Muon spectrometer design for the first muon facility in China

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In collaboration with

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China Spallation Neutron Source, IHEP

30th Oct 2023

The 24th International Collaboration of Advanced Neutron Source (ICANS XXIV)

Outline

I Brief introduction to muons

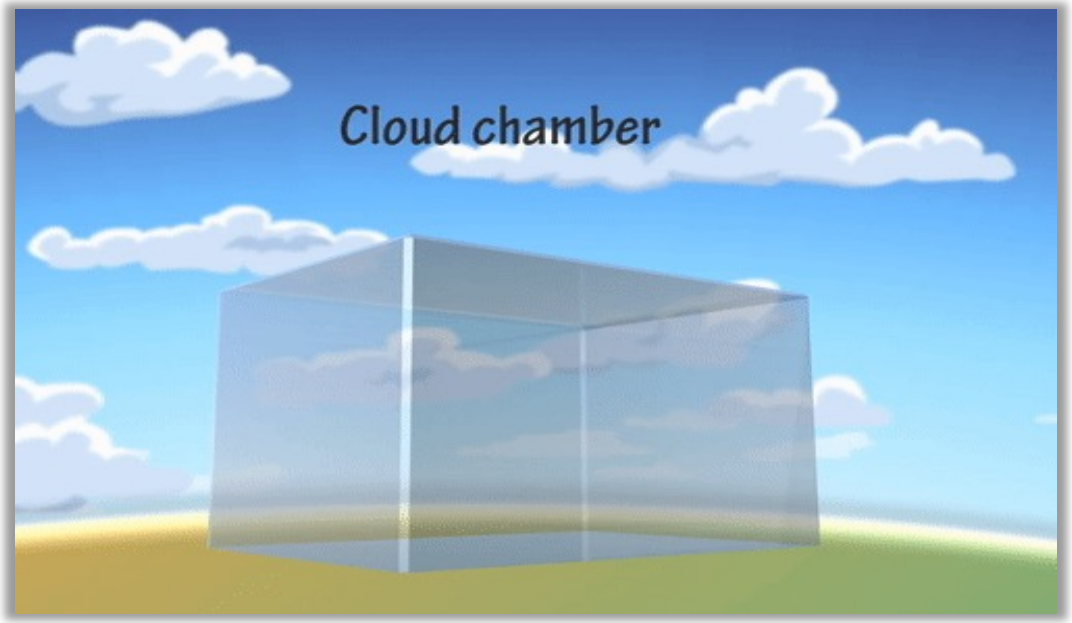
II Development of the demonstrator

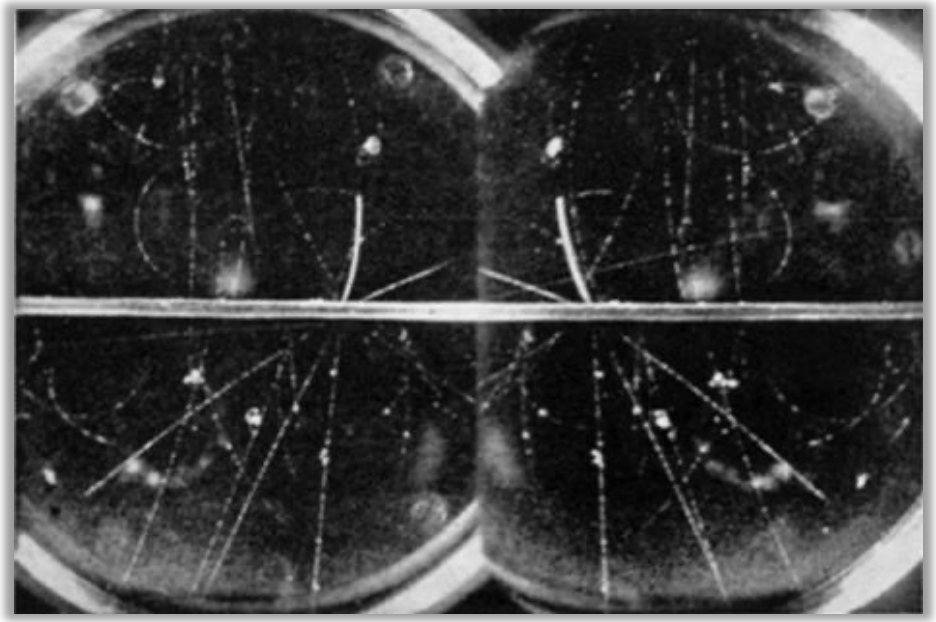
III Design of the SiPM-based spectrometer

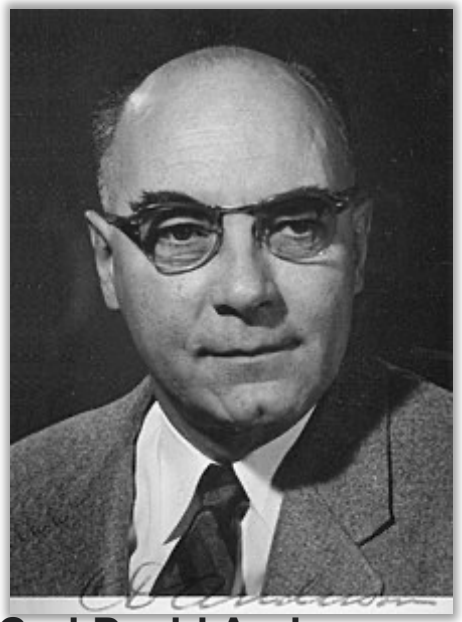
IV Summary and prospects


I. Brief introduction to muons
CSNS

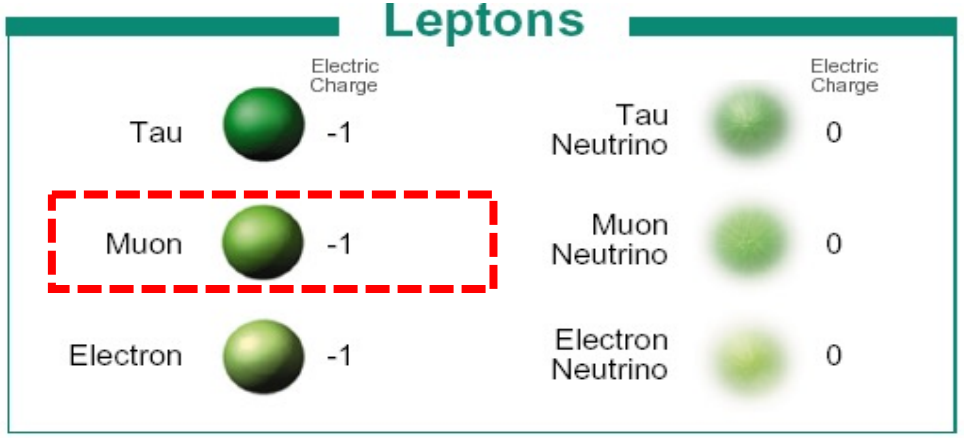
1.1 Physical nature of muons





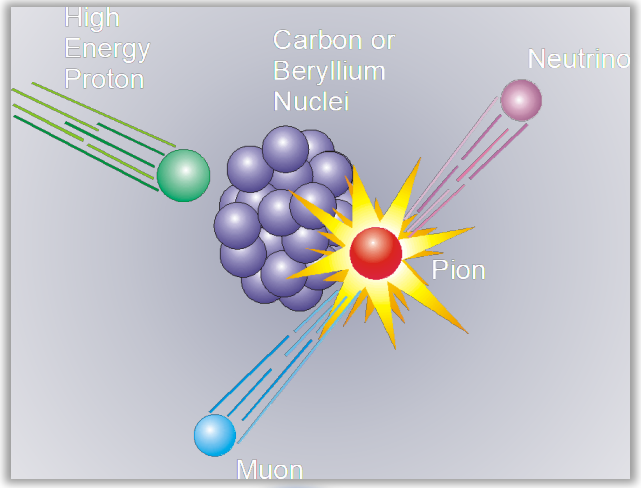


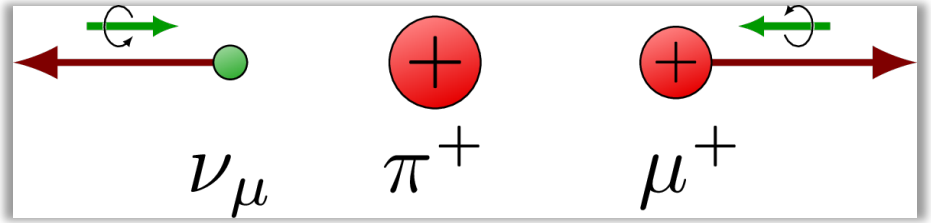
Carl David Anderson
(1905-1991)

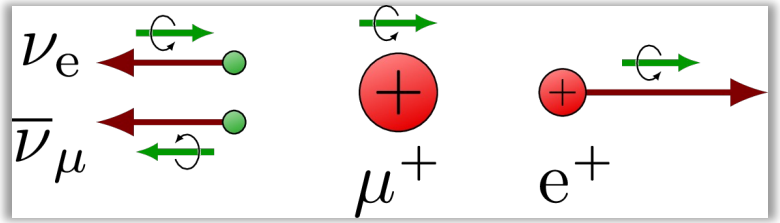


	charge	spin	mass	moment	$\gamma / 2\pi$ (kHz G^{-1})	lifetime (μs)
e	$\pm$e	1/2	m_e = 0.51 MeV	657 μ_p	2800	∞
μ	$\pm$e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	13.5	2.19
p	$\pm$e	1/2	1836 m_e = 938 MeV	μ_p	4.26	∞

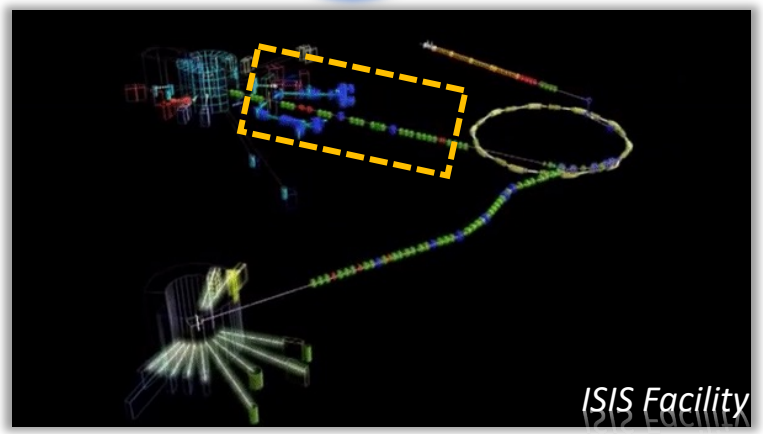
1.2 Generation of polarized muon beams

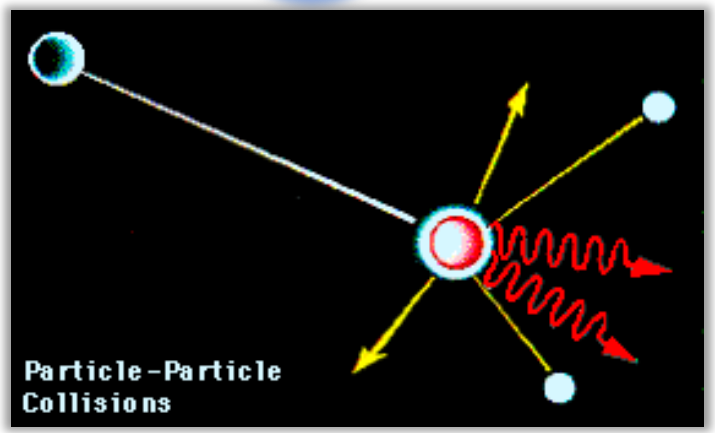


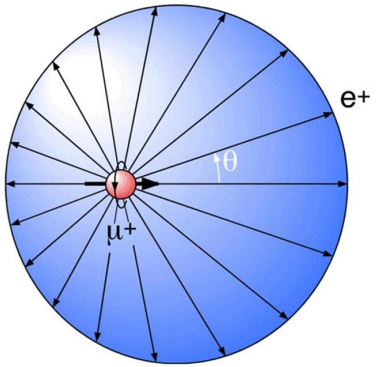




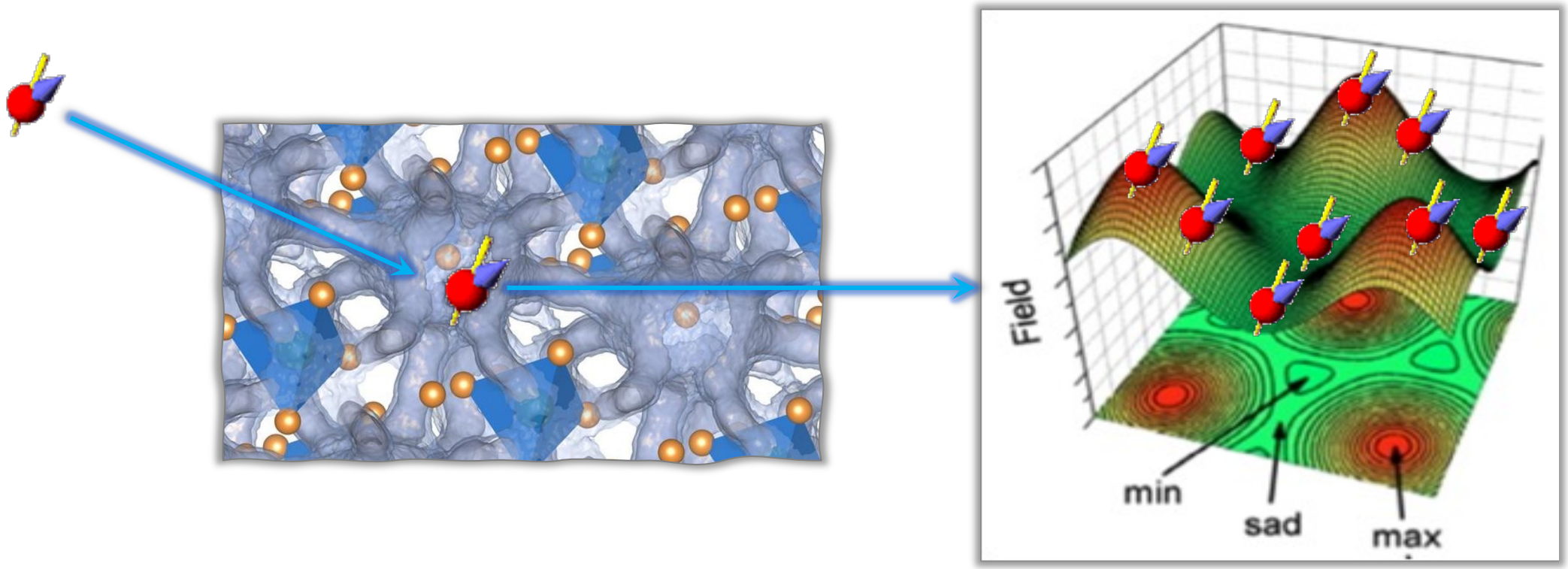
Target → **π^+** → **μ^+**







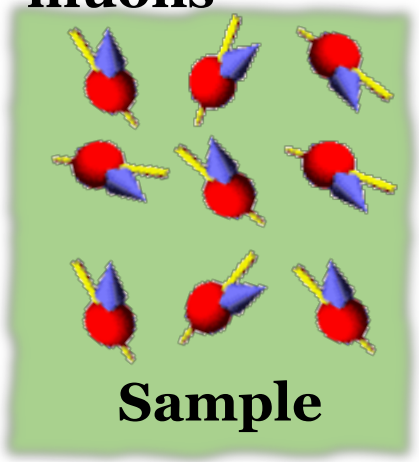
μSR: muon spin rotation/relaxation/resonance



