Muonic Atom of Unstable Nuclei

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Workshop on Physics with Ultra Slow Antiprotons
RIKEN, March 14-16, 2005.

Introduction

◆ **Physics Motivation**

X-RAY SPECTROSCOPY of **MUONIC ATOMS !**

- Precision tool to measure the **NUCLEAR CHARGE DISTRIBUTION**.
- Usefully complement the knowledge obtained from electron scattering and laser spectroscopy.
- Successfully used since more than 30 years to study **STABLE ISOTOPES** in condensed or gaseous states !

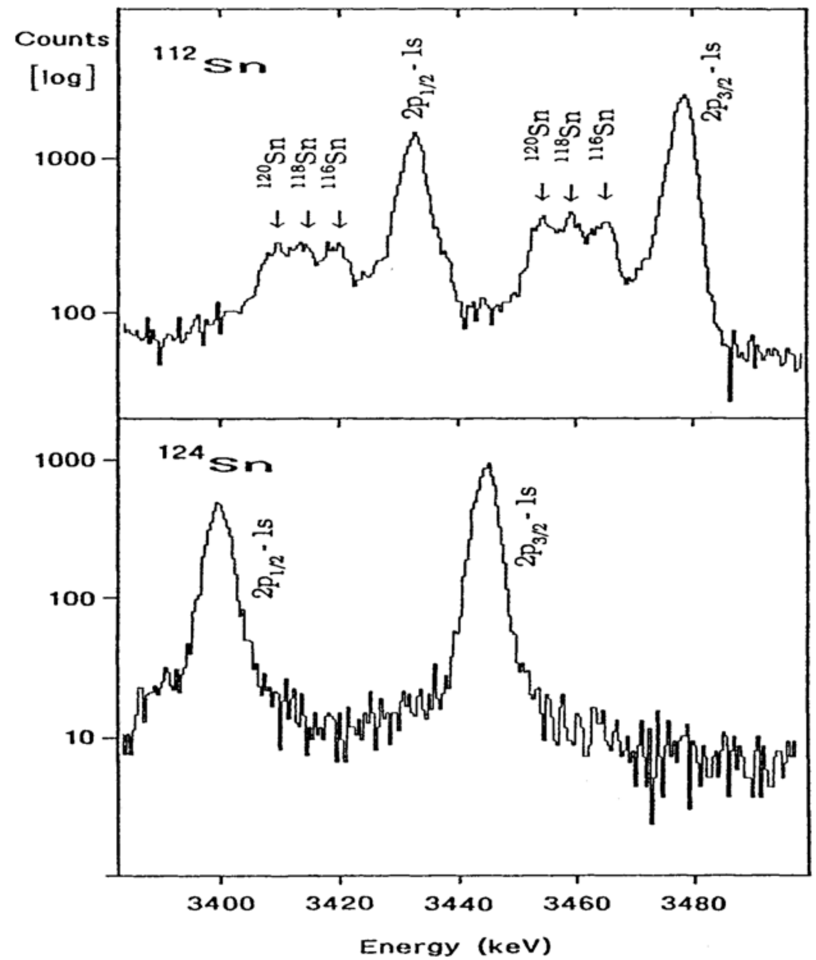


Fig. 3. Prompt muonic x-ray spectra showing the $2p_{1/2} - 1s$ and $2p_{3/2} - 1s$ transitions in the two tin isotopes at the extreme ends of stability, ^{112}Sn and ^{124}Sn (ref.2). The isotopic purity of ^{112}Sn was 68%, which explains the appearance of further tin isotopes in the upper half of this figure.

Nuclear Charge Radii of Tin Isotopes from Muonic Atoms

C. Piller et al., Phys. Rev. C **42** (1990) 182,
L.A. Schaller Z. Phys. C **56** (1992) S48.
(Fribourg Univ. / Mainz Univ.; Exp. PSI μE1)

Towards Radioactive Muonic Atoms ?

- Facilities with both **RI BEAM PROJECTS** and negative muon beams:
  - **TRIUMF** (**ISAC**), **J-PARC** (**E-arena**), ...
  - **RIKEN** (**RI Beam Factory**) if intense μ^- can be produced,
  - and maybe at a **NEUTRINO FACTORY PROJECT**

- **In the near Future**
  - **MUON BEAM** of significant higher flux (**PRISM,**), $10^{12}\mu$/s, 55MeV/c
  - **NEXT GENERATION** of RNB facility

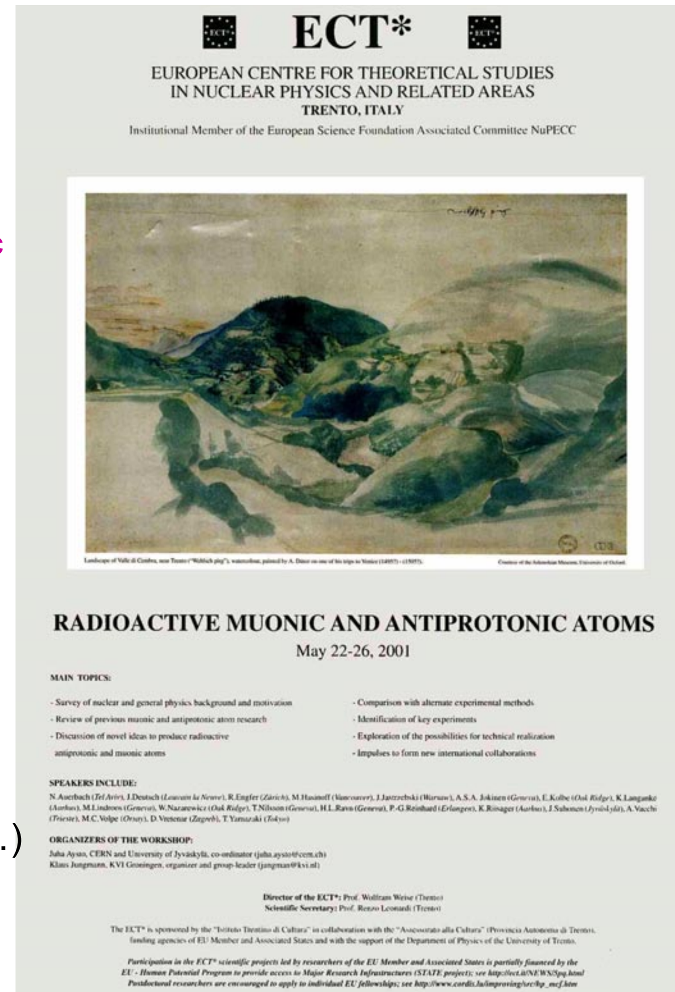
- **Experimental Methods using muons**
  - Merging Beams Scenario (M. Lindros, CERN) ,
  - Combined Cyclotron Trap & Penning Trap,
  - **SOLID HYDROGEN & MUON TRANSFER**

- **Other Methods for Unstable Nuclei**

  PRESENT: Optical Laser Spectroscopy (ISOLDE, RIKEN, …)

  FUTURE: Electron Scattering with e^- & RI collider Rings (GSI , MUSES at RIKEN, …)

RAMA WORKSHOP



Why Radioactive Muonic Atoms ?

- **Probing Nuclear Charge Distribution**

  Matter distribution deduced from measured interaction cross sections. Charge distribution needed to get information on proton and neutron distributions in nuclei.

  ➡ **X-RAY SPECTROSCOPY** of **RADIOACTIVE MUONIC ATOMS !**

- **Deformation Properties**

  Quadrupole hyperfine spitting of muonic X-rays yield precise and reliable absolute quadrupole moment values. Measure the deformation properties of nuclei.

  ➡ **IMPORTANT ROLE** in **ESTABLISHING** and **REFINING NUCLEAR STRUCTURE MODELS !**

- **Muon Capture**

  $${}^{A}_{Z}X_{N} + \mu^{-} \rightarrow {}^{A}_{Z-1}X_{N+1} + \nu_{\mu}$$

  Tools to explore changes in collective excitation modes of neutron-rich nuclei.

  Kolbe et al., Eur. Phys. J A **11** (2001) 39; T. Nilsson et al., Nucl. Phys. A 746 (2004) 513c

  ➡ **IMPORTANT ASTROPHYSICAL IMPLICATIONS !**

- **Novel nuclear structure effects may exist far off the valley of stability ?**

μA* Technical Feasibility

◆ How to produce such exotic μA* atoms ?

We propose:

- **SOLID HYDROGEN FILM** used to stop both simultaneously μ^- and A* beams.
- ***μA* ATOMS*** formed through **MUON TRANSFER REACTION** to higher Z nuclei, i.e.,

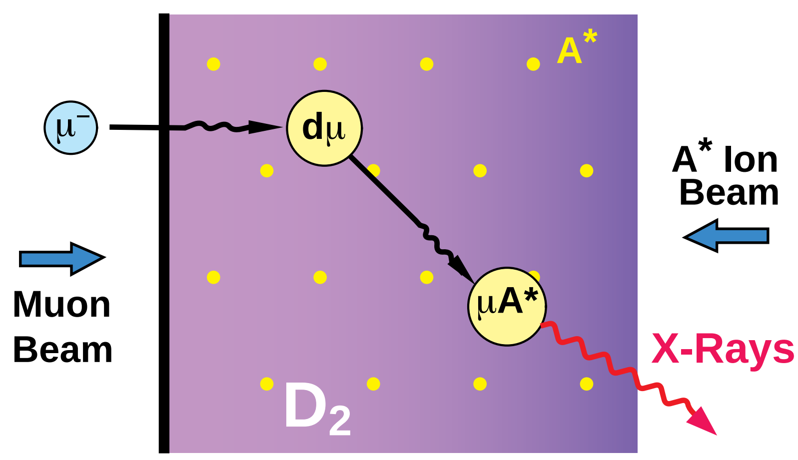
$$\mu H + A_z^* \rightarrow \mu A_z^* + H$$ with

TRANSFER RATE: $\lambda_z \approx C_z \, Z \, 10^{10} \ s^{-1}$

HIGH TRANSFER RATE & HIGH EFFICIENCY

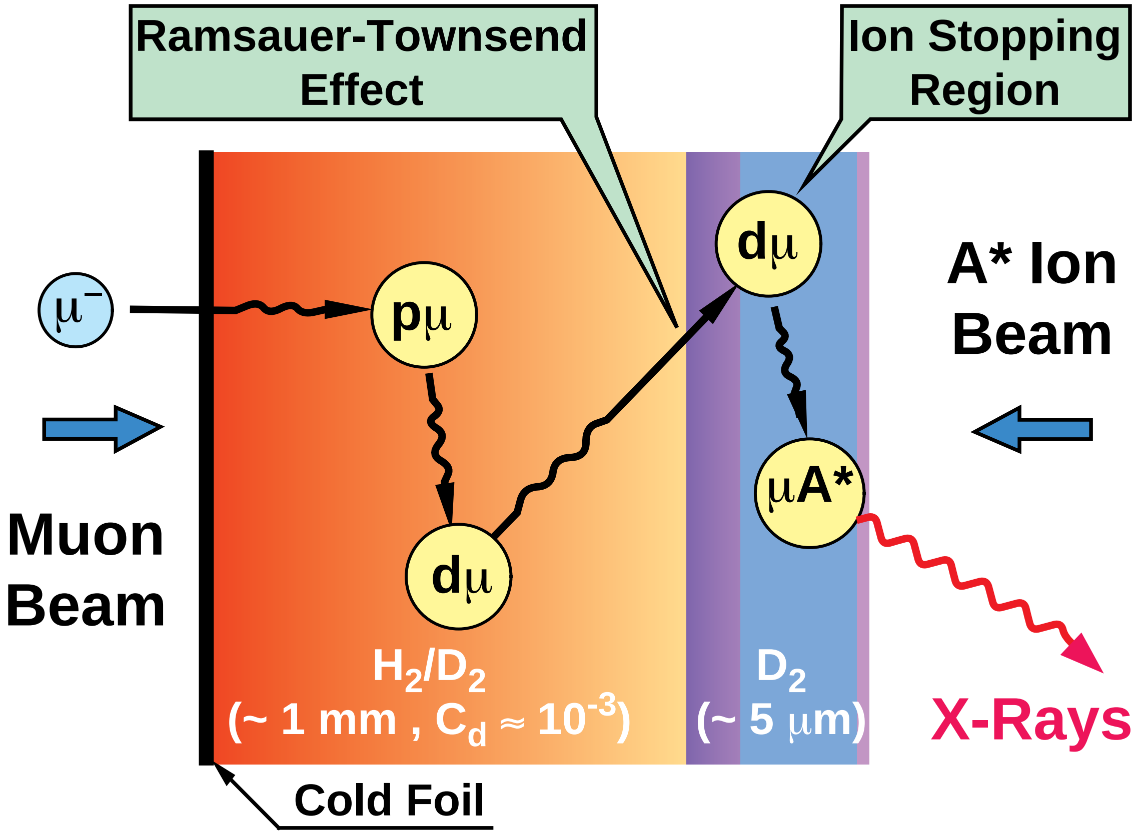
e.g., $Z = 50$ and
$C_z = 1$ ppm (5×10^{16} nuclei/cm^3)
⇒ $\lambda_z \approx 5 \times 10^5 \ s^{-1}$

Basic Concept



μA* Technical Feasibility (2)

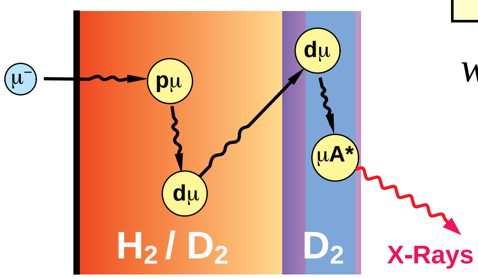
- **Basic Concept:** Two-Layer Arrangement



Preliminary Transfer Yield Estimation

◆ Transfer Yield Estimation
(Two-Layer Arrangement)

No dμ atom loss !



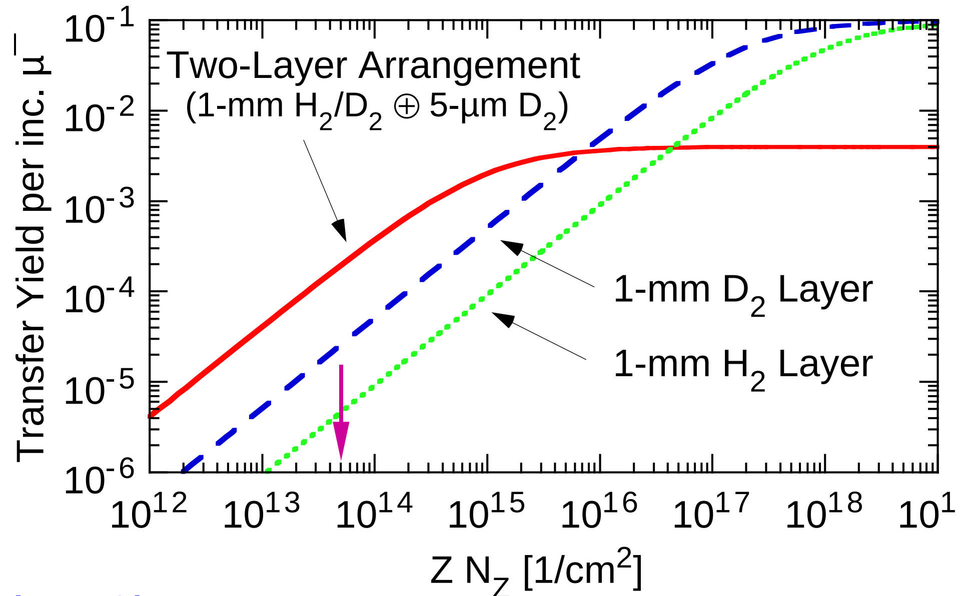
$$Y_X = \frac{\phi \lambda_Z}{\lambda_0 + \phi \lambda_Z} Y_{\mu^-} Y_{d\mu}$$

with $\lambda_Z \approx C_Z Z \times 10^{10} s^{-1}$,

$C_Z = N_Z / N_D$,

$Y_{\mu^-} \cong 0.1,\ Y_{d\mu} \cong 0.04$

μ⁻ Stopping   dμ Emission



◆ Preliminary Yield Estimation for Tin (Z=50):

Muon Intensity (1 cm^2, 30 MeV/c):		**1 × 10^8 [s^{-1}]**		21st Century Muon Beam SHC confinement Field
Implanted Sn Ions (1 cm^2, uniform):		**1 × 10^{12}**		
Transfer Yield per incident μ⁻:	Two-Layer Arrangement	**2 × 10^{-4}**	1-mm D_2	**2 × 10^{-5}**
Muonic Tin Atoms Formed:		**20'000 [s^{-1}]**		**2'000 [s^{-1}]**
Total X-Ray Number Detected:		**500 [hr^{-1}]**		**50 [hr^{-1}]**

Assuming for μSn 2p→1s X-ray detection (~3.4 MeV) : b.r. ~ 0.7, ε ~ 0.005 and ΔΩ ~ 0.002.

Practical Considerations

- **SIMULTANEOUS** implantation of unstable nuclei and measurement with μ^-.

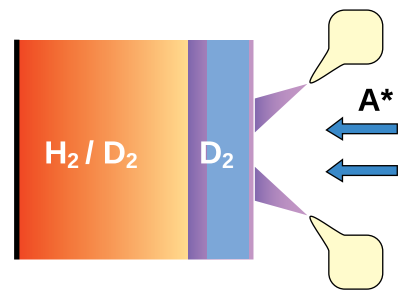
- Ion beam **ENERGY** and **SPREAD** determine the implantation **DEPTH** and **THICKNESS**.

  Ion range in solid hydrogen: 1 mm ➪ ~ 10 MeV/u
  5 μm ➪ ~ 30 keV/u
  ➡ **SWEEPING** Beam Energy

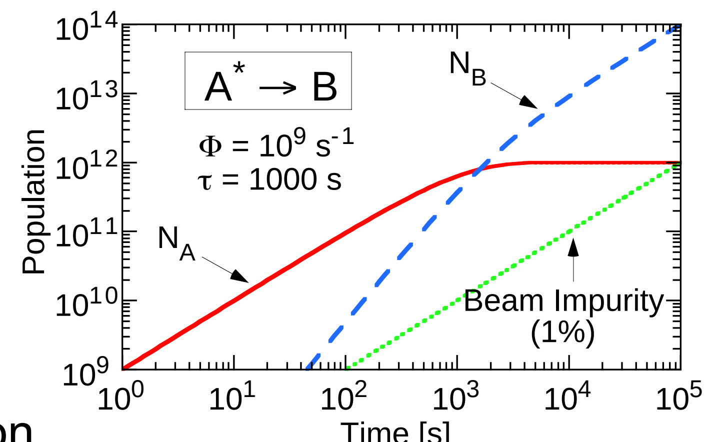
- **CONTINUOUS SPUTTERING** of solid hydrogen films.

  If proven important,

  ➡ **SIMULTANEOUS** | Hydrogen Deposition & Ion Implantation |



- RI beam **COMPLETELY** stopped in the target!
  - **ACCUMULATION** of **DAUGHTER NUCLEI**
    - ➡ **LIMITATION** (static target): $T_{1/2}$ > 10 min.
  - **ACTIVITY HIGH RADIATION BACKGROUND**
    - ➡ Pulsed Muon Beam
    - ➡ Active BG suppression, Detector segmentation, ...



