Muon Physics at RIKEN-RAL Muon Facility

K. Ishida (RIKEN)

About the facility

Research with unique beams and facilities

MuSR

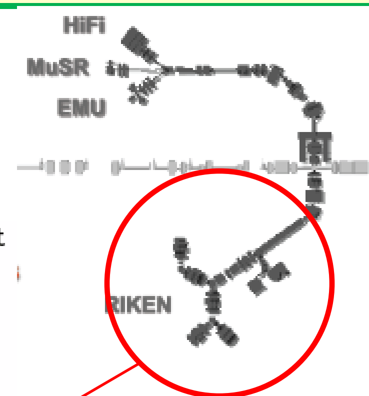
High pressure, Laser

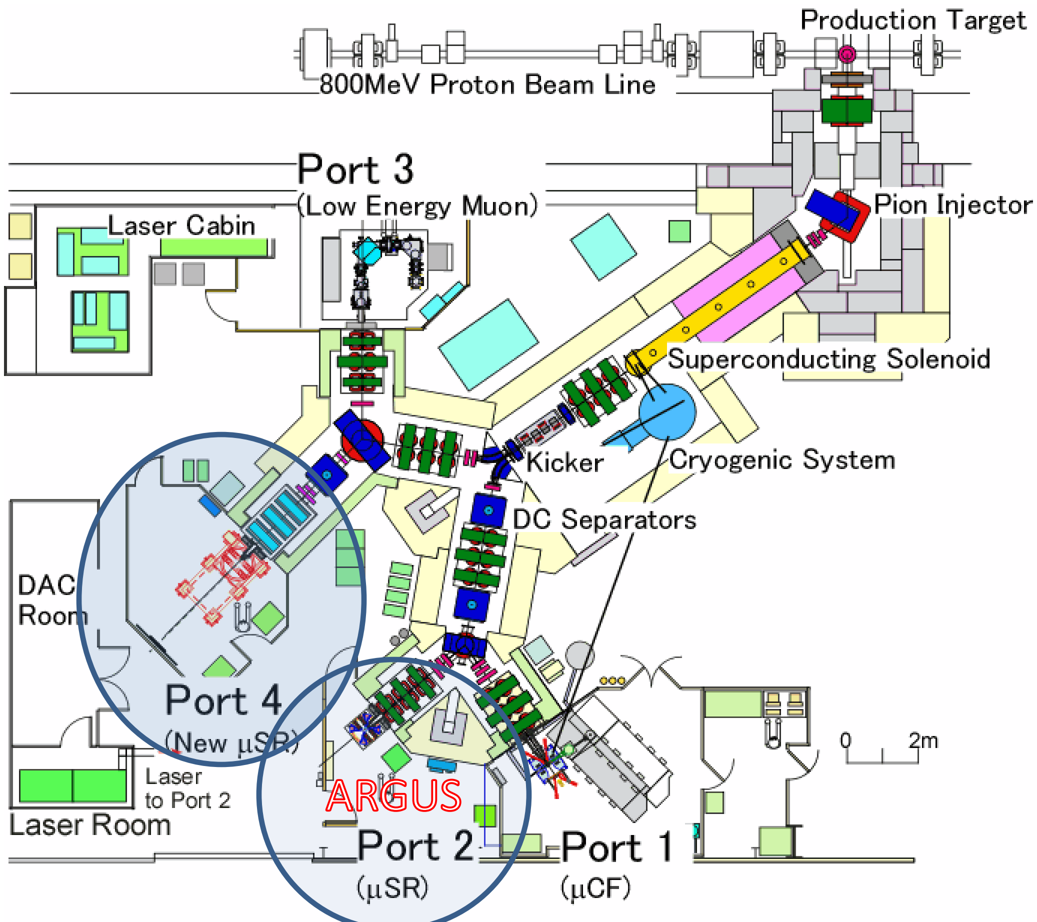
Slow Muon Beam

Muon Catalyzed Fusion

RIKEN-RAL

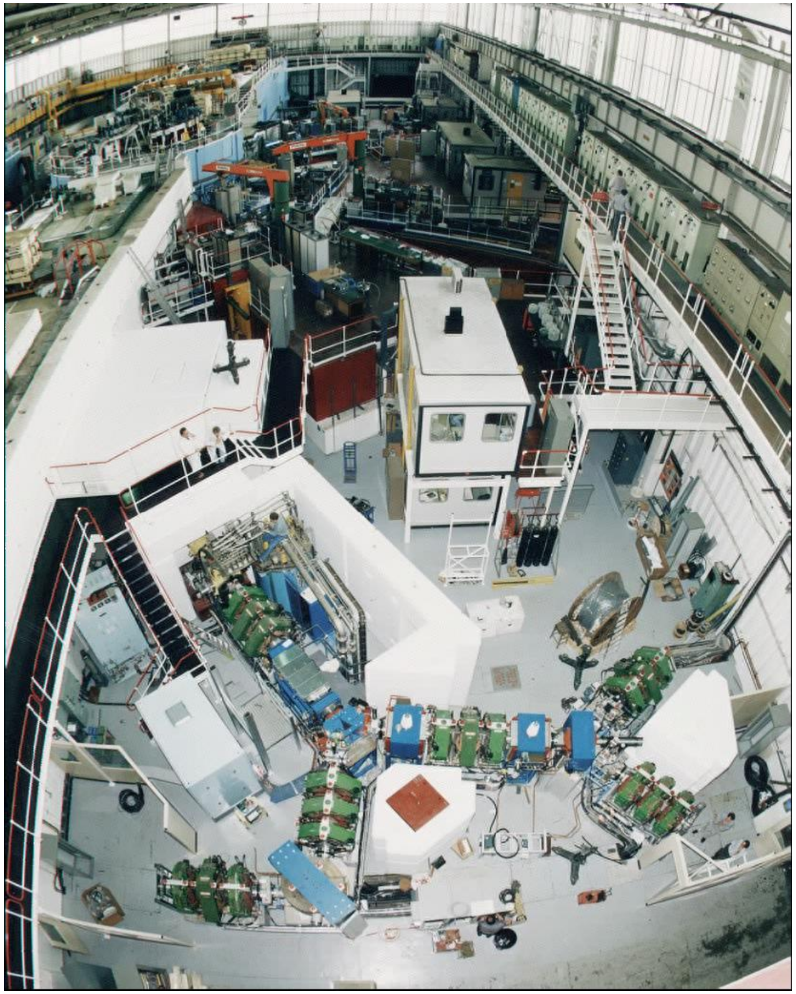
Located at north-side of ISIS



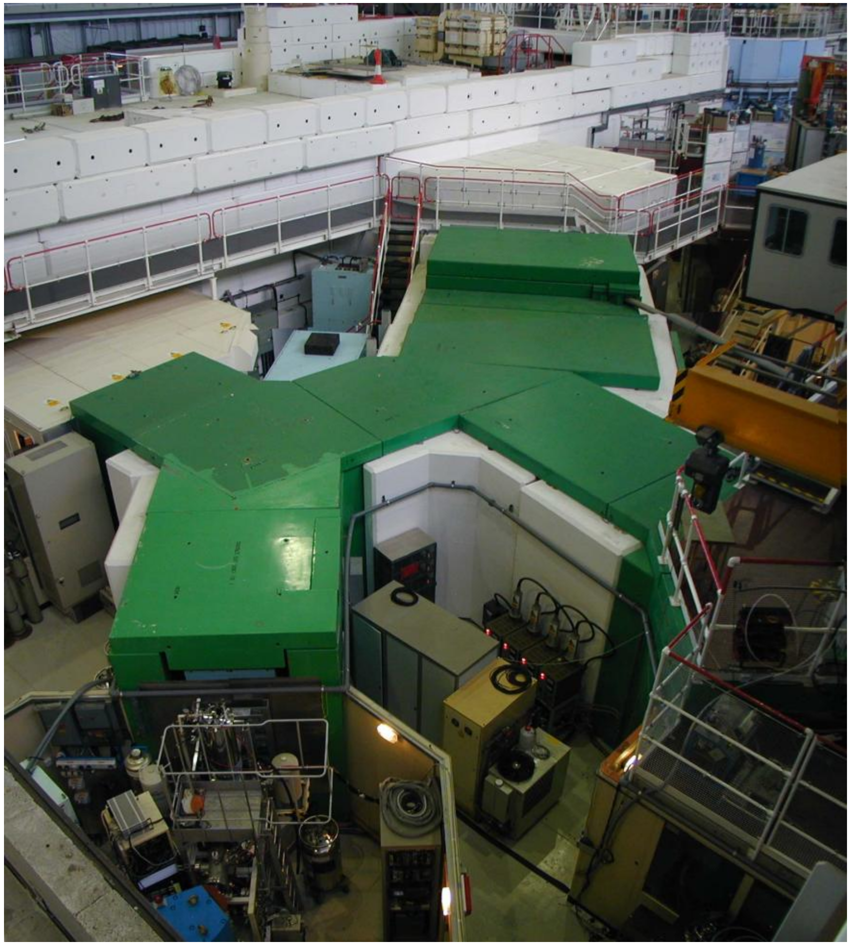


The RIKEN-RAL Muon Facility

RIKEN-RAL Muon Facility



Construction Stage (1994)



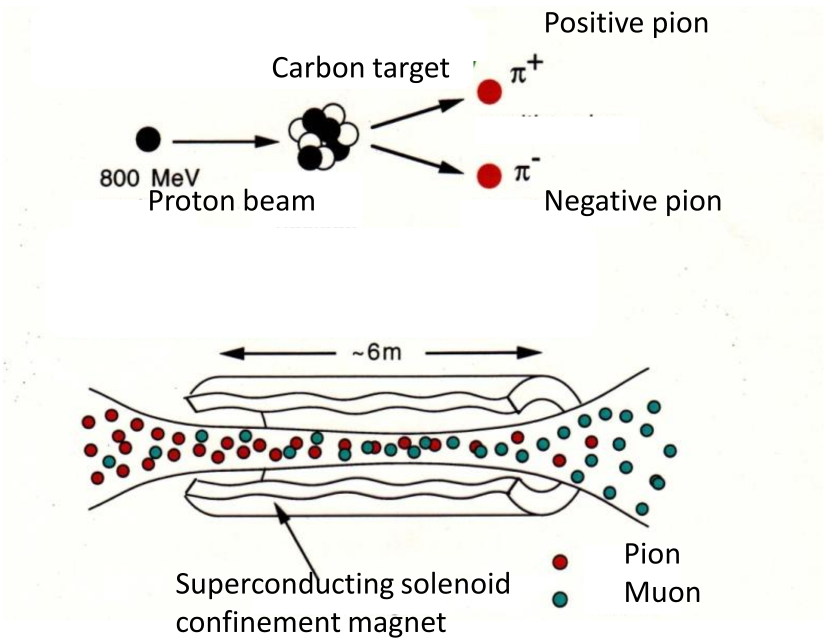
Recent

About RIKEN-RAL

It is operated by Japanese RIKEN Institute – since 1994.
It is open to users through RIKEN PAC and ISIS PAC.

RIKEN-RAL has many features in common with EC Muons,
but also has some unique features.

Backward decay muon beam
as well as surface muon beam
can be chosen at RIKEN-RAL Muon,
because of the solenoid decay section.