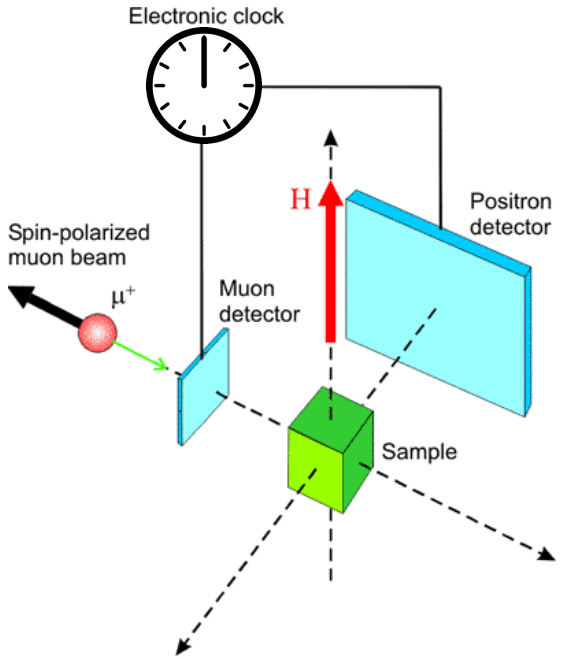
A quantum magnetism probe

1.3 Principles of μSR spectroscopy

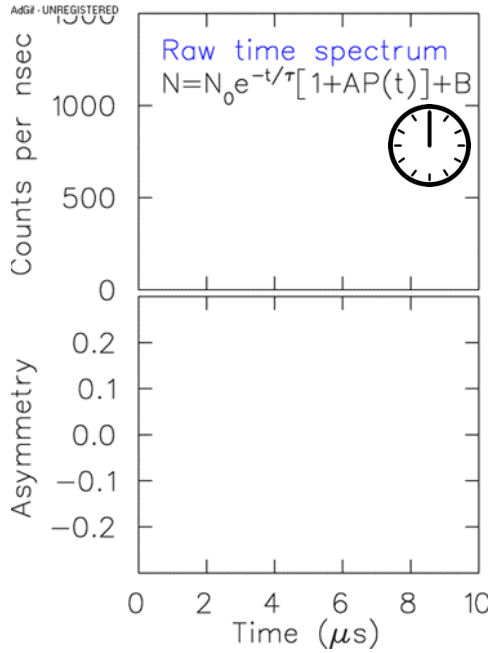
Precession (spin interaction) → **Asymmetry** (positron detection) → **μSR spectra** (analysis) → **Material** (properties)



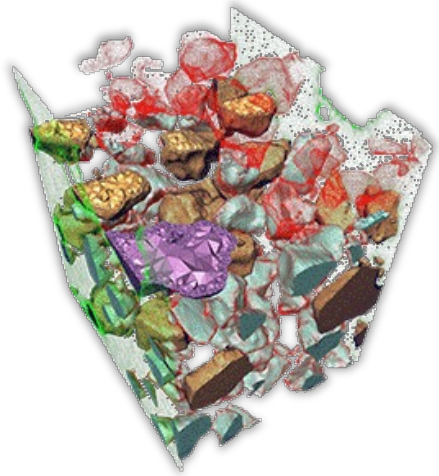
$$\frac{\mathrm{d}\boldsymbol{S}_\mu(t)}{\mathrm{d}t} = \gamma_\mu \boldsymbol{S}_\mu(t) \times \boldsymbol{B}_{\mathrm{loc}}(\mathrm{t})$$



$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

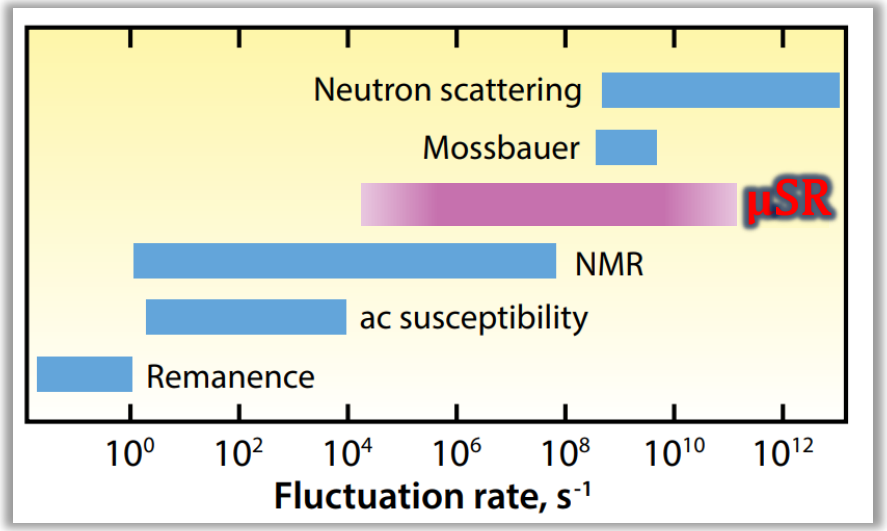


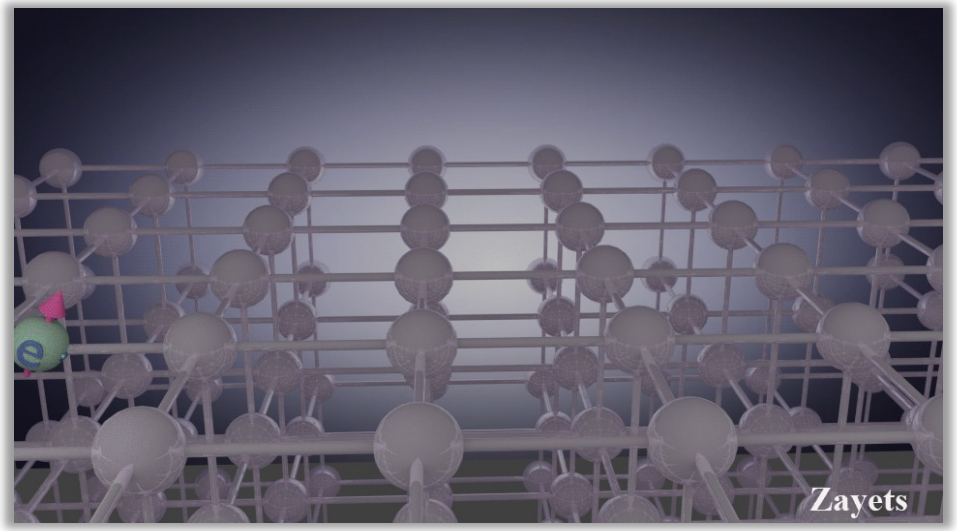
$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = A\boldsymbol{P}(t)$$



$$G_z(t) = \frac{1}{3} + \frac{2}{3}(1 - \boldsymbol{\Delta}^2 t^2) e^{-\frac{\boldsymbol{\Delta}^2 t^2}{2}}$$

1.4 Advantages of μSR spectroscopy





- **Unique & wide time scale** (complementary to NMR/neutron scattering)
- **Very weak effects** (small moment magnetism ~ 10^{-3} μ_B/Atom)
- **Random & inhomogeneous magnetism** (e.g. spin glasses)
- **Short range order** (where neutron scattering is not sensitive)
- **Full polarization in zero field** (independent of temperature, unique measurements without disturbance of the system)
- **Single particle detection** (with extremely high sensitivity)
- **No sample restrictions** (in choice of materials to be studied)
- **A local quantum magnetic probe** (no need to search reciprocal space)

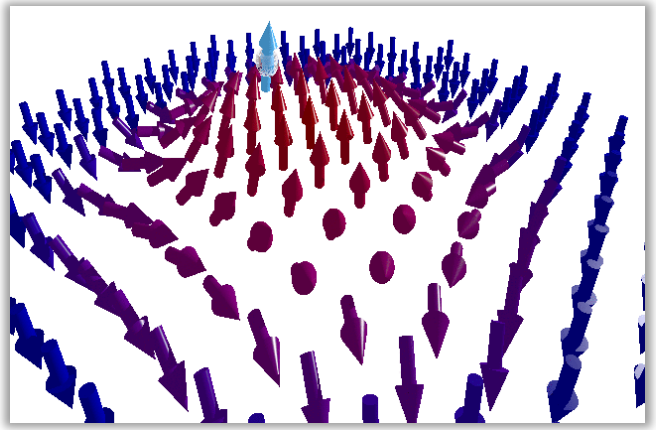
1.5 Applications of μSR spectroscopy

Passive probe

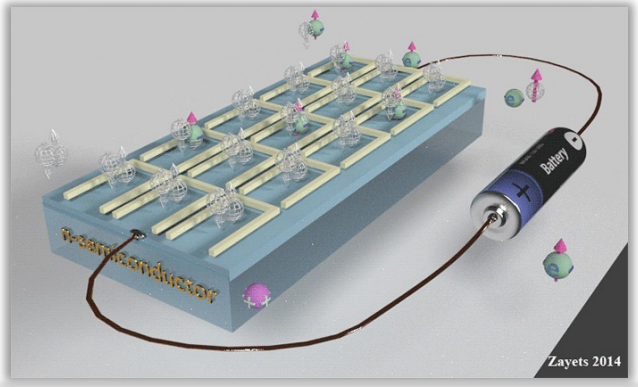
(heavy lepton)

Superconductor

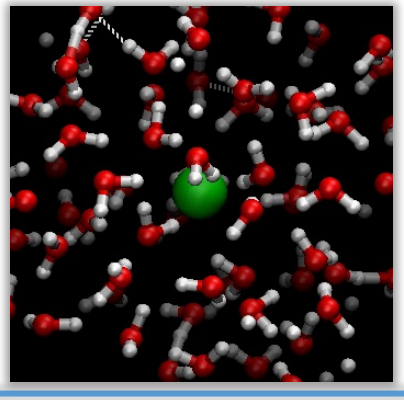
Magnetism



Charge transport



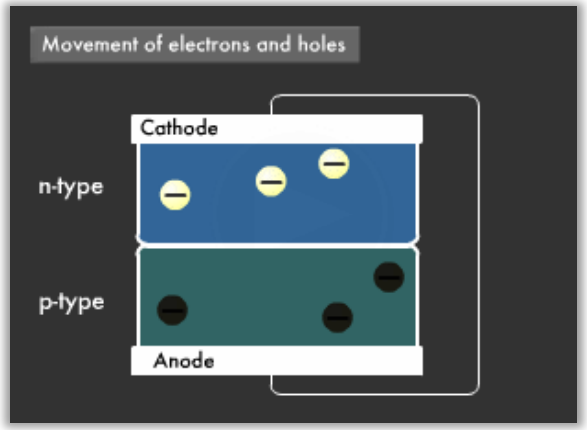
MD



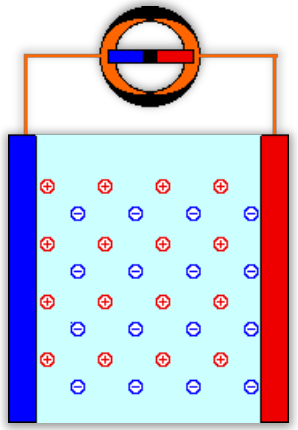
Active probe

(light proton)

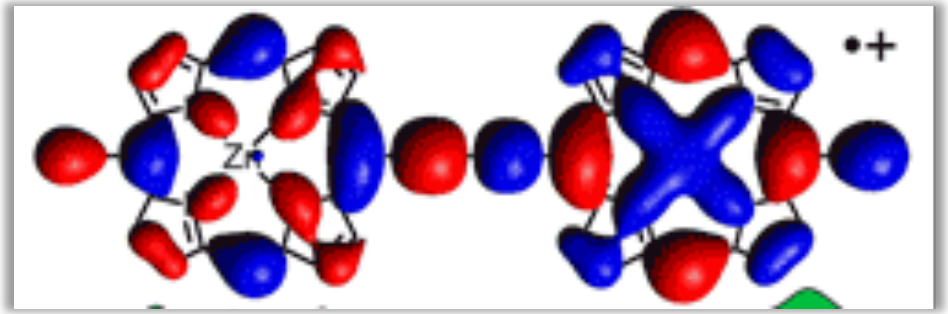
Semiconductor



Ionic conductor



Polaron motion



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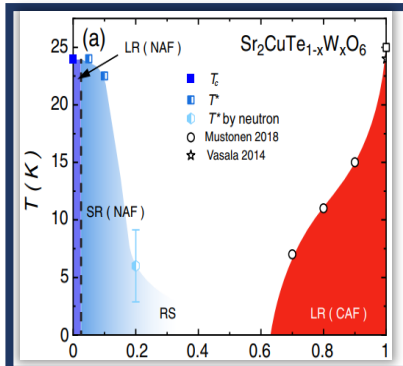
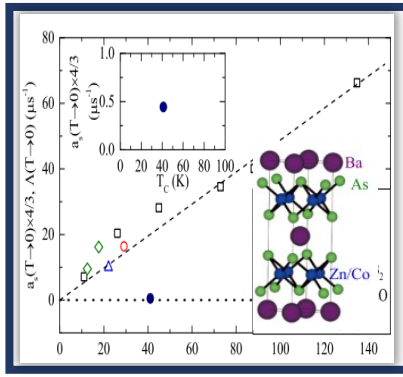
1.6 μSR research highlights @ China



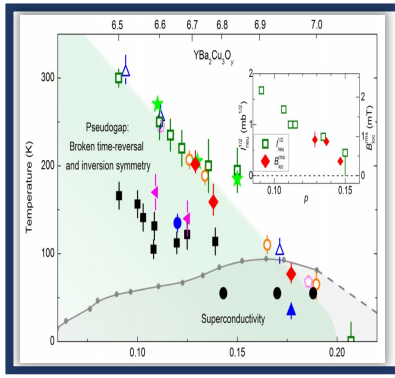
Prof. S.L. Li's group @ IOP, CAS 李世亮/物理所

- *Extreme Suppression of Antiferromagnetic Order and Critical Scaling in a Two-Dimensional Random Quantum Magnet,* **Physical Review Letters** *126, 037201 (2021)*
- Partially clarification of the doping evolution mechanism in two-dimensional quantum antiferromagnets



Prof. F.L. Ning's group @ Zhejiang University 宁凡龙/浙大

- *$Ba(Zn,Co)_2As_2$: A diluted ferromagnetic semiconductor with n-type carriers and isostructural to 122 iron-based superconductors,* **Physical Review B** *99, 155201 (2019)*
- Synthesized of a new type of dilute magnetic semiconductor and confirmed by μSR

