Negative Muon Cooling
and
Potential Applications of μCF

Patrick Strasser

Institute of Materials Structure Science (IMSS), KEK
&
Muon Section, Materials and Life Science Division, J-PARC Center

International Workshop on μCF and Future Applications
Department of Physics, University of Liverpool (and online), July 2-3, 2026.

Ultra-Slow Muon Generation

◆ J-PARC MUON FACILITY

- High intensity pulsed positive and negative muon beams (μ^+ and μ^-)
- New opportunity for ultra-slow muon beam projects (slow μ^+ and slow μ^-)
- Possibility to perform μSR, element analysis, etc., in

Atomic Scale Size Target, ***Thin Films***, ...

◆ ULTRA-SLOW POSITIVE MUON BEAM

- Laser resonant ionization of Muonium (developed at KEK)
- Solid gas moderator technique (Low-Energy Muon Beam at PSI)

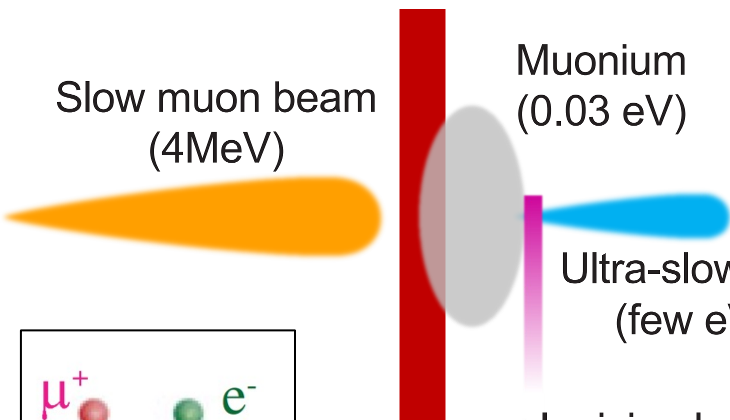
◆ ULTRA-SLOW NEGATIVE MUON BEAM

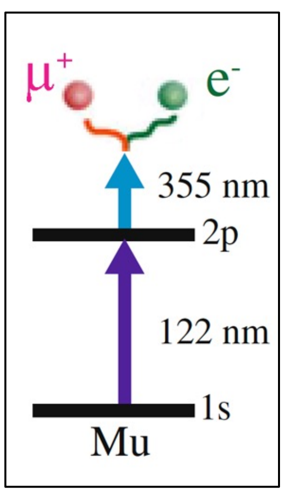
- Difficult to produce because of stopped μ^- are absorbed inside matter
- Muon Catalyzed Fusion (μCF) as a source of slow negative muons

Ultra-Slow μ⁺ Production Techniques

Laser Resonant Ionization of Muonium

Silica aerogel production target



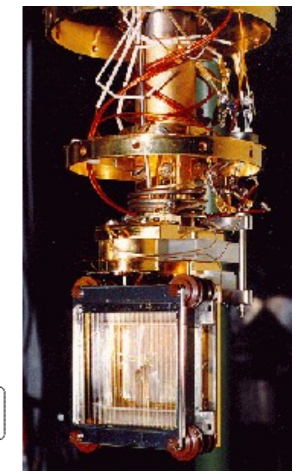


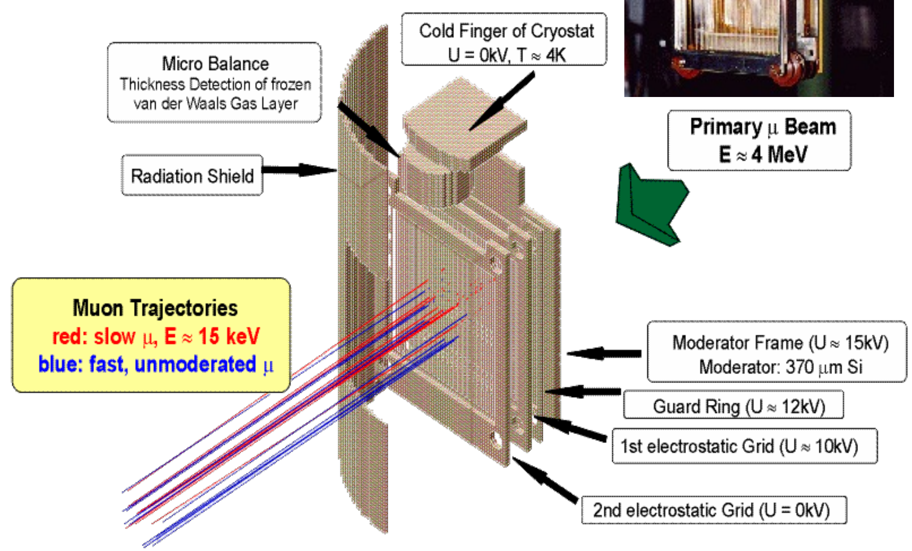
Muonium Ionization Scheme

Frozen Gas Moderator (LEM at PSI)

PSI

Solid rare gas (~10 K)

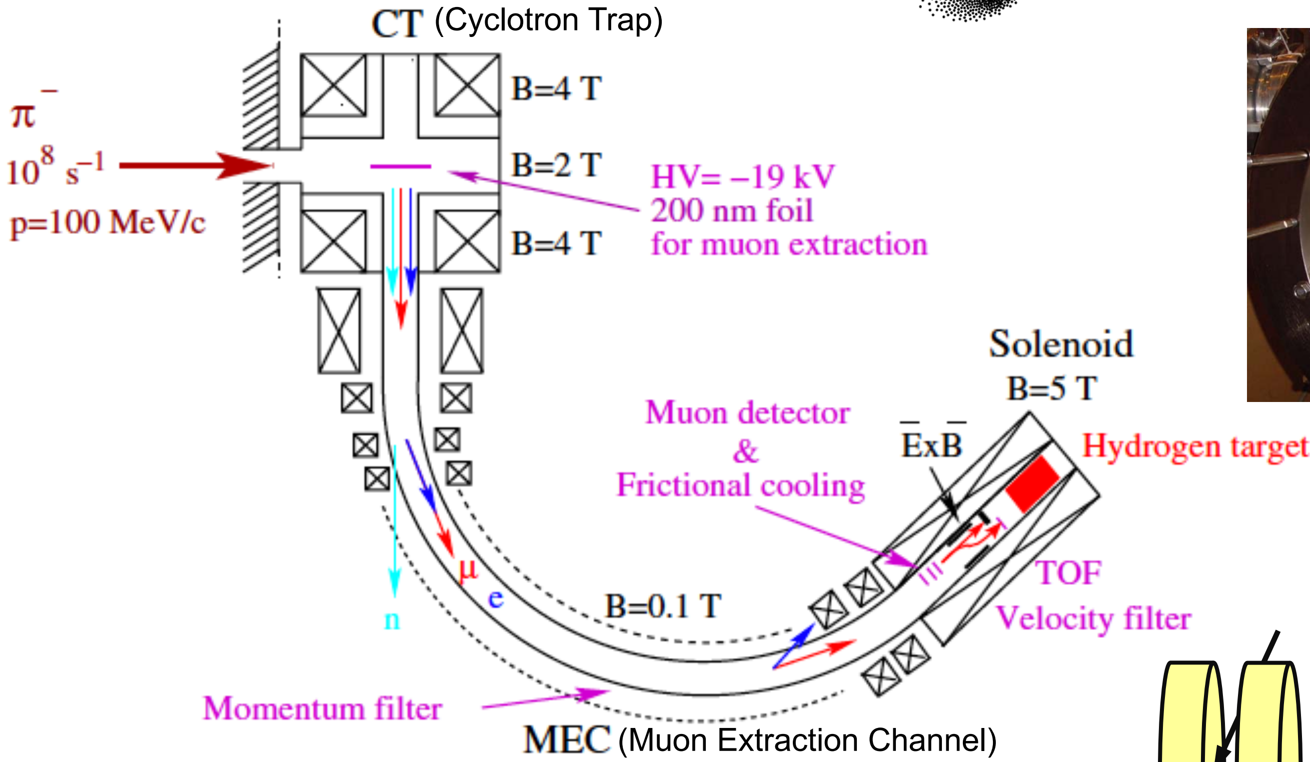




https://www.psi.ch/low-energy-muons/moderator

Ultra-Slow μ⁻ Production: Cyclotron Trap

- **Low-Energy Negative Muon Channel** PSI



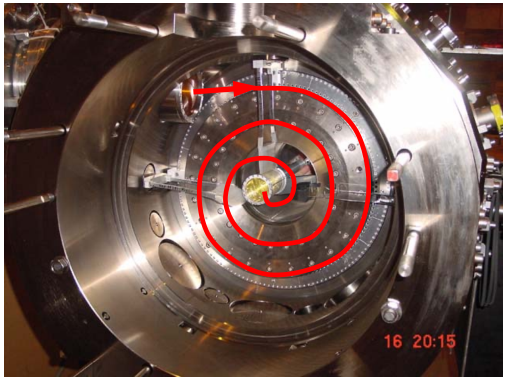
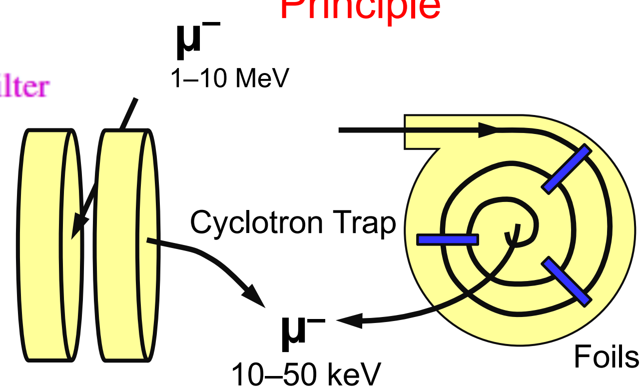


Figure from A. Antognini et al., AIP Conf. Proc. **796**, 253 (2005)
(*The 2S Lamb shift in muonic hydrogen and the proton rms charge radius*)

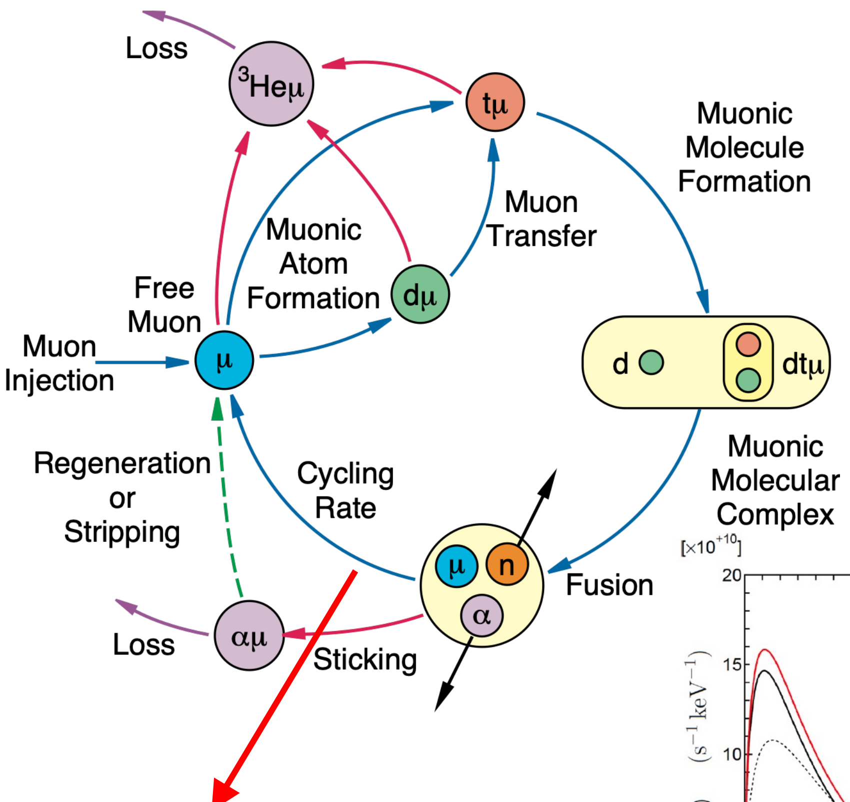


Advantage at J-PARC MUSE:

Pulsed muons ⇨ Efficient pulsed extraction is possible with a sharper time pulse.