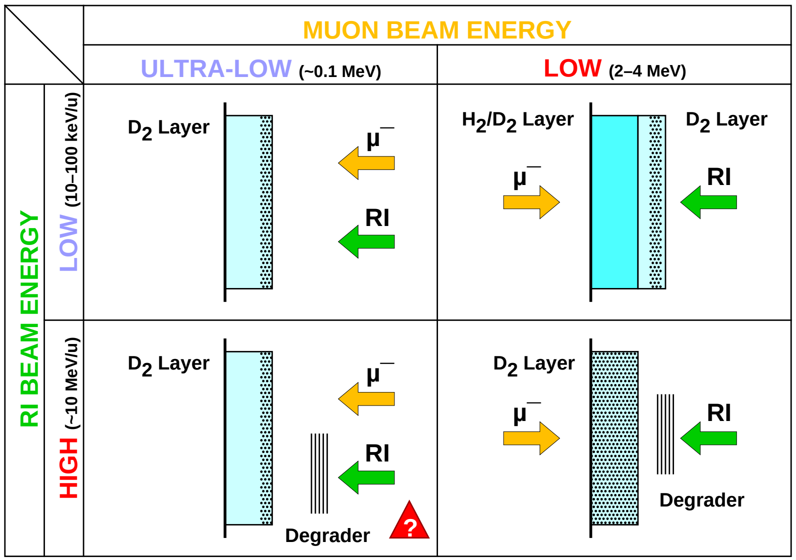
Using Solid Hydrogen Films

- **Advantages**
  - **WINDOWLESS TARGET** in vacuum
  - **WELL-DEFINED** interaction region
  - **EASY TARGET EVAPORATION** and **REPLACEMENT**
  - **RI BEAM**: Impurities, Emittance, Energy spread, ... ➡ **NOT CRITICAL**

    No Cooling Needed!
- **Disadvantages**
  - **SPUTTERING**
  - **ACCUMULATION** of **DAUGHTER NUCLEI**

    ➡ **NEW IDEAS !** e.g., using sputtering vs. daughter nuclei accumulation
- **Other Considerations**
  - Magnetic confinement field
  - Pulsed muon beam

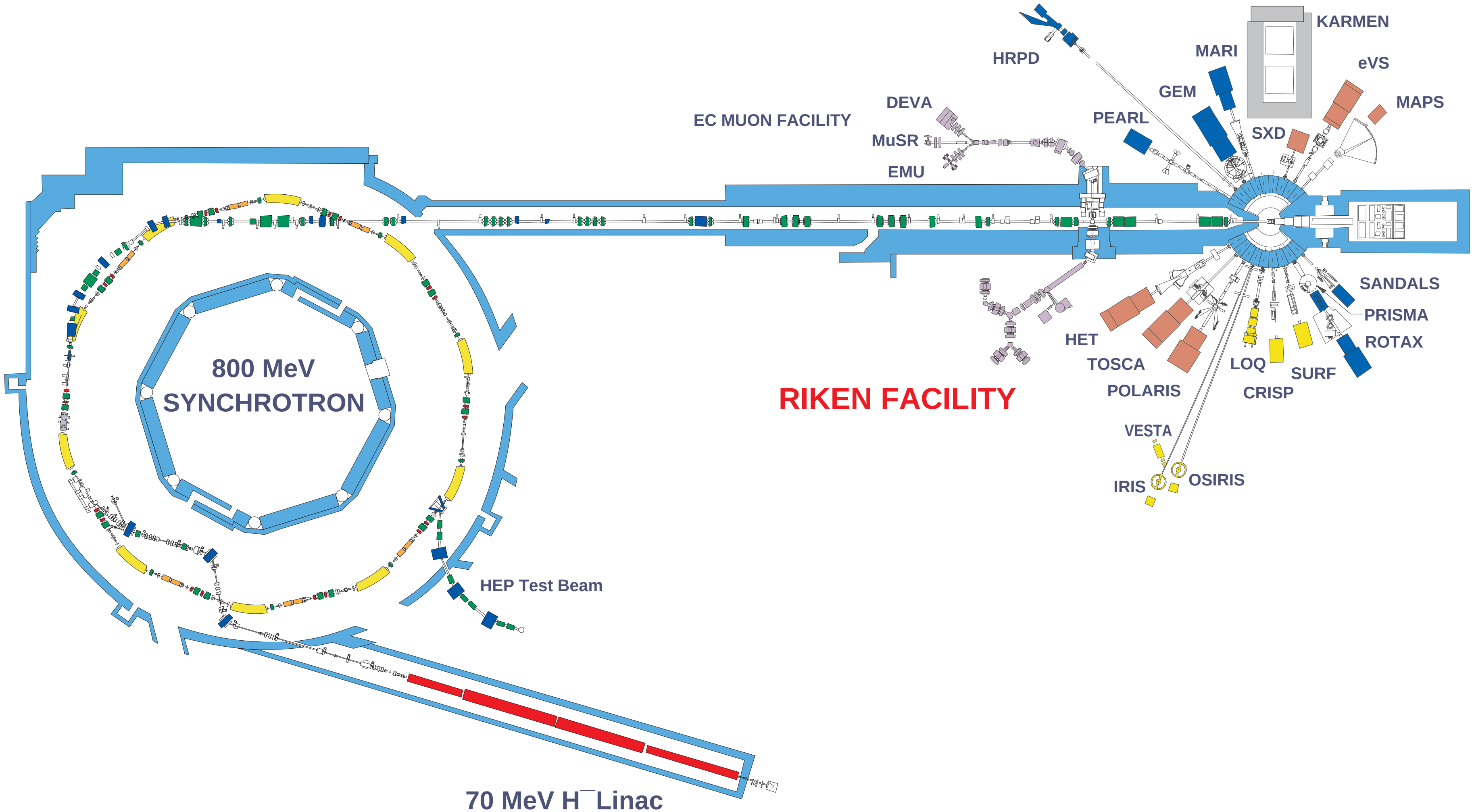
Different μA* Formation Schemes



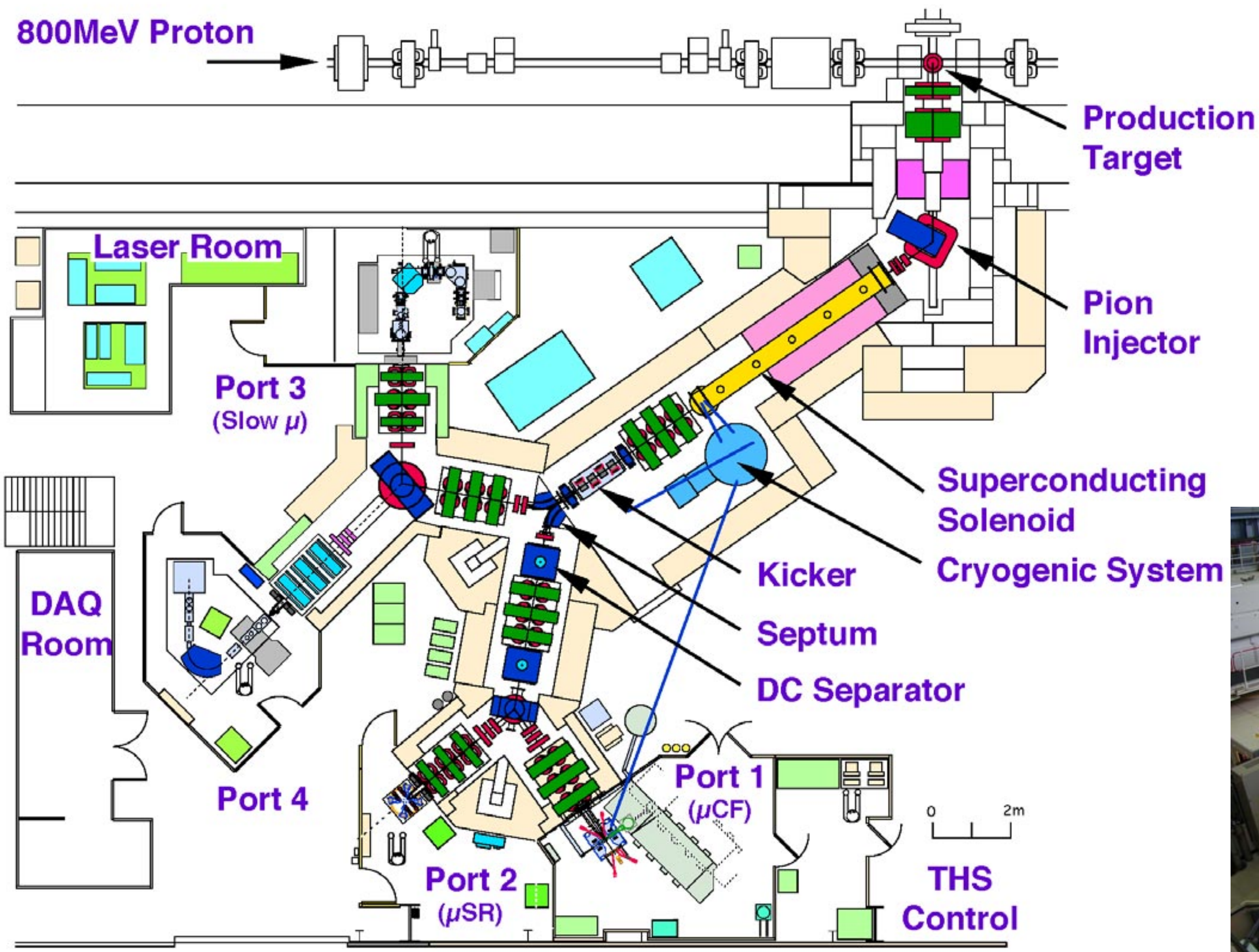
Feasibility Study

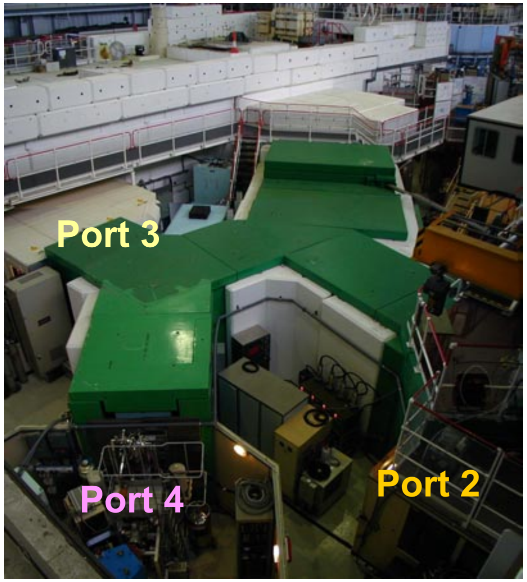
- **EXPERIMENTAL SETUP** for X-ray spectroscopy of muonic atoms formed from implanted ions in solid hydrogen
- **TEST EXPERIMENT** at RIKEN-RAL Muon facility.
- Establish the feasibility of this method by using **STABLE IONS**.
- **μCF RELATED STUDY**: Helium transfer in Solid Hydrogen Films
- In the near future, experiment using **LONG-LIVED ISOTOPES**.

ISIS Facility at RAL



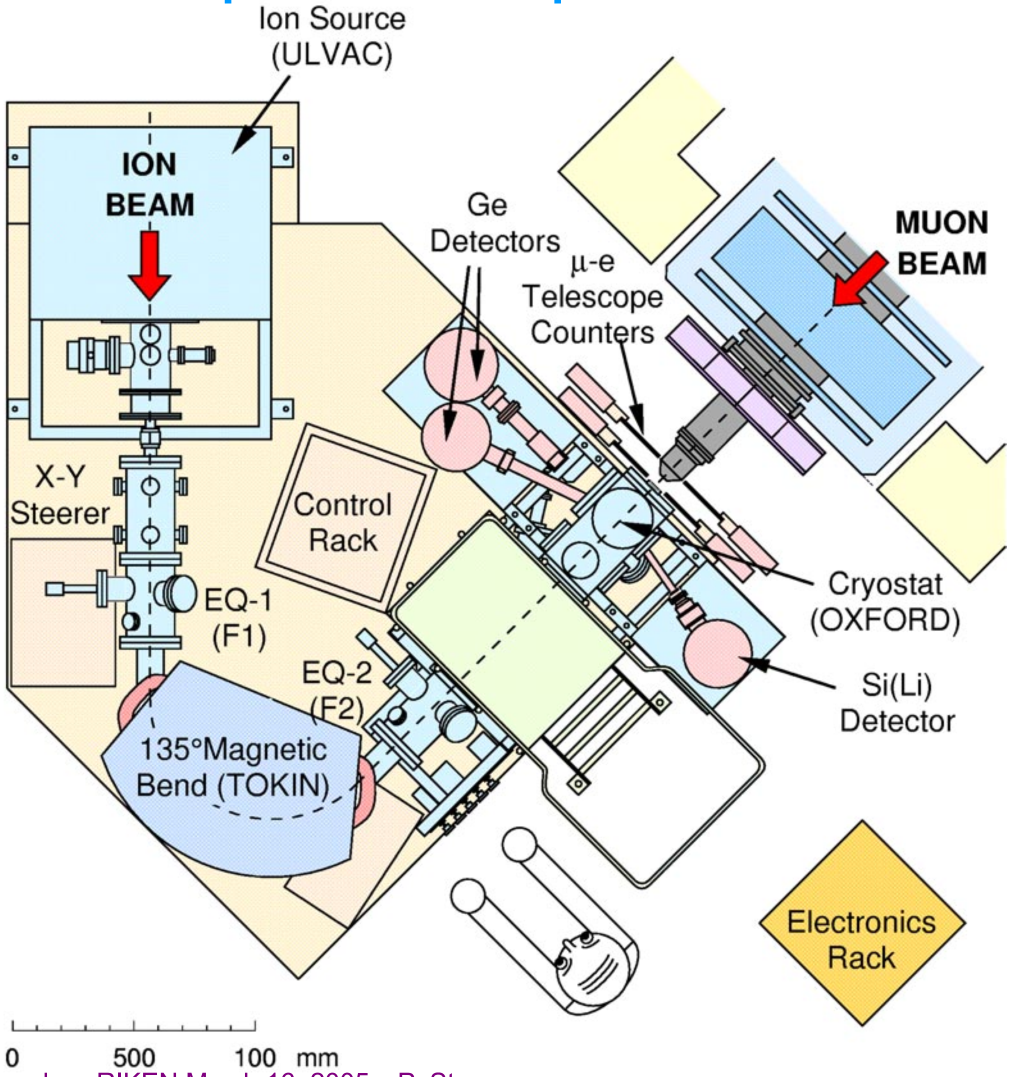
RIKEN-RAL Muon Facility at ISIS

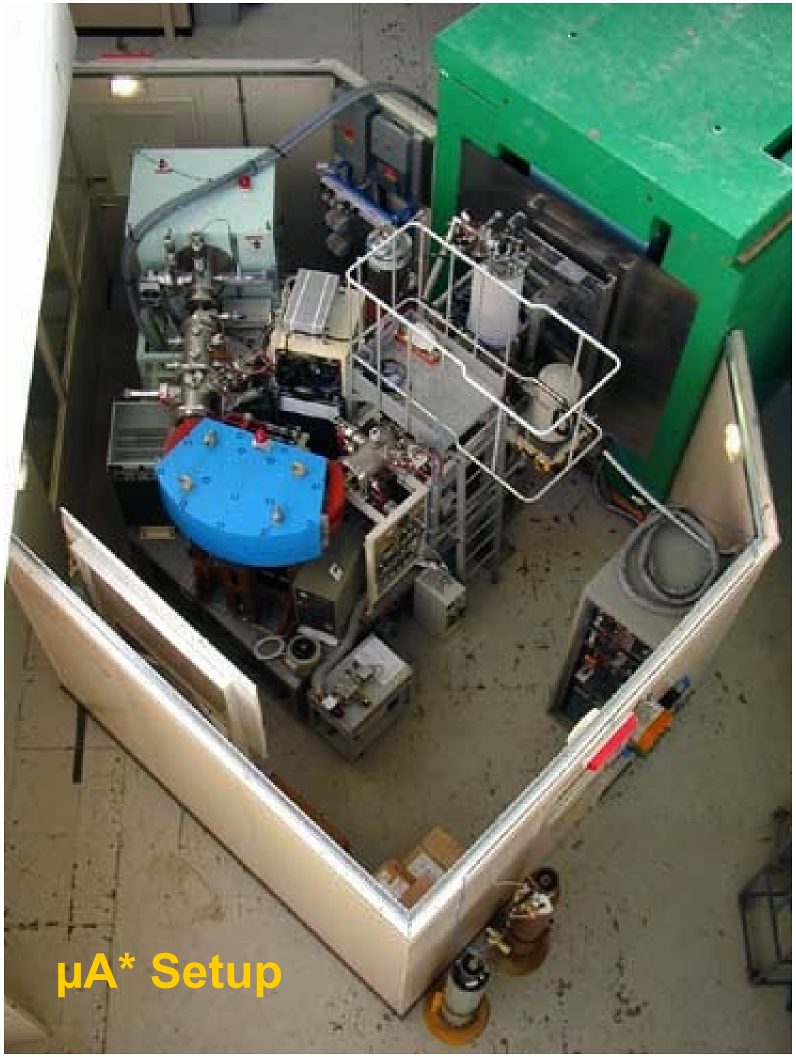




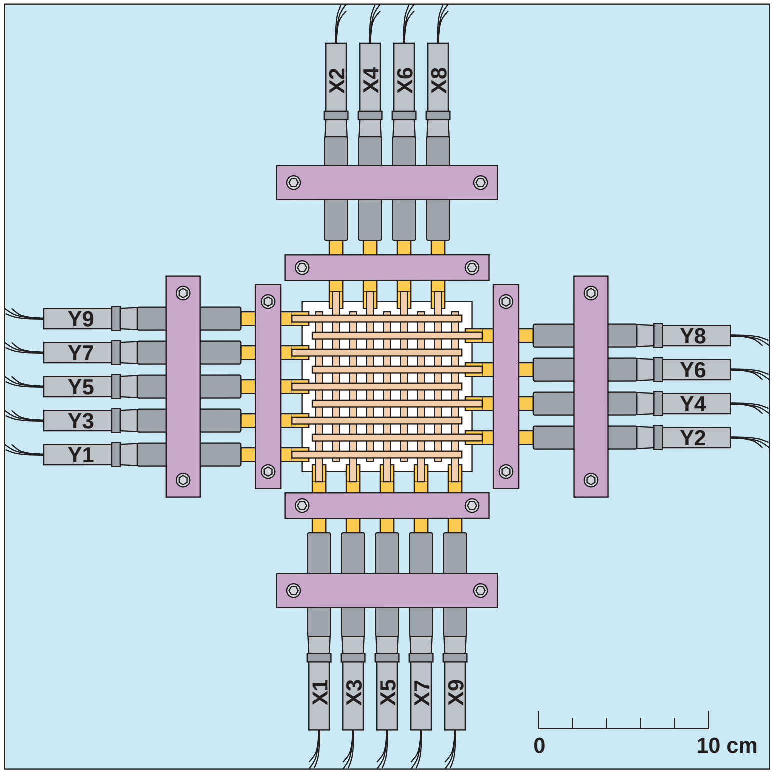
μA* Setup at RIKEN-RAL Port 4

Test Experiment to Implant Stable Ions in Solid Hydrogen Films.





