Ultra slow muon generation and applications

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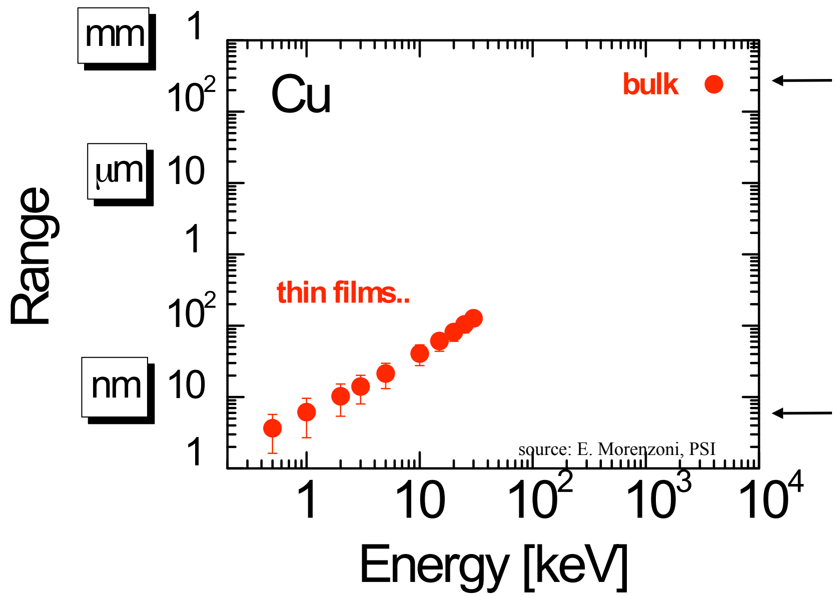
- Construction of new laser laboratory at Port 2
- Looking back over past 10 years and looking forward to the future laser experiments at RIKEN RAL

μSR with low energy muons



For "**surface muons**" with energy of 4 MeV the stopping range in a solid varies from 0.1 - 1 mm with a straggling of about 20% of the mean value. Beam size 40-50 mm (FWHM)

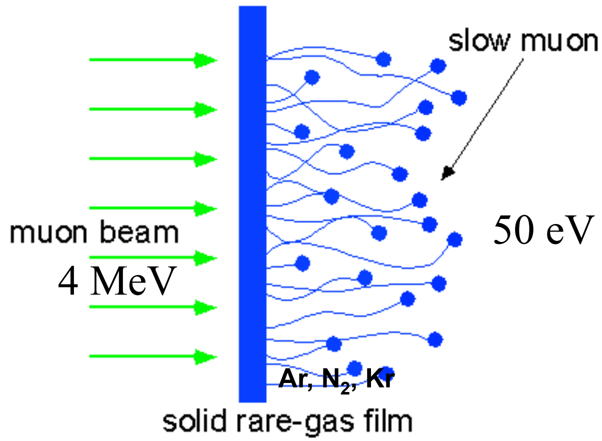
For "**low energy muons**" with energy 0.01-30 keV the stopping range in a solid varies from 1 - 200 nm. Implantation depth easily controlled on nm scale. Beam size is small 4-5 mm (FWHM)

- allows investigations of near-surface regions, thin films, interfaces and multi-layers, nanomaterials and of samples which can be grown only as thin films.
- allows to make depth resolved measurements.

Methods of LE-muon generation

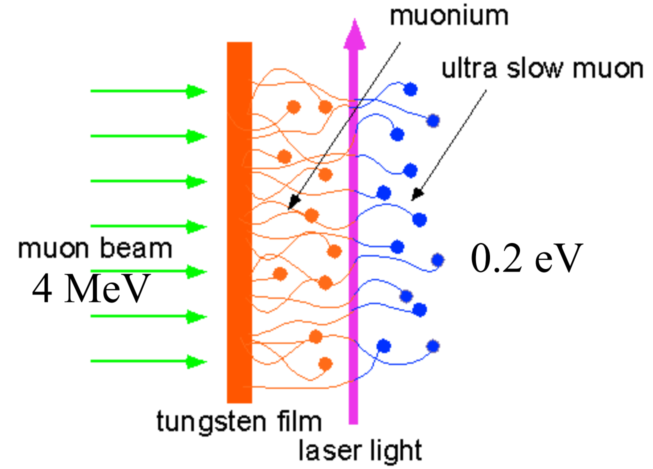
1) **Cold Moderator Method** (@PSI)

- **ideal for continuous muon source**
- layer of solid rare gas as a moderator
- conversion efficiency up to 10^{-5}
- 92 % Polarization
- 10-100eV Kinetic Energy
- DC, Requiring a start trigger (->5 ns resolution)
- Time structure determined by initial muon beam



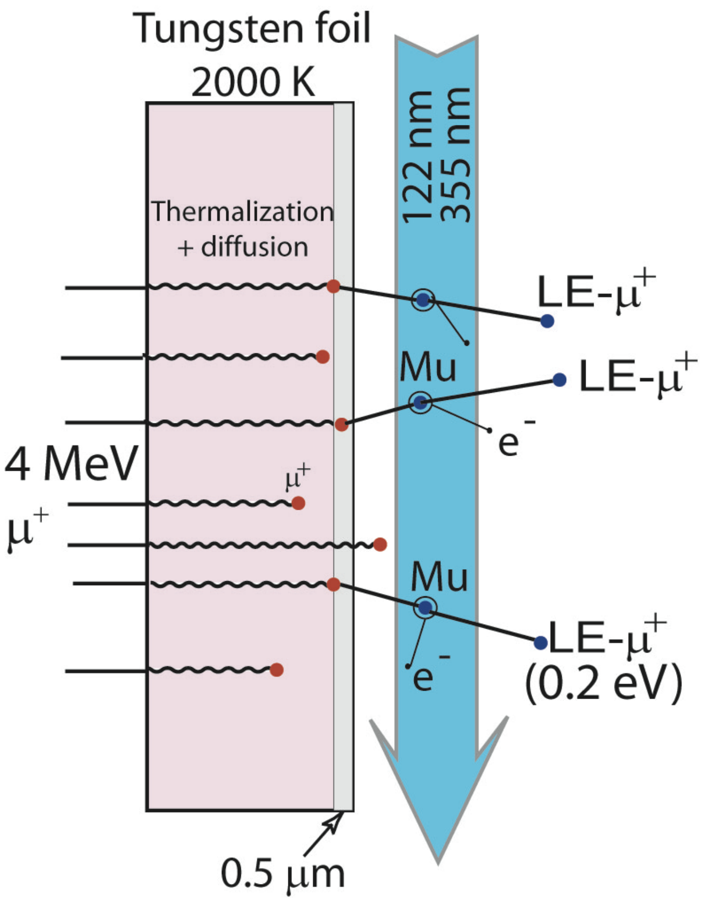
2) **Laser Resonant Ionization of Muonium** (@RIKEN-RAL)

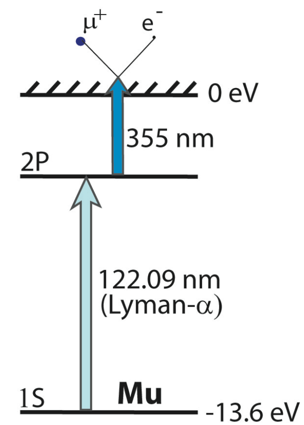
- **ideal for pulsed muon source**
- 1% efficiency of conversion to thermal muonium i.e. potentially much higher conversion efficiency to LE-muons
- 50 % Polarization reduction
- potentially 0.2eV Monochromatic beam
- Time structure determined by laser pulse (~10 ns) synchronized with pulsed muon beam
- external trigger allows synchronisation with sample excitation



Principle of ultra low energy muon generation

4 MeV muons $\xrightarrow{2\%}$ 0.2 eV thermal Mu $\Longrightarrow$ 0.2 eV μ^+





122.09 nm (Mu)
121.57 nm (H)
121.53 nm (D)

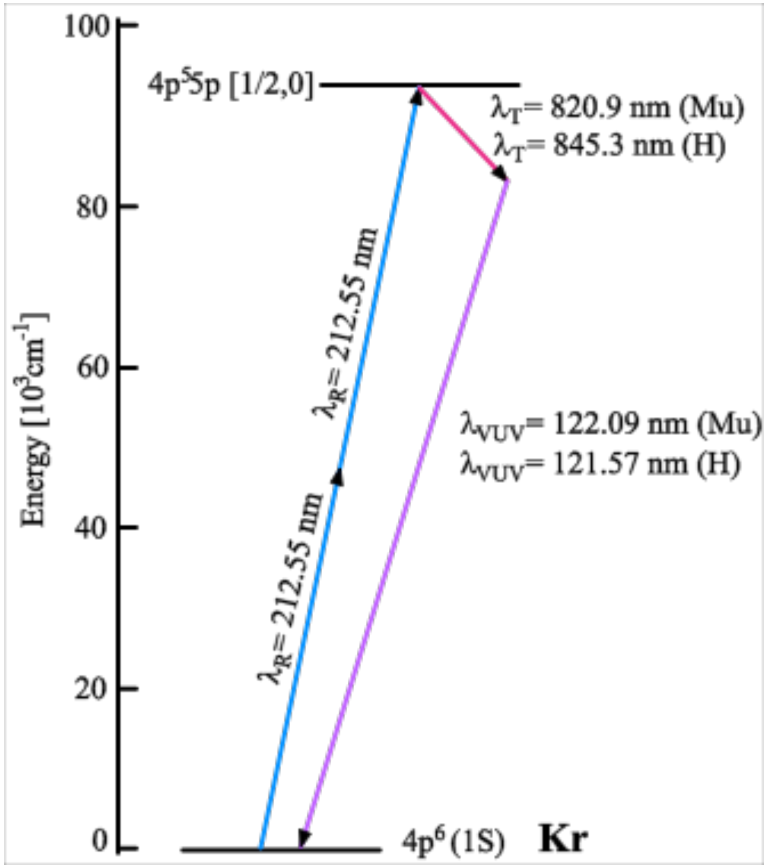
- **two** laser beams necessary for resonant ionization
- required very broad laser bandwidth due to thermal movement of atoms

1S-2P saturation intensity

I_{sat}=2.3 W/cm^2 monochromatic<100MHz $\Longrightarrow$ I_{sat}=4.6 kW/cm^2 (Doppler 200GHz)

Main challenge: to generate VUV @ 122 nm and with 200 GHz (+ 1 ns jitter rel. to ext. trig.)

