Workshop “Advanced Ideas and Experiments for DNS-IV”
6 – 8 December, 2018, Dubna

Muon physics at proton accelerator

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Why muons?

The popularity of muons in basic and applied research is due to the properties of the muon:

- τ_μ=2,2 mks;
- m_μ=106 MeV/c^2 which is 1/9 proton mass and 207 electron masses;
- a magnetic moment μ_μ is 3.2 times larger than that of the proton.

The muons interact mostly electromagnetically with surrounding atoms and molecules in matter.

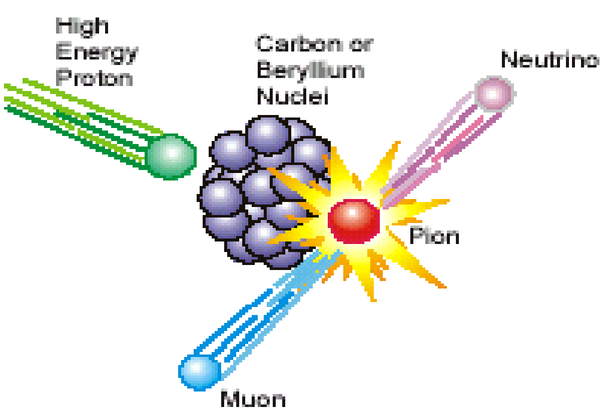
What is a Muon?

$$p + p \rightarrow \pi^+ + p + n,$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

	charge	spin	mass	moment	γ / 2π (kHz G^{-1})	lifetime (μs)
e	$\pm e$	1/2	m_e $= 0.51$ MeV	657 μ_p	2800	∞
μ	$\pm e$	1/2	207 m_e $= 105.7$ MeV	3.18 μ_p	13.5	2.19
p	$\pm e$	1/2	1836 m_e $= 938$ MeV	μ_p	4.26	∞



Muon beams are made here on earth using high-energy protons to produce short-lived pions.

- **A muon is a spin 1/2 particle.**
- **Helpful for to think of a *positive* muon as a *light proton*.**
- **Muons live only for 2.2 us (on average!).**
- **When implanted in a solid, the muon behaves as a *microscopic magnetometer*.**

Obtain a *time histogram* of positron count rate;

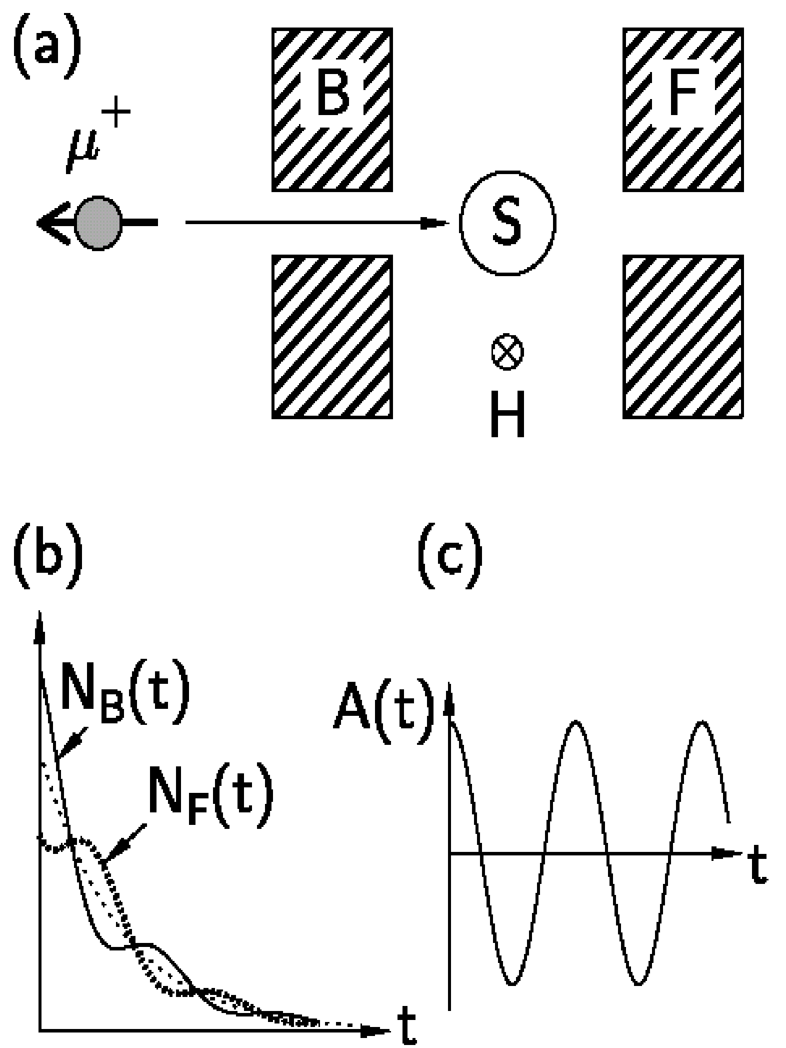
- Typically 10^6–10^8 events recorded. 10 min–10hr.

