



Muon spectrometer design for the first muon facility in China

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State Key Laboratory of Particle Detection and Electronics, USTC

In collaboration with

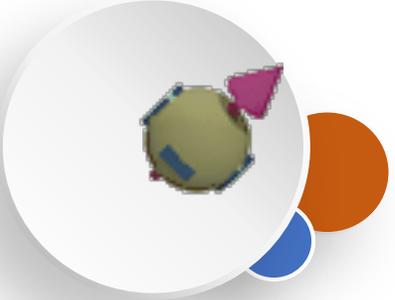
Yu BAO(鲍煜), Qiang LI(李强), Yang LI(李样), et al.

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

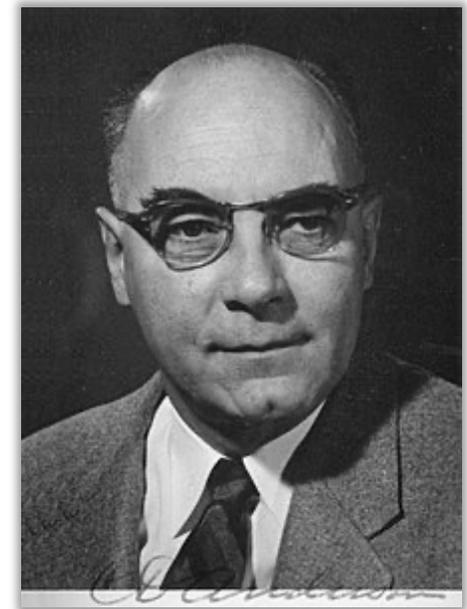
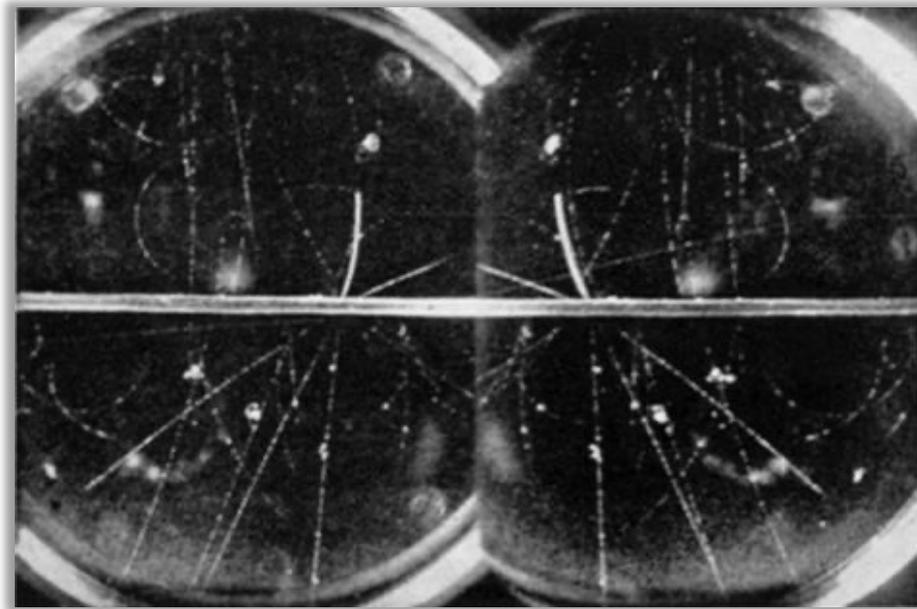
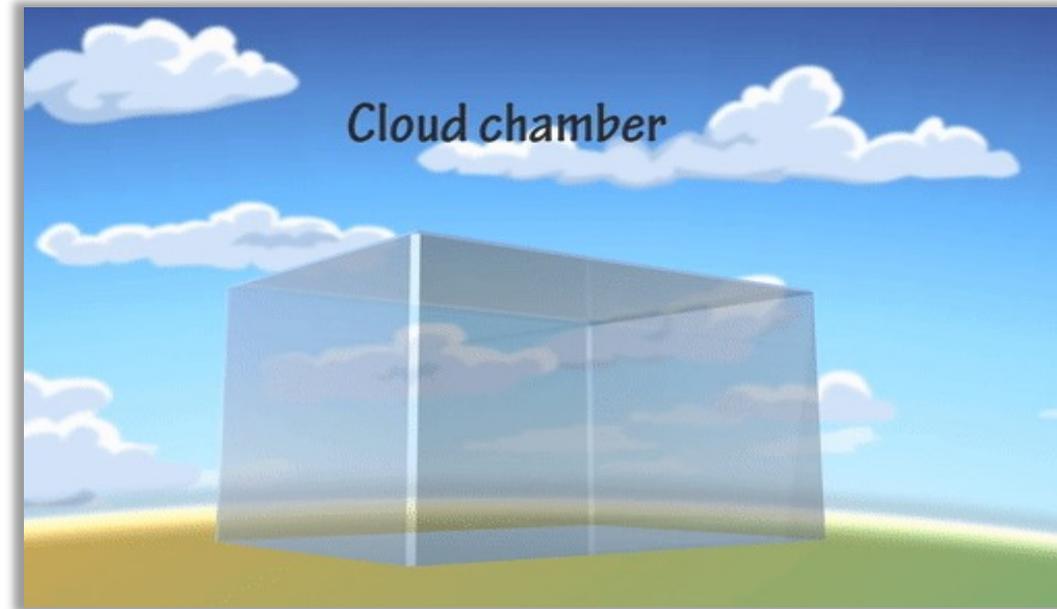
III Design of the SiPM-based spectrometer

IV Summary and prospects

An aerial photograph of a large scientific facility, likely a particle accelerator or laboratory. The image shows several large, modern buildings with white and grey facades, interspersed with green lawns and parking areas. A prominent feature is a long, white building with a series of vertical columns or supports. The facility is surrounded by dense green trees and a road with a few cars. The overall scene is well-maintained and organized.

I. Brief introduction to muons

1.1 Physical nature of muons

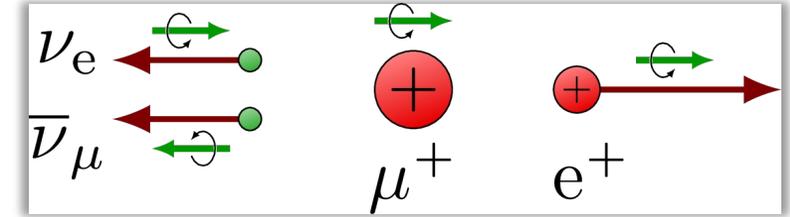
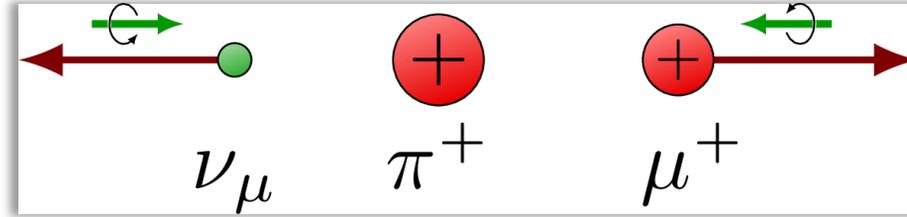
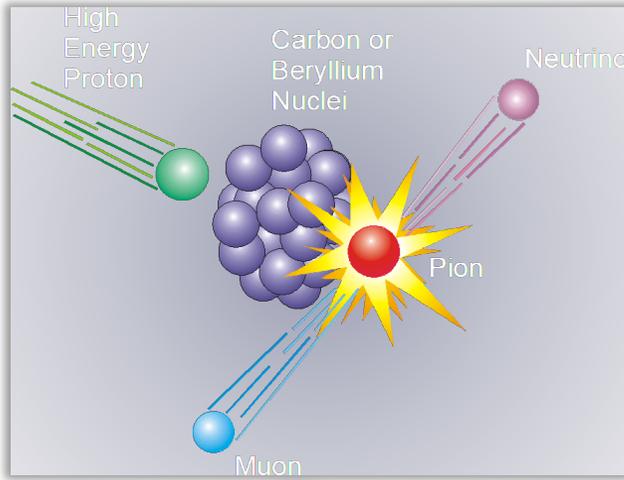


Carl David Anderson
(1905-1991)

Leptons			Leptons		
	Electric Charge			Electric Charge	
Tau	-1	Tau Neutrino	0		
Muon	-1	Muon Neutrino	0		
Electron	-1	Electron Neutrino	0		

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

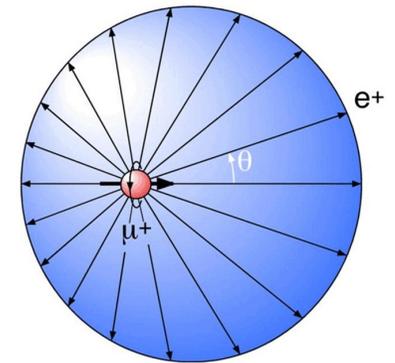
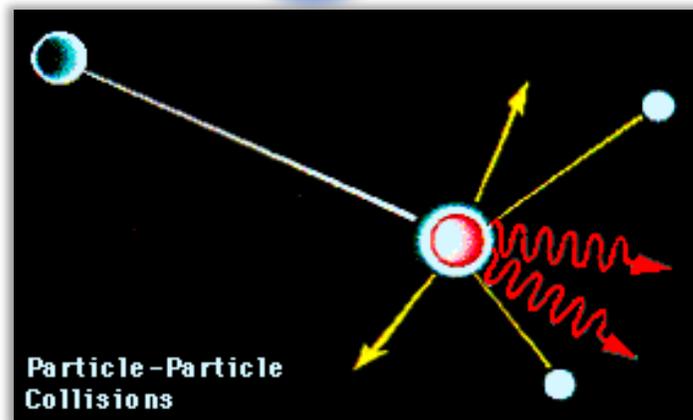
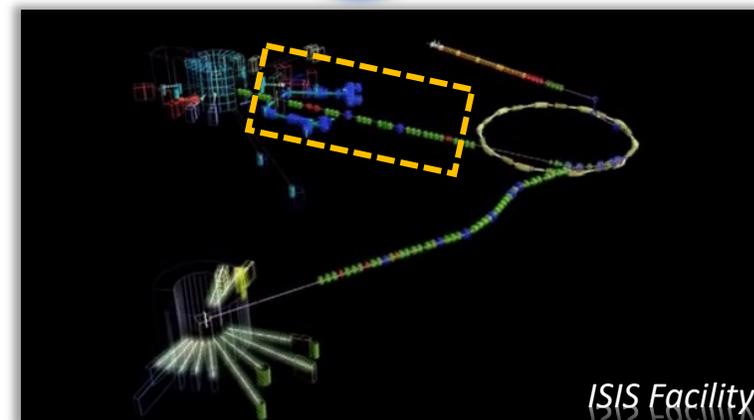
1.2 Generation of polarized muon beams



