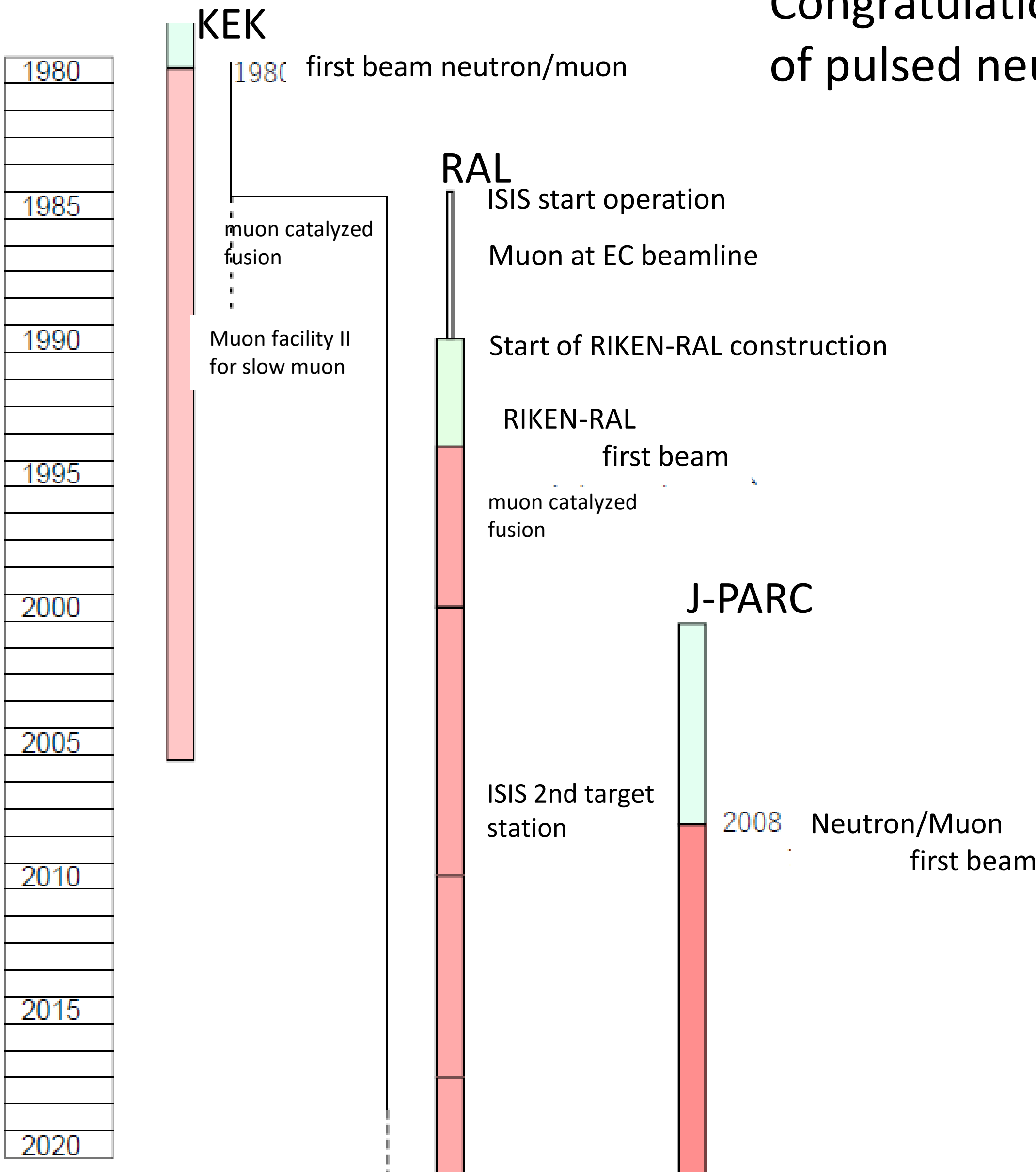
40th Year Anniversary of Pulsed Neutron and Muon Generation, Online Symposium, 23 Dec 2020

RIKEN-RAL and J-PARC

K. Ishida
RIKEN

40 Years of pulsed neutron and muon

Congratulations to 40th year anniversary of pulsed neutron and muon generation

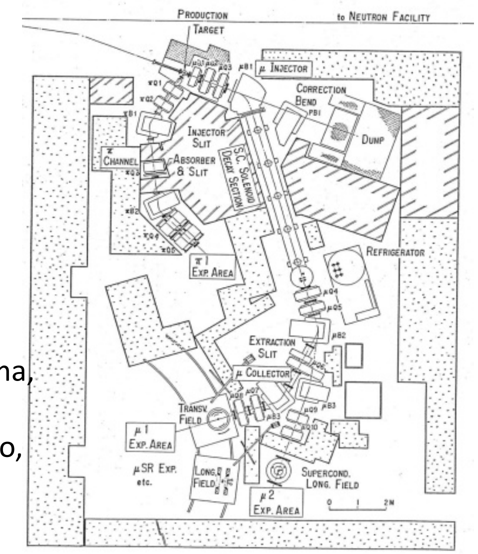


coincides my research life
1980 1st year as graduate student
1985 RIKEN

Meson Science Laboratory at KEK

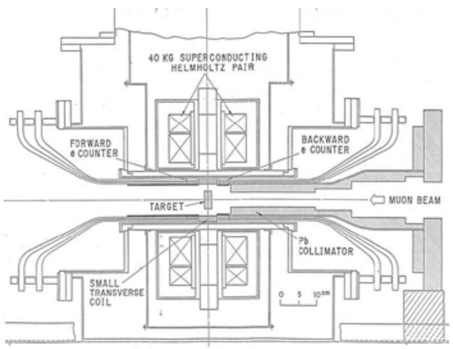
"World's first" pulsed muon beam

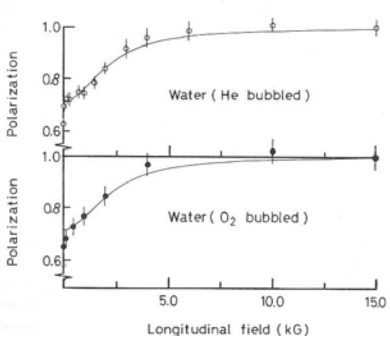
Research model: Own developments + Collaborative works



Thanks to
Mentors and Staffs : T. Yamazaki, K. Nagamine. H. Nakayama,
J. Imazato, K. Nishiyama, R. Hayano, T. Matsuzaki, ...
and colleagues: Y. Kuno, Y. Miyake, Y. Morozumi, R. Kadono,
K. Kubo, T. Azuma, ...

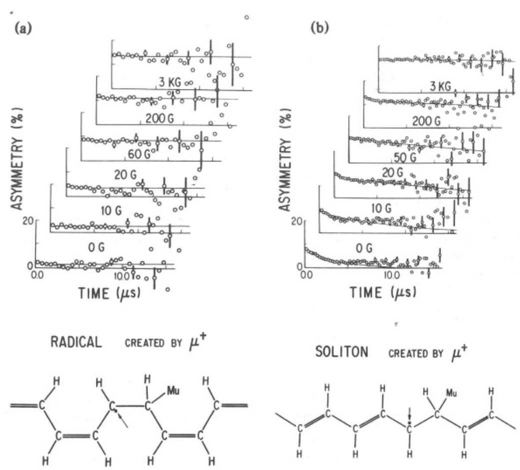
High field μSR

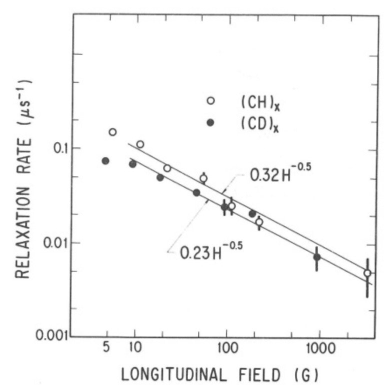


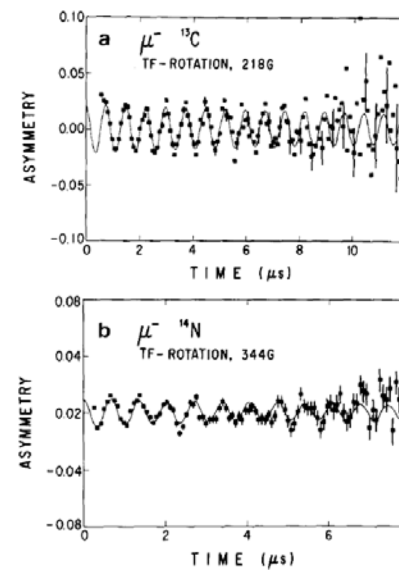


Negative muon spin rotation

Spin diffusion in polyacetylene



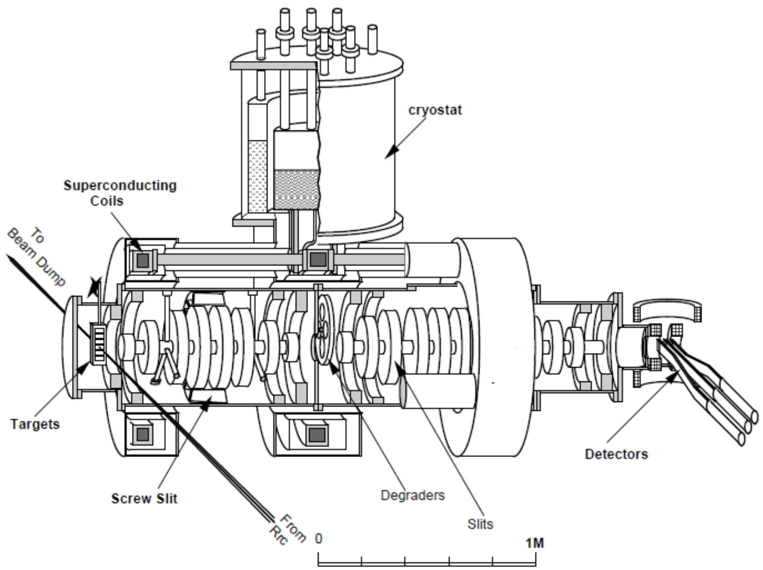




Muon at RIKEN

Nuclear research with Cyclotron (initiated by Y. Nishina)
- 1937 first cyclotron（2nd in the world）
- muon in cosmic ray 1937~1938

Pion and muon generation at Ring Cyclotron (1986~)
- ^{14}N, ^{40}Ar beam + target nuclei
- Large solid angle muon collection with axisymmetric magnetic field



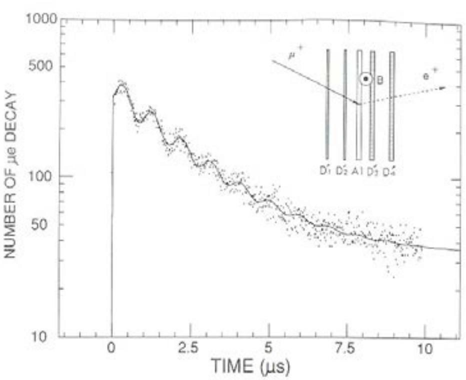


Fig. 8. The measured time spectrum of decay e^+ (μ_{decay}) relative to muon stop (μ_{stop}) in an aluminum sample. The precession signal of the muon spin in an applied transverse field is seen to be convoluted. Inserted figure shows the counter arrangement.