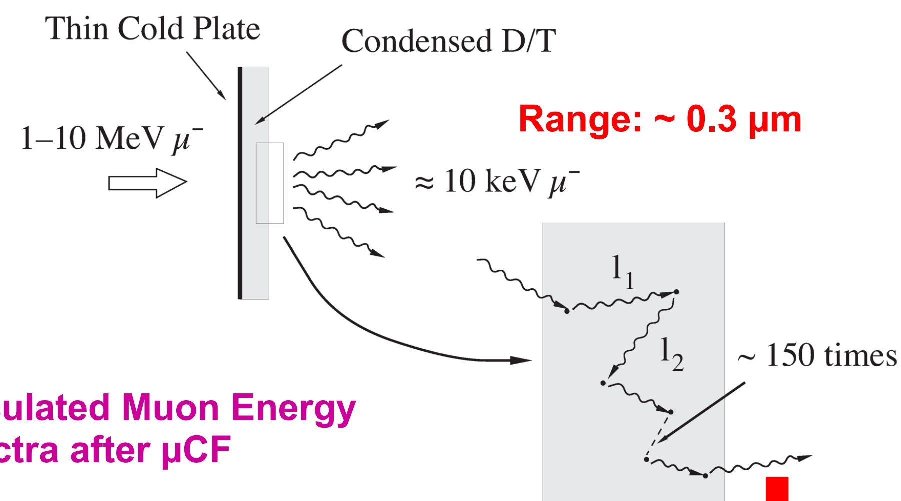
Ultra-Slow μ⁻ Production via μCF

Muon Catalyzed Fusion (μCF) Cycle

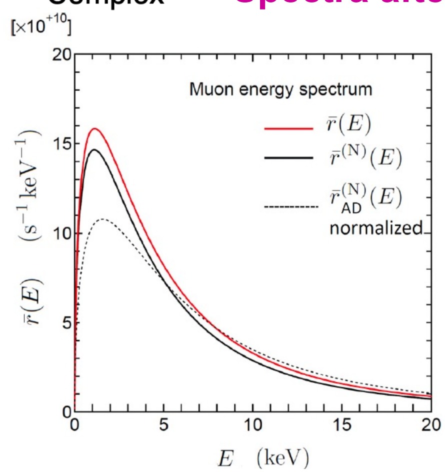


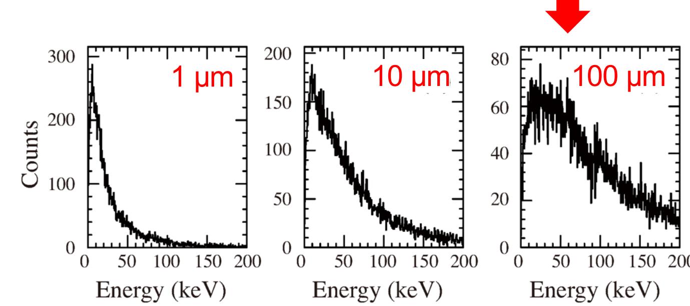
Liberation of ≈ 10-keV μ⁻ after μCF

Successive Liberation and Possible Emission from the Layer Surface



Calculated Muon Energy Spectra after μCF





Simulated energy spectra of slow μ⁻ released from a D/T layer

M. Kamimura, Y. Kino and T. Yamashita, Phys. Rev. C **107**, 034607 (2023)

~ 40 Years Old Idea from Prof. K. Nagamine

(1) μCF to produce ultra-slow μ^-

No. 10] Proc. Japan Acad., **65**, Ser. B (1989) 225

58. *Ultra-slow Negative Muon Production via Muon Catalyzed Fusion*

By Kanetada NAGAMINE
Meson Science Laboratory, University of Tokyo (UT-MSL), Bunkyo-ku, Tokyo, and Institute of Physical and Chemical Research (RIKEN), Wakoh, Saitama

(Communicated by Minoru ODA, M. J. A., Dec. 12, 1989)

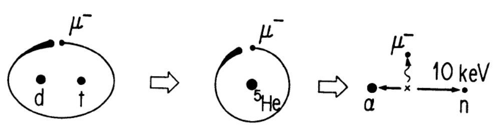


Fig. 1b: Schematic picture of the libration process of the μ^- right after the μ CF reaction in the (dtμ) molecule.

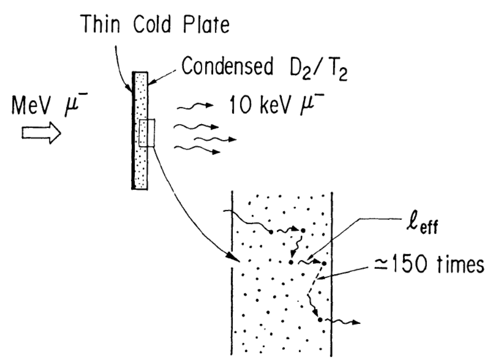


Fig. 2. Schematic view of the successive μ^- libration processes after μ^- injected into condensed D_2/T_2 thin layer.

K. Nagamine, Proc. Japan Academy **65**, 225 (1989)

(2) Ramsauer-Townsend effect

Proposed with the help of G.M. Marshall (TRIUMF)

μCF'90 (Vienna)

4. Ideas for improvements

Another remarkable idea was proposed with the help of G.M. Marshall (TRIUMF). Let us consider the MeV μ^- injected into a thick (around 1 mm) H_2 layer with a small T_2 impurity (concentration being around 1000 ppm) to which a thin D–T, or even a D_2 layer, is attached. Here, during the slowing down of the injected μ^-, because of the famous Ramsauer effect appearing in the (tμ) + p scattering cross section, the 3 eV (tμ) may have an extremely long range. Thus, the injected μ^- will be fully converted into 3 eV (tμ), and we can expect that a large fraction of 3 eV (tμ) will penetrate towards the D–T or D_2 layer. According to our estimation, this fraction might be close to 10%. Here, the (tμ) will be efficiently converted into slow μ^- via μCF.

K. Nagamine et al., Muon Catal. Fusion **5/6**, 371 (1990/1991)

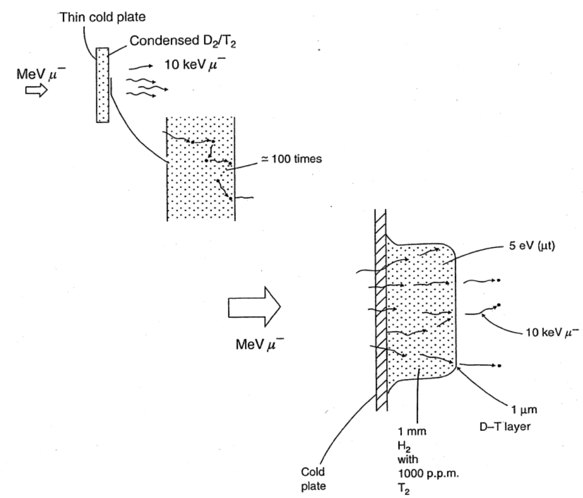
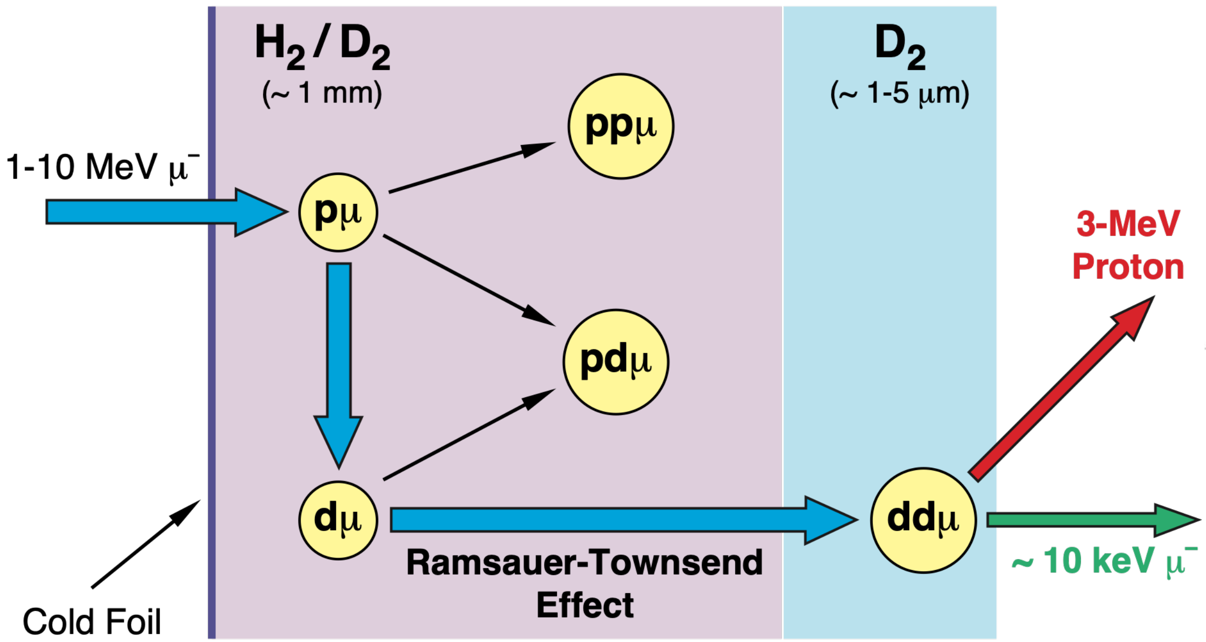


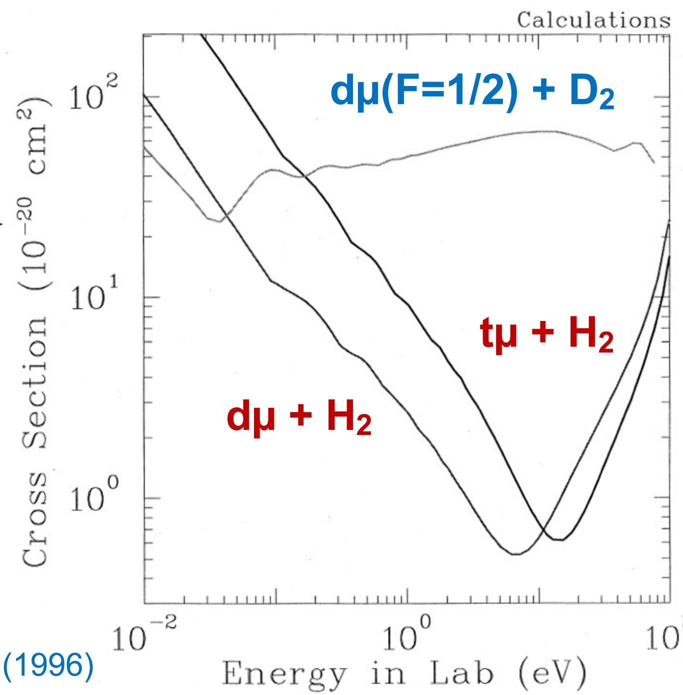
Figure 2.8 Concept of slow (keV-region) negative muon production using the muon catalyzed fusion (μCF) process in a thin D-T layer.

K. Nagamine in "*Introductory Muon Science*", Cambride University Press (2003), pp. 32-33

Ramsauer-Townsend Effect

Two-Layer Arrangement:





Calculated Elastic Cross Sections:

A. Adamczak et al., Atomic Data and Nuclear Data Tables **62**, 255 (1996)

Slow Muonic Hydrogen in Vacuum (1)

B. M. Forster et al., Hyperfine Interact. 65, 1007 (1990)

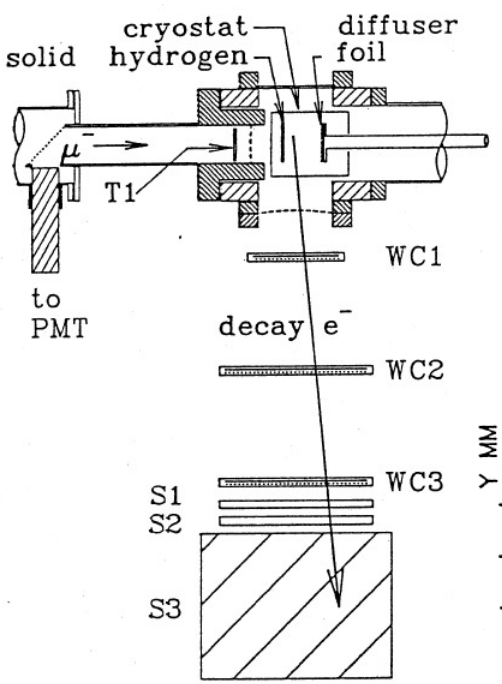


Fig. 1. A plan view of the apparatus shows the cold gold foil which supports the solid hydrogen film, and the imaging system for detection of electrons from muon decay.

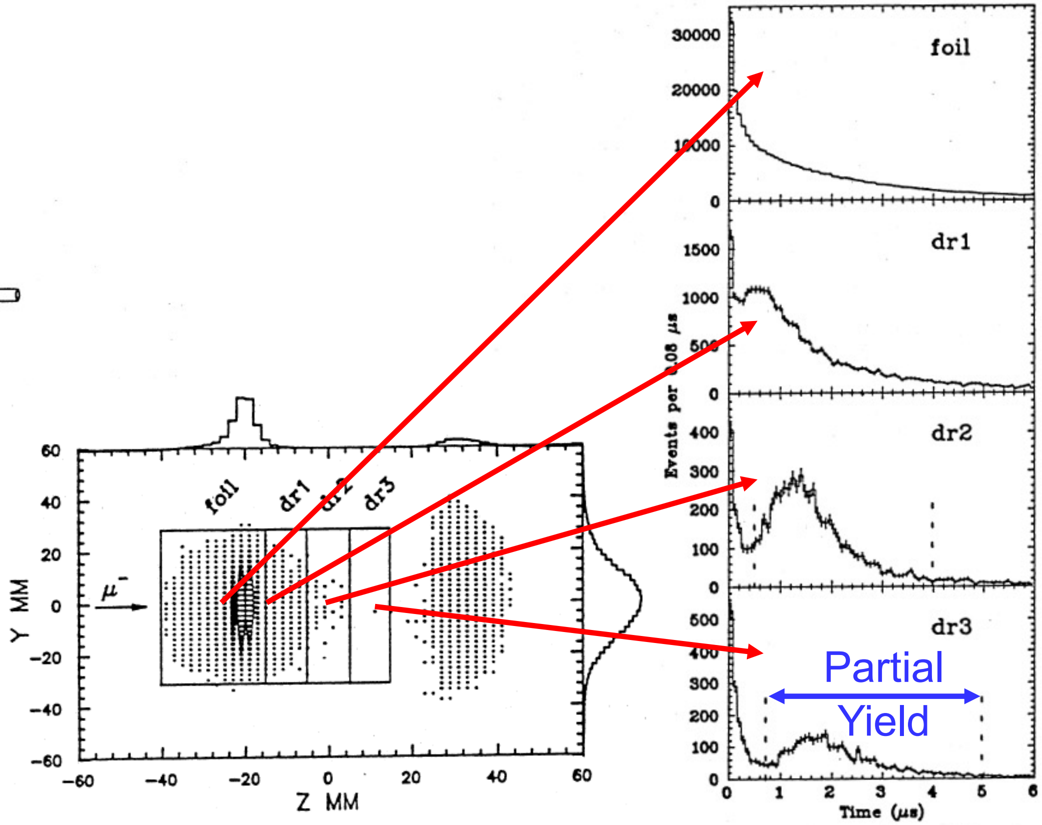


Fig. 3. Histograms show the decay time for events from the foil and three drift regions as defined in fig. 2. The non-exponential structure in each drift region is due to muonic hydrogen emitted from the solid hydrogen film and decaying in the region. Data between the dotted lines in *dr2* and *dr3* are summed to define the partial yield into these regions.