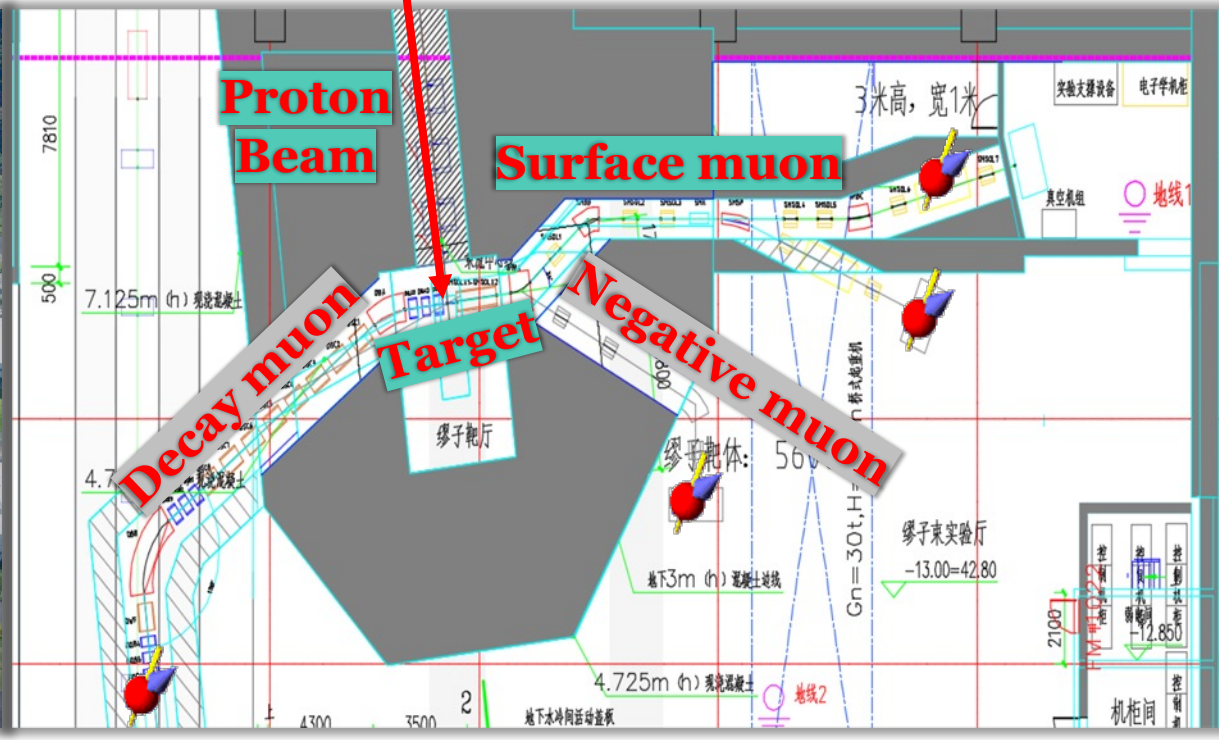


Prof. L. Shu's group @ Fudan University 殳蕾/复旦

- *Discovery of slow magnetic fluctuations and critical slowing down in the pseudogap phase of $YBa_2Cu_3O_y$,* **Science Advances** *4, eaao5235 (2018)*
- Breakthrough in research on pseudogap of high-temperature superconductors

1.7 Muon project @ CSNS, China

Muon station for sciEnce technoLOgy and inDustrY (MELODY) @ CSNS-II

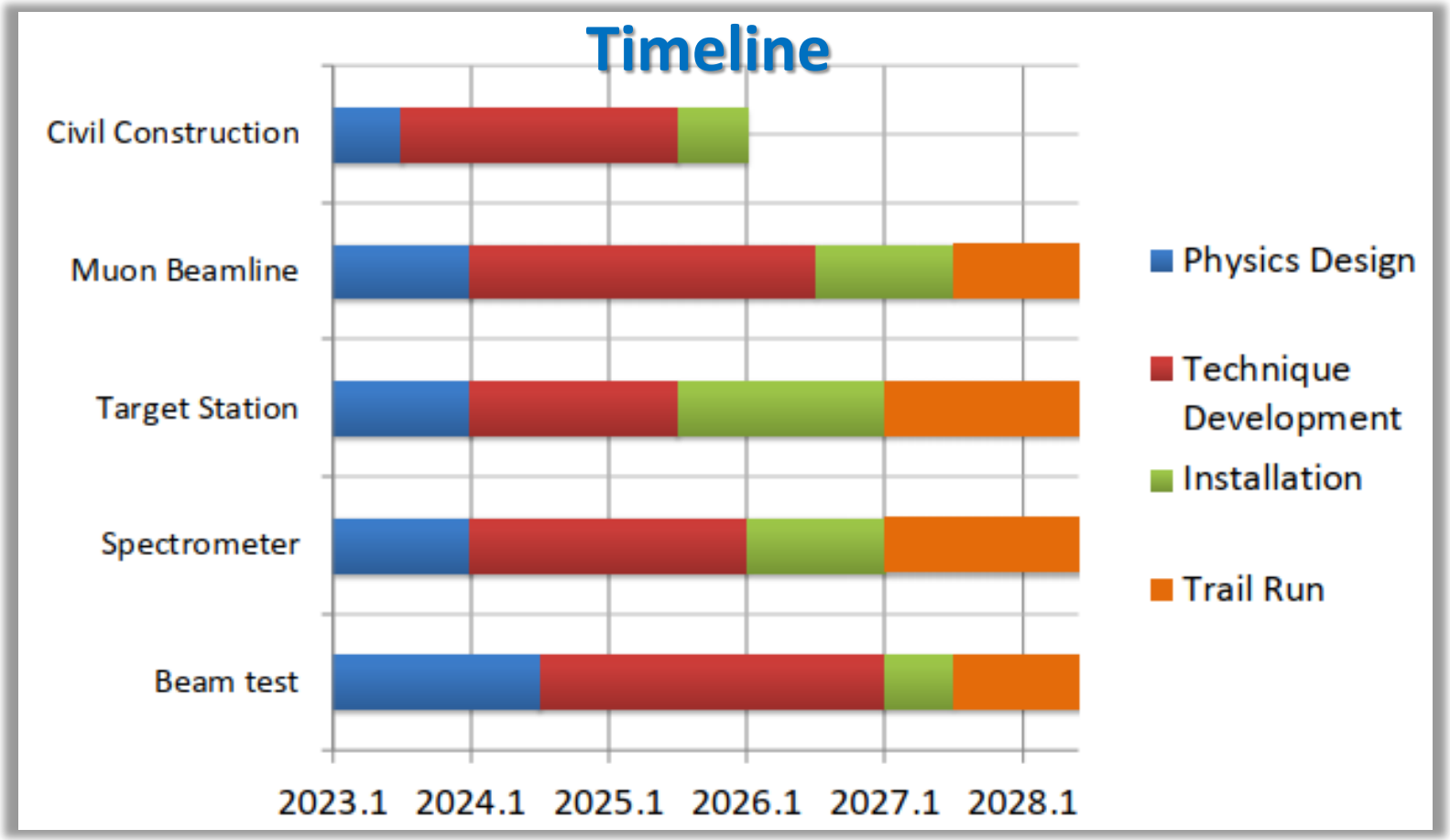


- Protons: 1.6 GeV, **1 Hz** (up to 5 Hz), **130 ns** double pulses
- Muon beamlines: **1 surface muon** beamline, **1** decay muon beamline, …
- Spectrometers: **1 μSR spectrometer** …

Details in Dr. Y Bao's talk!

Proceedings @ MuSR2020

1.7 Muon project @ CSNS, China



MELODY-CSNS:

- Team leader: Yu BAO
- Target station: Lei LIU et al.
- Beamline: You LV et al.
- Spectrometer: Qiang LI et al.

USTC collaborators:

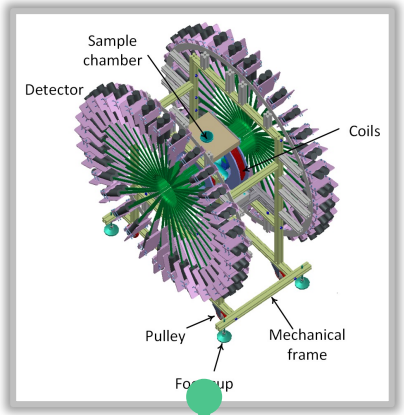
- Ziwen PAN, Bangjiao YE, et al.

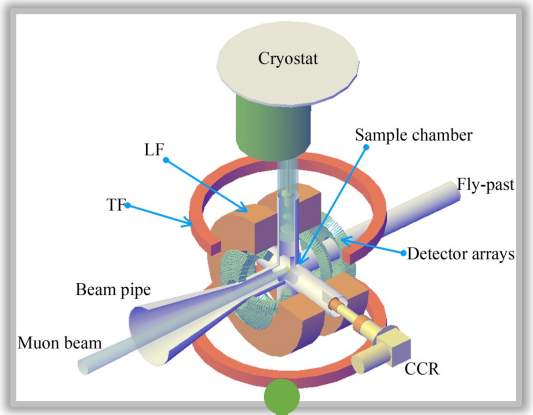
International collaboration:

- RIKEN: Isao WATANABE et al.
- ISIS: Adrian HILLIER et al.
- PSI: Thomas PROKSCHA et al.

Details in Dr. Y Bao's talk!

1.8 Collaboration in spectrometer development





USTC

SNS

Prototype R&D (2015-2020)

1st generation Demonstrator

Construction (2023-2028)

2nd generation SiPM Spectrometer

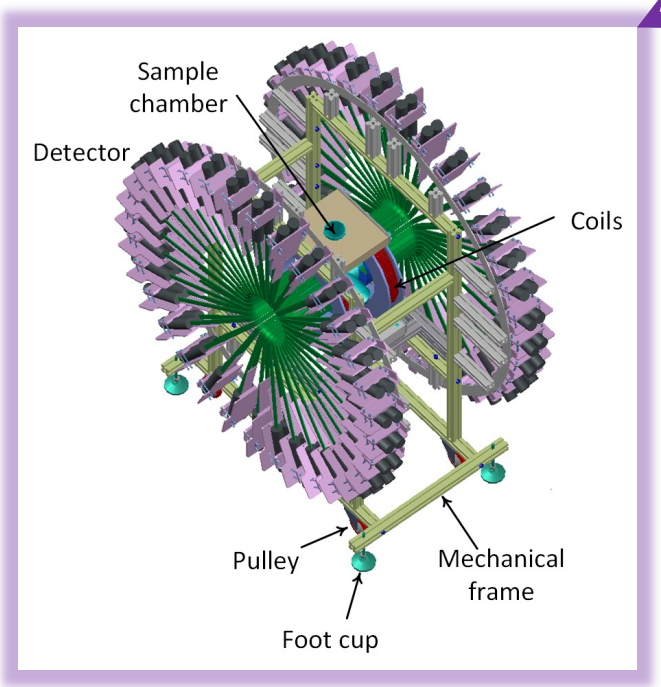
II. Development of the demonstrator

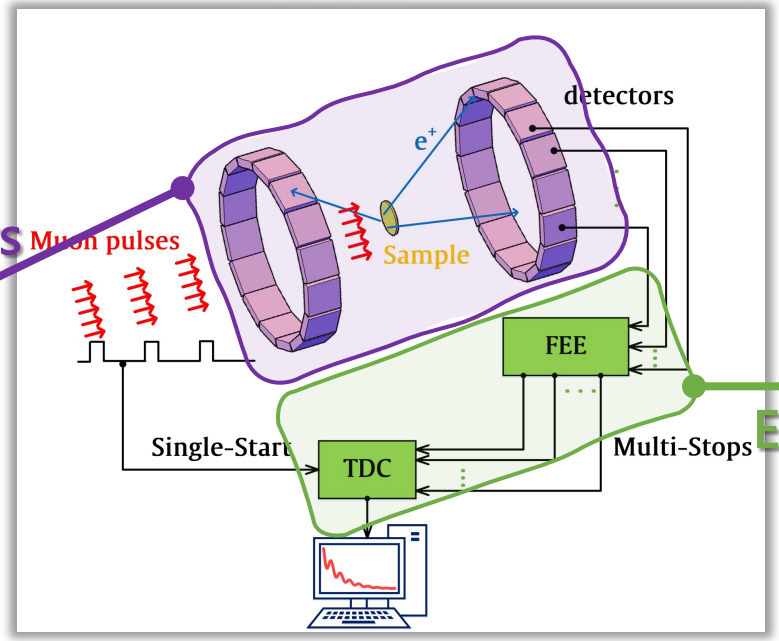
PMT

128-channel PMT-based μSR demonstrator

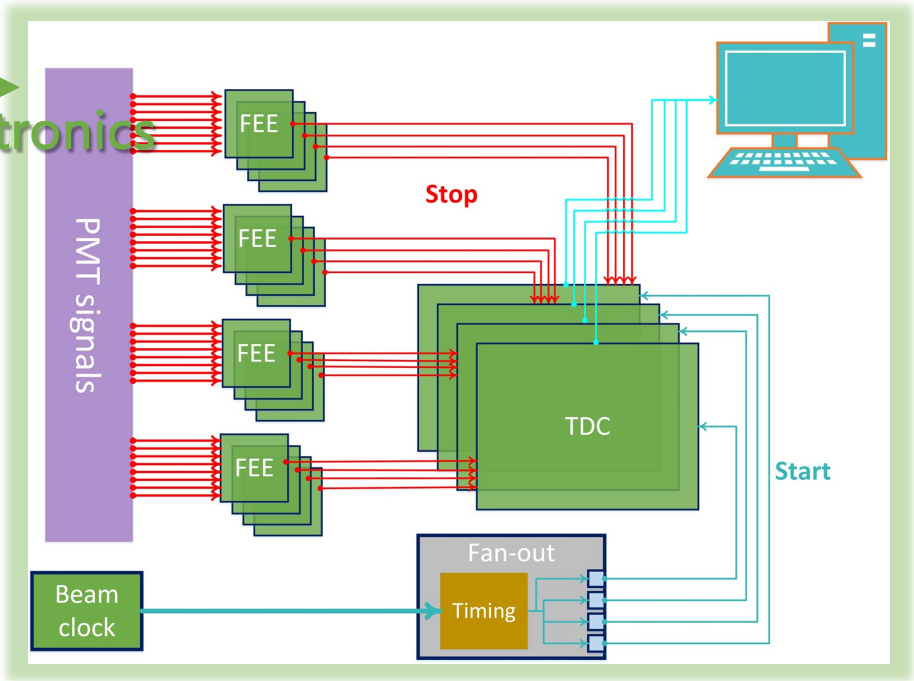
PMT: Photomultiplier tube
FEE: Front-End Electronics
TDC: Time-to-Digital Converter

