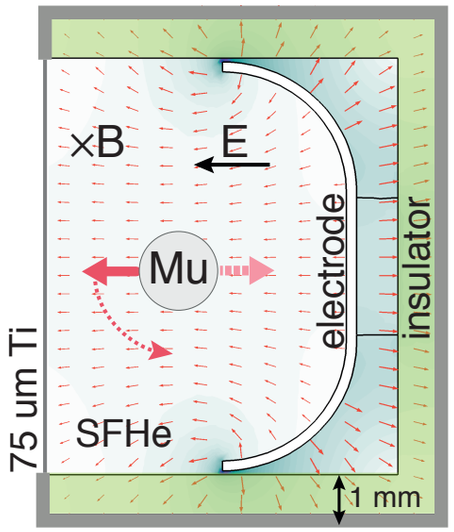
R. Abela et al., JETP Lett. 57, 157 (1993)

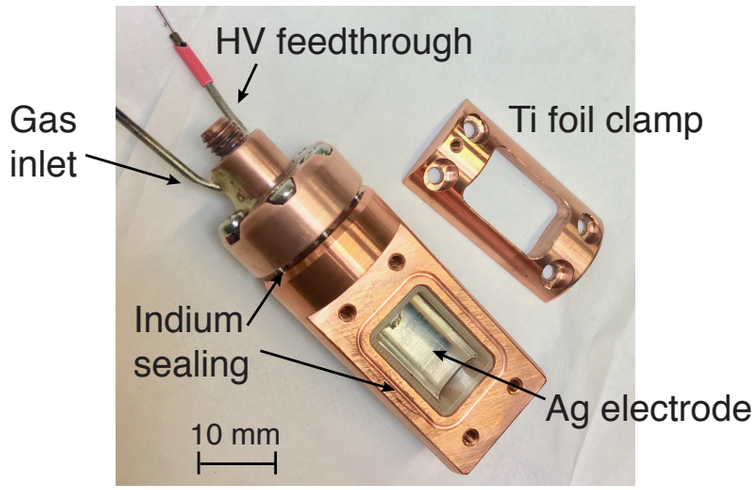
- We will also test the electric(E) and magnetic(B) field effect of the Mu formation rate