Muon beam momentum: ~ 30 MeV/c (Δp/p ~ 4%)
Beamline: M20 at TRIUMF

Slow Muonic Hydrogen in Vacuum (2)

B. M. Forster et al., Hyperfine Interact. 65, 1007 (1990)

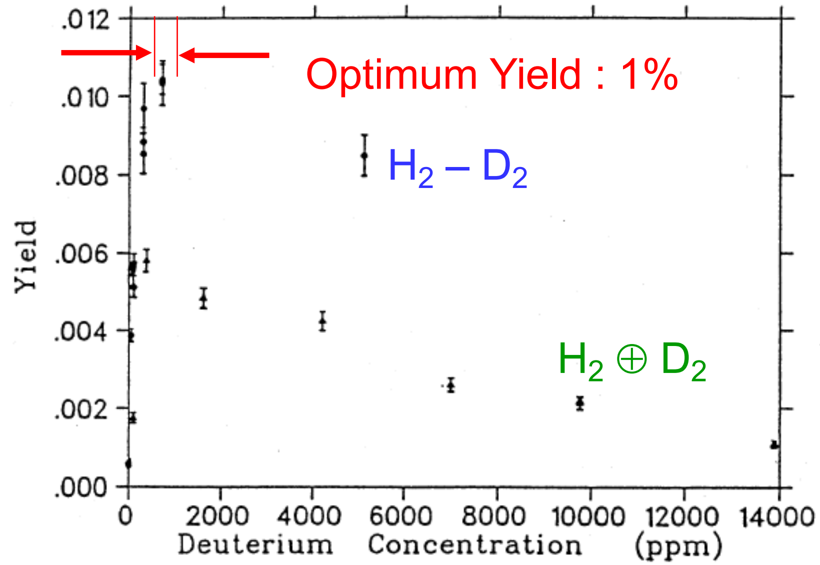


Fig. 5. Partial yields are shown for various deuterium concentrations. Circles represent targets made from H_2–D_2 mixtures, and triangles represent laminated targets with a thin layer of D_2 on top of the H_2 film.

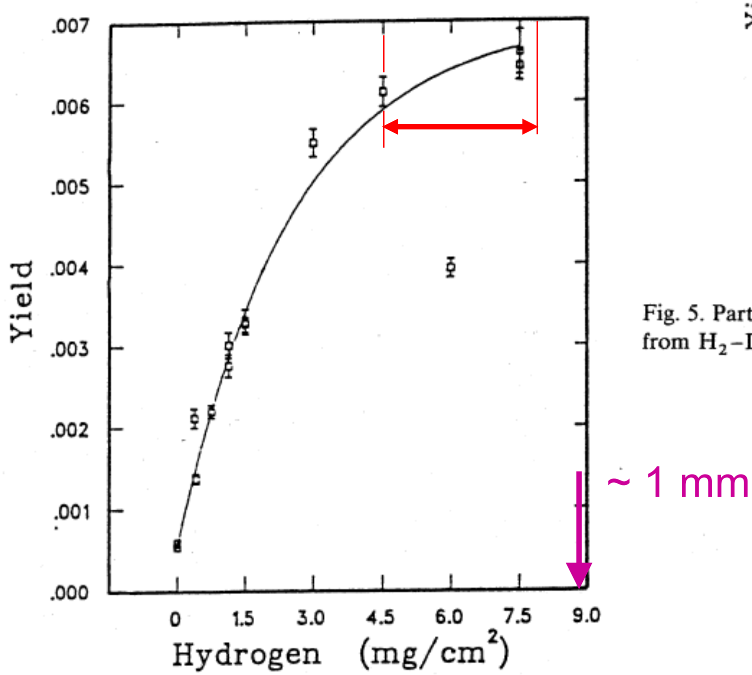


Fig. 4. The partial yield $\mathscr{Y}$ of μ^-d is plotted as a function of target thickness. All films were made with a mixture of H_2 and 100 ppm D_2.

Optimum Yield:

Thickness = 4.5 – 8 mg/cm^2

Concentration = 500 – 1000 ppm D_2

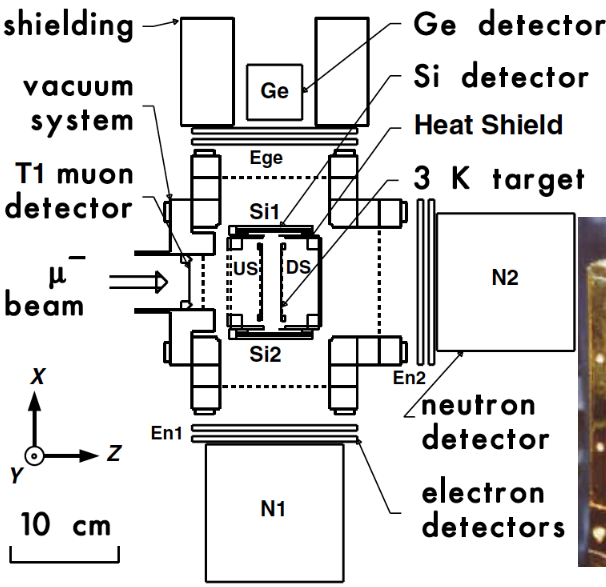
SH2 density = 88 mg/cm^2

μCF Experiments in Thin Solid Films

TRIUMF Muonic Hydrogen Group

A windowless frozen hydrogen target system

[P. Knowles, Nucl. Instrum. Meth. A 368 (1996) 604]



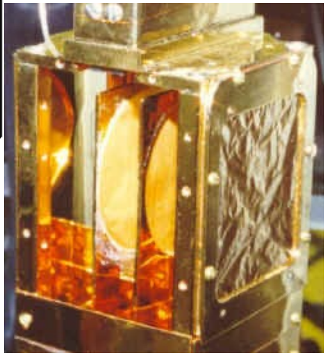


FIG. 1. Top view of the apparatus. Si detectors were placed in vacuum viewing target layers without a window, enabling the high resolution detection of fusion α particles [Fig. 2(b)]. The Ge detector monitored target impurities via muonic x rays, while plastic scintillators (En1, En2, Ege) were used both to detect muon decay electrons and to veto charged particles for Ge and neutron (N1, N2) detectors.

Figure from M.C. Fujiwara, Phys. Rev. Lett. **85**, 1642 (2000)

University of Tokyo Group

Toward Slow μ⁻ Production via μCF

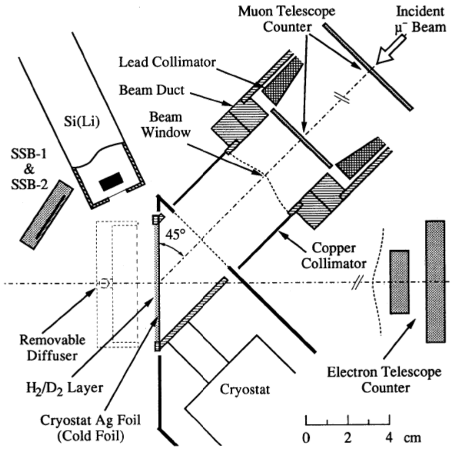
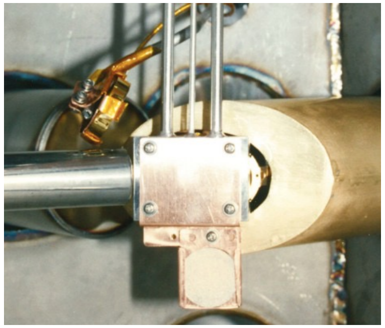
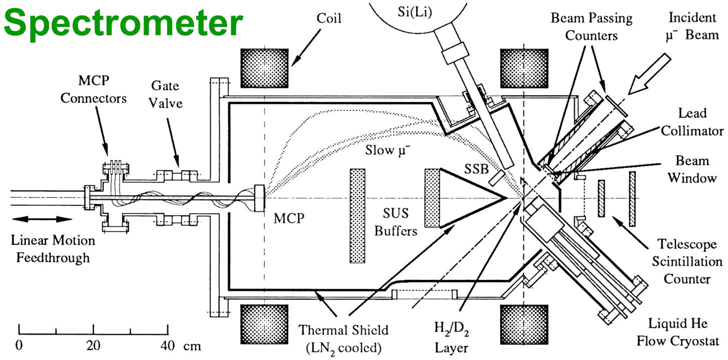


Fig. 2. Schematic view of the experimental setup for dd fusion proton and X-ray measurements.

Target system



Slow μ⁻ Spectrometer

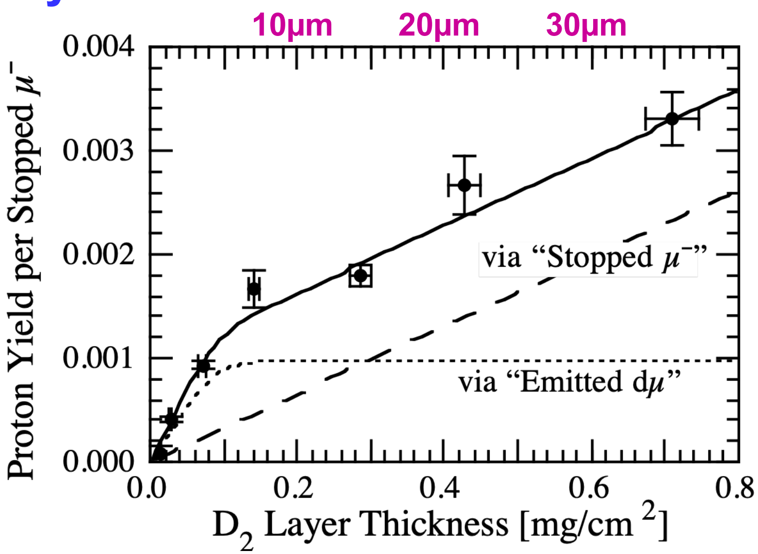


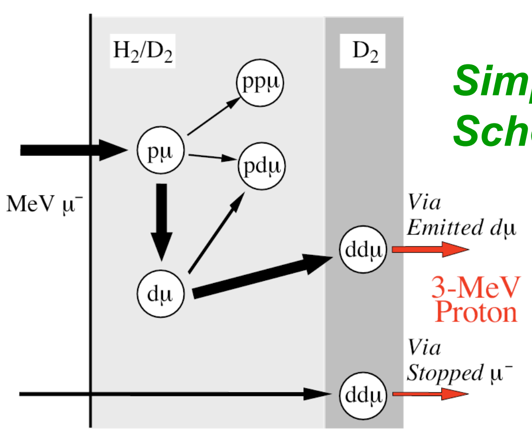
P. Strasser et al., Phys. Lett. B **368**, 32 (1996)
P. Strasser et al., Hyperfine Interact. **101/102**, 539 (1996)

ddμ Fusion Proton Distribution

μCF-95 Conference
(Dubna, 1995)

3-MeV Fusion Proton Yield vs. D_2 Layer Thickness:

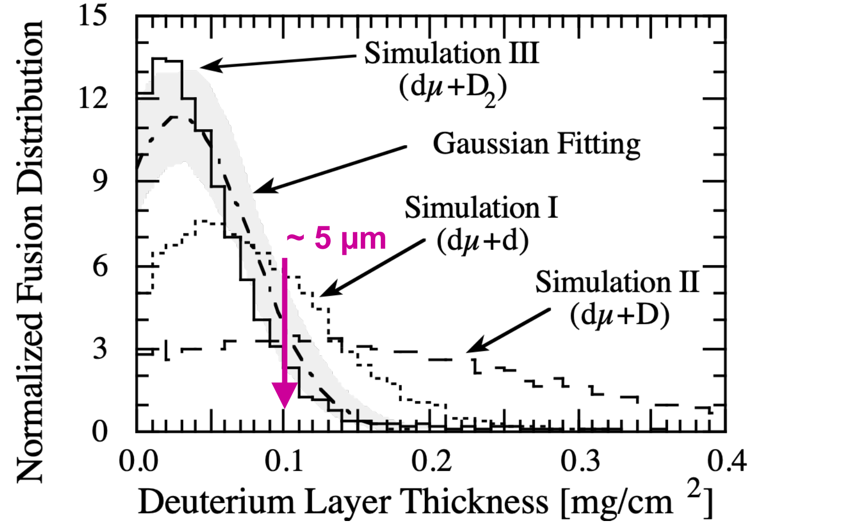




Simplified Scheme

Fusion Spatial Distribution in the D_2 Layer:

Experimental results compared with Simulations

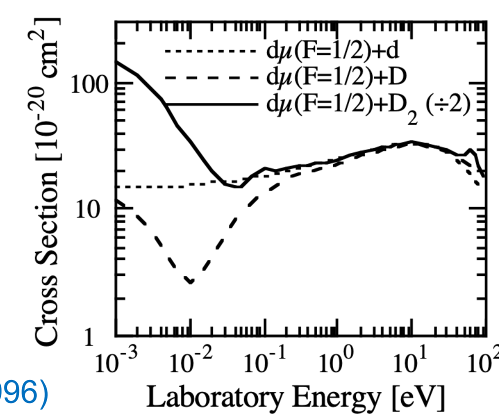


Elastic Cross Sections

$d\mu + X \rightarrow d\mu + X$,

with X = d, D, D_2

Calculated Cross Sections used in the Monte Carlo Simulations



P. Strasser et al., Phys. Lett. B **368**, 32 (1996)
P. Strasser et al., Hyperfine Interact. **101/102**, 539 (1996)

ddμ Fusion Proton Spectra

μCF-95 Conference
(Dubna, 1995)