Lyman-α generation (sum-difference frequency mixing in Kr gas)



- **212.55 nm** (single longitudinal mode) tuned to a resonance in Kr - yield resonantly enhanced
- **820 nm** (844 nm for H or D) broadband to match Doppler broadening of 200 GHz

⇓

- tuneable VUV output ~ **122 nm** (with 200 GHz bandwidth)

- Short laser pulses required to increase intensity (~4 ns)
- Scheme requires relative timing of all laser pulses ~ 1 ns with external trigger (!)

  ⟹ possible with **OPO lasers pumped by YAG**

Schematic diagram of the laser system

25 Hz operation

Output synchronised to 1 ns (!)

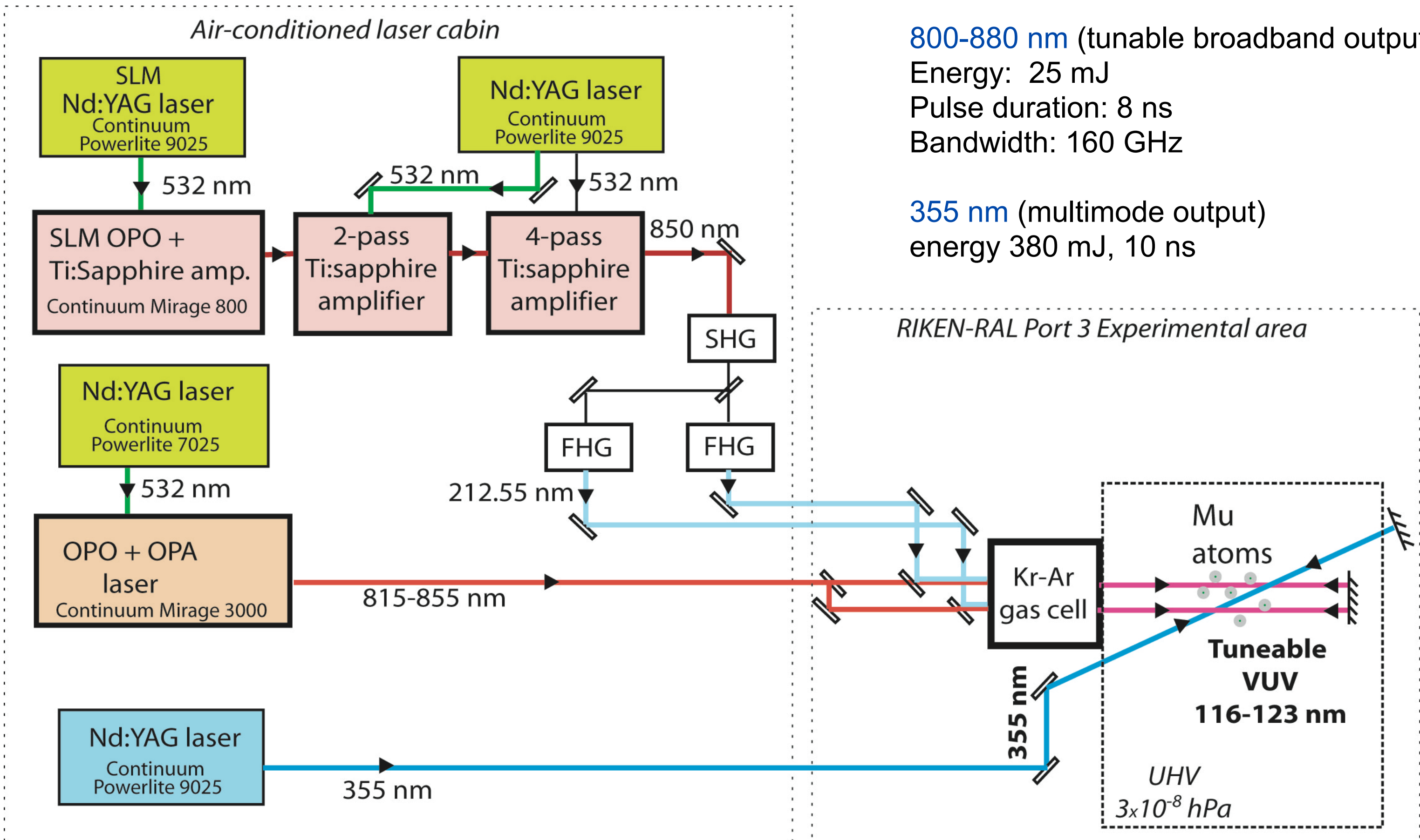
High stability : 20 days continuous 24/7 operation

Solid State Laser parameters:

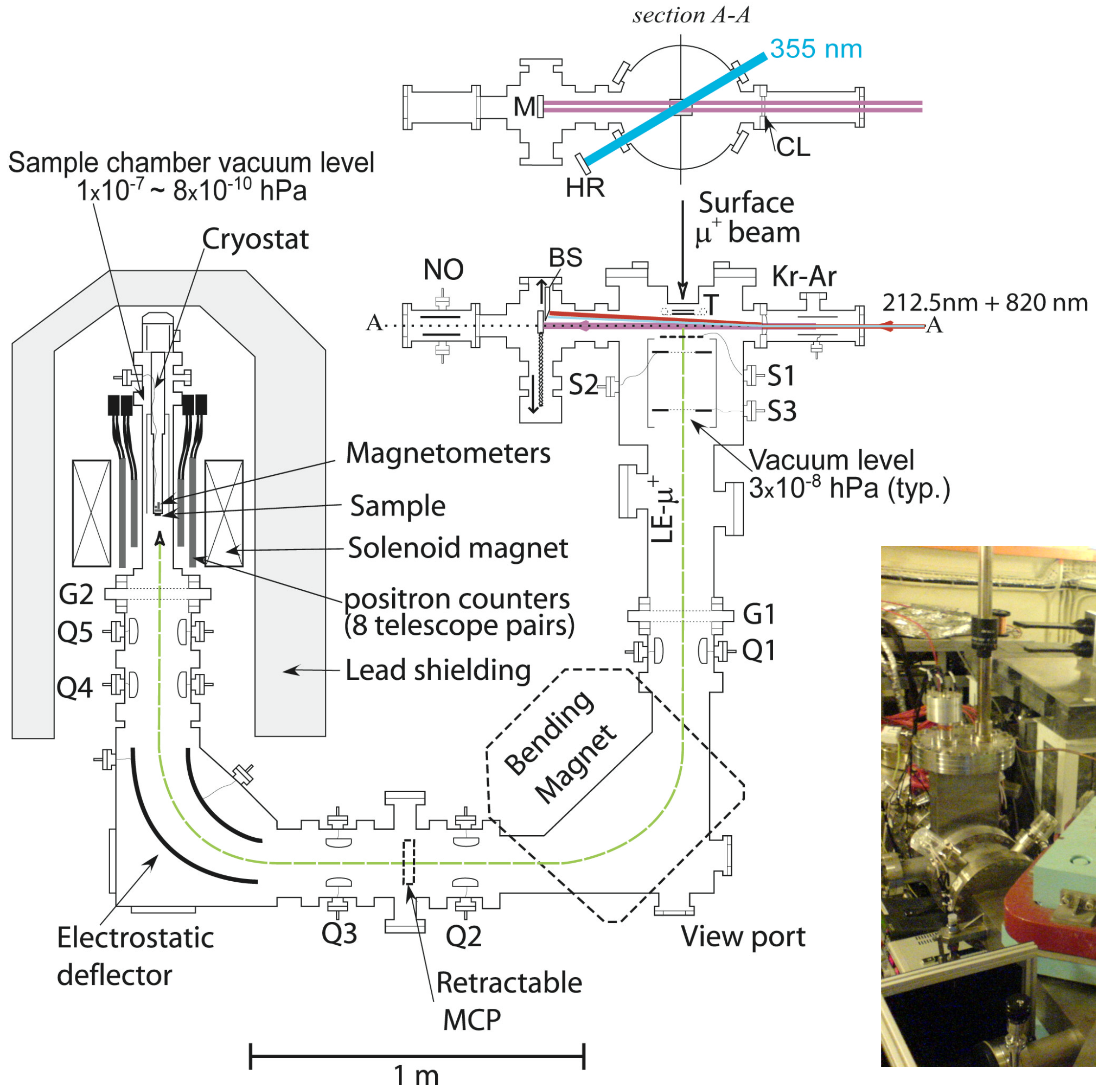
212.55 nm (single mode, tuned to Kr resonance):
Energy: 10-15 mJ /pulse x 2 beams
Pulse duration: 4 ns