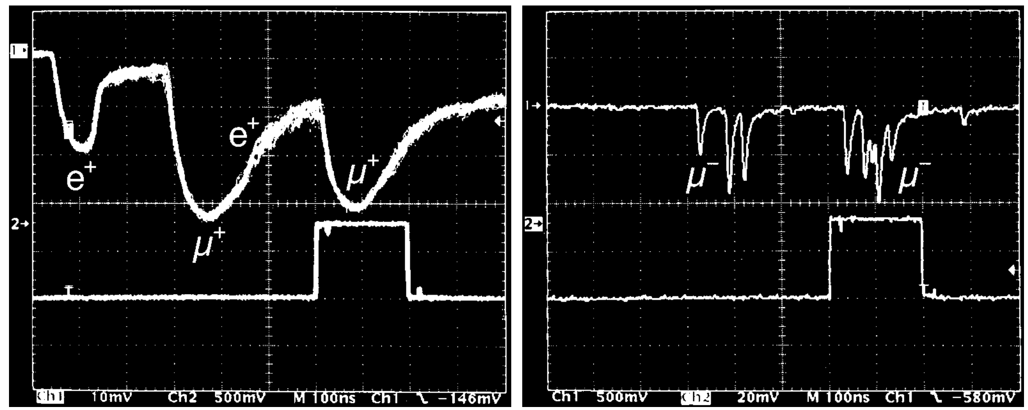
Muon Beam Profile (1)



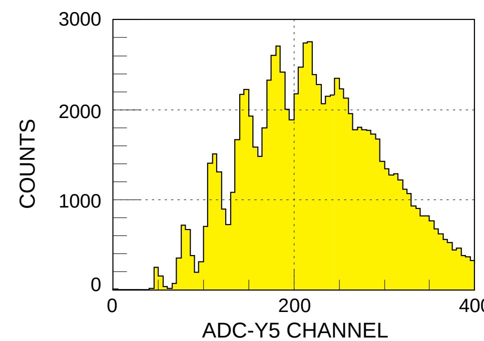
Muon Beam Profile Monitor

Photomultiplier output signal of counter X5

27 MeV/c surface μ⁺ | **27 MeV/c decay μ⁻**

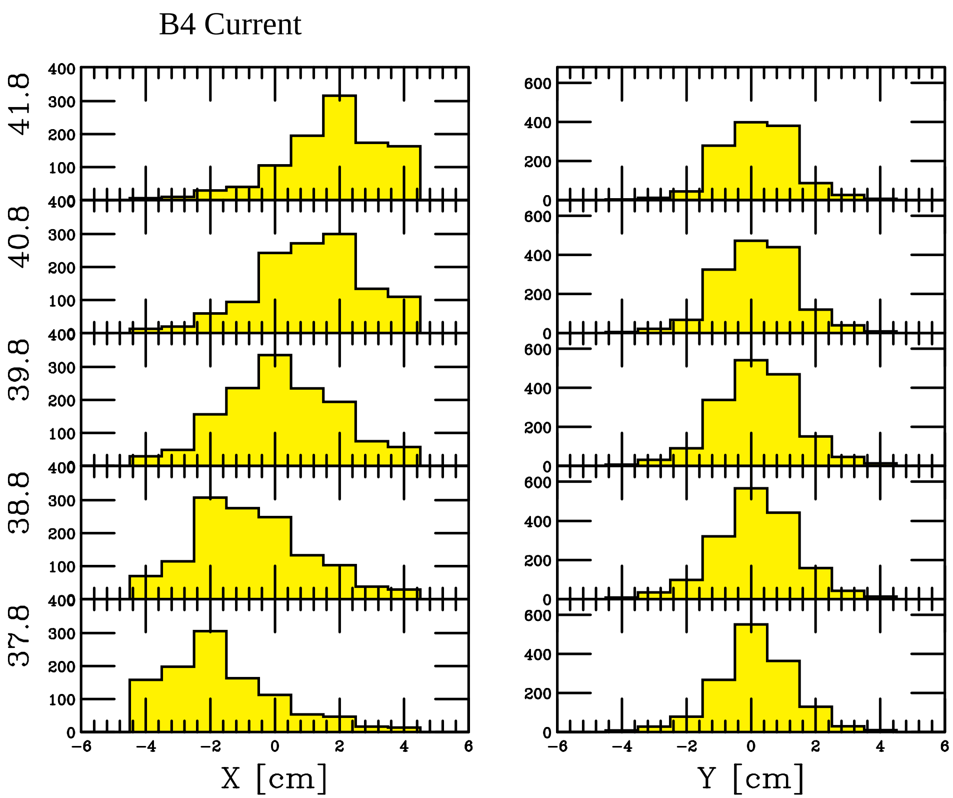


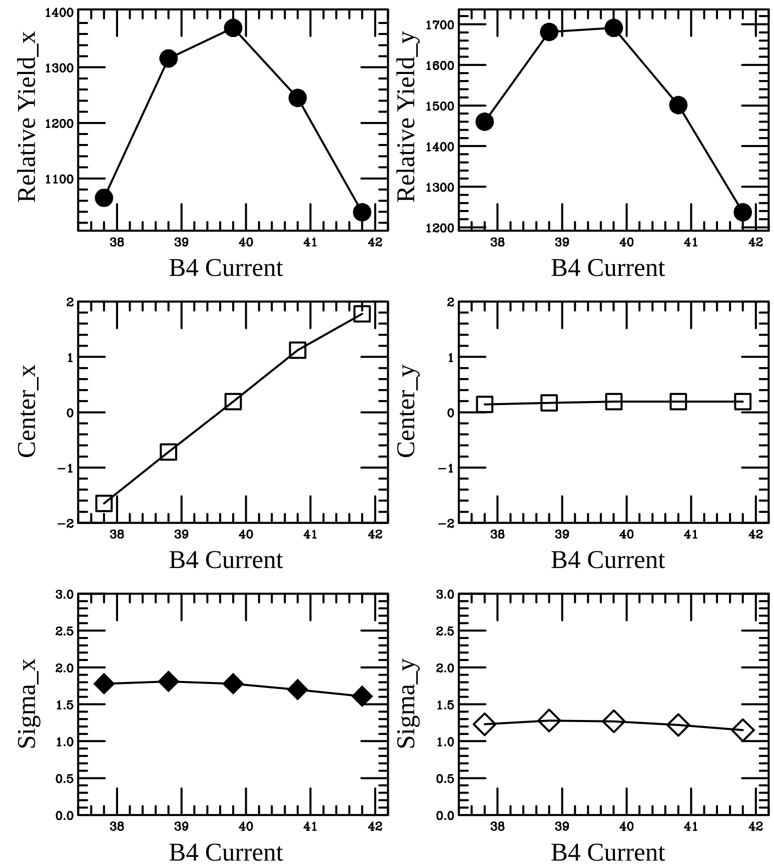
ADC output with 27 MeV/c decay μ⁻



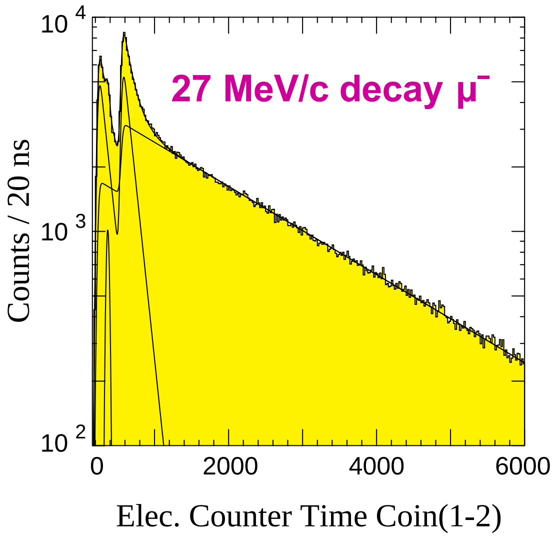
Muon Beam Profile (2)

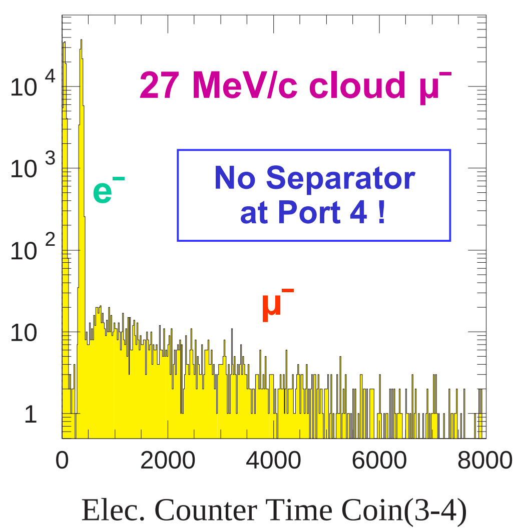
Horizontal and vertical muon beam profiles as a function of B4 dipole magnet measured with surface muons at Port 4.



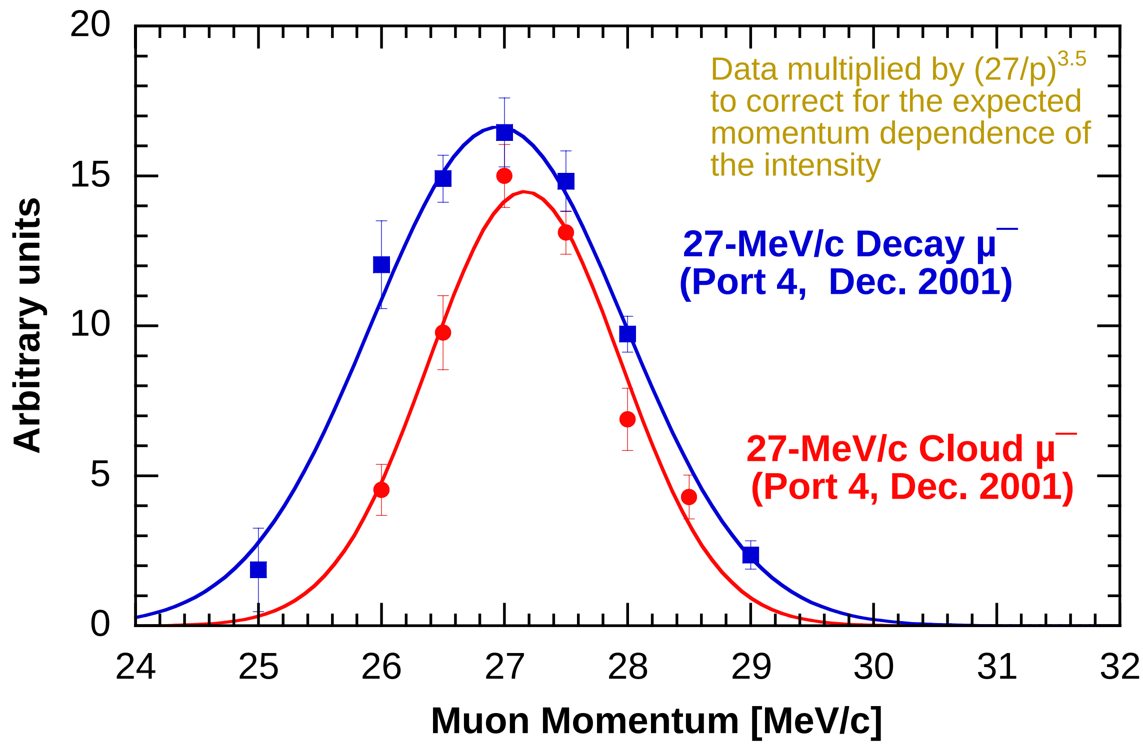


Muon Beam Momentum Tuning





Target: 1-mm H_2 Layer



y = b*exp(-((x-c)/d/c)^ 2/2)

	Value	Error
b	8.3152	0.31079
c	26.948	0.054839
d	0.038189	0.0021276
Chisq	1.4064	NA
R	0.99803	NA

y = b*exp(-((x-c)/d/c)^ 2/2)

	Value	Error
b	14.478	0.67035
c	27.165	0.044866
d	0.028824	0.0016279
Chisq	3.96	NA
R	0.98548	NA

Muon Stopping Distribution

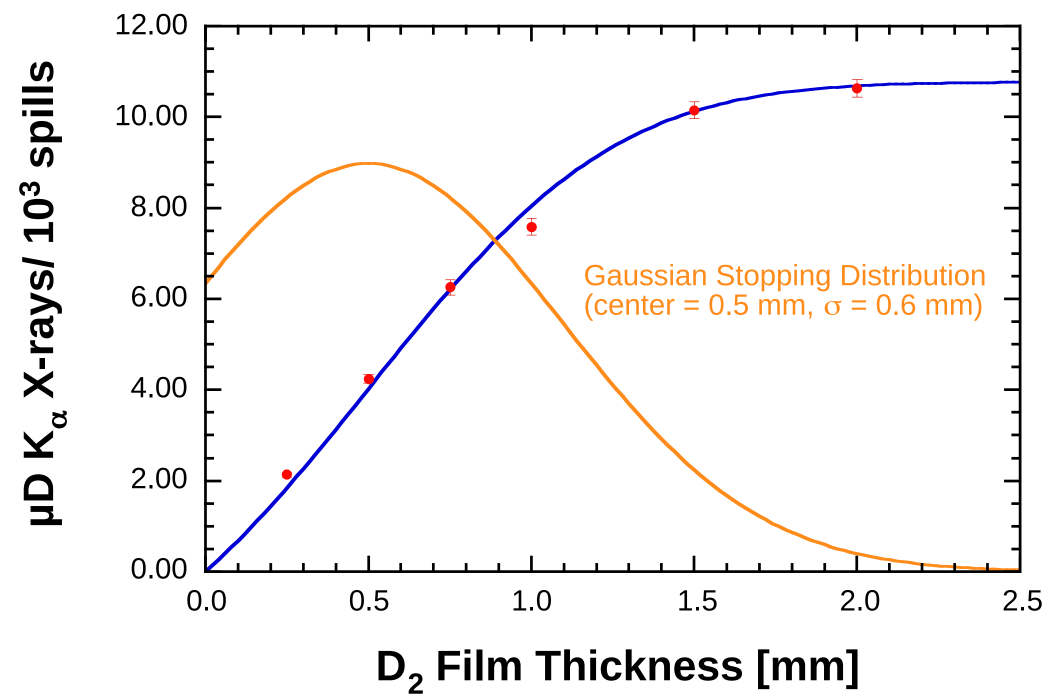
◆ Negative Muon Beam at RIKEN-RAL Port 4

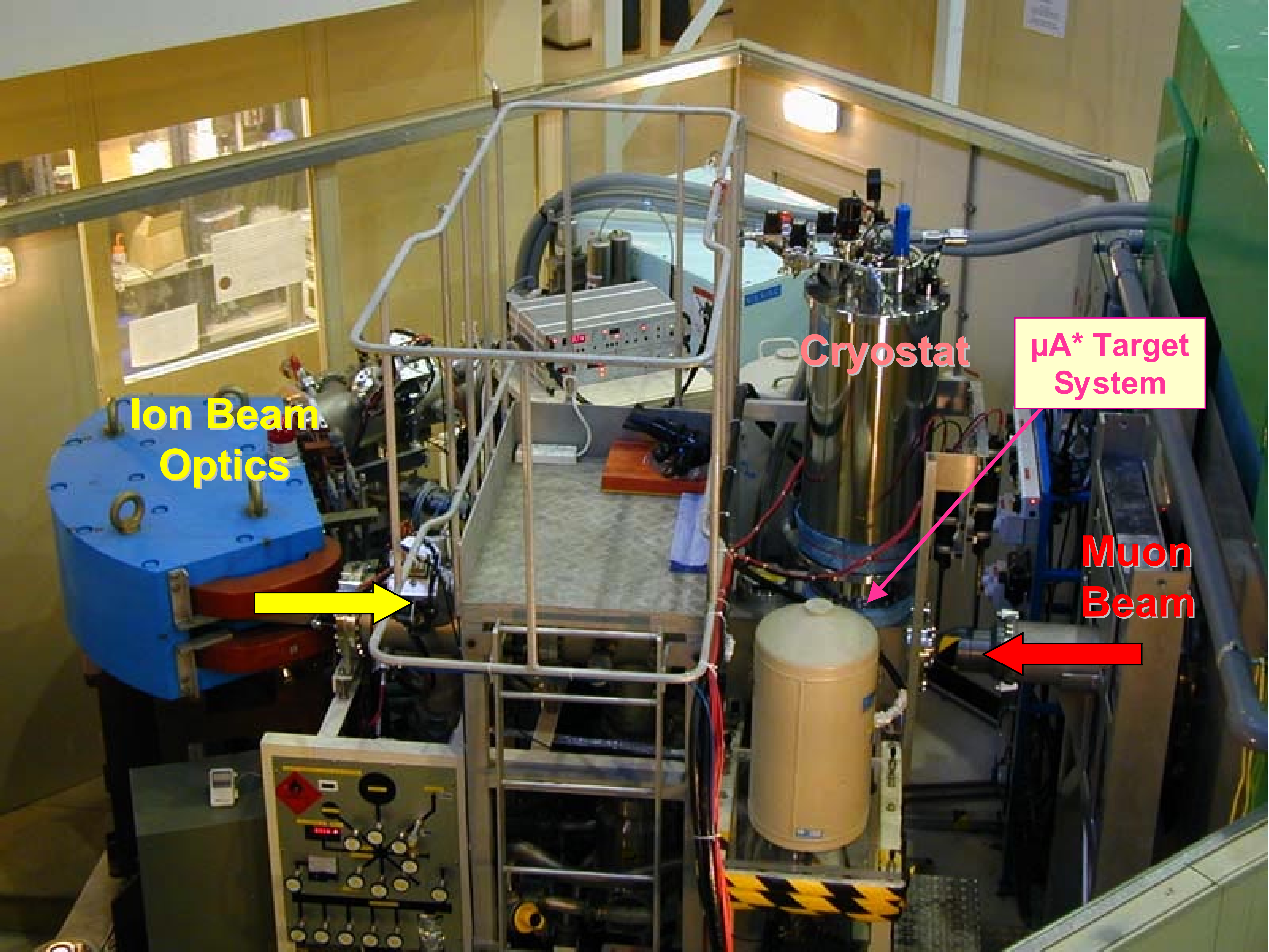
Muon Source:	Decay Muon	Cloud Muon	if separator installed !
Momentum:	27 MeV/c	27 MeV/c	
Width ($\Delta p/p$):	~ 10 %	~ 7%	
Intensity:	~ 5000 s^{-1}	~ 15000 s^{-1}	(~3x)