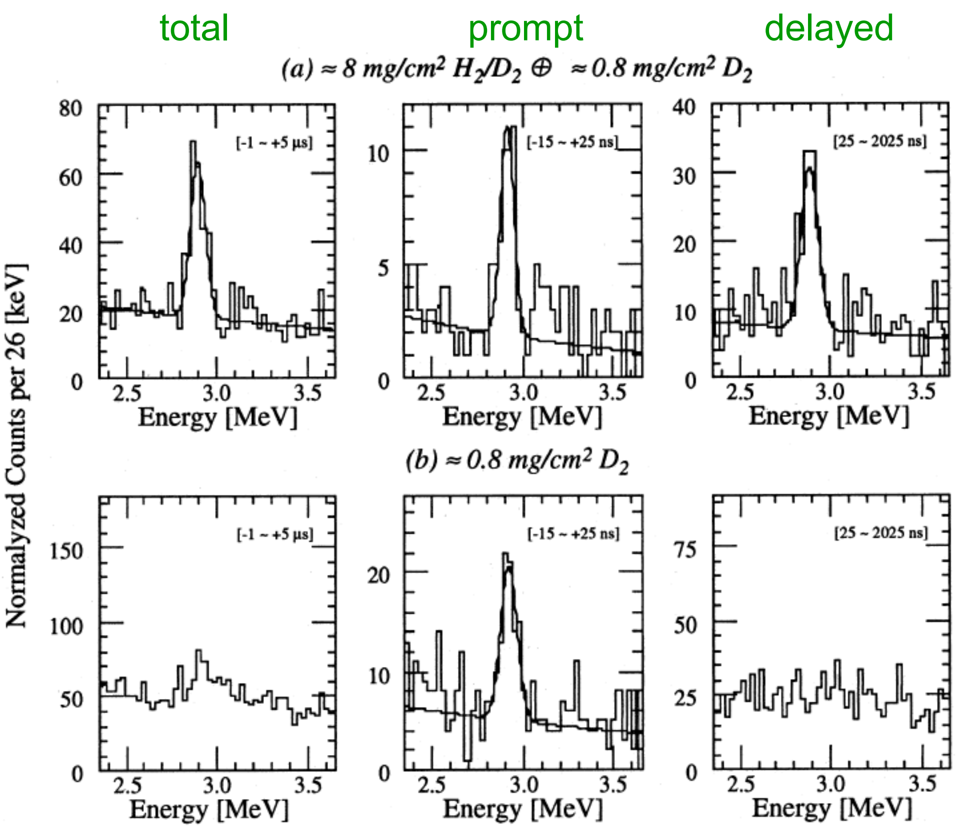
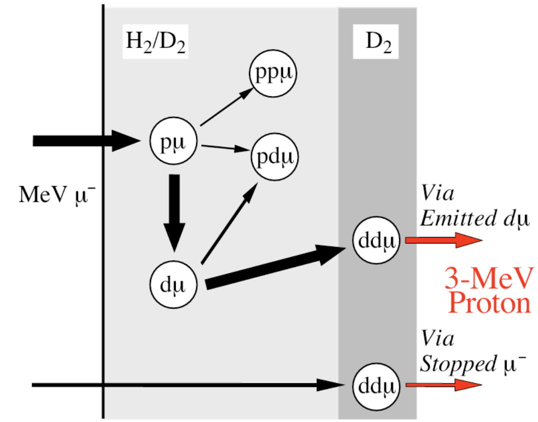


Figure 7.10. SSB-1 energy spectra: (a) with ≈ 8 mg/cm² H_2/D_2 ($C_d \cong 0.001$)⊕ 0.82 mg/cm² D_2, and (b) with only 0.82 mg/cm² D_2. (December 1993 - January 1994 Experiment)



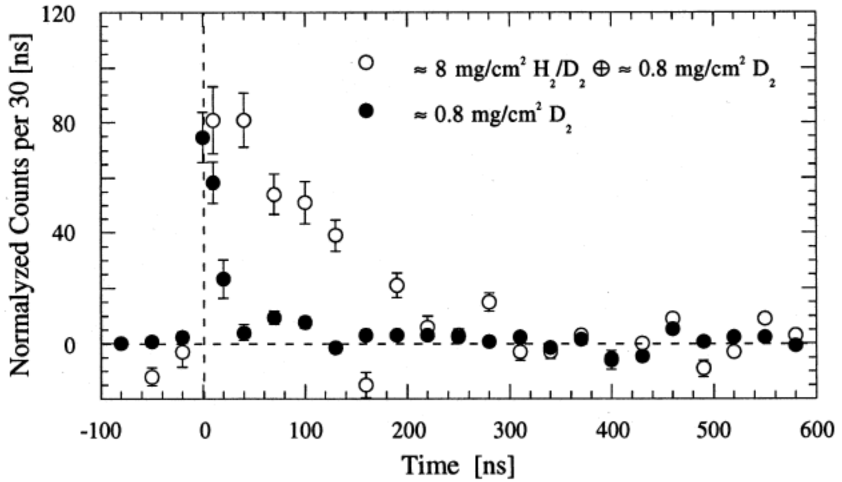
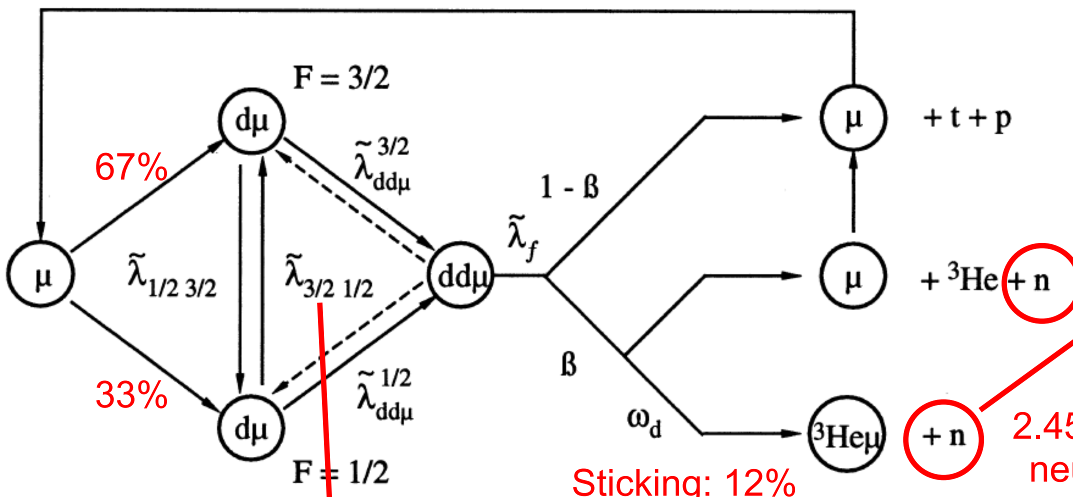


Figure 7.11. Fusion Proton time spectra (SSB-1 detector): (a) with ≈ 8 mg/cm² H_2/D_2 ($C_d \cong 0.001$)⊕ 0.82 mg/cm² D_2, and (b) with only 0.82 mg/cm² D_2.

ddμ Fusion Reaction Kinetics



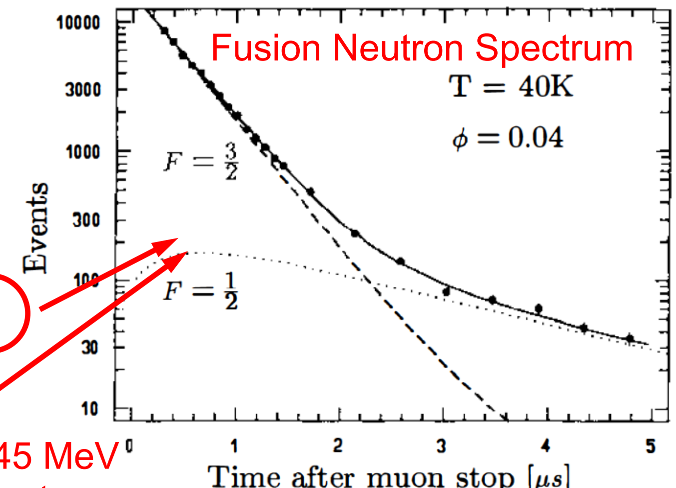


Figure from W. H. Breunlich (1989)

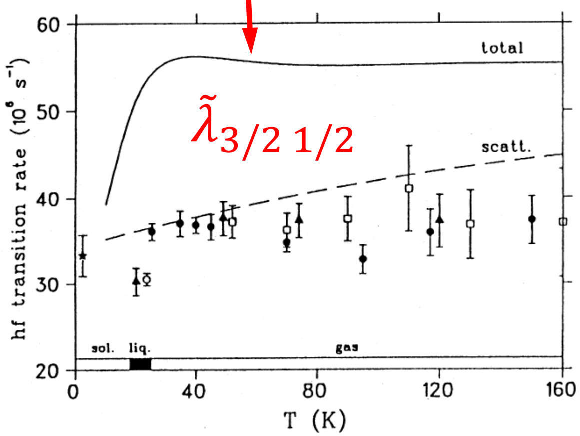


Figure 5.3. "dμ(F=3/2) → dμ(F=1/2)" hyperfine transition rates; the total theoretical hyperfine transition rate (solid line) is the sum of the scattering (dashed line) and back-decay contributions; and experiments from ●: Zmeskal et al. (1990), □: Balin et al. (1990), ▲: Bystritsky et al. (1990) and ★: Marshall et al. (1993a) (figure from Kammel 1992).

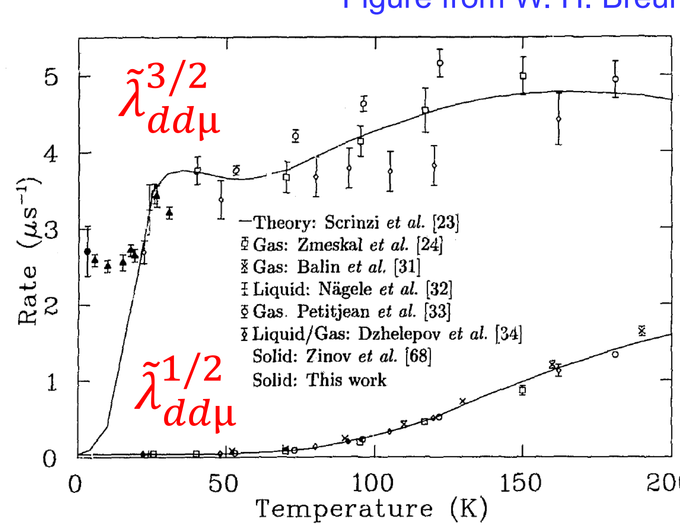
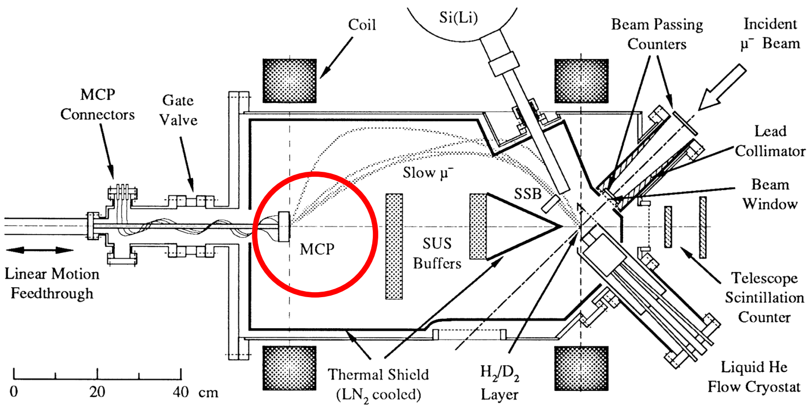


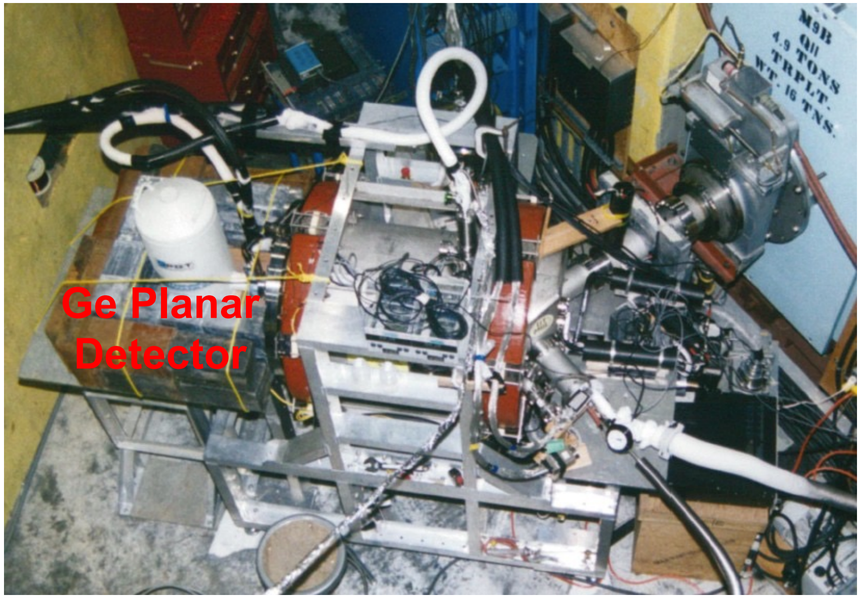
Figure 6.1.1: *A graph of molecular formation rates as measured in solid, liquid and gas, and calculations for liquid and gas. The points of Zinov et al. do not include the systematic uncertainty associated with the* $\tilde{\lambda}_{\frac{1}{2}}$ value.