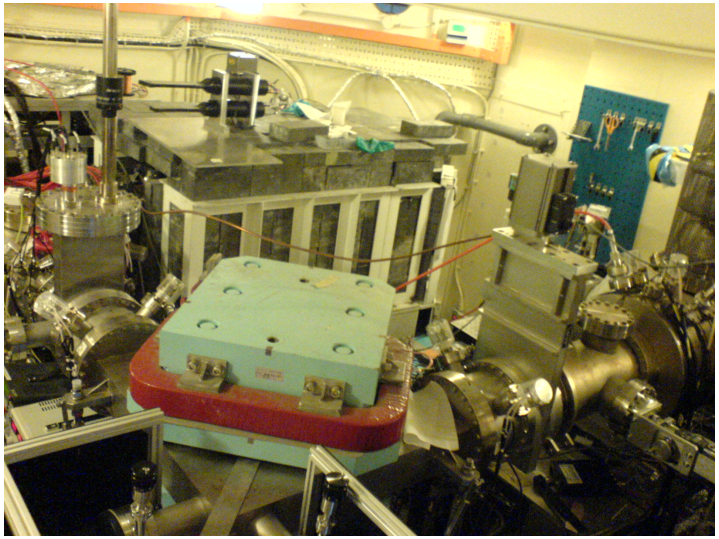
800-880 nm (tunable broadband output)
Energy: 25 mJ
Pulse duration: 8 ns
Bandwidth: 160 GHz