Experimental Setup

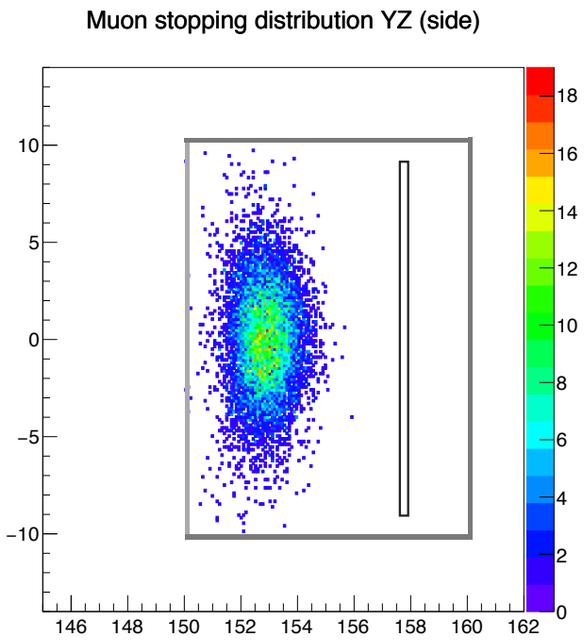
- Design of a SFHe container

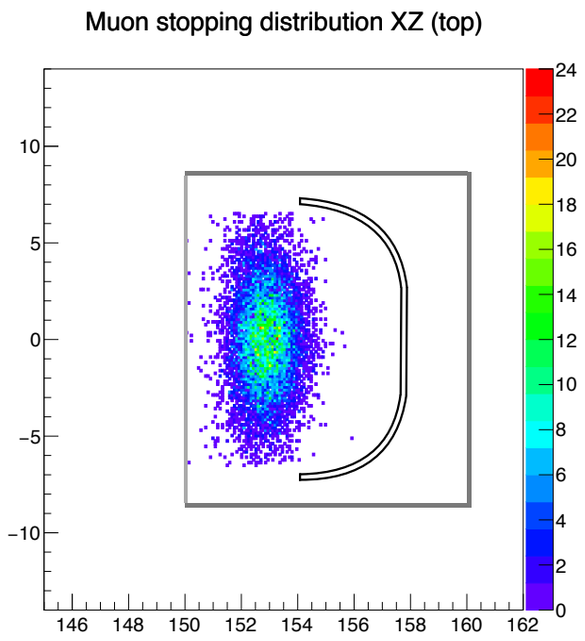




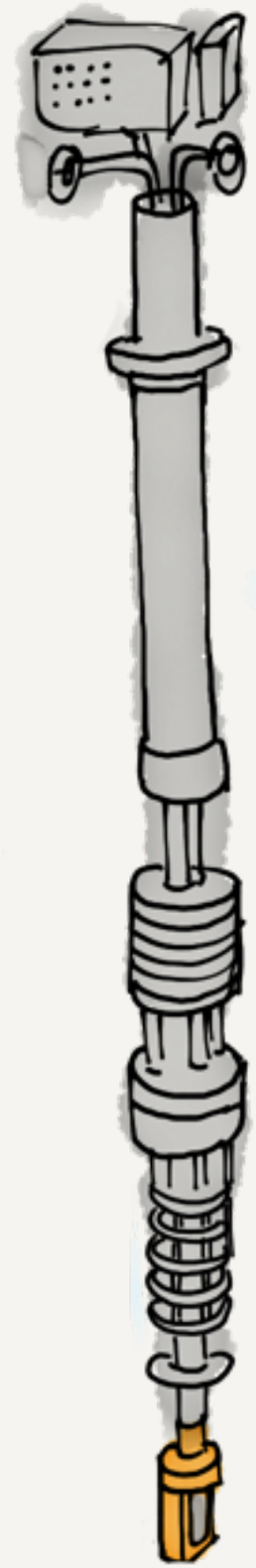


- Stopping distribution of muon in SFHe by G4beamline

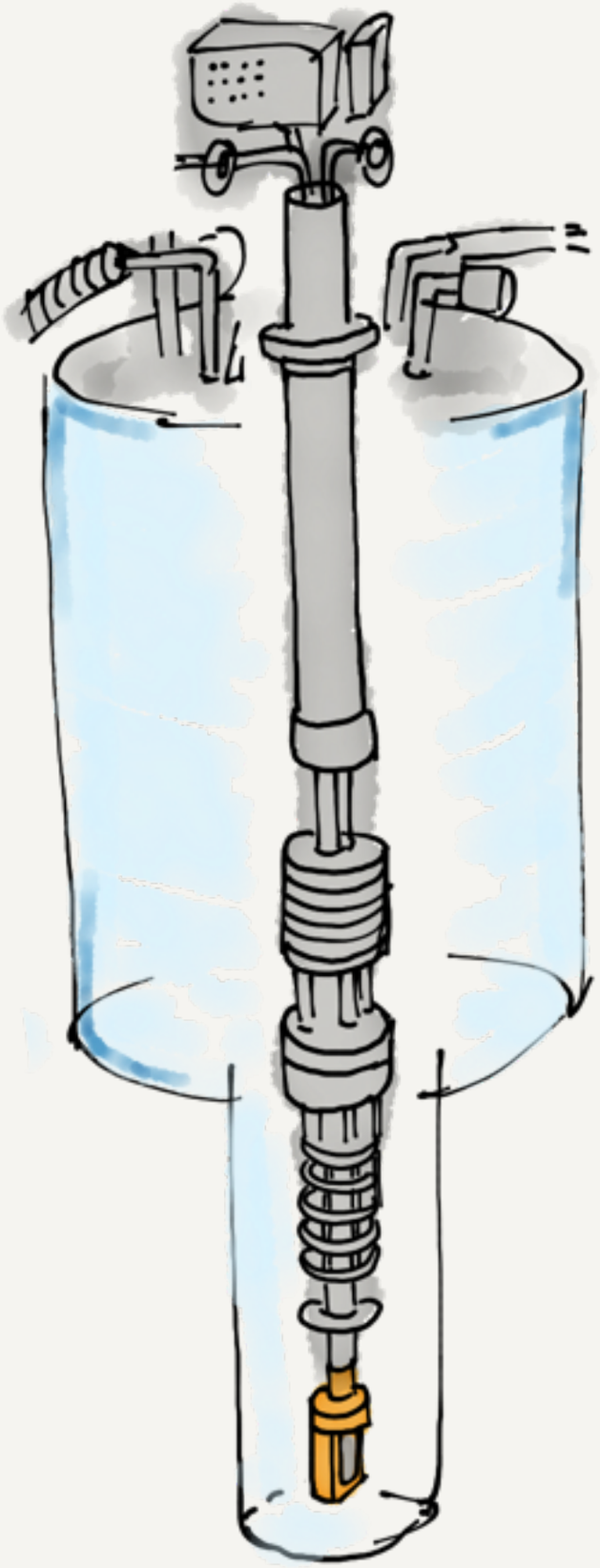


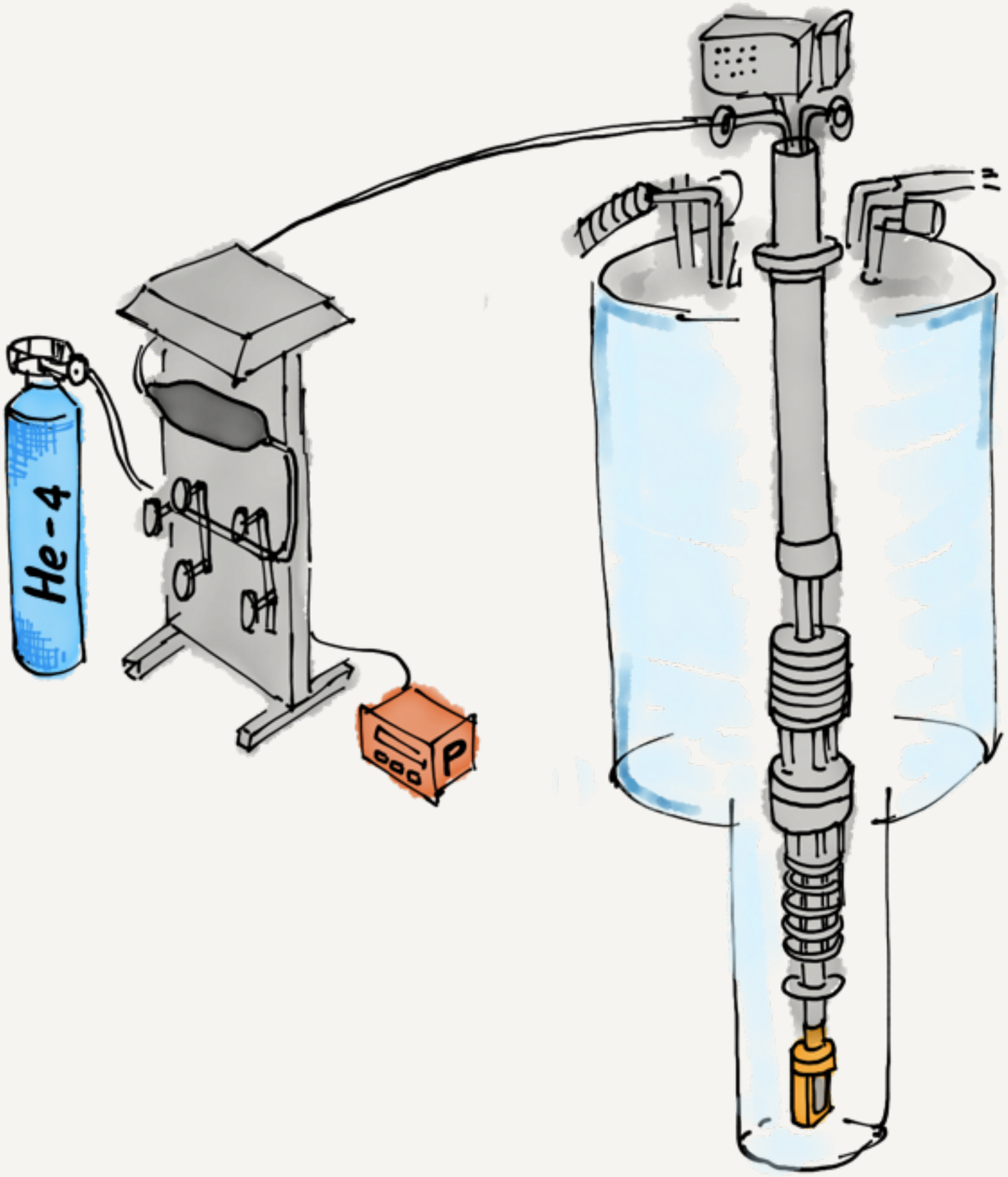


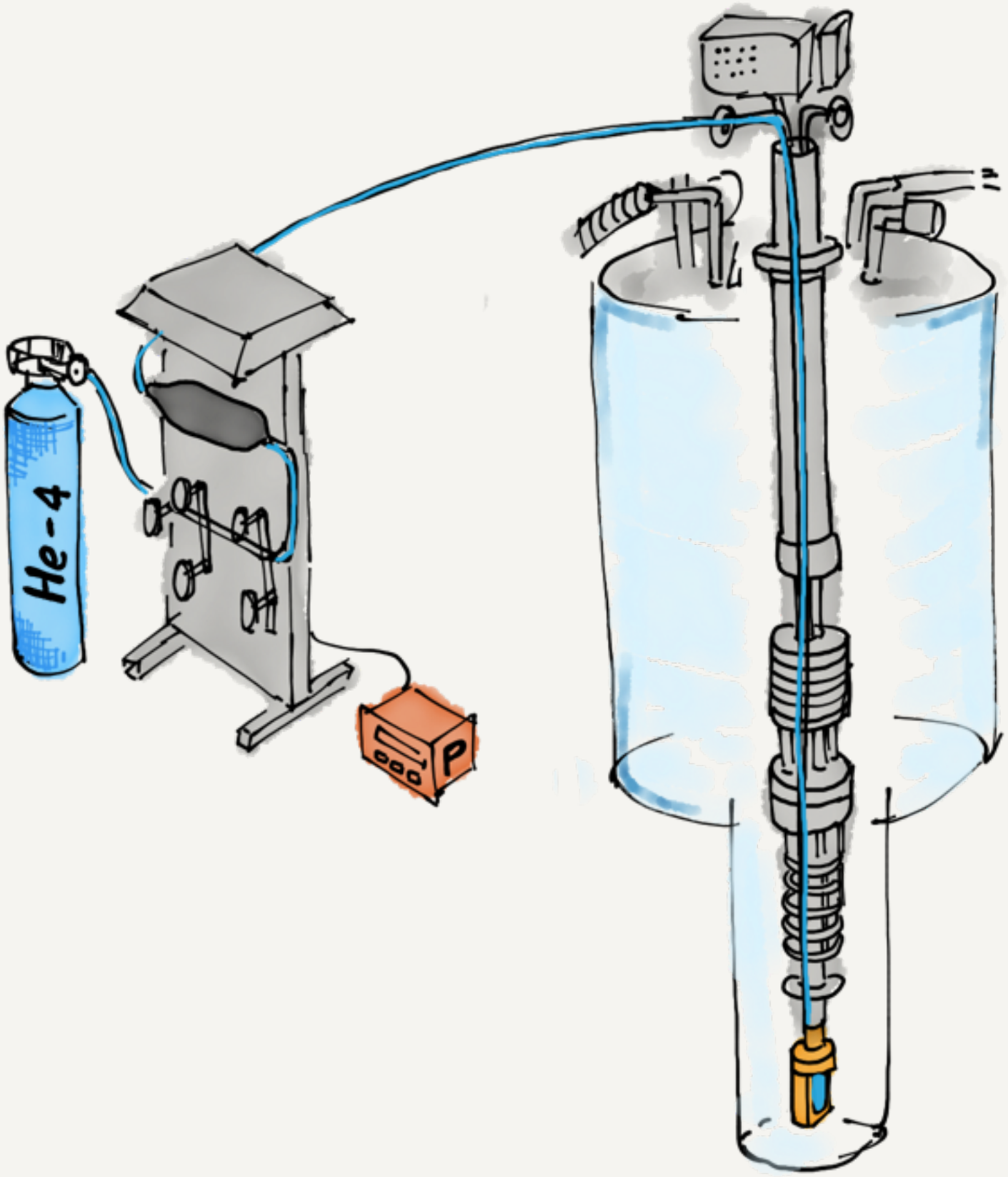
- Momentum = 31.5 MeV/c
- Mean_stop = 2.88 mm from Ti foil
- RMS_z = 0.70 mm
- 97.5% of mu+ stopped in SHe