Figure from P. Knowles (1996)

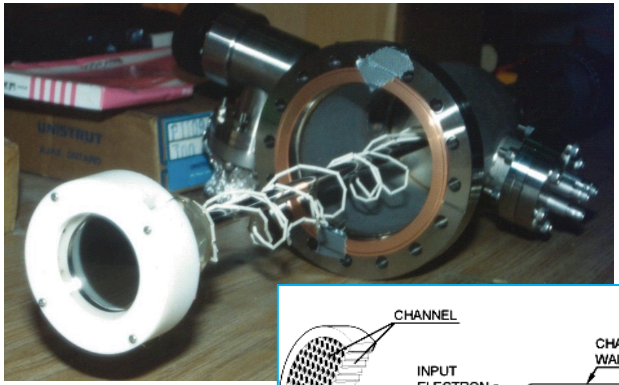
Low-Energy μ⁻ Detection (≈ 10 keV)

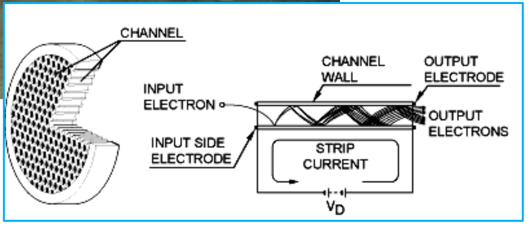
Slow μ⁻ Spectrometer (1990-1994)



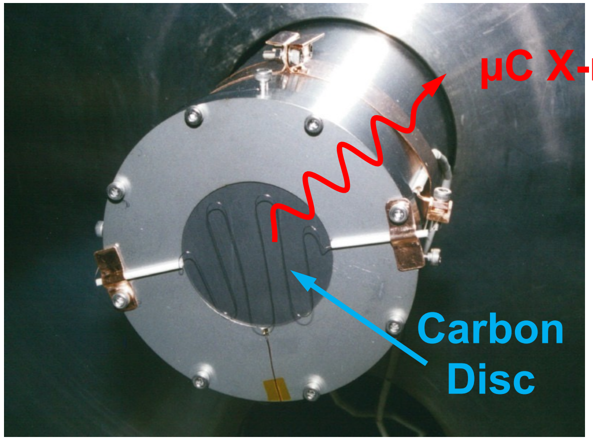


(1) Micro-Channel Plate (MCP)





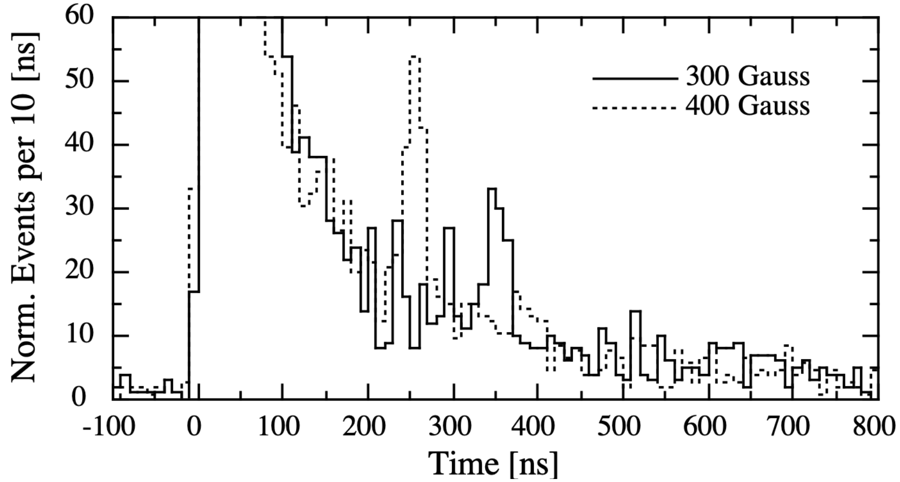
(2) Muonic X-Rays (Ge detector)



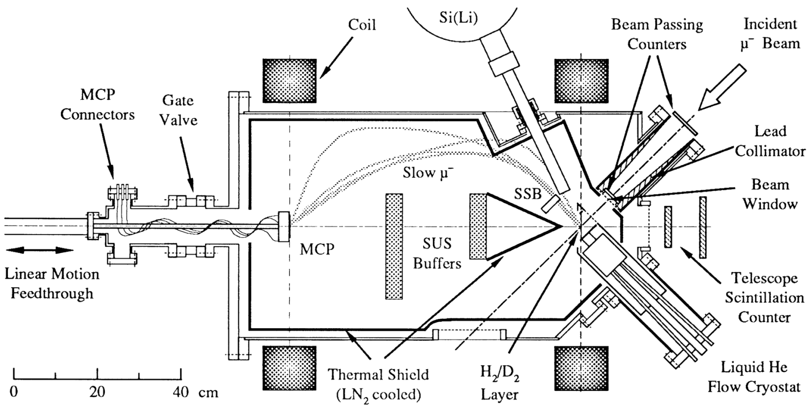
Slow μ⁻ Measurements

μCF-95 Conference
(Dubna, 1995)

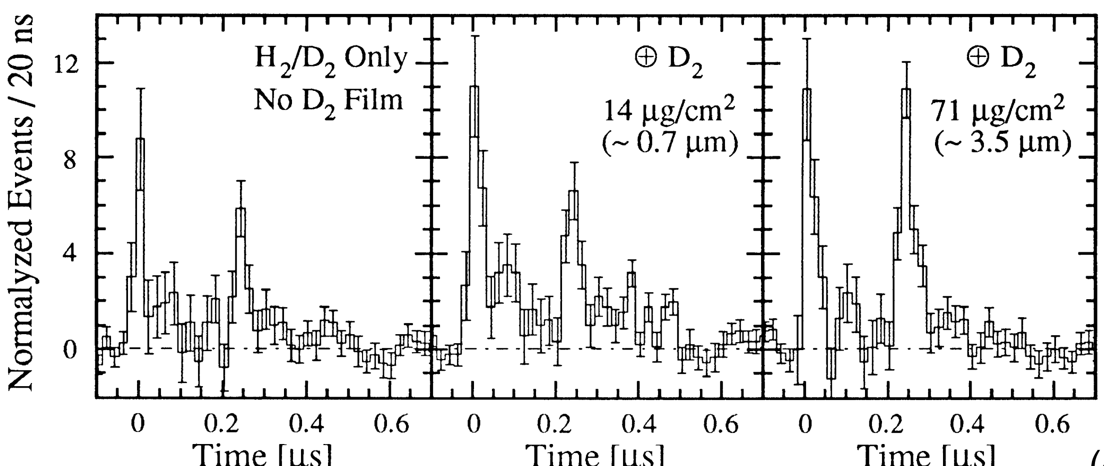
MCP Detection System:



Slow μ⁻ Spectrometer (1990-1994)

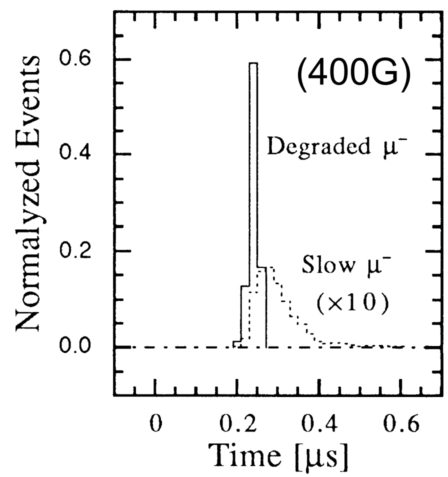


Muonic X-Ray Detection System: (μC K_α X-rays at 75.3 keV)



(400G)

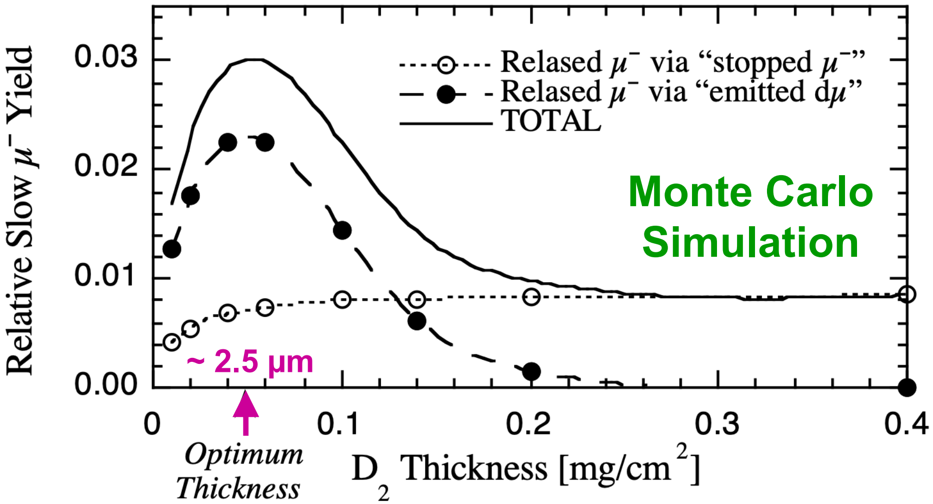
Monte Carlo Simulation:



Slow μ⁻ Production Yield Estimation

μCF-95 Conference
(Dubna, 1995)

Released Slow μ⁻ from the D_2 Layer after dd-μCF:



Gain with dtμ Fusion:

- dtμ/ddμ yield: 1 / 0.1
- dtμ fusion cycle: (thin film) 3–5 (?)
  - **Slow μ⁻ Yield: ~ 40 x**

Further Improvements:

- Magnetic confinement field, ...

Slow μ⁻ Efficiency per Incident μ⁻:

Process	Slow μ⁻ Yield — dd-μCF —		Degraded μ⁻ Yield	Slow μ⁻ Yield — dt-μCF —	
Incident μ⁻	1		1	1	
Emitted dμ	1×10^{-2}			1×10^{-2}	
Fusion	1×10^{-3}	ddμ	[5<E<15keV]	1×10^{-2}	dtμ
Slow μ⁻ Emission	**3×10^{-5}**	(~1)	3×10^{-5}	**1×10^{-3}**	(~40)
μ⁻ Collection (~10keV)	2×10^{-6}		6×10^{-6}	6×10^{-5}	

Slow μ⁻ Beam Improvement by Cooling

Frictional Cooling: Principle

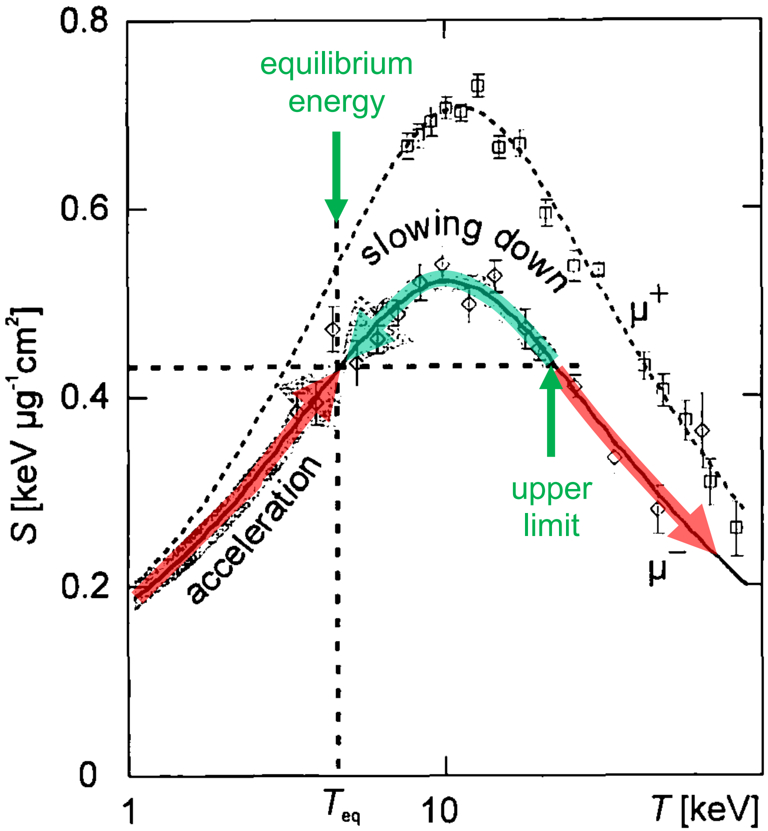
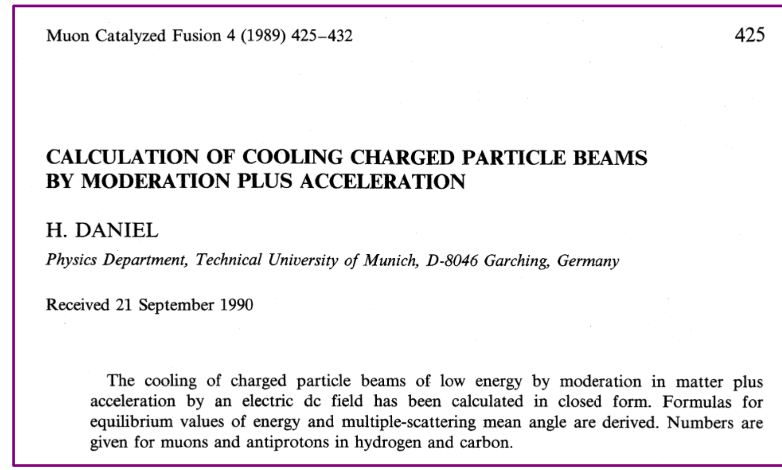


Fig. 1. Average stopping power $S(T)$ of carbon for both, positive muons and negative muons as a function of energy T [7,8]; T_{eq} denotes the equilibrium energy; the energy region where cooling takes place is marked by the arrows labeled "acceleration" and "slowing down".

Figure from M. Mühlbauer et al., Hyperfine Interact. **101**, 607 (1996)

Originally proposed by H. Daniel (1989):



Muon Catalyzed Fusion 4 (1989) 425–432 425

CALCULATION OF COOLING CHARGED PARTICLE BEAMS BY MODERATION PLUS ACCELERATION

H. DANIEL

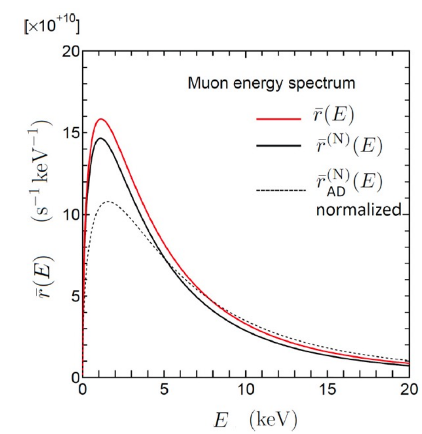
Physics Department, Technical University of Munich, D-8046 Garching, Germany

Received 21 September 1990

The cooling of charged particle beams of low energy by moderation in matter plus acceleration by an electric dc field has been calculated in closed form. Formulas for equilibrium values of energy and multiple-scattering mean angle are derived. Numbers are given for muons and antiprotons in hydrogen and carbon.