Unique capabilities at RIKEN-RAL

Compared with surface-muon beam,

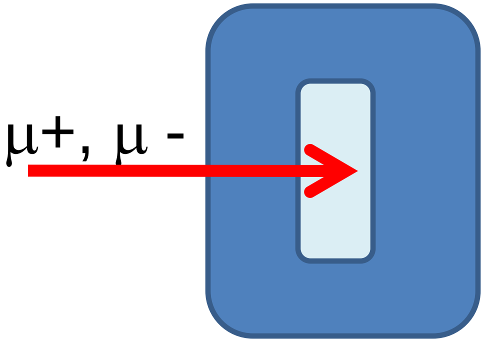
backward decay muon beam has

advantages

- higher momentum (thick samples)
- choice of positive/negative muon

disadvantages

- lower muon stopping density (difficulty with small samples)



And also, unique facilities

1) Laser MuSR
2) Slow muon with laser

Muon Physics at RIKEN-RAL

1. MuSR at ARGUS

   Laser, High pressure, …

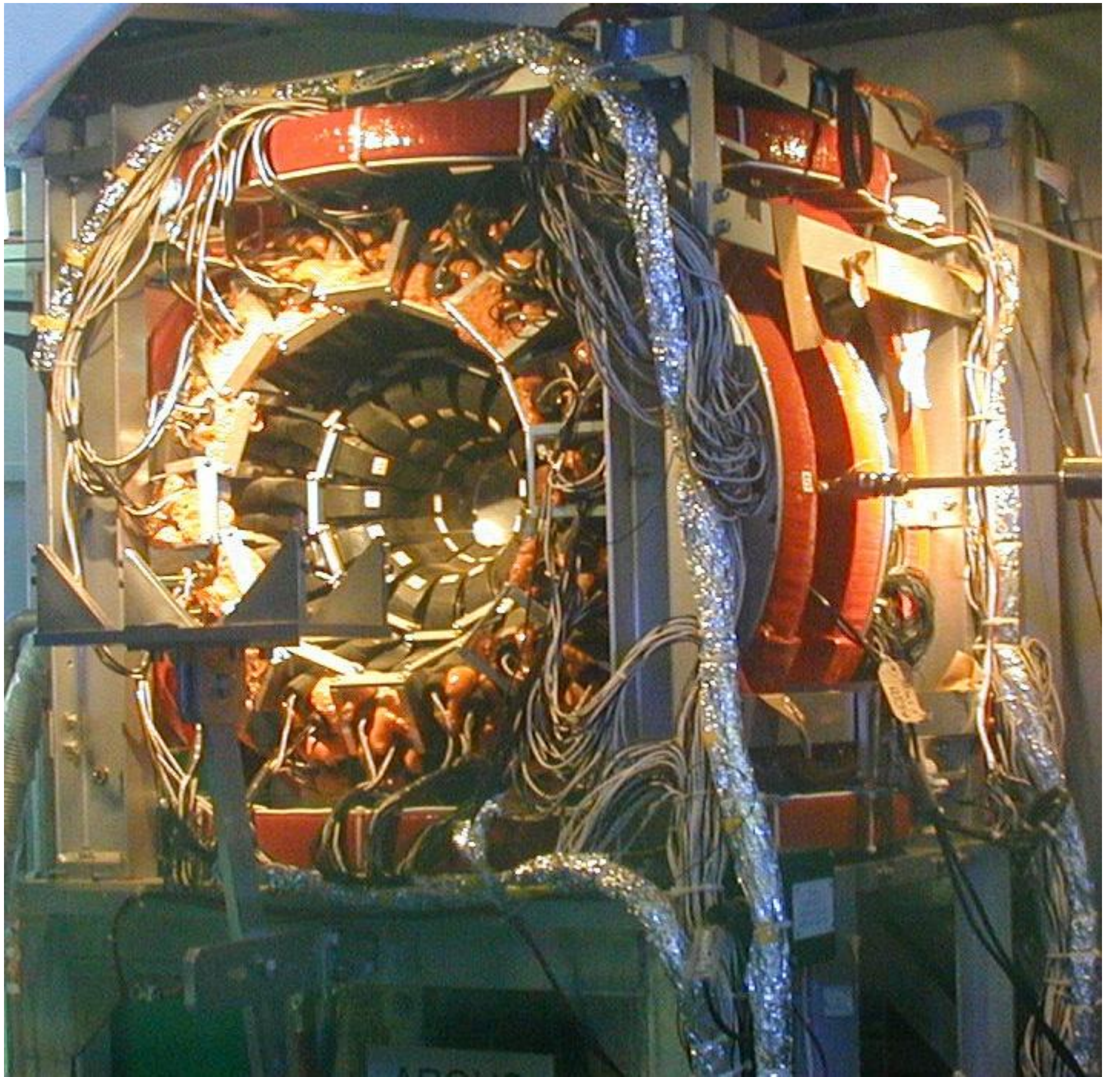
2. Slow Muon Beam

3. Muon Catalyzed Fusion

   with negative muon

μSR (ARGUS)

μSR with surface/decay muon beam under various target conditions



μSR at RIKEN-RAL

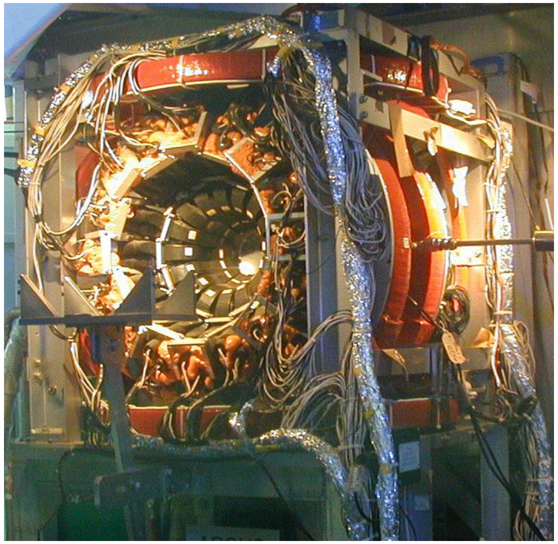
ARGUS Spectrometer

Highly segmented detector (96+96)

High data rate (70 M/hr)

Magnetic field up to 0.4 T (LF) and 0.015 T (TF)

Various cryostats (dilution, 3He, He, Flow type)



Choice of backward decay or surface muon

high momentum muon for high pressure chamber

Other capabilities

coupling with laser excitation, high pressure

MuSR with Laser

Laser has many good features

- intense photon
- good energy resolution, variable wave length
- polarized photons
- short pulse

though

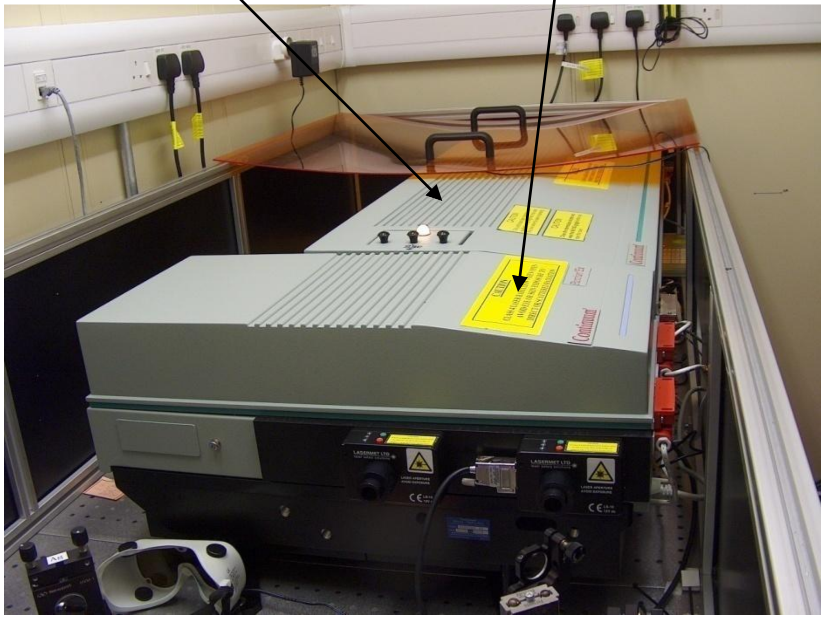
- it is not cheap, need some expert, safety issue etc

Intense pulsed laser is a good match for pulsed muon

Laser facility started in RIKEN in Feb 2008

Installed laser system (RIKEN Port 2)

Nd:YAG (1064 nm; 532 nm; 355 nm) + **OPO**



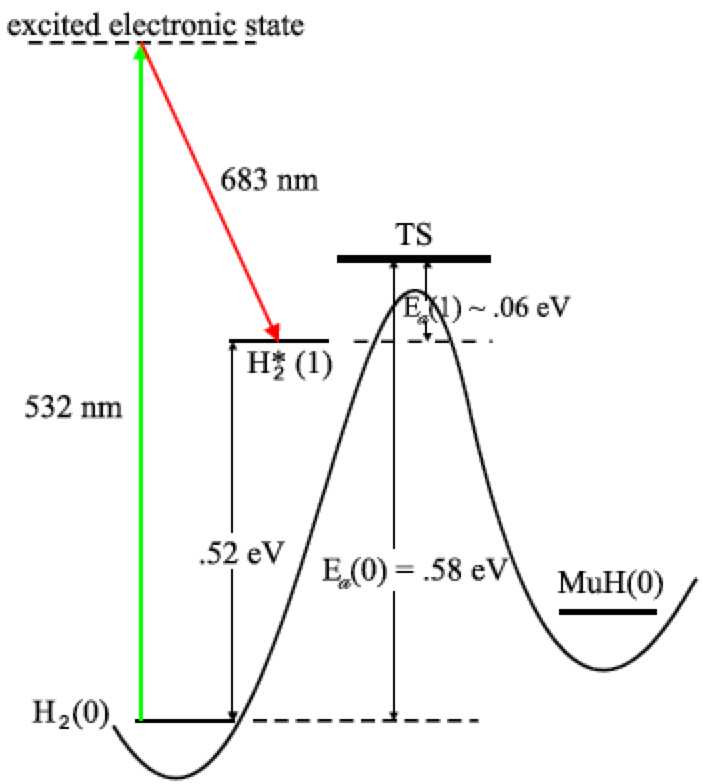
Pulse repetition rate	**25 Hz**
Pulse duration (FWHM)	8 ns
Pulse energy @ 1064 nm	1400 mJ
Pulse energy @ 532 nm	600 mJ
Pulse enery @355 nm	350 mJ
OPO energy 420-700 nm (signal)	<80 mJ
OPO energy 700-2600 nm (idler)	<30 mJ

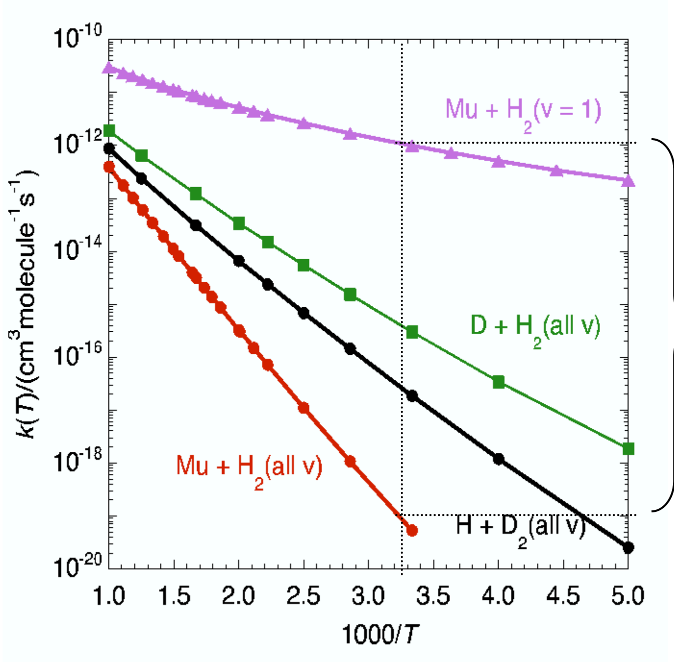
wide tuning range of 400-2500 nm (photon energy of 0.5-3.1 eV)

typical energies required for sample excitation are below 1 mJ/cm^2.