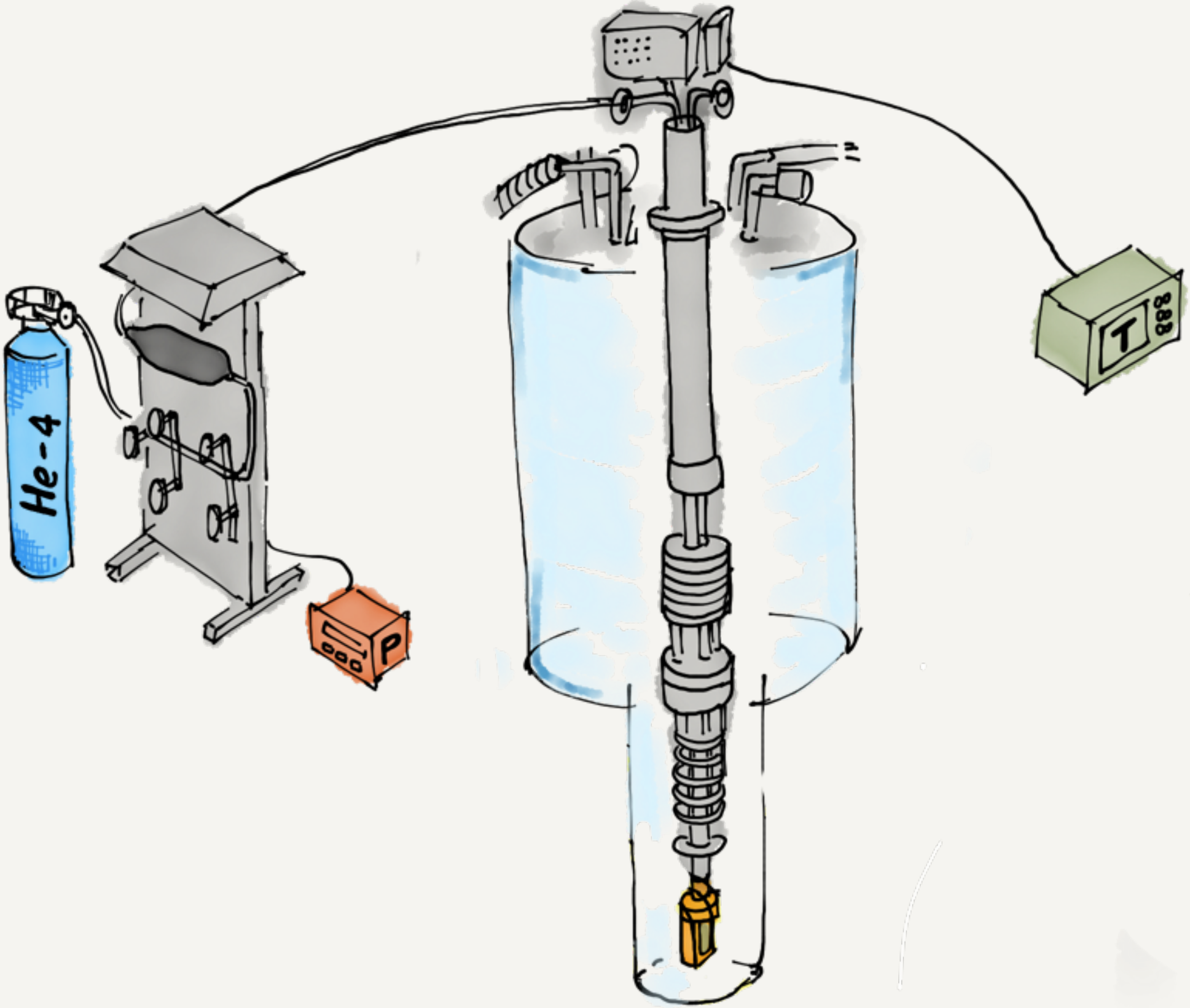


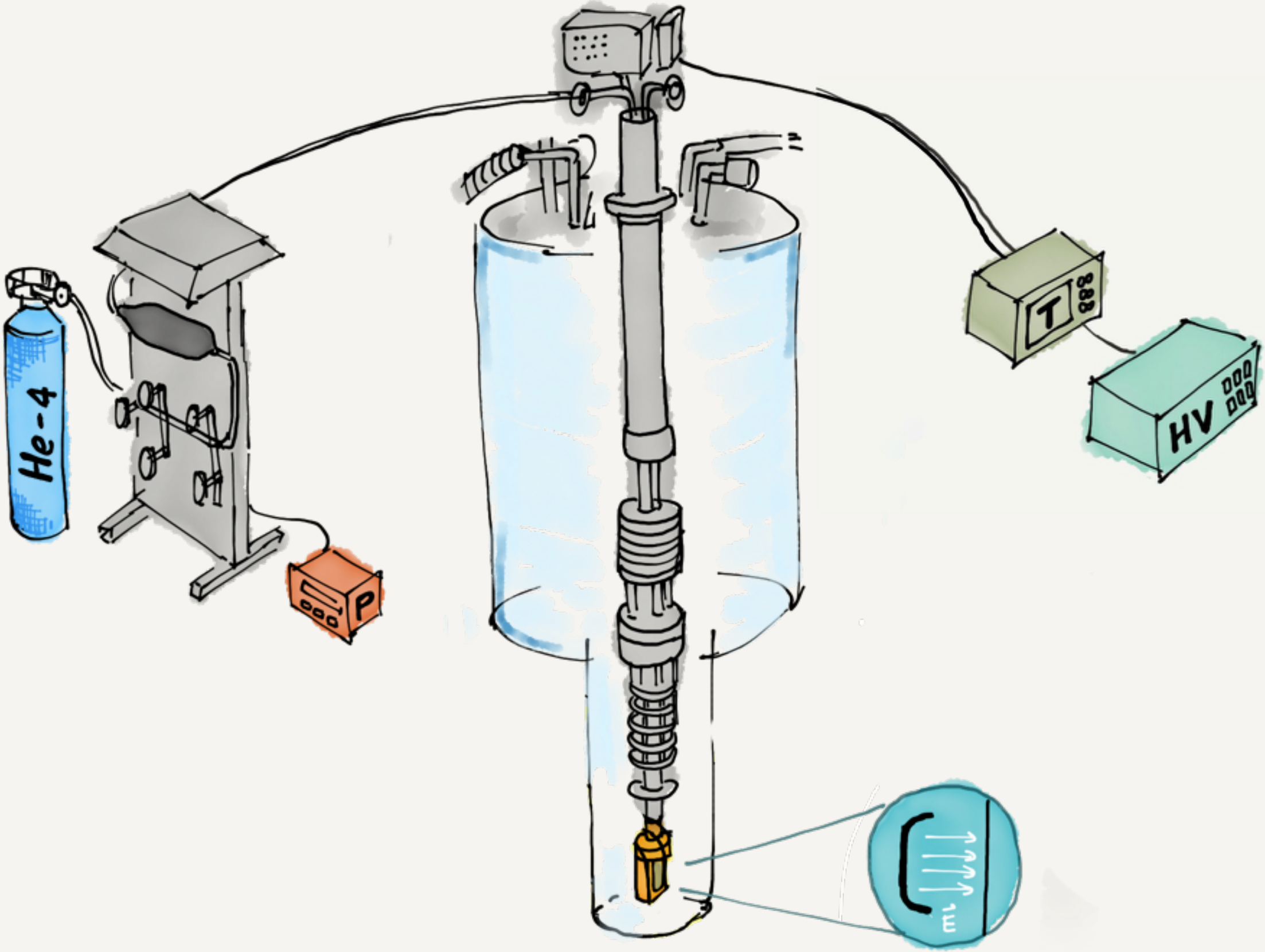
^3He-^4He dilution refrigerator

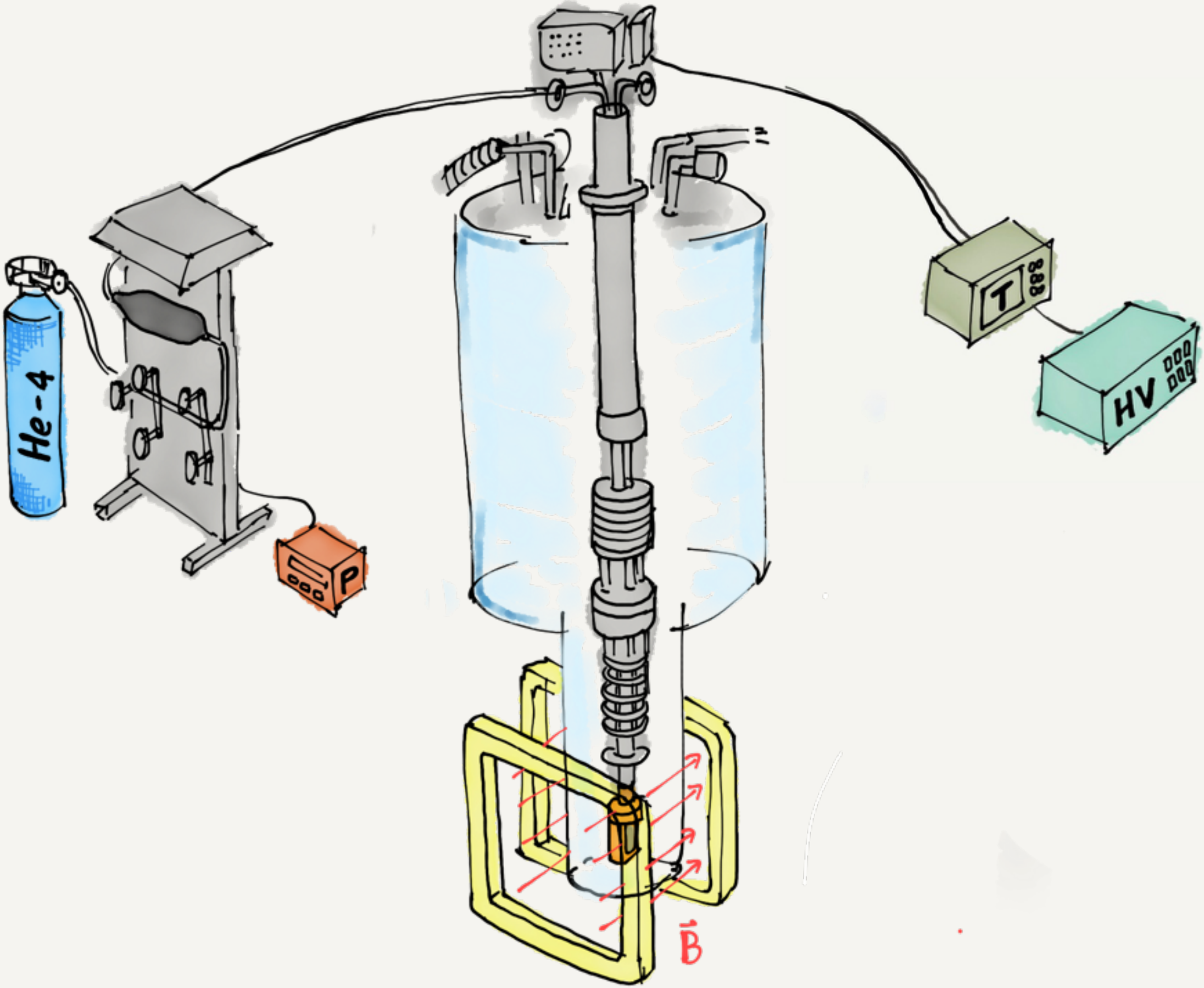


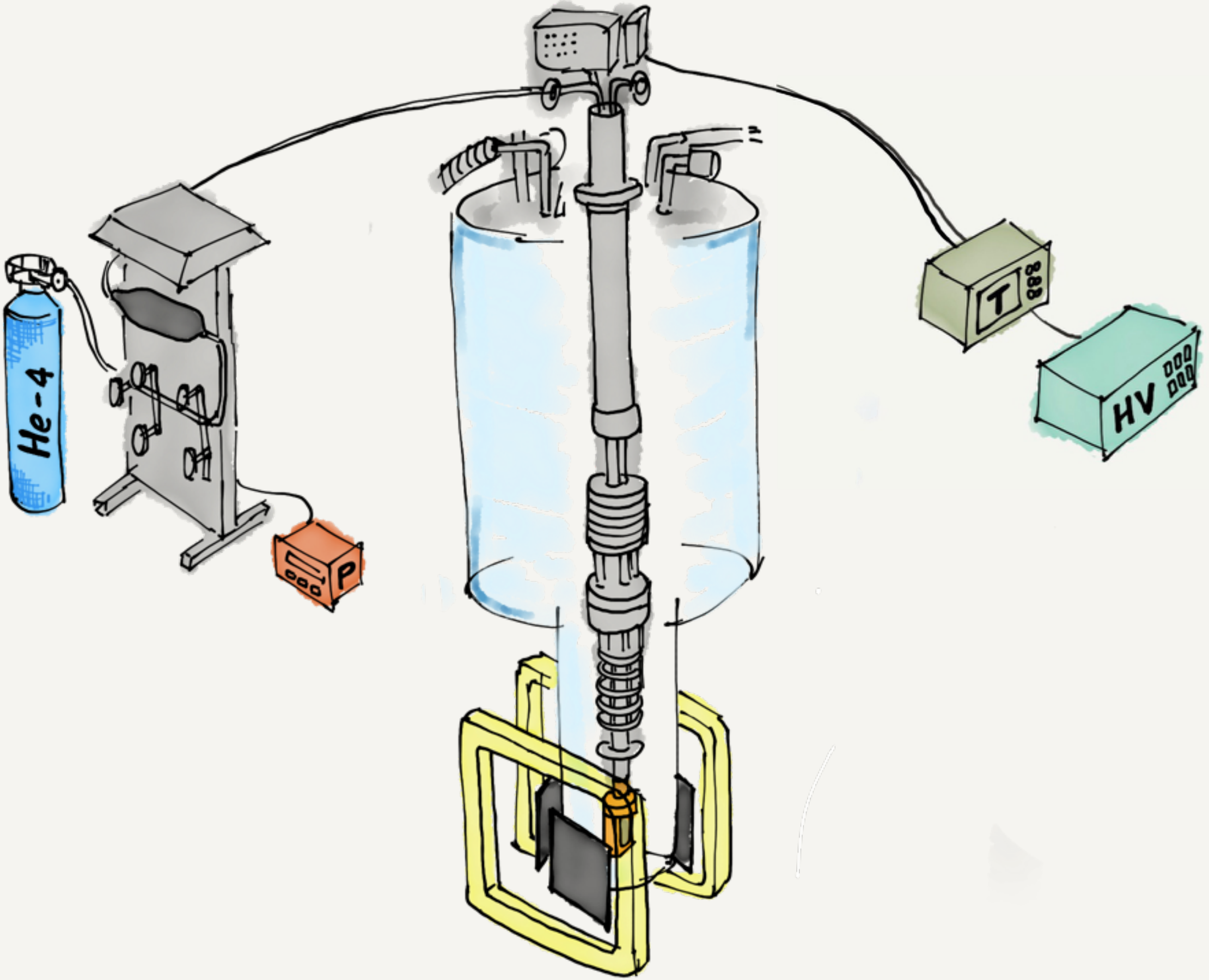

He-4
P

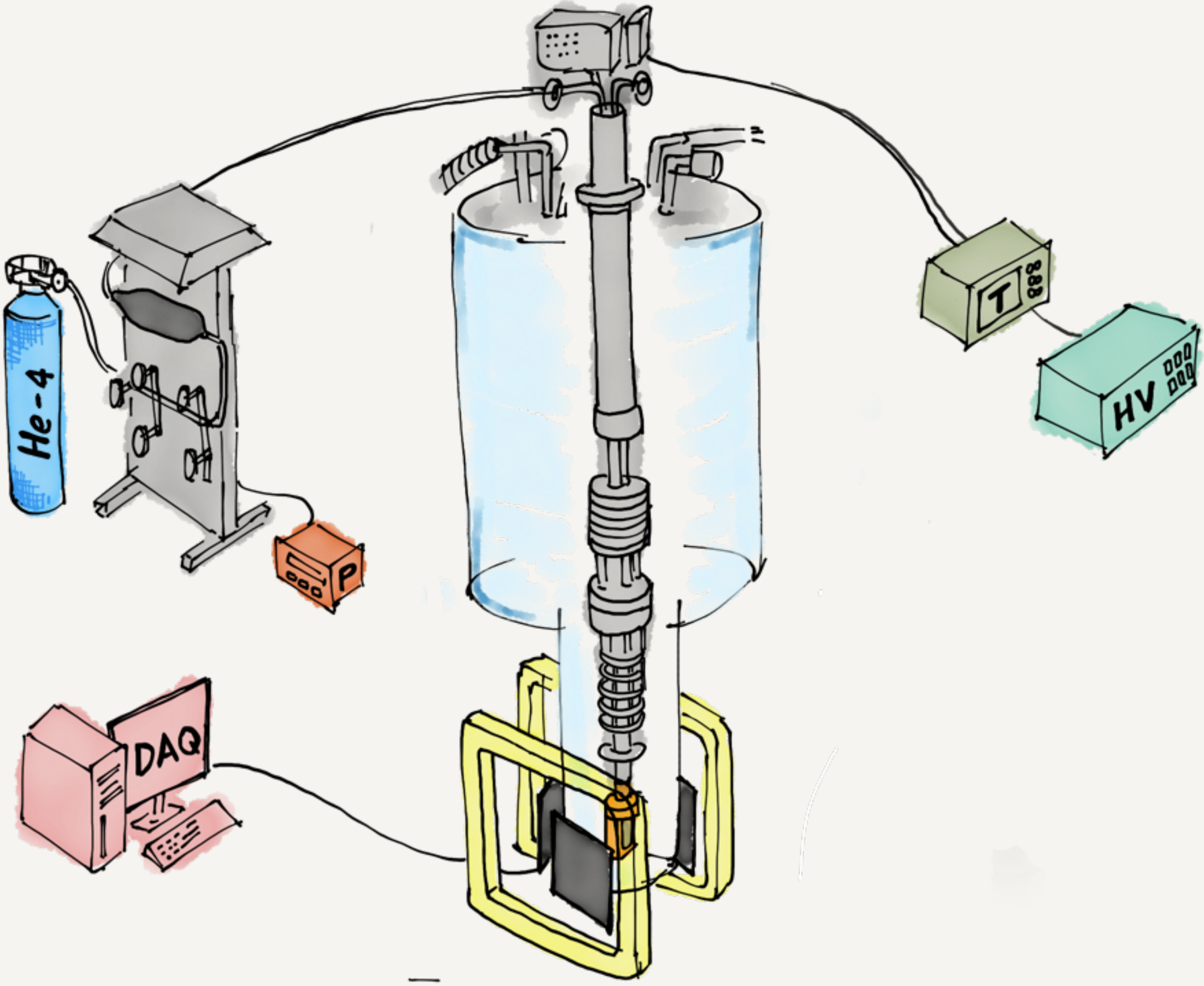

He-4
P

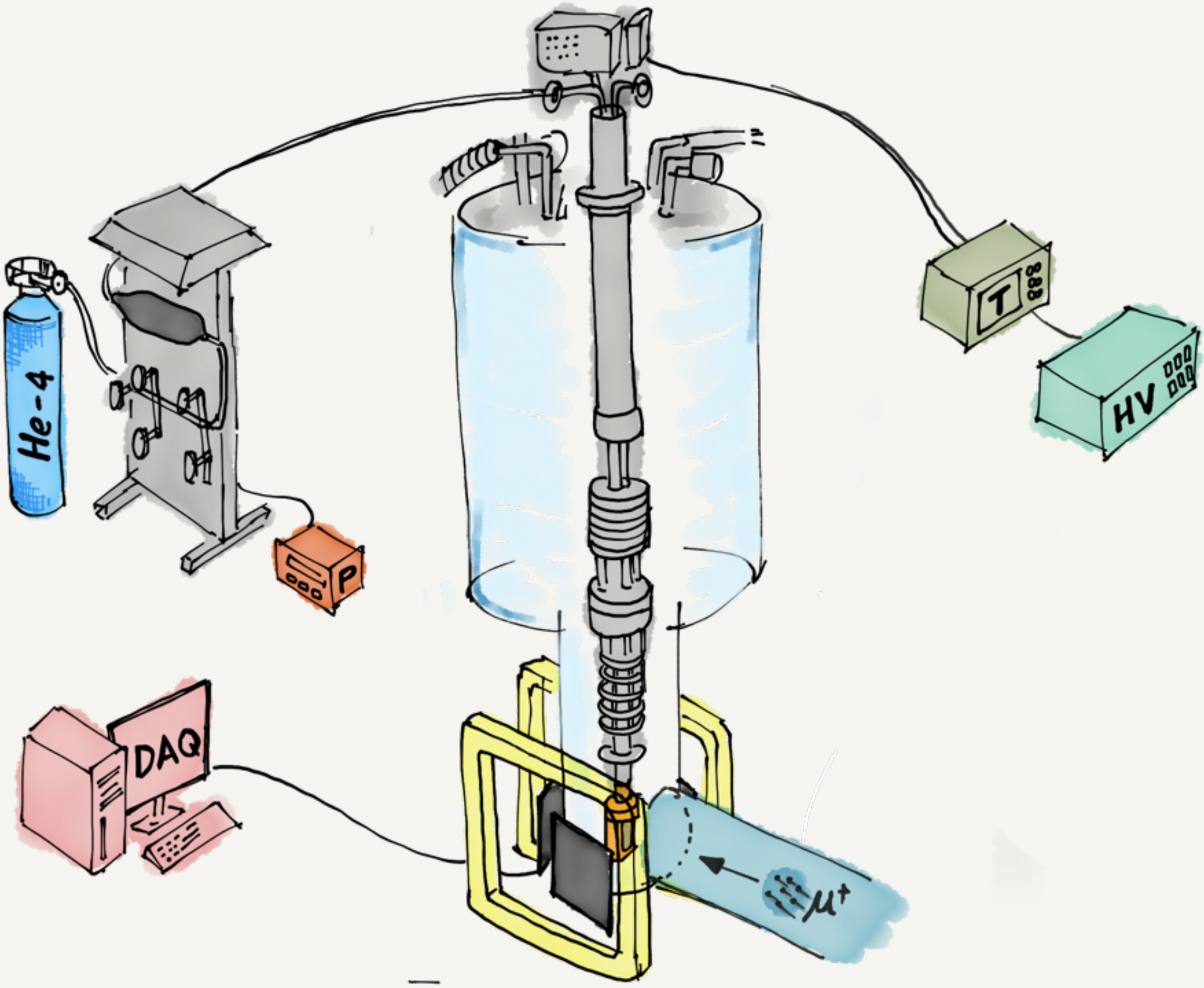

He-4
P
T
888


He-4
P
T
HV


He-4
P
T
HV
$\vec{B}$

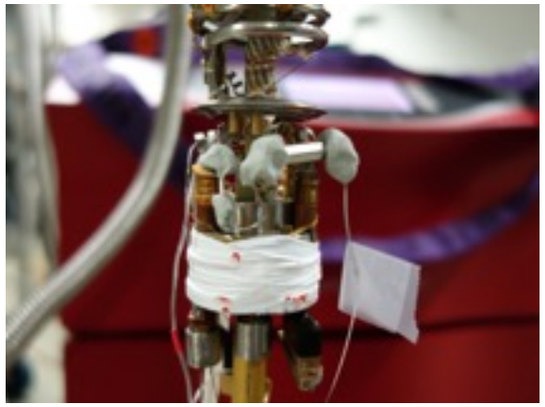

He-4
P
T
HV

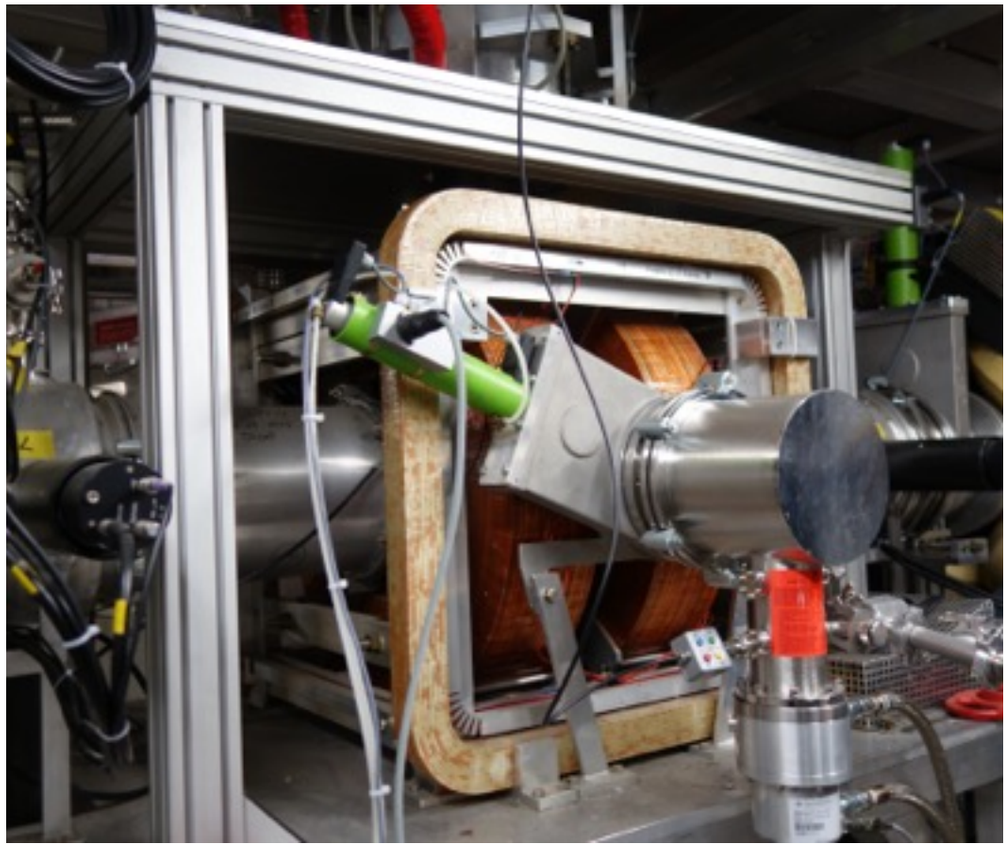

He-4
P
T
HV
DAQ

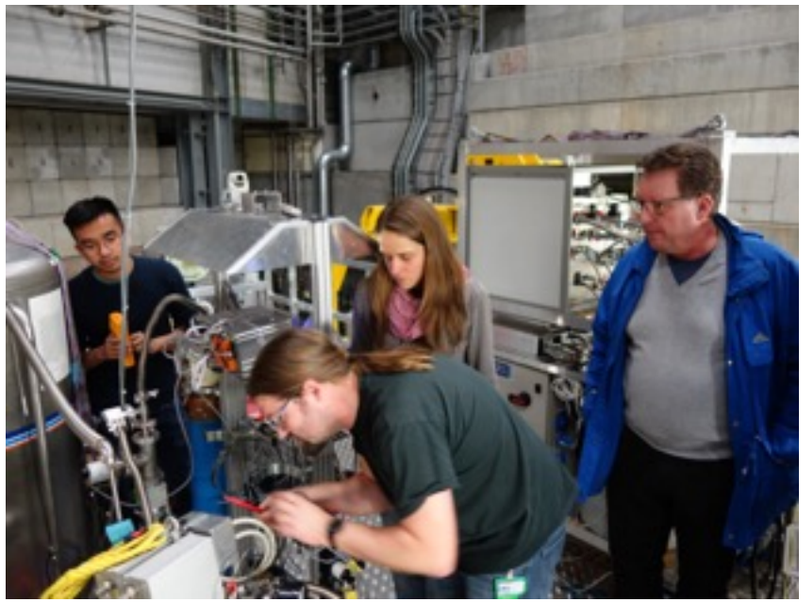

He-4
P
T
HV
DAQ
μ^+

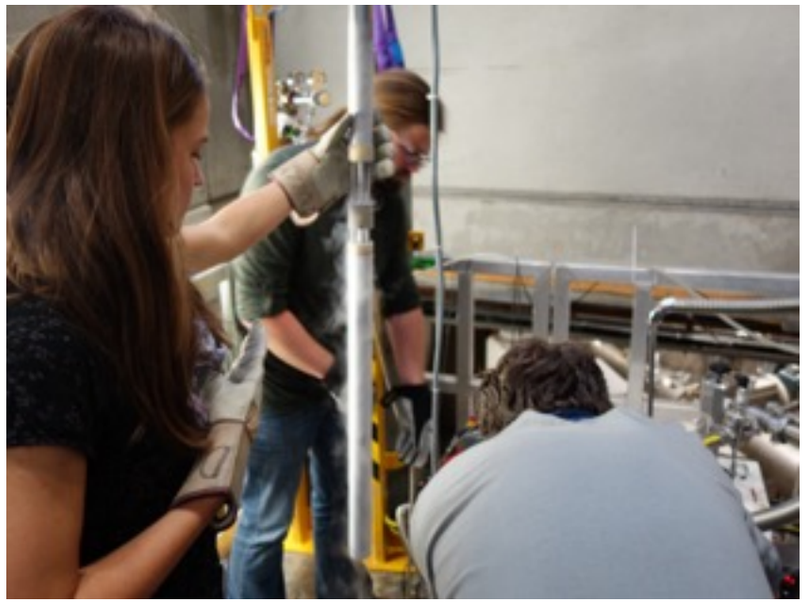