355 nm (multimode output)
energy 380 mJ, 10 ns



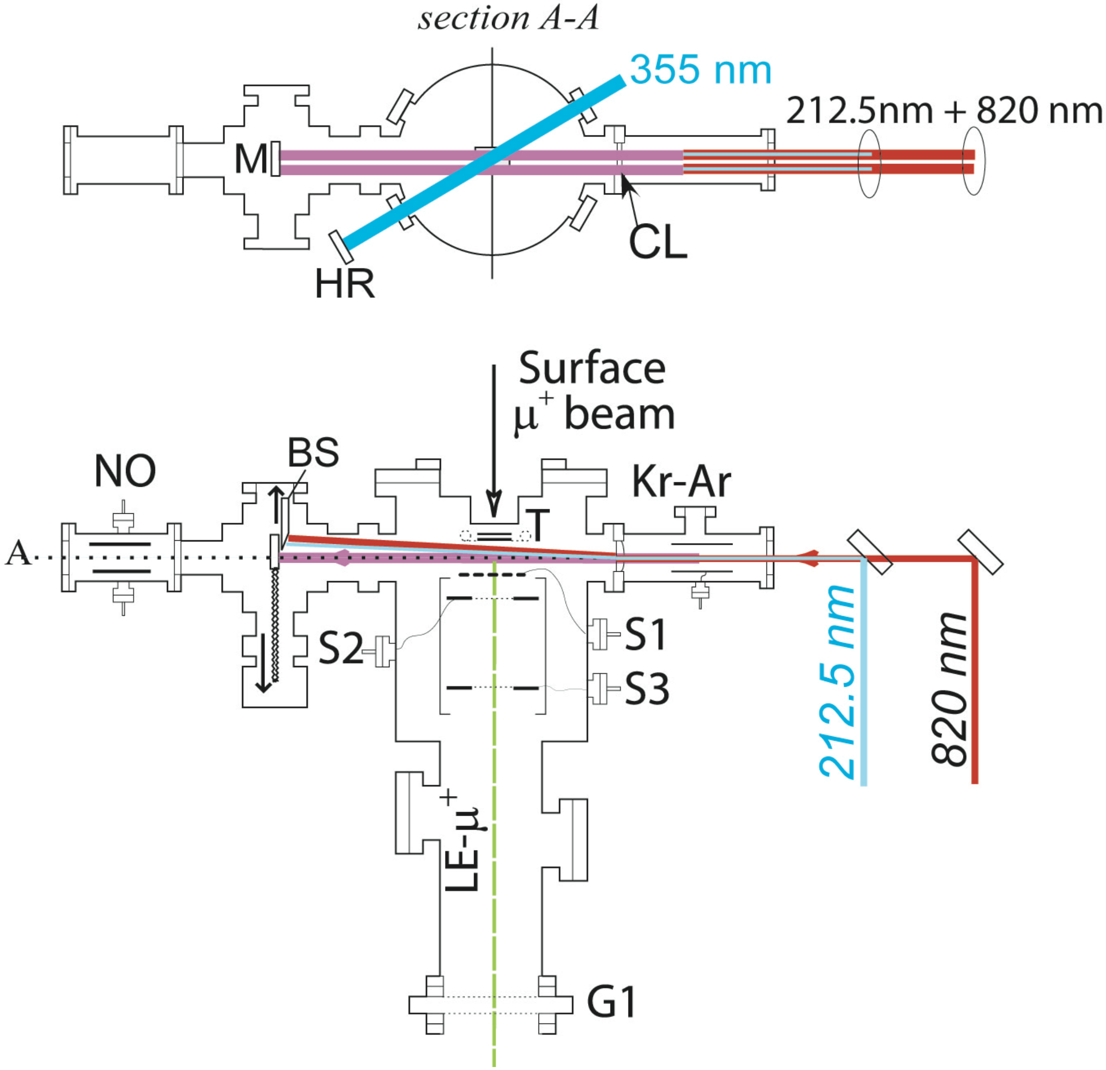
Transport beamline for low energy μ^+

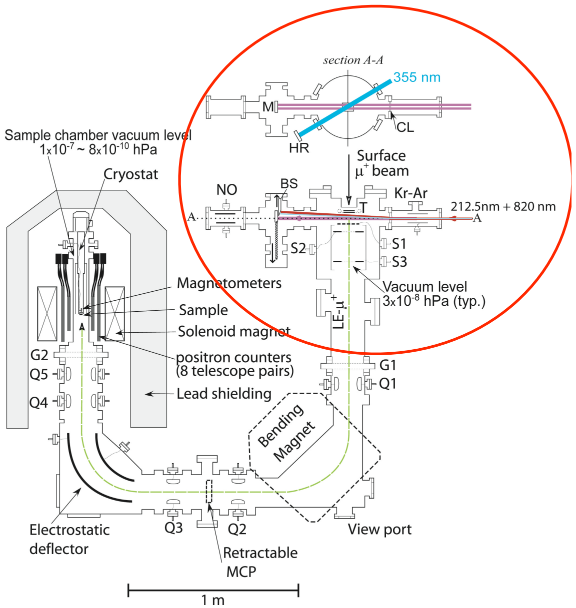




Laser beam overlap with muonium

In laser beam (per pulse):
Mu: 1-10 atoms
Deuterium: 10^3-10^4 atoms

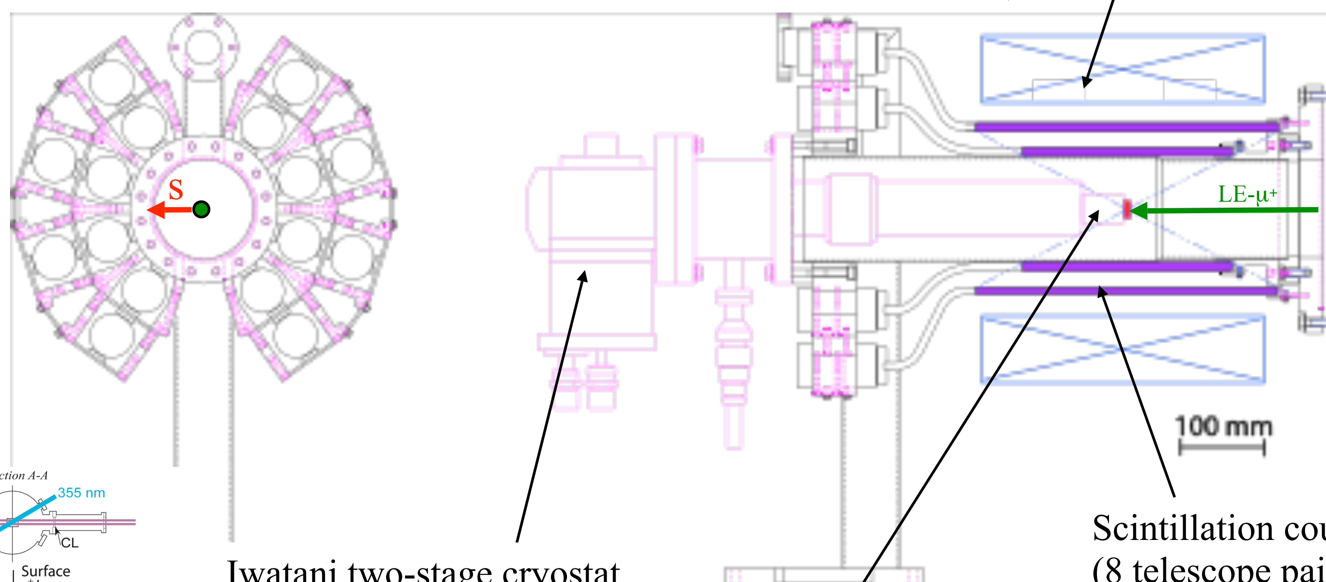




μSR setup for LE-muon experiment

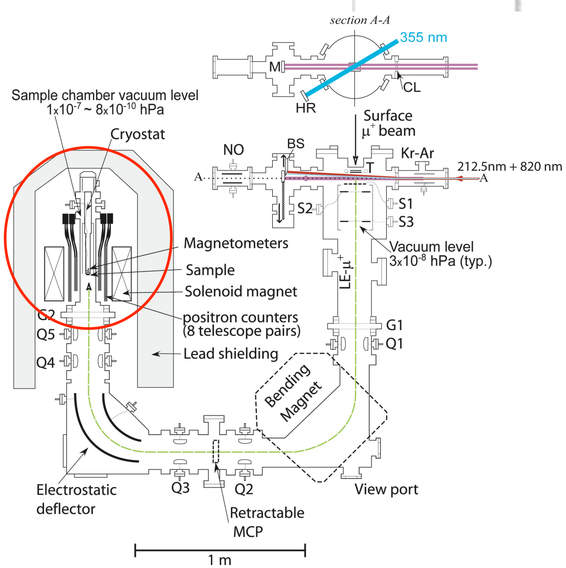
Diamagnetic asymmetry
in Ag sample:
10.1% ± 0.2%

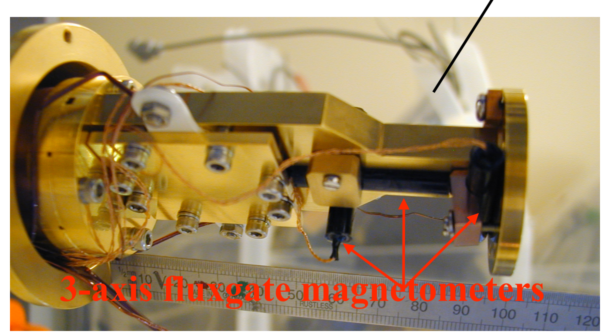
Solenoid type magnet
(transverse field < 60 mT)



Iwatani two-stage cryostat
cooling power 0.5W @4K

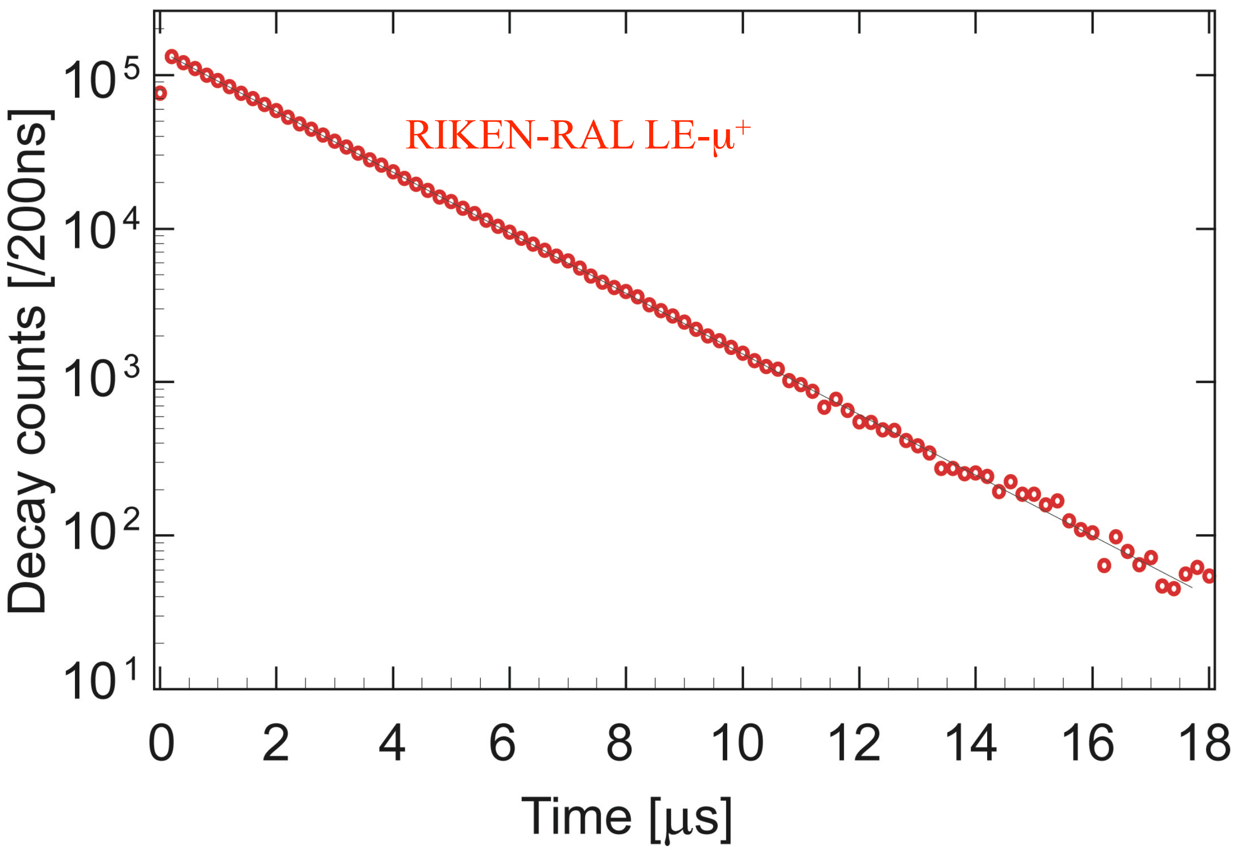
Scintillation counters
(8 telescope pairs)
solid angle coverage
80% of 4π sr.





TF measurement to 60 mT
ZF compensation to 0.1 μT

LE-μ^+ decay spectrum

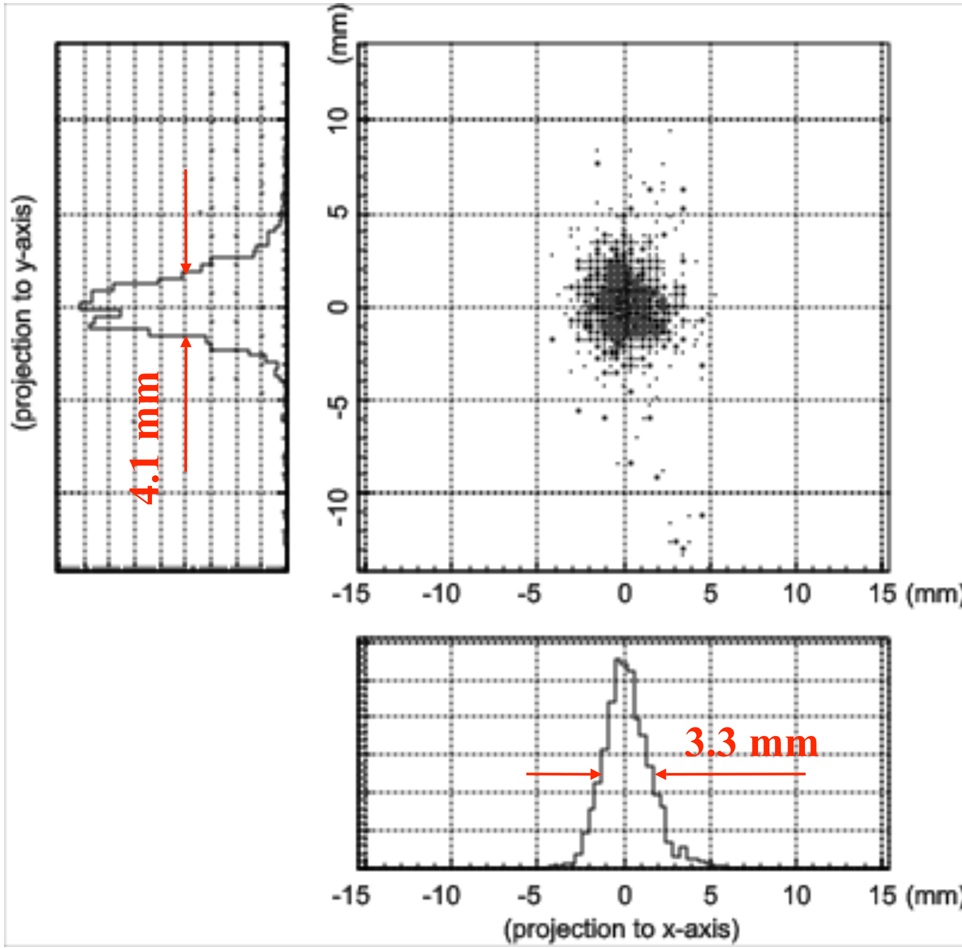


Background suppressed below **0.01 counts** over 15 μs period after slow μ^+ arrival.