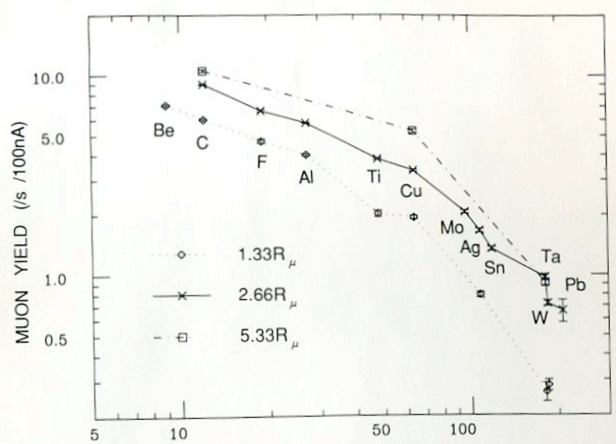
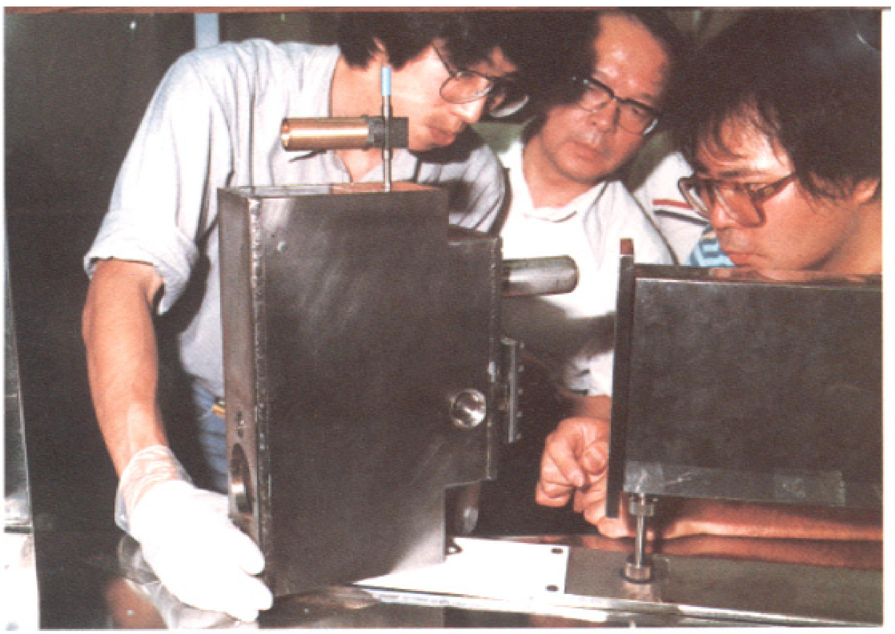


Fig. 9. Yields of surface μ^+ as a function of the target mass number for three target thicknesses, where R_μ is the range of the 4.1 MeV μ^+

Muon catalyzed fusion at muon facility in KEK

K. Nagamine, T. Matsuzaki, K. Ishida, Y. Watanabe,
K. Nishiyama, Y. Miyake, S. Jones,
H. Kudo, M. Tanase, M. Kato, ...

1986, 1988



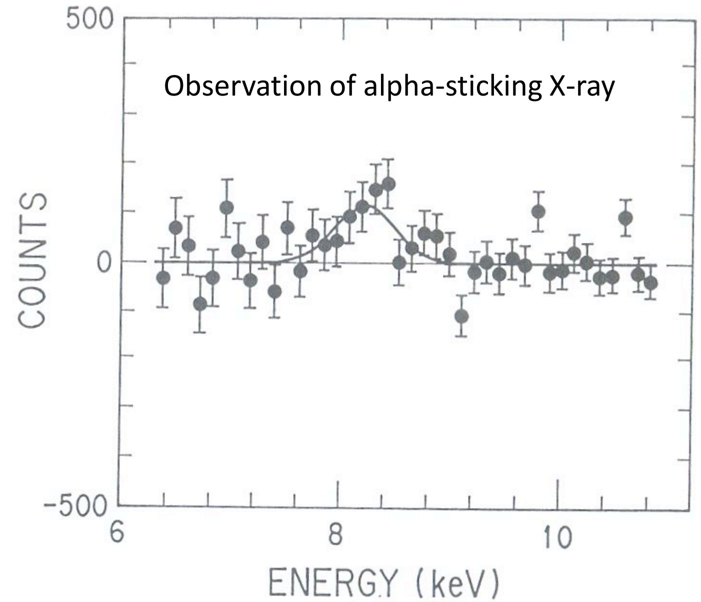


Fig. 2. Sum of the observed delayed X-ray spectra in the time range 0.24–1.84 μs for the earliest one-third of the data. The data were obtained after removal of bremsstrahlung and beam associated backgrounds.

Confirmation of effectiveness of pulsed muon while :

Need of high rate data accumulation to compete hindrance by ^{3}He buildup from tritium-decay

Beginning of RIKEN-RAL

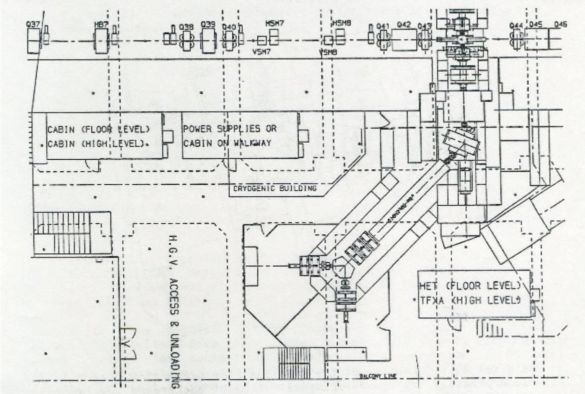


Figure 25. Layout of a conventional decay channel on the north side, including 2 experimental areas, cryogenic building and 2 barracks.

Neutron and Mon Facility, ISIS, in UK (Start operation 1985)

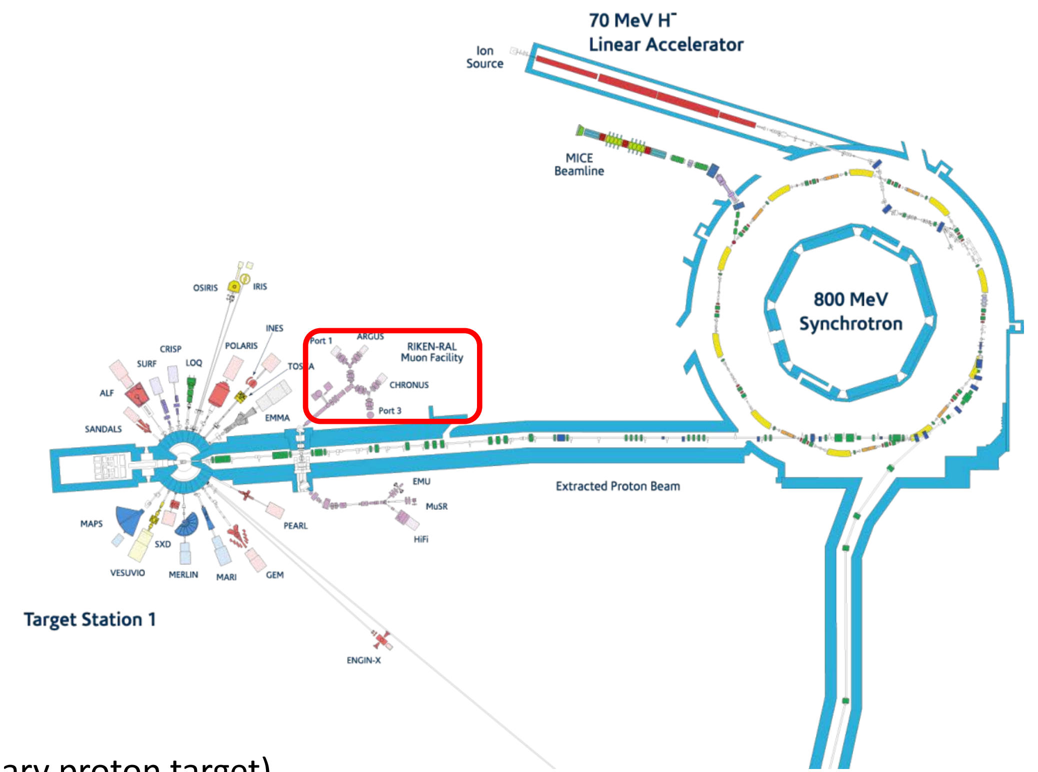
Muon area had been reserved on both sides of the proton beam line
（One was constructed by EC funding & started 1987)

RAL's approach to RIKEN <-> RIKEN's interest as place for muon catalyzed fusion

Attracted high attention by cold fusion claim in 1989 (Fleishman/Pons, S.E.Jones)

supported by muon experience at KEK and RIKEN

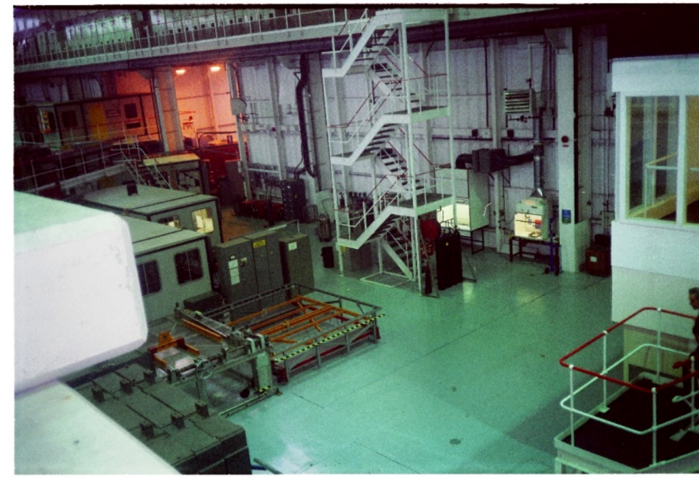
RIKEN-RAL project started in 1990

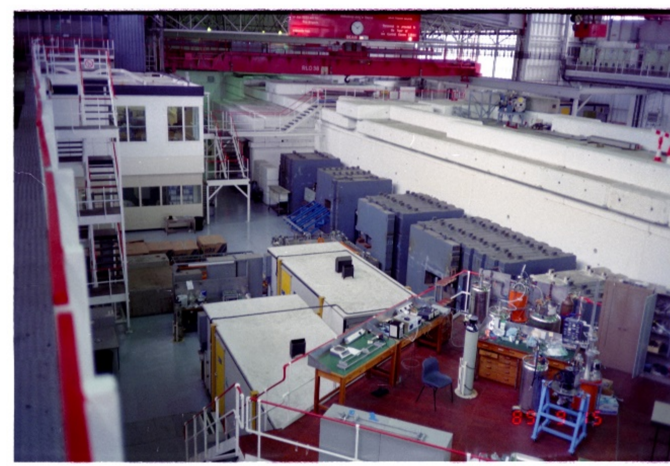


(Almost at the same time
Ultra-slow muon project started at KEK
Slow muon line directly coupled to the primary proton target)

理研RALの始動

Signing of the agreement on muon science using ISIS facility at RAL: 28 Sep 1990
RIKEN President M. Oda and SERC chairman Sir. W. Mitchel.