Target

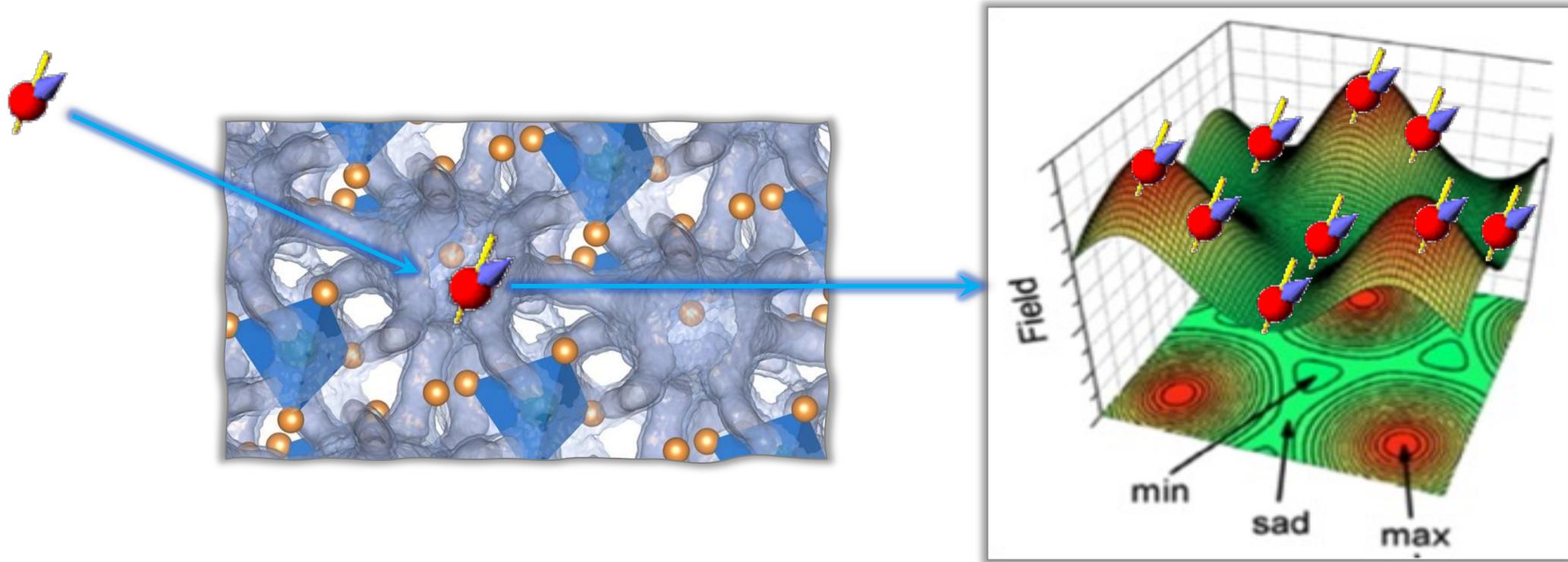
π^+

μ^+



1.3 Principles of μ SR spectroscopy

μ SR: muon spin rotation/relaxation/resonance



A quantum magnetism probe

1.3 Principles of μ SR spectroscopy

Precession
(spin interaction)



Asymmetry
(positron detection)

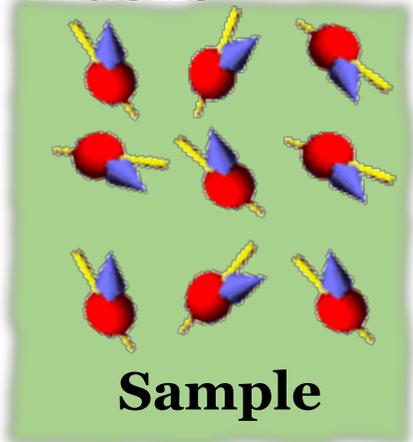


μ SR spectra
(analysis)



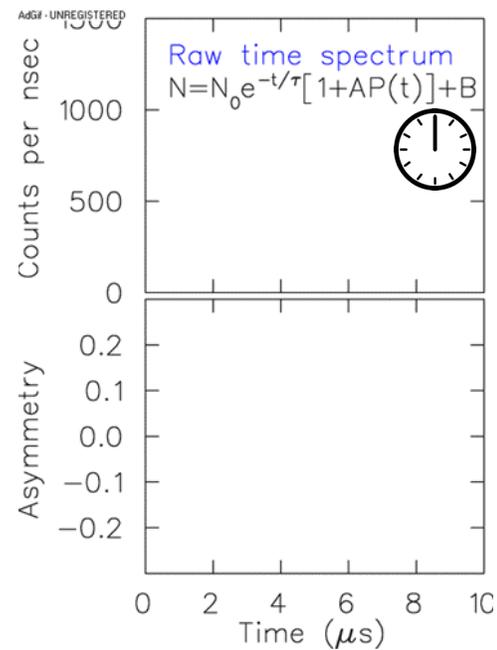
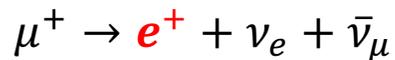
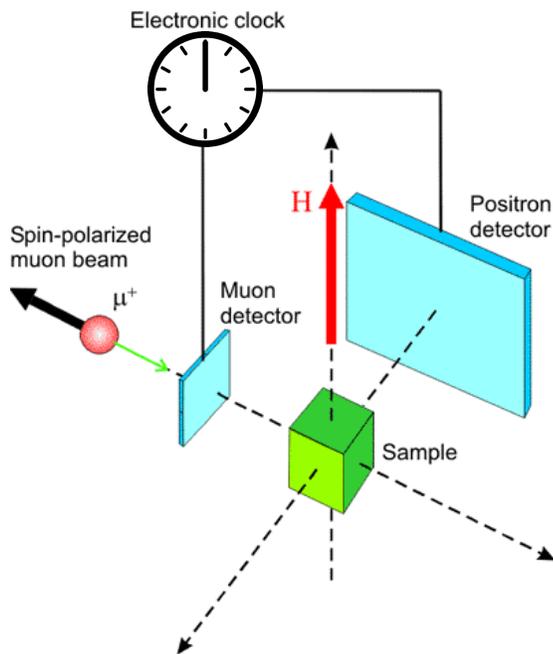
Material
(properties)

muons

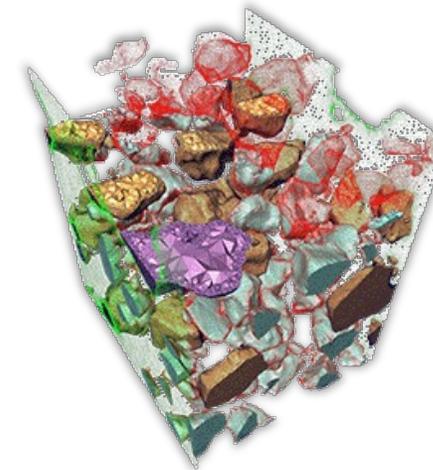


Sample

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

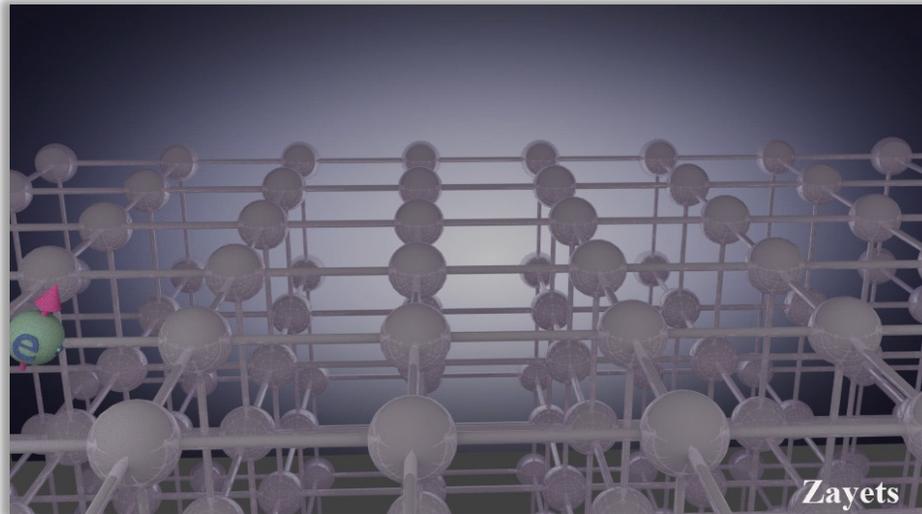
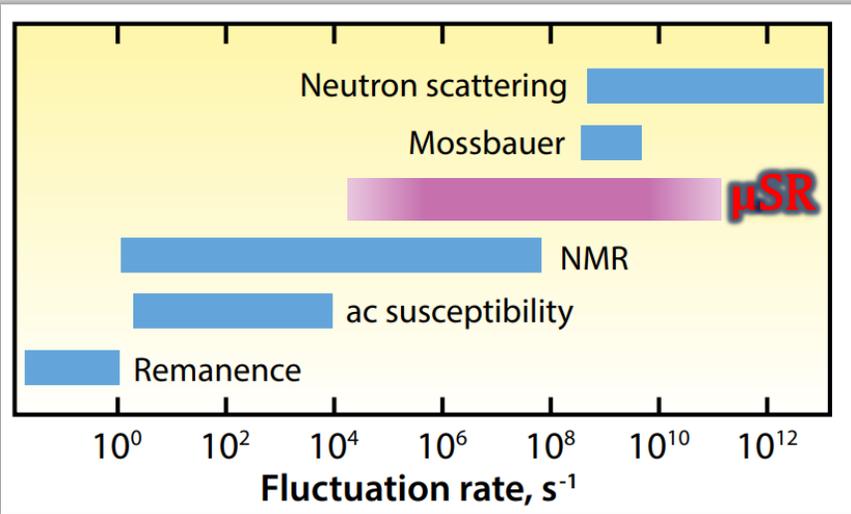


$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = AP(t)$$



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

1.4 Advantages of μ SR spectroscopy



- **Unique & wide time scale** (complementary to NMR/neutron scattering)
- **Very weak effects** (small moment magnetism $\sim 10^{-3} \mu_B/\text{Atom}$)
- **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)