Detectors



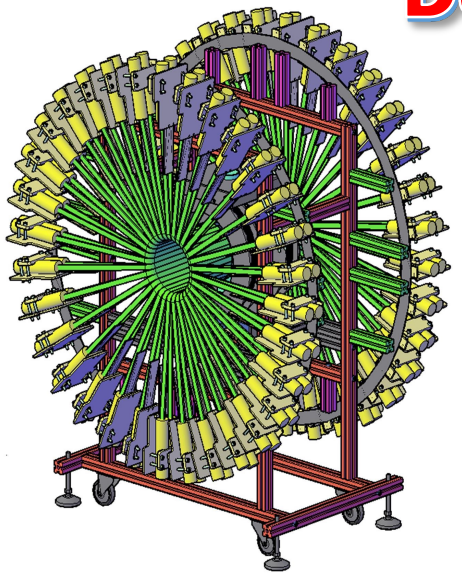


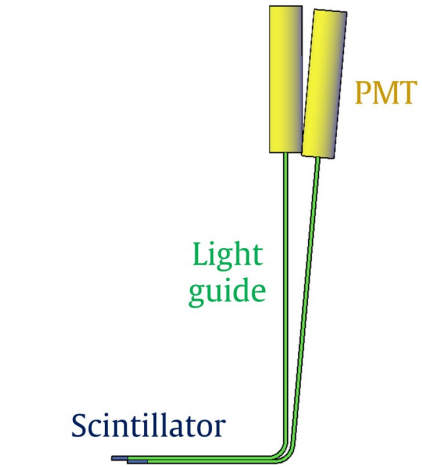
Electronics

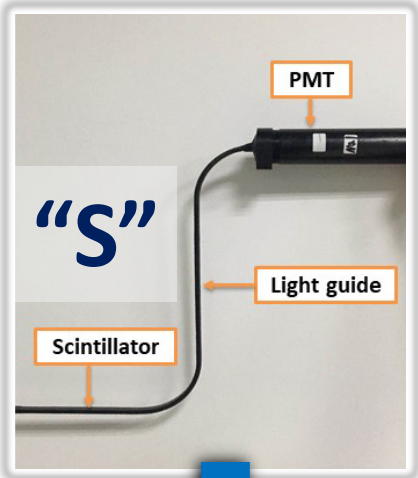


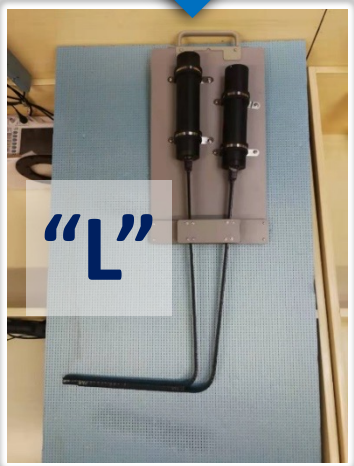
2.2 Prototype detectors and electronics

Detector

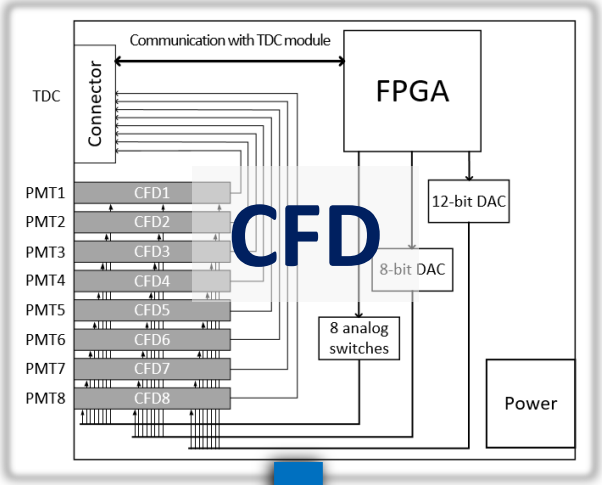


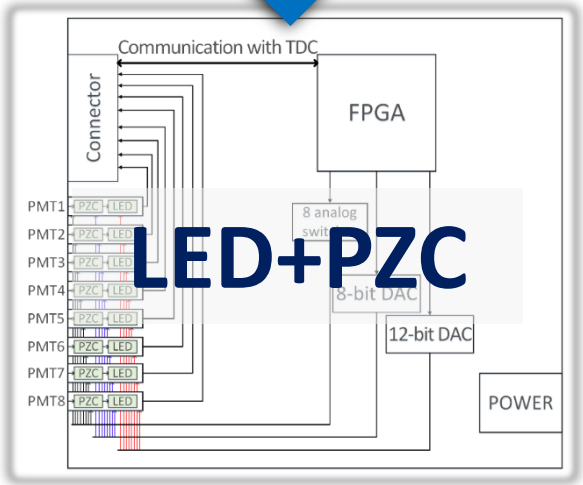




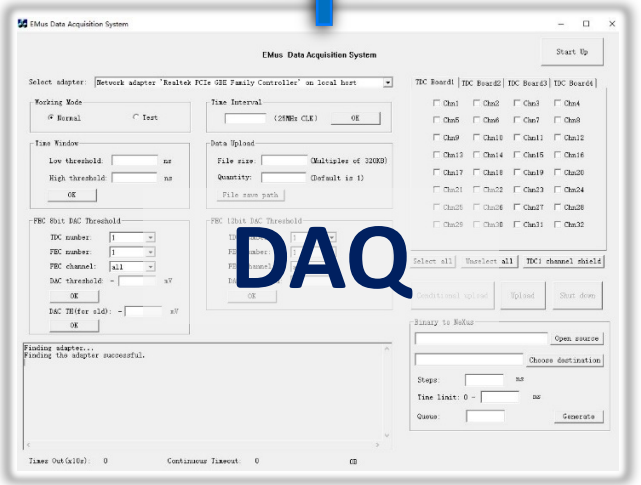


FEE





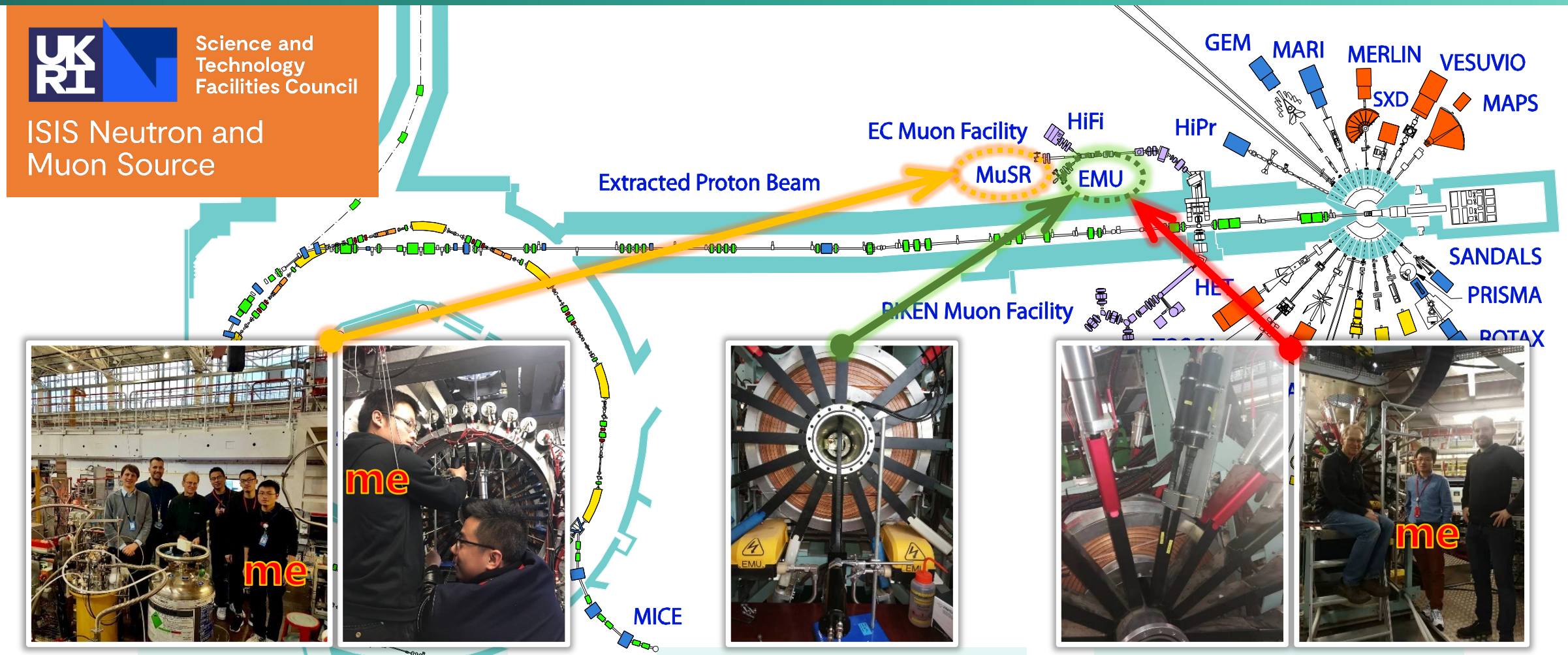
Readout



2.3 Beam tests

Science and Technology Facilities Council

ISIS Neutron and Muon Source



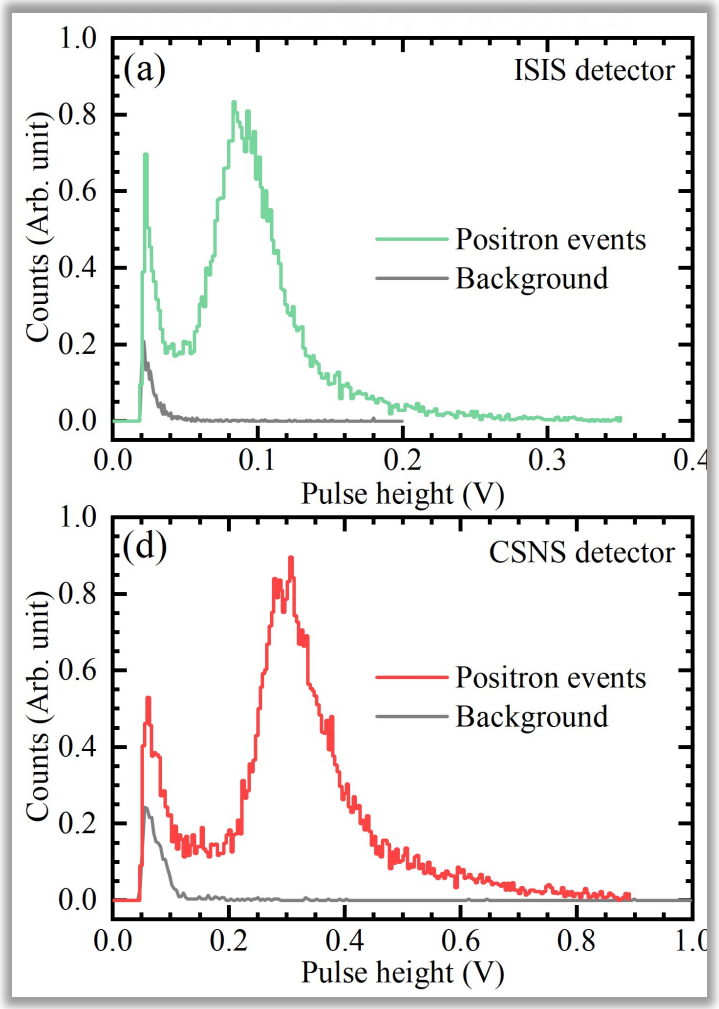
1st beam test
2018/03/14

2nd beam test
70 MeV H⁻ Linac
2018/09/25

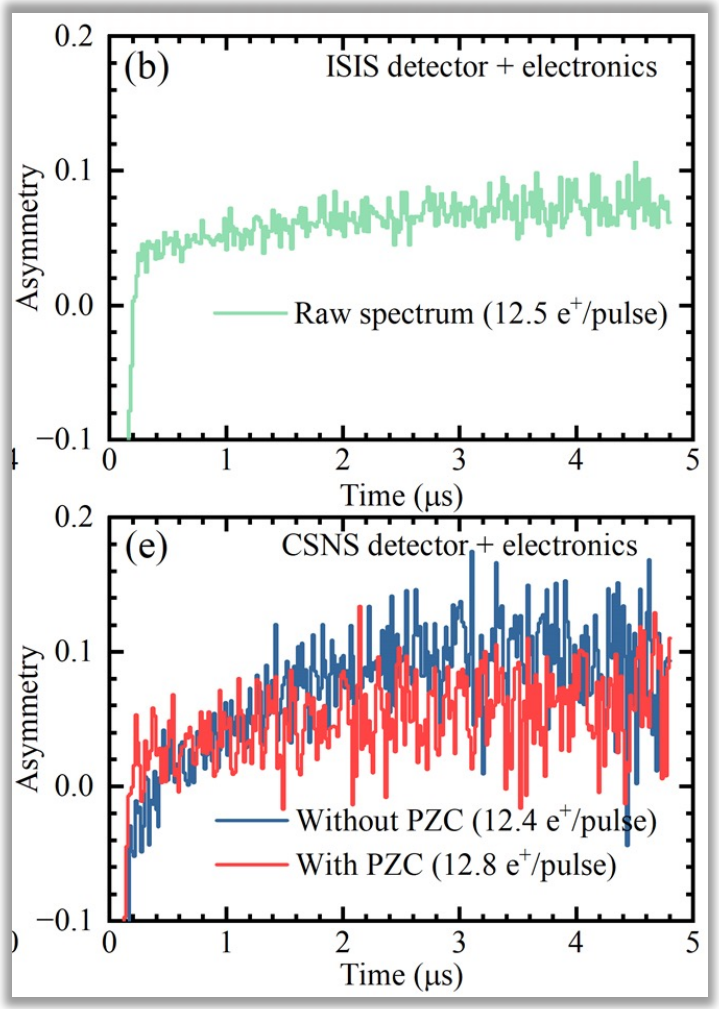
3rd beam test
2019/11/13

2.3 Beam tests

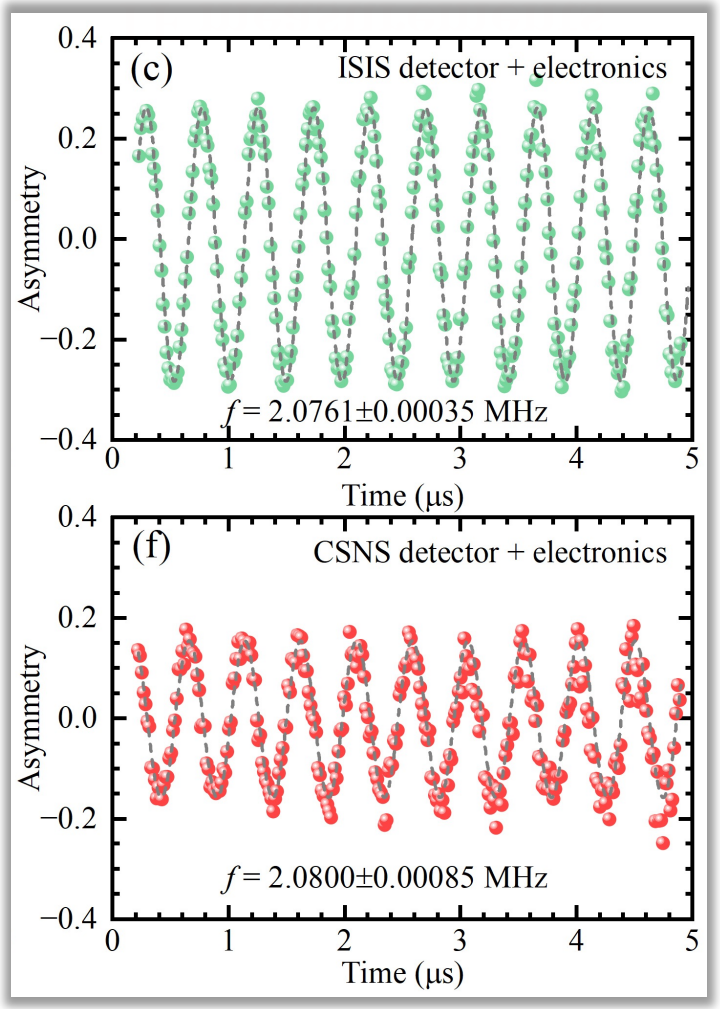
Pulse height spectra



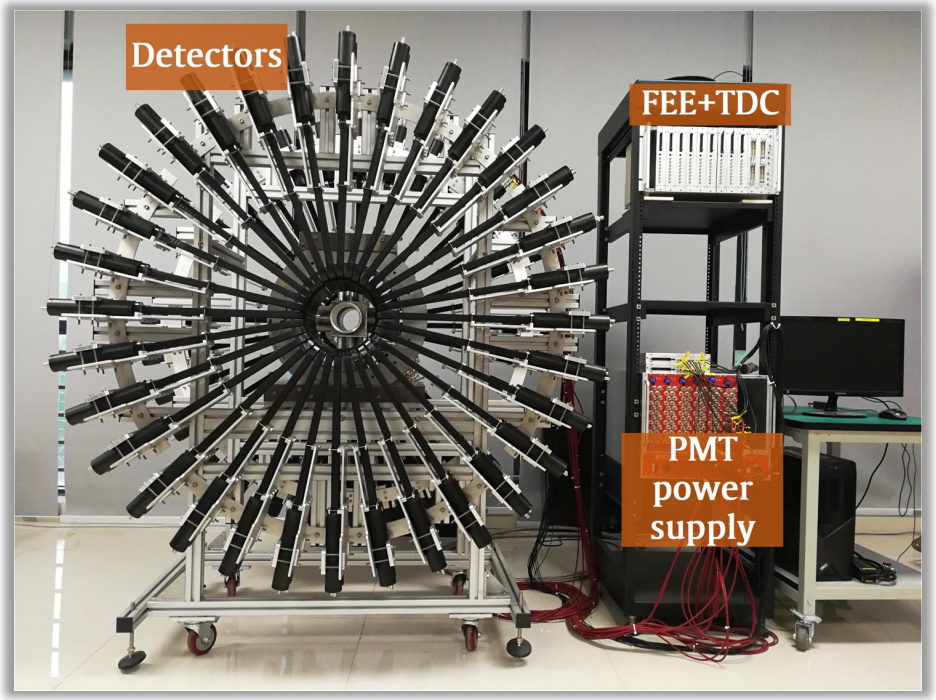