$N_{B(F)}(t) = N_0 exp(-t/t_{\mu})[1+A_0P(t)]$

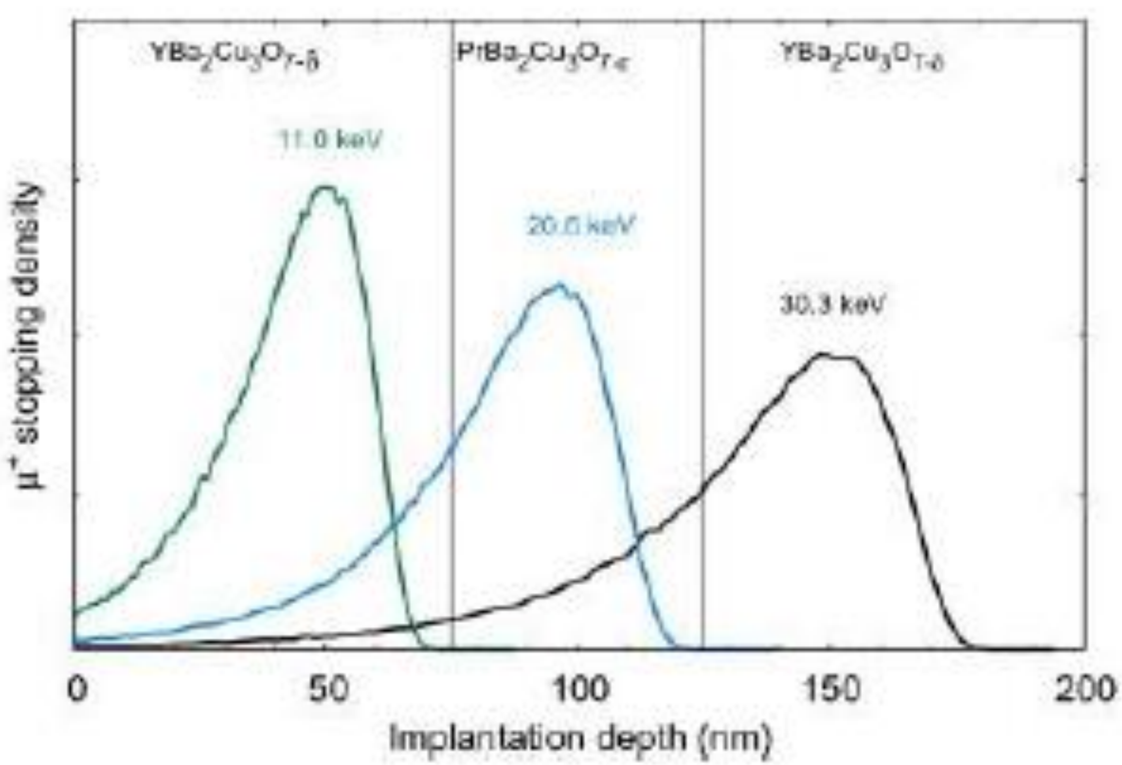
Asymmetry plot: time evolution of muon spin polarization.