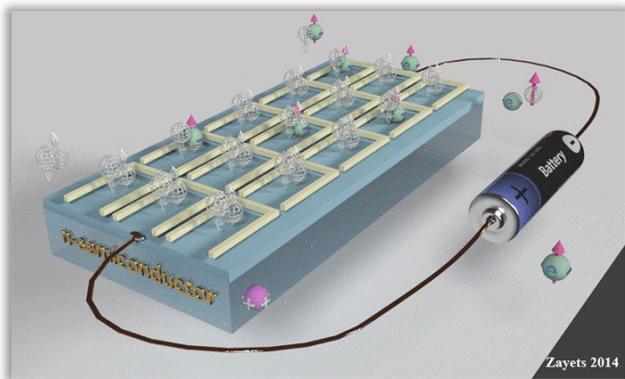
1.5 Applications of μ SR spectroscopy

● Passive probe (heavy lepton)

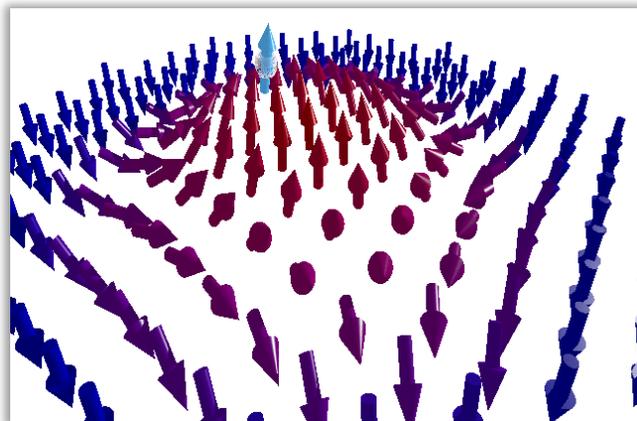
Superconductor



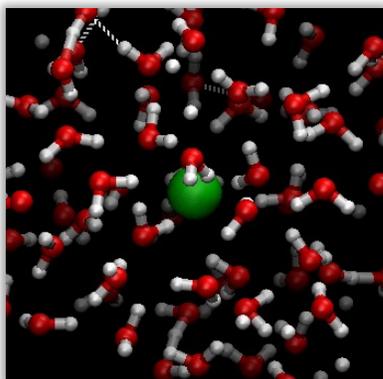
Charge transport



Magnetism

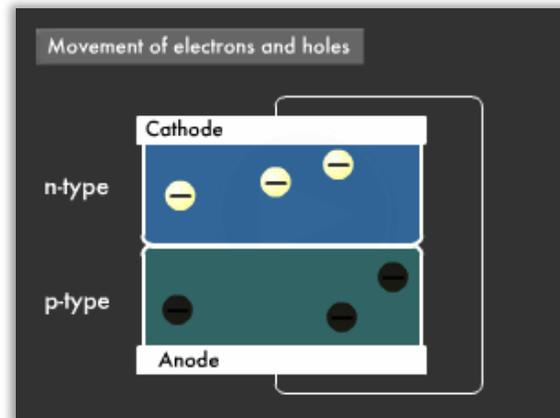


MD

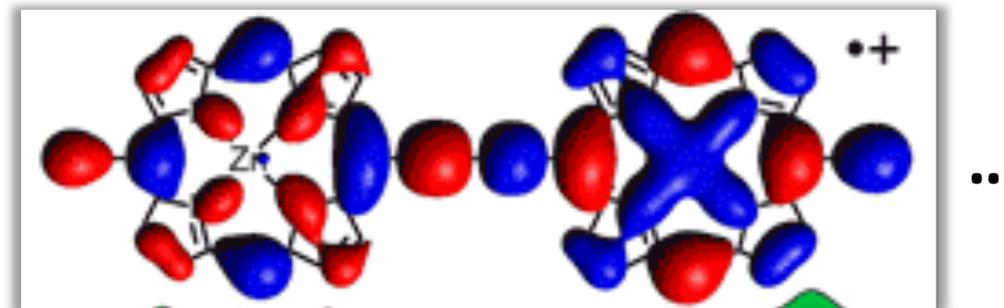


● Active probe (light proton)

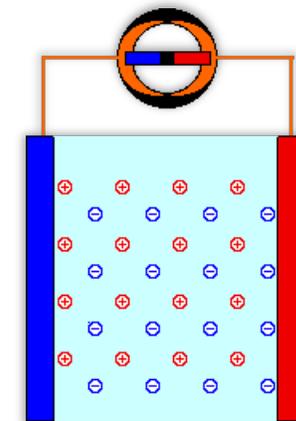
Semiconductor



Polaron motion



Ionic conductor

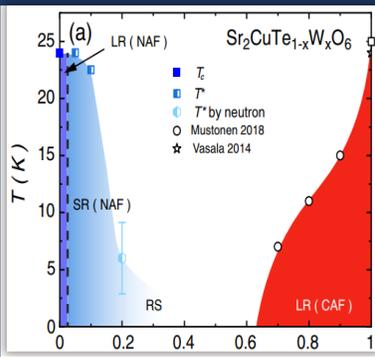


1.6 μ SR research highlights @ China

Prof. S.L. Li's group @ IOP, CAS

李世亮/物理所

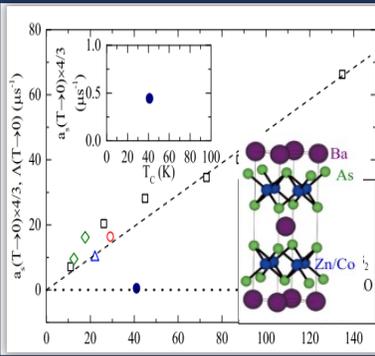
- Extreme Suppression of Antiferromagnetic Order and Critical Scaling in a Two-Dimensional Random Quantum Magnet, [Physical Review Letters](#) 126, 037201 (2021)
- Partially clarification of the doping evolution mechanism in two-dimensional **quantum antiferromagnets**



Prof. F.L. Ning's group @ Zhejiang University

宁凡龙/浙大

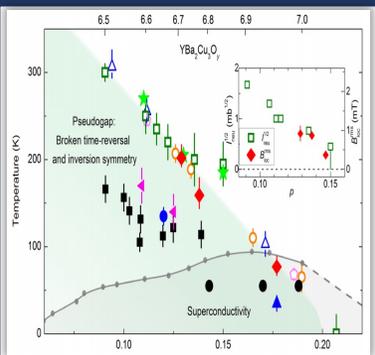
- $Ba(Zn,Co)_2As_2$: A diluted ferromagnetic semiconductor with n -type carriers and isostructural to 122 iron-based superconductors, [Physical Review B](#) 99, 155201 (2019)
- Synthesized of a new type of **dilute magnetic semiconductor** and confirmed by μ SR