Dead-time distortions

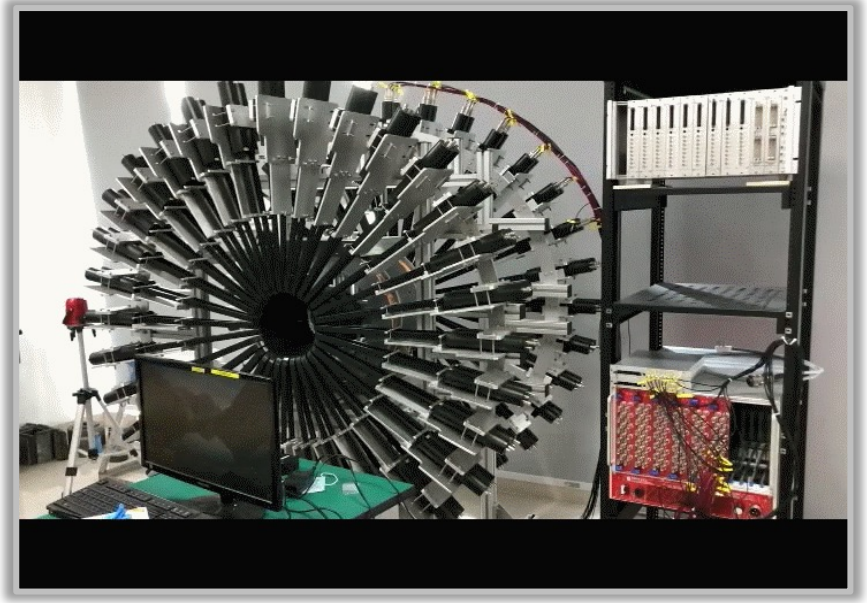


TF measurements

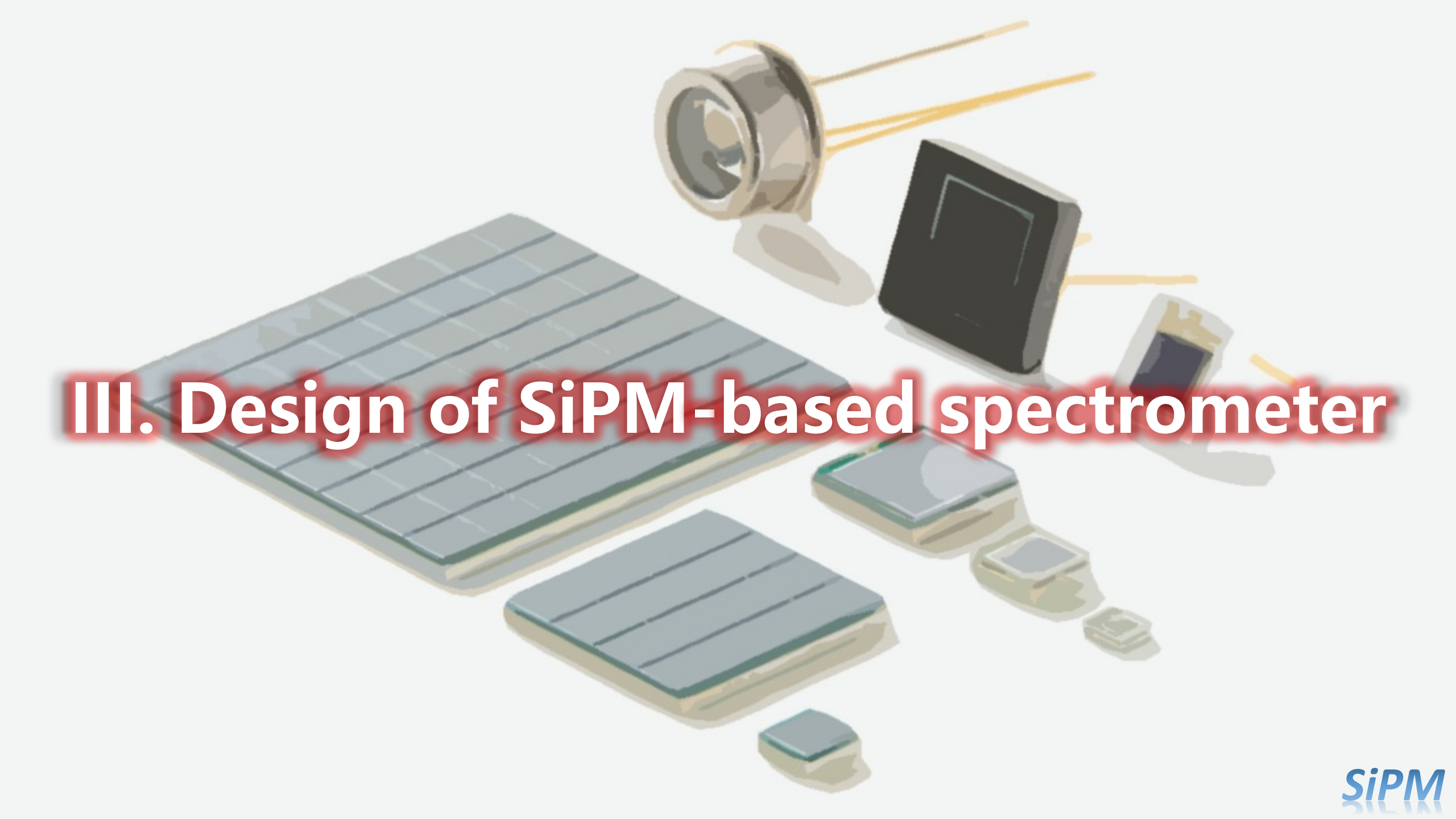


2.4 Mass production and assessment





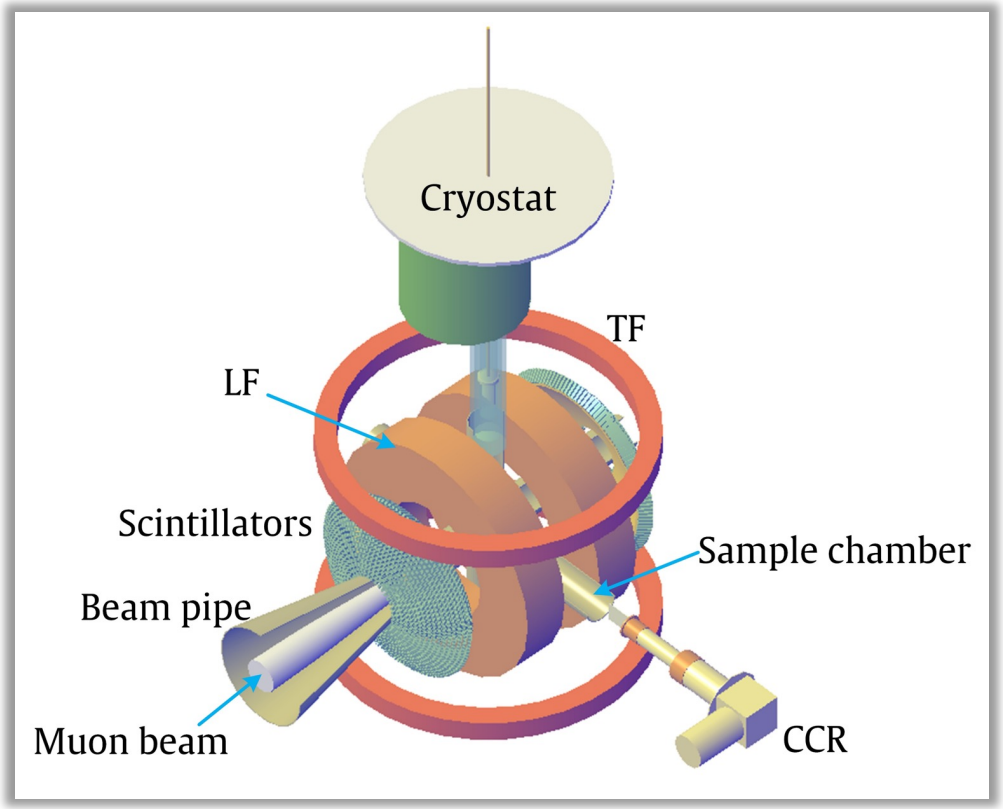
- ✓First μSR demonstrator in China
- ✓Good counting capability
- ✓Awarded "A" by the NSFC



III. Design of SiPM-based spectrometer

SiPM

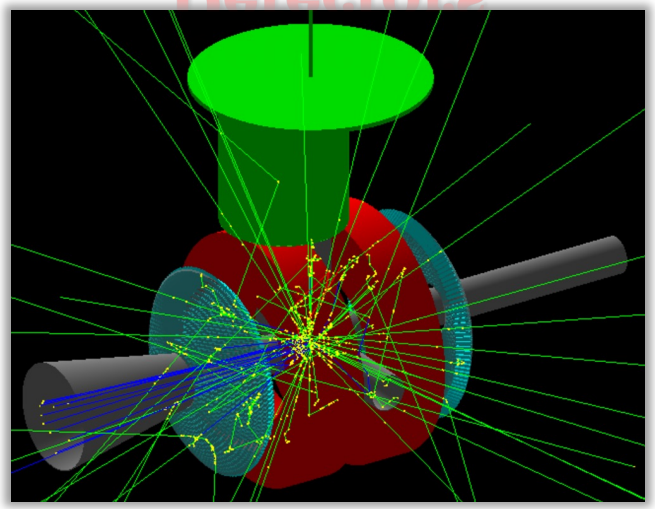
3.1 Spectrometer design



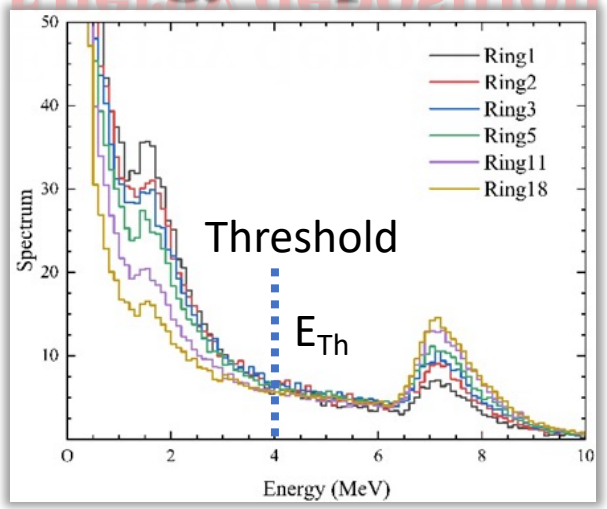
- **Detectors:**
  - 3024 plastic scintillators ($8 \times 8 \times 40$ mm^3)
  - Sensl SiPM (6 mm × 6 mm)
  - FEE+TDC readouts
  - Spherical placement
- **Sample environment:**
  - Cryostat: 2 – 600 K
  - CCR: 10 – 600 K
- **Magnets:**
  - Longitudinal field: 0 – 5000 G
  - Transverse field: 0 – 400 G
  - Zero field: < 10 mG
- **Beam:**
  - 2×10^5 μ^+/pulse @ Φ30 mm