$A(t) = A_0P(t) =$
$[N_B(t)N_F(t)]/[N_B(t)+N_F(t)]$

Schematic illustration of a μSR experiment

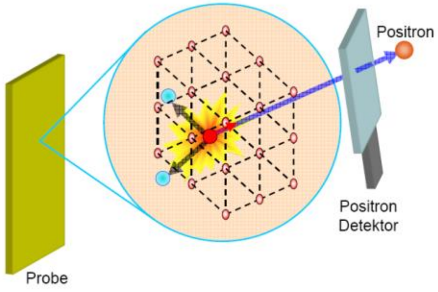


Example of low energy muon stopping profiles in a YBa2Cu3O7 (75nm) – PrBa2Cu3O7(50nm) – YBa2Cu3O7 (75nm) heterostructure, showing the layer by layer sensitivity.(PSI)



Advantages of μSR

The muon is a local probe



2 μs

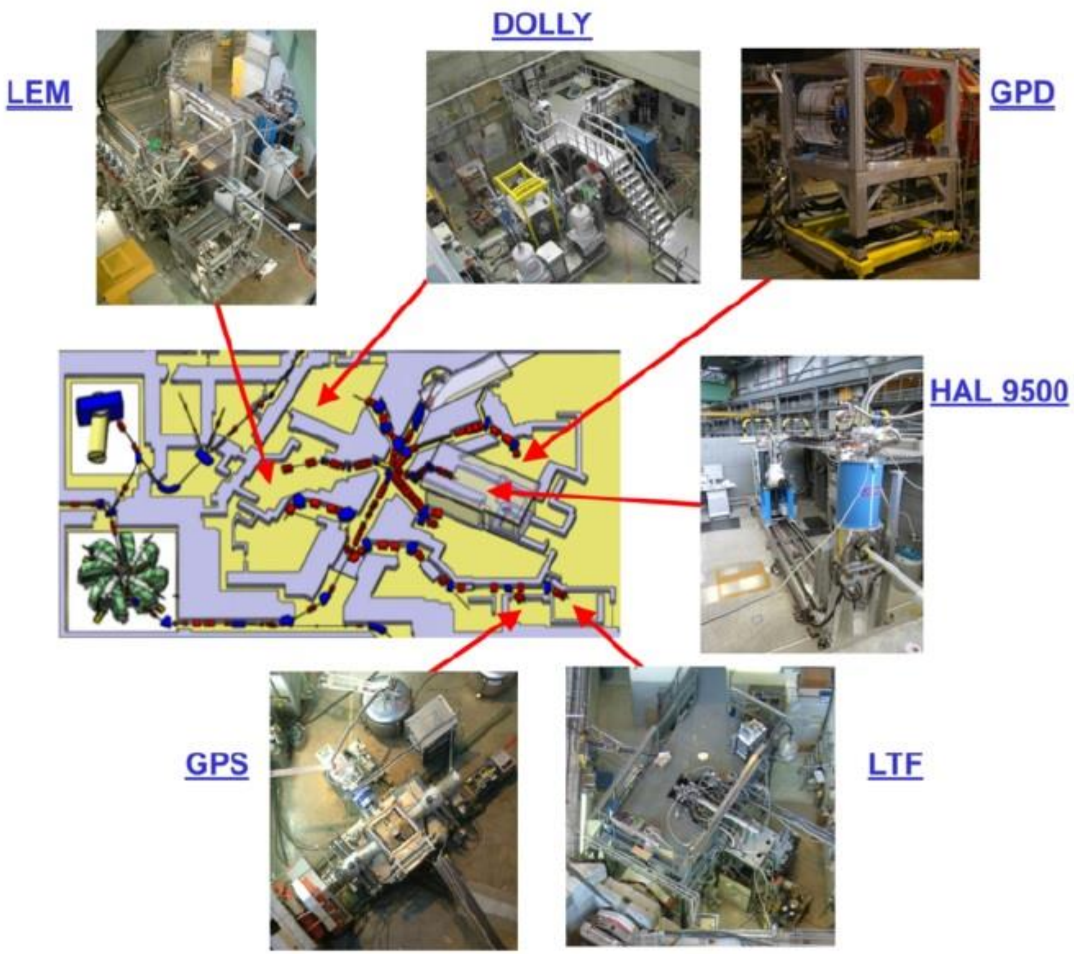
- Can be used on any system – No problems with neutron absorbing or NMR unfavorable nuclei;
- A local probe – No need to search a reciprocal space (but need scattering to obtain structure);
- Extremely high sensitivity – Can easily detect magnetic moments ~ 10^{-3} μ_B;
- Needs no applied field, unlike NMR;
- Simple spin -1/2 probe;
- it can be used to follow an **order parameter** as a function of temperature, it works very well at milli-Kelvin temperatures (the incident muons easily pass through the dilution refrigerator windows),
- Can provide information about internal magnetic field distributions, magnetic fluctuations and spin dynamics, even above the magnetic transition temperature.
- The technique can also be used to obtain dynamical information through the anisotropy of the electron-nuclear hyperfine interaction.