RIKEN-RAL area before construction

Construction of the RIKEN-RAL Muon Facility

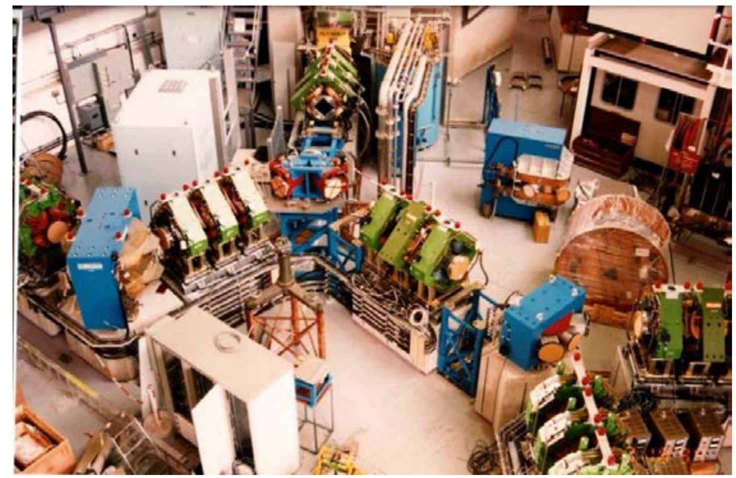
Base of the international collaboration lasting more than 30 years

First large scale international collaboration by RIKEN

MARI experience helped

Collaboration of RIKEN's research staff, administrative staff, RAL administrators and engineers

Planning discussion at project committee

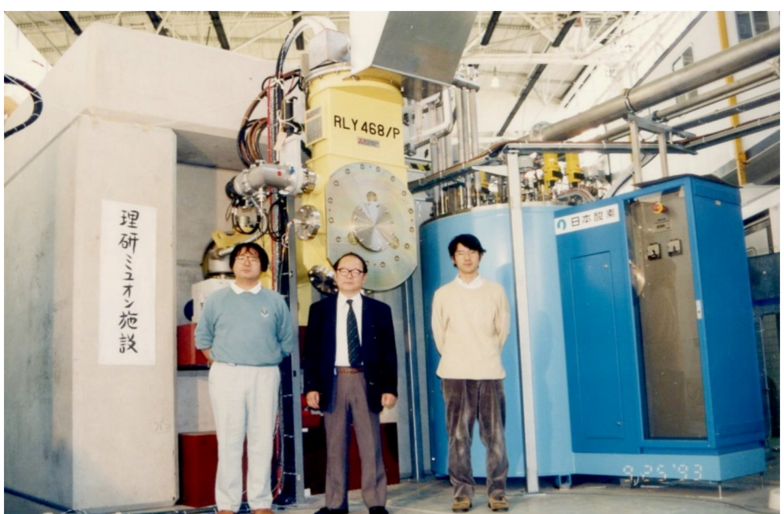


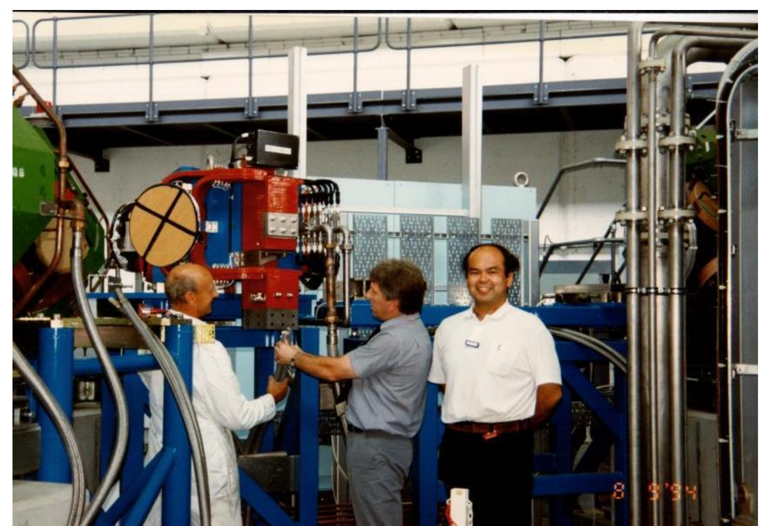
Large involvement of Japan technology

Superconducting solenoid + cryogenics

Pulsed kicker + Septum, DC separator

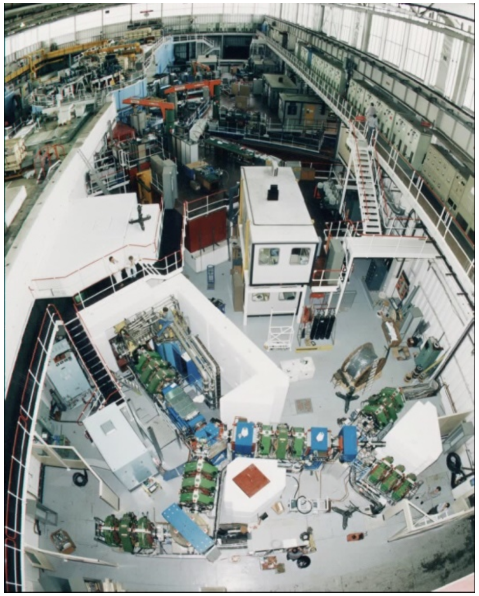
μSR spectrometer, μCF apparatus

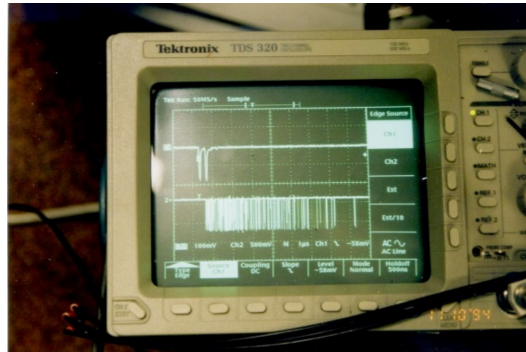




RIKEN-RAL Muon Facility: First beam and inauguration

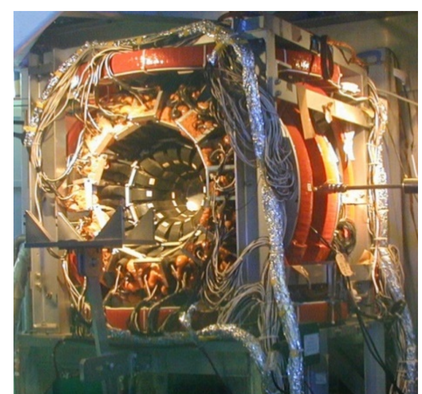
On 9 Nov 1994, muons were observed as soon as the operation started





Inauguration : 29 Apr 1995

start of experiments based on PAC system

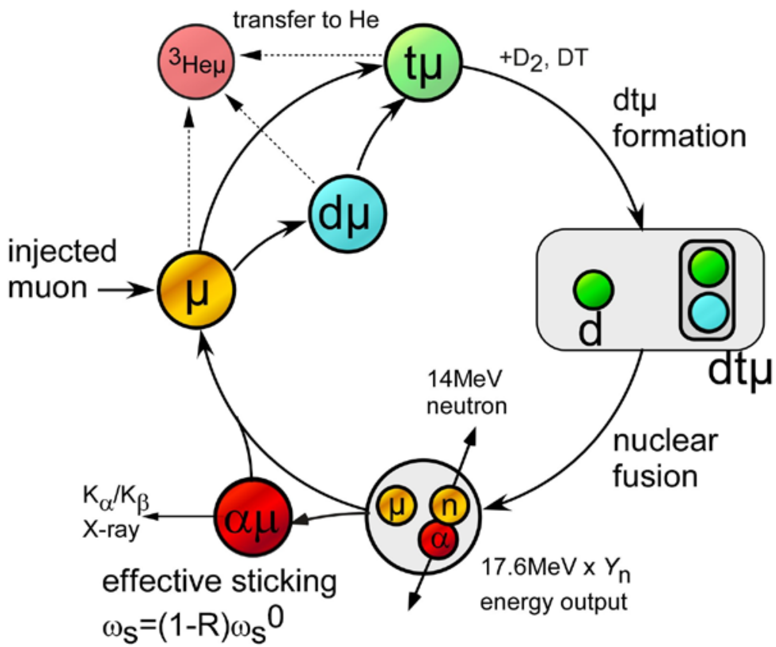


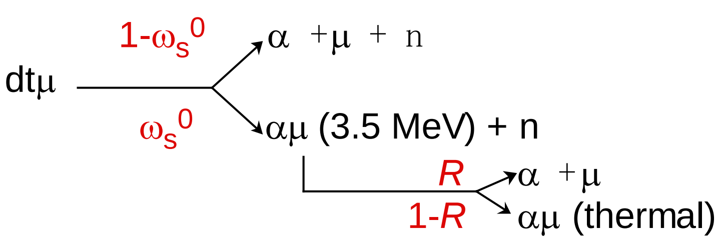
Muon catalyzed fusion and α-sticking loss

Muon to α sticking : largest loss process in μCF

Confirmation of the process and μCF limit

using muonic atom x-ray and nuclear fusion detection

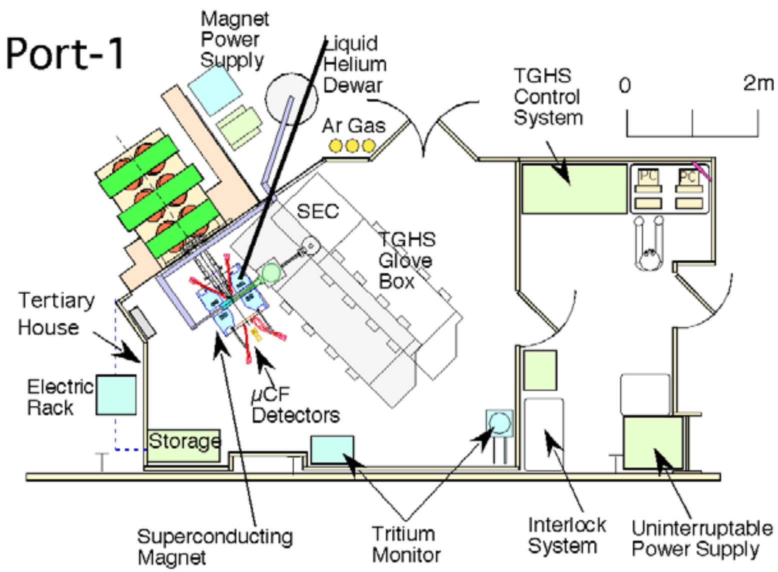


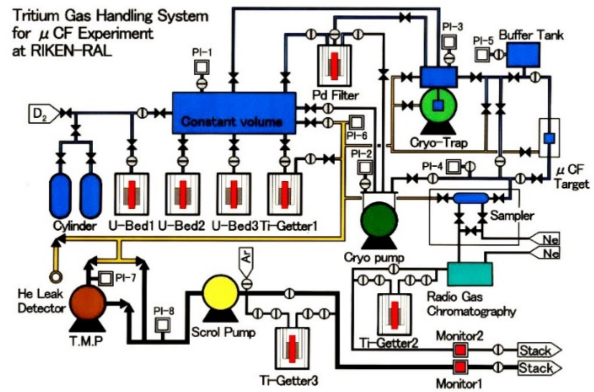


Muon catalyzed fusion : Apparatus

μCF dedicated facility based on experience at KEK:

Tritium handling system, detectors, strong beam focusing with magnetic field





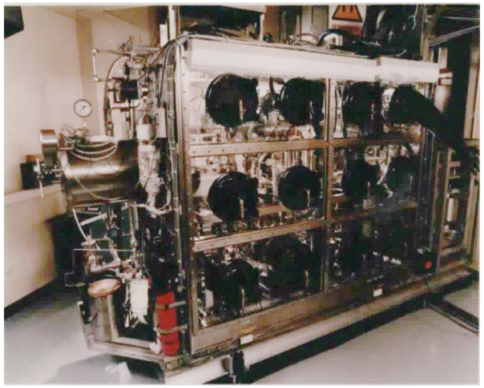
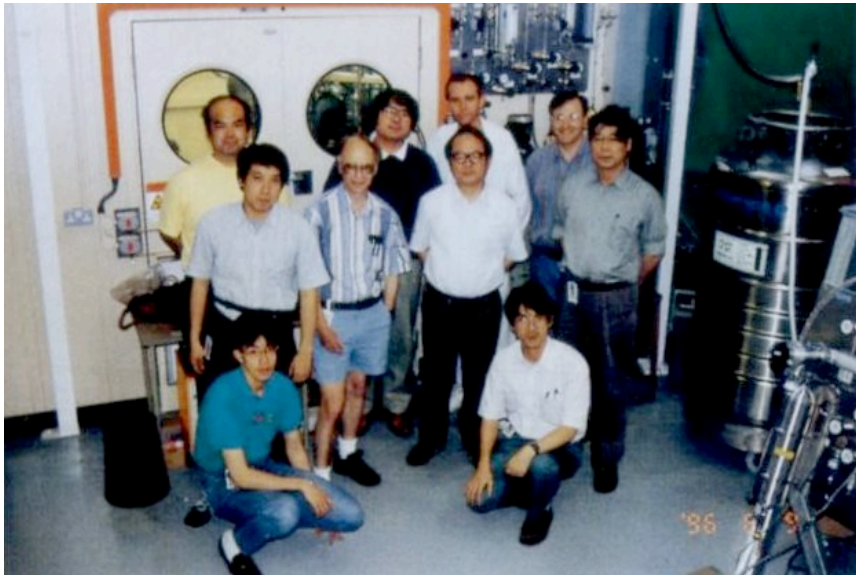
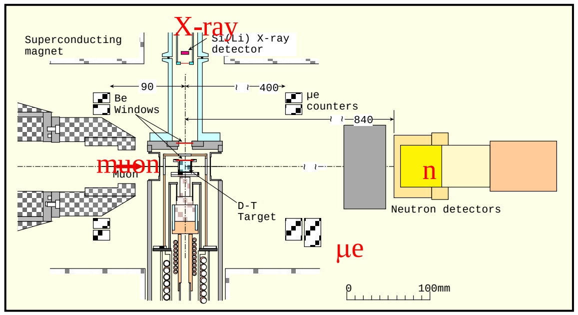
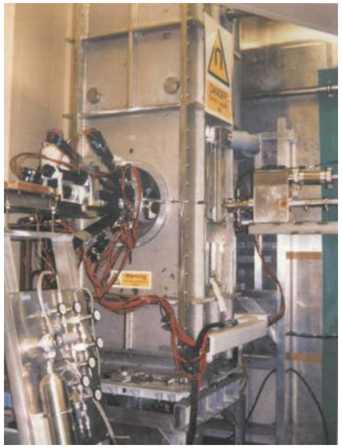


Figure-3





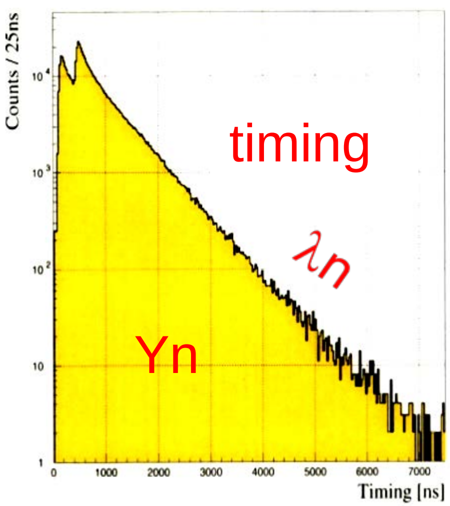


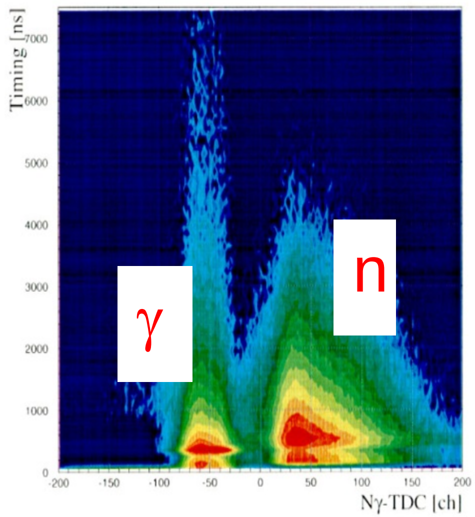
Muon catalyzed fusion measurement : benefit of intense pulsed muon beam

With the strong pulsed muon beam and the dedicated tritium facility

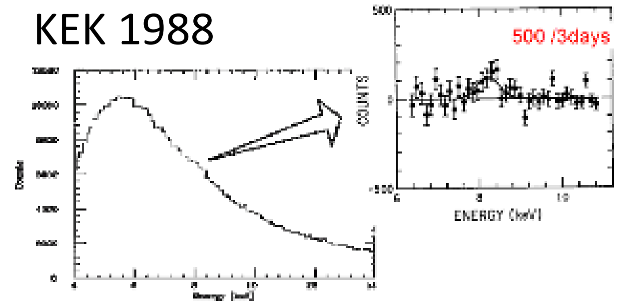
- Highly improved S/N and statistics
- Allowed measurement for various target conditions in short time

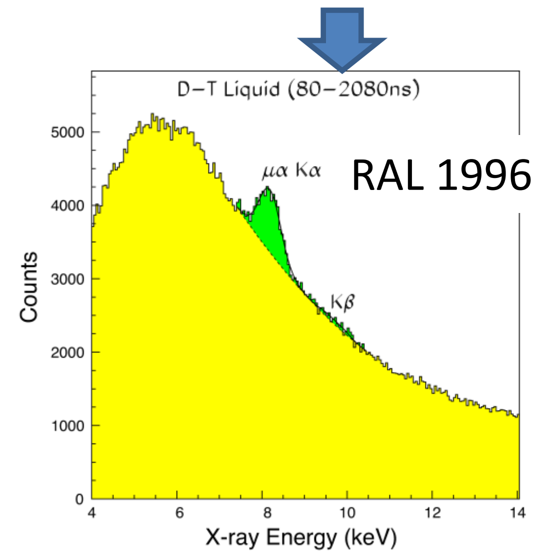
Nuclear fusion





KEK 1988





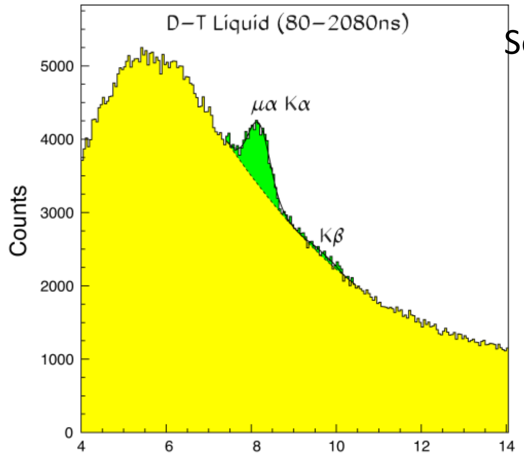
RAL 1996

α-sticking x-ray

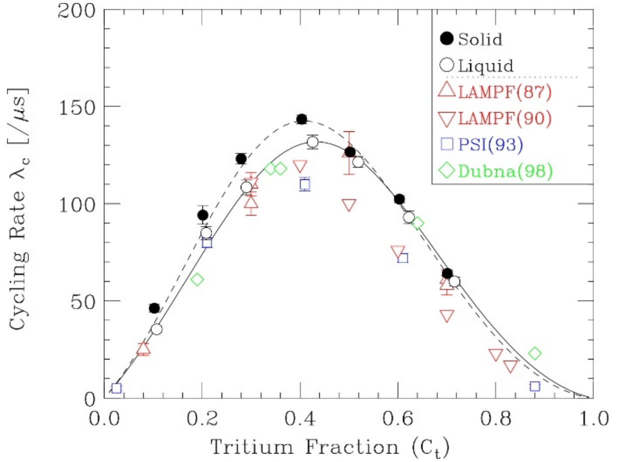
Y(Kβ) /Y(Kα)=0.06<< theory(0.12),

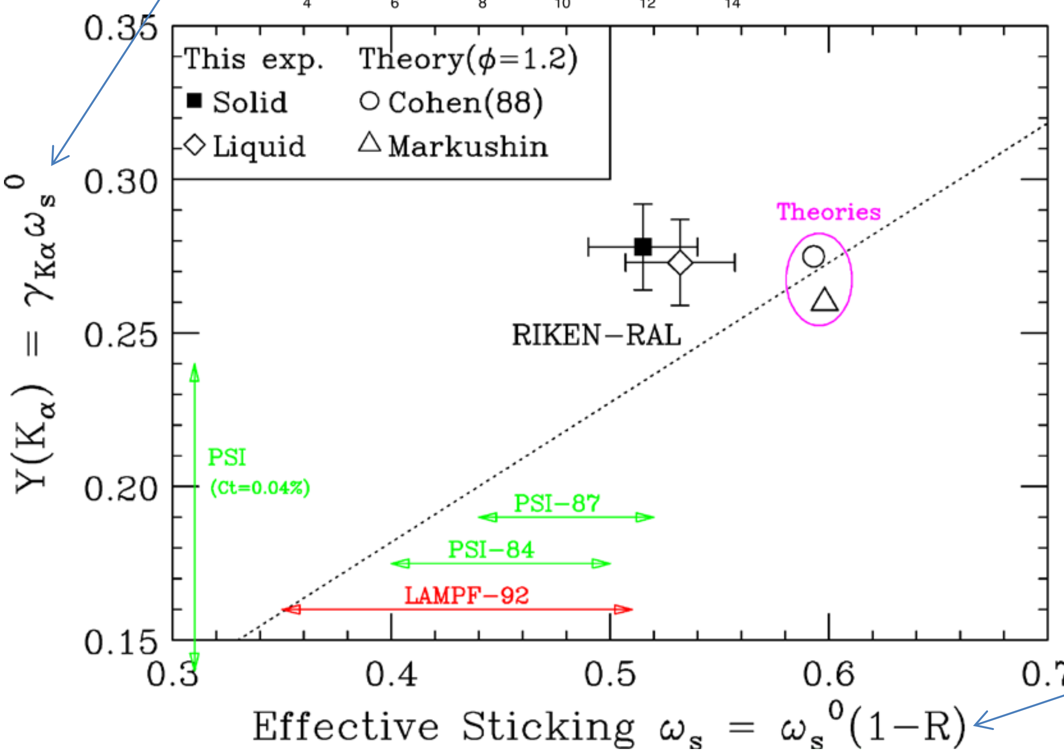
Muon catalyzed fusion: α-sticking loss

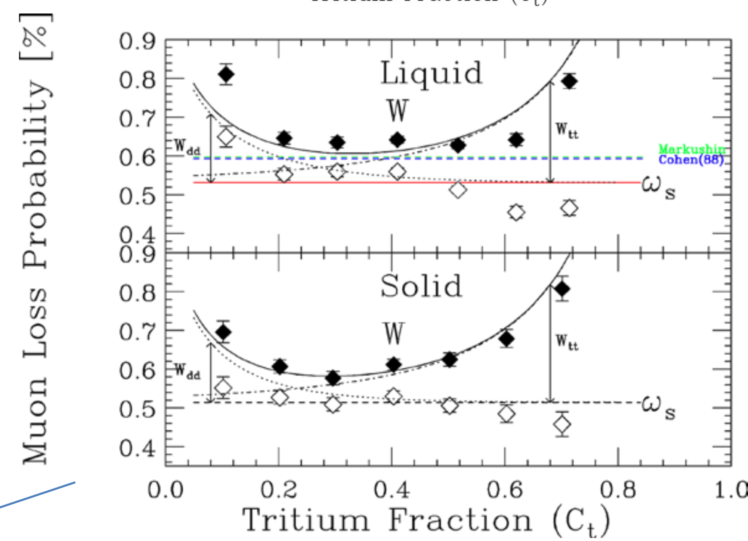
Quantifying the muon loss using neutron and x-ray measurements with several target conditions