3.2 Detector arrangement

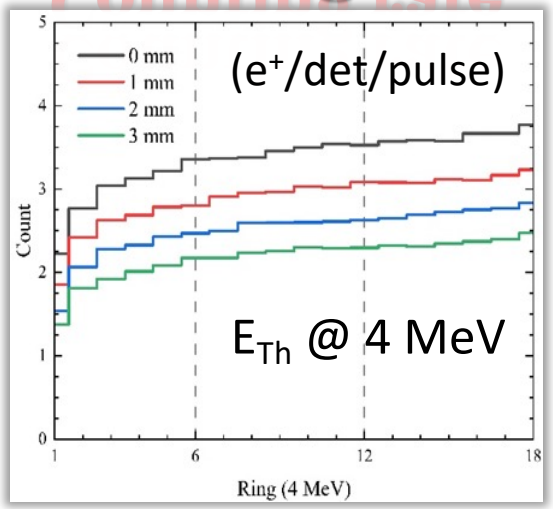
Detectors



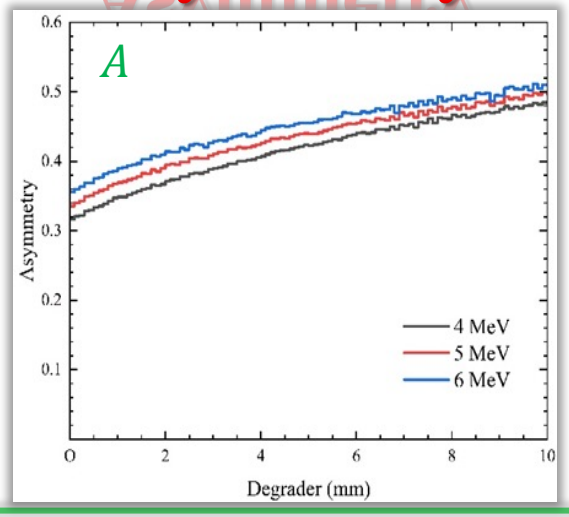
Energy deposition



Counting rate



Asymmetry



Detection rate

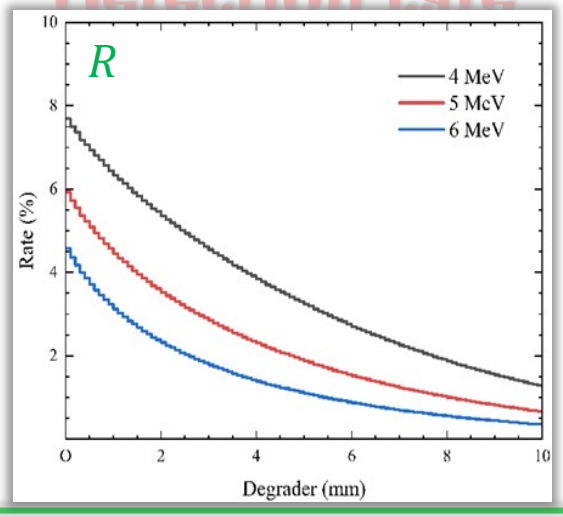
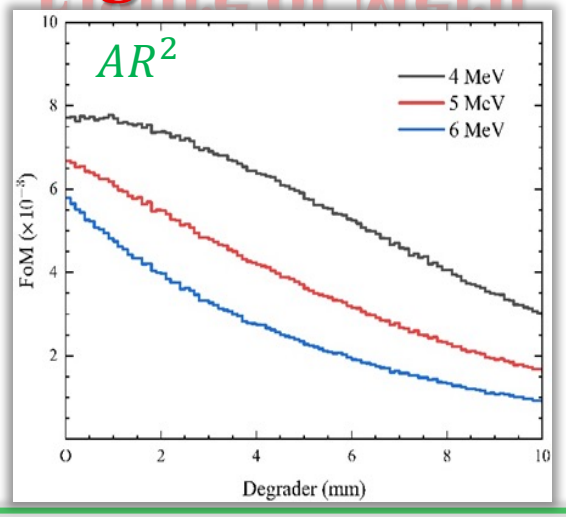
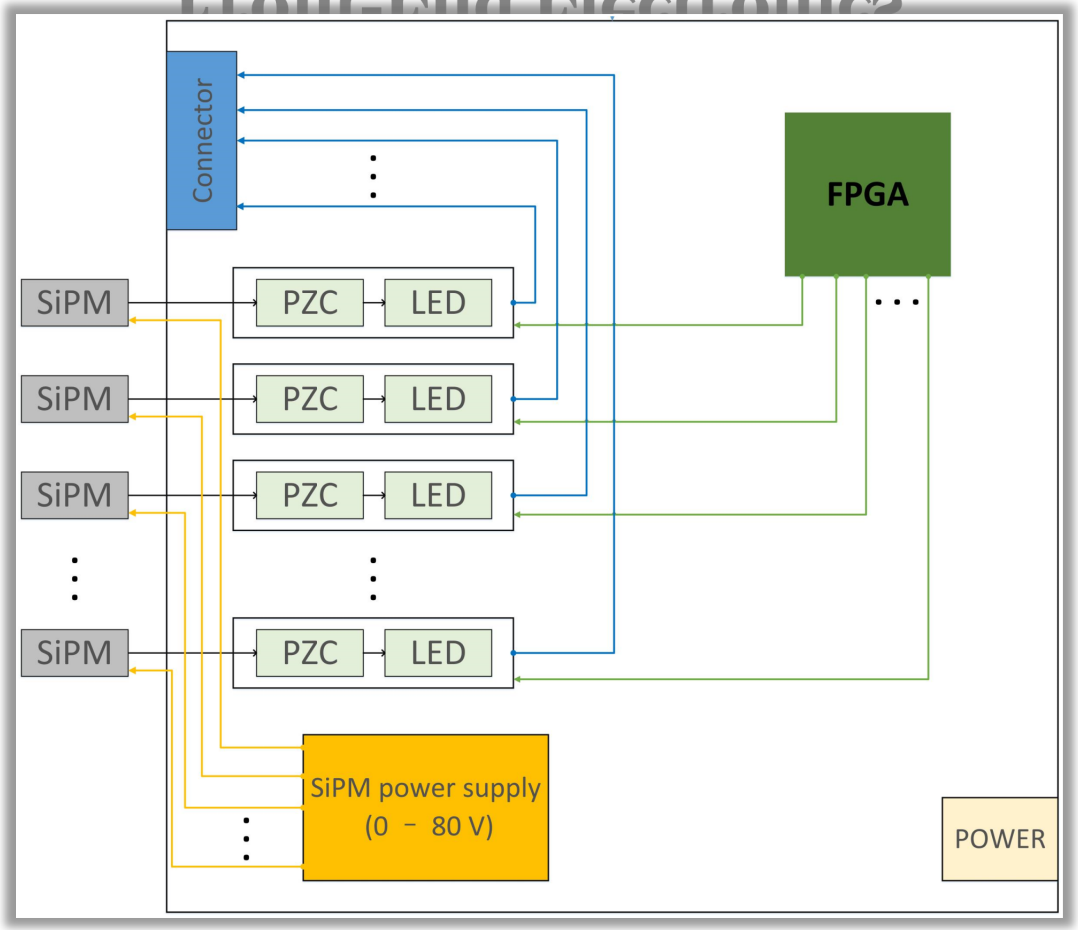


Figure of Merit

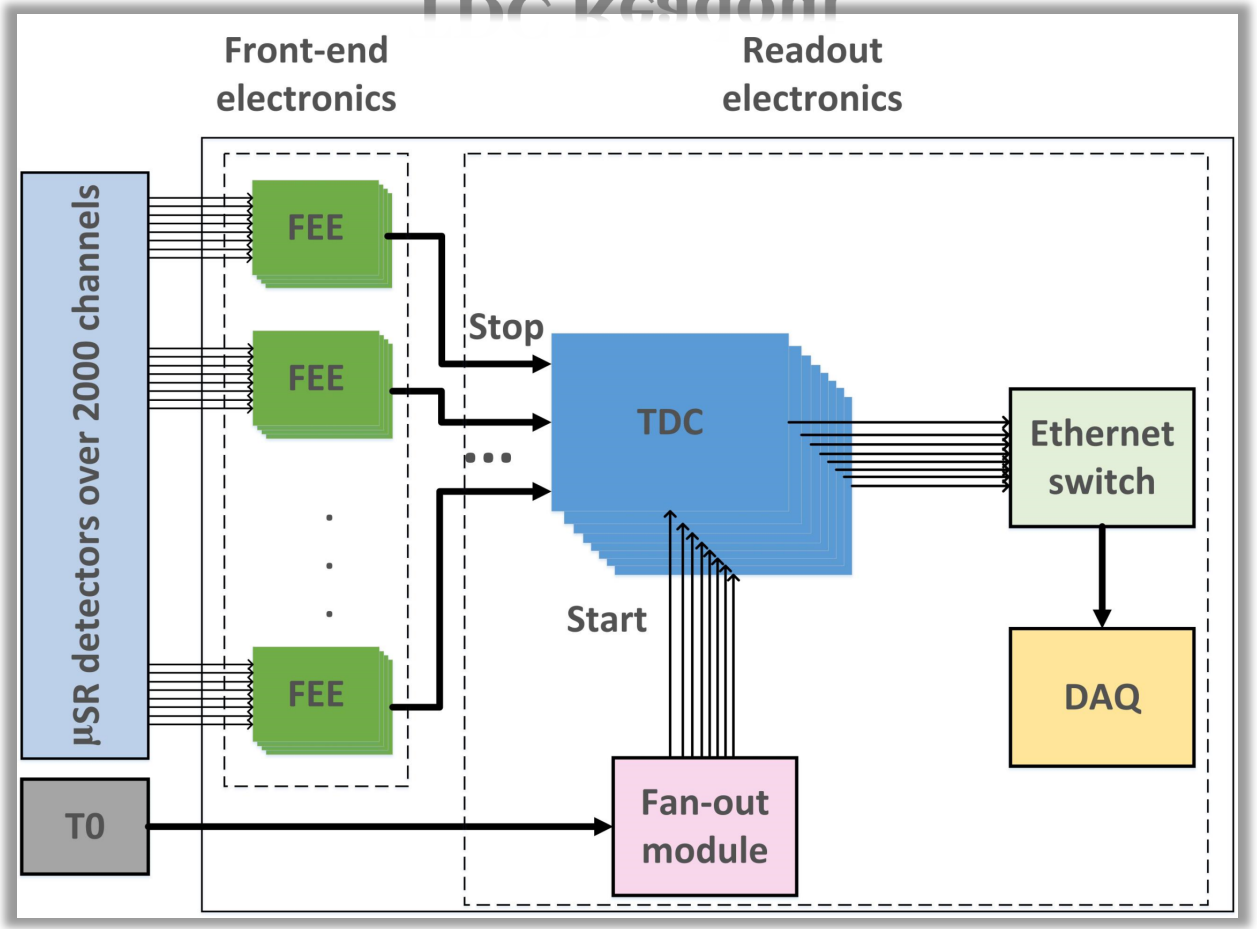


Leading-edge discrimination + TDC

Front-End Electronics



TDC Readout

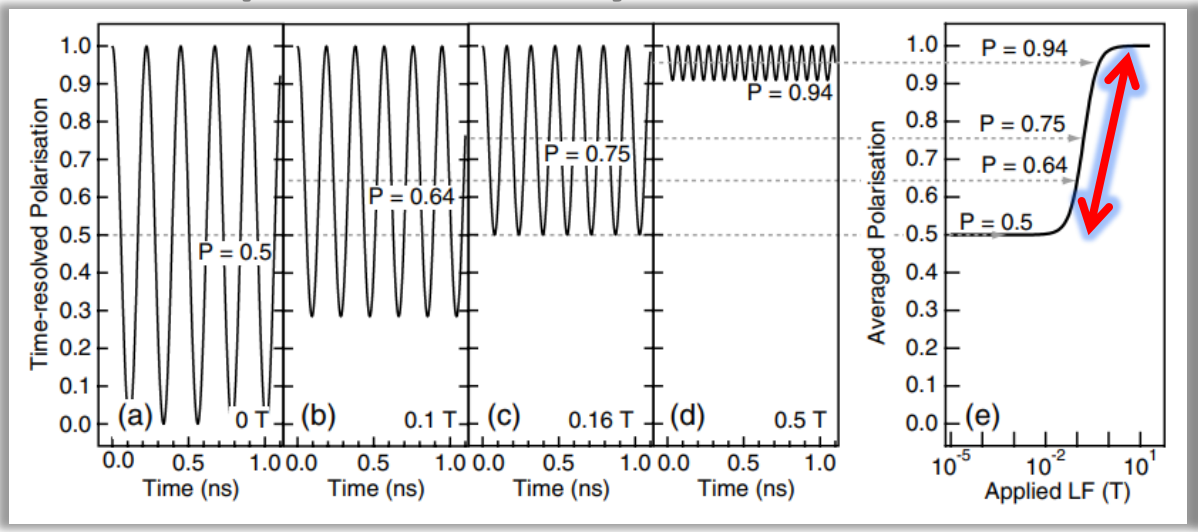


FS Deng, et al., JINST *Proceedings @ MuSR2020*

3.4 Field range selection

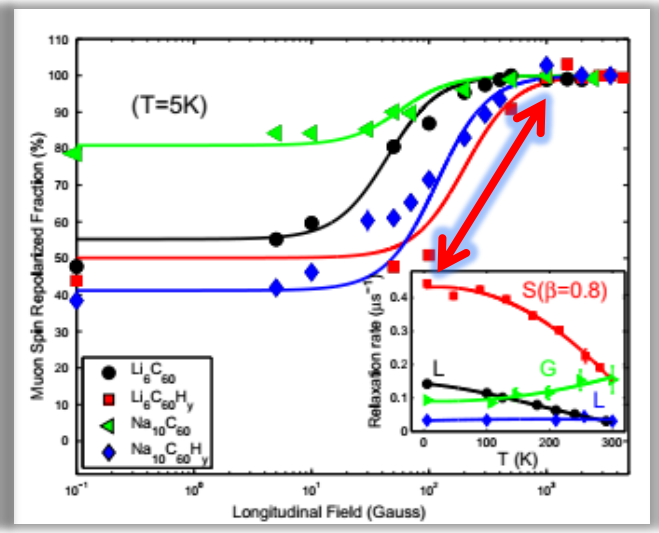
Muon spin repolarization in a longitudinal field

Topical review by L Nuccio et al.



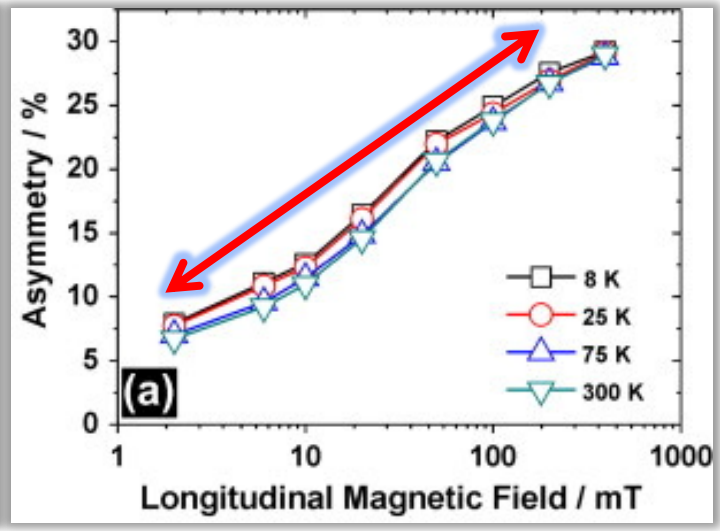
J. Phys. D: Appl. Phys. 47 (2014) 473001