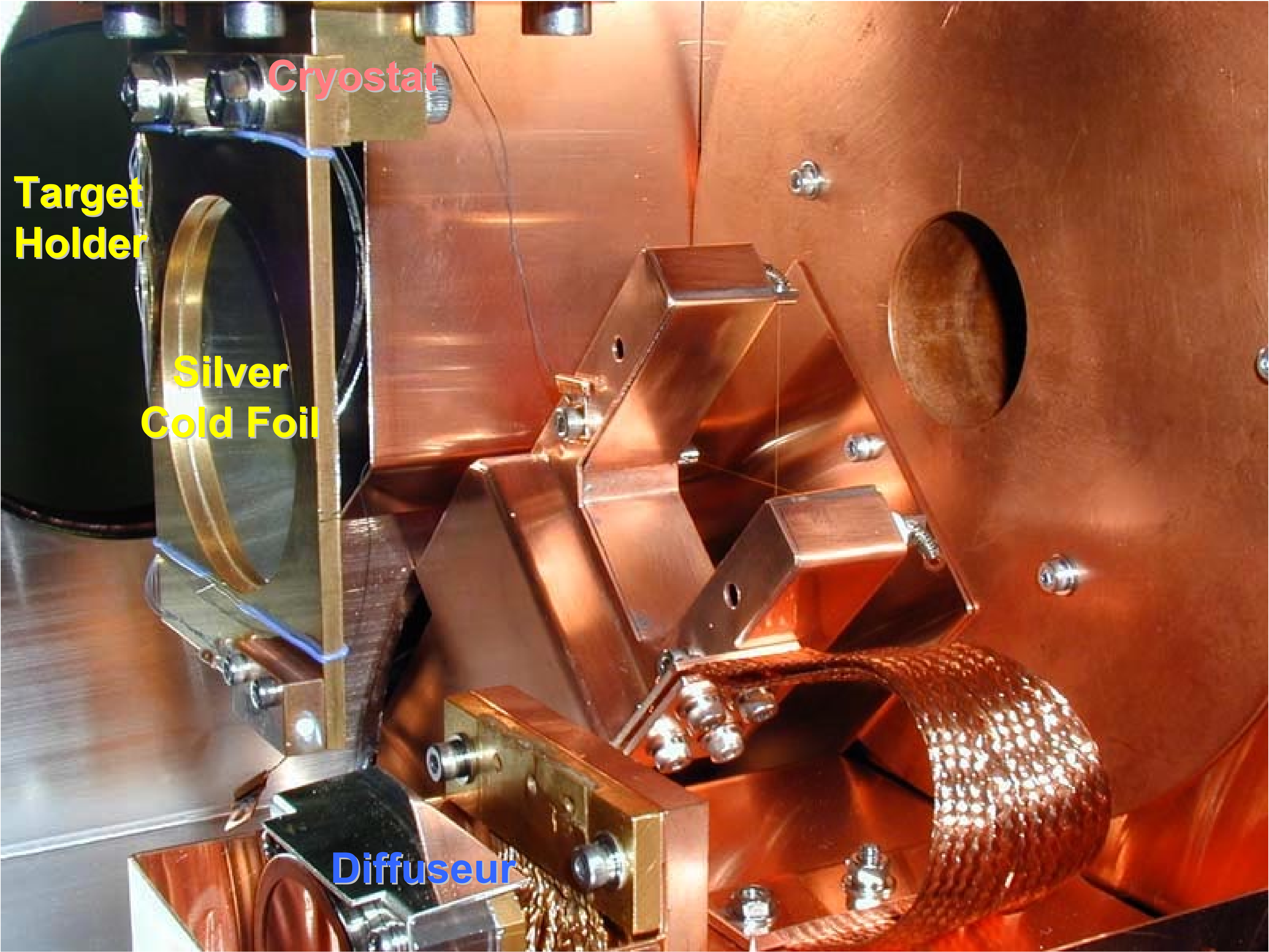
- Beam size: ~ Ø40 mm

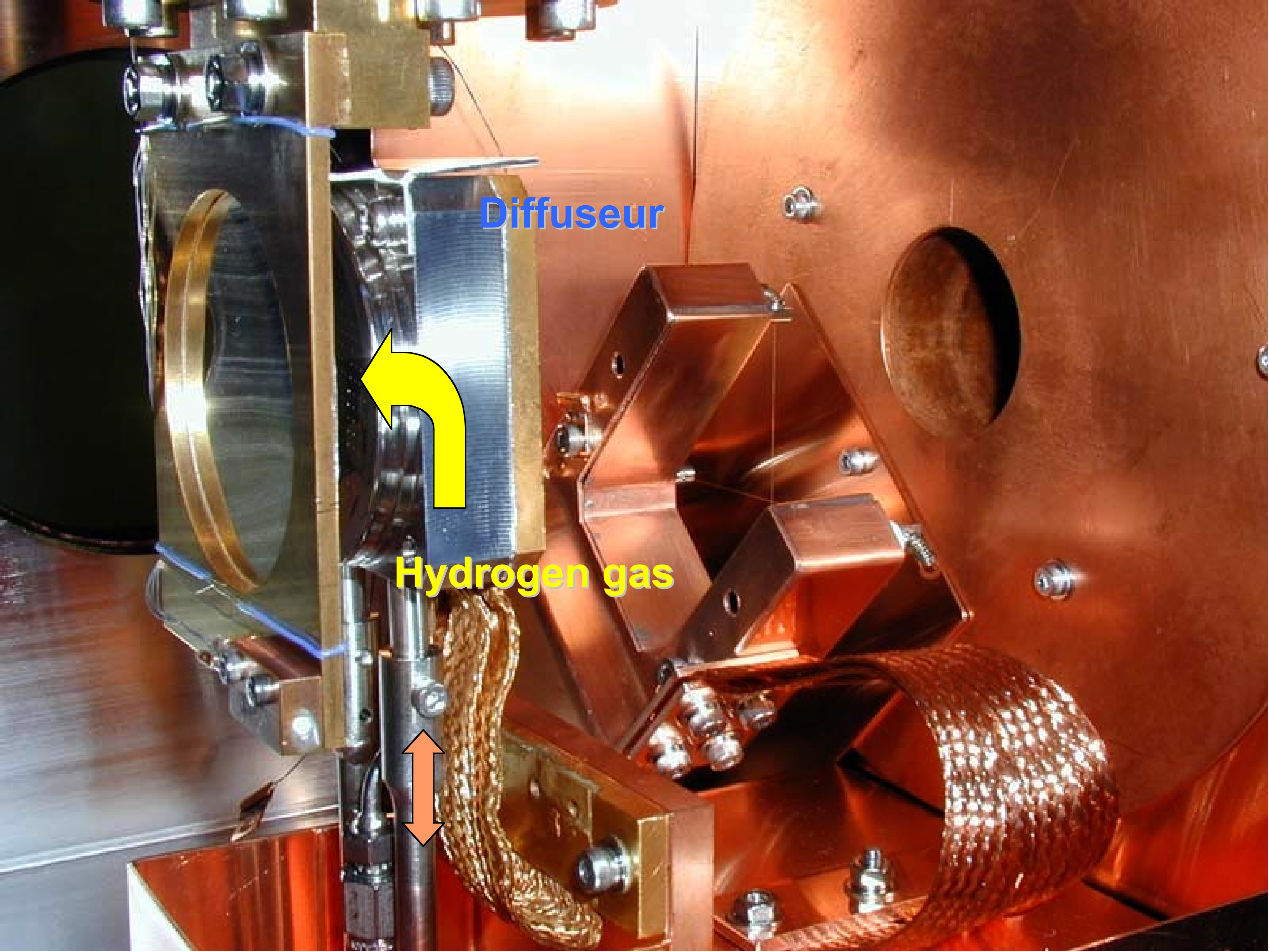
◆ Muon Stopping in Solid D_2

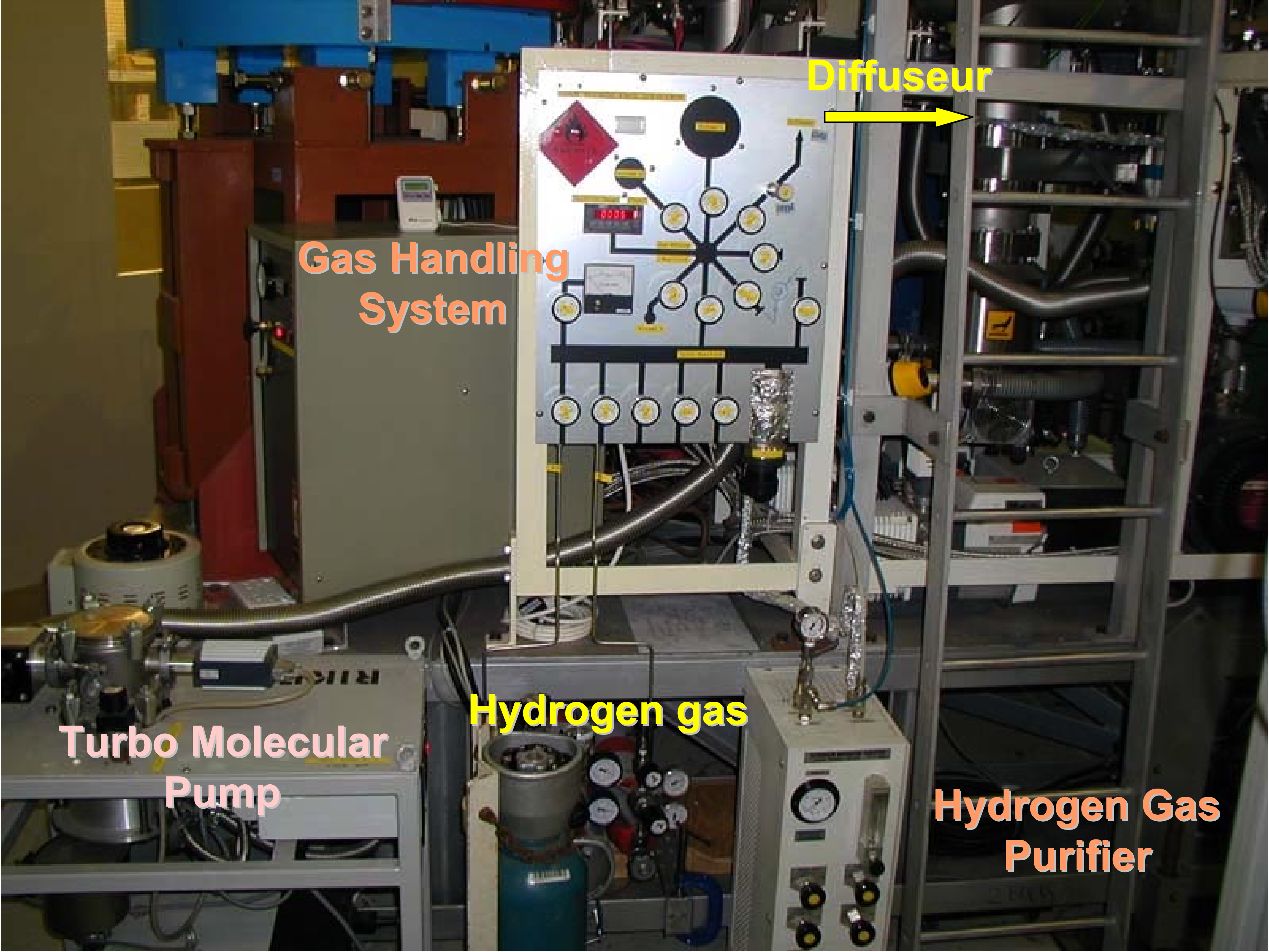
- 1-mm D_2 : ~ 60% (3000 s^{-1})
- Silver Foil: ~ 20%
- Ratio: 3

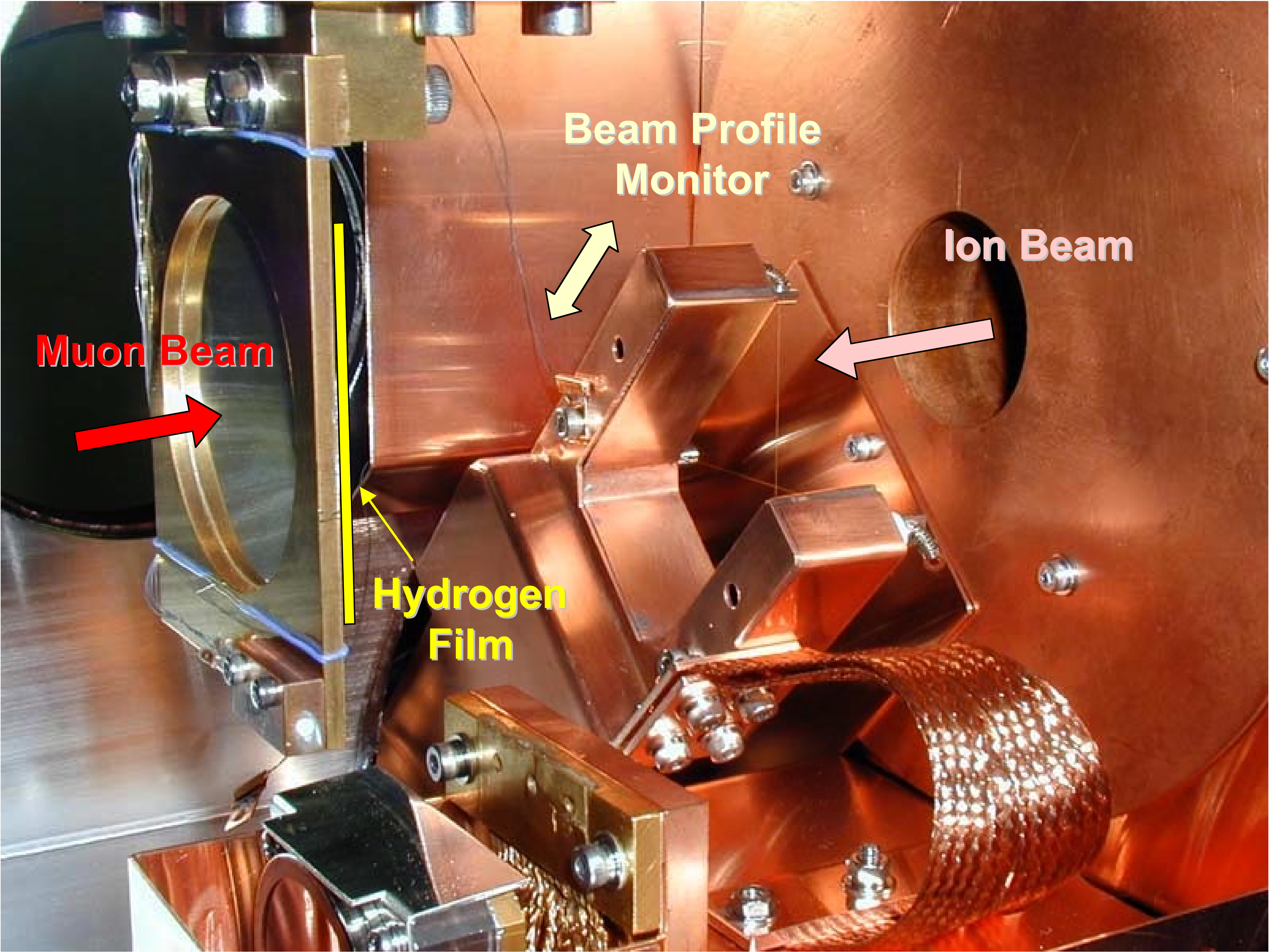



Ion Beam Optics
Cryostat
μA* Target System
Muon Beam

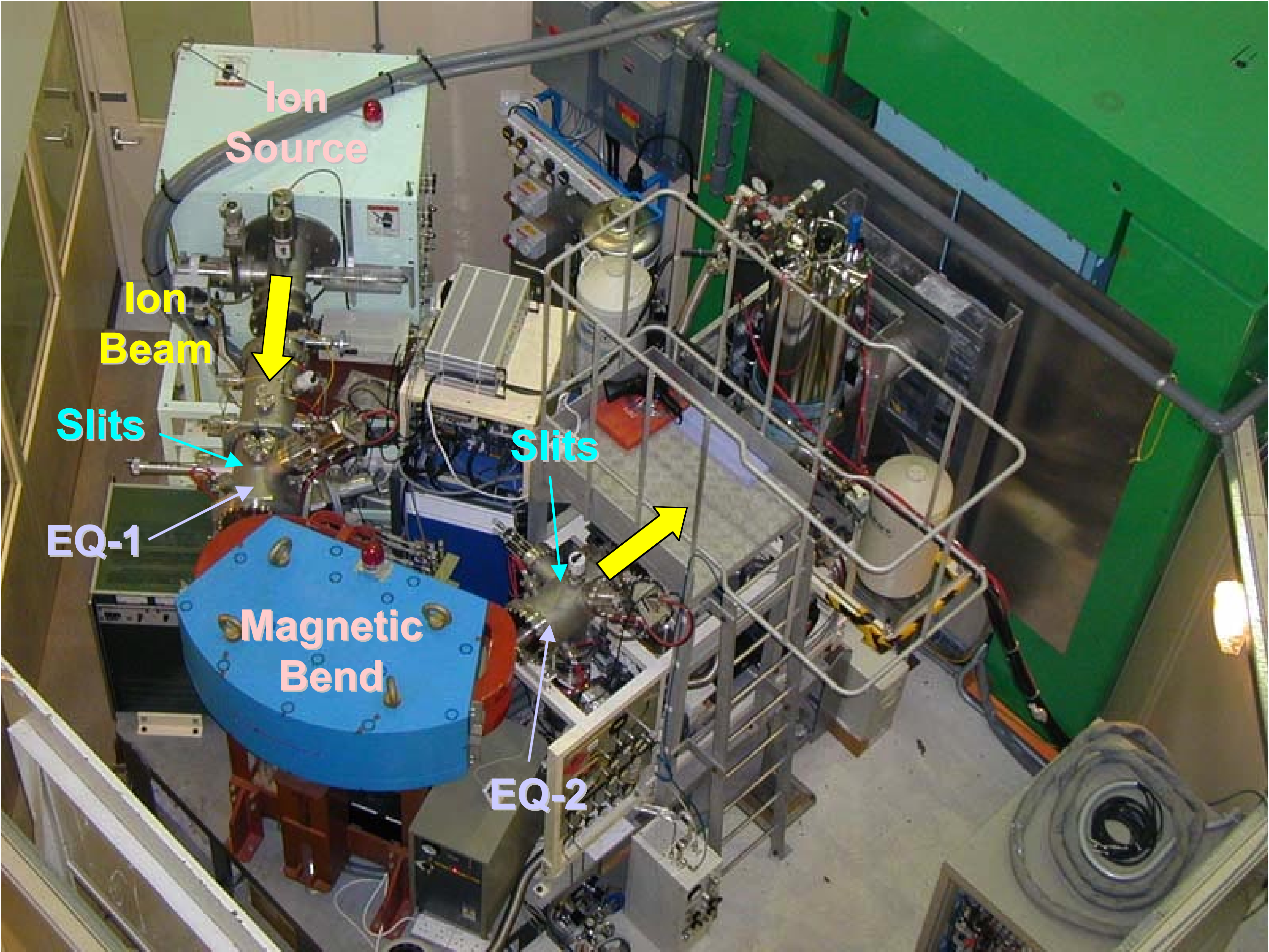

Cryostat
Target Holder
Silver Cold Foil
Diffuseur


Diffuseur
Hydrogen gas


Diffuseur
Gas Handling System
Hydrogen gas
Turbo Molecular Pump
Hydrogen Gas Purifier