H. Daniel, Muon Catalyzed Fusion **4**, 425 (1989)

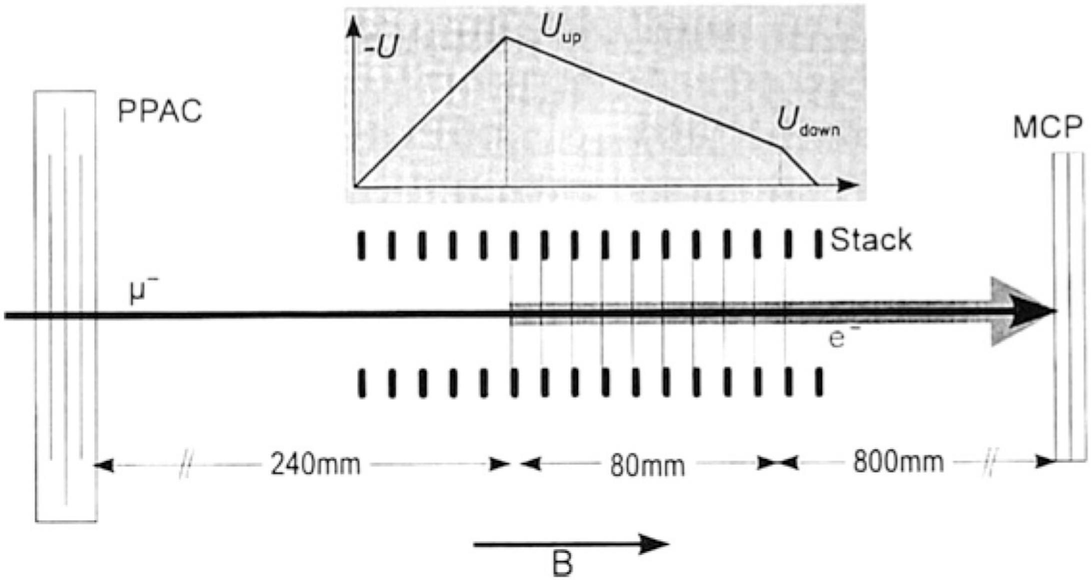
Muon energy after μCF



M. Kamimura *et al.*, Phys. Rev. C **107**, 034607 (2023)

Frictional Cooling: Setup & Results

Fig. 2. Schematic view of the experimental set-up as it is housed by the superconducting solenoid. This solenoid, generating a high magnetic field in the beam direction, is not shown in this sketch. The inset shows the voltage distribution in the region of the foil stack.



Presented at the µCF-95 Conference (Dubna, 1995)

M. Mühlbauer et al., Hyp. Interact. **101**, 607 (1996)
M. Mühlbauer et al., Hyp. Interact. **82**, 459 (1993)

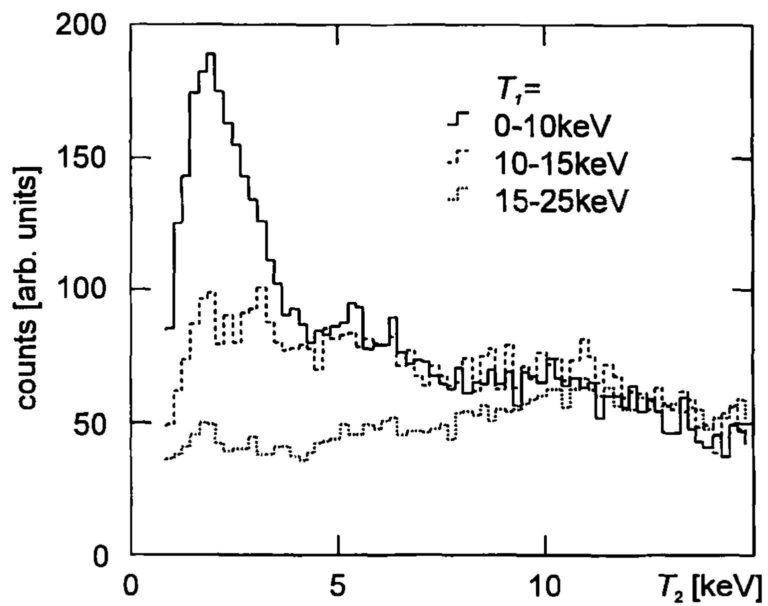


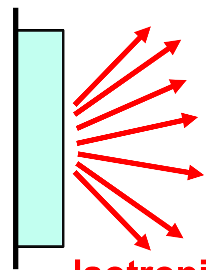
Fig. 3. Energy spectra of the outgoing muons as a function of the energy T_1 of the incident muons (10 foils 4.3 $\mu g/cm^2$C(+1 $\mu g/cm^2 H_2O$) each, $U_{up} = -18$ kV, $U_{down} = -3$ kV and $\Delta U = 1.7$ kV). The energy calibration is preliminary (cf. text).

Note: If used with positive muons, it will act as a trap for secondary electrons leading to HV breakdown in the stack region !!!

μCF-Muon Cooling Simulation

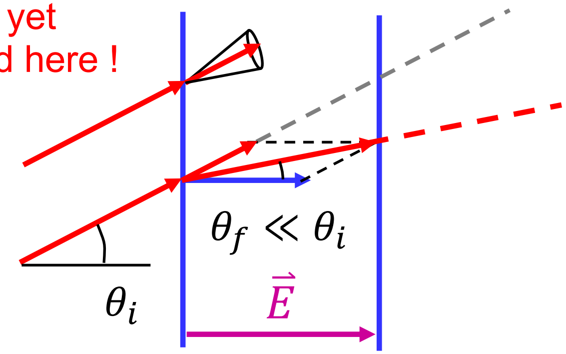
<u>Simple Simulation</u>:

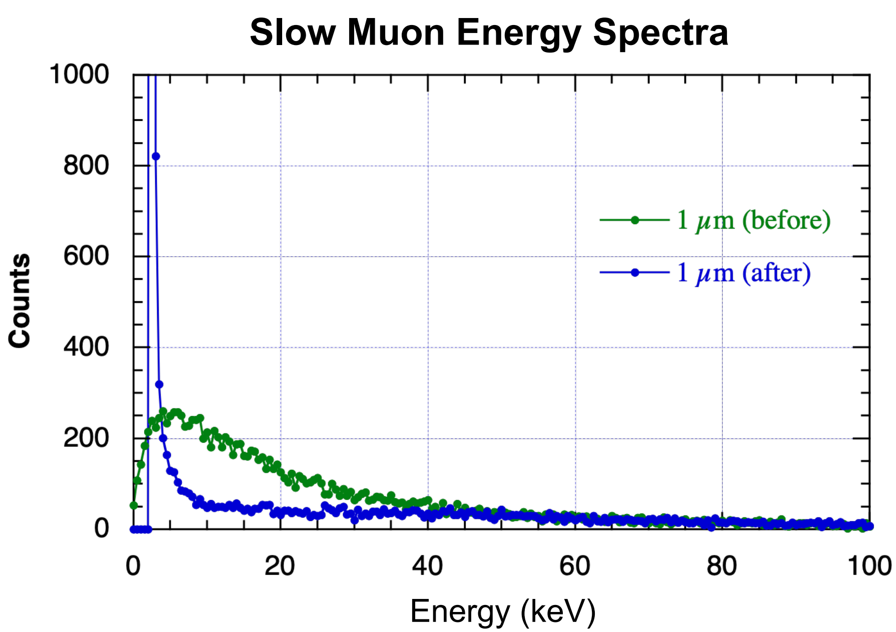
- arbitrary energy cut-off below 1.0 keV
- multiple scattering and straggling not yet included !

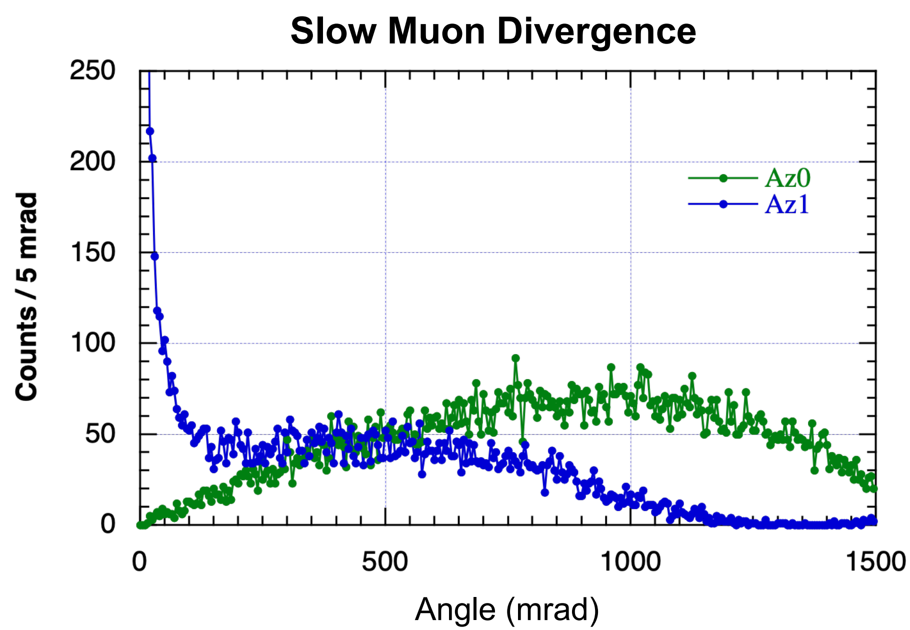


Isotropic Emission

Not yet included here !







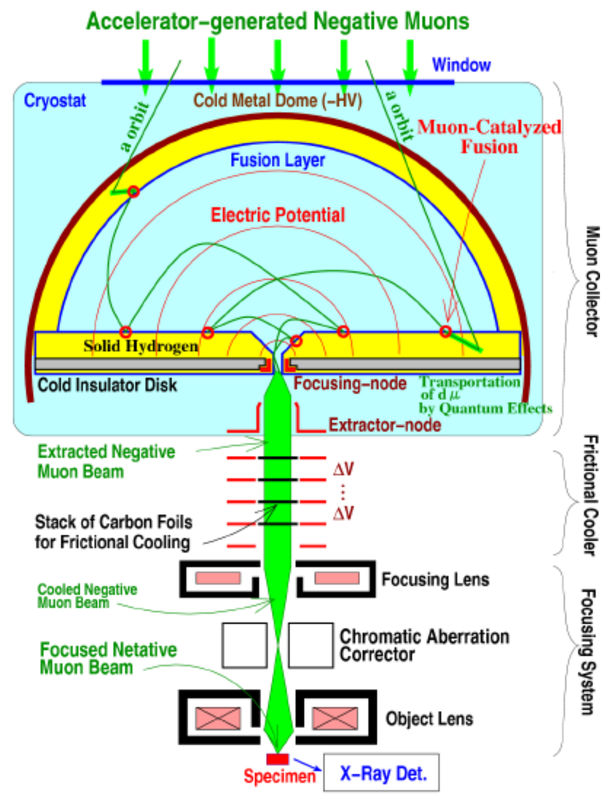
<u>20 cooling stages</u>: th_{Foil} = 4.3 μg/cm², ΔU = 1.4 kV, Δd = 8 mm

Recent Developments

新学術領域研究「宇宙観測検出器と量子ビームの出会い。新たな応用への架け橋。」
(Grant-in-Aid for scientific Research on Innovative Area;
Toward new frontiers : Encounter and synergy of state-of-the-art astronomical detectors and exotic quantum beams)

C02 最先端負ミュオンビーム開発 **Y. Miyake (KEK), Y. Nagatani (KEK)** **(FY2018-2022)**
(Advanced Negative Muon Beam Development)

- **Muon Catalyzed Fusion** (μCF) is applied to muon beam-cooling. After fusion, the muons is released with an ultra-low energy (≈ 10 keV)
- **Ramsauer-Townsend** effect is used to confine the production region of ≈ 10keV muons to a minimum film thickness
- Released muons are then transported into the center by E-field, extracted, frictionally cooled, and focused onto a target



Conceptual design by Y. Nagatani (KEK)

The Need for Tritium

by Y. Nagatani (KEK)

When comparing systems using only deuterium (DD fusion) with those using tritium (DT fusion), using of DT is 300,000 times brighter.

	DD-Fusion (only D)	DT-Fusion (using T)
Re-emission probability	2.0%	85.3%
Number of μCF cycles	only 1 step	more than 10 steps
Extracted beam diameter	10 mm	< 0.1 mm
Focusable beam diameter	**1 mm**	**< 10 μm**
Beam intensity	~ 1 μ^-/sec	> 30 μ^-/sec

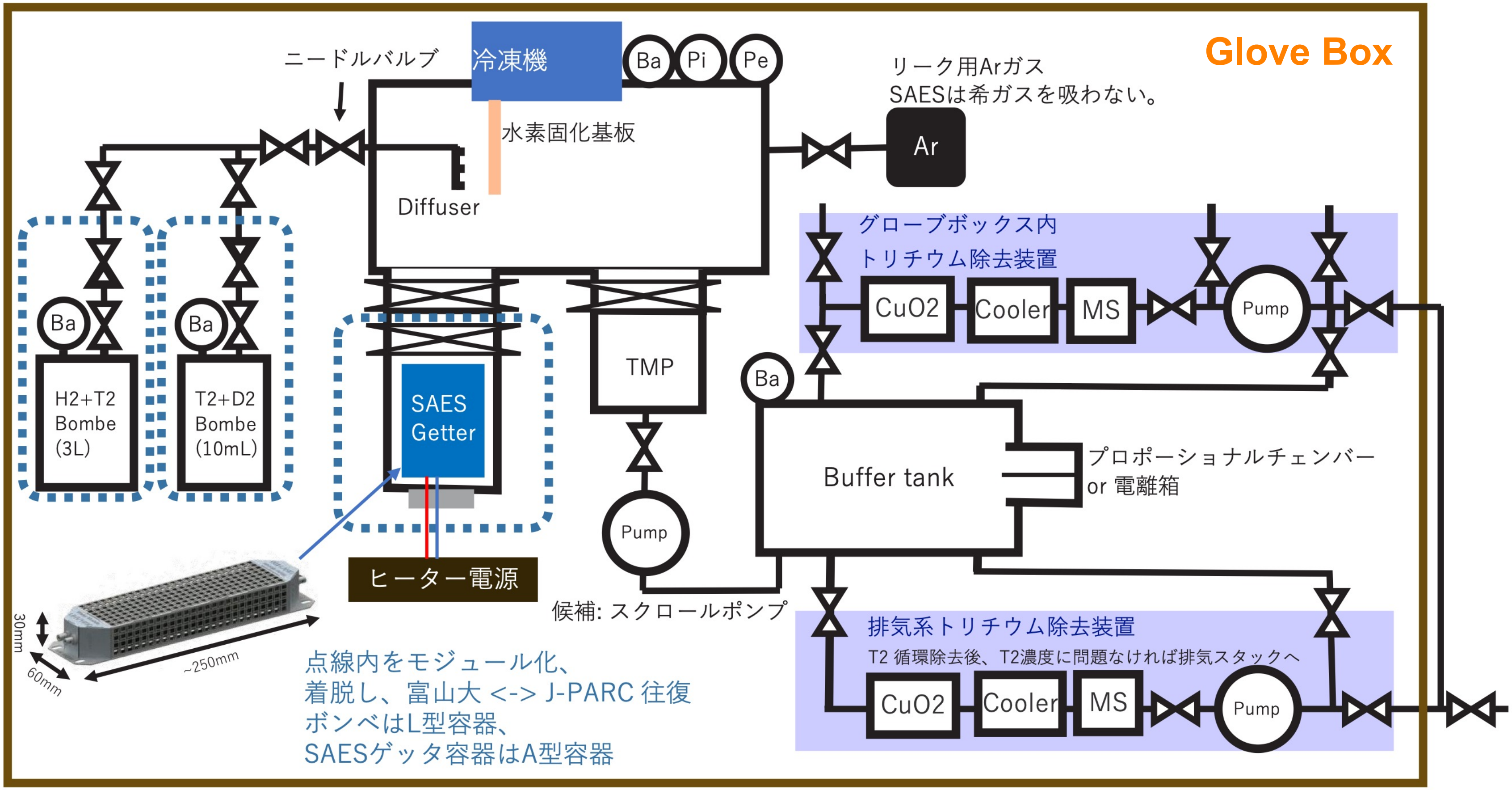
Luminosity ratio = 100 × 100 × 30

The use of tritium is essential

Tritium-Hadling Equipment Design

by Y. Nagatani (KEK)