Proton beams

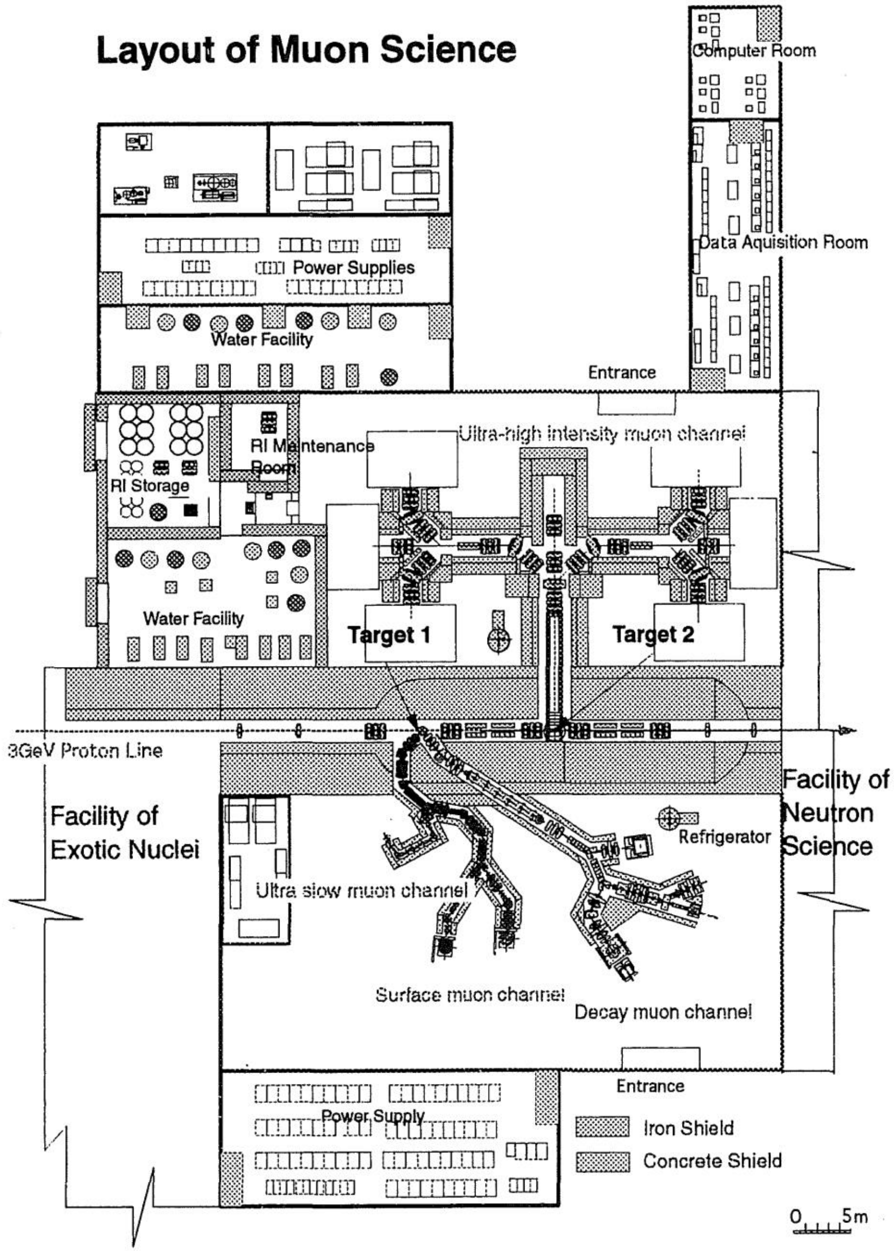
Accelerator	PSI	TRIUMF	ISIS/RAL	ESS	JPARC	SNS
Proton energy, Gev	0.590	0.520	0.800	2.5	3	1.2
Proton intensity	2.2 mA	0.15 mA	0.2mA	50 mA(macro -puls)	1MW, $6.44*10^{13}$ p/puls	2 mA (2 MW)
Beam time structure	50 MHz, 2 ns	23 MHz	50 Hz, 80 ns, $4x10^5$ μ^+ / s	14 Hz, 2.86 ms (RF 352 MHz)	25 Hz 30 ns (slicer) (RF 1.23-1.67 MHz)	60 Hz, < 1.0 μs
Number of muon beamlines	6	4	5	(8)	6	
Tasks performed	muSR, mu-e-gam, mu3e	**muSR, muon properties**	**muSR**		**muSR, muon properties**	