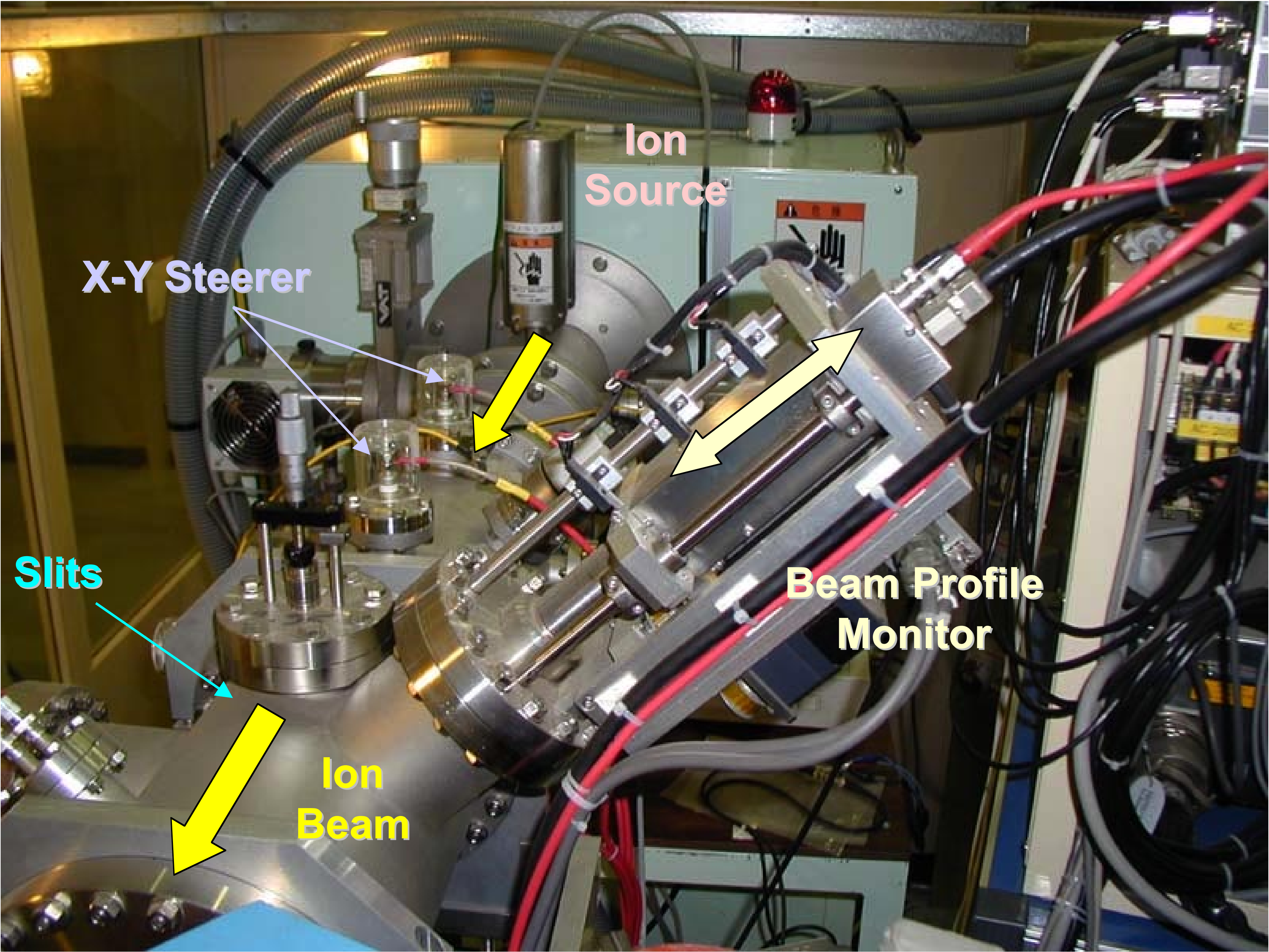


Beam Profile
Monitor
Ion Beam
Muon Beam
Hydrogen
Film

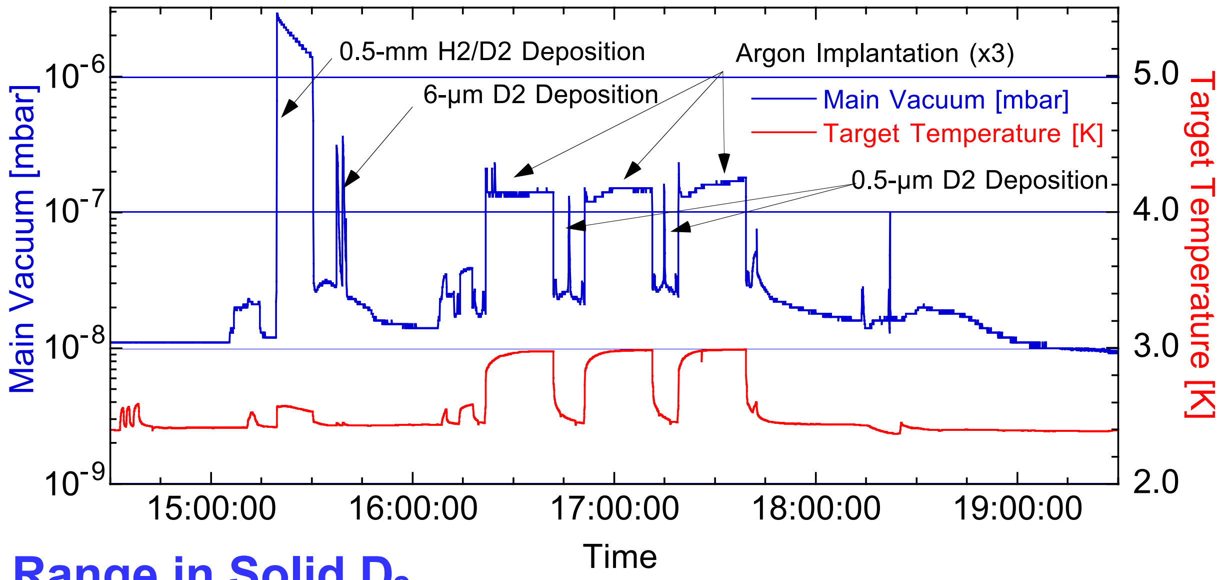


Ion Source
Ion Beam
Slits
Slits
EQ-1
Magnetic Bend
EQ-2

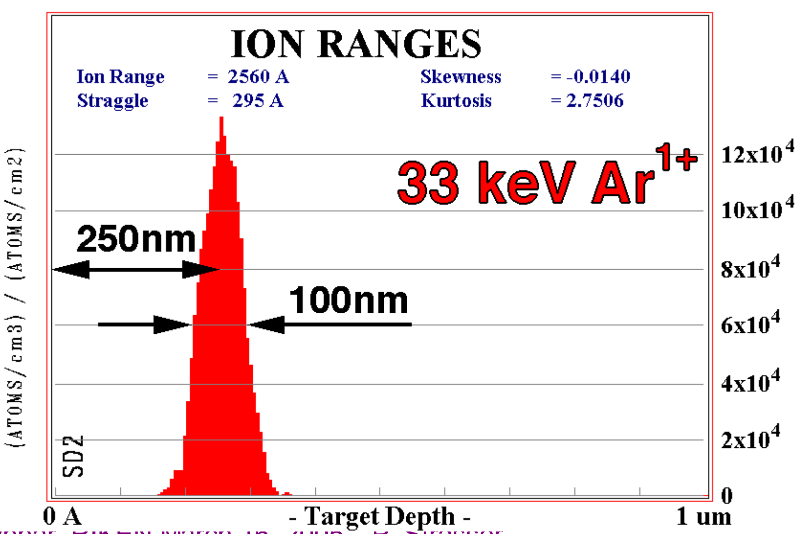

パネルリミットスイッチ
Ion Source
(Duoplasmatron)
iEC-400


Ion Source
X-Y Steerer
Slits
Beam Profile Monitor
Ion Beam

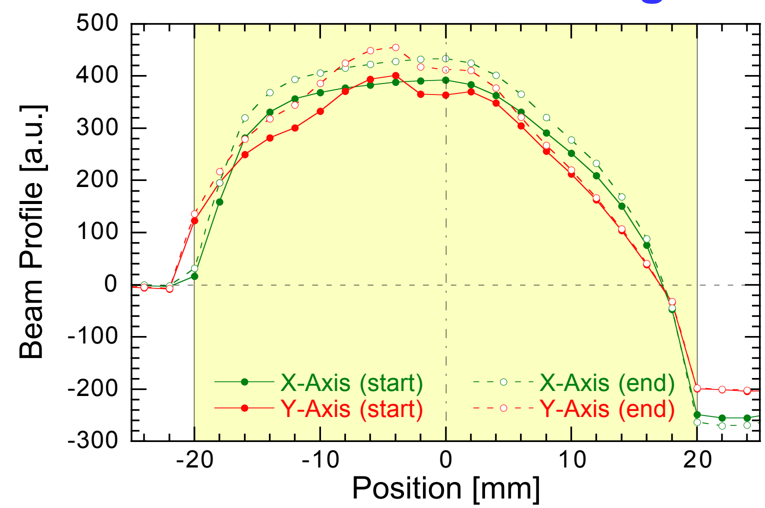
Target Preparation



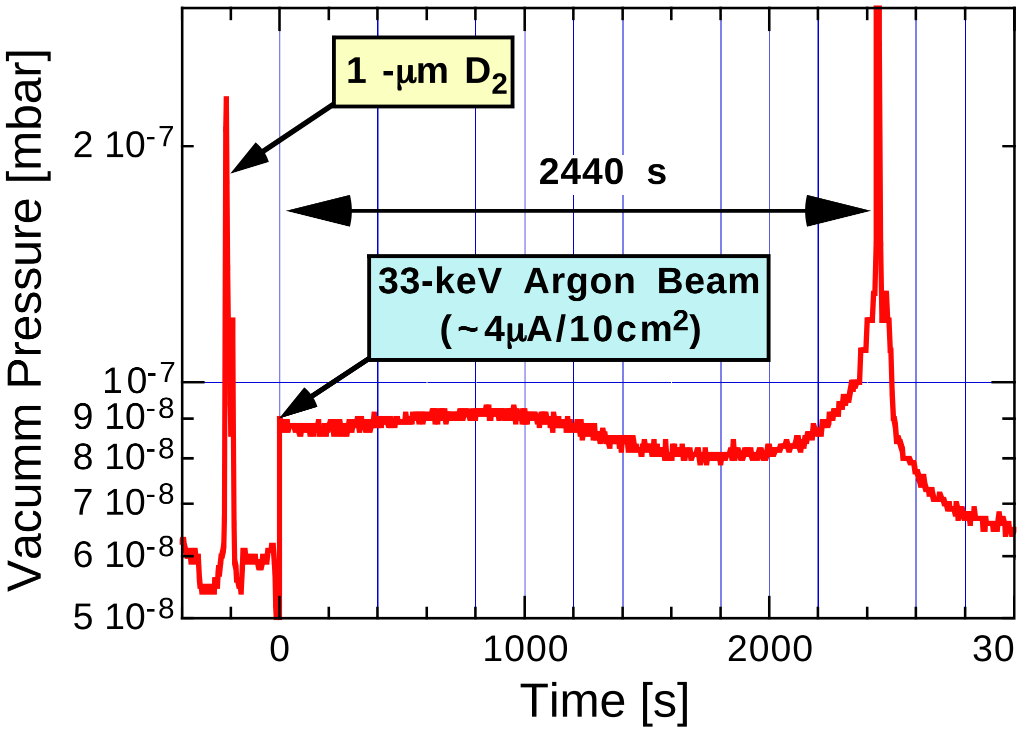
Argon Ion Range in Solid D_2

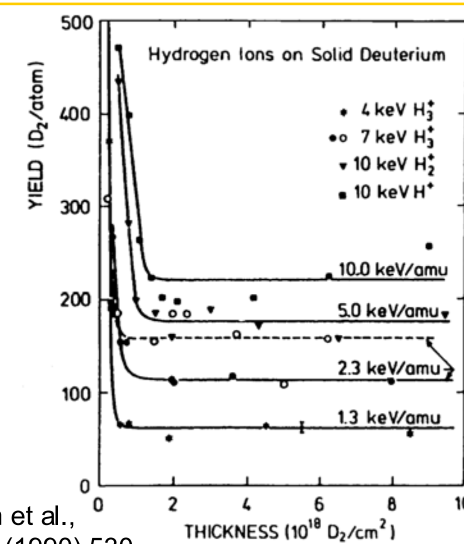


Beam Profile on Target

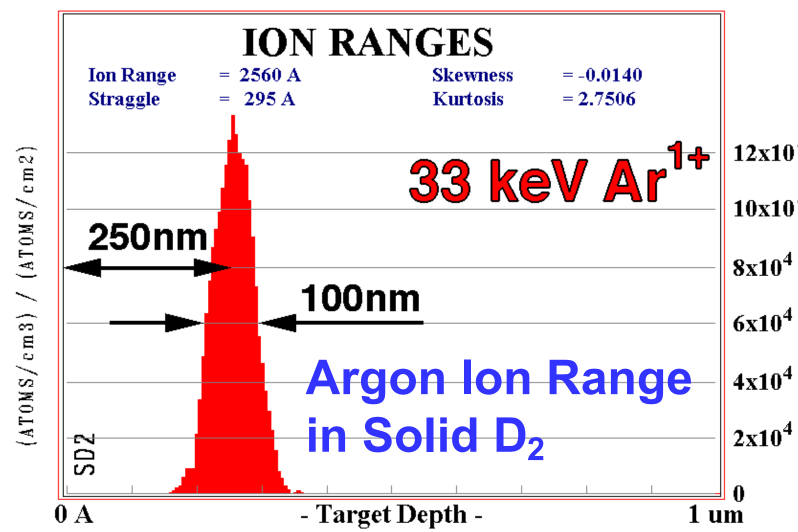


Sputtering of Solid Deuterium Films



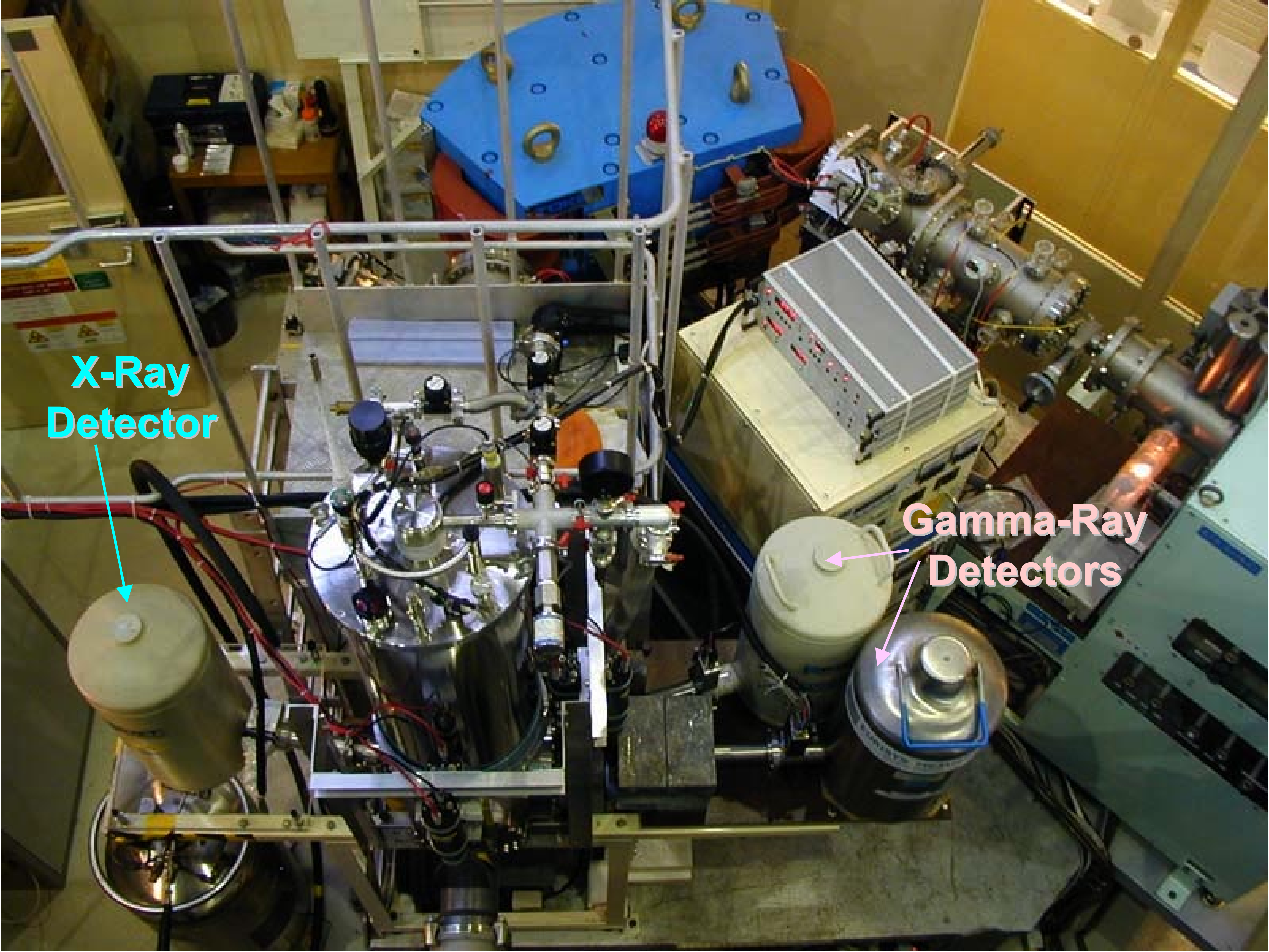


B. Stenum et al., NIM. B **48** (1990) 530.



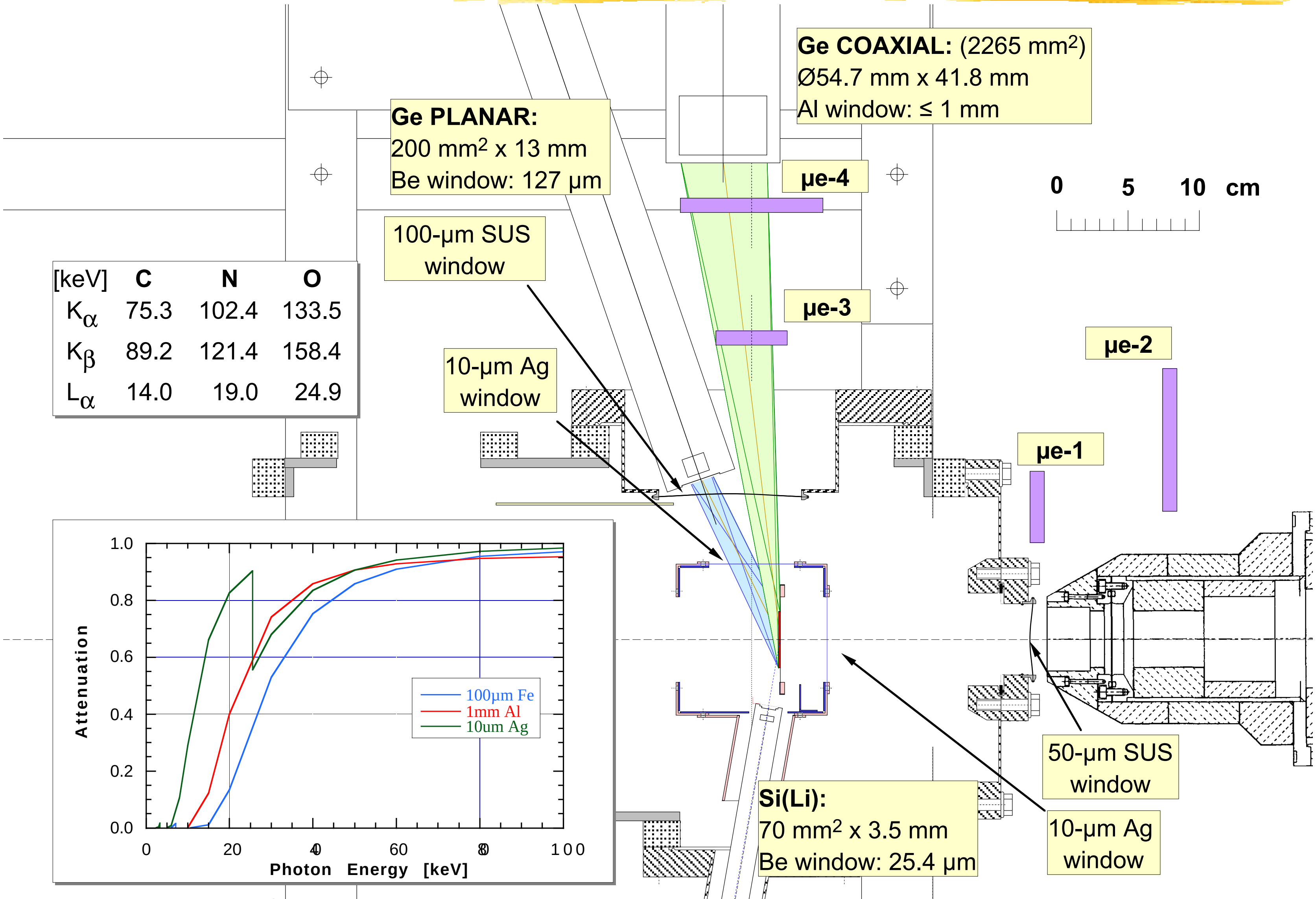
➡ **Sputtering Yield ≈ 350 D_2/Ar Ions**

(~40 nm/µA/cm^2)