Experiment

- November 2017, PiE1 area at PSI

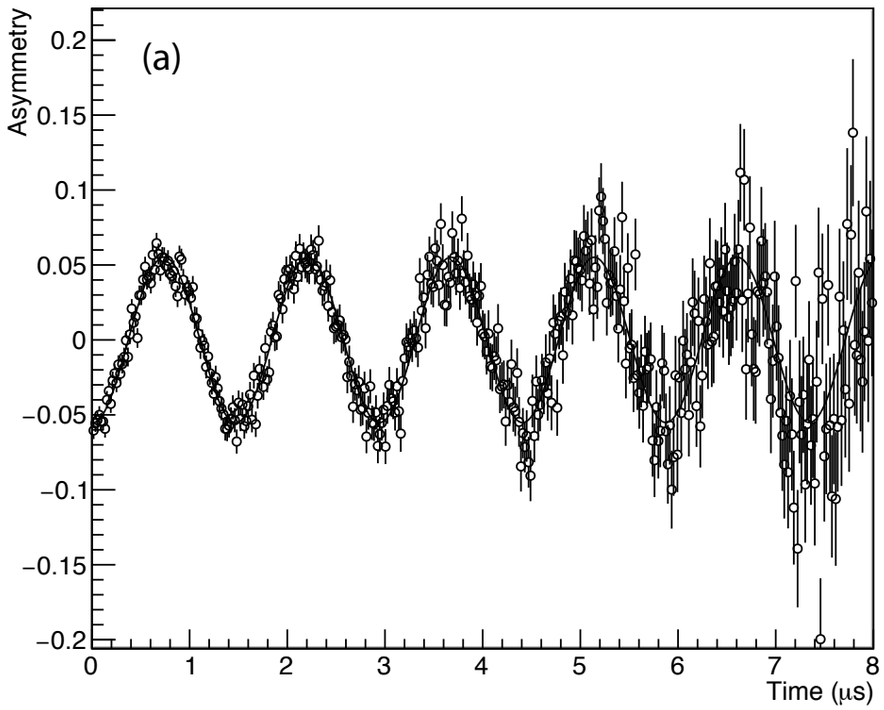




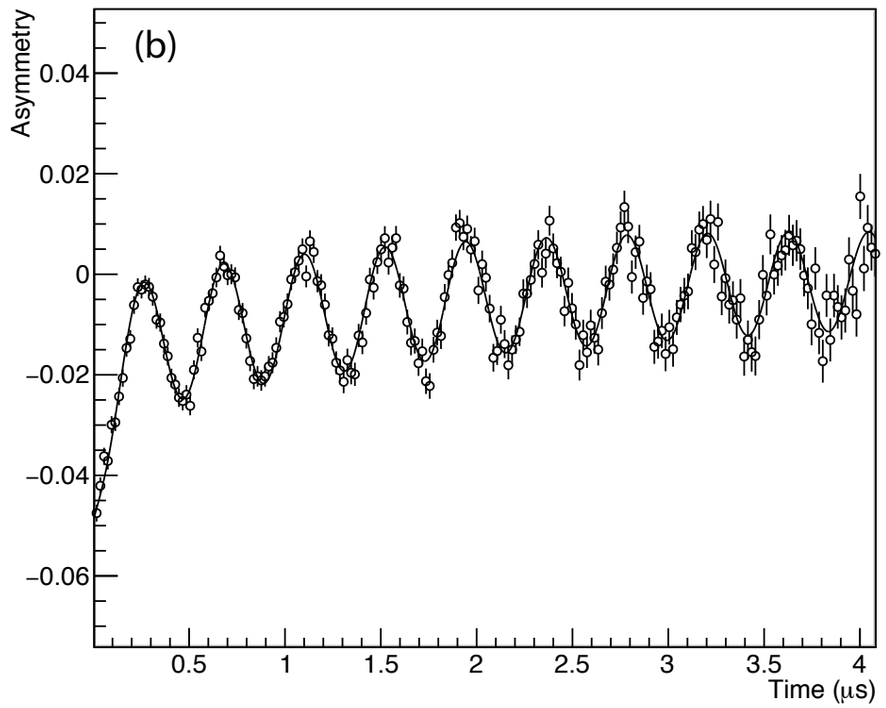




Results

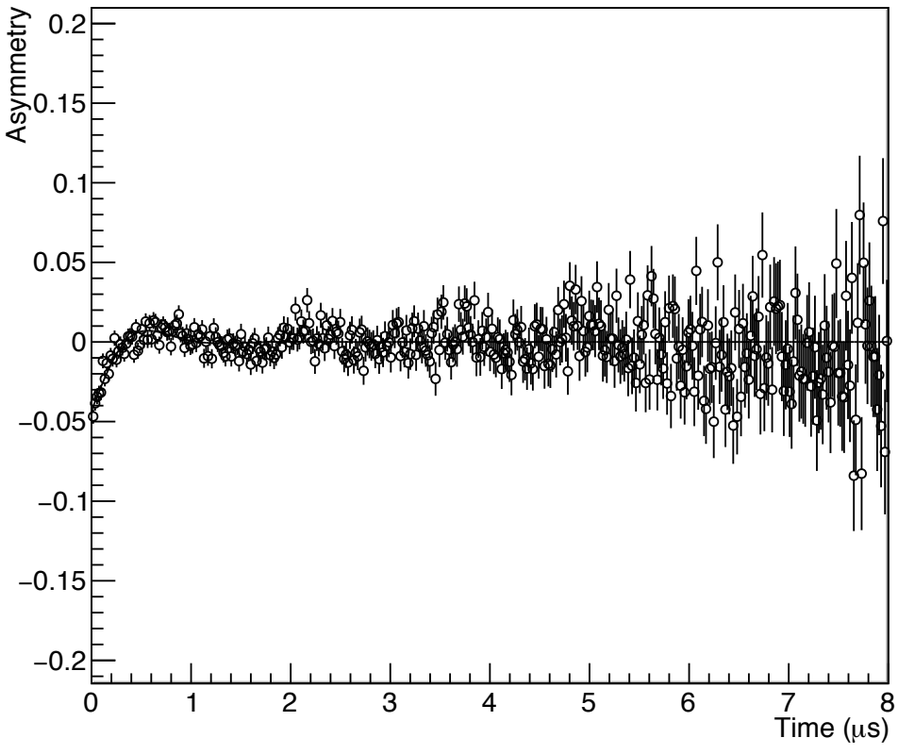


- Empty cell
- Muon stopped at the silver electrode
- Muon decay asymmetry at B = 50 G
- $A_\mu = 0.0555 \pm 0.0015$



- Full cell with superfluid He-4, T = 0.5K
- Muon stopped in the superfluid and formed muonium
- Muonium decay asymmetry at B = 1.6 G
- $A_{Mu} = 0.0136 \pm 0.0005$

Results

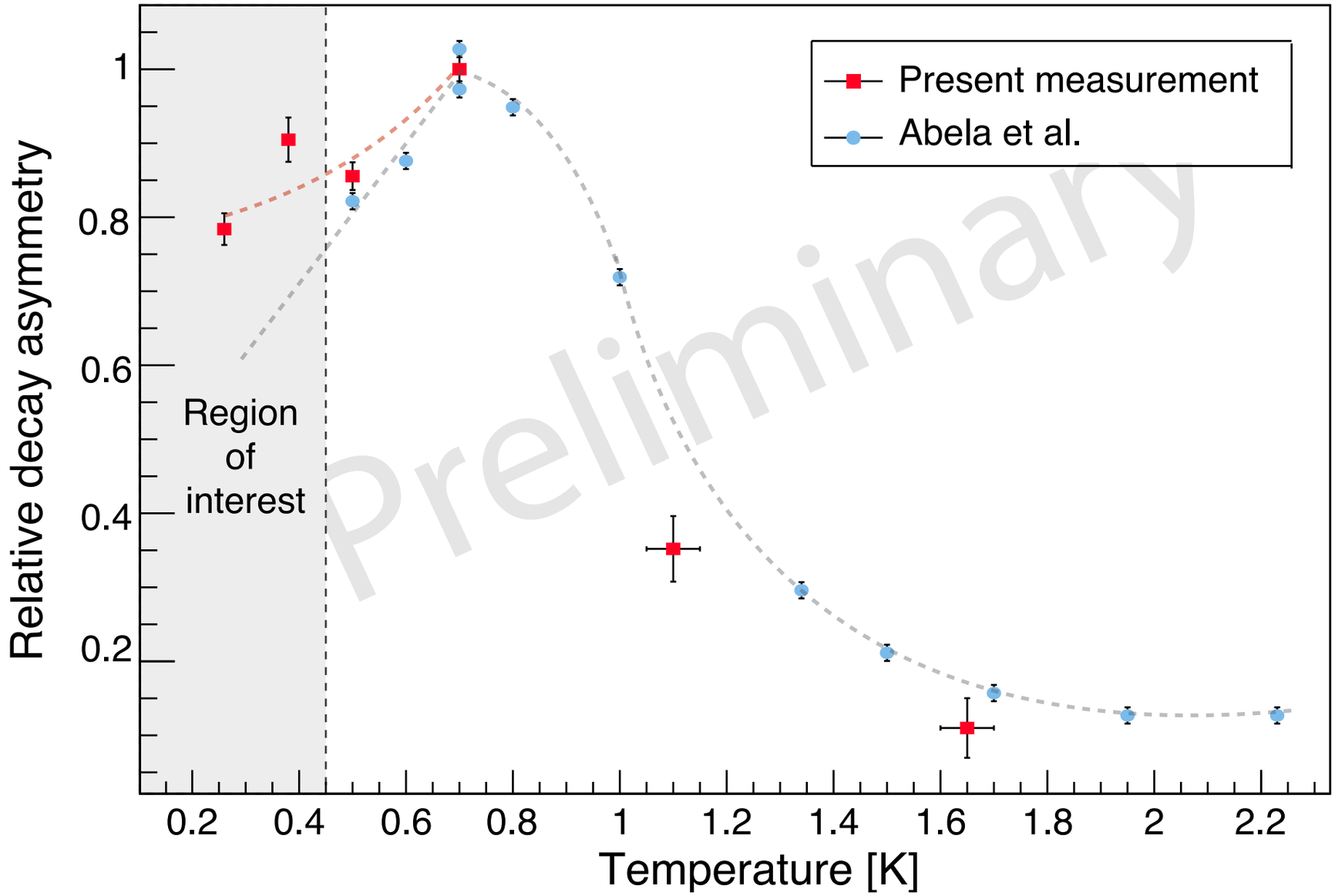


- Full cell with superfluid He-4, T = 0.5K