Large number of photons available: 1mJ@830 nm = 4.2 x 10^{15} photons

Laser for Chemistry: Mu + $H_2 \rightarrow$ MuH + H reaction rate





Precise calculation of potential surface and reaction rate is one of the fundamental chemical physics problem

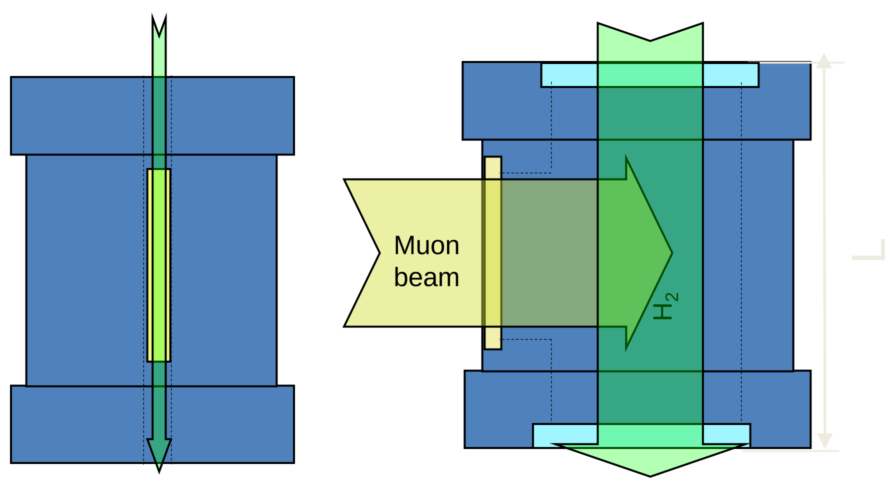
Unprecedented new tests will be possible using H2 in v=1 excited state <- use pulsed laser for excitation

Laser for Chemistry: H2 target

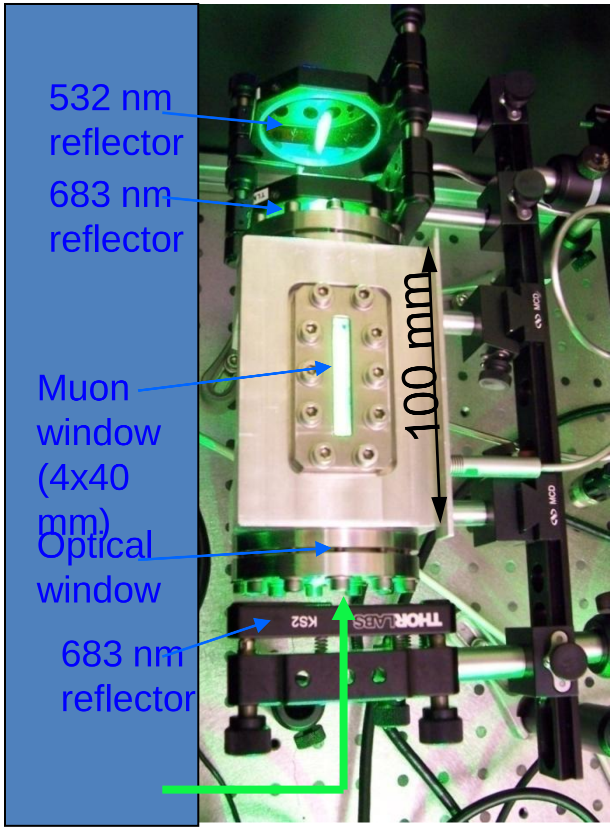
High pressure H2 gas (50 bar)

to increase the reaction rate, number of excited molecules

need a maximum overlap of the muon beam and the laser beam



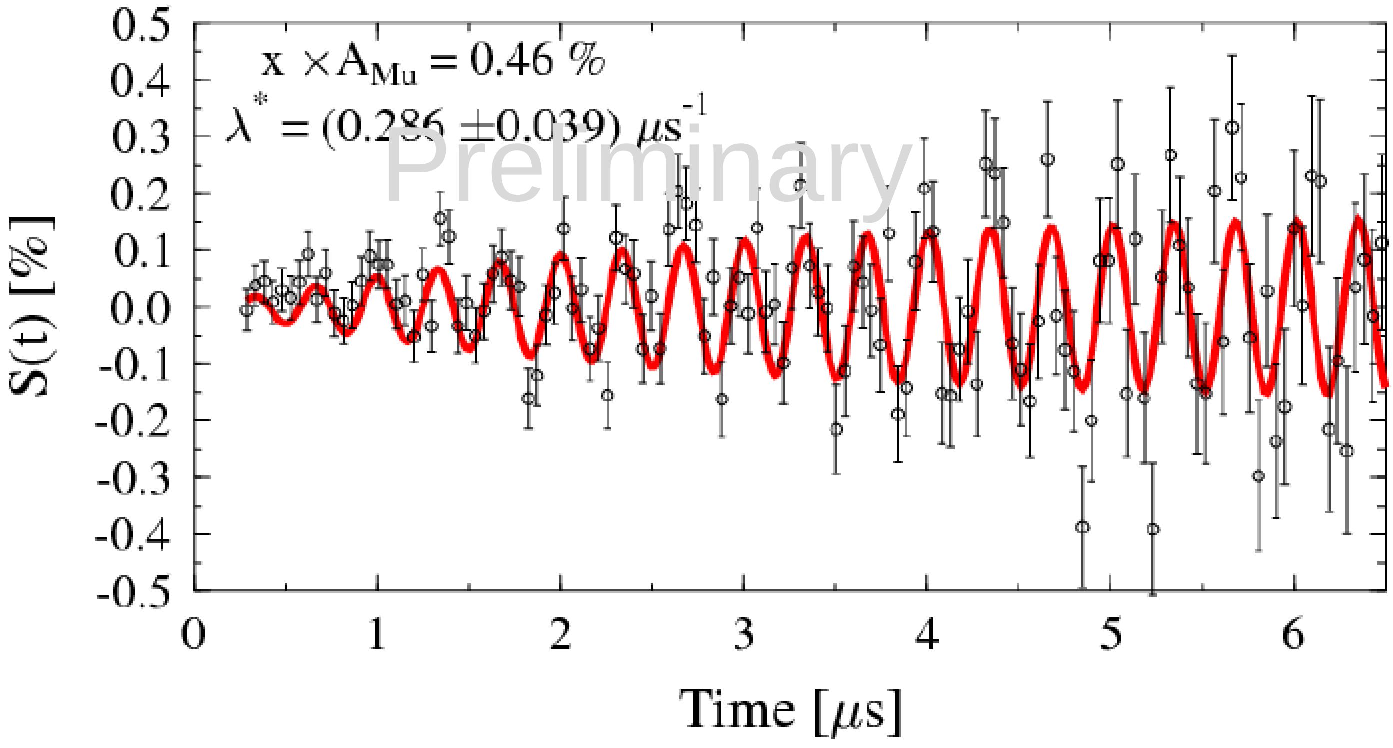
Max practical working pressure 50 bar H_2



Laser for Chemistry: Result (Preliminary)

A large laser ON-OFF effect was observed – first result

Mu polarization lost by Mu+H2*



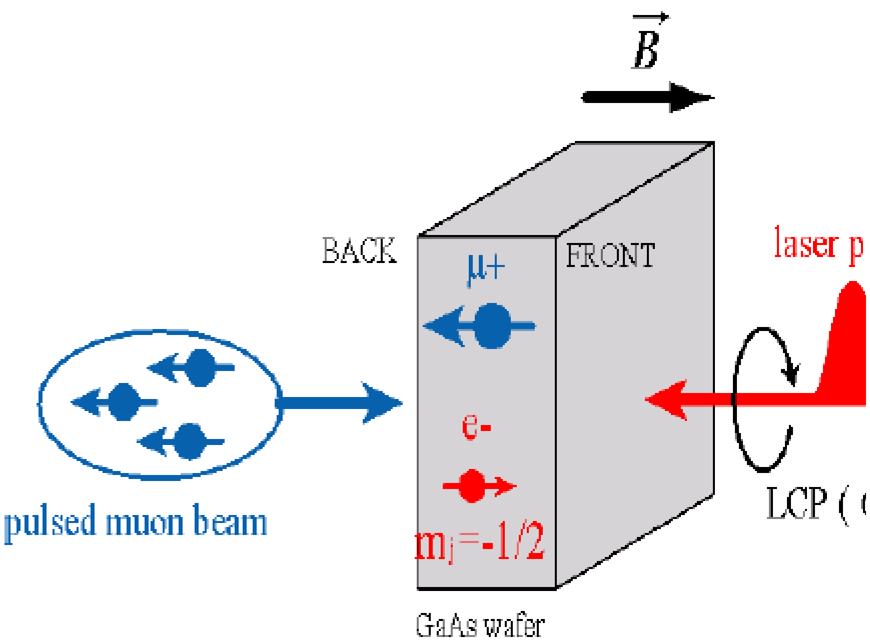
Muon for Spintronics: Muon probing electron spin

Polarization photon is easily obtained

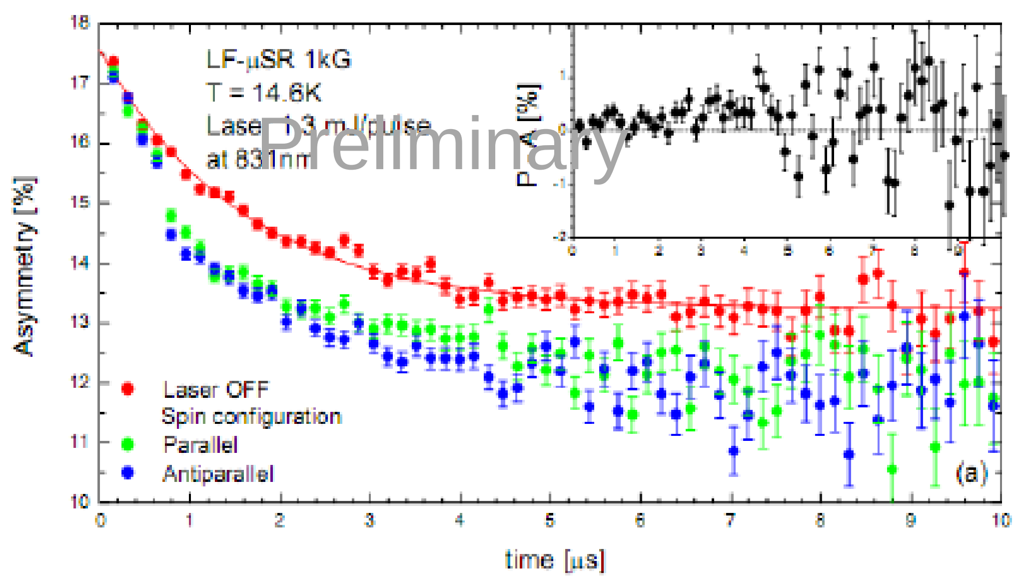
It can be used for polarization phenomena:

good match for polarized muon also

Monitor of polarized conduction electron is one example.