Twice a year, the International Committee reviews the proposals, selects the best and allocates time on the instruments. The competition is very strong.

PSI

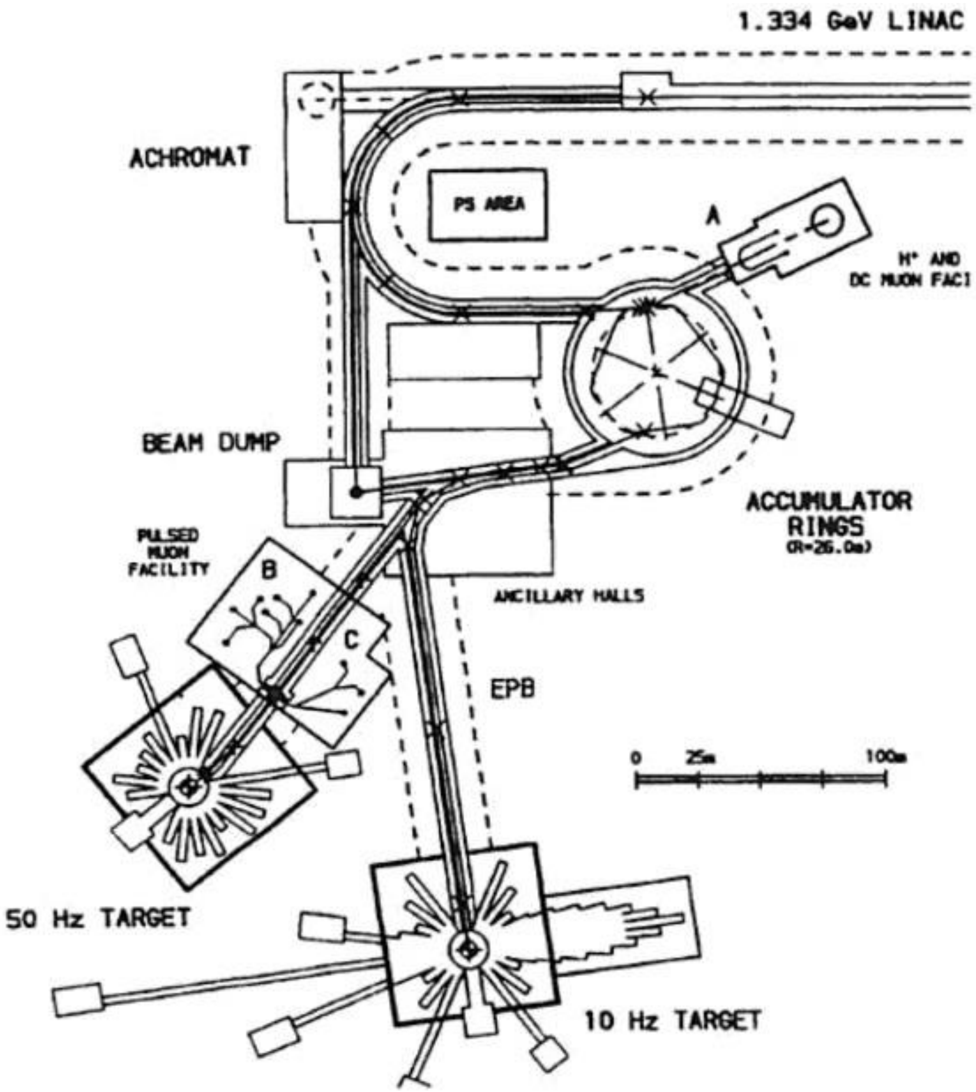


J-PARC



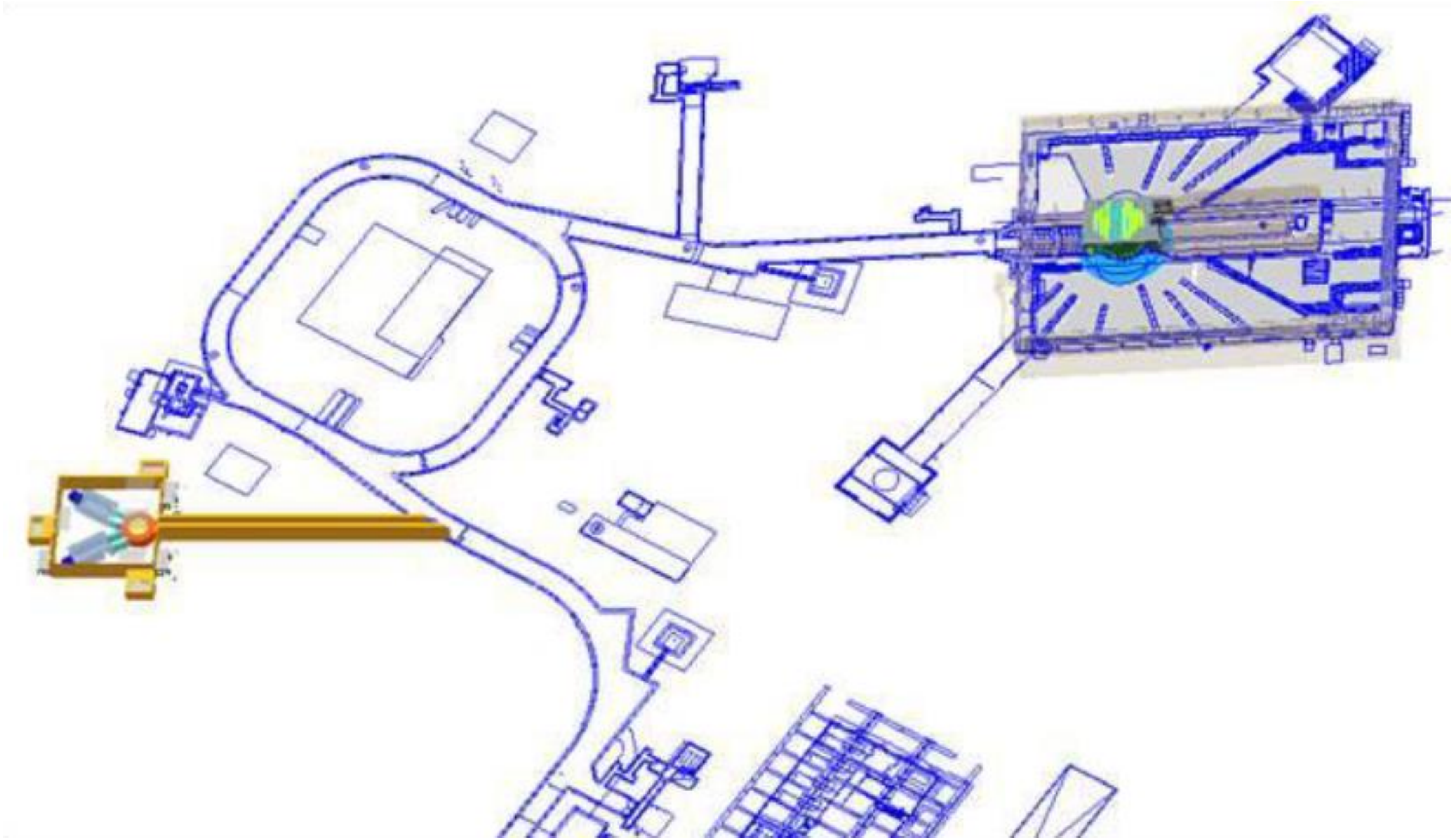
Layout of Muon Science
Computer Room
Data Aquisition Room
Power Supplies
Water Facility
Entrance
Ultra-high intensity muon channel
RI Maintenance Room
RI Storage
Water Facility
Target 1
Target 2
3GeV Proton Line
Facility of Exotic Nuclei
Facility of Neutron Science
Refrigerator
Ultra slow muon channel
Surface muon channel
Decay muon channel
Entrance
Power Supply
Iron Shield
Concrete Shield
0 5m