Prof. L. Shu's group @ Fudan University

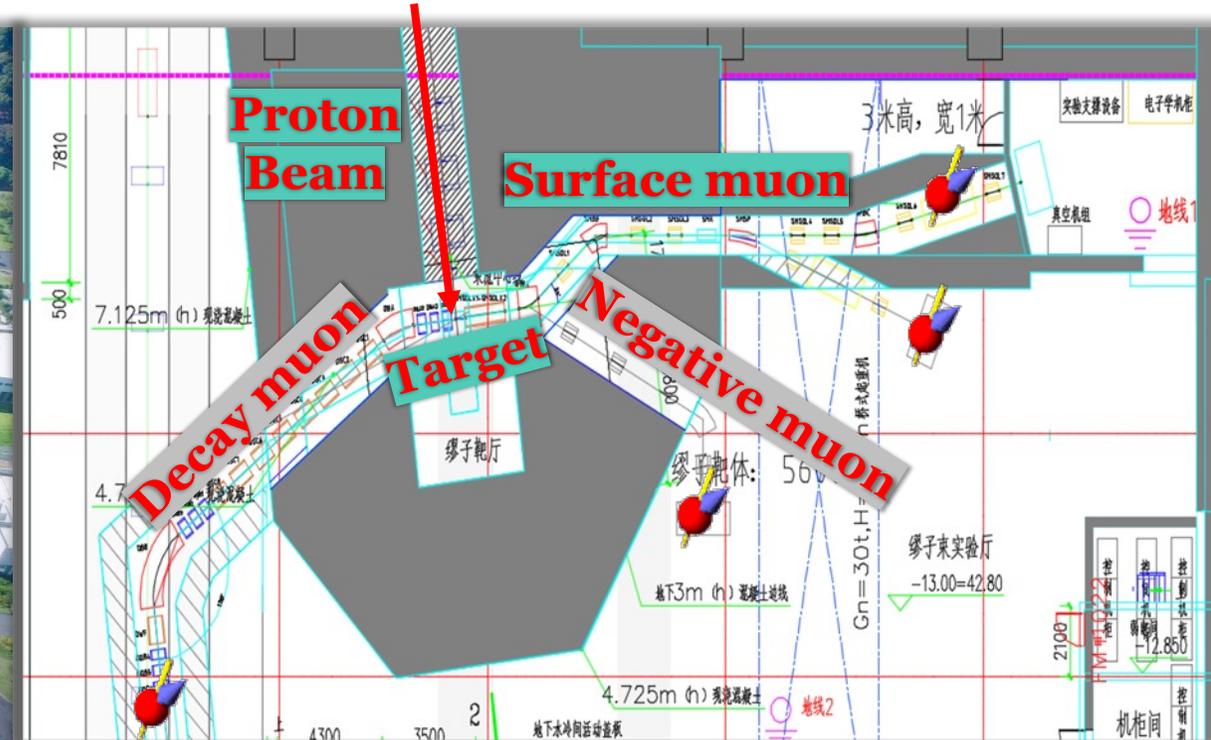
宓蕾/复旦

- 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

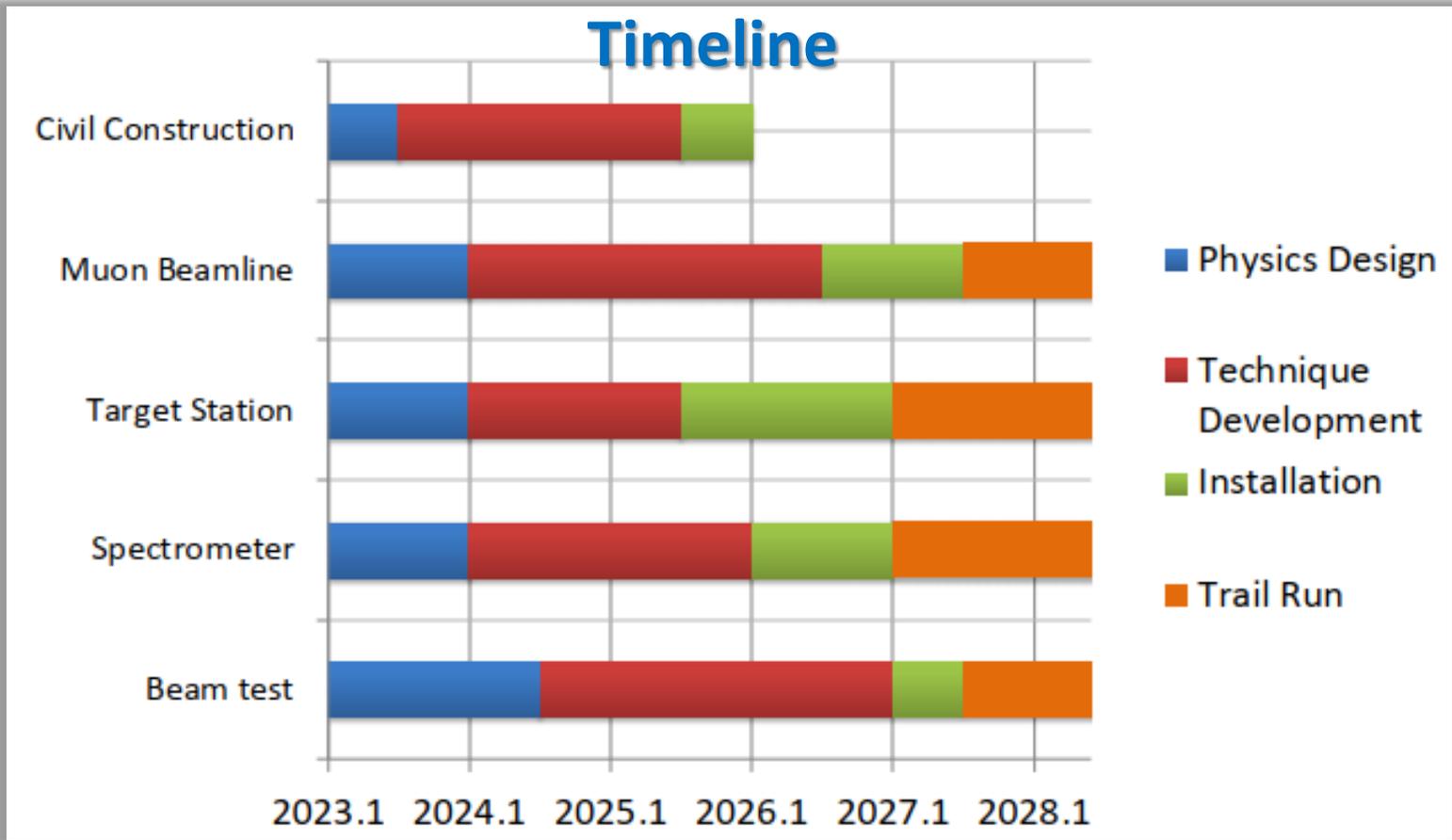
Muon station for sciENCE technoLOGY and inDustrY (MELODY) @ CSNS-II



- Protons: 1.6 GeV, **1 Hz** (up to 5 Hz), **130 ns** double pulses **Details in Dr. Y Bao's talk!**
- Muon beamlines: **1 surface muon** beamline, 1 decay muon beamline, ...
- Spectrometers: **1 μSR spectrometer** ...

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:

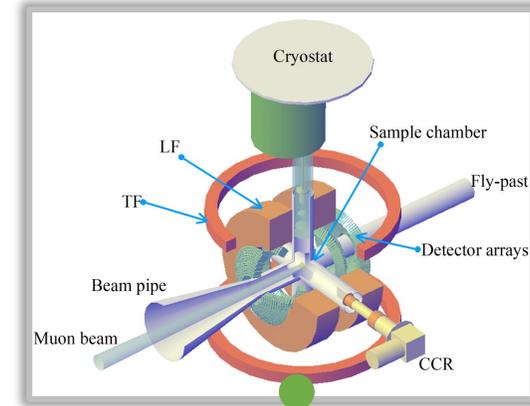
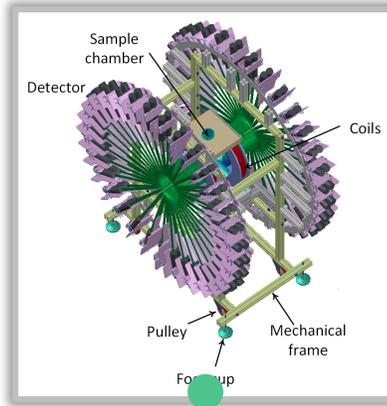
- Ziwen PAN, Bangjiao YE, et al.

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



Prototype R&D
(2015-2020)

Construction
(2023-2028)



1st generation Demonstrator

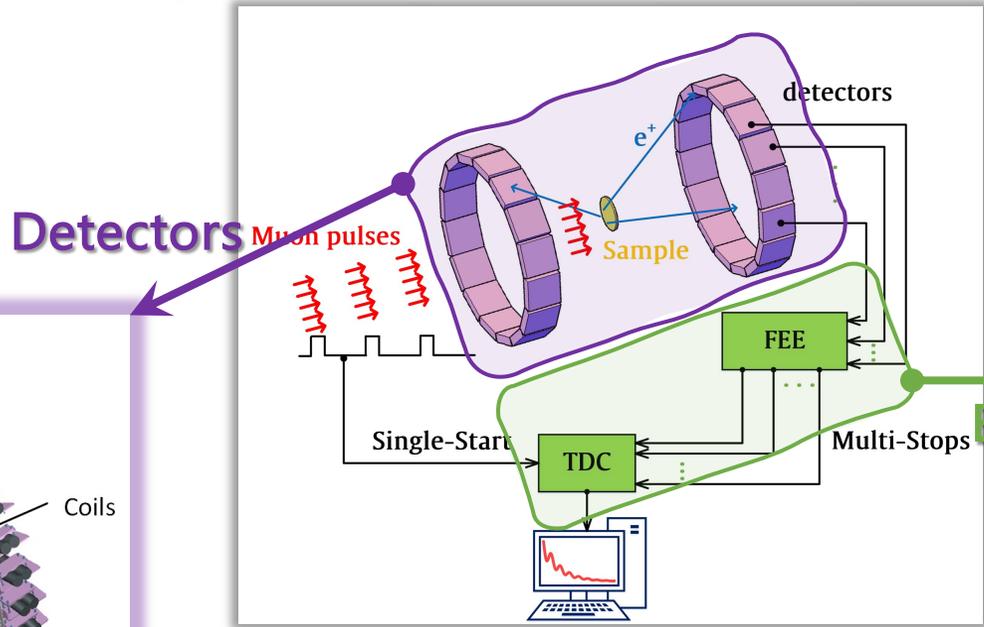
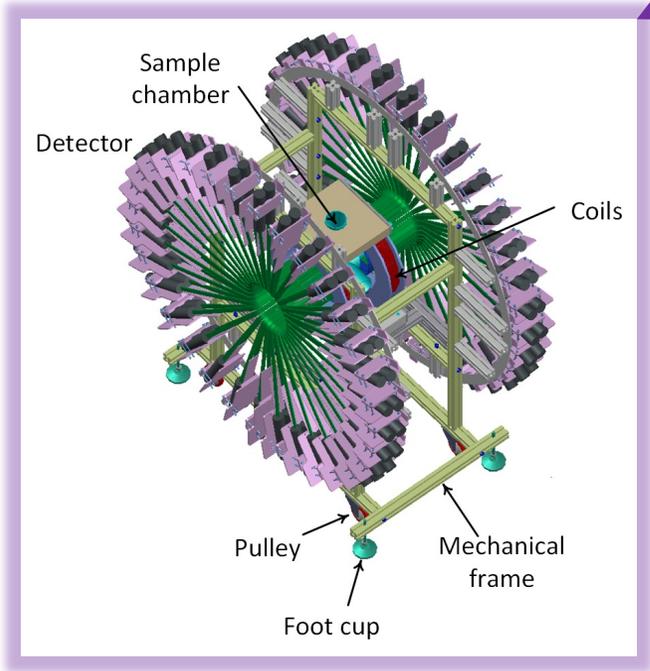
2nd generation SiPM Spectrometer

An exploded view diagram of a photomultiplier tube (PMT) assembly. The central component is a cylindrical glass tube with a black base. Surrounding it are various parts: a large blue lens on the left, a square black base with a yellow grid, a small black cap, a small lens, and a complex metal housing with multiple pins on the right. The text "II. Development of the demonstrator" is overlaid in white with a red shadow across the center.