- Muon stopped in the superfluid and formed muonium
- Muonium decay asymmetry at B = 50 G
- Disappearance of muon signal

- Scanned Parameters
  - Temperature
  - Electric field (Voltage)
  - Magnetic field
  - Which configuration will give the highest yield of Mu ?

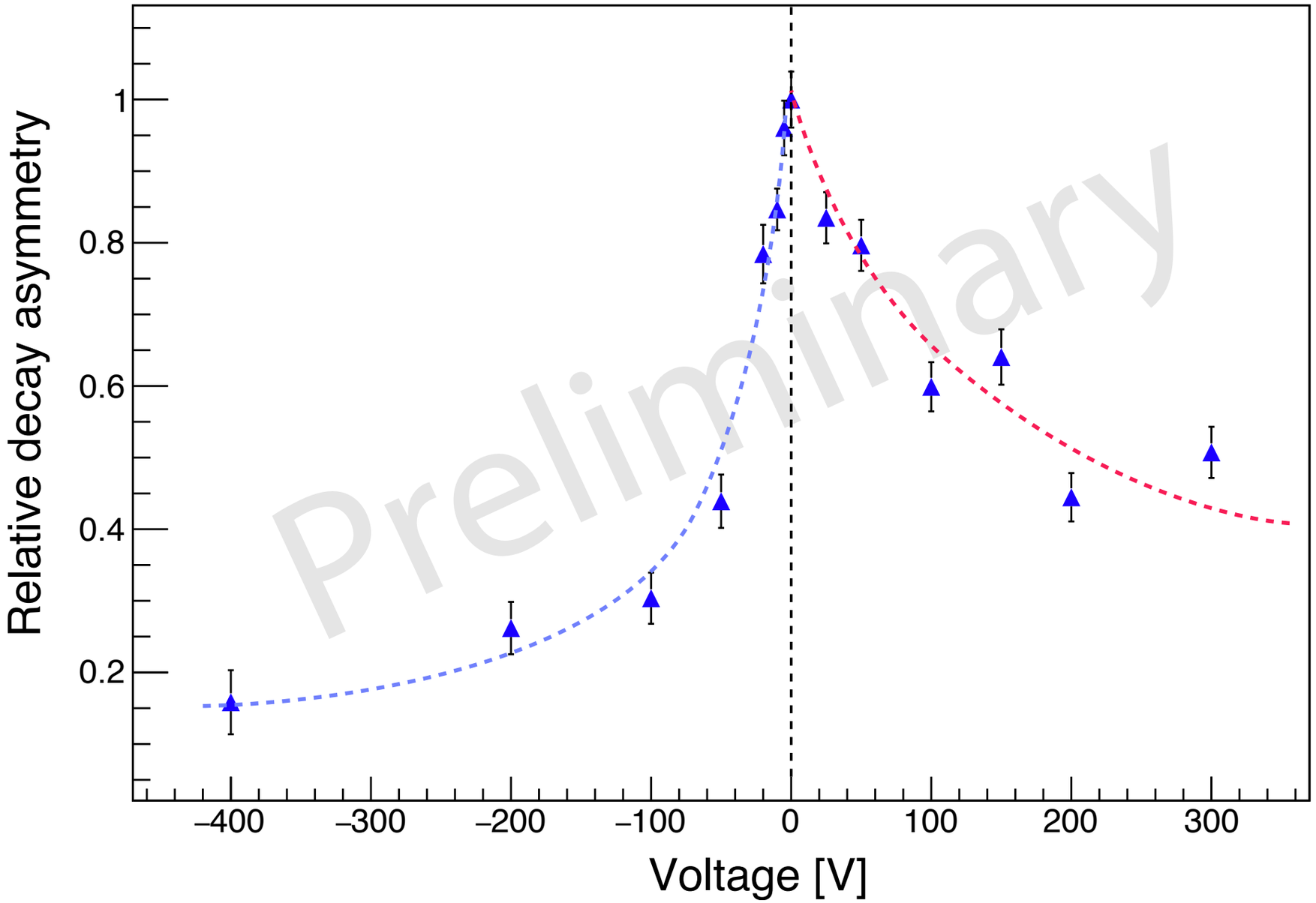
Results

- Temperature scan
- First measurement of muonium formation in SFHe at T<0.5K



Results

- Voltage scan
- Perform the electric field scan at low temperature 0.26 K
- Muonium formation rate decreases when the voltage increases