ESS



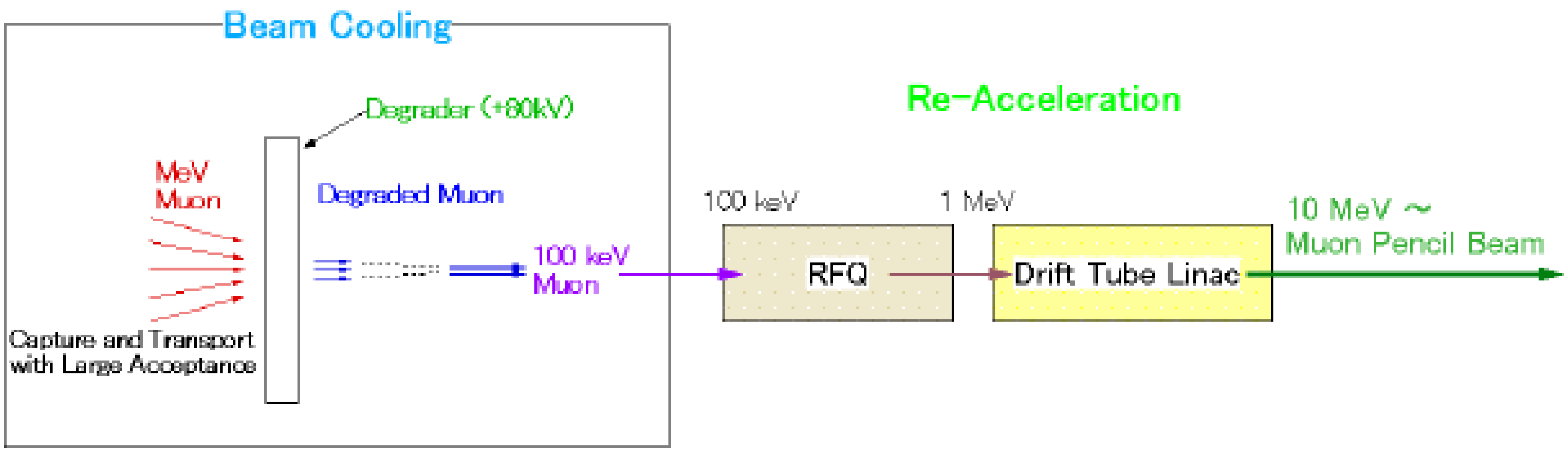
1.334 GeV LINAC
ACHROMAT
PS AREA
A
H⁺ AND
DC MUON FACI
BEAM DUMP
ACCUMULATOR
RINGS
(R=26.0m)
PULSED
MUON
FACILITY
B
C
ANCILLARY HALLS
EPB
0
25m
100m
50 Hz TARGET
10 Hz TARGET