Set strict upper limit on μCF cycling efficiency (~200 fusions per muon)
Still below the breakeven for energy production (300 fusions) at that time
(⇒recent revival at J-PARC, new reaction process)







Muon catalyzed fusion: many byproducts

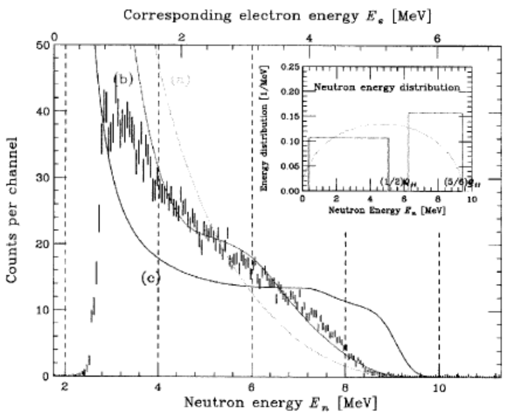
Interesting play ground for few body theories

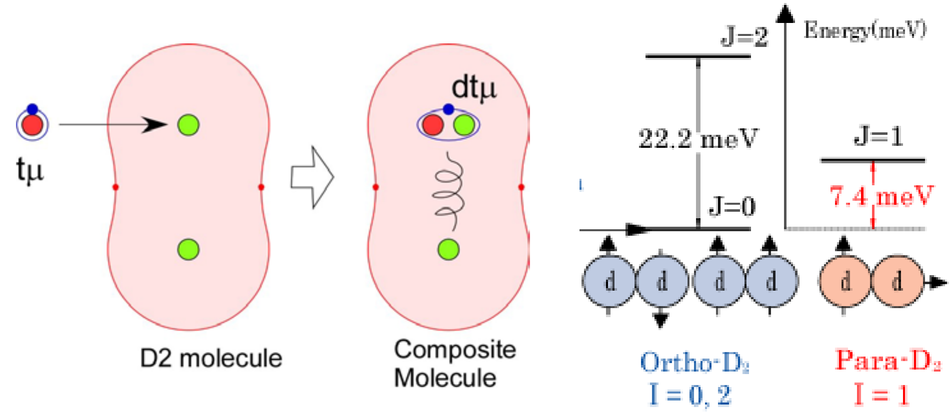
tt-fusion

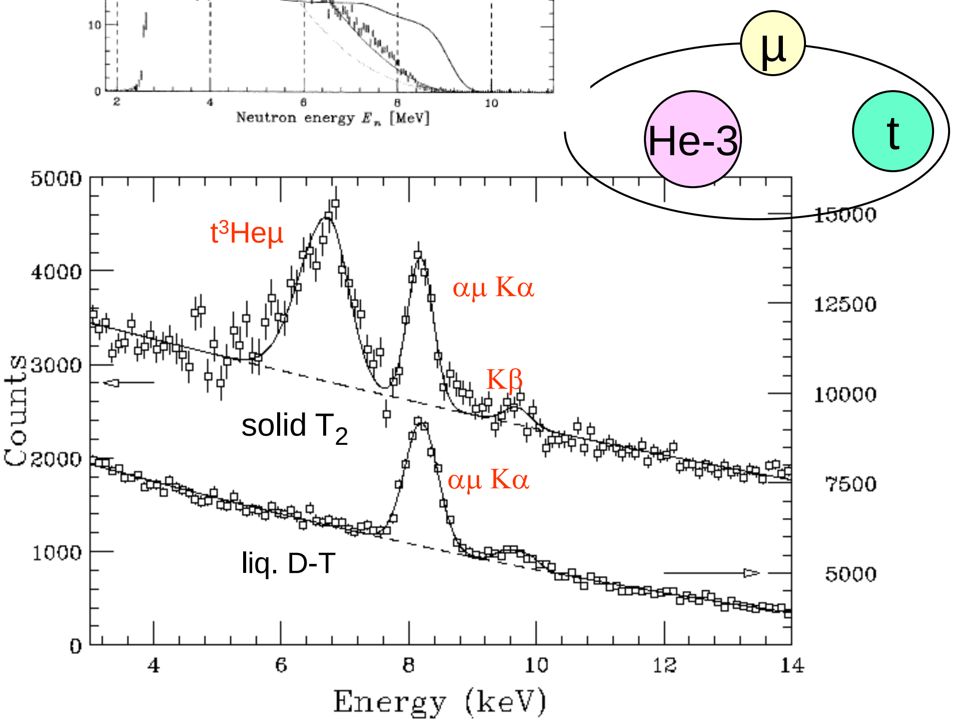
- neutron energy (nn, nα correlation)
- muon transfer to 3He

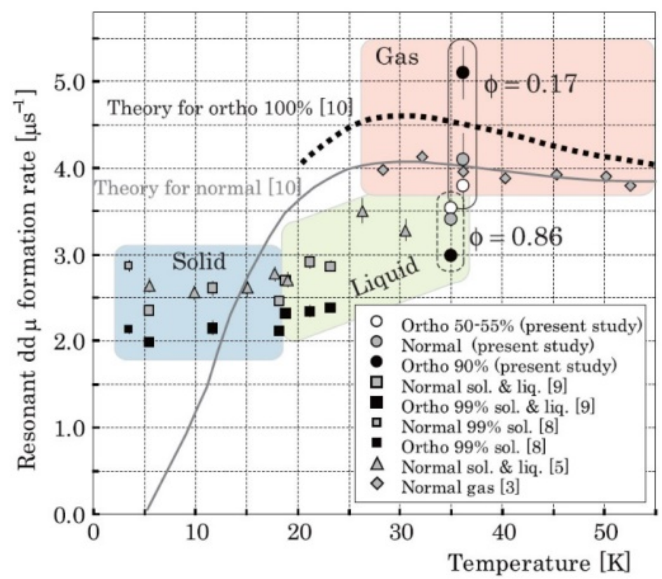
dd-fusion

- molecular effect (ortho-para)

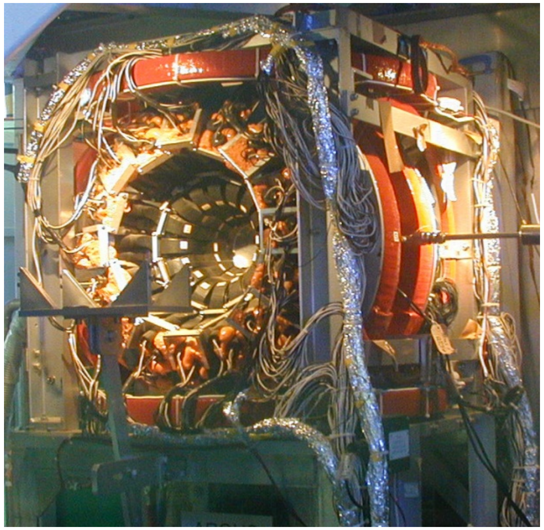




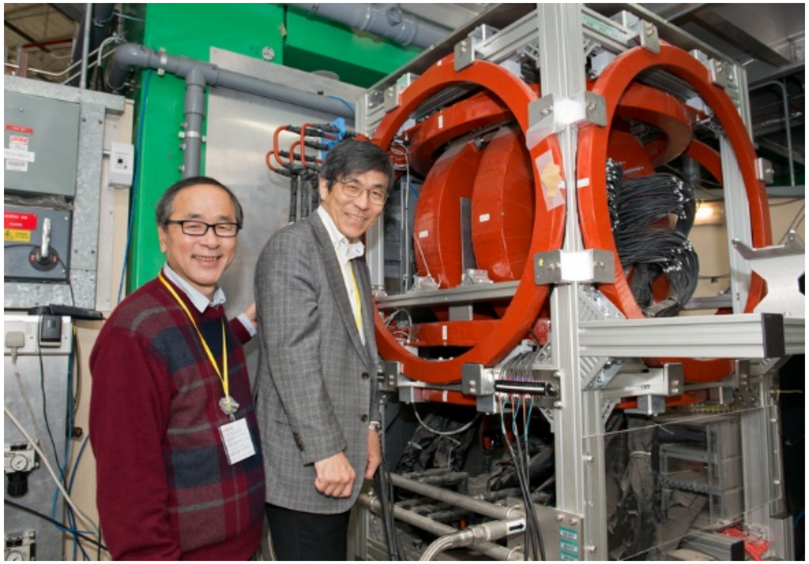




Muon spin rotation/relaxation for Materials Science



Need to compete high detection rate
more that 10 times than the rate at KEK
LHC 32 counters -> ARGUS 192 counters（R. Kadono in 1995）
+ direction sensitive detector
from 1M statistics 10M~100M statistics
=> Still the reliable μSR spectrometer
Counter failure rate <10%
Upgrade of DAQ



Advanced form
CHRONUS in Port 4（2009~）
606 counters

μSR: Benefit of intense pulsed muons

μSR

Materials probe using spin of positive muons Magnetism, Super conductivity, Semiconductors, Gas, Life

Measurement in short time using intense muon beam（<10 minutes/1 condition）:

Conduction of many experimental proposals（1~2 days/measurement）

Allows variety of experimental conditions/samples

Temperature range

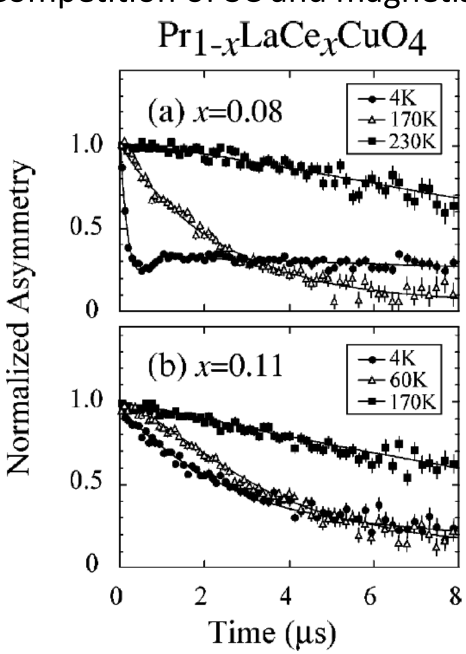
dilution, 3He, 4He, flow type cryostats

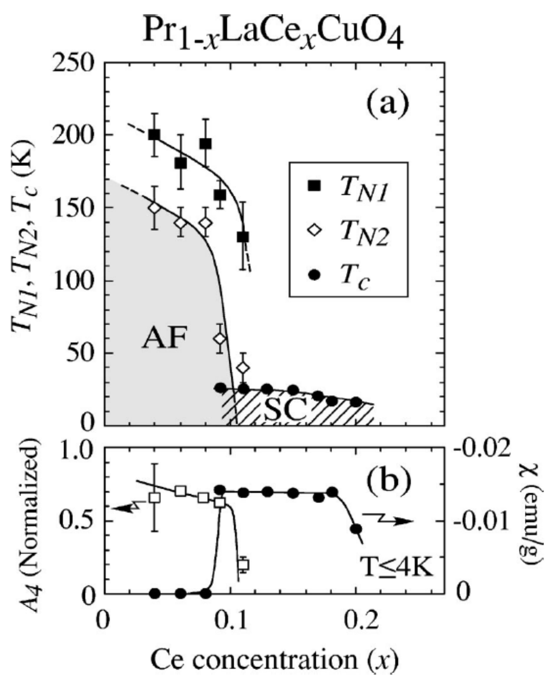
high pressure + low temperature

laser, light, electric field

small samples, small signal, small effect

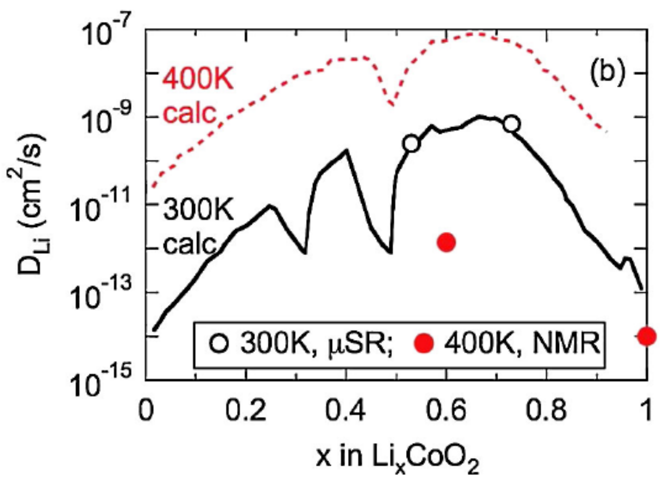
Competition of SC and magnetism





Ion diffusion in battery

Sugiyama et al

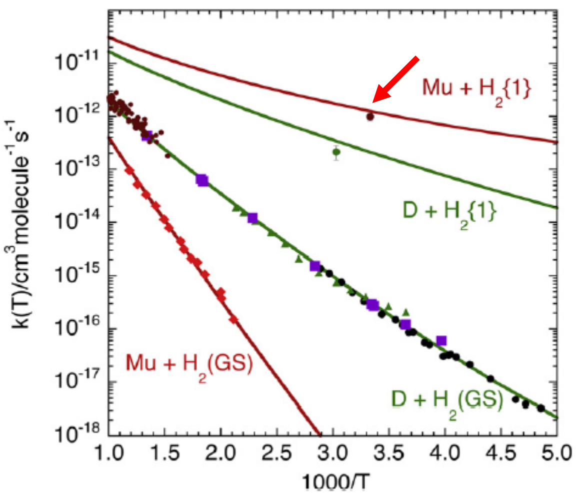


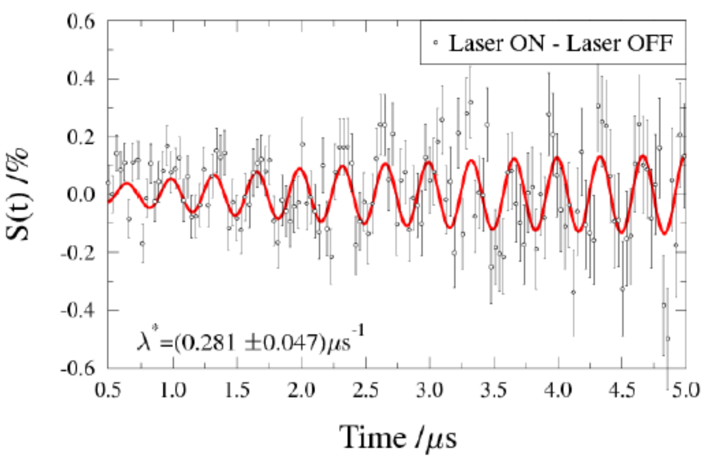
Laser and μSR

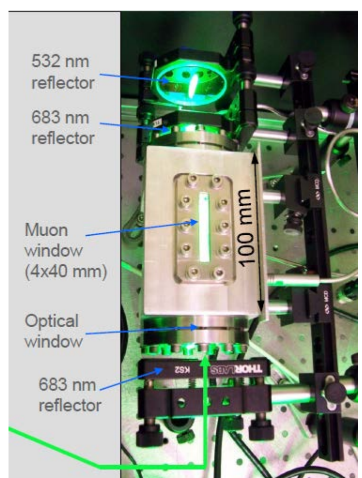
Good matching with pulsed muon

Mu reaction with laser excited hydrogen molecule

D. Fleming , P. Bakule, et al

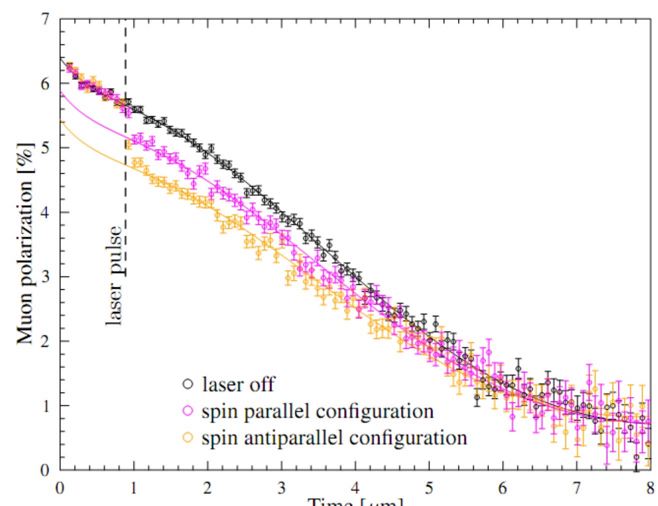






Spintronics: Mu and polarized electron

K. Nagamine , E. Torikai, H. Tom et al



Ultra-slow muon beam development in Port 3

Conventional muon beam : for bulk measurement

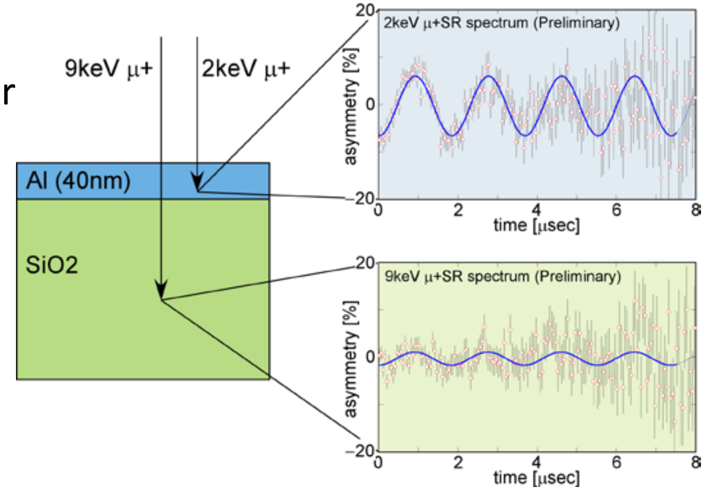
Slow muon beam: surface, interface, microscopic region

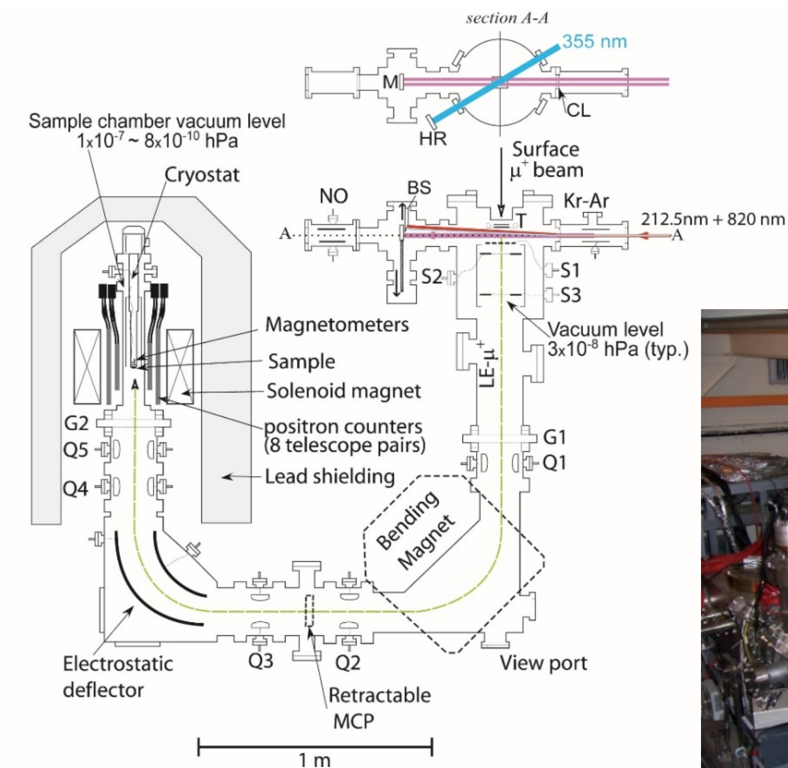
KEK apparatus (laser, beamline) were brought to RIKEN-RAL

Y. Matsuda, P. Bakule, Y. Miyake, K. Shimomura, ...

Techniques development + confirmation of good character

⇒base for further development at J-PARC





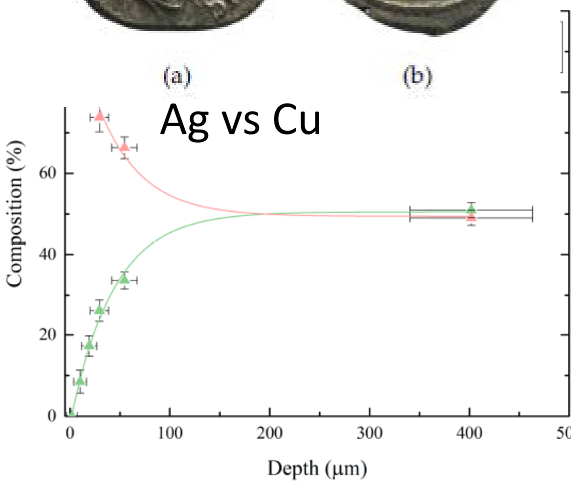
Application of muonic atom x-rays, gamma-rays

Elemental analysis

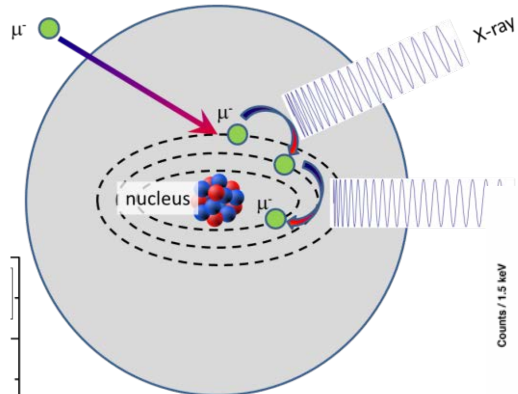
A. Hillier et al

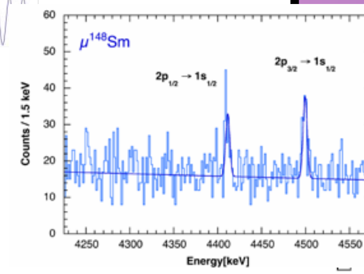
Roman Coin

(a) (b)