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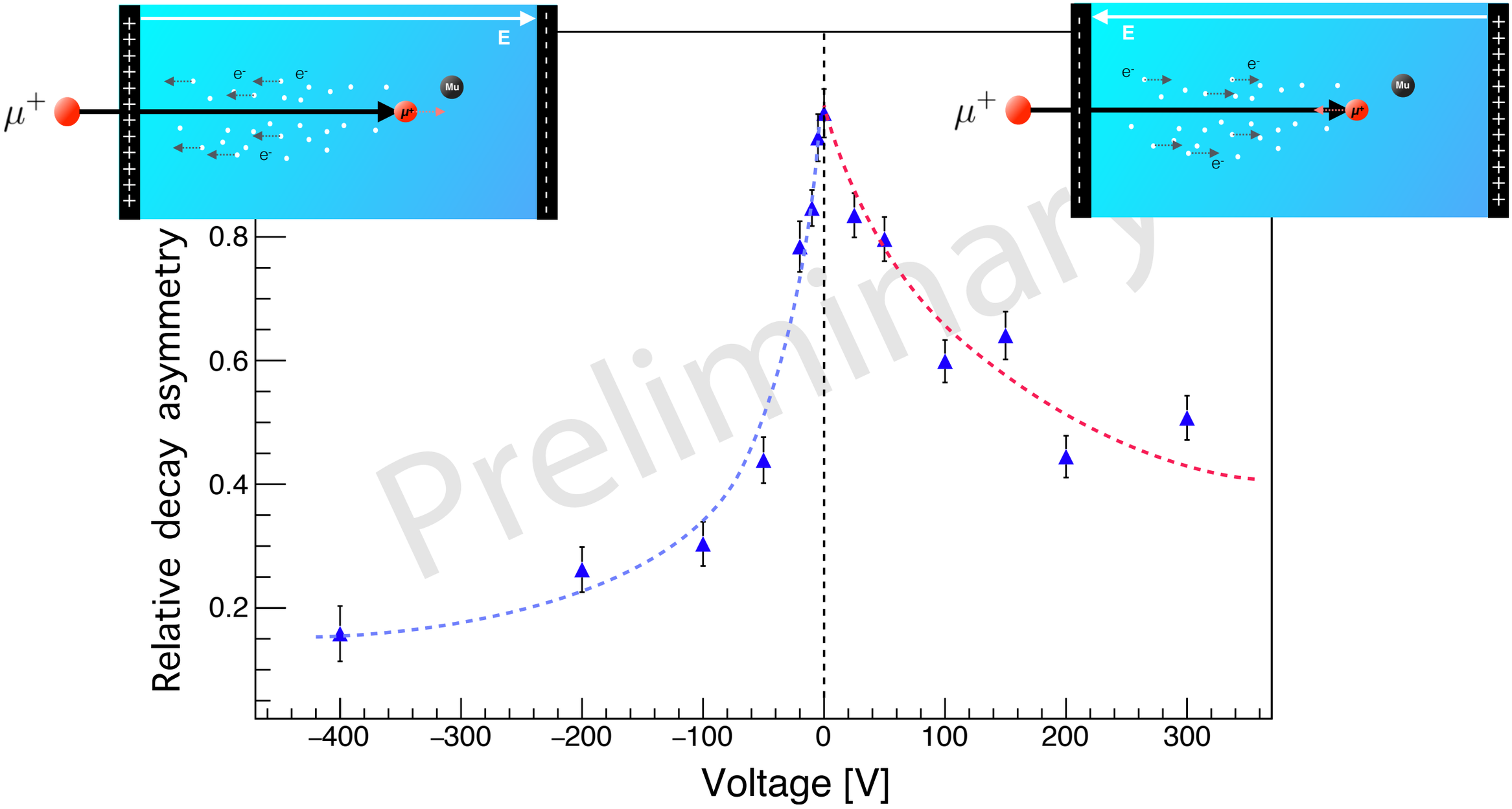

Conclusions

- The first measurement of the Mu formation rate was done at T<0.5 K
- The highest Mu formation rate is at T=0.7 K
- The Mu formation rate at lower temperature is still reasonably high
- An applied electric field prevents the muonium formation rate

Next episode . . .

- In this year, our experimental goal is to measure emission of muonium into vacuum from SFHe

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DAVID ROUSSOⁿ
ROBERT SCHEUERMANN

UNIVERSITY OF CAMBRIDGE
MICHAEL DE VOLDER

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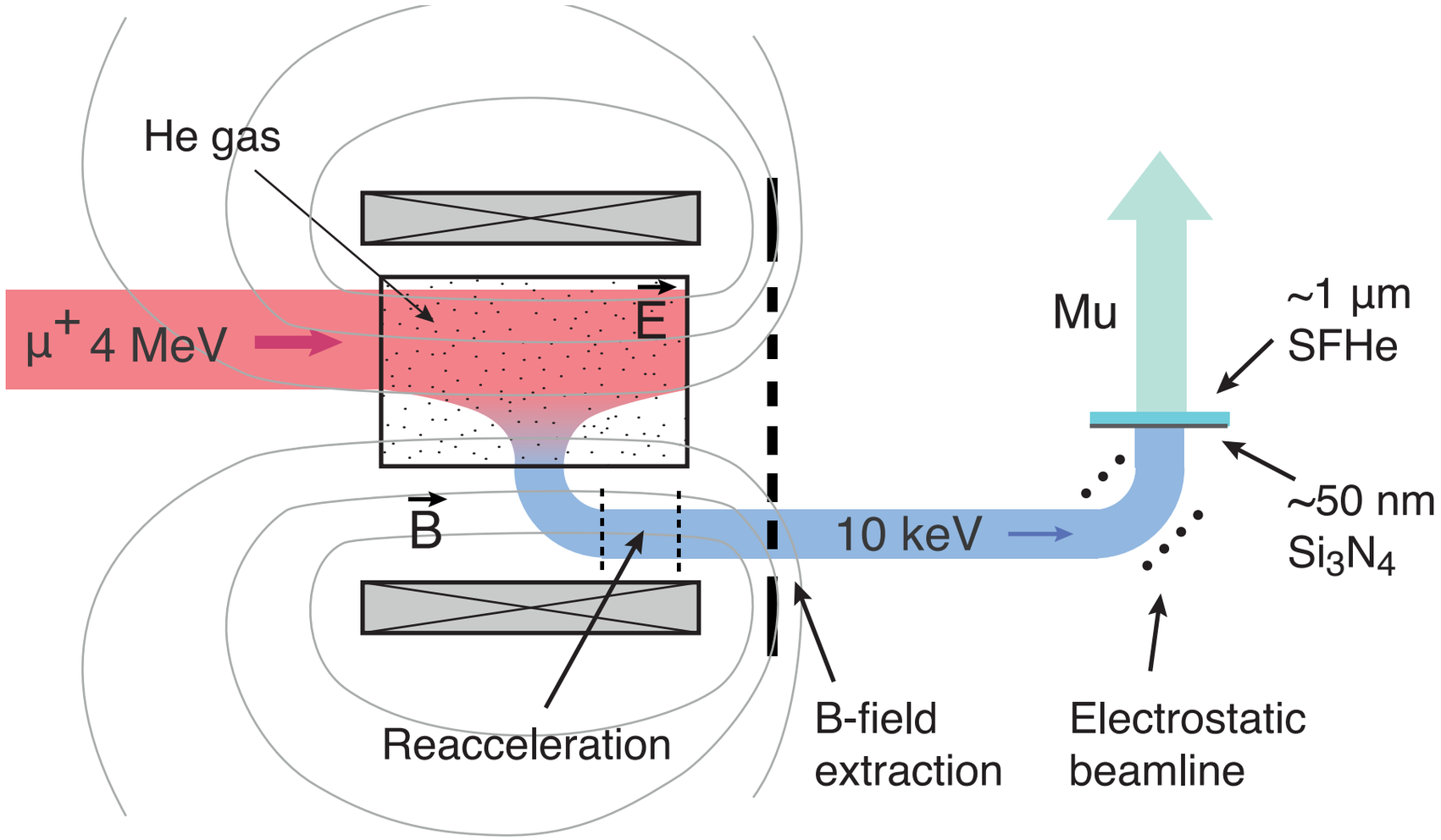
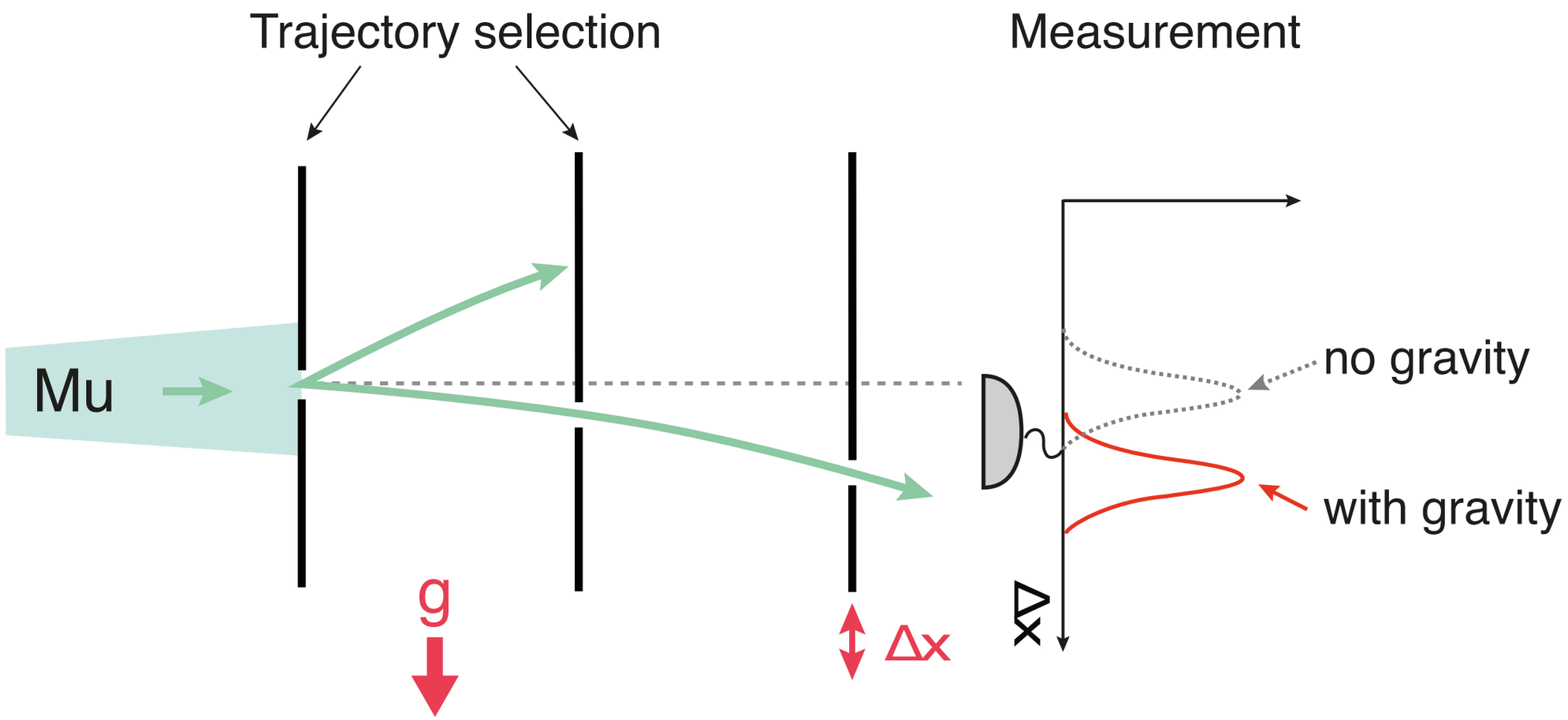
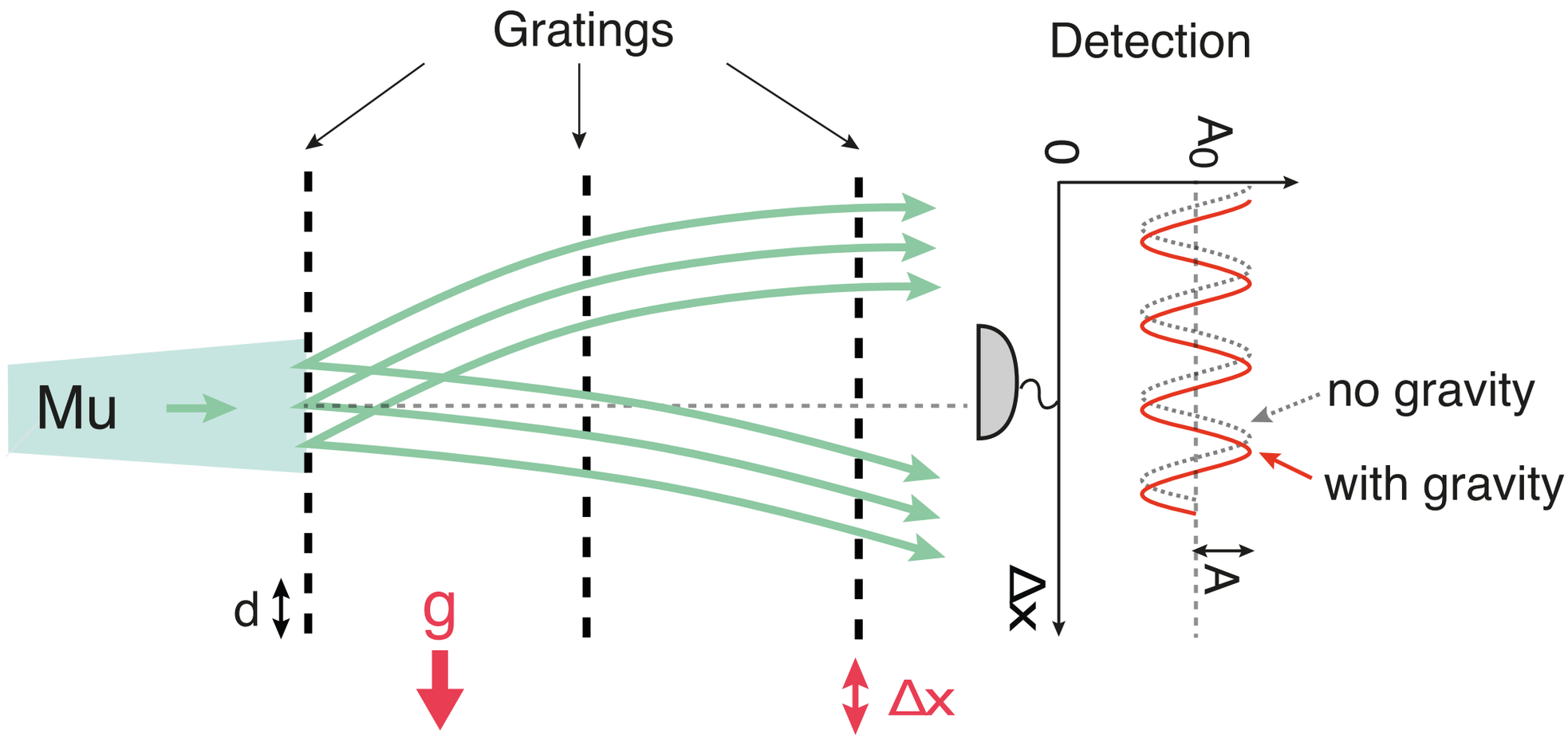
BACK UP