X-Ray Detector
Gamma-Ray Detectors

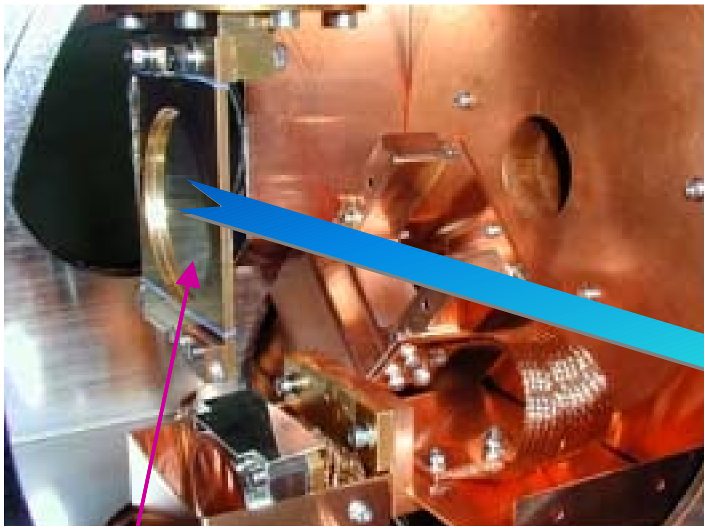
μA* Setup Detector-Target Layout

[keV]	C	N	O
K_α	75.3	102.4	133.5
K_β	89.2	121.4	158.4
L_α	14.0	19.0	24.9



Muonic Siver X-Rays

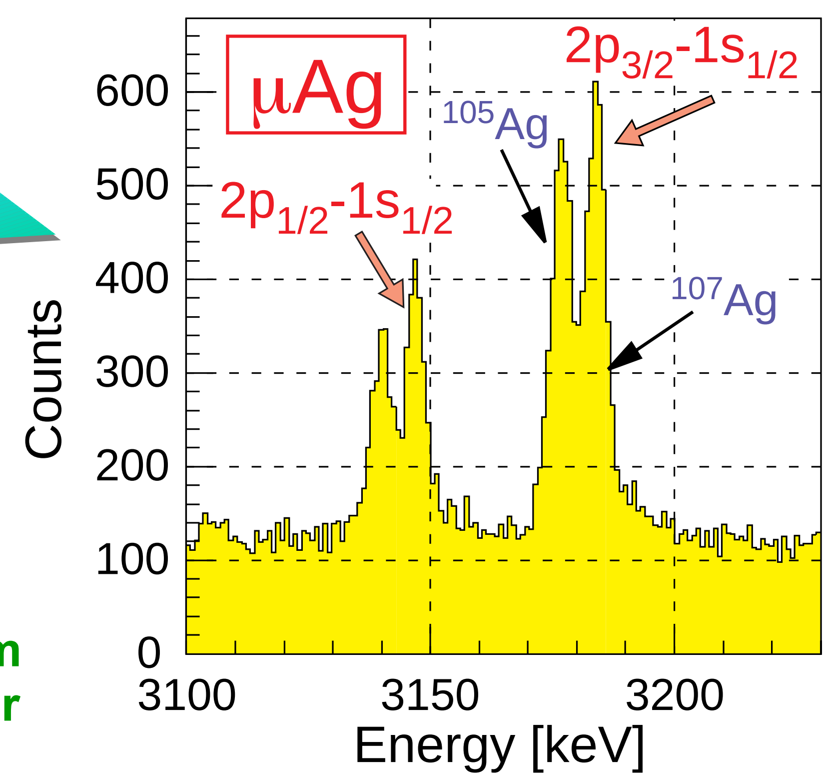
μA* Target System



Cold Foil (100-μm Ag)

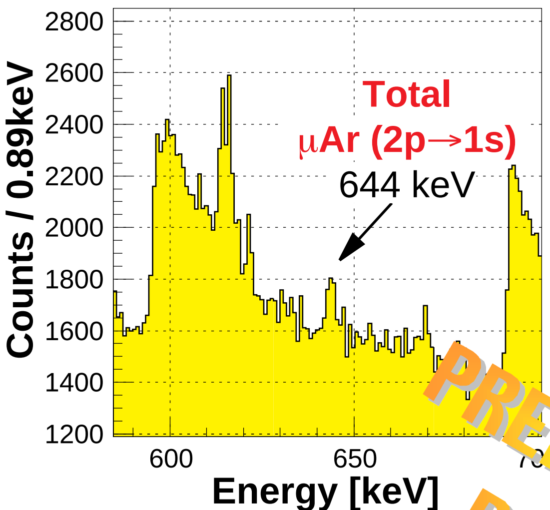
Germanium γ-Ray Detector

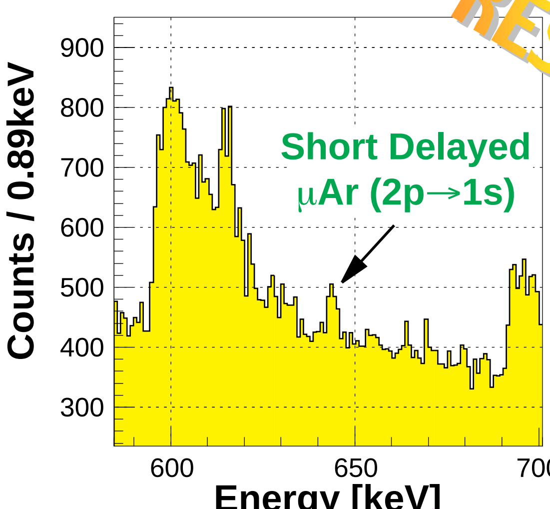
Muonic Silver X-rays from the Cold Foil

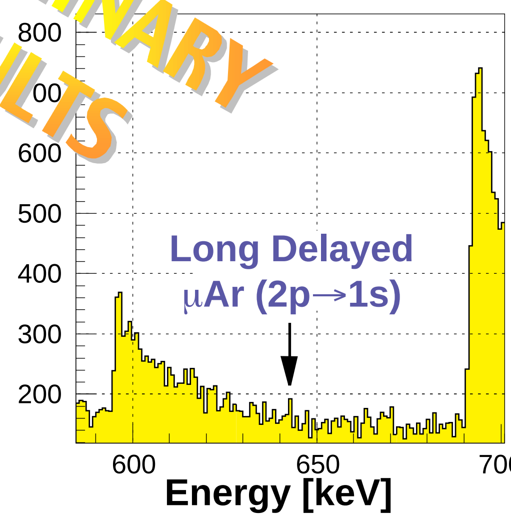


(1) 0.5-mm H_2/D_2 + 7-μm D_2(Ar-multi)

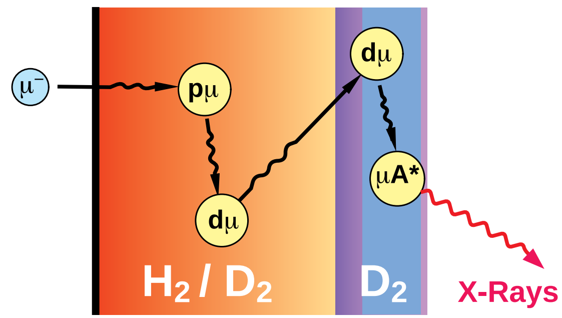
Ge(coaxial) γ-Ray Energy Spectra





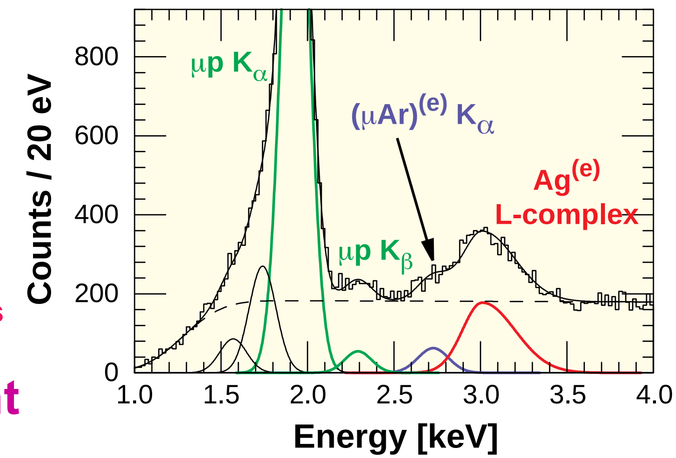


PRELIMINARY RESULTS



Two-Layer Arrangement

Si(Li) X-Ray Energy Spectrum

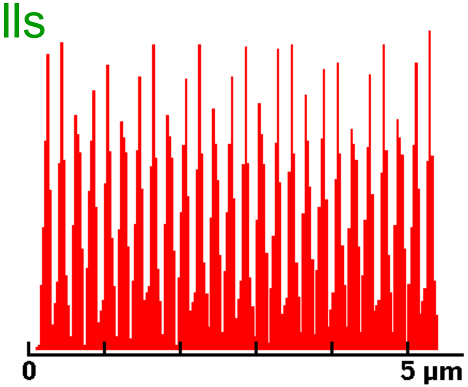


Implanted ^{40}Ar Ions in 5 μm

~10^{16} at/cm^2 (500 ppm)

12'170 kspills

(67.6 hrs)



dμ Atom Scattering in Solid Deuterium

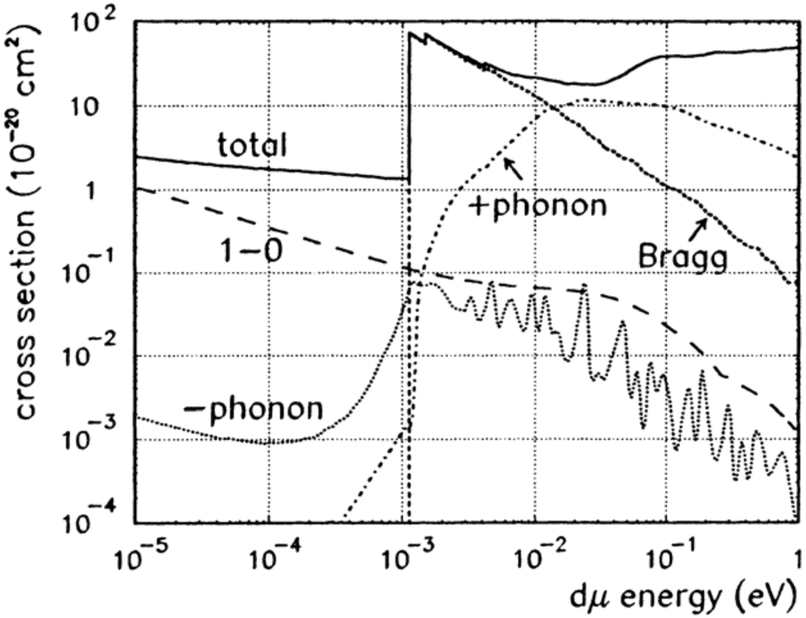
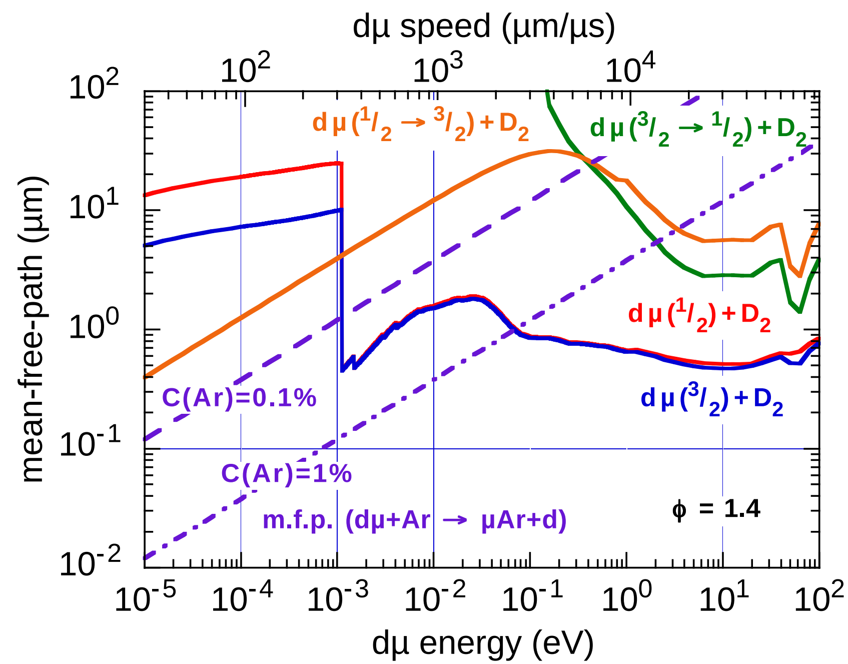


Figure 5. Total cross-section for $d\mu(F = 1/2)$ scattering in 3 K solid deuterium ($K = stat$). The label 1–0 denotes the rotational de-excitation $K = 1 \rightarrow K = 0$.

Deceleration of Muonic Hydrogen Atoms in Solid Hydrogens

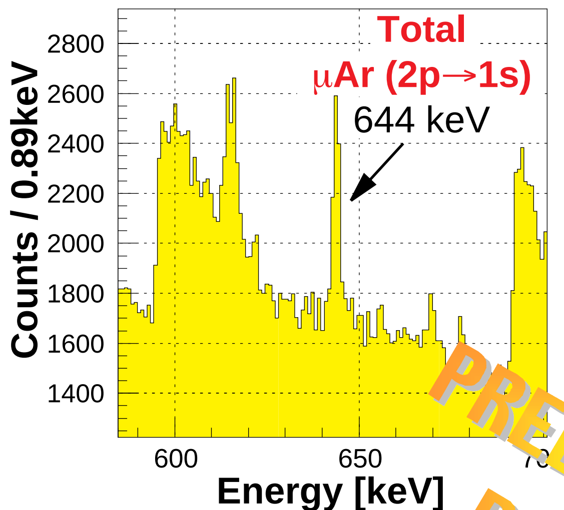
A. Adamczak, Hyperfine Interactions **119** (1999) 23.

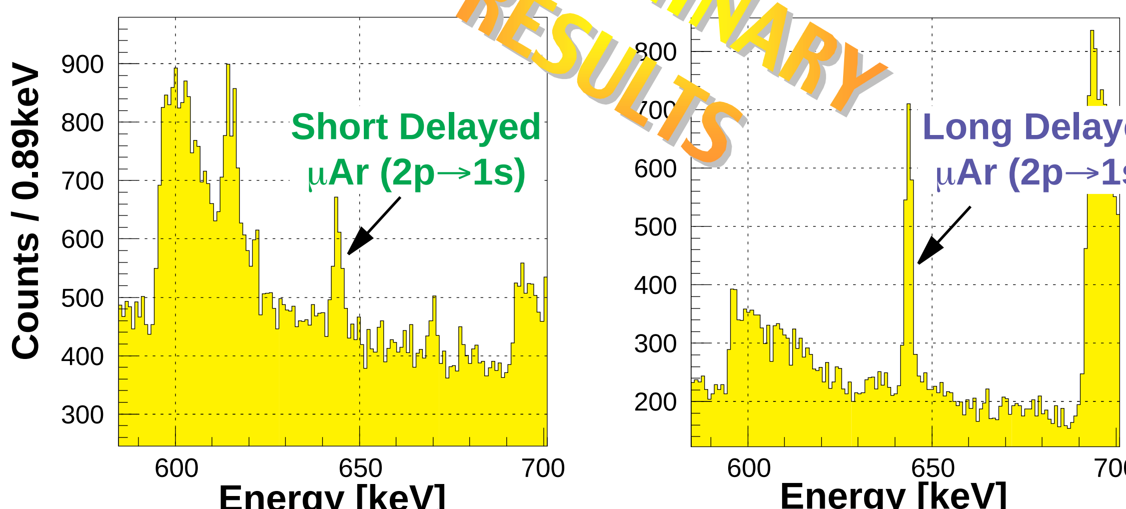
dμ Mean-Free-Path in Solid D_2

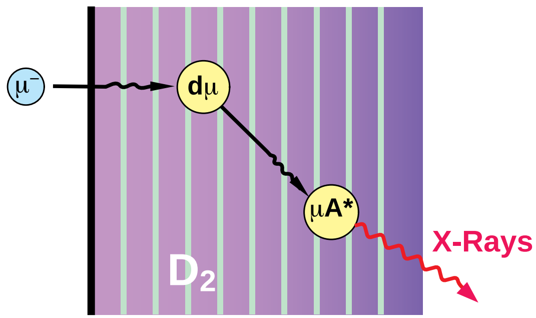


(2) 0.5-mm D_2(Ar-multi)

Ge(coaxial) γ-Ray Energy Spectra

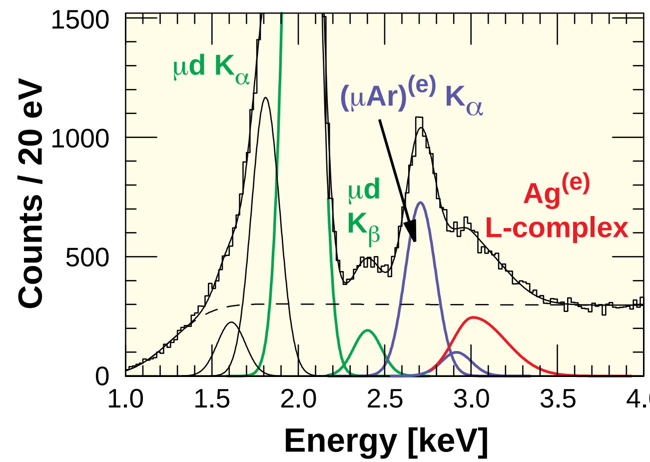






Single D_2 Layer

Si(Li) X-Ray Energy Spectrum

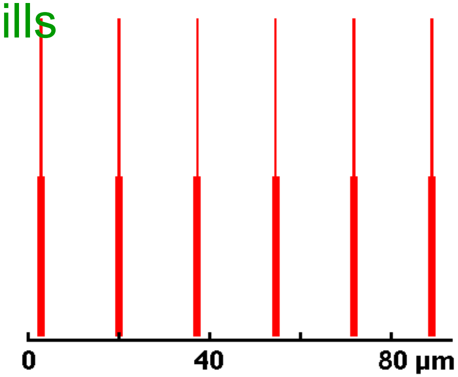


Implanted ^{40}Ar Ions in 0.5 mm

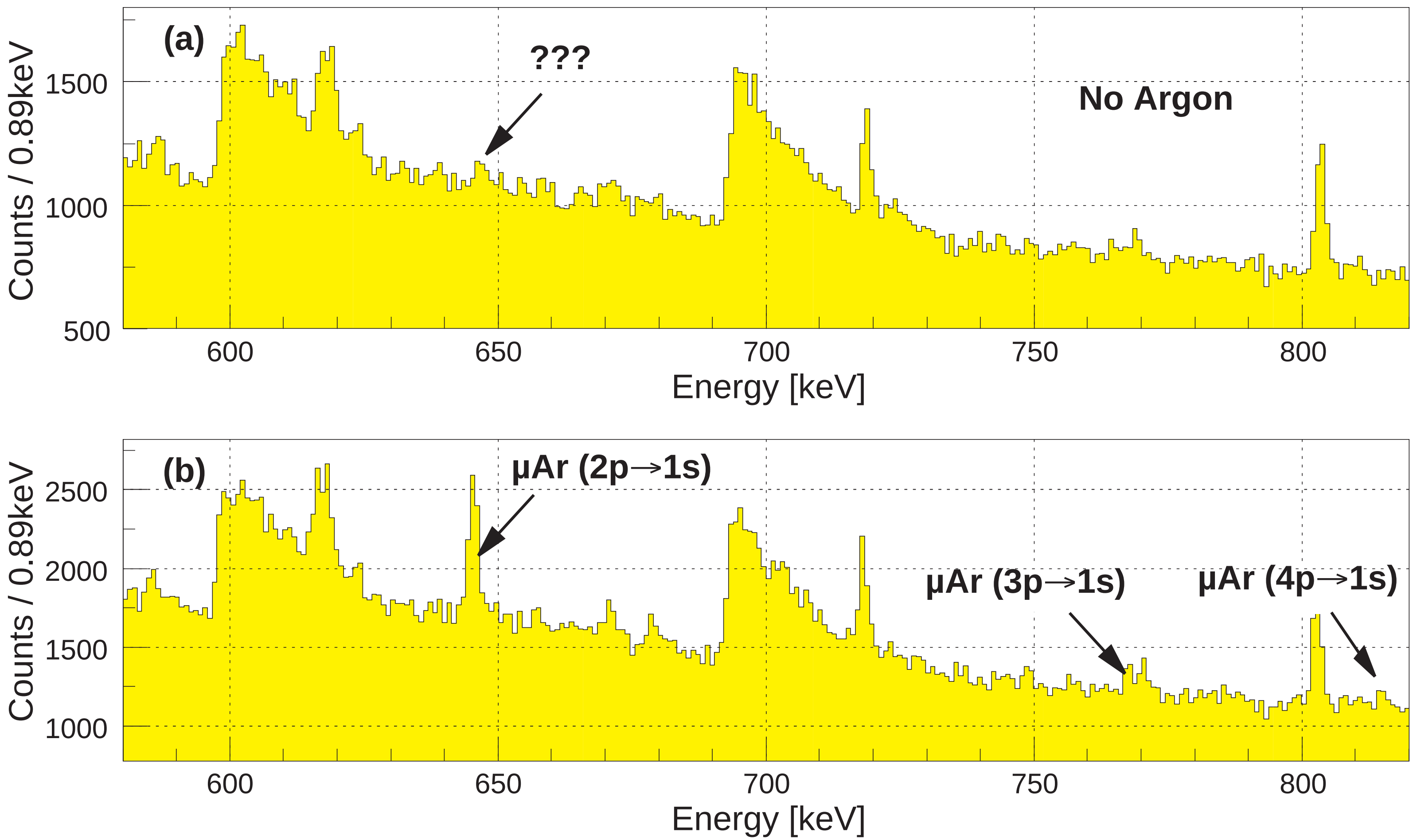
~10^{16} at/cm^2 (~ 6 ppm)