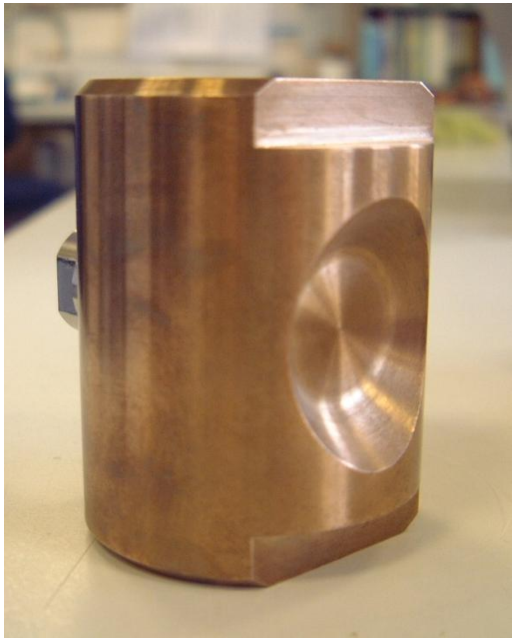
Large laser ON/OFF,
and left/right polarization effect



Application of laser is not limite

High pressure MuSR

Gas Pressure



6.4 kbar, 1.5 K

Hydrostatic Pressure

10 kbar, 30 mK

120 MeV/c muon can penetrate 2 cm of copper walls

What High Pressure can do?

For example

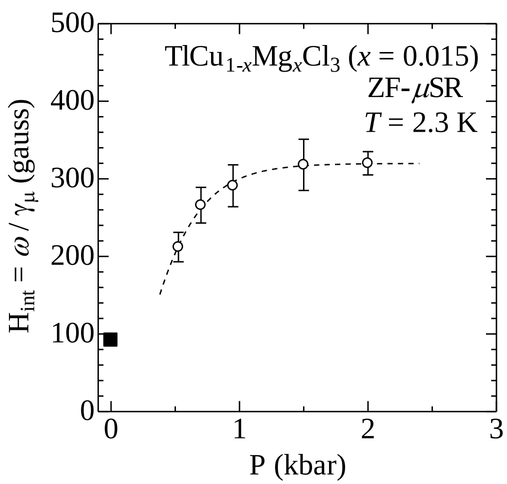
pressure decrease the lattice constant

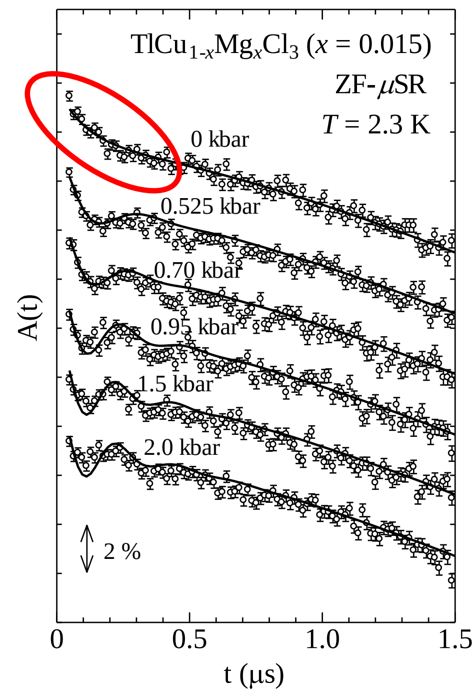
-> Magnetic interaction between spins can be increased

Shift of frequency, new magnetic phase, …

$$\omega = \gamma_\mu H_{\rm int}$$

$(DMe\text{-}DCNQI)_2Cu$





New MuSR Spectrometer (CHRONUS)

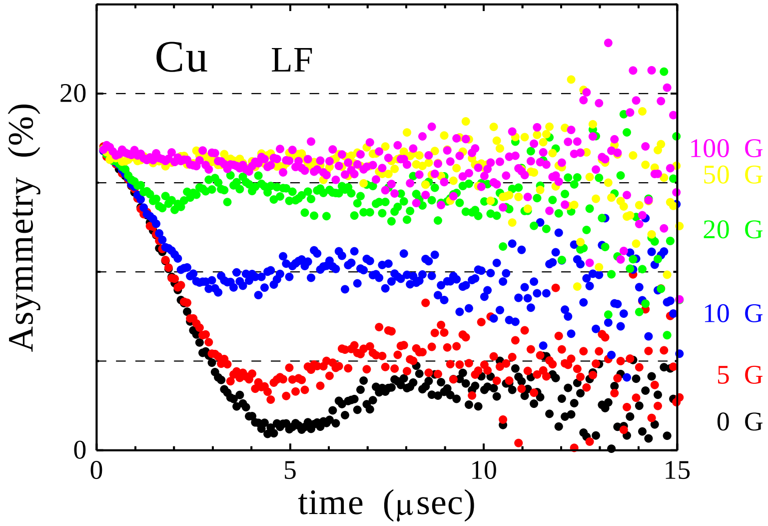
In order to meet high demands for MuSR opportunities at RIKEN-RAL

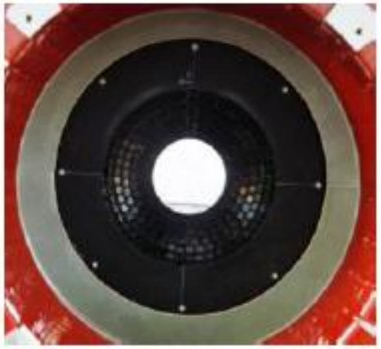
New face to MuSR Spectrometer (in RIKEN Port4)

	ARGUS	CHRONUS
Detectors	96+96	300+300
Max Field	0.4 T	0.4 T

Higher data rate

Larger sample area





Muon Physics at RIKEN-RAL

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   Laser, High pressure, …

2. Slow Muon Beam

3. Muon Catalyzed Fusion

   with negative muon

Slow muon beam (Port3)

Ultra slow muon beam by laser ionization of thermal muonium

Slow muons

The surface muon beam make experiments possible

with a thin sample (~100 μm)

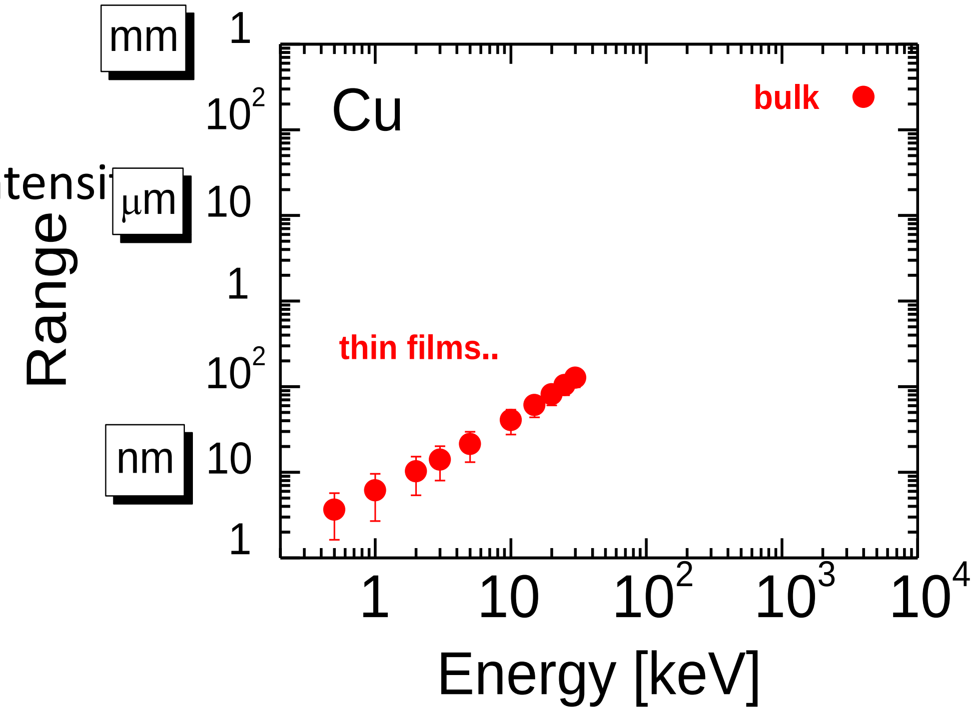
but still not enough to be used for very thin layer or interface

To make it possible, slow muon beam is developed

You will hear lots of applicationsat PSI from Dr. Salman

with simple moderation, the energy

is spread rapidly and we lose beam intensi



Producing low energy muon with laser

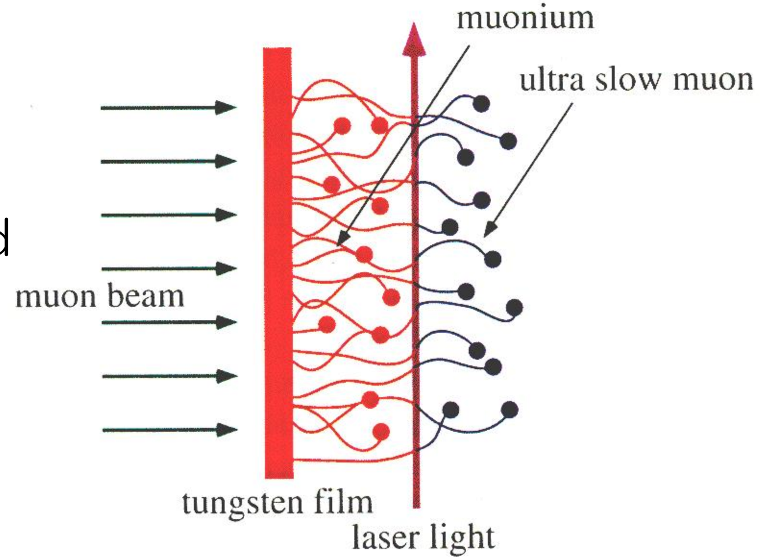
Thermal Muonium

muons stopped in hot W film

diffuse to surface and thermally emitted

(with 4 % efficiency)