Background further reduced by subtracting "laser off" events

Background much lower than at continuous muon source -> much wider time window for measurement
10ns – 15μs

Size of low energy muon beam at sample



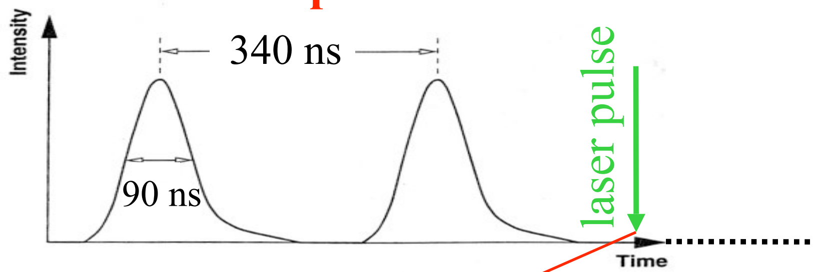
Measured with Roentdek position sensitive MCP (0.8 mm resolution)

~ 100 times smaller cross-section than incident surface muon beam.

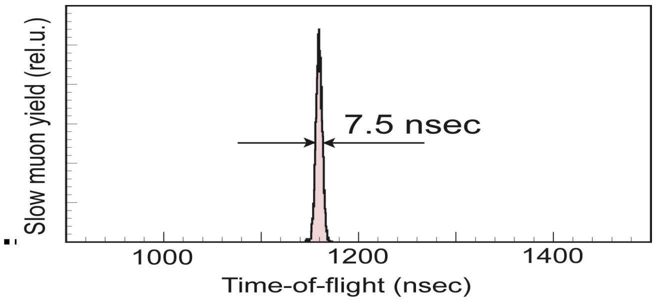
Allows us to measure small samples of 10-20 mm diameter with excellent S/N ratio

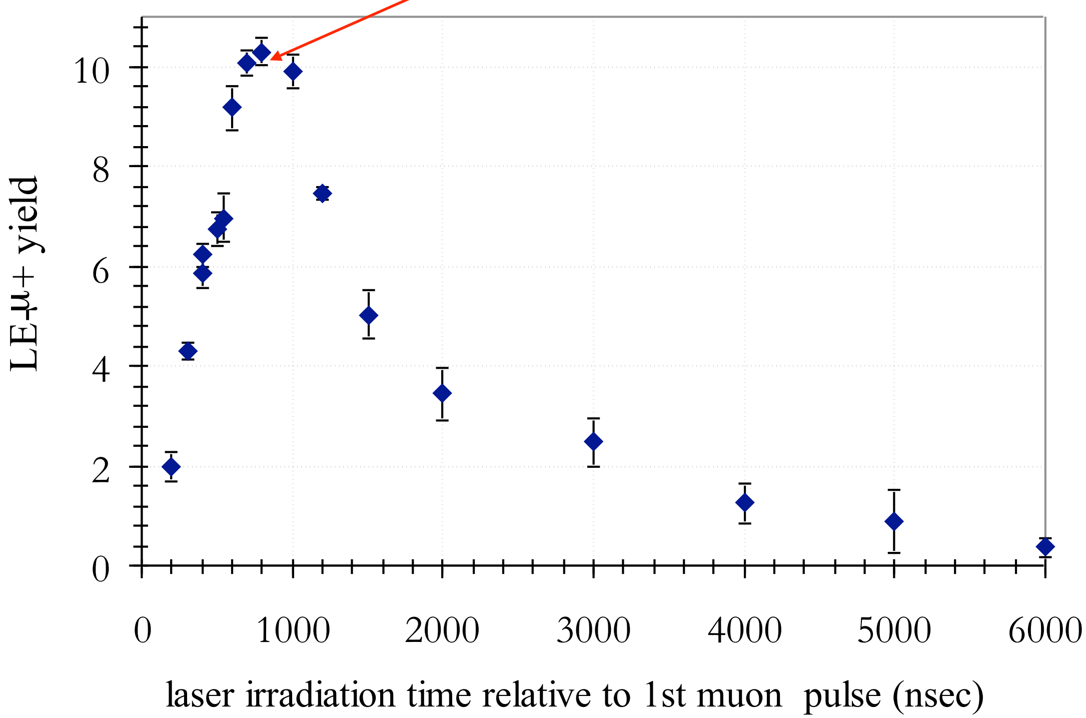
Muon implantation with external trigger

ISIS muon pulse structure



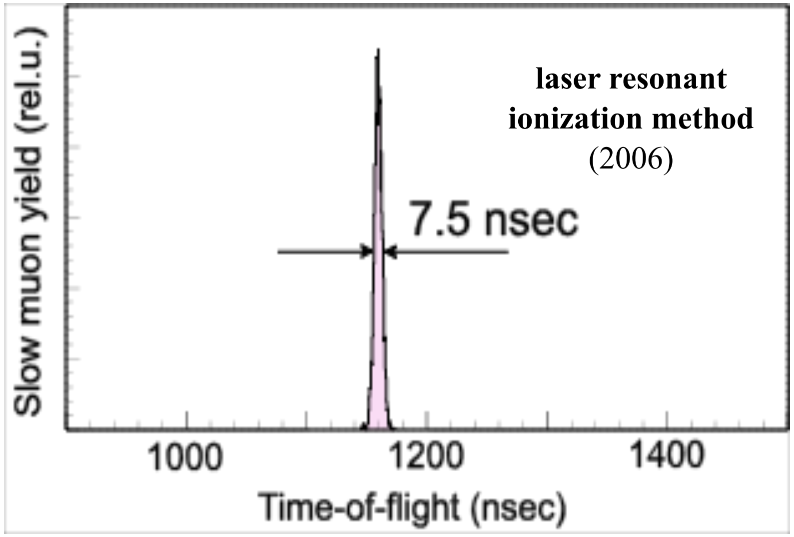
LE muon TOF

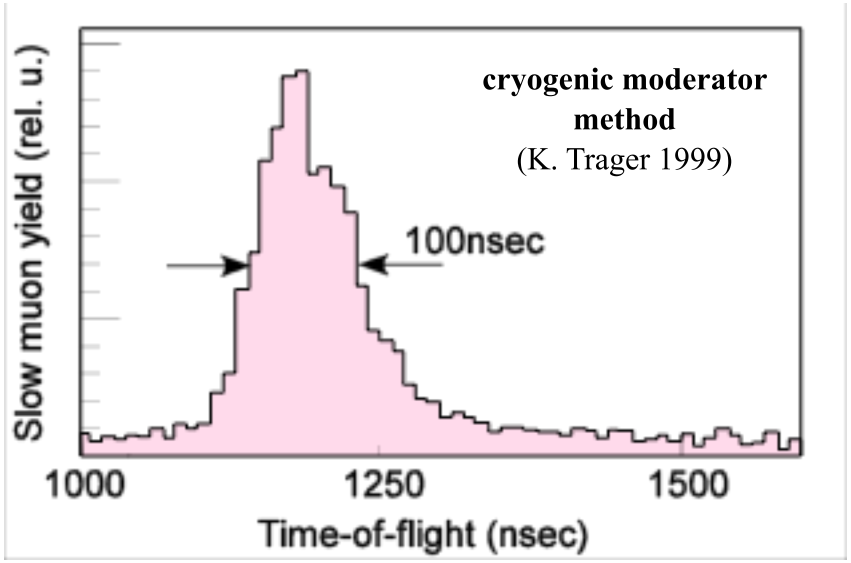




- The timing between muon injection to the tungsten film and laser ionization was scanned to find optimum timing.
- Proportional to muonium density as a function of time.
- Double-pulsed structure of initial muon beam visible from this chart.