He gas
μ+ 4 MeV
E
B
Reacceleration
B-field
extraction
Mu
~1 μm
SFHe
~50 nm
Si3N4
10 keV
Electrostatic
beamline

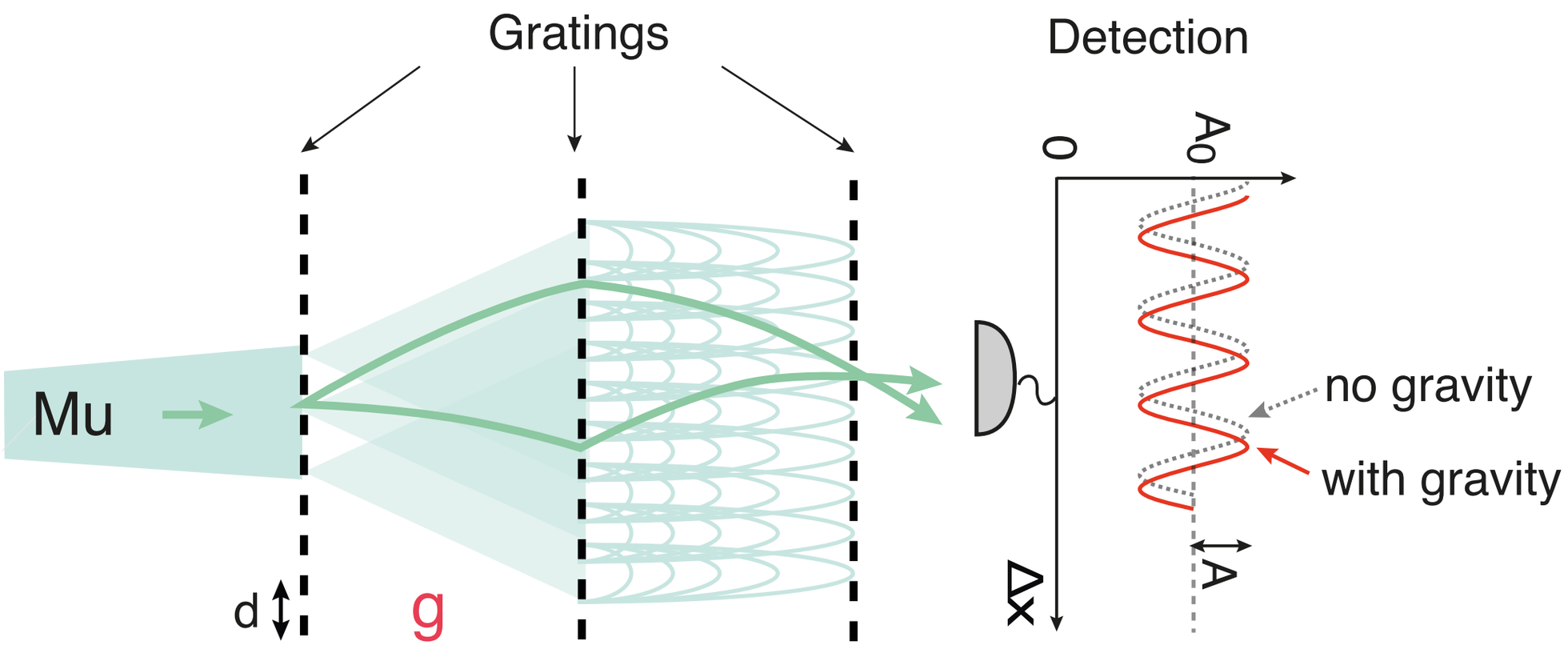


Trajectory selection by collimation: large losses in atom number!



- Increasing intensity: series of collimators = gratings.
- Effects of gravity: vertical shift in the periodic pattern of shadows
- If this effect is small, small grating period (d) needed

- Challenging: Mu falls less than
  1 nm during its few us flight!



$$\frac{\Delta g}{g} \approx \frac{1}{2\pi T^2} \frac{d}{C\sqrt{N}}$$

Small grating period

Interaction time

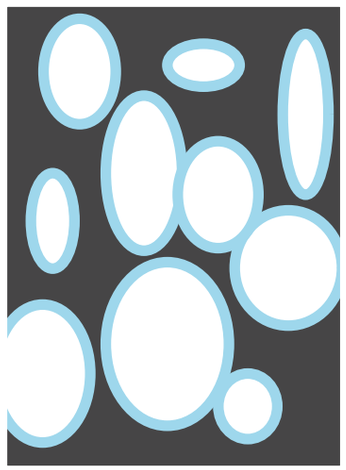
~ τ = few μs !

Many atoms $N \sim N_0 b^3 e^{-(t_D+T)/\tau}$

Large contrast $C = A/A_0$

New concept: nanostructured targets coated with SFHe

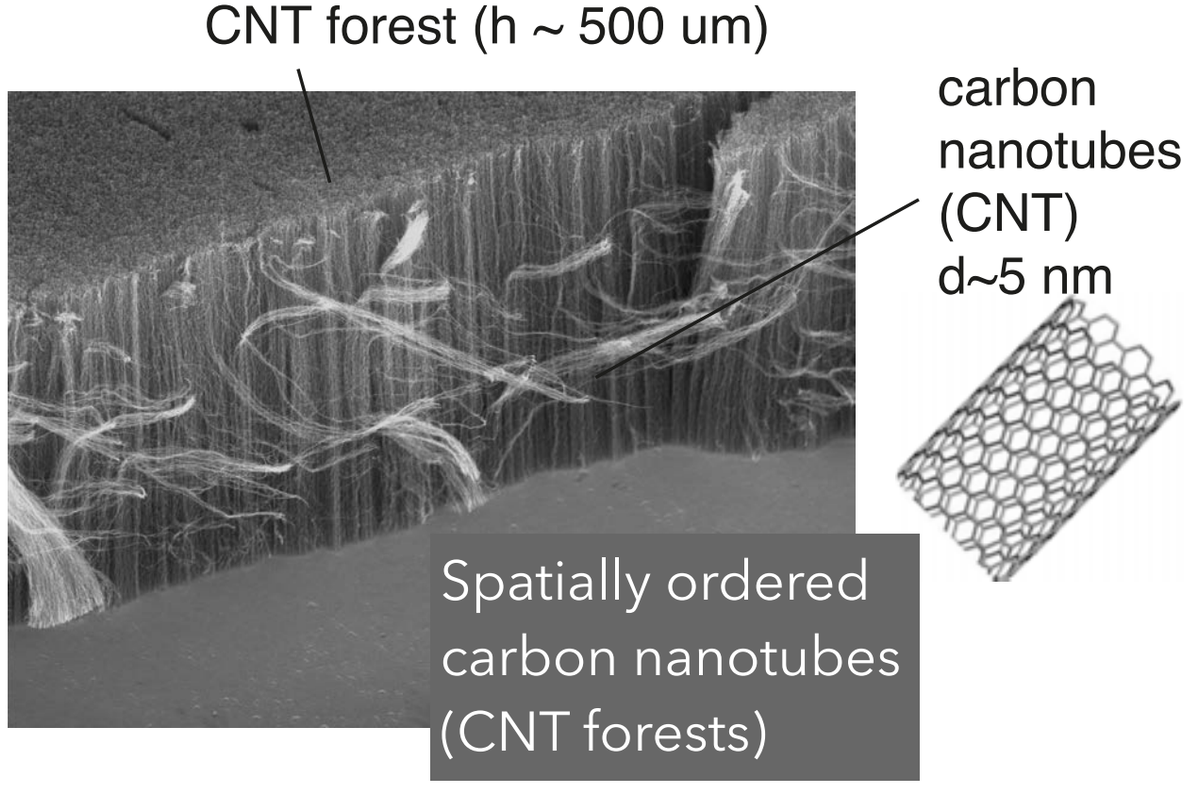
- Large μ^+ stopping power and surface area for Mu escape
- SFHe film prevents atoms sticking to the wall



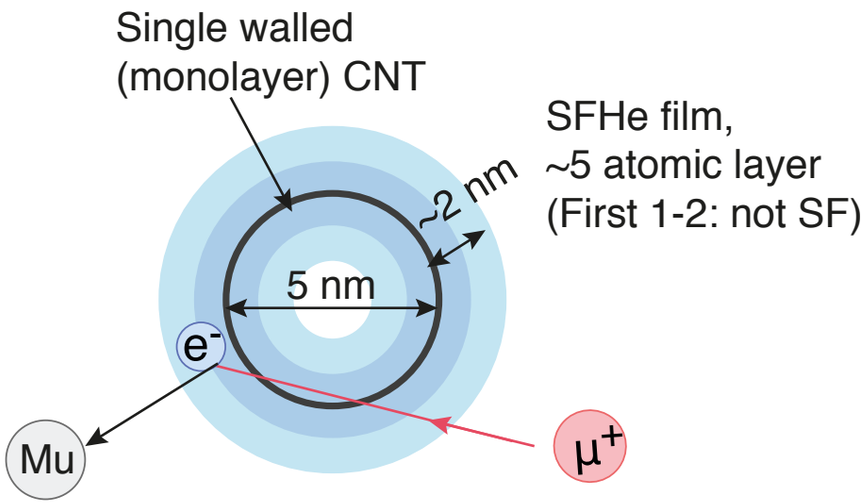
- e.g. coating mesoporous SiO_2 with SFHe?