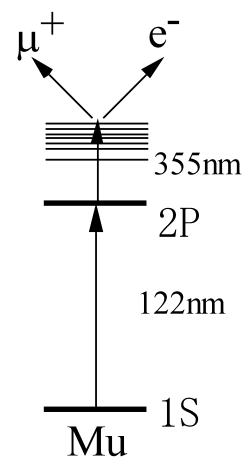
+



Laser ionization

Thermal muonium + laser ionization

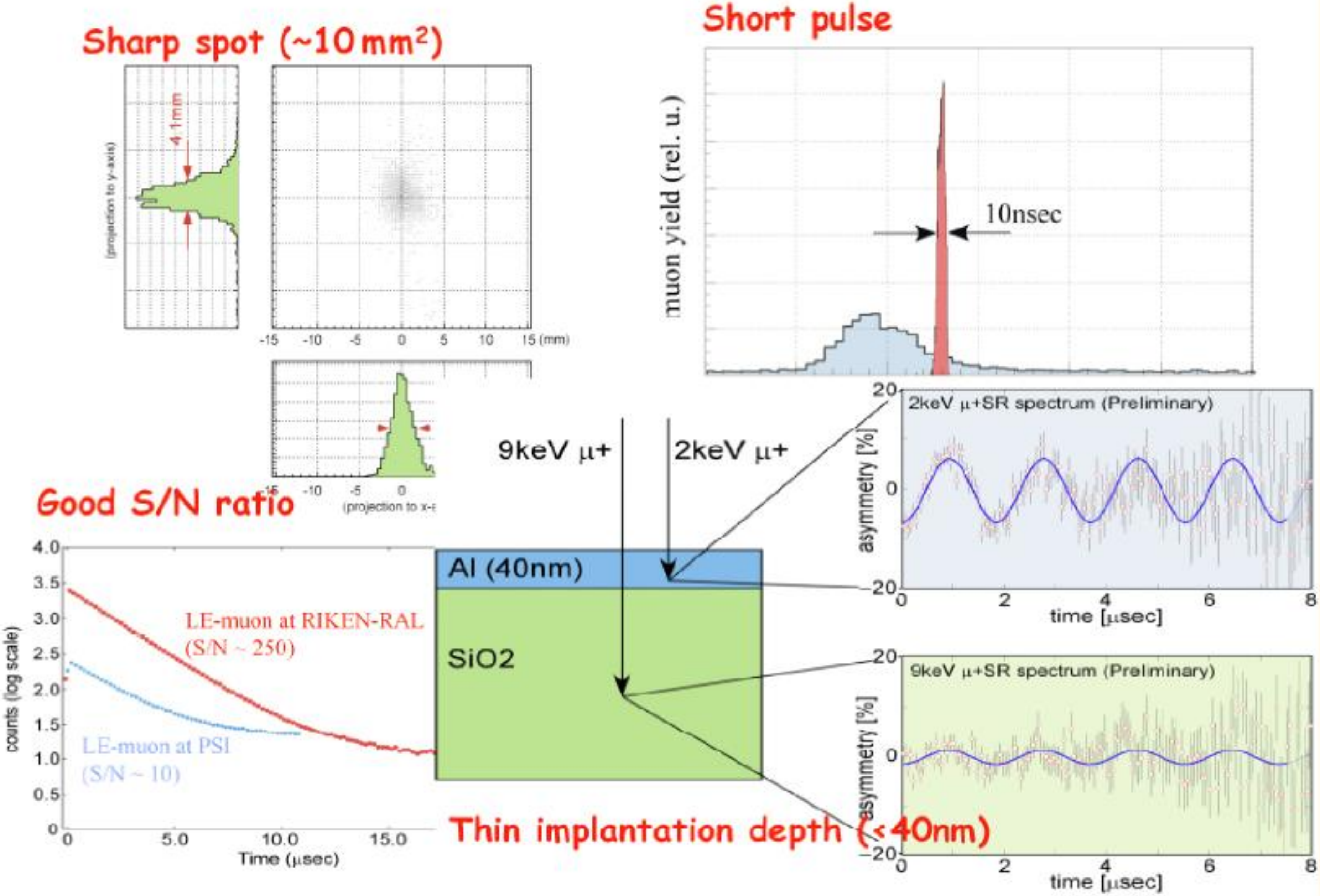
1s -> 2p(122nm) -> unbound



PSI use other methods for slow μ production

(rare gas solid moderator)

Laser ionizing Ultra-Slow muon beam



Slow μ: Comparison with the PSI method

PSI: rare gas solid moderator emits ~15eV muons
during moderation in rare-gas solid, energy loss process terminates below energy gap in solid rare-gas film
(Presentation by Dr. Salman)

RIKEN-RAL: laser ionization method has achieved similar 10^{-5} ~ 10^{-4} efficiency for the moderation

PSI produces higher intensity low energy muons,

Laser ionization method has several advantages
- smaller energy distribution (thermal)
- smaller spot size after acceleration from thermal energy
- timing capability (narrow pulsed beam controllable by laser timing)

and potentially higher efficiency
- with improvement of laser power, etc

We also aim to use slow muons for muon g-2 measurement.

Application of cold muon beam: muon g-2

Muon is one of the most elementary particles, and
its g-factor is one of the fundamental parameters.
It is also related to muon spin precession frequency.

The difference (g-2) from pure Dirac particle expectation
is by vacuum polarization
and sensitive to new particle, new physics.
Most precise measurement was achieved at BNL, NY.
Its measures precession of muon in the storage ring.

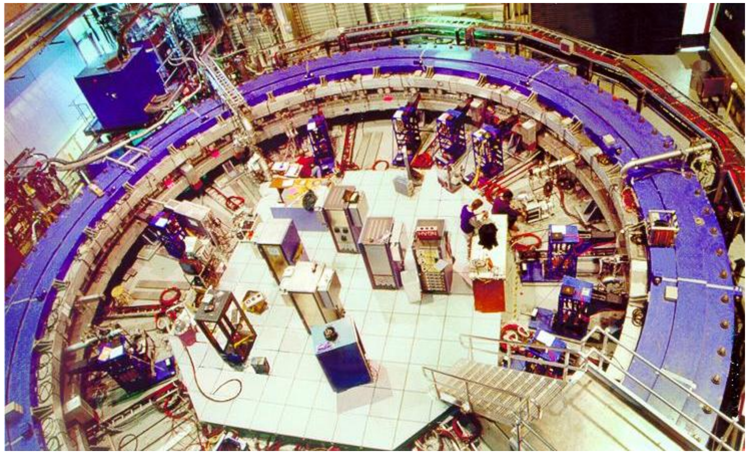
muon g-2 experiment

Acceleration of slow muon makes cold muon beam

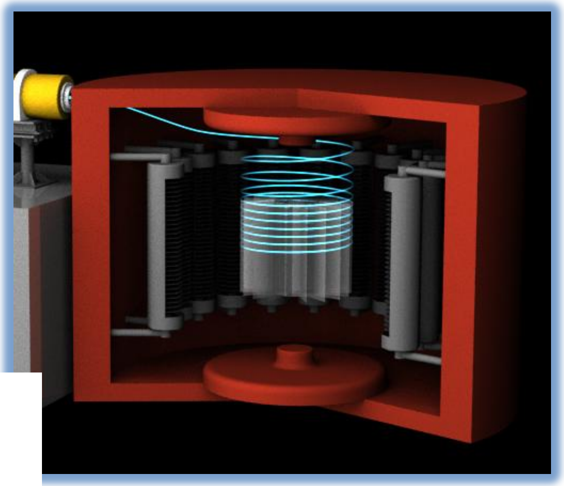
with small spread of size and momentum (even if it's at high energy)

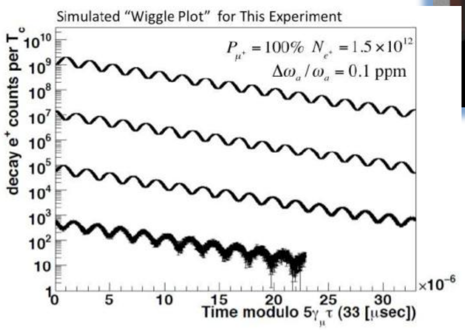
We can store the beam in compact muon storage ring to measure muon g-2 precisely.

@BNL (~14m)



@RAL->@J-PARC (~1m)





Key to increasing the slow muon intensity

Intense generation of cold muon is a key for precision measurement

several developments are in progress

Good intense surface muon source

High muonium yield in vacuum

target search & development

High intensity ionizing laser generation

and ionization process

Good slow muon beam optics

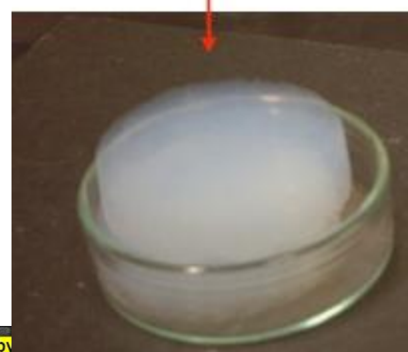
without beam heating, low background

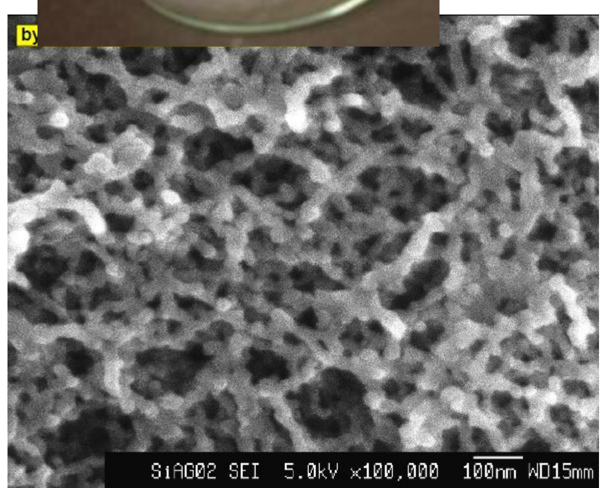
Search for Muonium emitting target

We have started search for various porous materials

Muon stop in bulk -> muon emission to void -> muon diffuse through void channels -> emission to vacuum