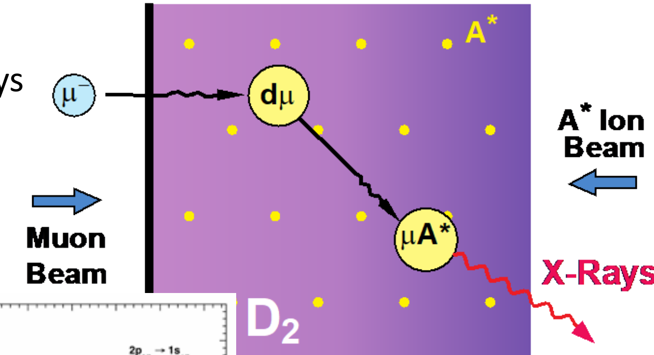
Characteristic muonic atom x-rays



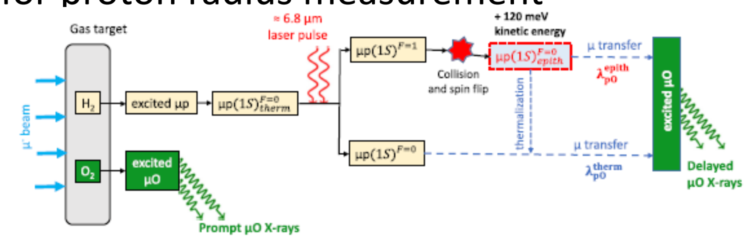


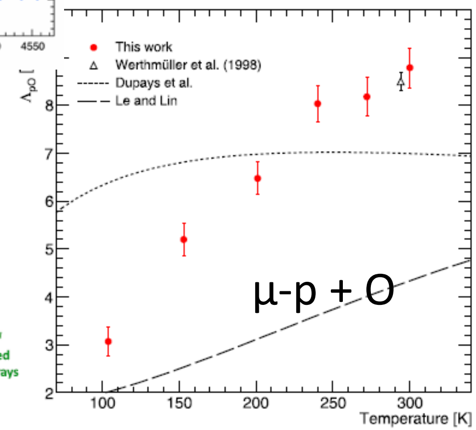
Probing nuclear size: μA*

P. Strasser et al

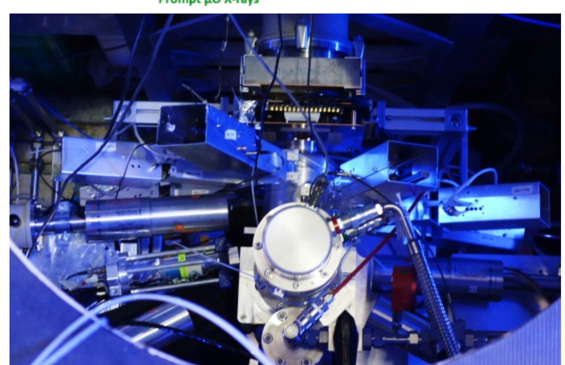


Muon transfer effect (by FAMU group) for proton radius measurement



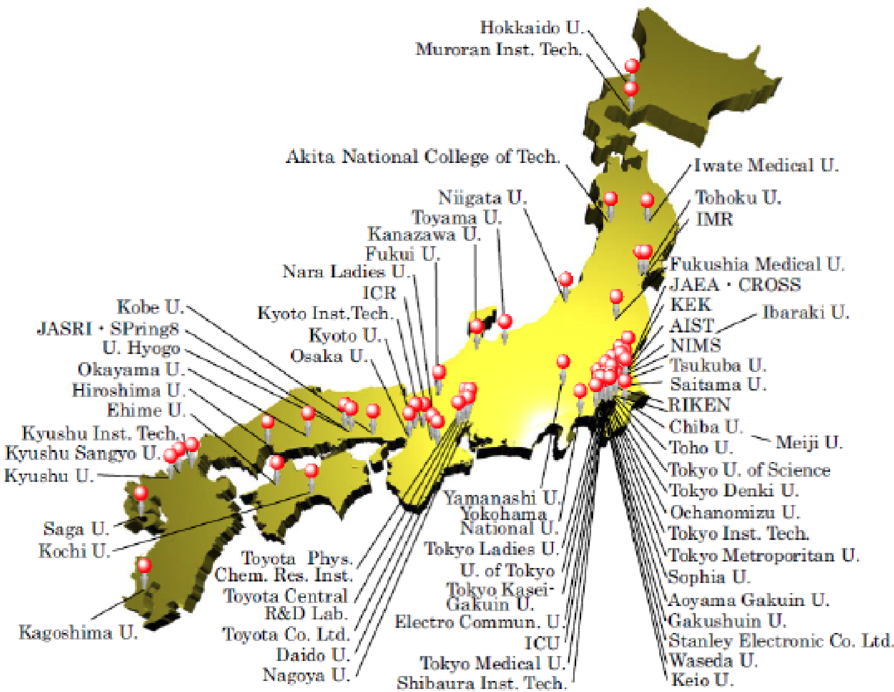


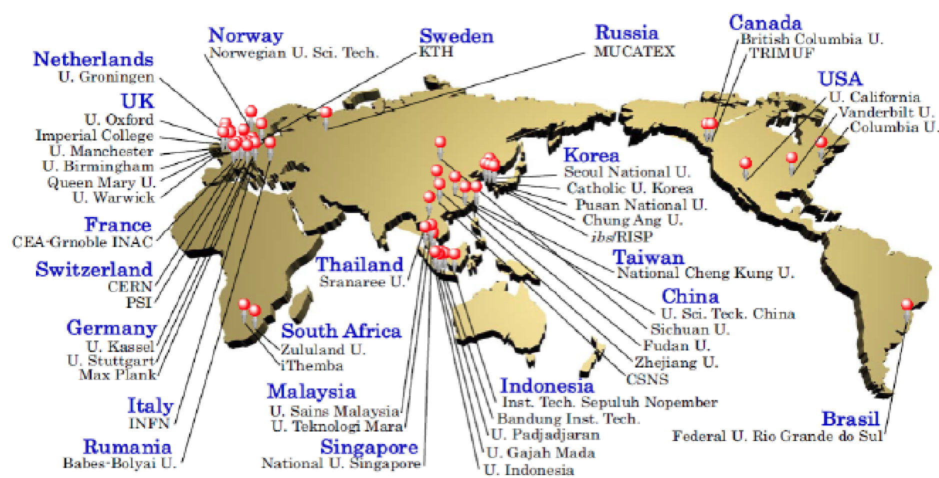
muon nuclear capture



Research staff, visitors, users

Domestic and international collaborations
especially UK, Europe, Asia





Proposal Advisory Committee system

All beam usages are through proposal review (only exceptions are beam/detector development < 5%)

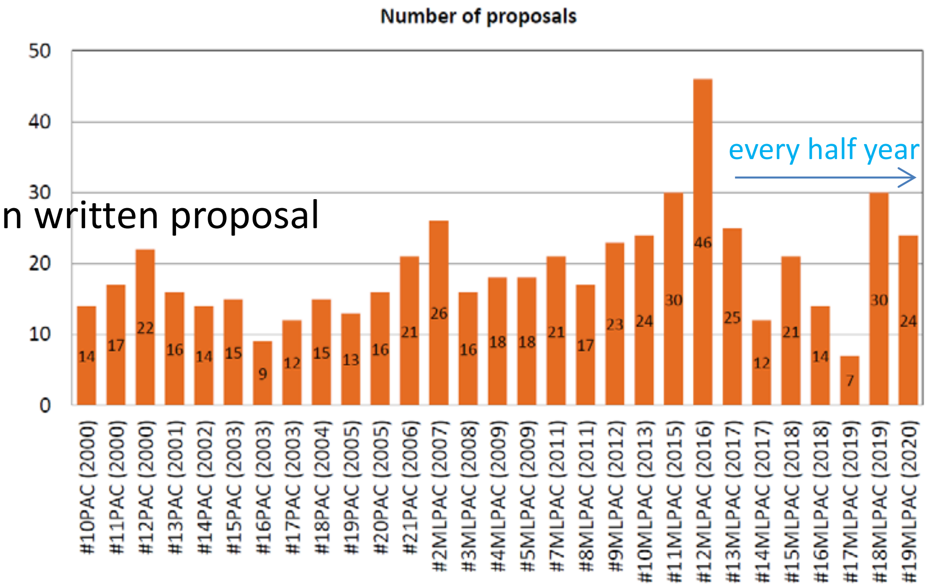
PAC held Twice a year

RIKEN-RAL PAC 1st (1995)-21st(2006)

Nishina ML-PAC 1st (2006) - 19th

until 2016：with PI's presentation

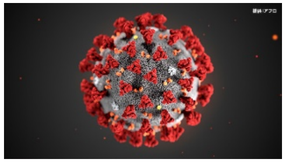
after 2017：by member's discussion based on written proposal



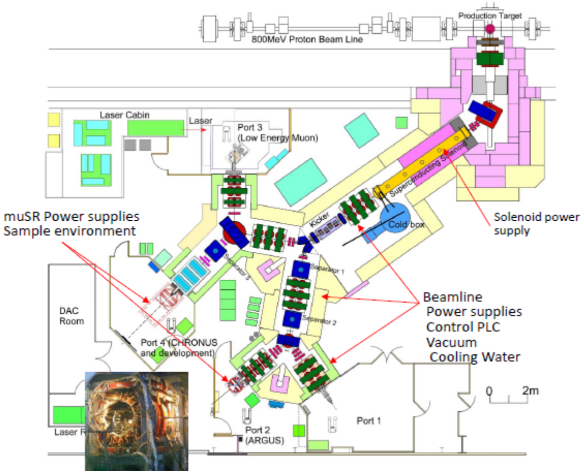
RIKEN-RAL present

Renewed the agreement on Apr 2018 (for 5 years)
  Transfer of the facility ownership to RAL
  Continue independent PAC by RIKEN

However, COVID-19 seriously affected in 2020
  UK rock-down in March 2020
  Resume of ISIS beam in September
    strong limitation on user's attendance (2 m rule)
    mailed sample only
  situation is still unclear



On the other hand
Large scale refurbishment is planned
 during ISIS long shutdown in 2021
This will solve facility aging problem
and we expect the muon beam will be available
for research into the long future