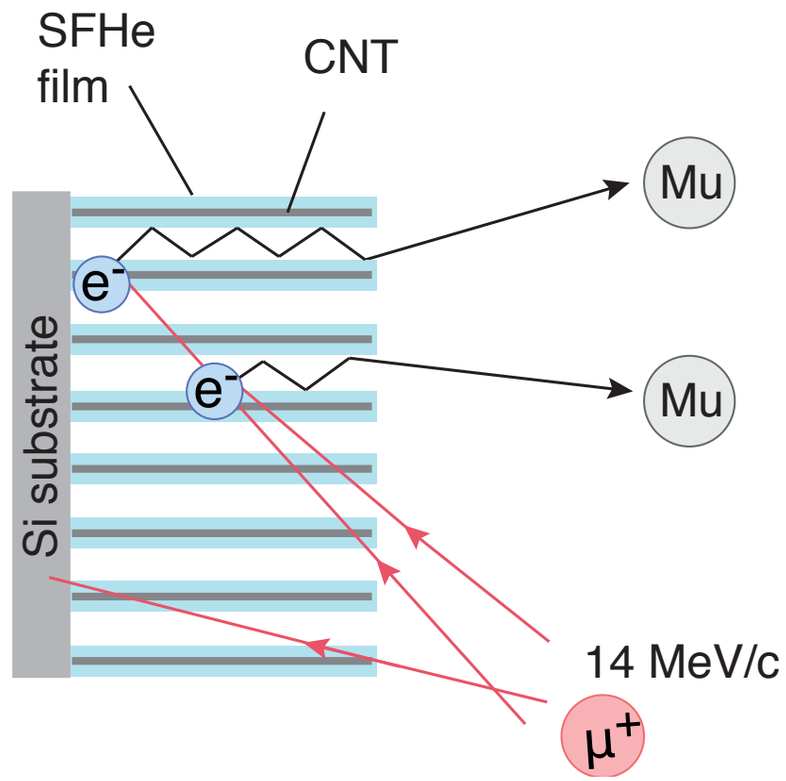
New concept: nanostructured targets coated with SFHe

- Large μ^+ stopping power and surface area for Mu escape
- SFHe film prevents atoms sticking to the wall

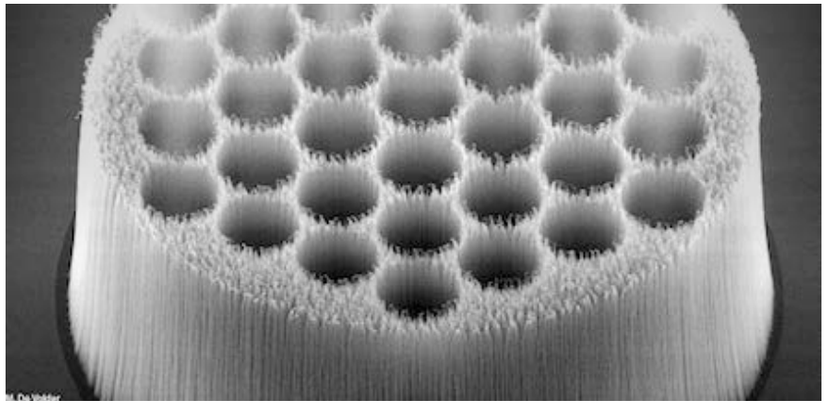


The potential of SFHe coated CNT forests



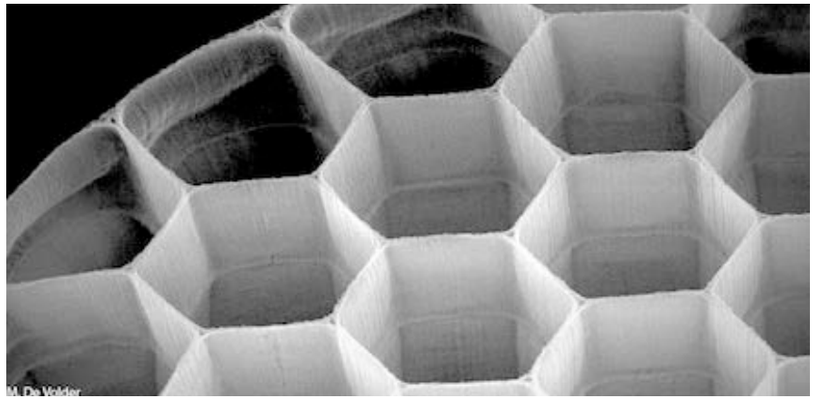


- significant stopping power in SFHe vs carbon
- forest: ~5% graphite density, quasi-ordered structure - fast Mu escape?

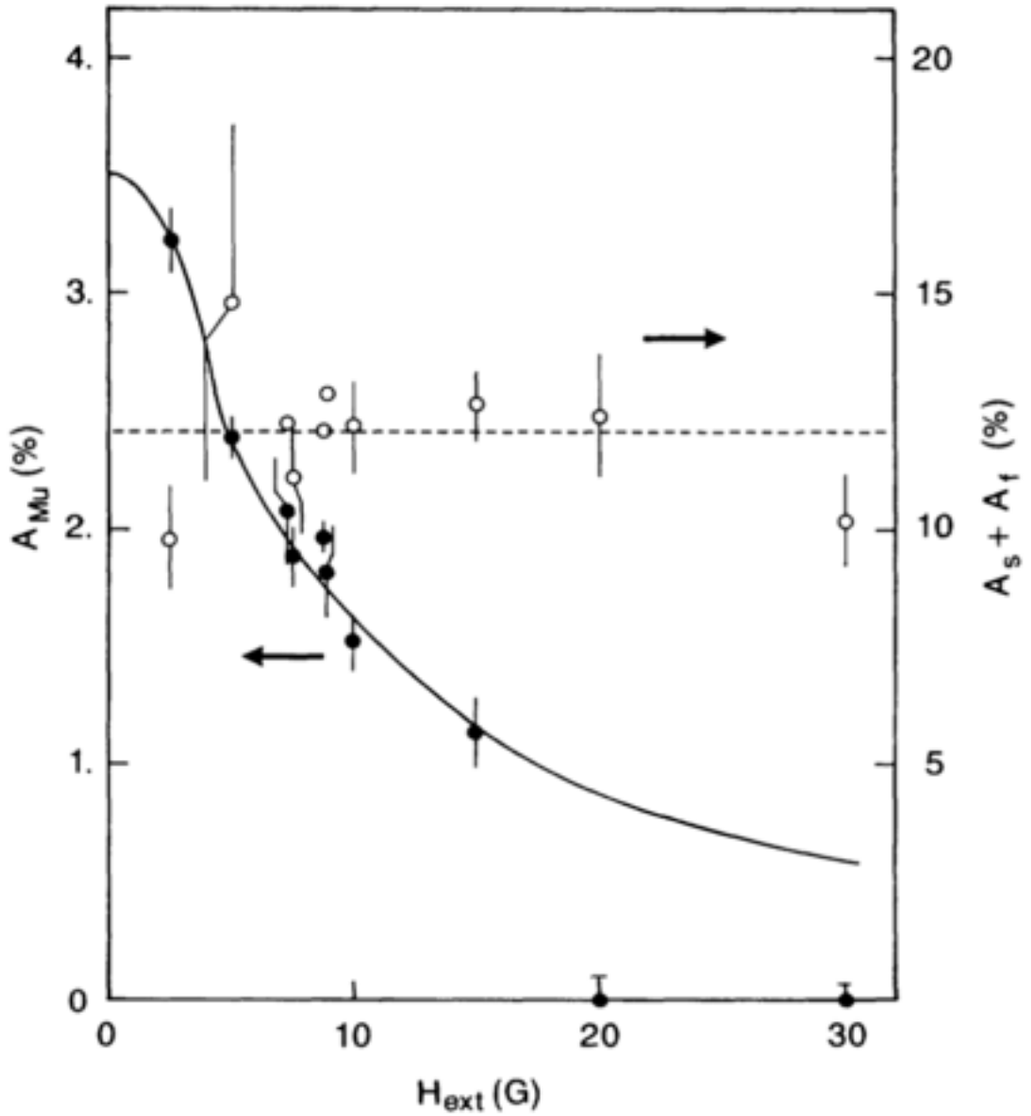


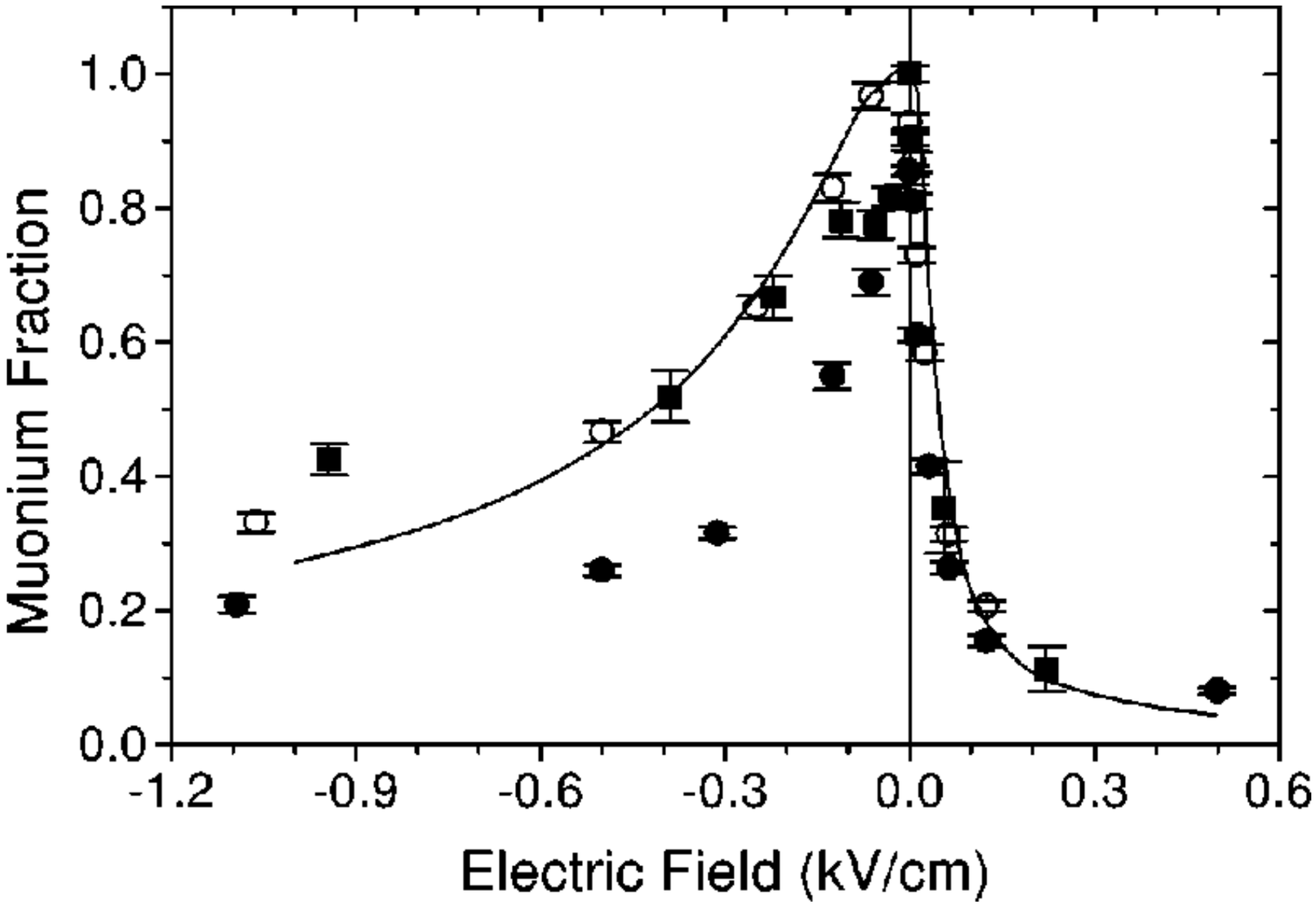
- Prefabricated holes for better Mu extraction

And, the possibility for:



- Free-standing structures for back-implantation


4.
3.
2.
1.
0
0
10
20
30
20
15
10
5
A_{MU} (%)
$A_s + A_f$ (%)
H_{ext} (G)


Muonium Fraction
1.0
0.8
0.6
0.4
0.2
0.0
-1.2
-0.9
-0.6
-0.3
0.0
0.3
0.6
Electric Field (kV/cm)