With the Hydrogen Isotope Research Center of the University of Toyama

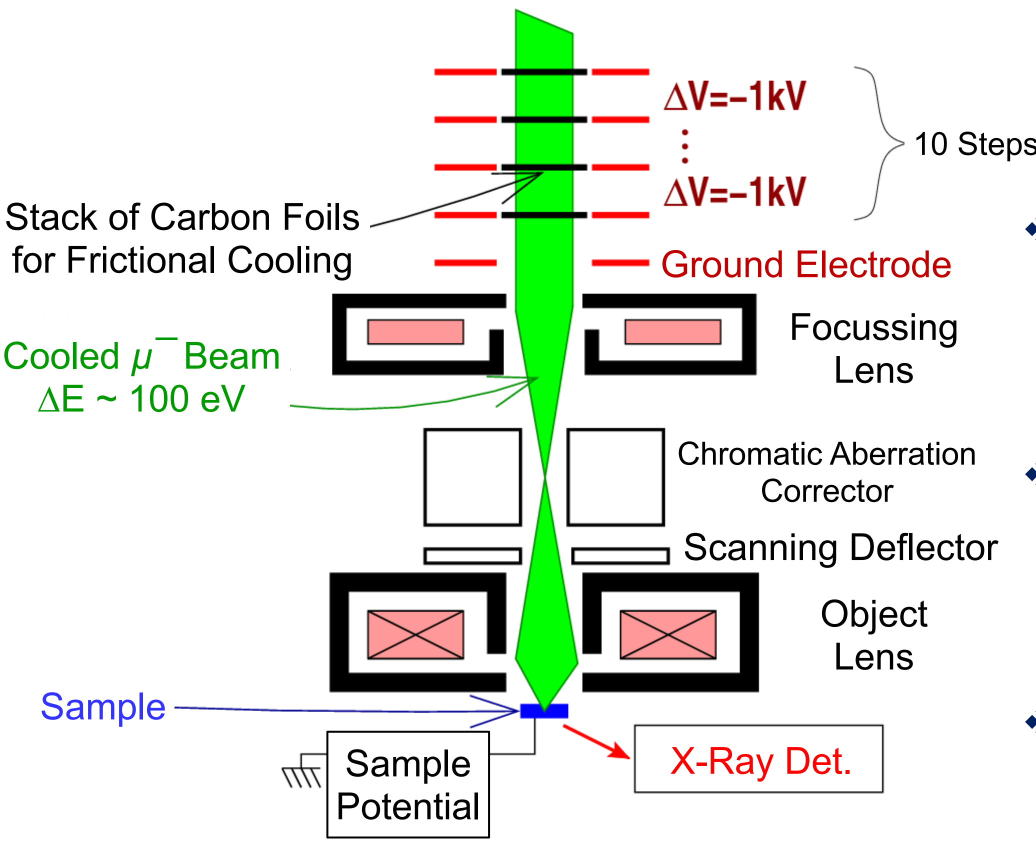


to exhaust stack
~30 L/h

In collaboration with Y. Hatano and M. Hara (Toyama University)
H. Natori (KEK) carried out the detailed design

Negative Muon Element Analysis Scanning Microscope

by Y. Nagatani (KEK)



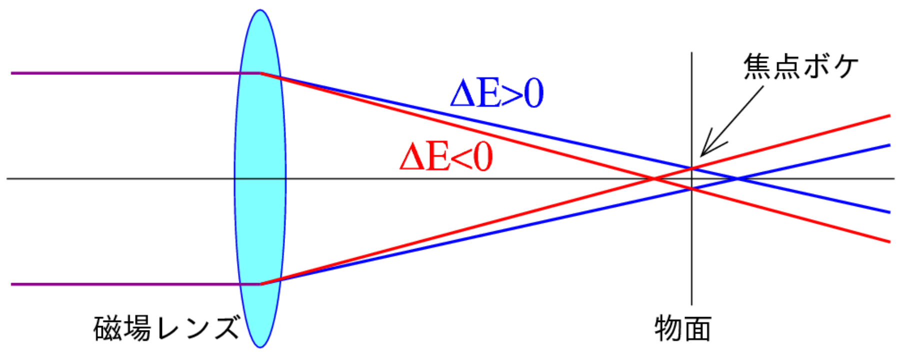
- ❖ Negative muons focused and irradiated onto a sample are captured by atoms, emitting high-energy muonic X-rays
- ❖ By detecting these elements, isotopes, and chemical states at specific points can be identified with ultra-high sensitivity
- ❖ In addition to XY scanning, scanning the sample potential allows for scanning of the penetration depth as well (3D scanning)
- ❖ Alternatively, by continuously imaging while ablating the surface of frozen cells, it is also possible to obtain macroscopic 3D distributions

➢ Visualizing 3D distribution of elements and isotopes within materials with ultra-high sensitivity

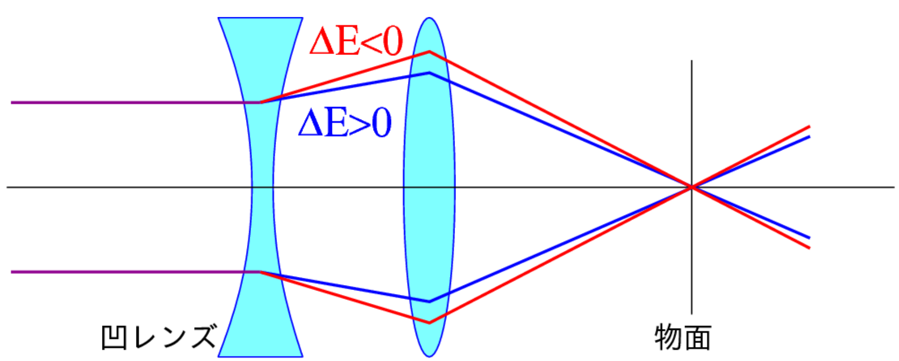
Beam Focusing Correction

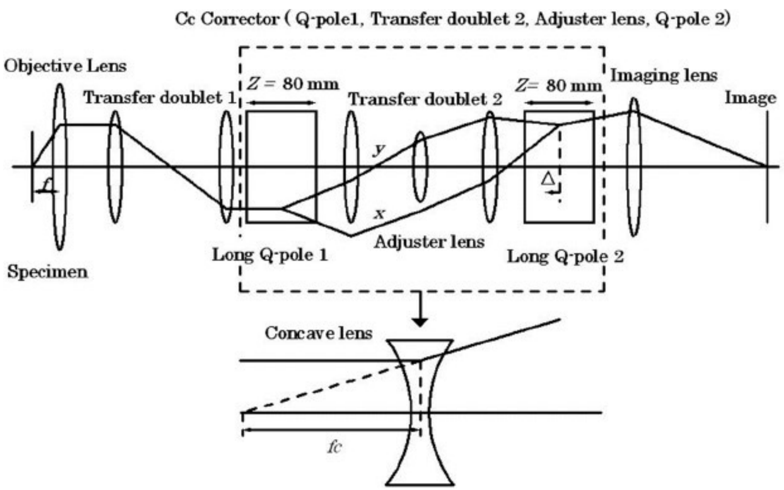
Developed by Y. Nagatani (KEK)

- Even with frictional cooling, energy dispersion still ΔE ~ 100 eV
  To achieve submicron focusing, chromatic aberration in the lens is a problem
- Particles with higher energy have a longer focal length → out-of-focus image



- Solved by a chromatic aberration corrector

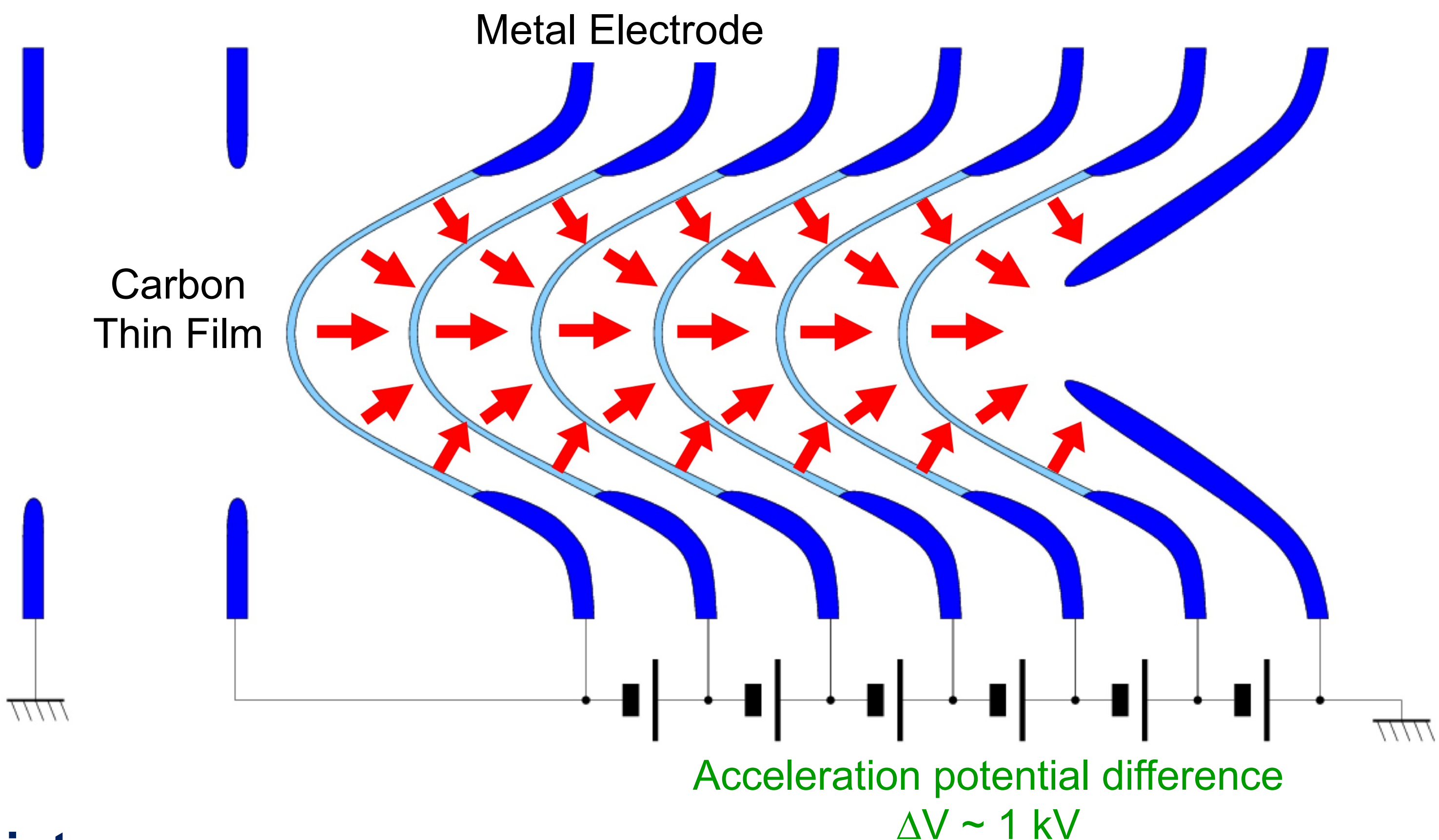




Example of specific configuration (Hosokawa)

Friction Cooling using Curved Films

Developed by Y. Nagatani (KEK)



Key Point:

- Shaping a conductive deceleration thin film into a curved surface
- In addition to the re-acceleration electric field, a central converging electric field is also generated simultaneously