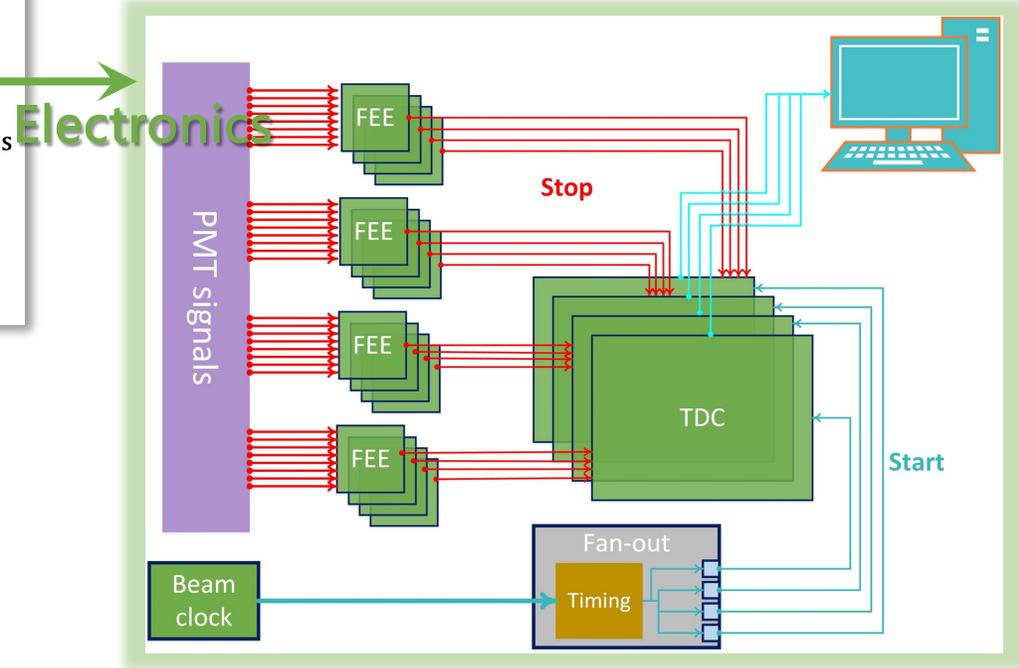
II. Development of the demonstrator

2.1 Conceptual design

128-channel PMT-based μ SR demonstrator

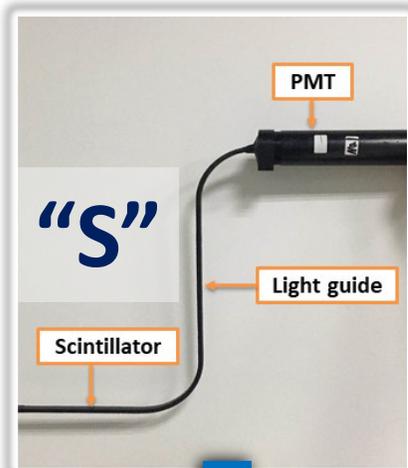
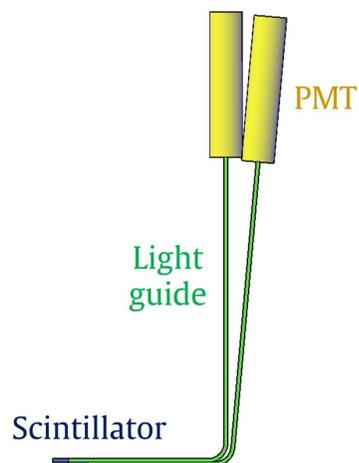
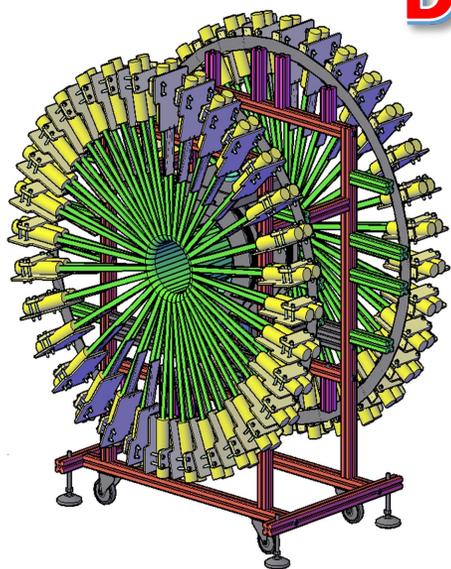


PMT: Photomultiplier tube
FEE: Front-End Electronics
TDC: Time-to-Digital Converter

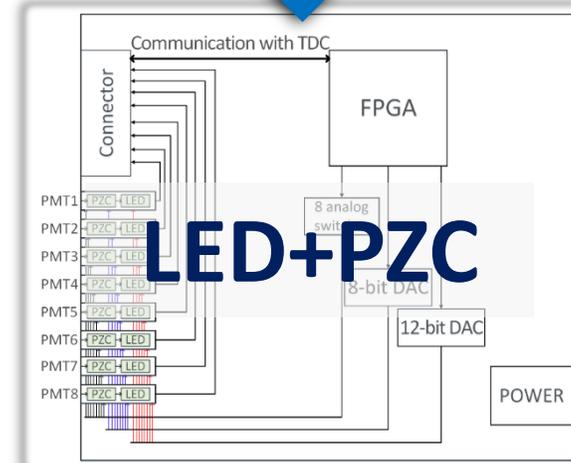
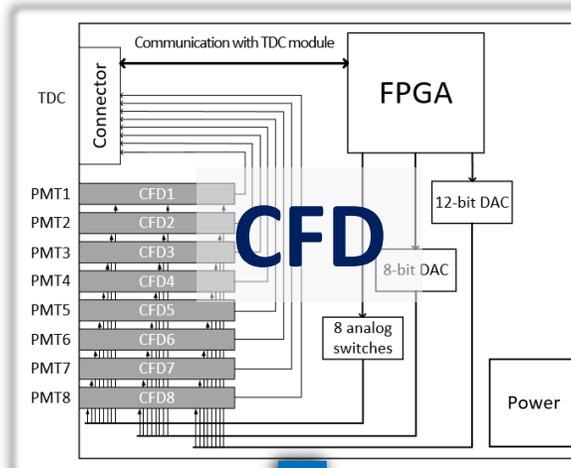