12'560 kspills

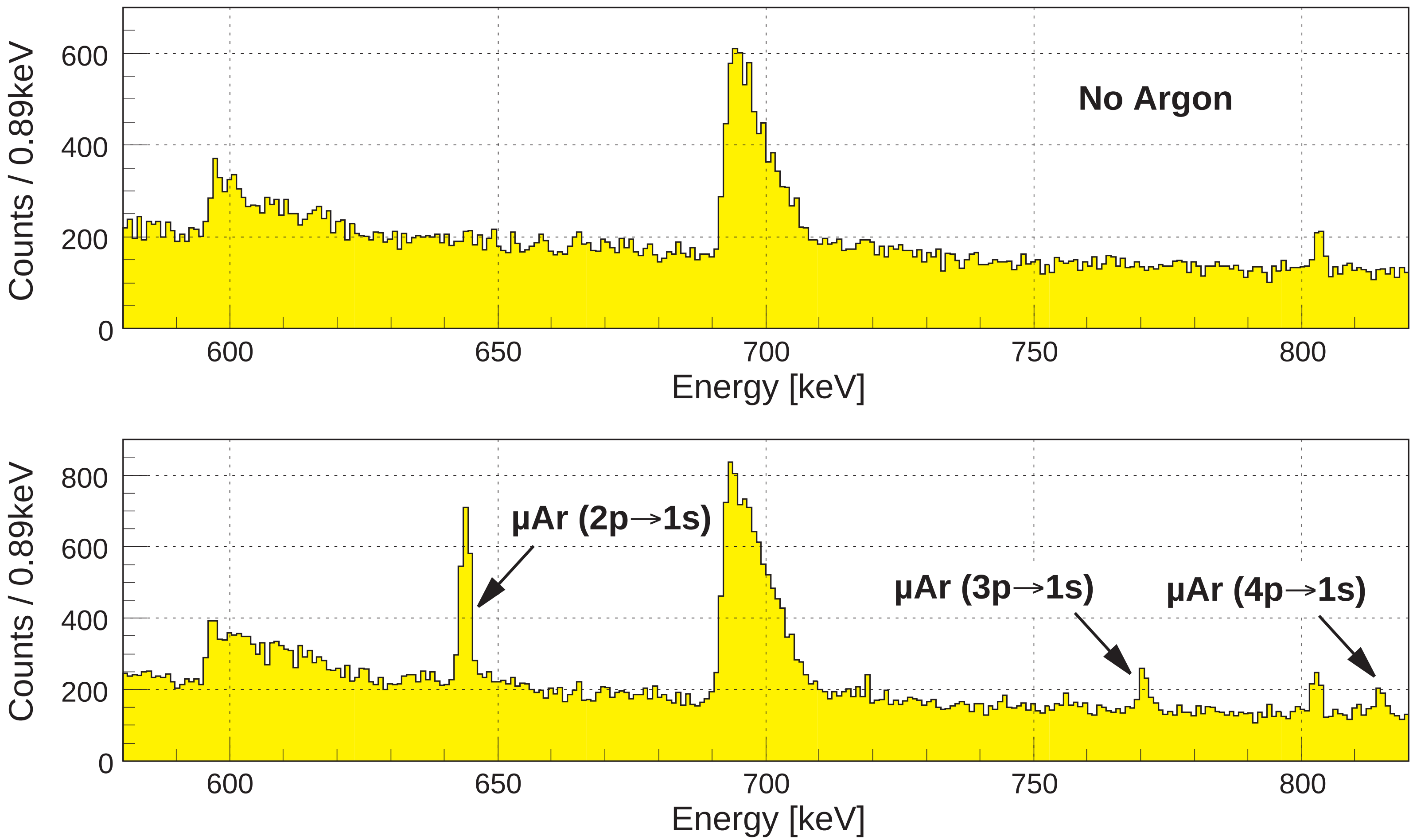
(69.8 hrs)



Total Energy Spectra (1-mm D_2)



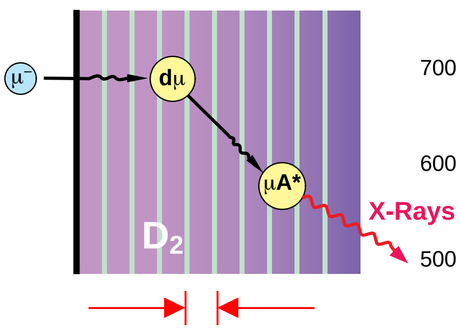
Delayed Energy Spectra (1-mm D_2)



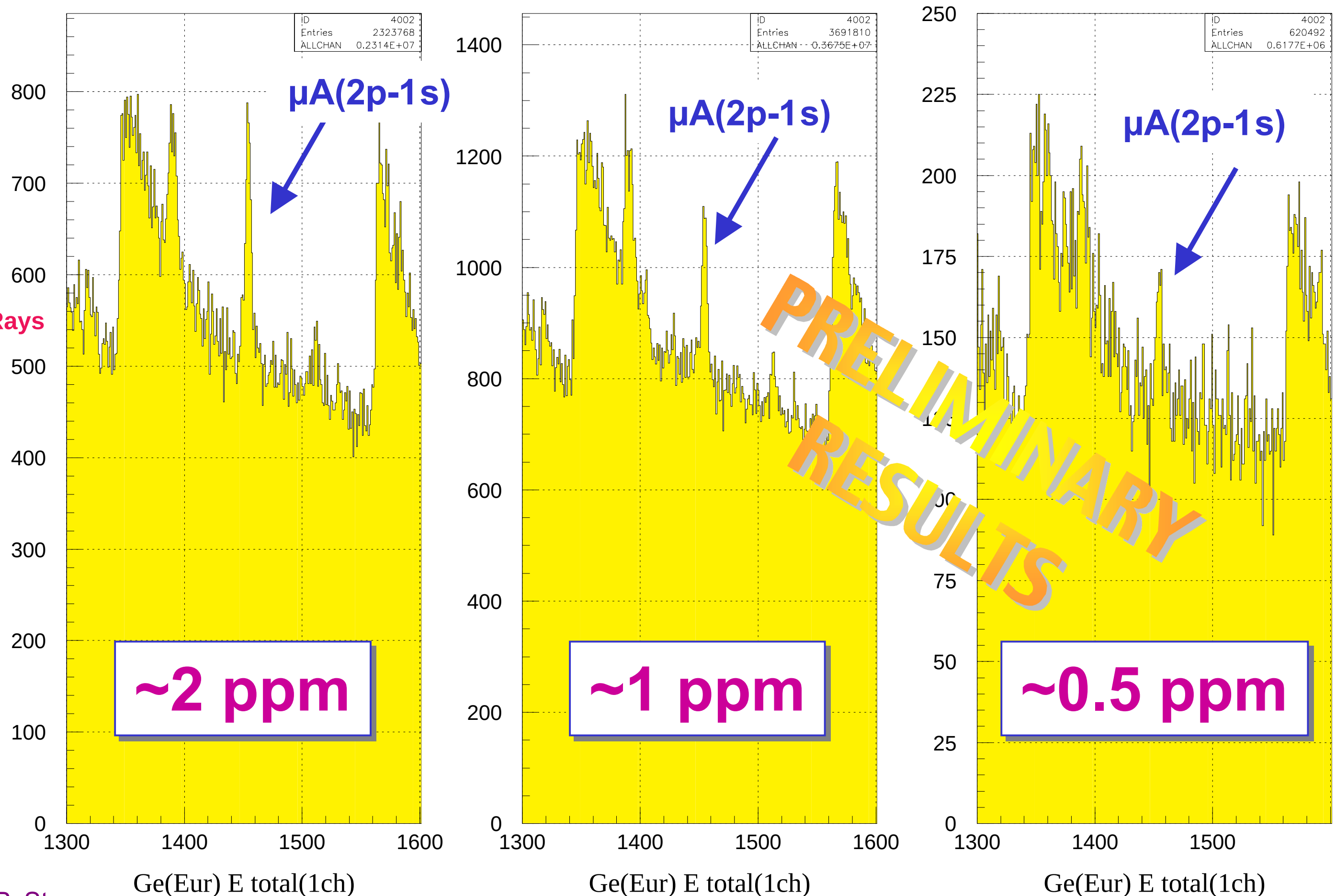
(3) 1.0-mm D_2(Ar-multi)

Implantation:	20x	10x	5x
Distance:	50μm	100 μm	200 μm

Single D_2 Layer

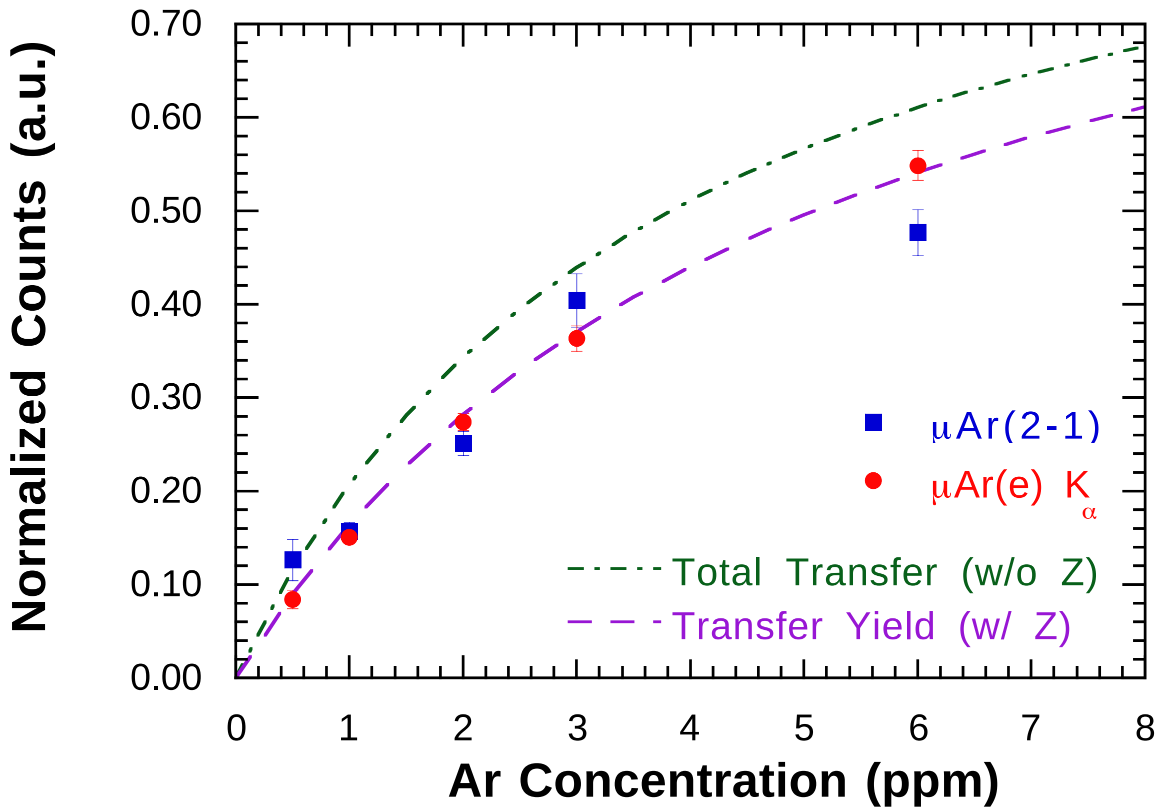


distance between implantation



Total γ-Ray Energy Spectra

Transfer Yield



PRELIMINARY RESULTS

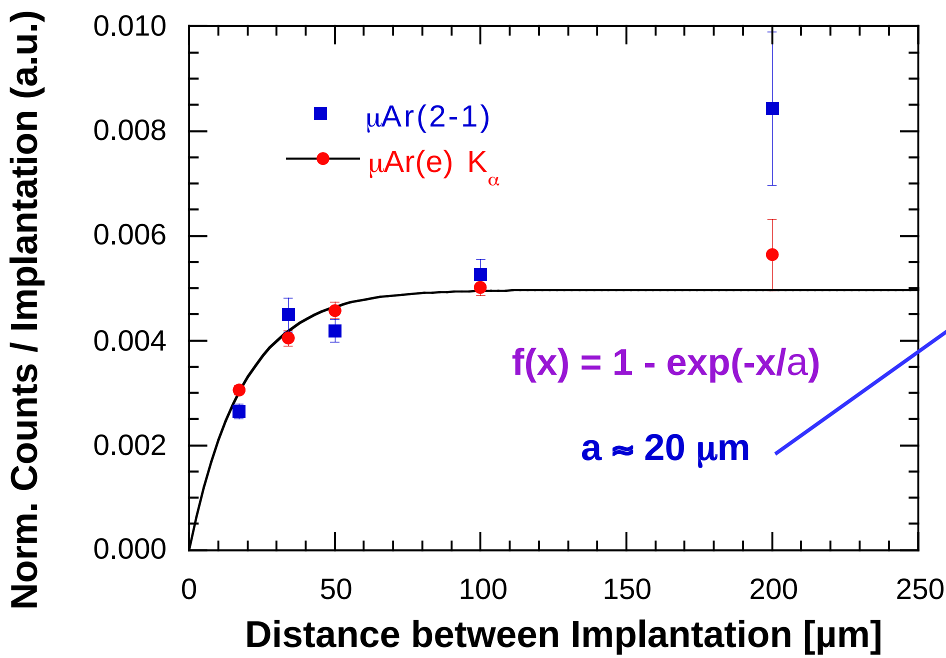
Z = Air (N_2, O_2)

For a uniform target

$$Y_{dAr} = \frac{\phi C_{Ar} \lambda_{dAr}}{\lambda_0 + \phi C_{Ar} \lambda_{dAr} + \phi C_Z \lambda_{dZ}}$$

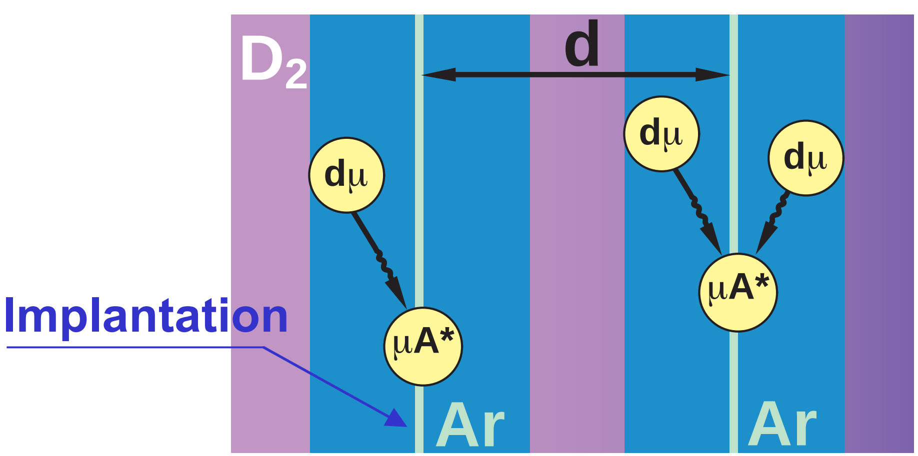
Normalized data only
No correction applied yet !

dμ Atom Diffusion in Solid D_2

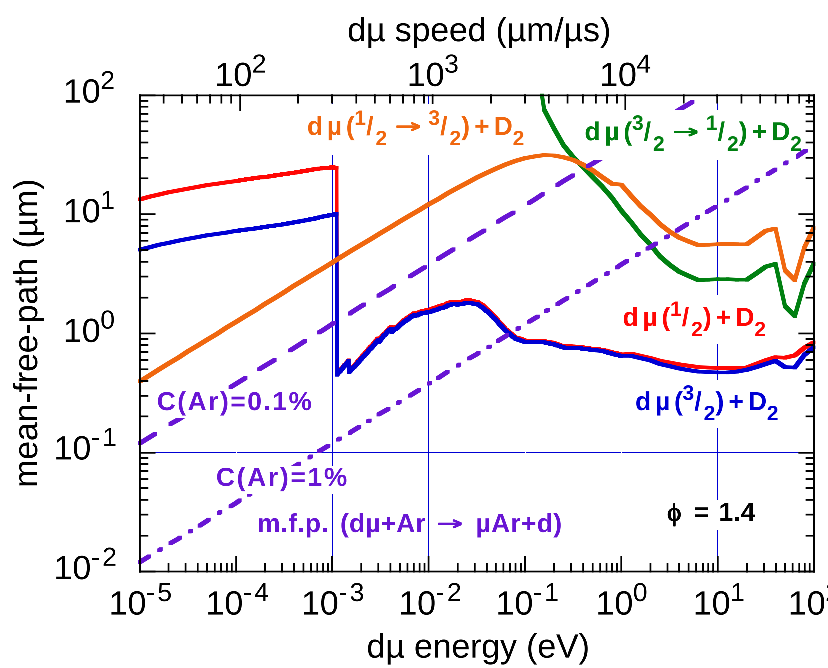


Limitation on the minimum film thickness!

PRELIMINARY RESULTS



dμ Mean-Free-Path in Solid D_2



Towards Radioactive Muonic Atoms

- Experiment using **LONG-LIVED ISOTOPES** under consideration, e.g., radium isotopes of special interest for P&T violation in atoms (K. Jungmann, KVI).

- Need a **NEW ION SOURCE** to produce **LONG-LIVED RI BEAMS**.

- **NOW** at RIKEN-RAL: **10^{16} atoms** needed in Ø5cm x 1mm D_2 target (3000 μ^-/s).