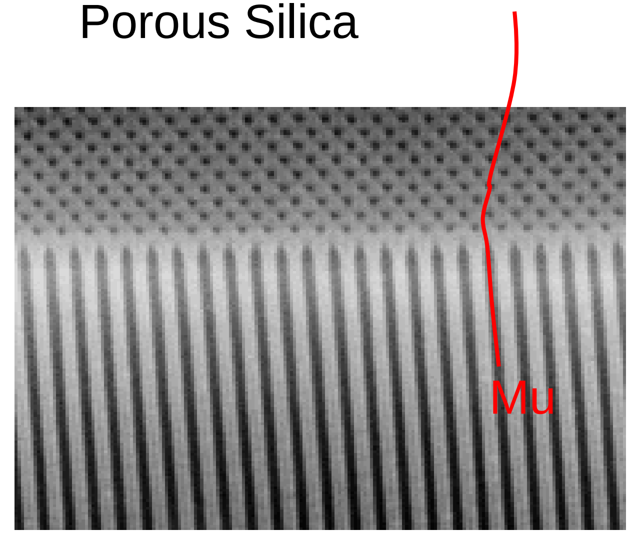
Silica Aerogel





Silica Powder

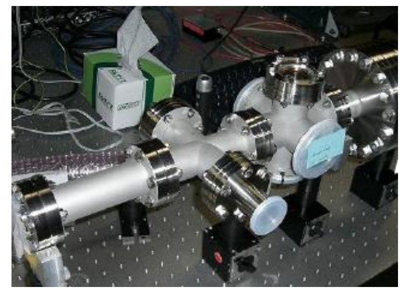
Porous Silica

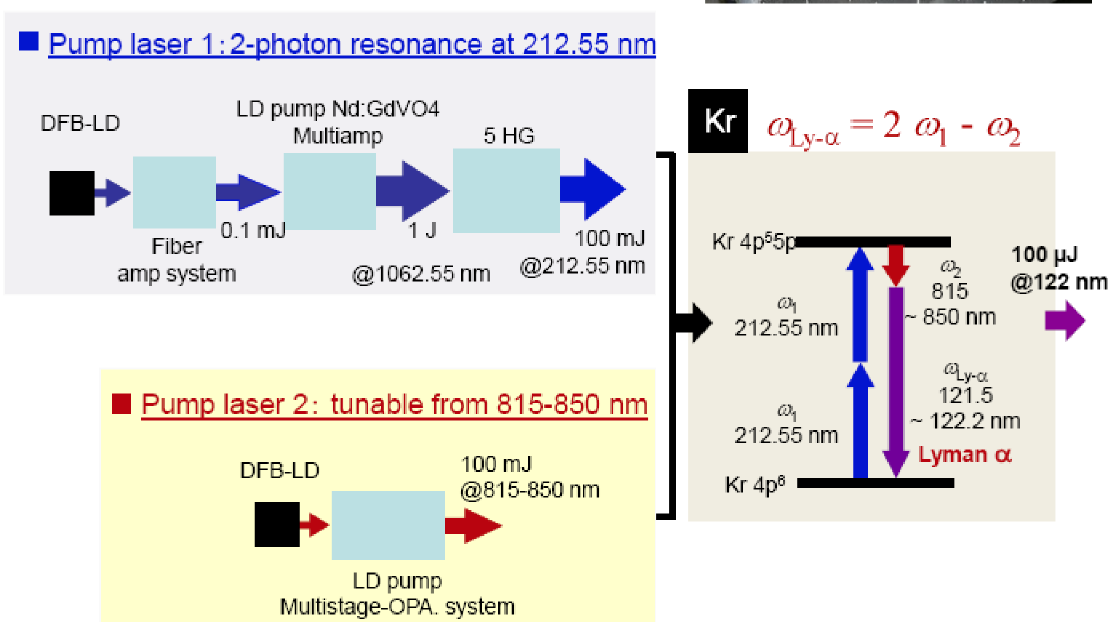


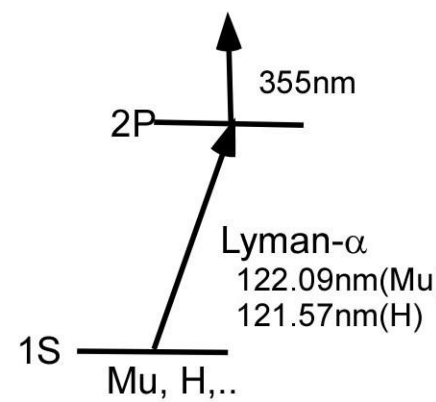
Laser Development at RIKEN

Under development by RIKEN laser group with latest laser technology

To increase laser power by two orders



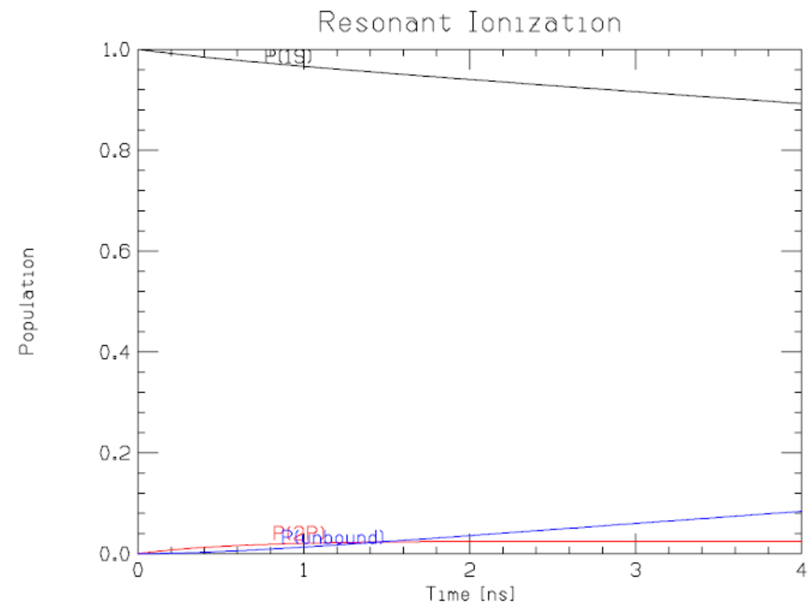




Laser intensity and Mu Ionization

Estimation of ionizing process versus

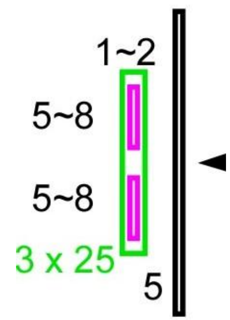
laser intensity



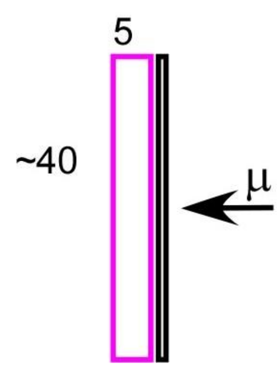
based on rate equation & transition rate

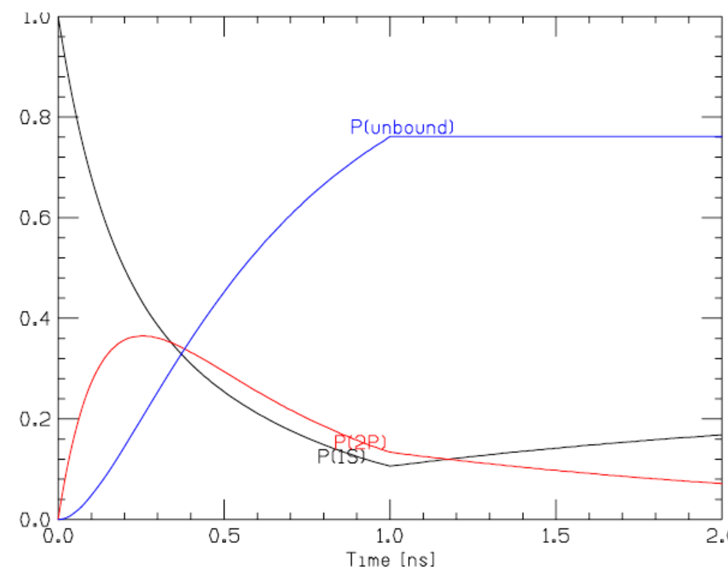
Olad laser system

Case for *I*(Lyman-α) = 1 μJ,
I(355) = 300 mJ
length=4ns
ionization 0.11 (??)



New laser system
Case for I(Lyman-α) = 100 μJ
I(355) = 300 mJ
length = 1ns
gives ionization efficiency = 0.76 after 1 ns





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1. MuSR at ARGUS

    Laser, High pressure, …

2. Slow Muon Beam

3. Muon Catalyzed Fusion

    with negative muon

μCF (Port 1)

Negative Muon

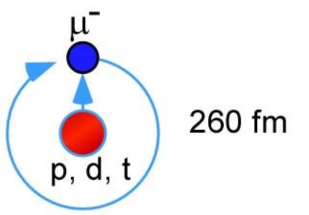
Positive muon mostly stays at interstitial site or makes chemical bonding like a hydrogen

while

Negative muon behaves as “a heavy electron” ($m_\mu = 207\ m_e$).

μ^- is attracted by the positive charge of a nucleus

and forms a muonic atom



$E_{1s}(p\mu^-) = -2.5$ keV

The muonic atom typically has 1/200 times smaller size than a normal atom, and its binding energy is 200 times larger.

An example

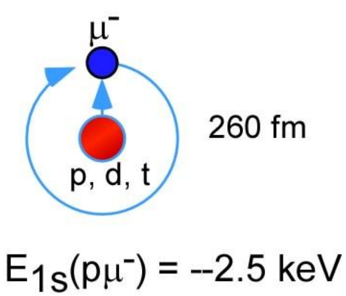
Muon Catalyzed Fusion

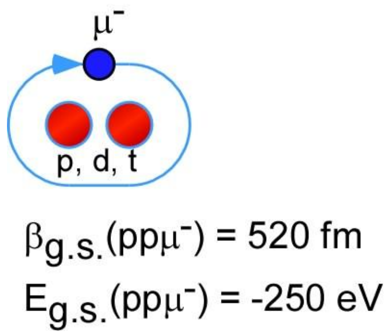
MuCF: Introduction

Muon Catalyzed Fusion

=> A negative muon can catalyzes nuclear fusions

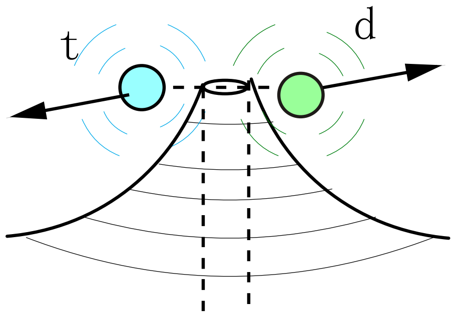
via the formation of muonic atoms and molecules



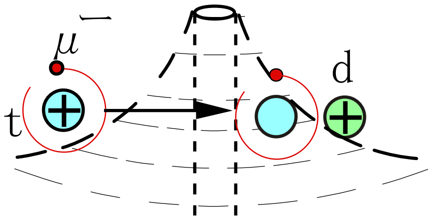


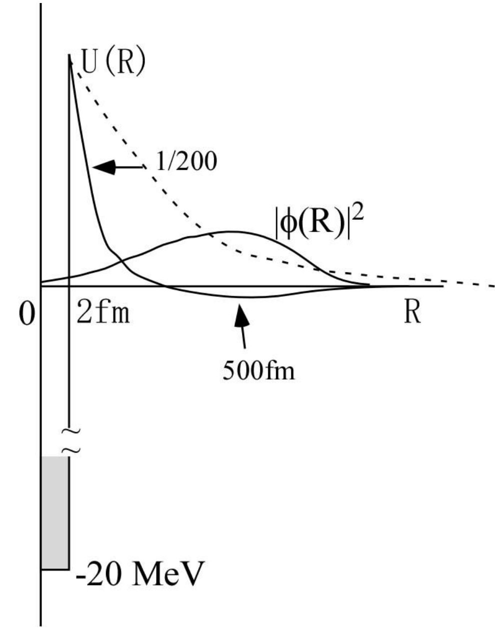
dt fusion in muonic molecule

thermo nuclear (plasma) fusion



muonic molecule





high temperature overcome the Coulomb barrier

Coulomb barrier is largely shielded by muon's negative charge
=> dt fuse in 10^{-12} s in molecule