2.2 Prototype detectors and electronics

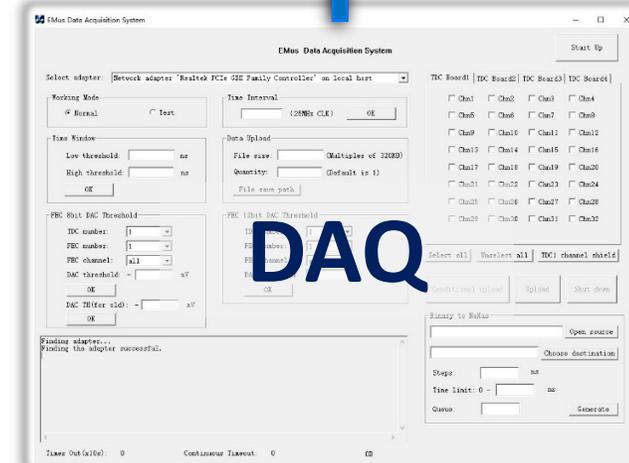
Detector



FEE



Readout

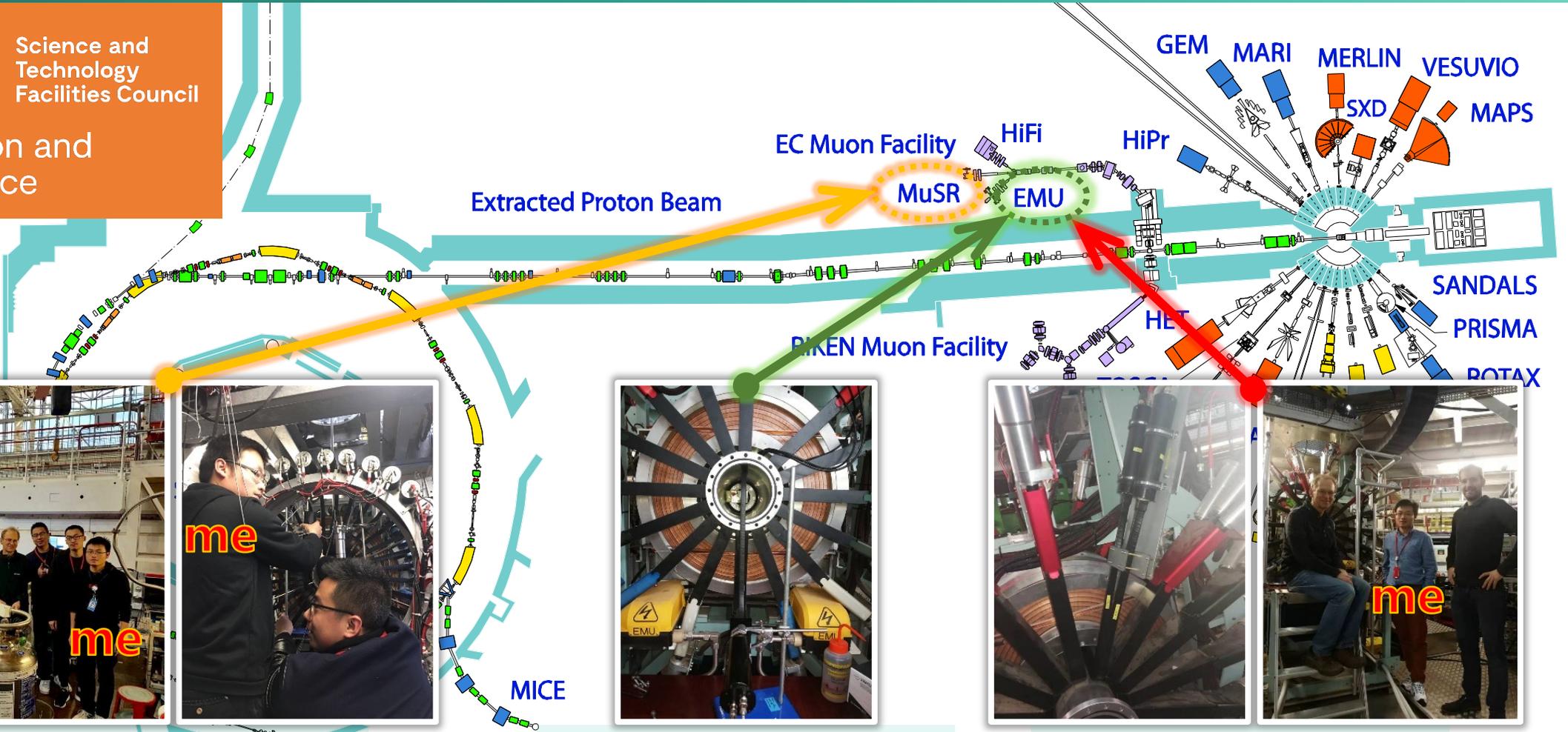


2.3 Beam tests



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

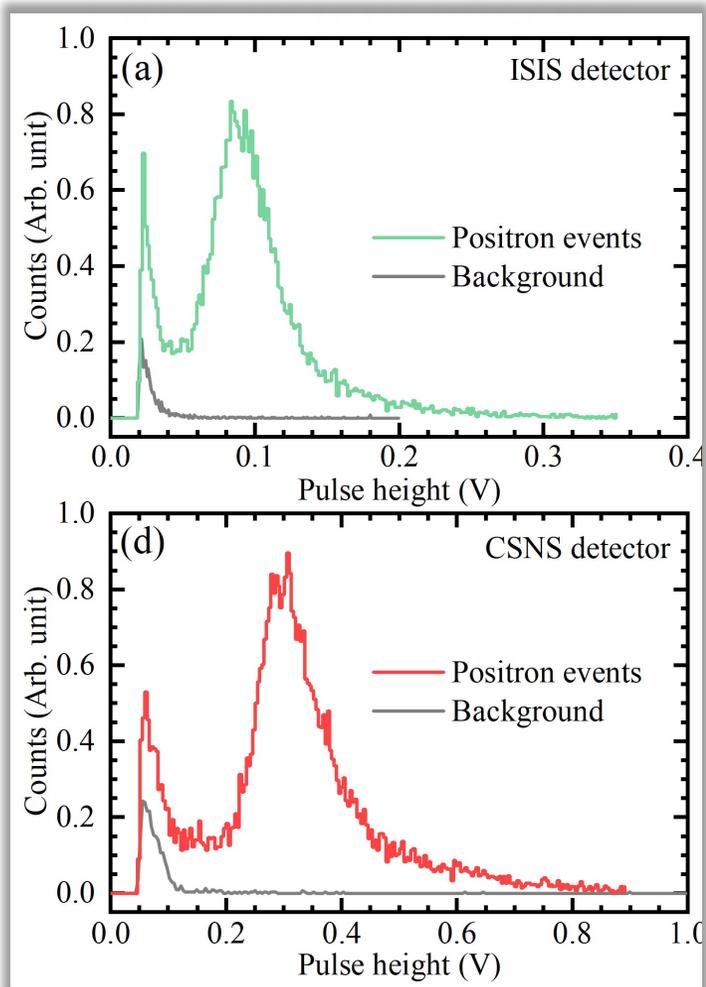


3rd beam test
2019/11/13

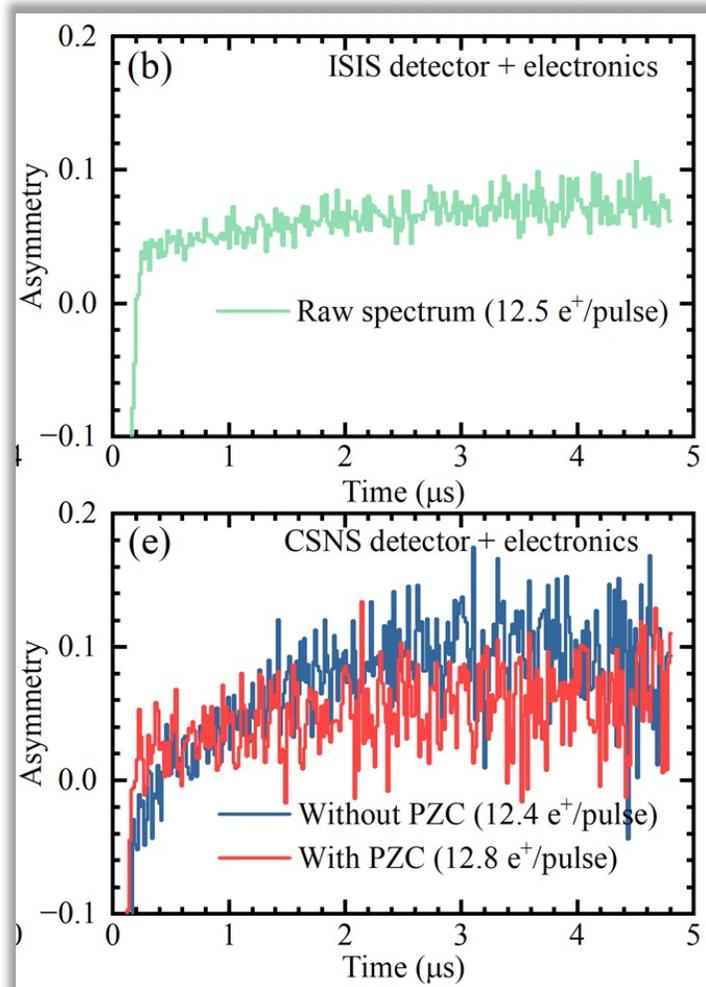


2.3 Beam tests

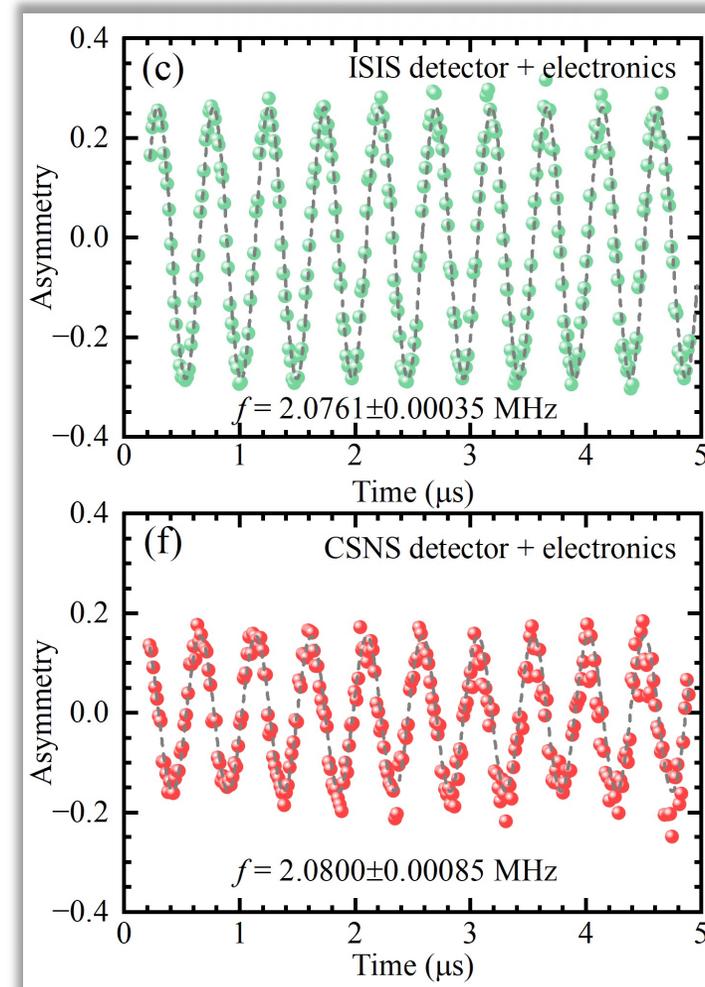
Pulse height spectra



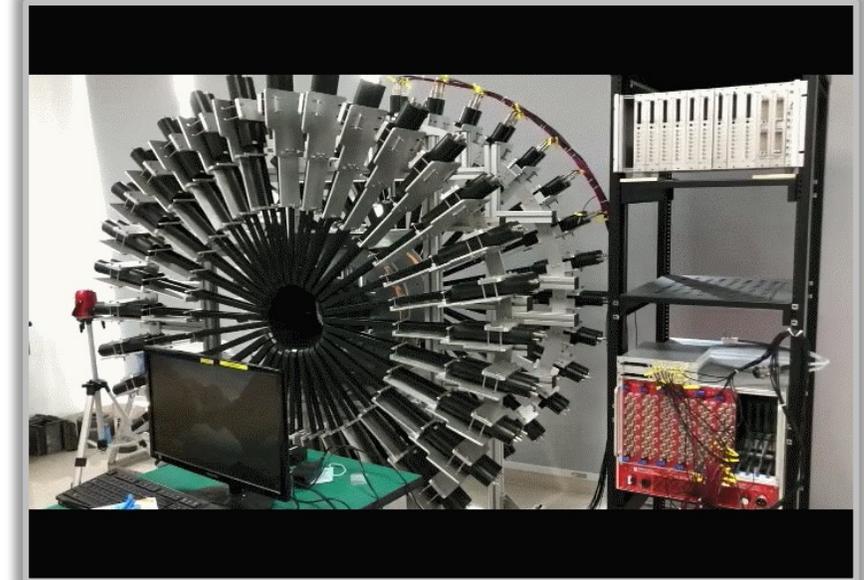
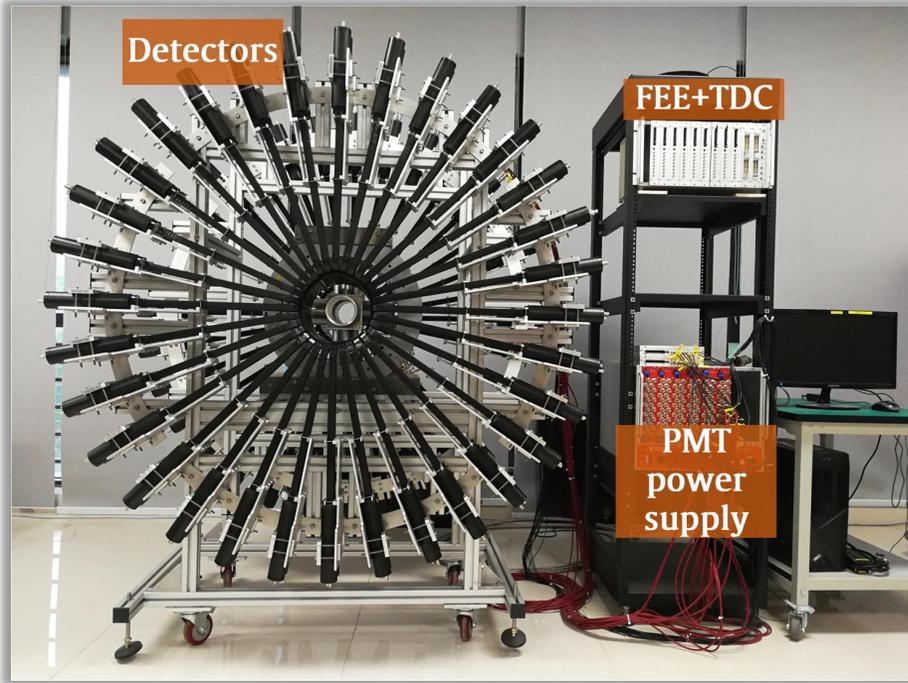
Dead-time distortions