Test @ EMU, ISIS



Carbon 67 (2014) 92 - 97

Test @ RIKEN-RAL, ISIS



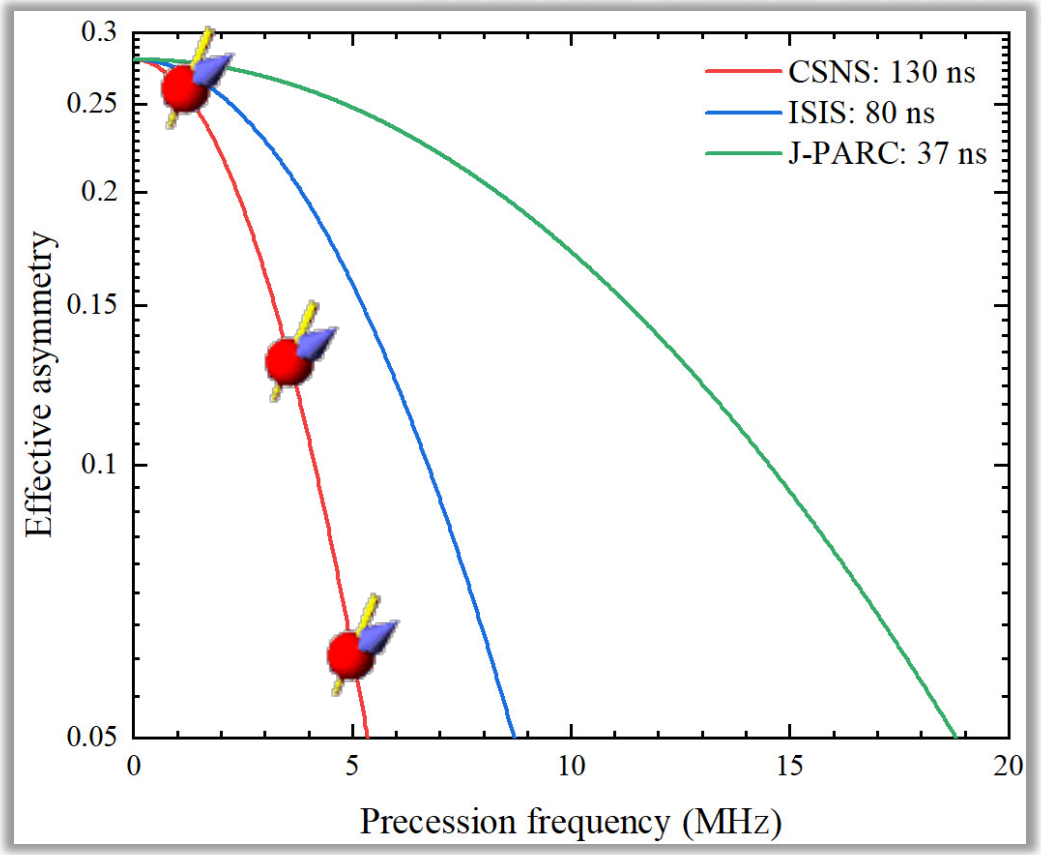
Organic Electronics, 14 (2013) 62 - 66

Longitudinal field: 0 – 5000 G

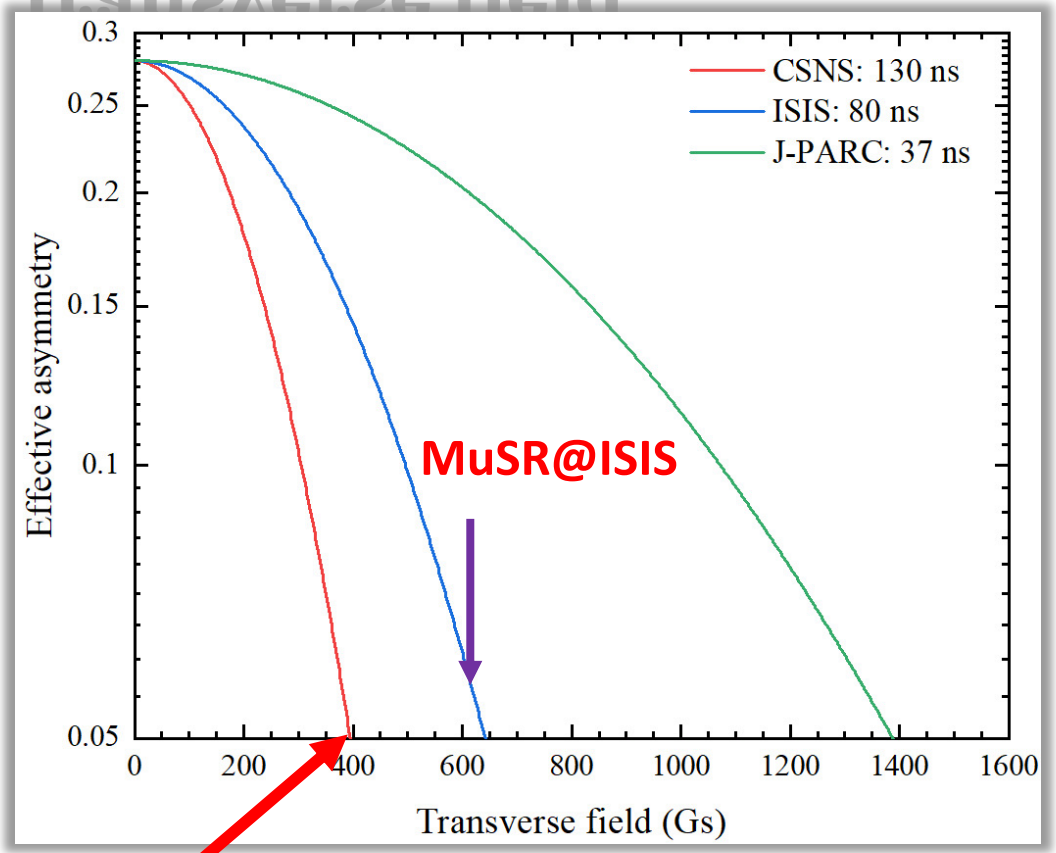
Details in Muon Spectroscopy: An Introduction

3.4 Field range selection

Muon spin rotation in a transverse field



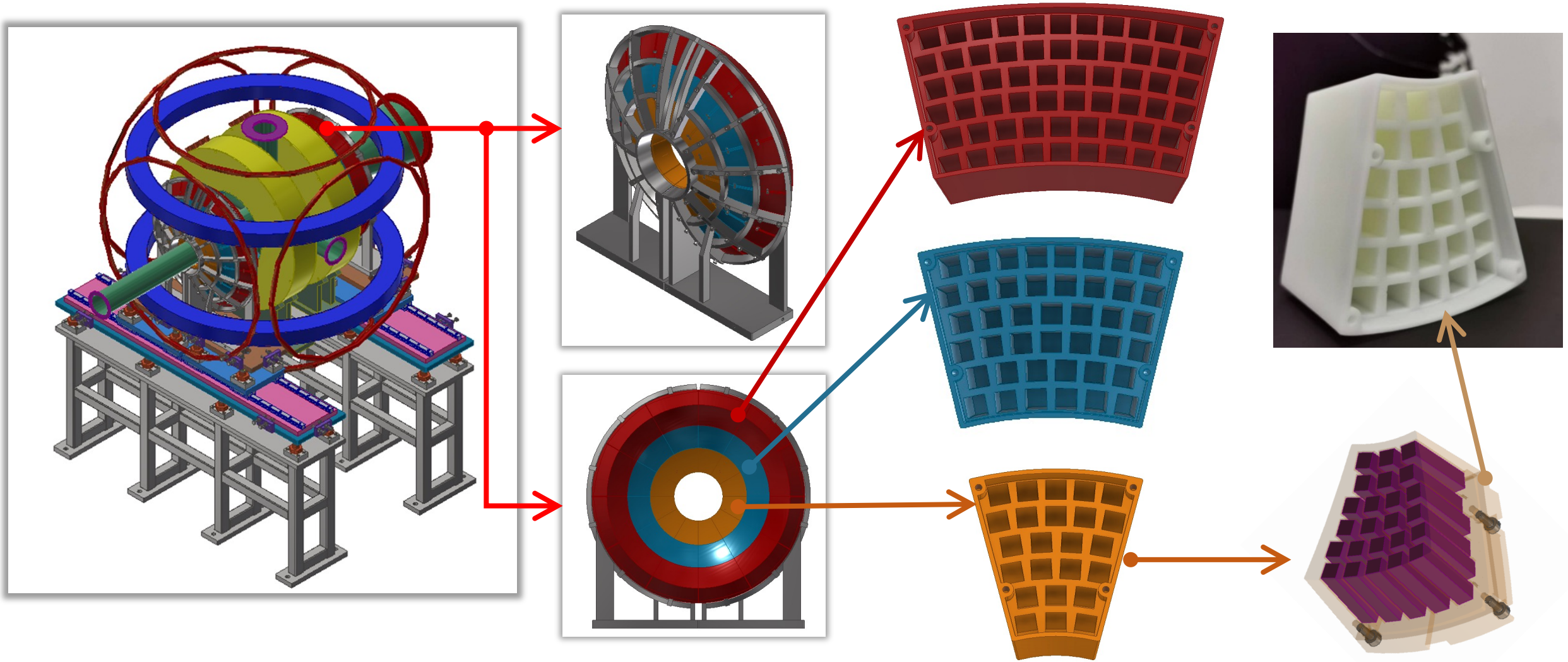
$$2\pi f = \gamma_\mu B$$



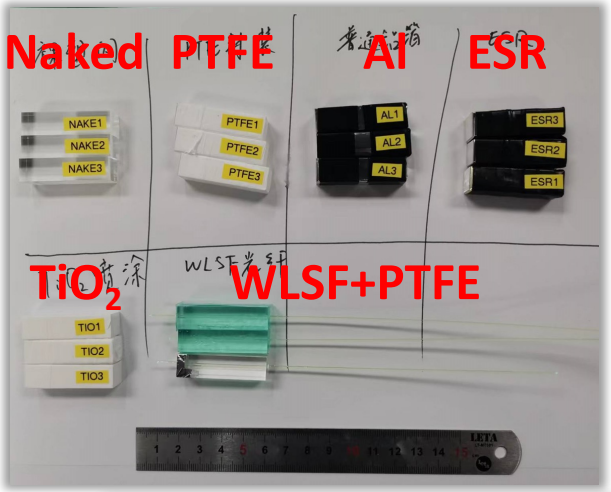
Transverse field: 0 – 400 G

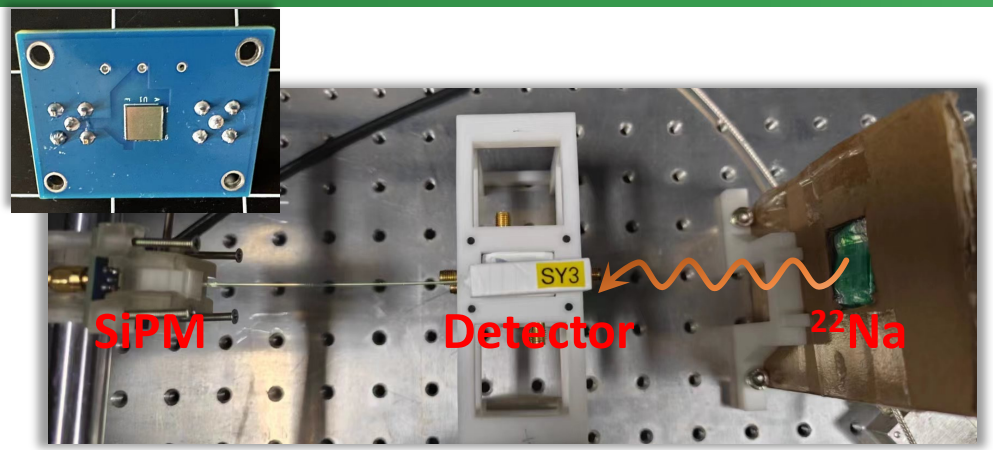
Z Pan et al., NIM A 1024 (2022) 166121; *Hyperfine Interact. 65 (1991) 1113-1119*