μCF Cycle

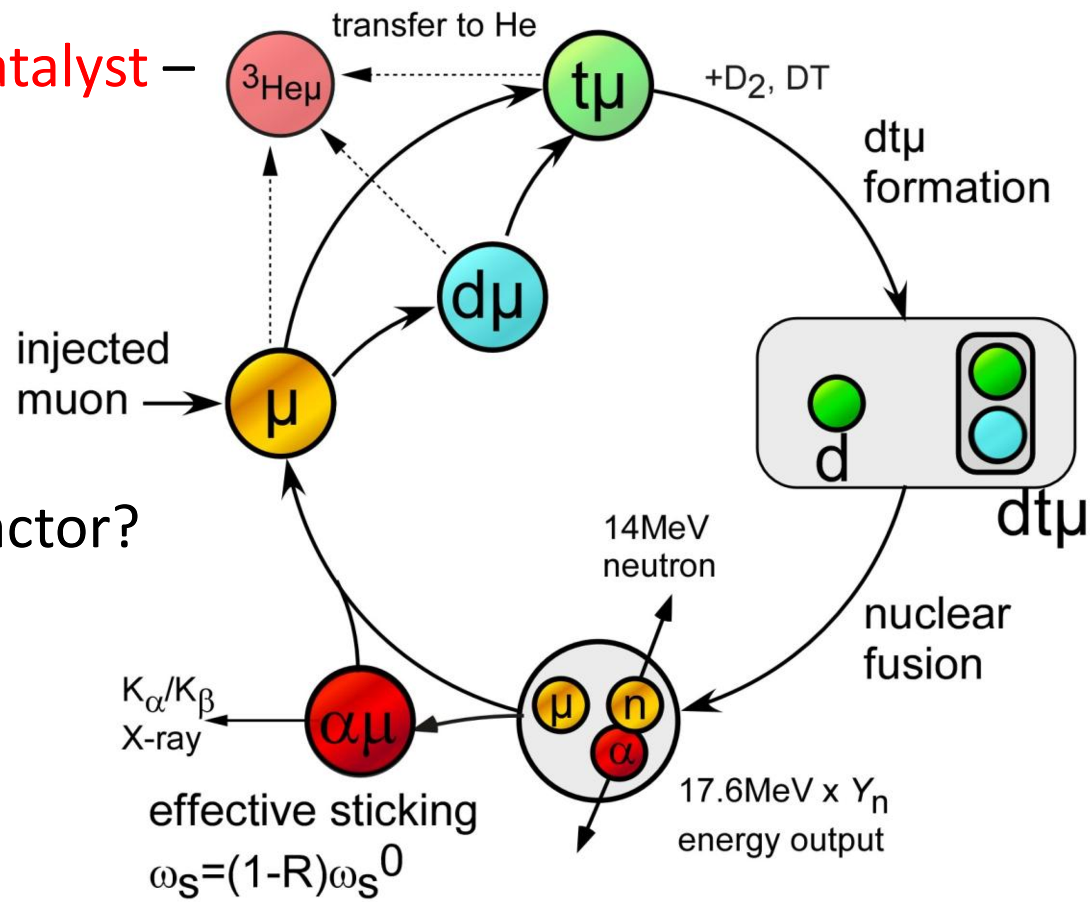
After injection of muons into D/T mixture

Formation of muonic atoms and molecules

d-t fusion in small dtμ molecule

muon released after d-t fusion

- muon works as catalyst –



Why not make a MuCF reactor?

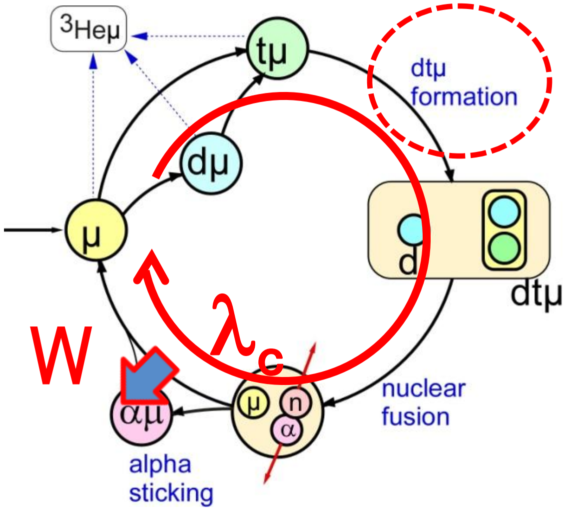
Maximizing μCF efficiency

Fusion Energy

~120 fusions per muon (2 GeV)

/ muon production cost ~5 GeV

= ~40% the scientific break-even



Increasing the efficiency is the key

(1) Cycling rate λ_c (↑) (vs λ_0: muon life)

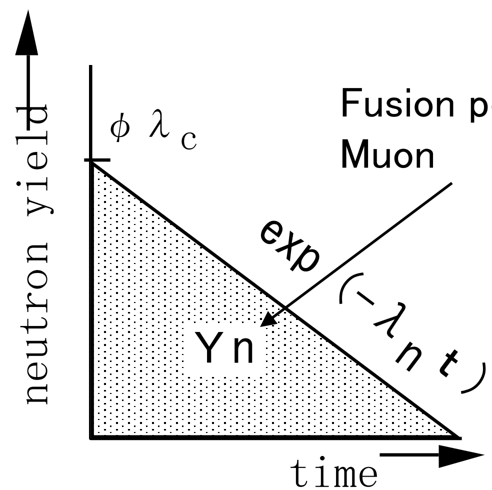
dtμ formation : tμ + D_2 →[(dtμ)dee]

(2) Muon loss per cycle W (↓)

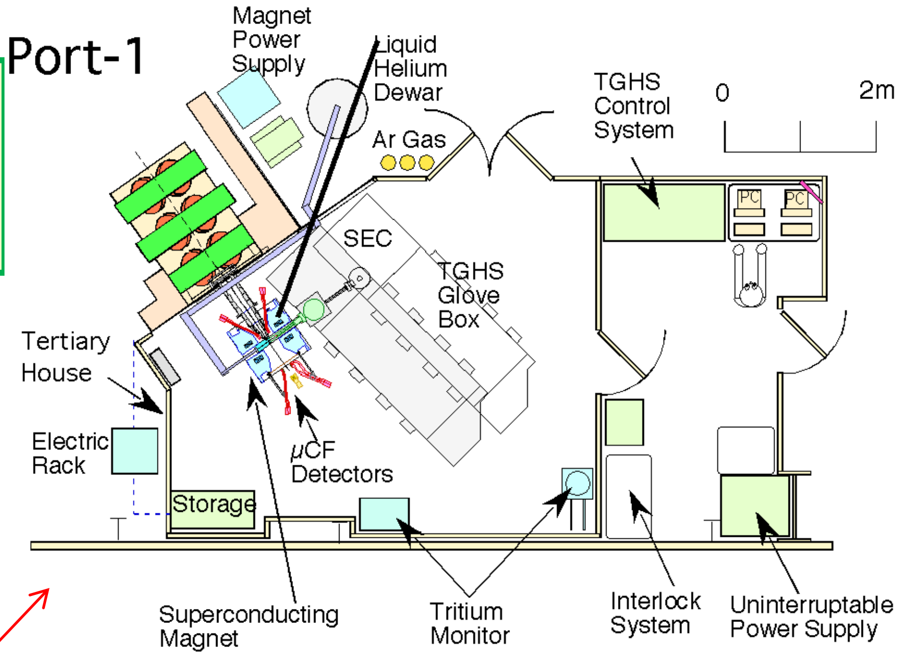
muon sticking to α-particle, etc

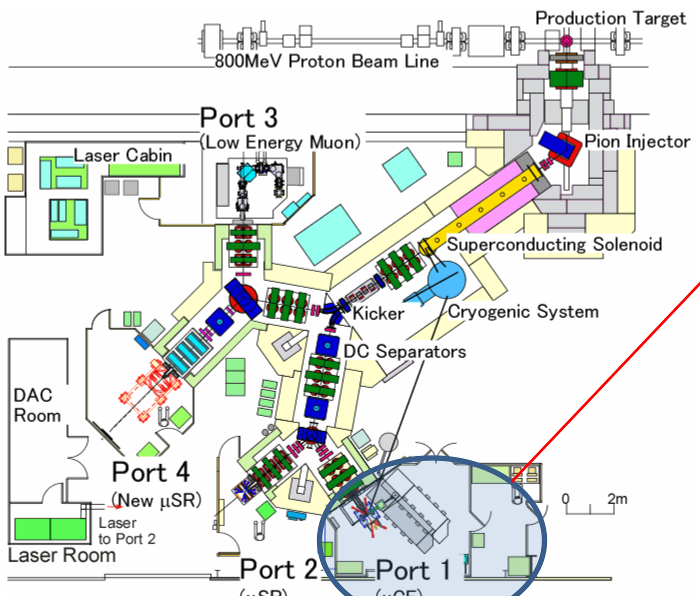
Number of fusion per muon:

$Y_n = \phi\lambda_c/\lambda_n = 1 / [(\lambda_0/\phi\lambda_c)+W]$ (↑)



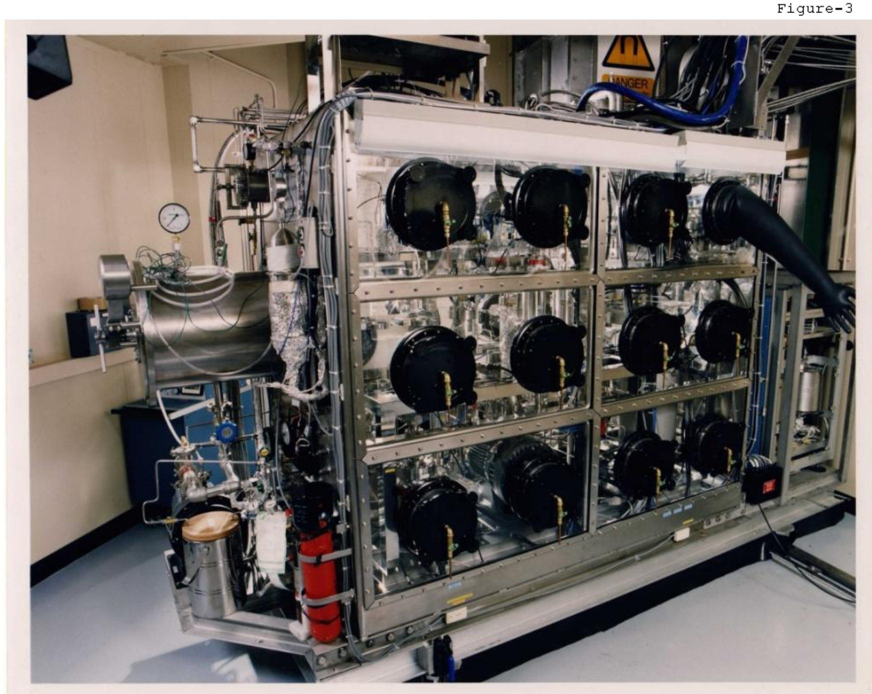
Dedicated μCF facility with safe tritium handling