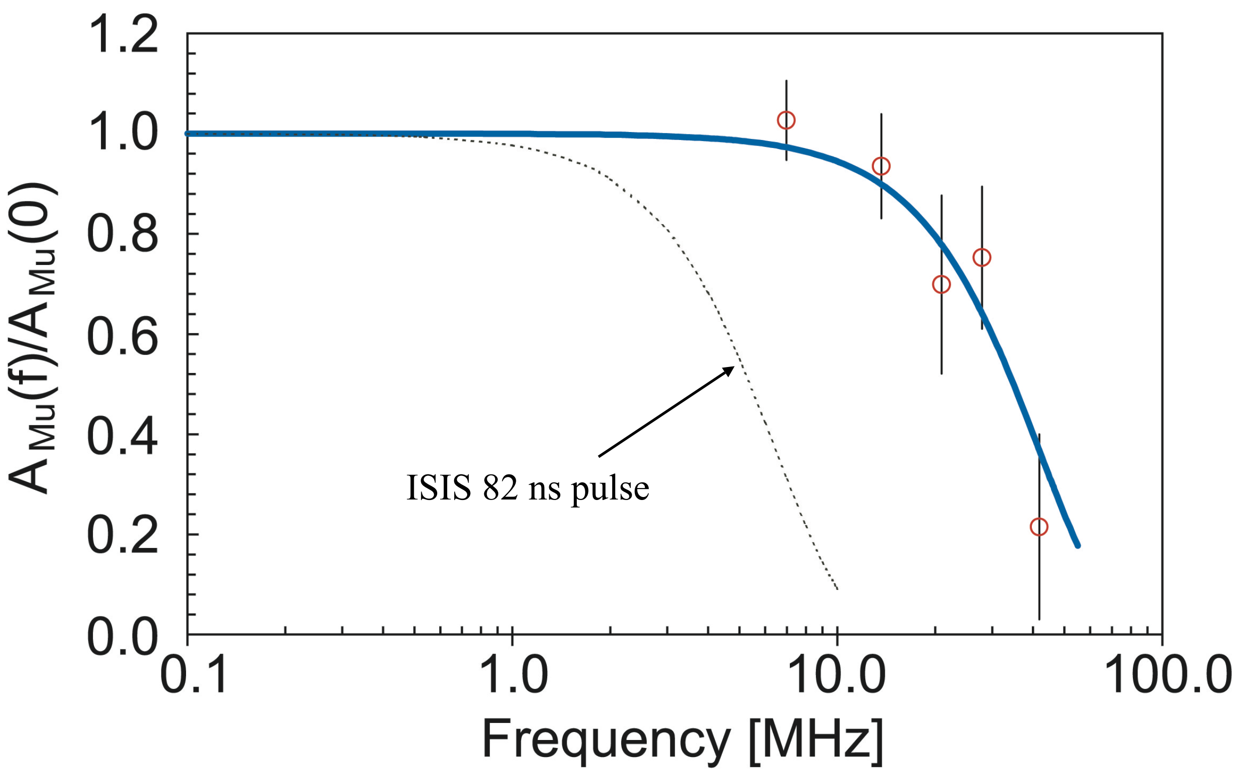
Comparison of muonium ionization and cryogenic moderator methods on ISIS pulsed source





- Laser resonant ionization method makes slow muon beam with good timing resolution.
- Time resolution is 7.5 nsec (FWHM). When cryogenic moderator method was used in ISIS, the time resolution was about 100ns.
- Laser ionization allows to trigger LE muon generation by <u>external trigger</u> with nanosecond resolution → synchronization with pulsed fields

LE-μSR: frequency response plot



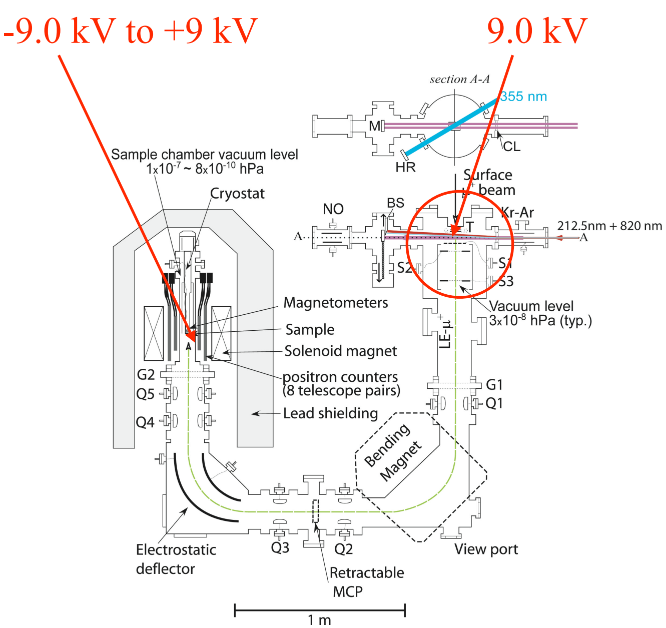
Higher frequency limit for pulsed μSR is significantly extended.

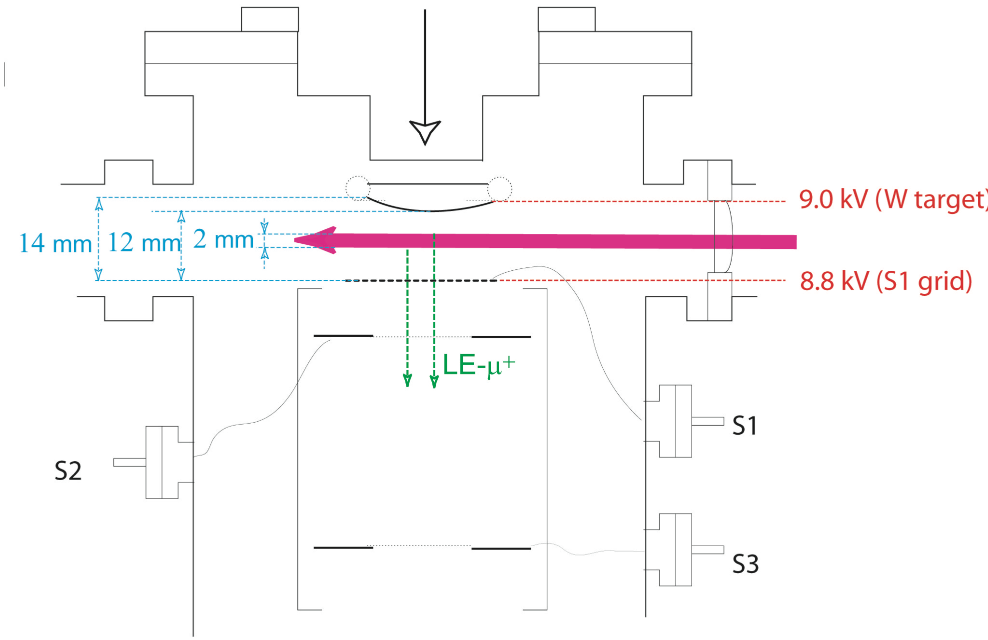
Measured using muonium spin precession

Muon implantation energy

Implantation energy range of **0-18 keV** controlled by applying potential on sample

Implantation depth in
Au : 0-55 nm
Cu : 0-73 nm
Al : 0-135 nm





Energy resolution of the LE-μ^+ beam

Initially only 0.2eV (thermal energy)

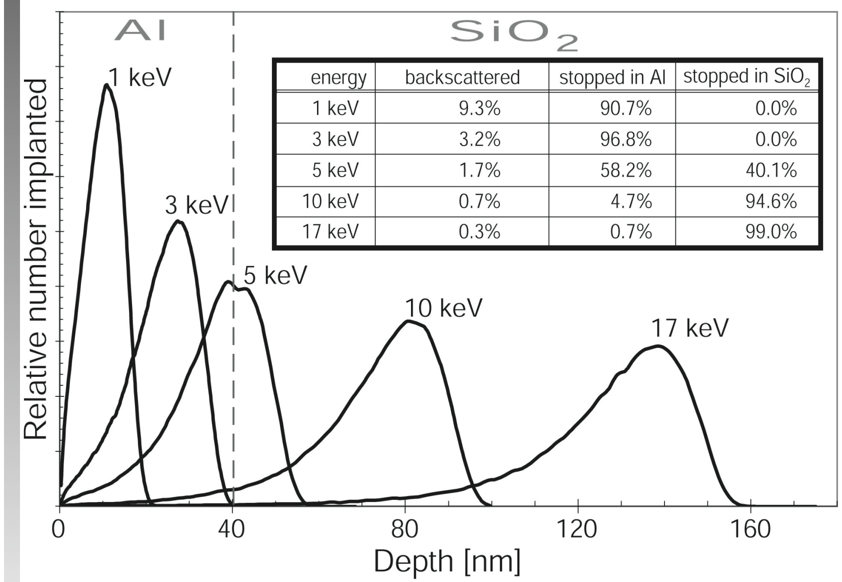
Energy resolution at sample determined by extraction i.e. differences in potential seen by individual muons:

- Width of the laser ionization region (σ_E=~13 eV)
- Uneven distance between W and S1 (σ_E=~4 eV)
- Differences due to laser beam alignment (σ_E=~4 eV)

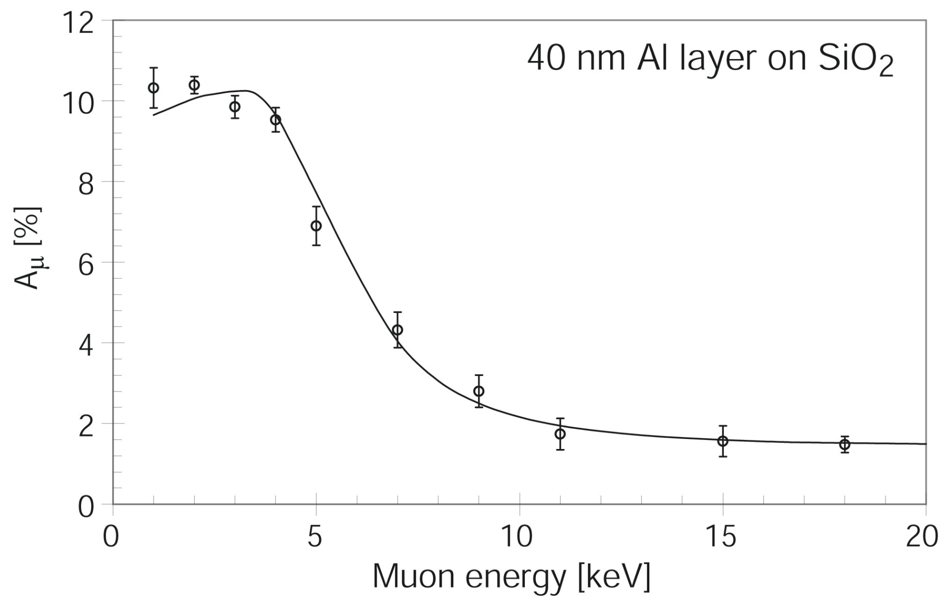
⇒ σ_E = 14 eV (33 eV at FWHM)