TF measurements

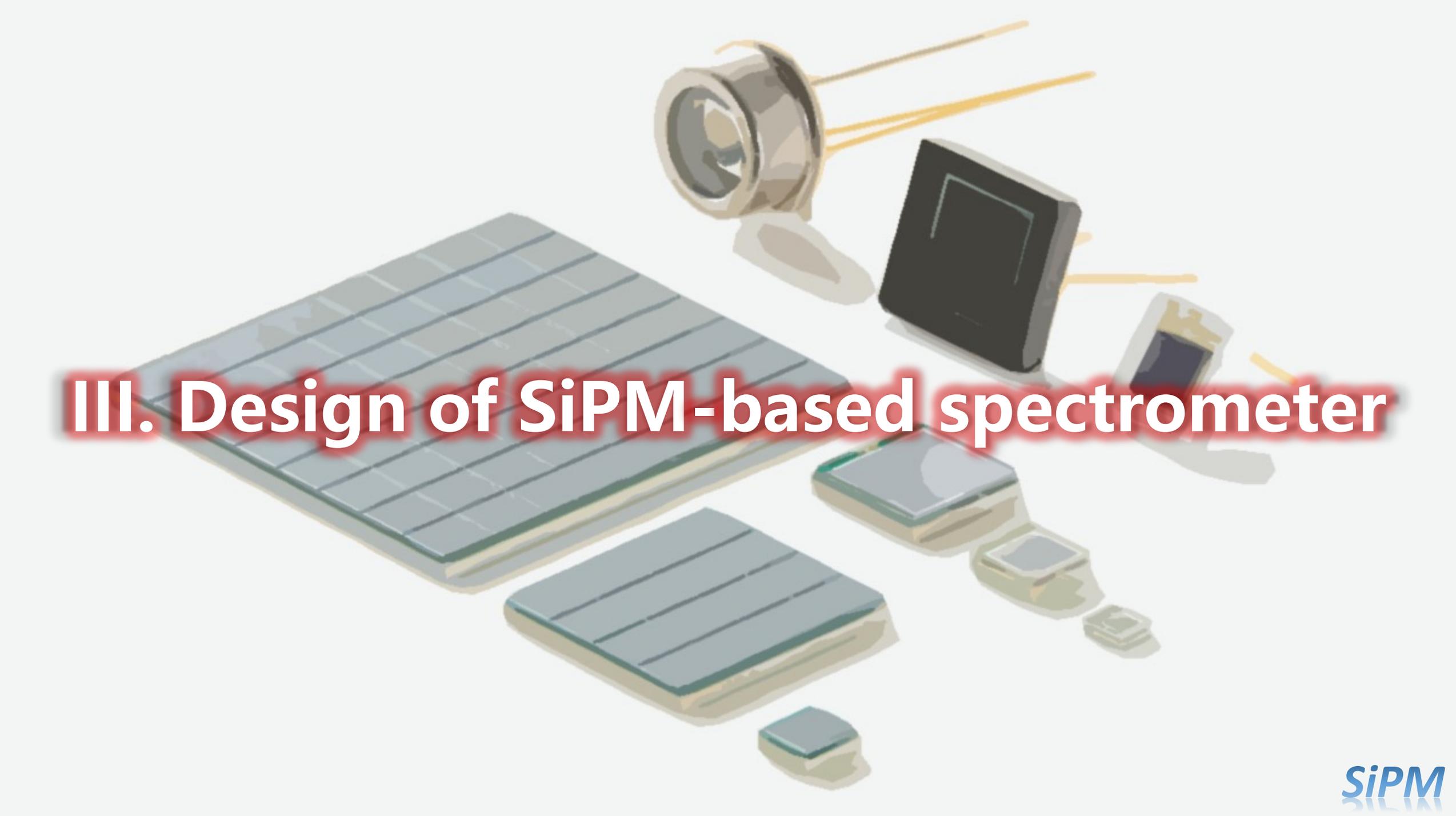


2.4 Mass production and assessment



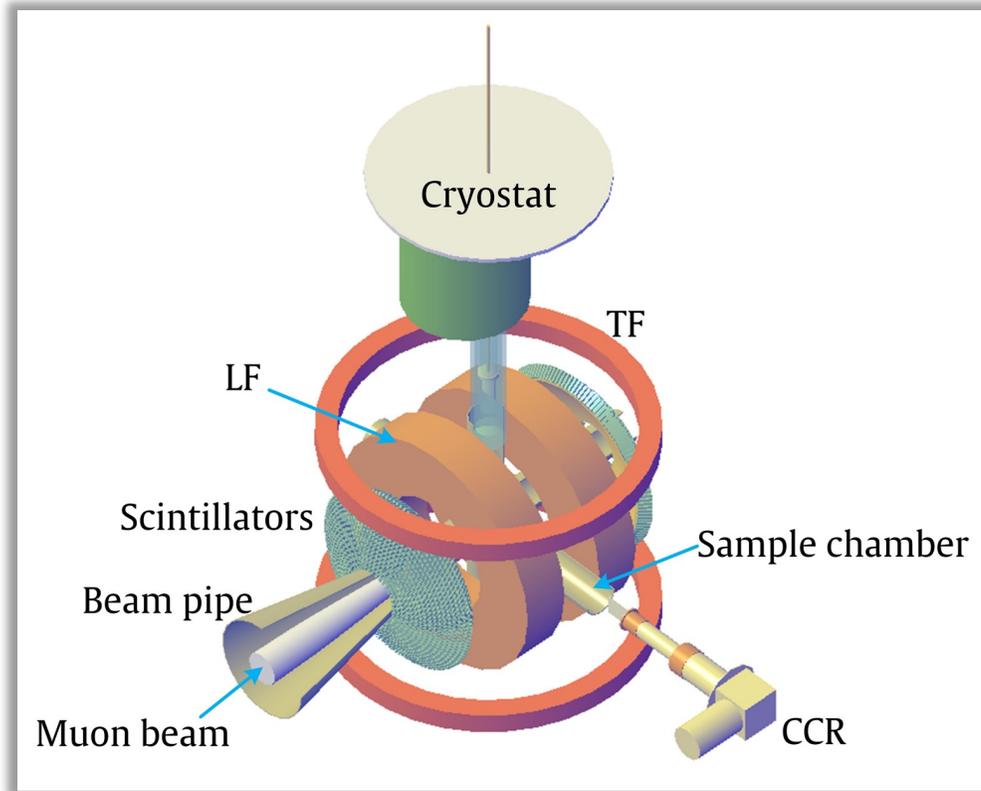
- ✓ First μ SR demonstrator in China
- ✓ Good counting capability
- ✓ Awarded "A" by the NSFC



A 3D perspective illustration of various components for a SiPM-based spectrometer. The components include a large rectangular SiPM array with a grid of channels, several smaller individual SiPMs of different sizes, a cylindrical lens assembly with two thin rods, a black square detector or filter, and a small rectangular component with a blue surface. The text 'III. Design of SiPM-based spectrometer' is overlaid in a bold, white font with a red glow effect across the center of the image.

III. Design of SiPM-based spectrometer

3.1 Spectrometer design



➤ Detectors:

- 3024 plastic scintillators ($8 \times 8 \times 40 \text{ mm}^3$)
- Sensl SiPM ($6 \text{ mm} \times 6 \text{ mm}$)
- FEE+TDC readouts
- Spherical placement

➤ Sample environment:

- Cryostat: 2 – 600 K
- CCR: 10 – 600 K

➤ Magnets:

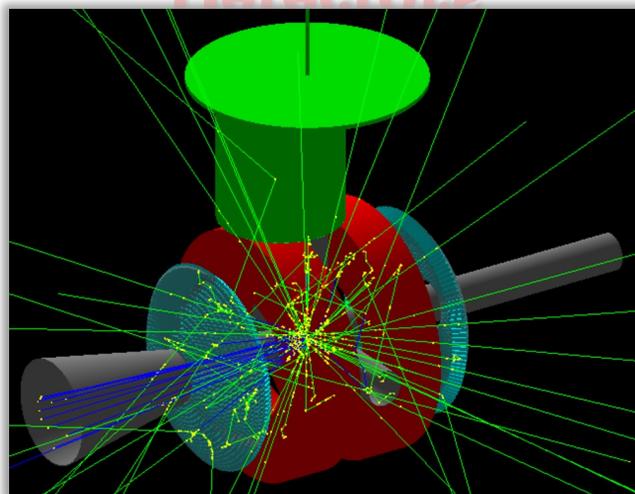
- Longitudinal field: 0 – 5000 G
- Transverse field: 0 – 400 G
- Zero field: $< 10 \text{ mG}$

➤ Beam:

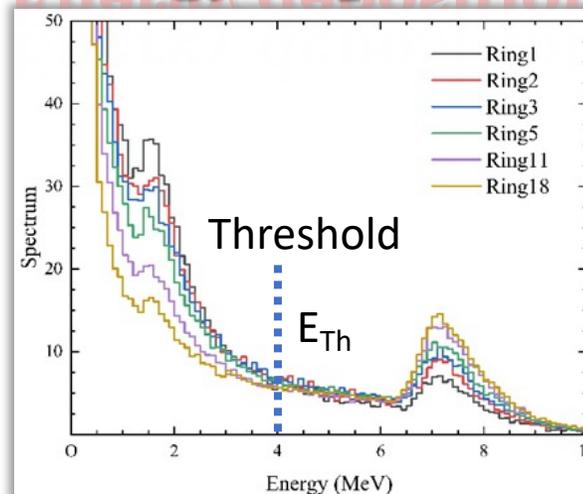
- $2 \times 10^5 \mu^+/\text{pulse}$ @ $\Phi 30 \text{ mm}$