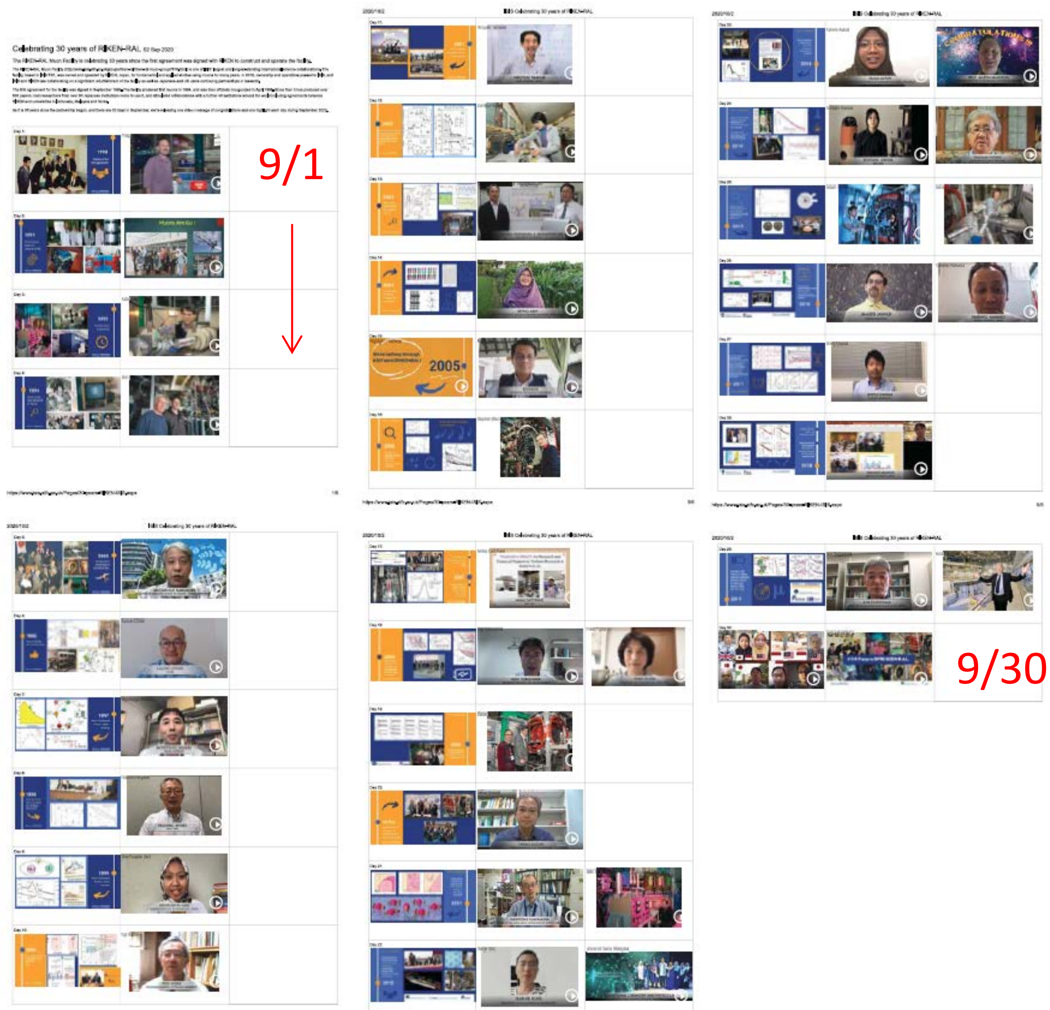


RIKEN-RAL 30 years celebration

We gave up get-together due to COVID-19

Dedicated web page（Sep 2020）
https://www.isis.stfc.ac.uk/Pages/30-years-RIKEN-ISIS.aspx

- 30 years history (in 30 days)
- Video messages



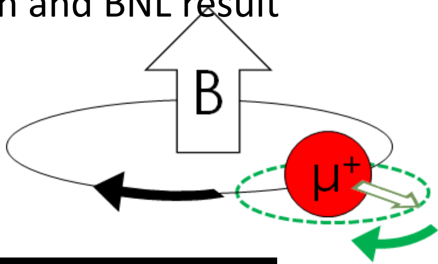
Development at J-PARC

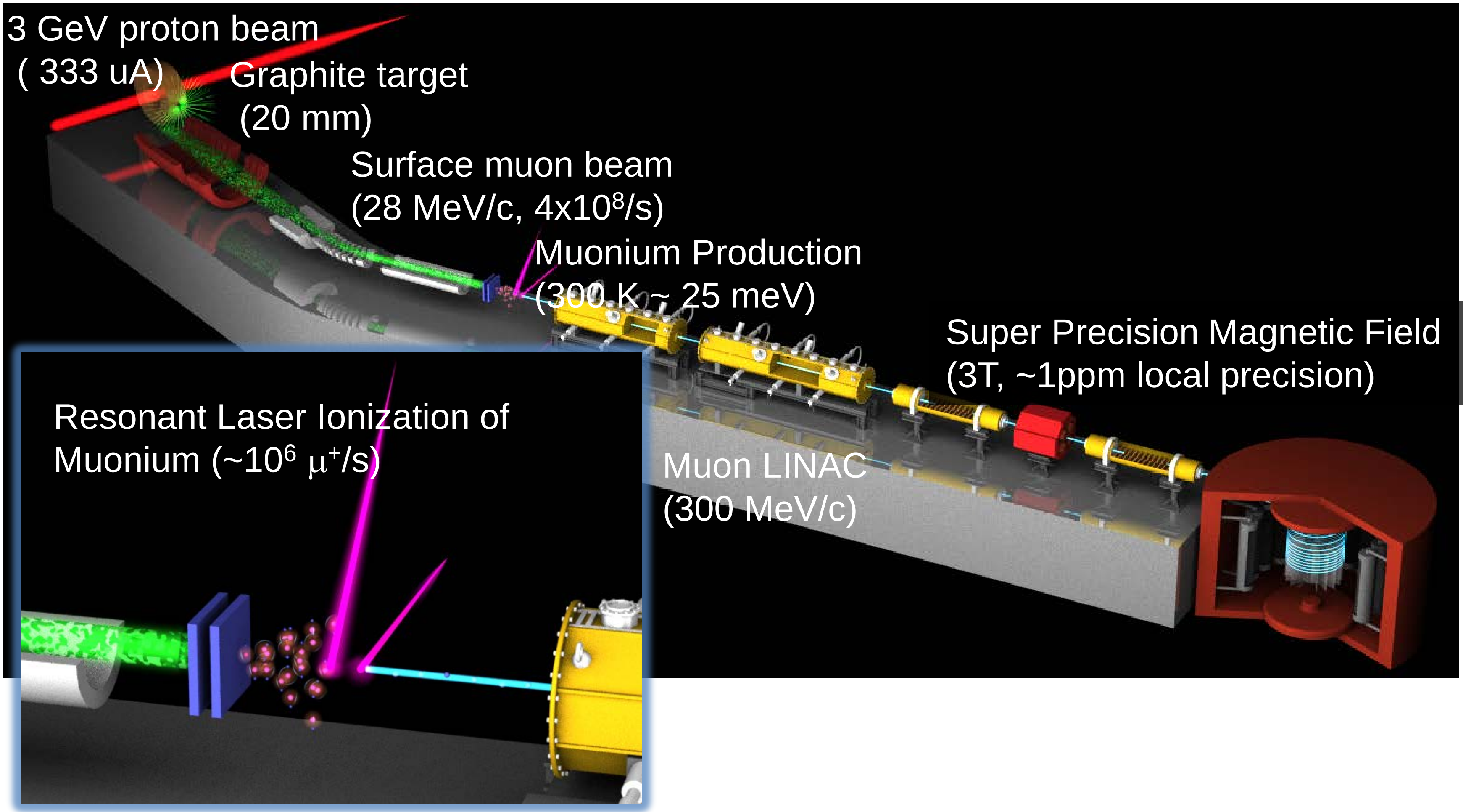
Ultra-slow muon beam and application

muon g-2/EDM (2008-) Verify discrepancy between Standard model prediction and BNL result

muon acceleration : store unprecedented high quality beam

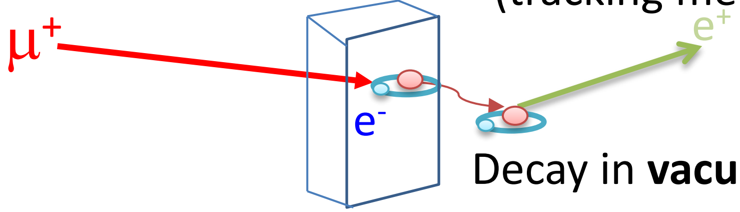
High precision g-2/EDM measurement⇐High intensity muon beam





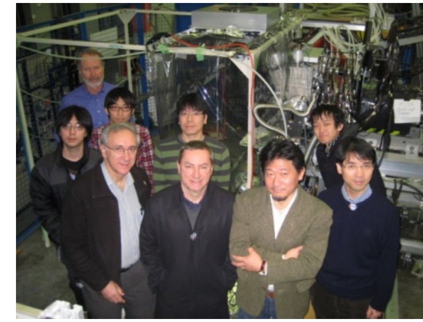
Thermal Mu production target development for muon g-2

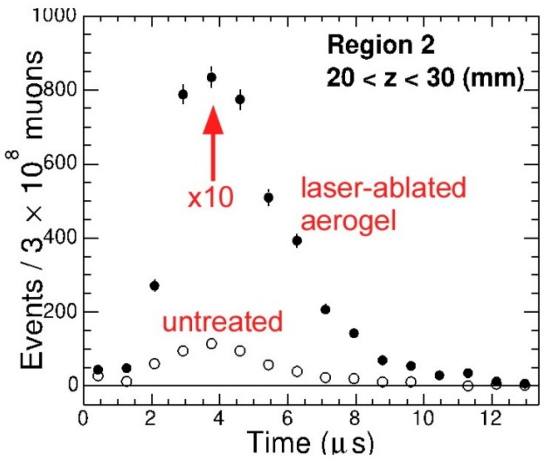
(tracking method)@TRIUMF,J-PARC



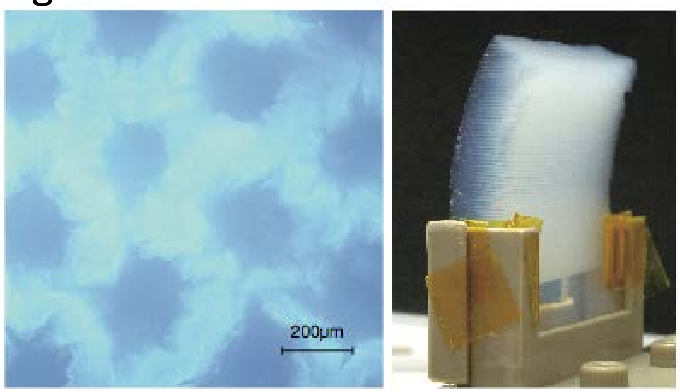
Decay in **vacuum**

Muonium Target



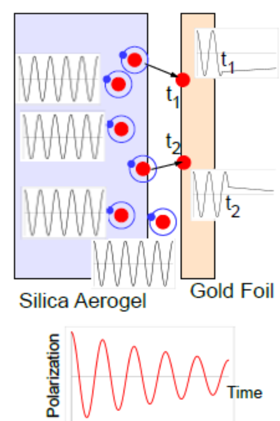


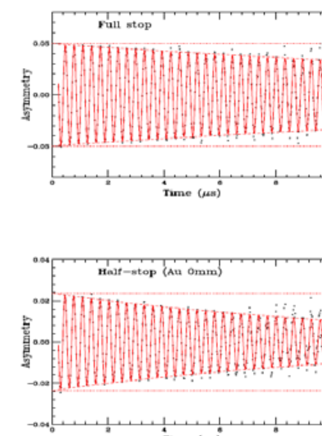
2013, 2017



laser ablated silica aerogel

(MuSR method)@RIKEN-RAL





H-line construction
+ g-2 apparatus construction
⇒target 2025 for start of g-2 measurement

Expectation for development at J-PARC

Basics parameters of Mu atom => progressing towards the world record

- Mu HFS
- Mu 1S-2S

Muonic atom

- Muonic atom x-rays
  - with detectors break through
- Muon catalyzed fusion
  - new ideas, new theory models, new measurement, applications

High quality beam development

- Low energy
- Phase space

μSR

- highly segmented detectors
- dedicated beam lines with dedicated instruments

Congratulation to the achievement in 12 years
at J-PARC neutron and muon beams,
and expect great future and further development