SNS began to think about muon beams. Again…



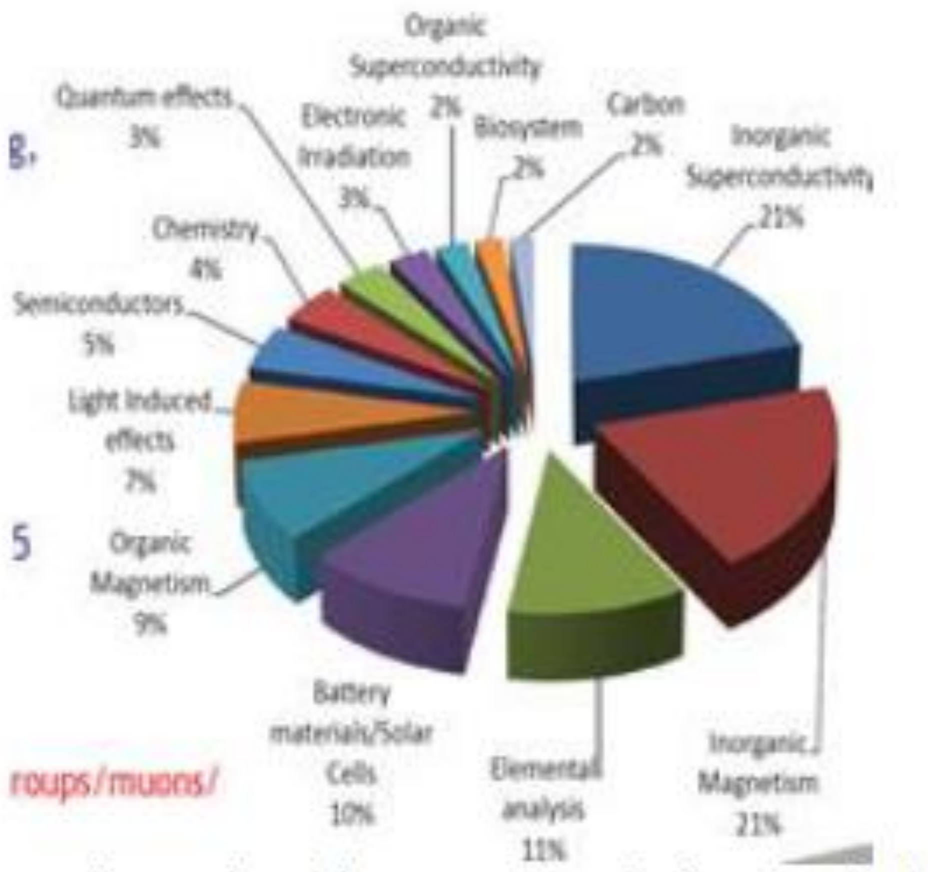
SEE facility @ SNS - allows to level the temporal structure of the beam.
Williams, Travis J., and MacDougall, Prof. Gregory J. Future Muon Source Possibilities at the SNS. United States: N. p., 2017. Web. doi:10.2172/1364319

Muon microbeam production



Design studies show this muon micro-beam will be a 10 MeV straight beam, with a narrow spatial size (<1 mm diameter), narrow energy width (a few 0.1 %) and a high luminosity of $10^9/(cm^2s)$.

Distribution of science topics (ISIS/RAL)



Conclusions

1. The muons are produced parasitically and have the time structure of the neutron source or alternative options are to kick a fraction of the beam onto a dedicated target.

2. Muons at DNS-4 would significantly enrich the spectrum of material research possibilities at one location.

3. Muons at high rates from a multi-MW proton driver could open new dimensions for particle physics, both for searches for rare decays and for the determination of fundamental constants.

THANK YOU FOR ATTENTION