The RIKEN-RAL Muon Facility

Figure-3



MuCF target and detectors

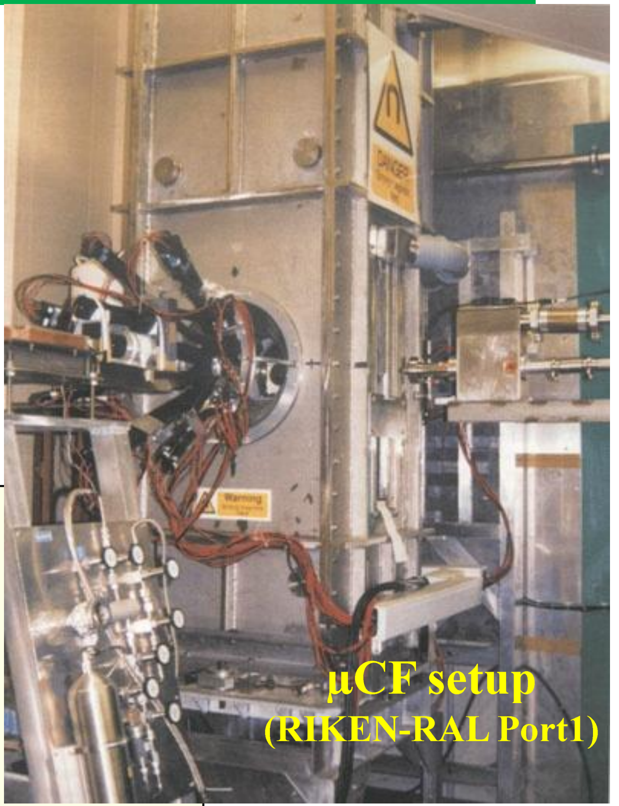
2.4T magnets for strong focusing of muon beam

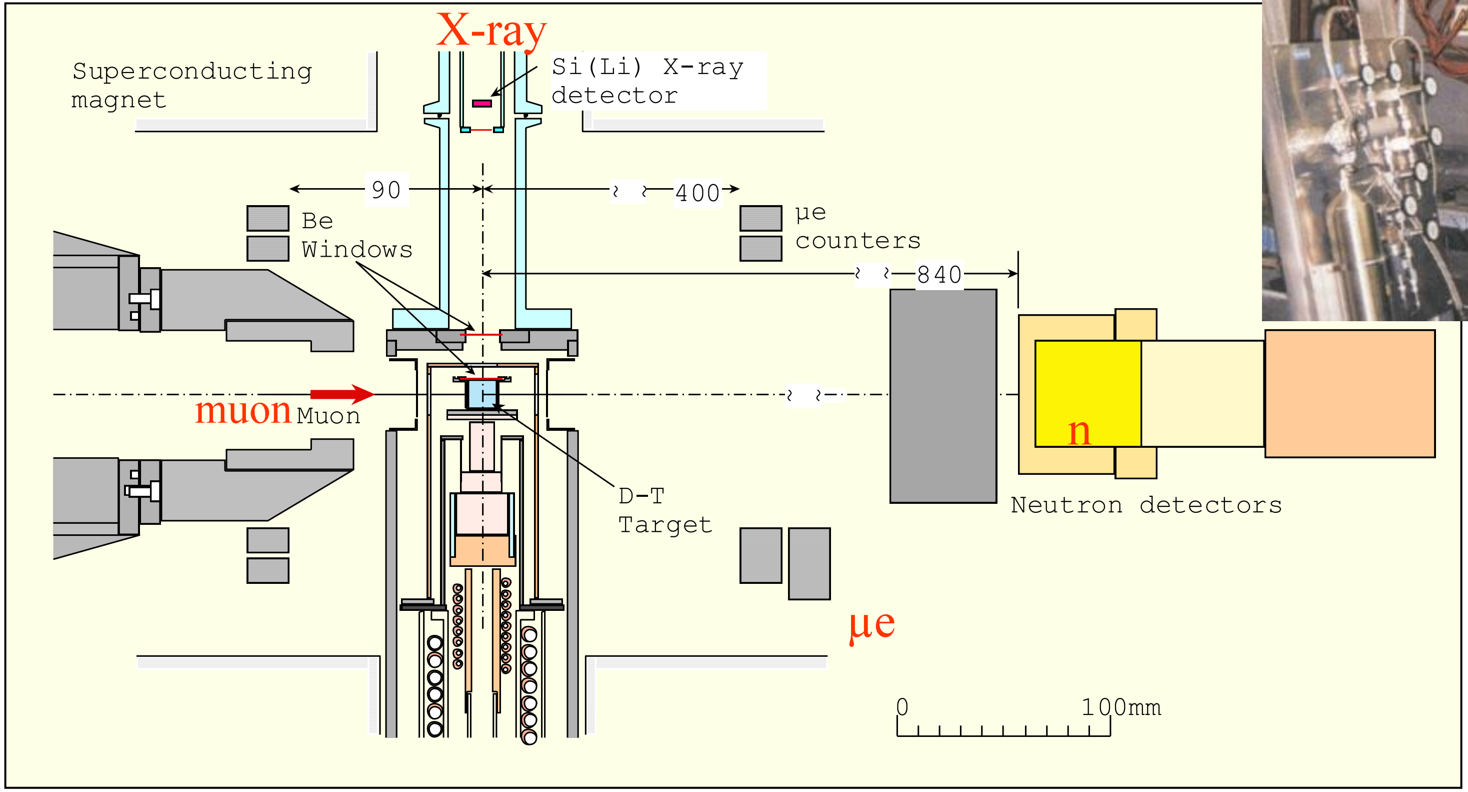
in 1 c.c liquid D/T target

NE213 neutron detector

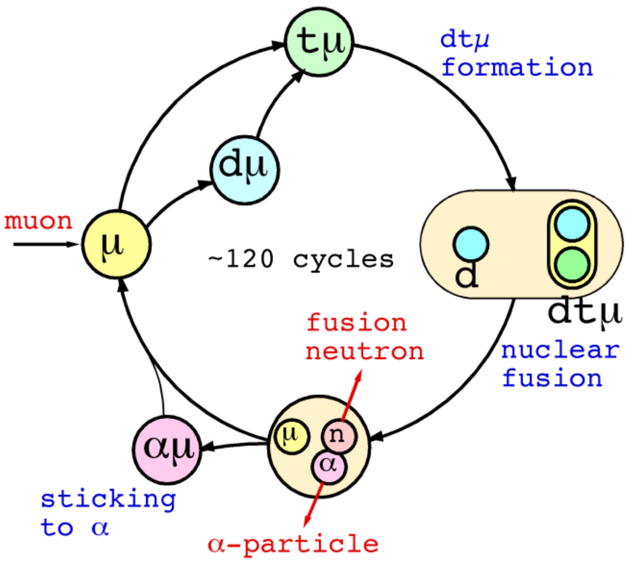
Si(Li) X-ray detector（muonic atom X-ray）

μe decay detector

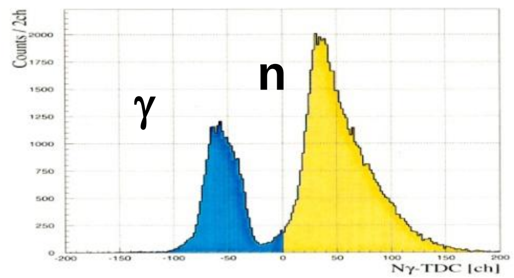




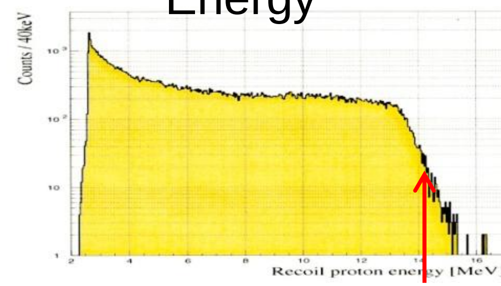
Muon Catalyzed d-t Fusion

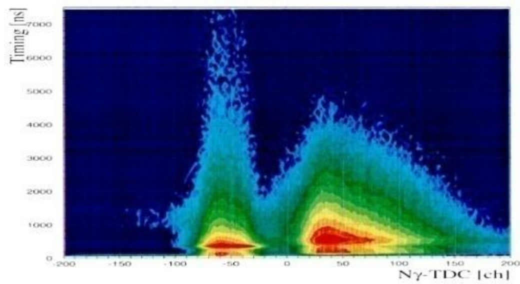


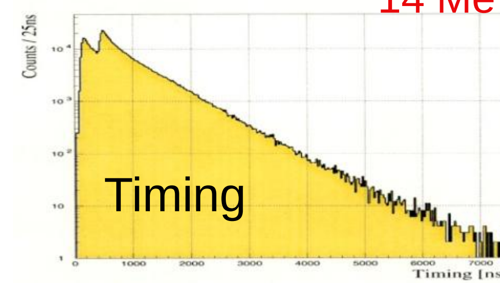
Fusion neutron spectrum

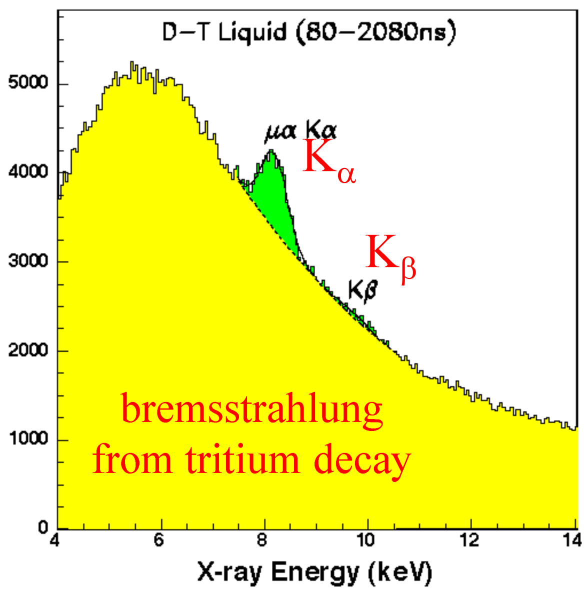


Energy









n-γ spectrum

MuCF topics at RIKEN-RAL

muCF in D/T targets with controlled molecular states

- to better understand the basic process
- to achieve higher rate

muCF in high density/high temperature target

- muCF under unexplored condition,
- large increase is expected

Many other issues on basic processes

- Muon transfer between isotopes (d, t)
- Muon transfer to helium
- muCF of other isotopes

Summary

RIKEN-RAL Muon Facility
has been operating since 1994
It can deliver both backward decay μ^+/ μ^- and surface μ^+ beam.

Scientific research
1. For μSR, RIKEN-RAL has optional features such as
   Use of laser
   Use of high pressure
   and good spectrometers (ARGUS, CHRONUS)

2. RIKEN-RAL has also unique program using muons.
   slow muon beam development (for MuSR, muon g-2)
   muon catalyzed fusion

about RIKEN

RIKEN (RIkagaku KENkyujo, The Institute of Physical and Chemical Research)

is one of the largest basic research institute in Japan

covering physics, chemistry as well as biology with ~3,000 staffs.

RIKEN was established in 1917.

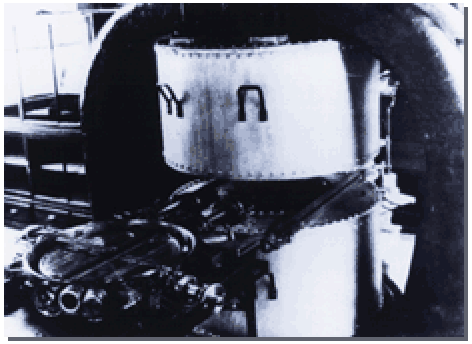
The second cyclotron in the world was built there in 1937.

The world largest SC cyclotron (8300 ton) has started operation in Dec 2006.

It provides heavy ion (450 MeV/u) and RI beam for nuclear physics research.

RIKEN-RAL Muon Facility was funded, constructed and maintained by RIKEN.

1937
(World's second cyclotron)



第１号サイクロトロン（1937年完成）

2006
(Largest cyclotron in the world)