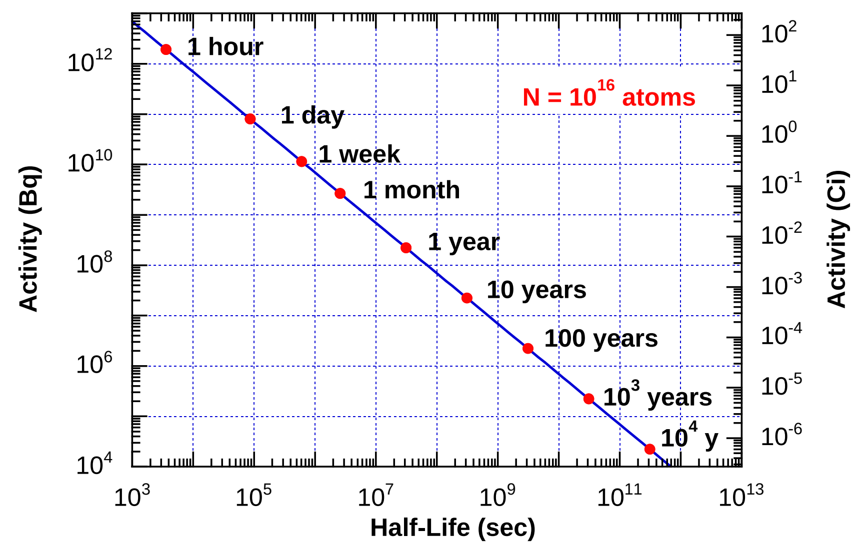
  Possible Improvements: **60 times!**

  ➡ 20 times (1 cm^2 target)

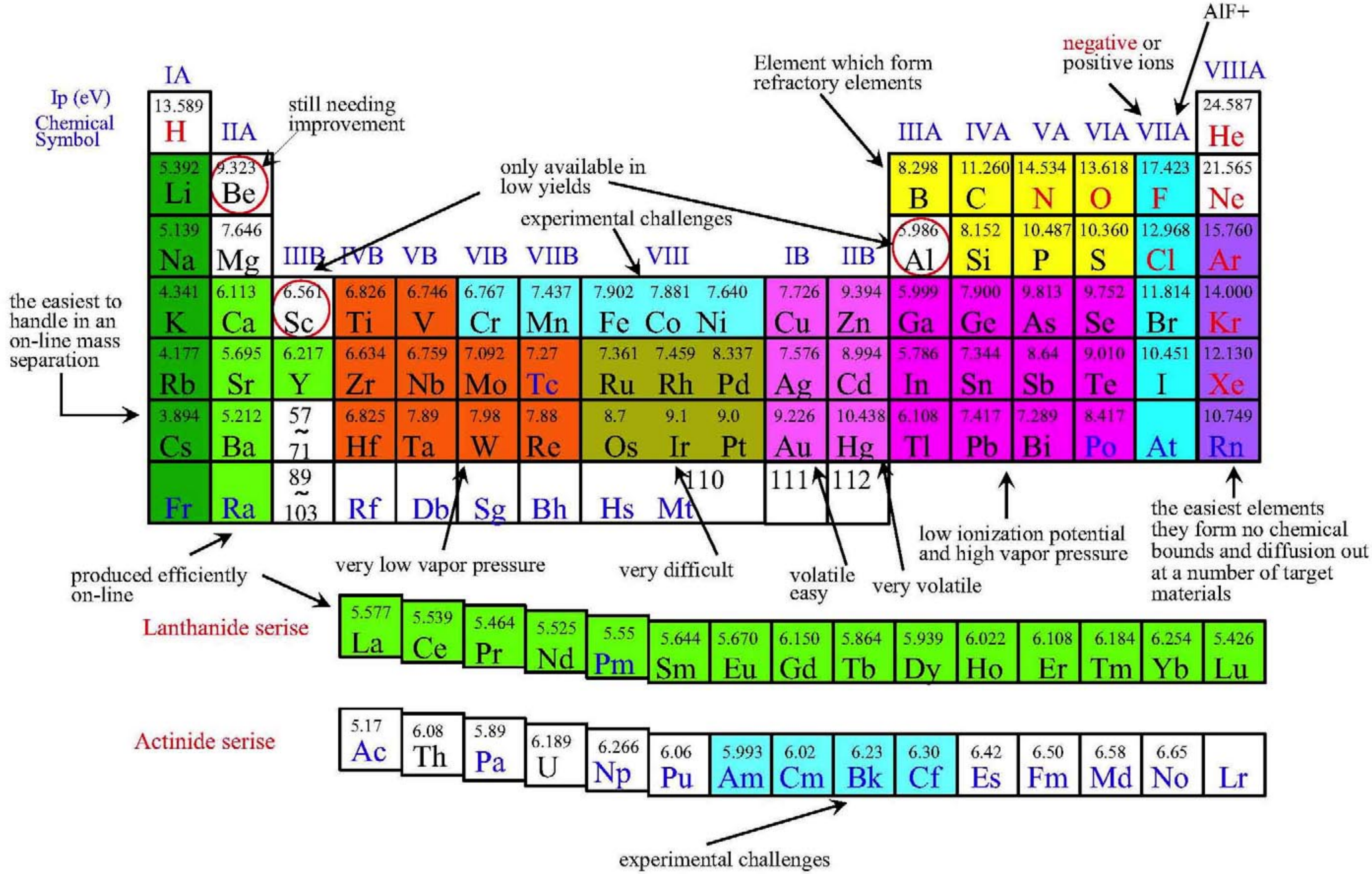
  ➡ 3 times (cloud μ^-)

- Need **~100x** more in the **ION SOURCE**.

- **ACTIVITY** versus **HALF-LIFE**.

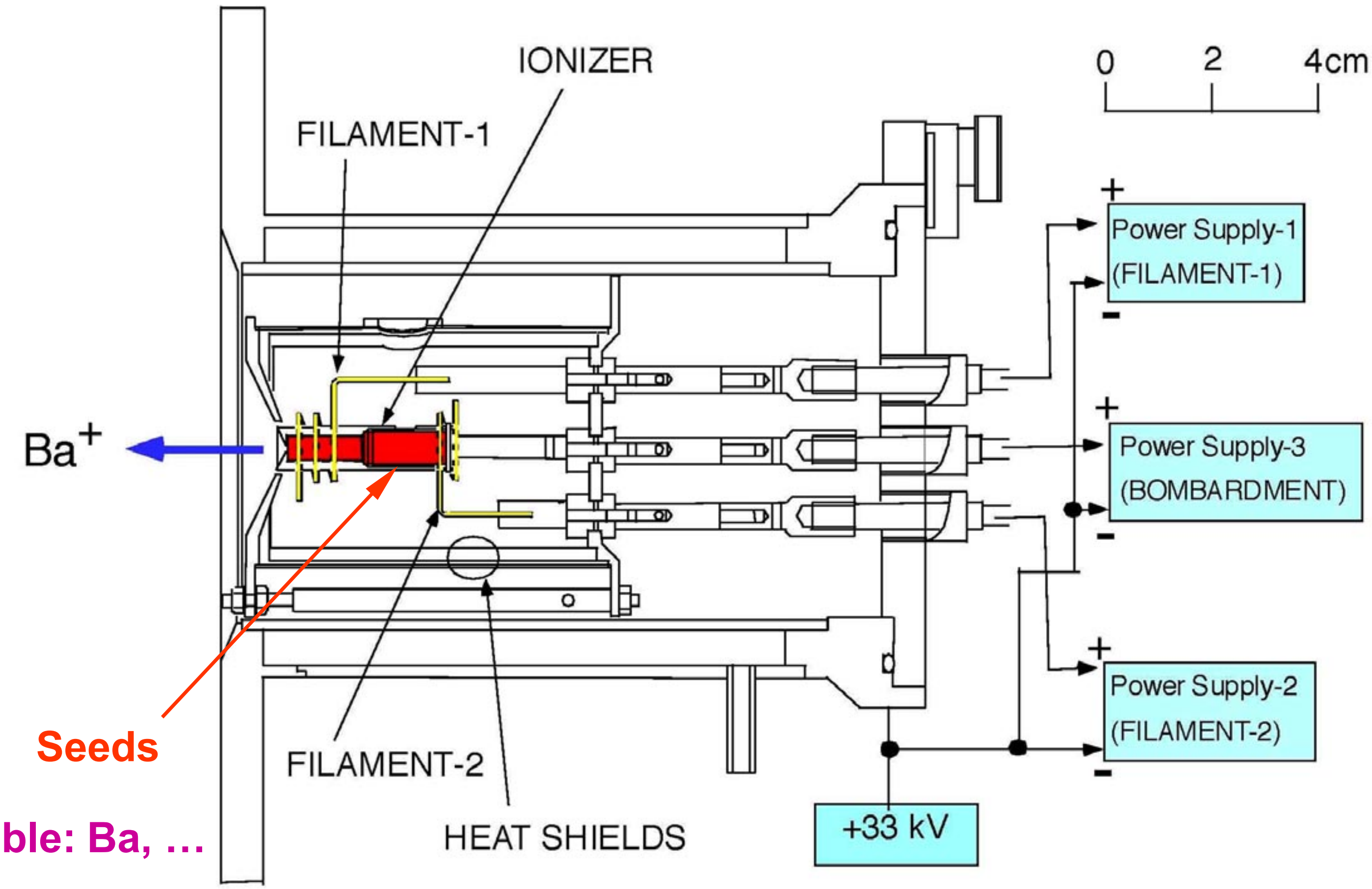


Periodic Table of Elements



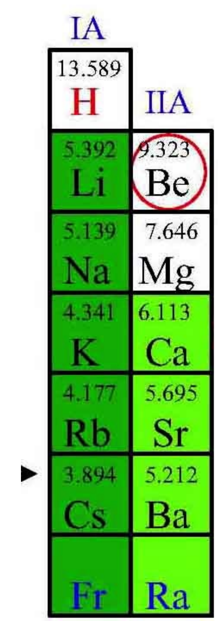
New Surface Ionization Ion Source

New Collaborators: **A. Taniguchi (Kyoto), S. Ichikawa (JAERI), H. Miyatake (KEK)**



Seeds

First stable: Ba, … then RI



Good for alkali metals & alkaline-earth metals!

Future Prospects

Muon Beam Requirement for μA* Experiment:

High Intensity Accelerator

Muon Stopping in Solid Deuterium

- Momentum: ~ 27 MeV/c
- Width ($\Delta p/p$): ≤ 5 %
- Beam intensity: > 1 x 10^{7-8} s^{-1}
- Beam size: ≤ $1 cm^2$

X-Ray and γ-Ray Detection System

- Muon beam: pulsed
- Pulse structure: single
- Pulse width: ≤ 20–50 ns
- Repetition rate: 1–10 kHz

Muonic Atoms (in brief)

Transfer Rate: $$Y_X = \frac{\phi\lambda_Z}{\lambda_0 + \phi\lambda_Z}$$

We need $\lambda_Z \approx C_Z Z \times 10^{10} s^{-1}$

(approximation) → $$N_Z \, N_\mu \approx \frac{10^{17}}{Z}$$ ($\lambda_Z << \lambda_0$)

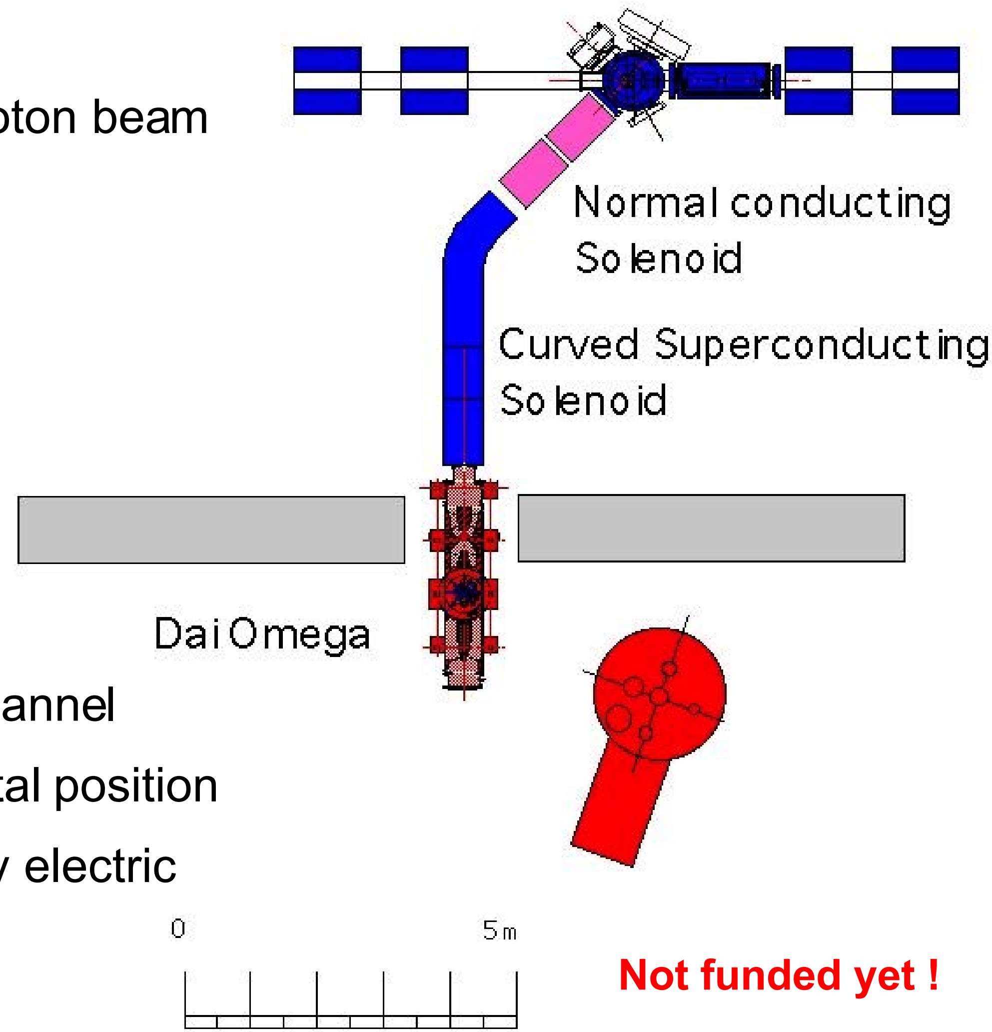
to produce **1 μA* per cm²**.

N_Z, N_μ: Z and μ^- in **0.5-mm D_2**

SUPER OMEGA Project (K. Shimomura et al., KEK)

- **Injection**
  - 2 normal solenoids ~ 400mSr
  - Residual magnetic field on the proton beam line ~10 Gauss
- **Transport**
  - Curved superconducting solenoid
  - Reduction of neutral background
  - Selection of charged particle
- **Extraction**
  - Dai Omega type axial focusing channel
  - Strong focusing at the experimental position
  - Selection of muon and positron by electric separator

at J-PARC Muon Facility

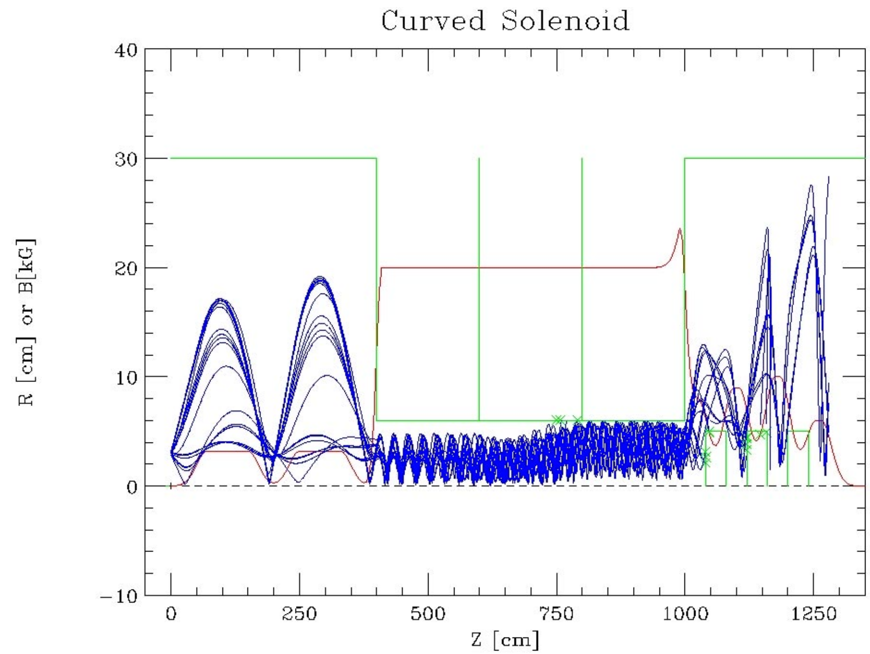


Not funded yet !

SUPER OMEGA Project (K. Shimomura et al., KEK)

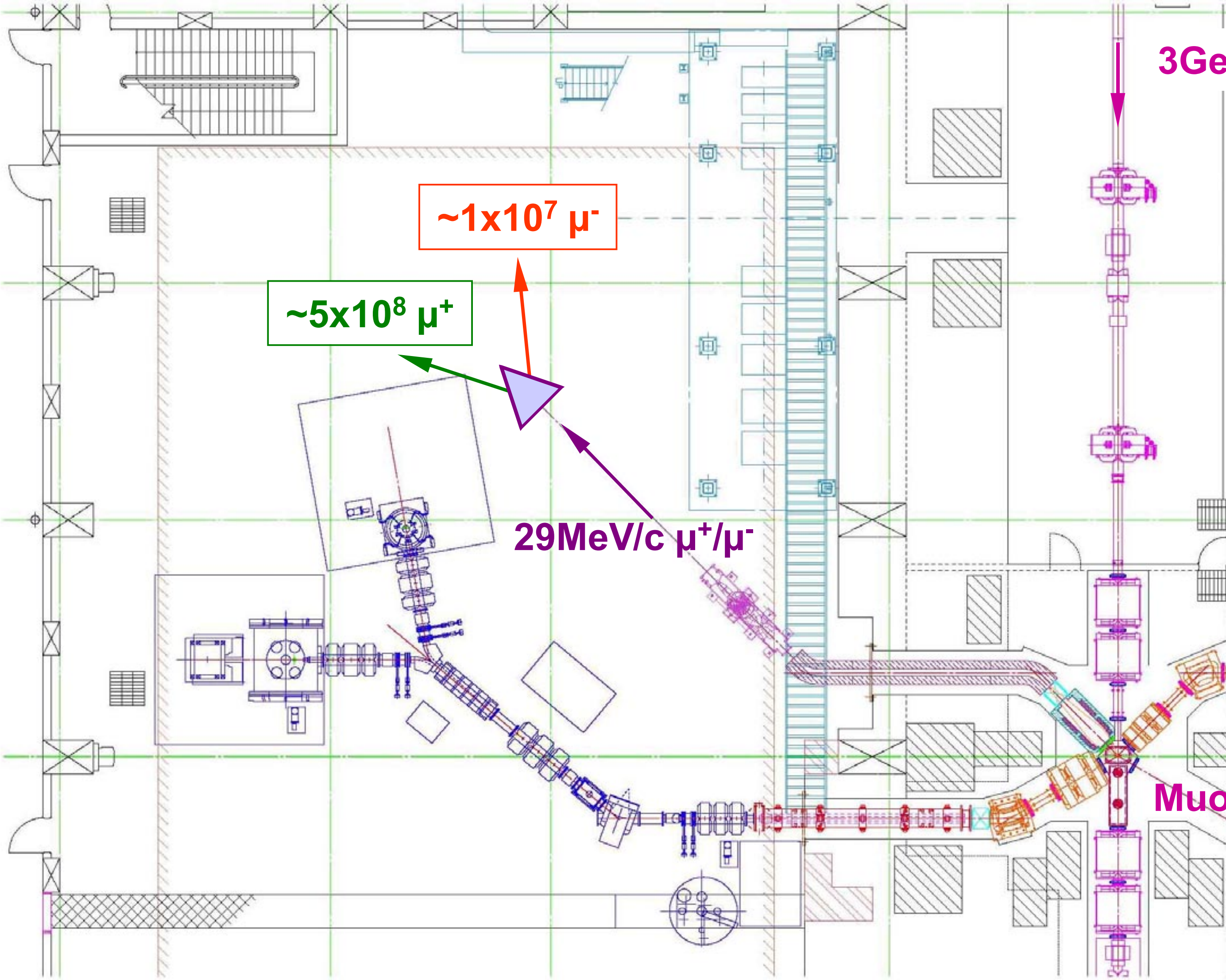
- **Yield Estimation**
  - Solid angle: ~ 400mSr
  - Momentum: 27 MeV/c
  - Momentum width: 4–10%
  - Surface Muons (μ^+): 2–5 x 10^8 s^{-1}
  - **Cloud Muons (μ^-): 4–10 x 10^6 s^{-1}**
- **Science (μ^+)**
  - Ultra-Slow Positive Muon 2–5 x 10^4 s^{-1}
  - Muon micro-beam, ...
- **Science (μ^-)**
  - μA* Formation
  - Element Analysis by Muon Spectroscopy
  - ...

Beam Optics Calculation



by K. Ishida (RIKEN)

My Dream at J-PARC Muon Facility



Summary

- In the near future, investigations of unstable nuclei using muonic atom spectroscopy will become possible at facilities with intense μ^- and RI beams.
- Meanwhile, using dedicated long-lived RI ion source, radioactive muonic atom study will soon be a reality at new intense muon facility.

⇒ **There will be a unique opportunity at the new J-PARC MUON FACILITY.**

and maybe in the near future at a NEUTRINO FACTORY !