Improving Frictional Cooling

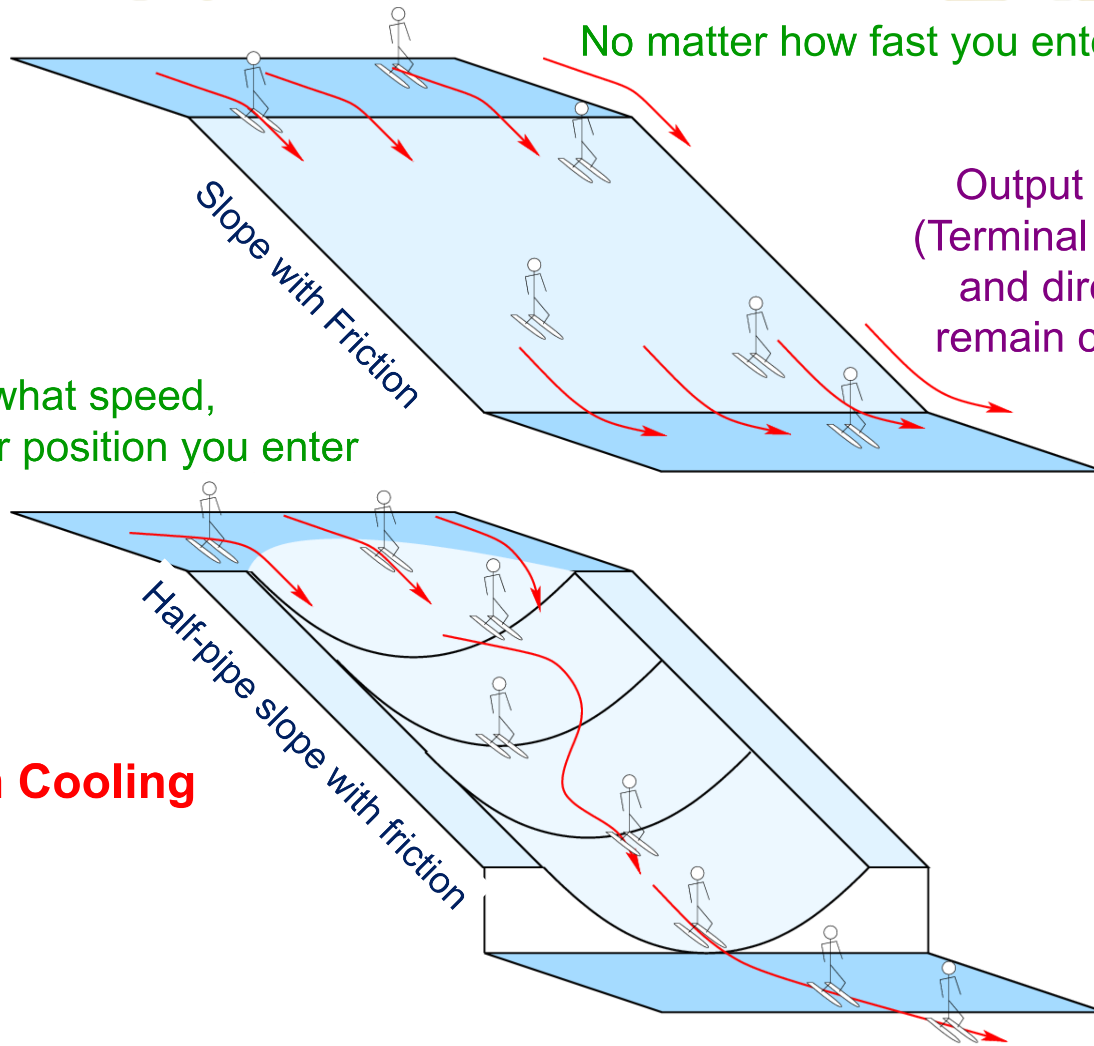
Developed by Y. Nagatani (KEK)

Conventional:
Planar Thin-Film Cooling

No matter how fast you enter,

Output Speed
(Terminal Velocity)
and direction
remain constant

No matter what speed,
direction, or position you enter

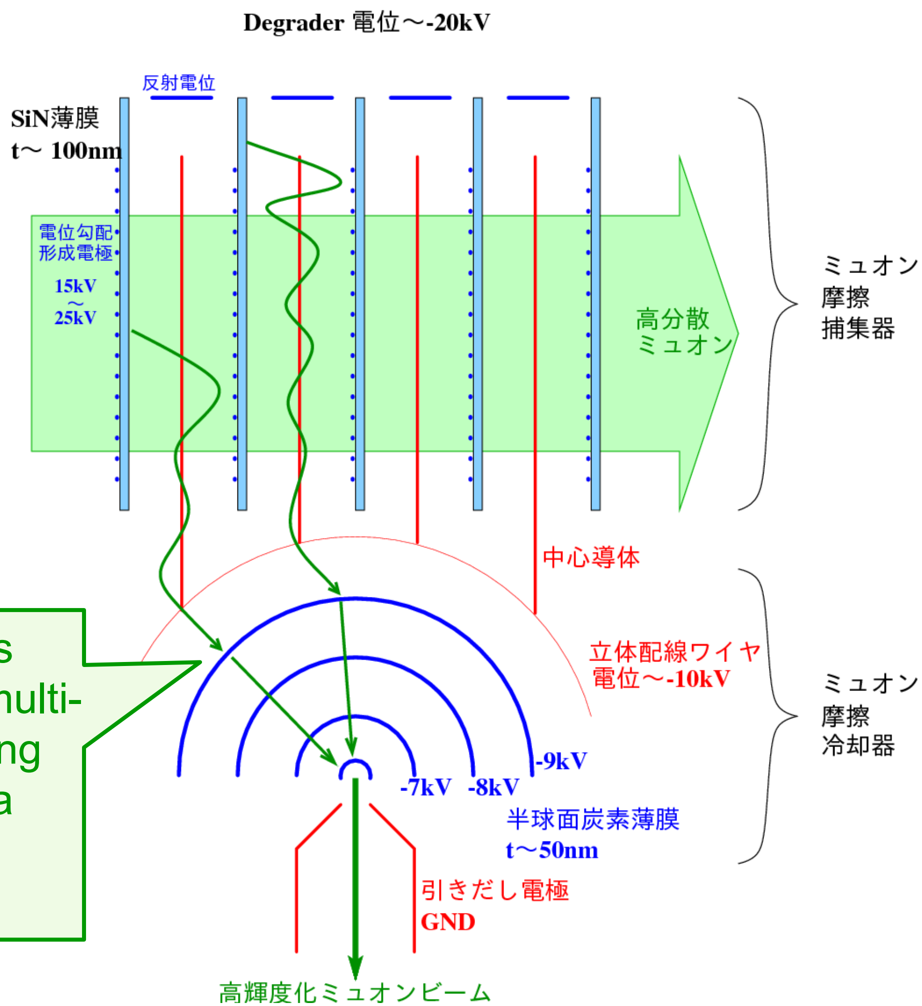


New:
Curved-Surface Thin-Film Cooling

Output is a narrow beam at a constant speed
Monochromatic and high-emittance

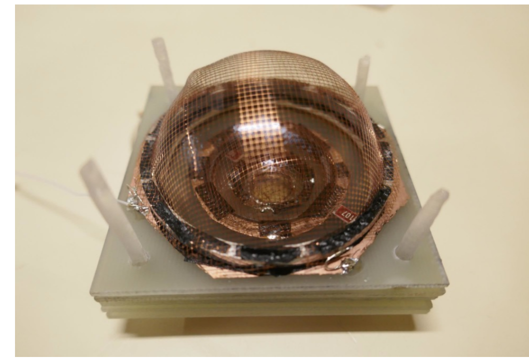
Concentric Spherical Cooler

Developed by Y. Nagatani (KEK)

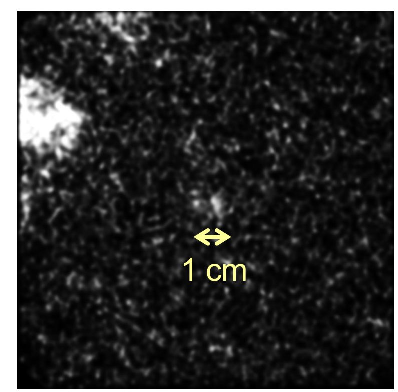


Negative muons collected by a multi-layer decelerating collector using a curved thin-film cooler

Hemispherical Electrodes with Membrane



Muon Detection:
Mg-activation IP image
(Enhanced image)

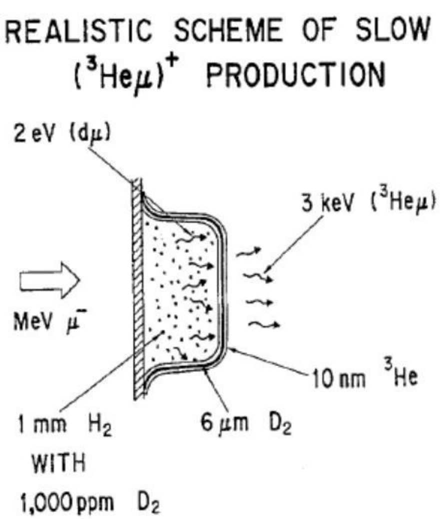


Stack 100 sheets for 100 times the strength

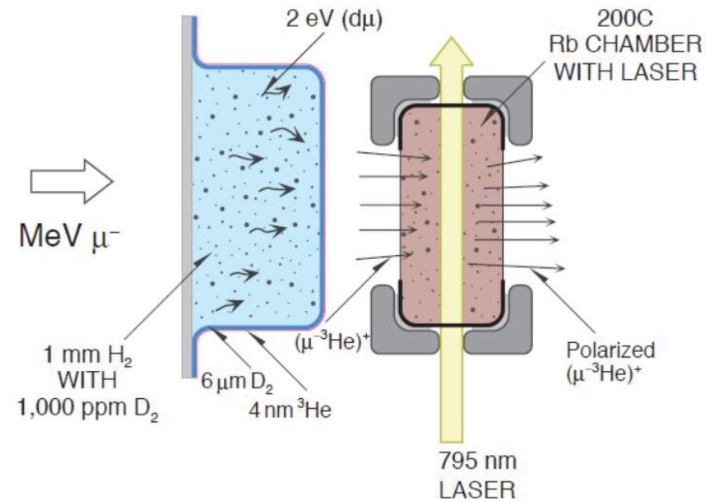
Utilization of Muonic Helium Ions

Nagamine proposal [1993]: Generation of μ^3He ions

μ^- → Generation of μ^3He ions → $(^3He^{++}\mu^-)^+$ (~3 keV) → Accelerate μHe to >1 MeV, pass through a stripper foil, and dissociate μ^- from He → μ^-



K. Nagamine, Hyperfine Interactions **82**, 539 (1993)



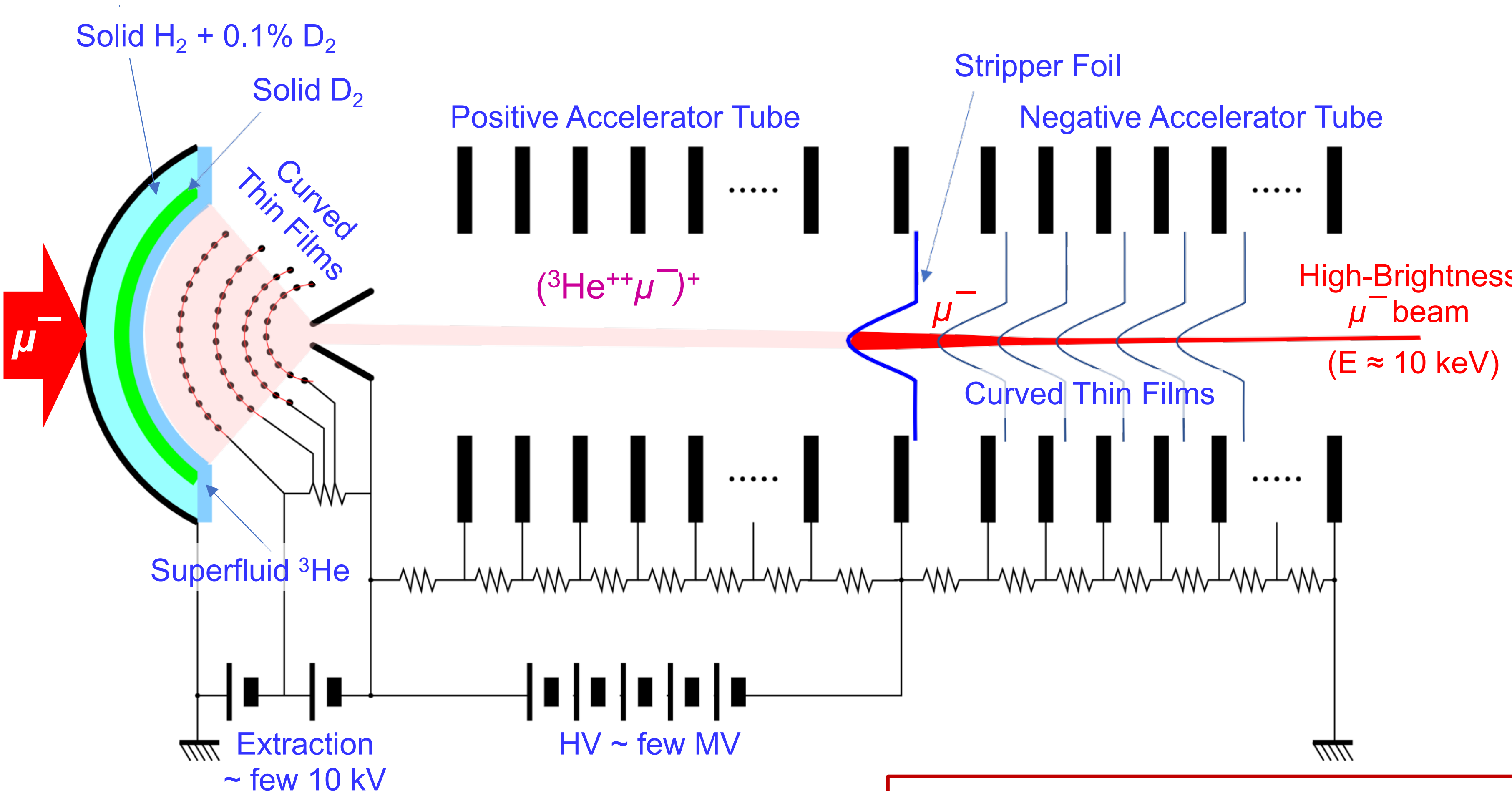
- ❖ Utilizes the long-range (sub-mm) diffusion of dμ in solid hydrogen and the Ramsauer-Townsend effect
- ❖ Isotope exchange: dμ + He → d + μHe (~3 keV)

Nagamine proposal [2011]:
With muon repolarization

Tandem System for High-Brightness Negative Muon Beam

by Y. Nagatani (KEK)

Nagamine Proposal + Tandem Acceleration + Curved Surface Friction Cooling
+ Pierce Extraction + Curved-Surface Friction Cooling of μHe Ions



Method with no tritium and no μCF!

Summary and Outlook

- **Ultra-slow negative muons** are challenging to produce due to the irreversible formation of muonic atoms
- **Muon Catalyzed Fusion** (μCF) can be used as a cooling method
- The use of DT fusion is critical to get higher luminosity
- Technical challenges in using tritium …
- **Potential Applications of Scanning Negative Muon Microscopy**
  - Comprehensive mapping of the three-dimensional distribution of elements, isotopes, and chemical states within biological samples (tissues and cells)
  - Semiconductor device soft error evaluation by stopping muons at targeted locations in three dimensions within semiconductor devices
  - And many others …

FIN