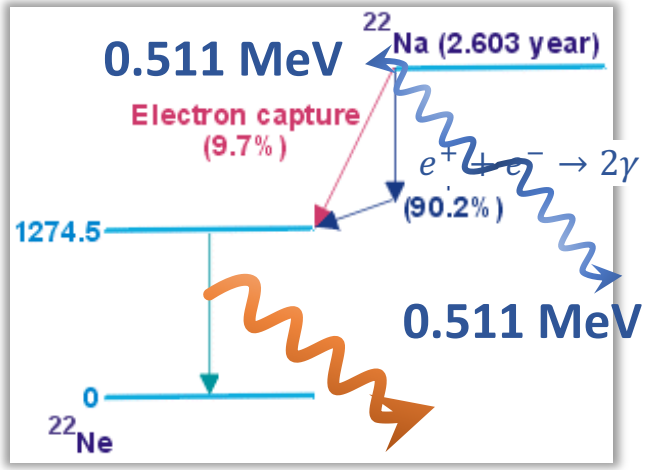
3.5 Technical considerations

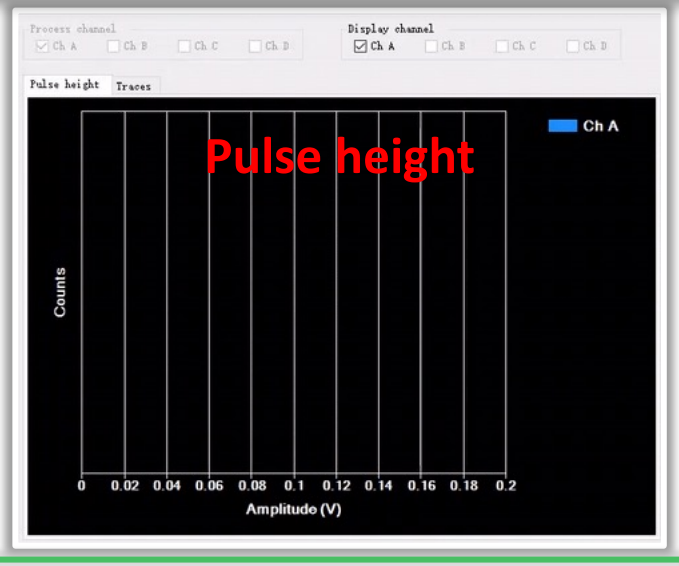


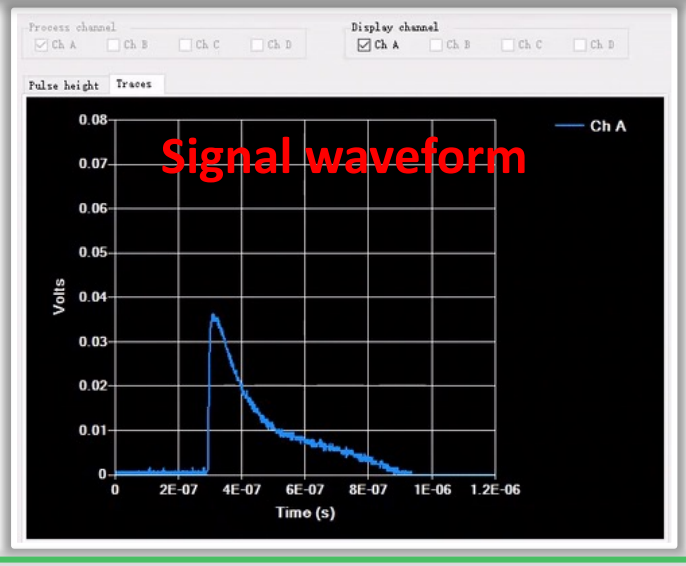
3.6 Preliminary scintillator tests







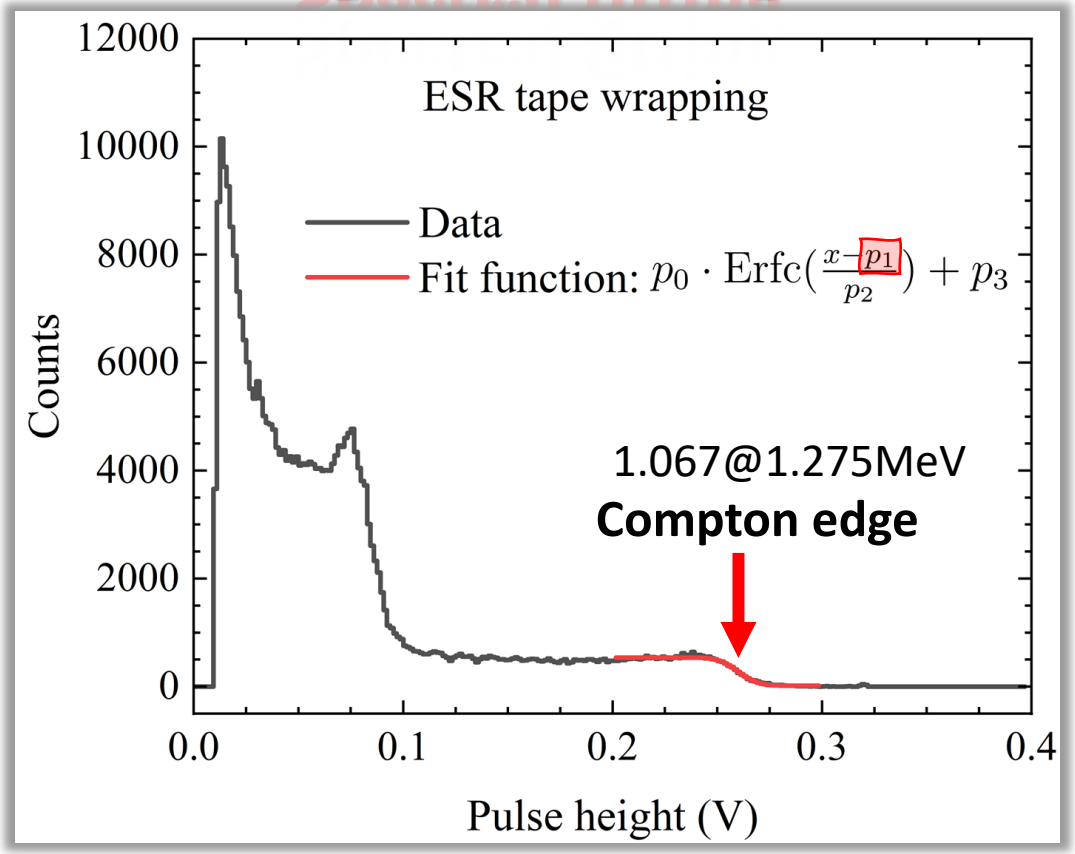




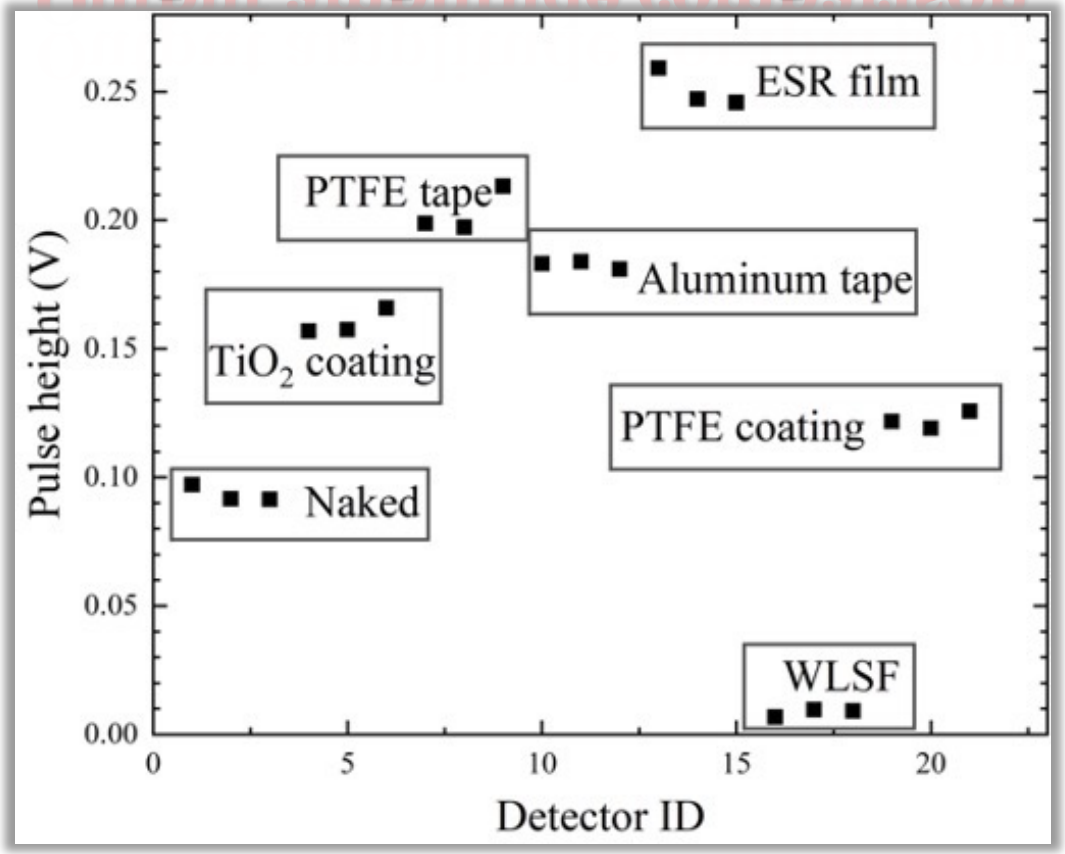
Courtesy of Dr. Erik Schooneveld (STFC ISIS Detector Group) for providing DAQ software!

3.6 Preliminary scintillator tests

Spectral fitting



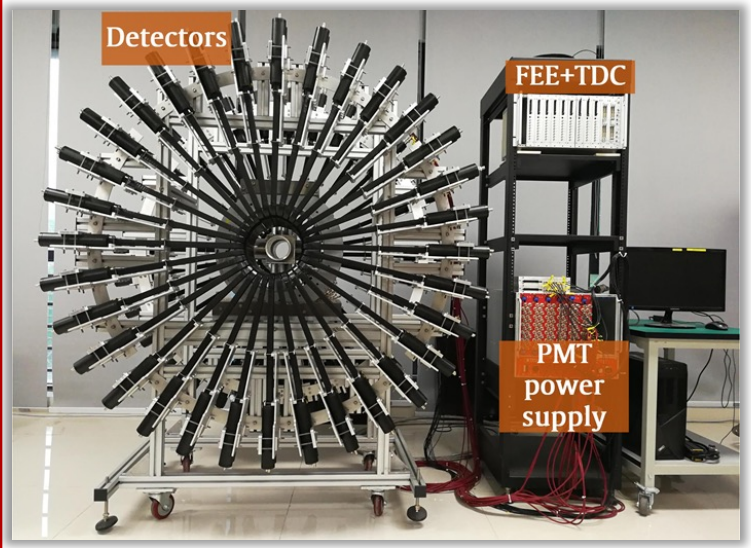
Output amplitude comparison



ESR wrapping outperforms, while PTFE wrapping has less difficulty in manufacturing .


IV. Summary and prospects
Spinning toward future

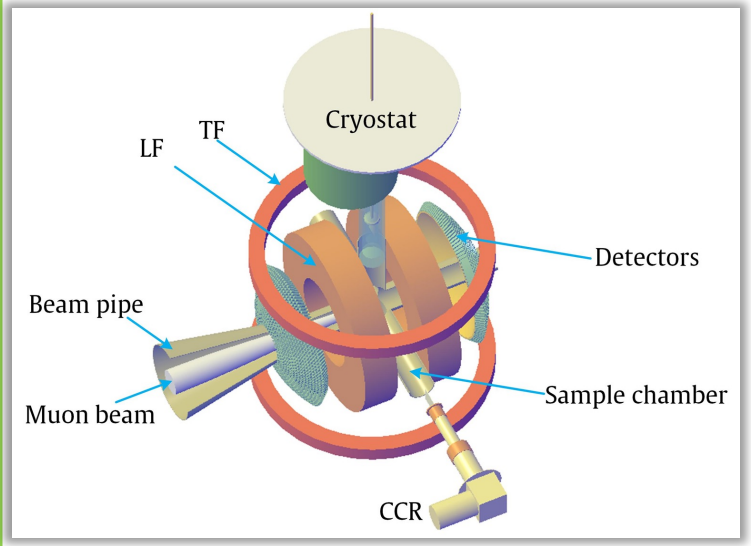
4.1 Summary: μSR spectrometer development



First μSR spectrometer demonstrator

- 128 plastic scintillator + PMT
- Good counting capability (short deadtime)
- Multiple beam tests

2015 - 2020



X Spectrometer @ MELODY-CSNS

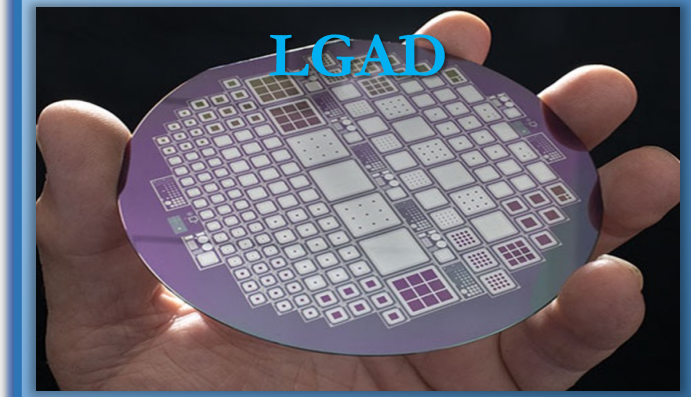
- 3024 plastic scintillator + SiPM
- Asymmetry: > 0.28
- Counting rate: 8×10^7 e^+/hour @ 1 Hz
- Fast readout

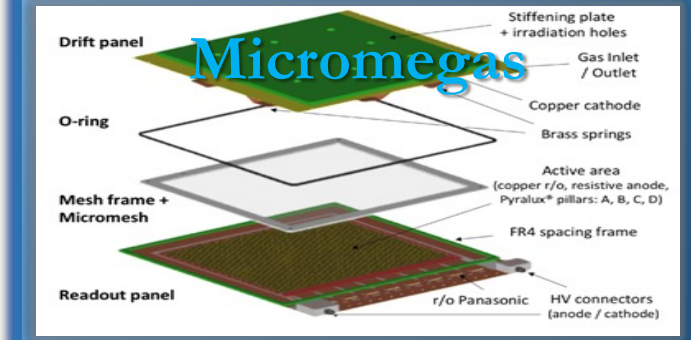
2023 - 2028

4.2 Prospect: pulsed μSR spectroscopy

●Detector

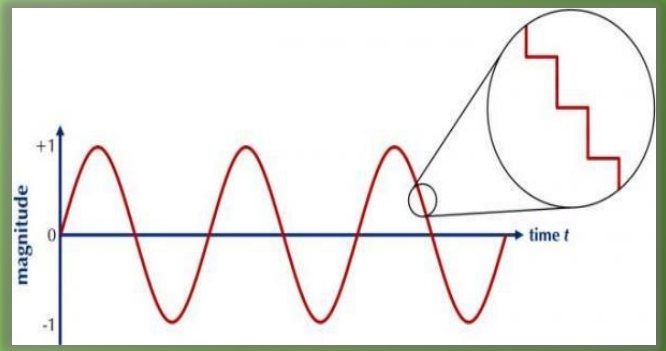
- ✓ High granularity
- ✓ Fast output

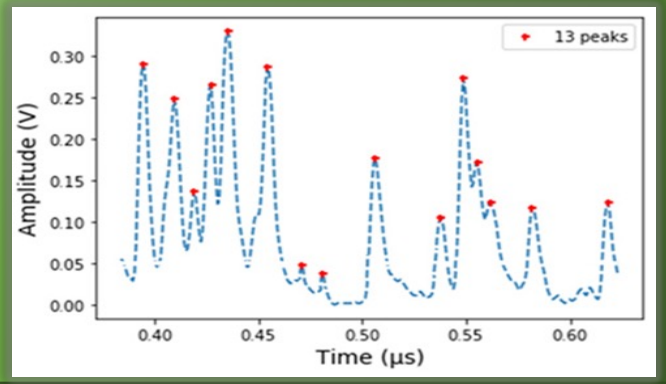




● Electronics

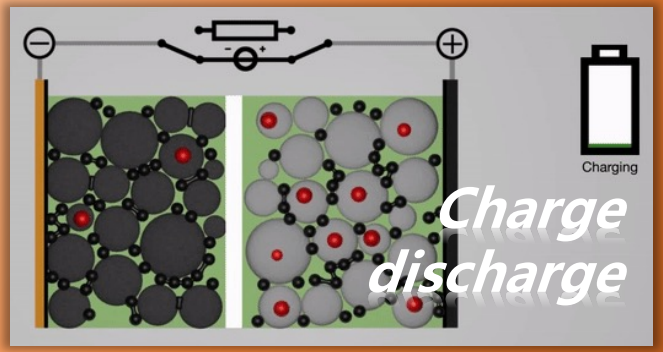
- ✓ Digitization
- ✓ High precision

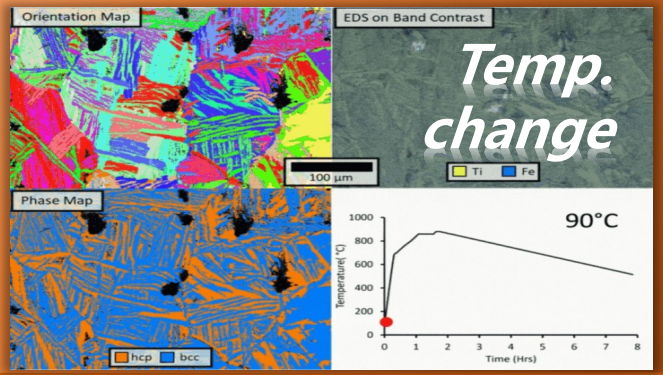




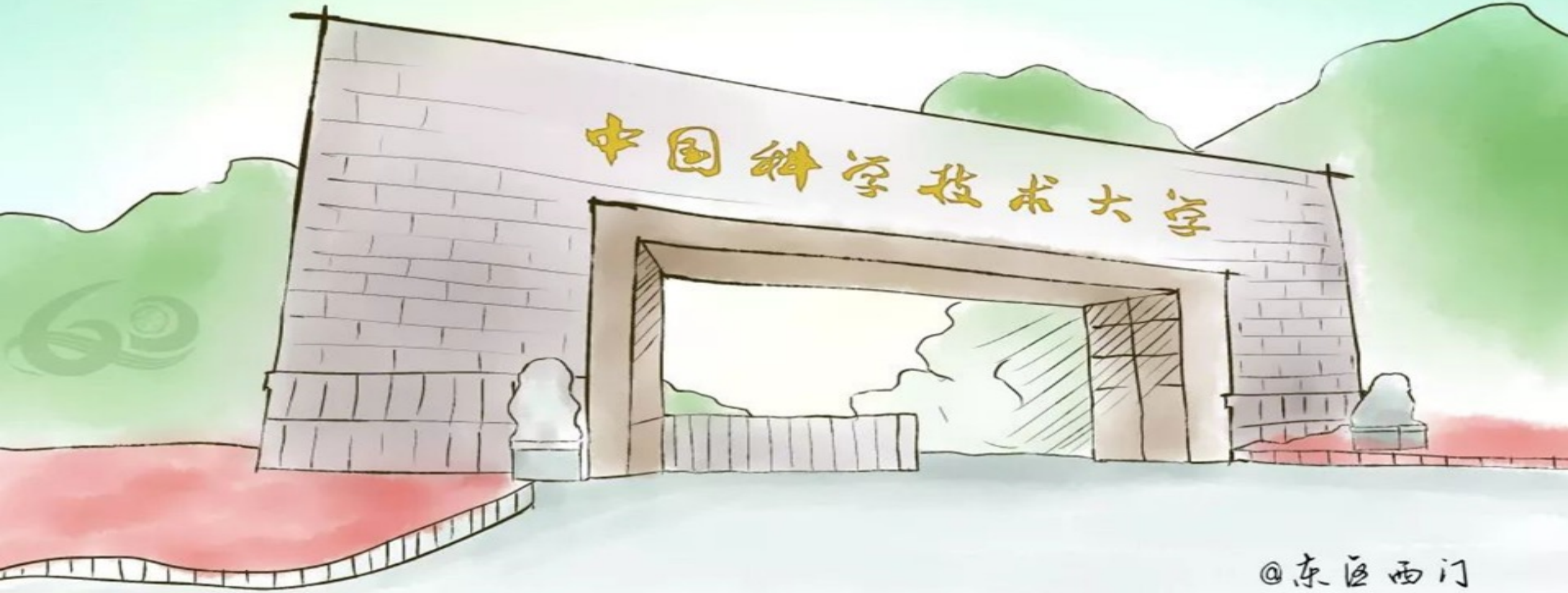
● Measure

- ✓ In-situ
- ✓ Operando





Thanks!



Main Gate of USTC