Energy dependence of A_μ in Al(40 nm) on SiO_2

We have demonstrated that we can control muon implantation range within 10nm resolution by changing energy of LE-muons.
→ **provides magnetic probe with depth resolution on nm scale**

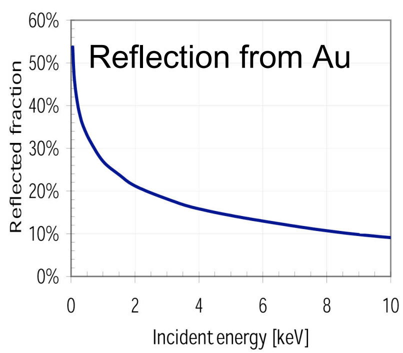


energy	backscattered	stopped in Al	stopped in SiO_2
1 keV	9.3%	90.7%	0.0%
3 keV	3.2%	96.8%	0.0%
5 keV	1.7%	58.2%	40.1%
10 keV	0.7%	4.7%	94.6%
17 keV	0.3%	0.7%	99.0%

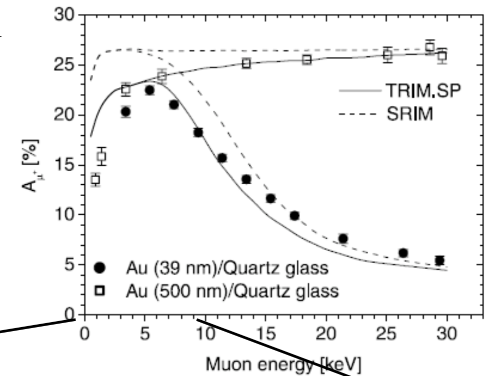


The LE muons are transported through the LE muon beamline at 9 keV. Muon energy is controlled by applying a potential on the sample in the range of 9.0 kV to -9.0 kV giving control over the **implantation energy in the range of 0 – 18 keV**.

Muon implantation at very low energies



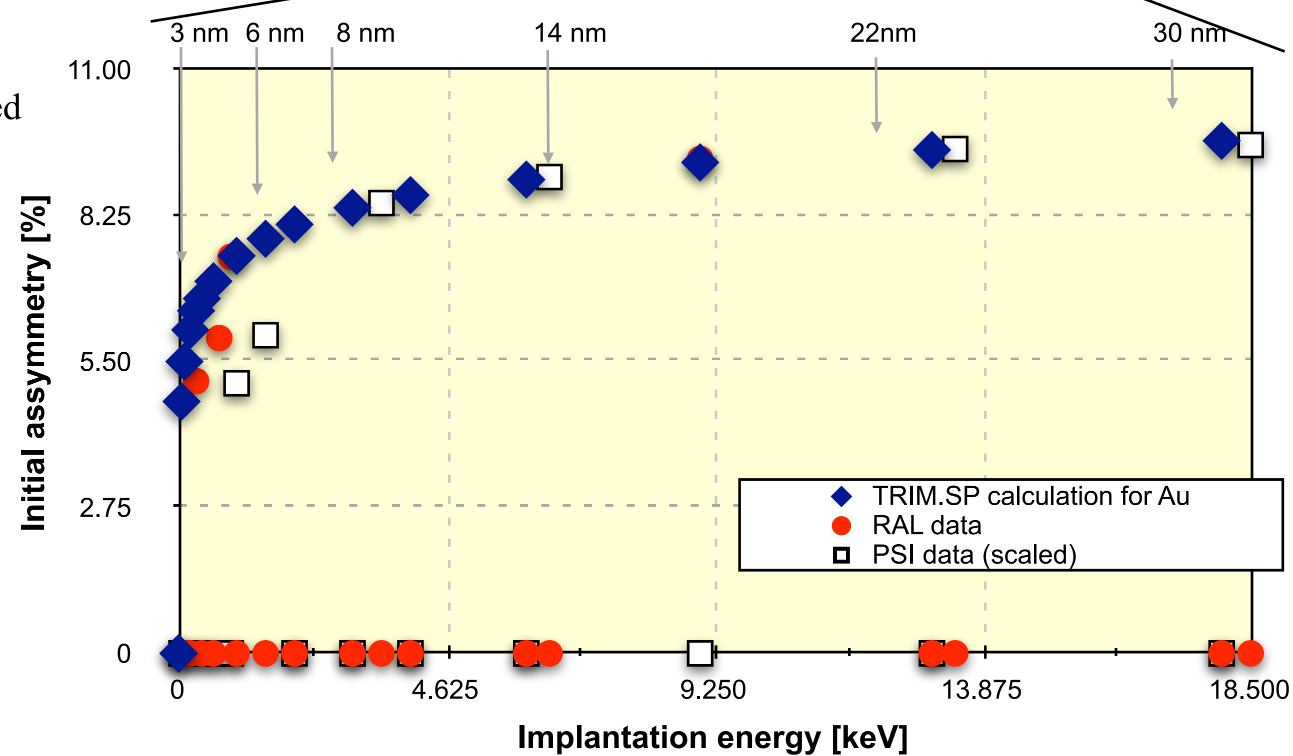
E. Morenzoni et al., NIM B 192 (2002) 254–266



Au sample

At low incident energies (E < 3 keV) :

- large fraction is reflected
- nearly all reflected muons form muonium

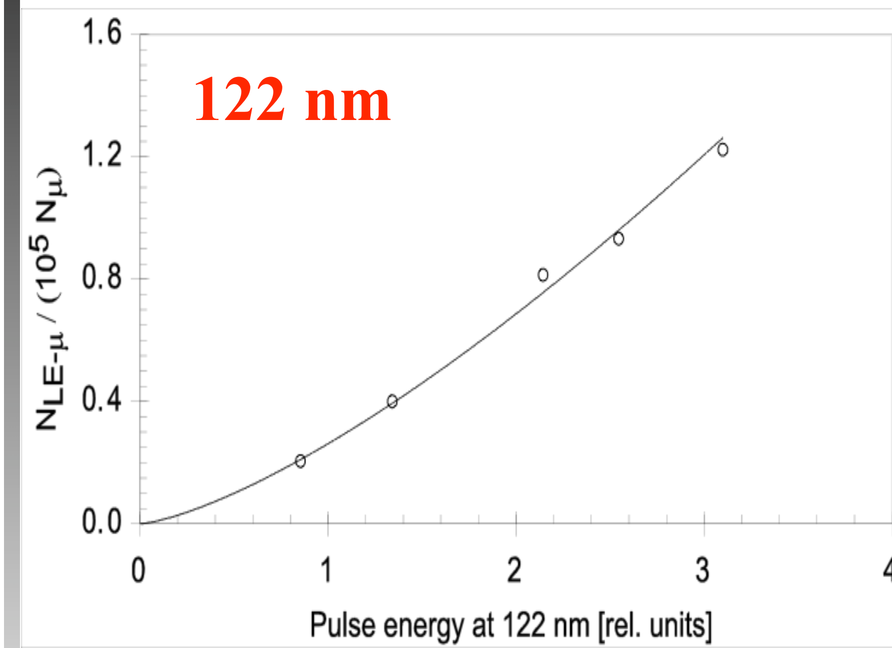


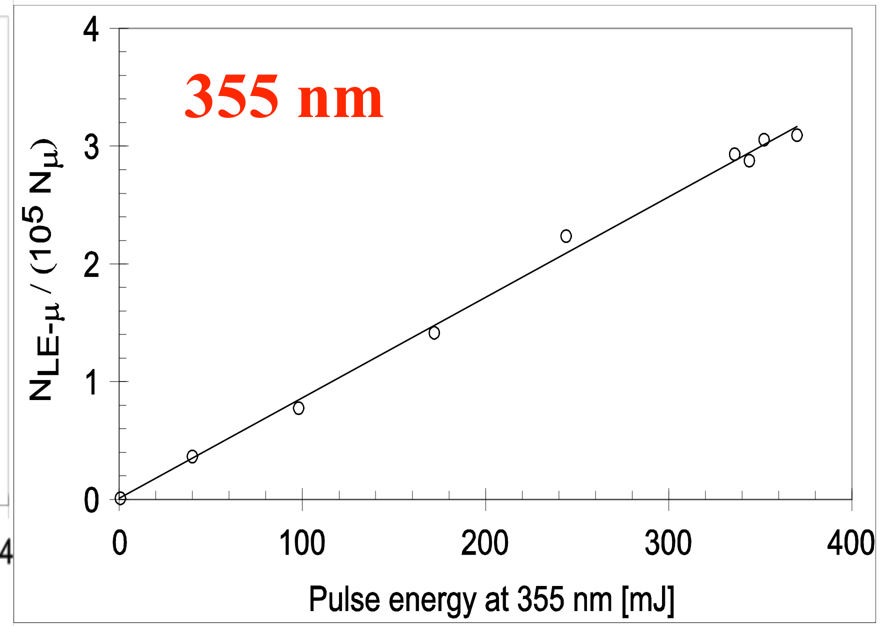
Efficiency of LE muon generation

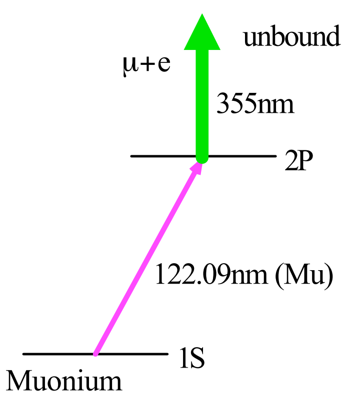
	RIKEN-RAL (muonium ionization)	PSI (cryogenic moderator)
Surface muon beam intensity	$1.2 \times 10^6\ \mu^+$/sec (50 Hz) $6 \times 10^5\ \mu^+$/sec (25 Hz)	$2 \times 10^8\ \mu^+$/sec (new beamline)
LE μ^+/ intensity at sample	20 μ^+/sec	8000 μ^+/sec
Overall efficiency	**3×10^{-5}**	**4×10^{-5}**

Muonium ionization method is capable of much higher efficiency – potentially up to 10^{-3} level!

Dependence of yield on laser pulse energy

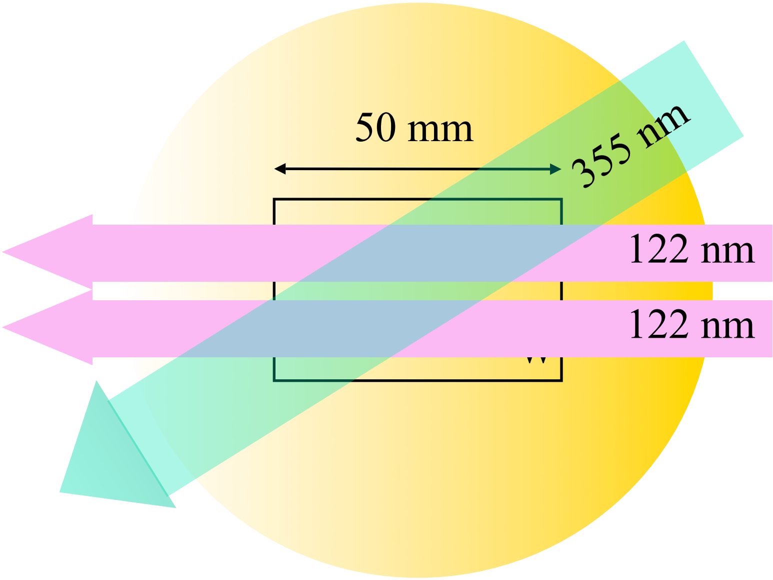






- VUV energy is currently in μJ range. While one of the brightest Lyman-α sources available there is still large scope for improvement!

Muonium ionization efficiency



1) Increase VUV laser pulse energy

We expect modest improvements to VUV energy : 50%
(In principle muonium can be ionized with close to 100% efficiency, with ~ 100 μJ at 122 nm)

2) Increase muonium density

- Tighter focusing of the incident muon beam would allow better overlap with laser
- increasing W target surface area (laser drilled or porous W, tungsten coated aerogel)
- SiO2 aerogel

Other factors increasing the number of LE muons available at sample:

- Planned upgrade of ISIS proton current from 200 μA to 300 μA → immediate 50% increase
- Increasing the thickness of muon production target from 10 to 15 mm
- Increasing the acceleration voltage in LE muon beamline from 9.0 kV to 18.0 kV
  (TOF reduced by ~400 ns i.e. 16% increase in μ^+ on sample)

More intense VUV?

Can we get more intense 122 nm beam from different laser system?

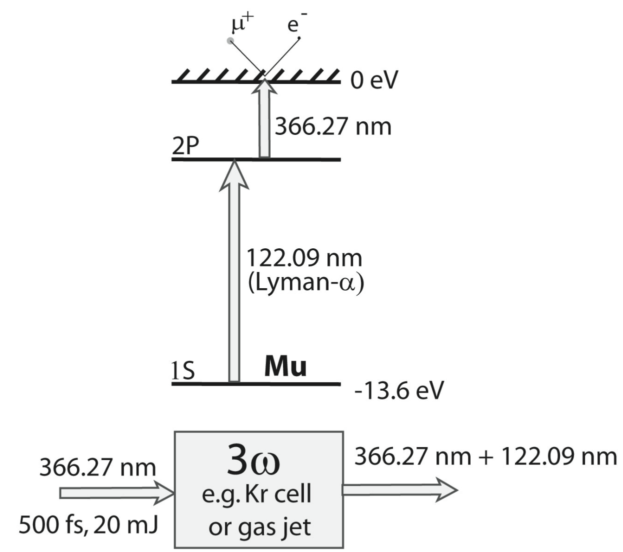
C. Dölle et al., Appl. Phys. B 75, 629–634 (2002)
Generation of 100 μJ pulses at 82.8 nm by frequency tripling of sub-picosecond KrF laser radiation

Non-linear conversion efficiency in gases is typically 10^{-4} to 10^{-7} but in this case it is claimed to be 0.7% !

100 μJ pulses at 82.8 nm generated by frequency tripling (249 nm) in Ar gas jet.

On the other hand: Ganeev RA, Usmanov T, J. OPTICS A 2 (6): 550-556 NOV 2000:
350 nm ps pulses converted to 116.6 nm with 8×10^{-4} efficiency (max. 2.4 μJ)

If this conversion efficiency can be reproduced with 0.5 ps pulses at 366.27 nm it could:
- increase the muonium ionization efficiency to nearly 100% (with ***100 μJ pulses)***
- greatly simplify the laser system (only one wavelength needed & need to overlap several laser beams is eliminated)
- automatically match the Doppler broadened bandwidth of Mu since the transform limit would be about 300 GHz
- time resolution of LE-μ^+ would be reduced to ~ 1 ns (limited by extraction ion optics)



366.27 nm generated by SHG solid-state system at 732.54 nm (e.g. Ti:Sapphire)

Main features of the of this method

- **Positive**
  - Timing determined by laser pulse, which is externally triggered
  - Pulse duration only 7.5 ns (comparable to continuous source) and independent of the surface muon pulse structure
  - Good energy resolution ~ 14 eV– (in principle as low as 0.2 eV)
  - Extremely low background
  - Small beam spot size
  - Efficiency of conversion from surface muon beam can be, in principle, as high as 10^{-3}.

- **Negative**
  - Only suitable for pulsed sources with low repetition rate
  - Inherent loss of muon polarization (50%) - BUT can be recovered

Summary - Present characteristics

Low energy μ^+ beam	μSR spectrometer
Intensity at sample ~ **15-20 μ^+/s** Beam diameter (FWHM): **4 mm** Energy at target region **0.2 eV** Energy after re-acceleration **0.1-18 keV** Energy uncertainty after re-acceleration ~14 eV Pulse repetition rate **25 Hz** Single pulse structure 7.5 **ns** (FWHM) at 9.0 keV Spin polarisation ~**50%**	Background: <0.01 per 15 μs after μ^+ pulse Count rates: ~ **50 kev/hour** (compared to 20-50 Mev/hour @ bulk μSR at ISIS) TF : < **60 mT** ZF compensation to 0.1 μT Sample temperature: **10K-300K** **External LE-μ^+ trigger**

J-PARC facility

– projected muon intensity ~ 10^8 μ^+**/s** (comparable to current PSI beam)
– projected smaller diameter of the surface muon beam
– 25 Hz operation (double pulse structure – 600 ns separation)

We can expect more than **10^4 LE-μ^+/s in <10 ns pulse**

Comparison with PSI LE-muon beam

	PSI	RIKEN-RAL	LE-muons @PSI	LE-muons @RIKEN-RAL
time structure	DC	pulsed	DC	pulsed
beam intensity	$5x10^{7}$/sec	10^{6}/sec	$8x10^{3}$/sec	$2x10^{1}$/sec
external trigger capability	**No**	**Yes**	**No**	**Yes**
polarization	100%	100%	100%	50%
time resolution	**2nsec**	**100nsec**	**7nsec**	**7.5nsec**
implantation energy	**4.1MeV**	**4.1MeV**	**1y 30keV**	**0.1y 20keV**
energy resolution	0.4MeV	0.4MeV	500eV	14 eV
S/N (=N0/B0)	～150	～100000		**>10000**
observable relaxation time	5y 9000	200y 32000		20y 12000
beam size (FWHM)	**30mm**	**30mm**	**15mm**	**4mm**