3.2 Detector arrangement

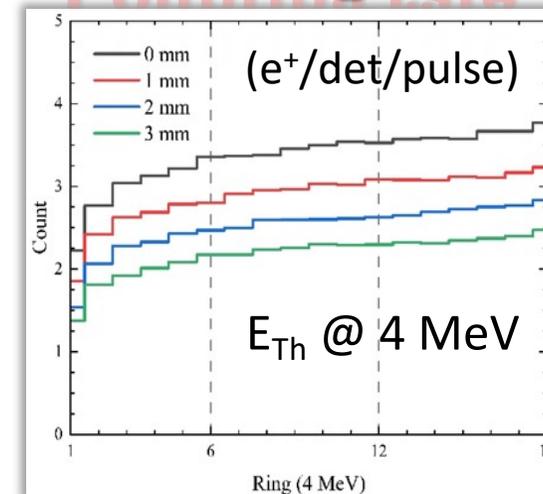
Detectors



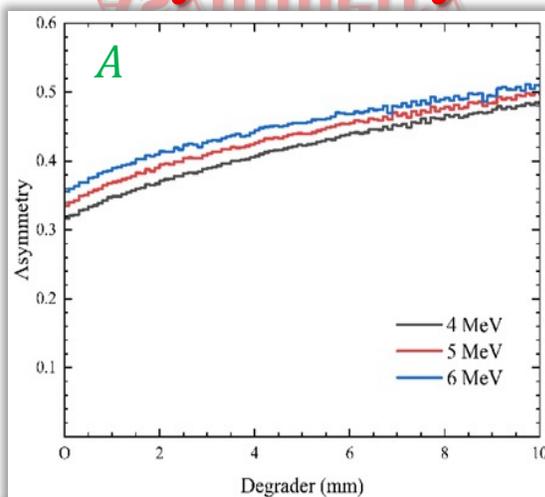
Energy deposition



Counting rate



Asymmetry



Detection rate

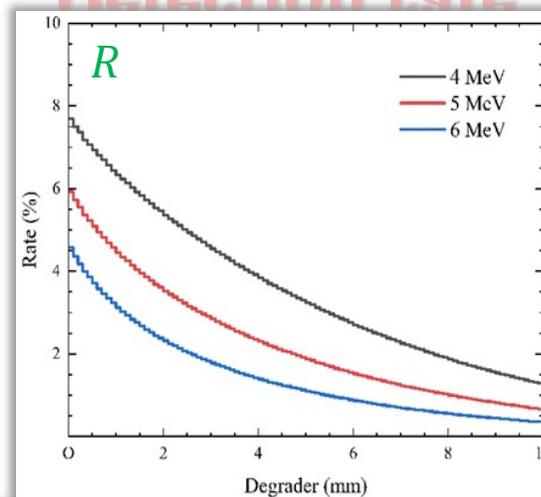
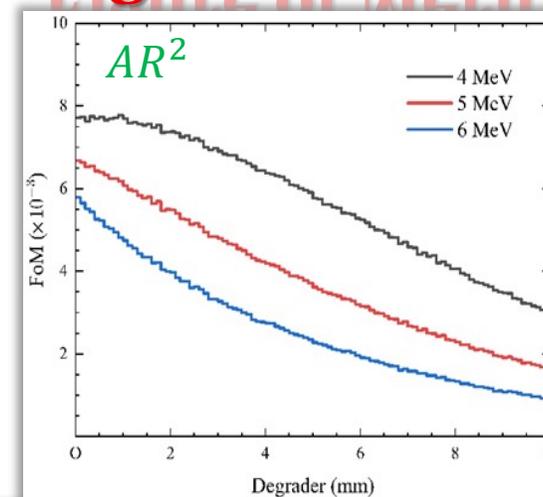


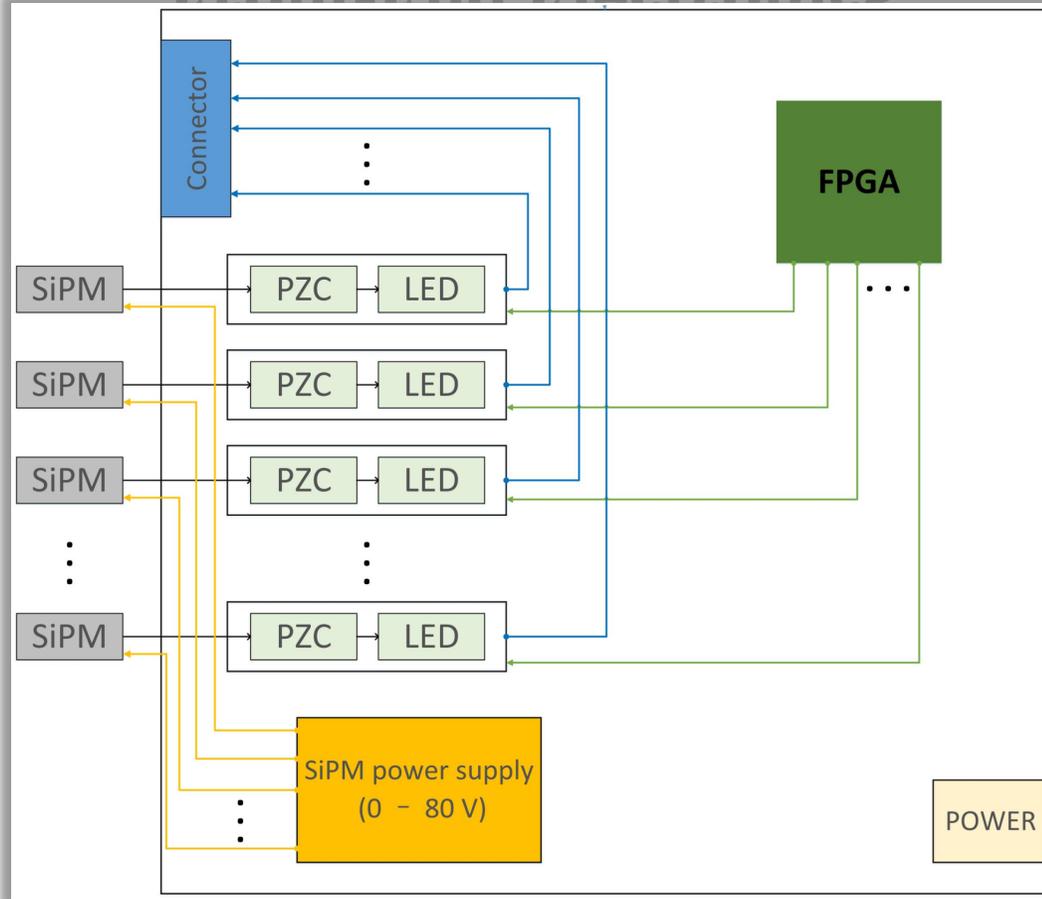
Figure of Merit



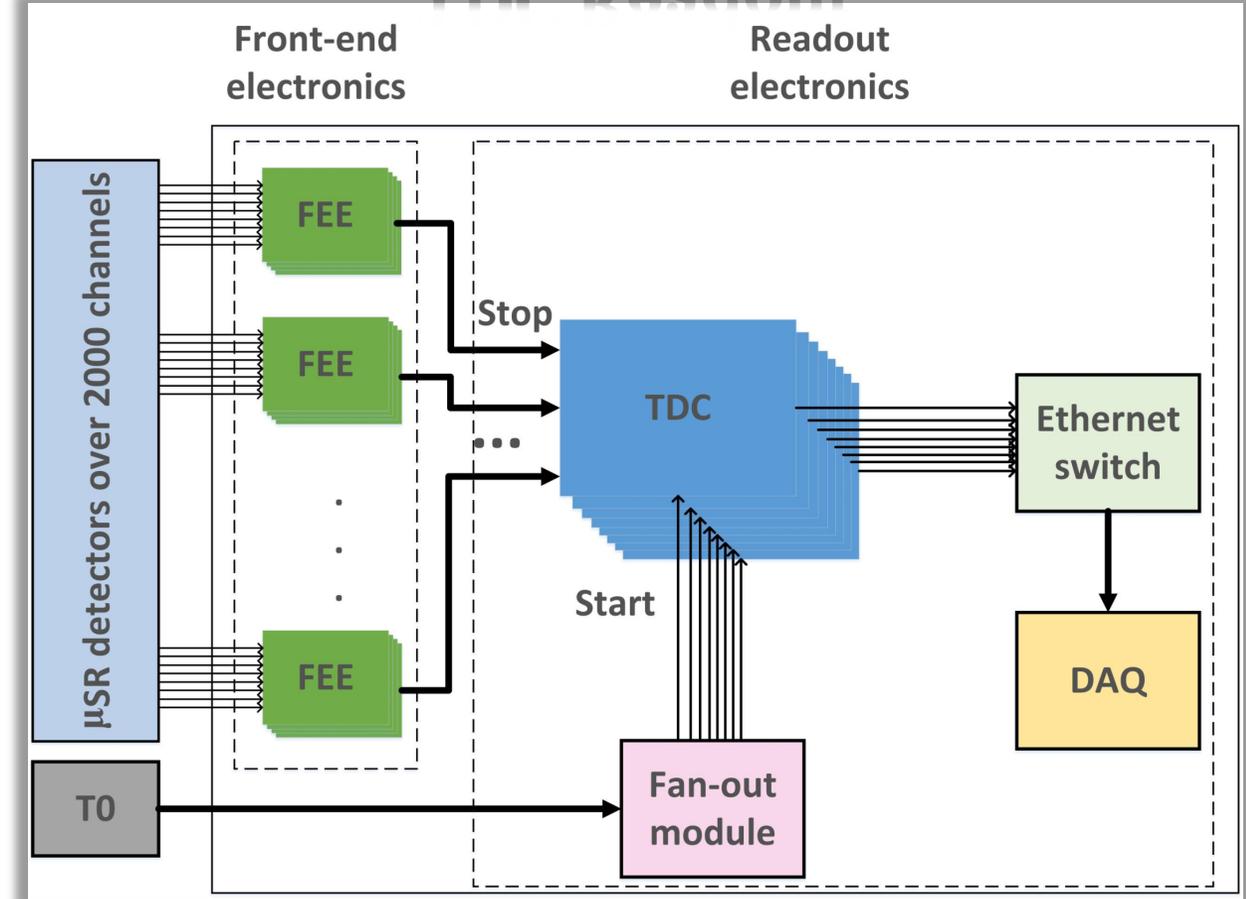
3.3 Electronics design

Leading-edge discrimination + TDC

Front-End Electronics



TDC Readout



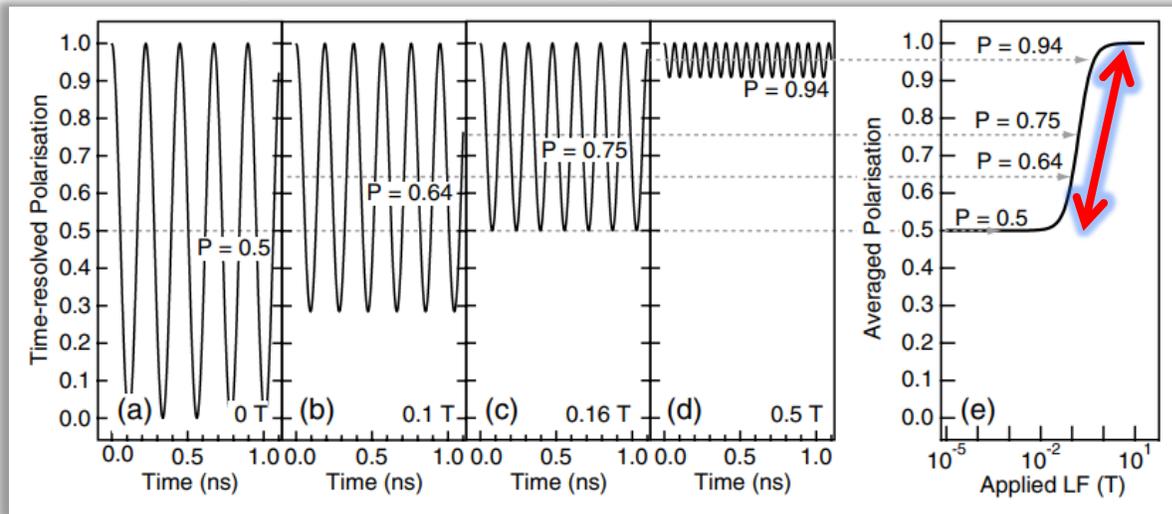
FS Deng, et al., JINST

Proceedings @ MuSR2020

3.4 Field range selection

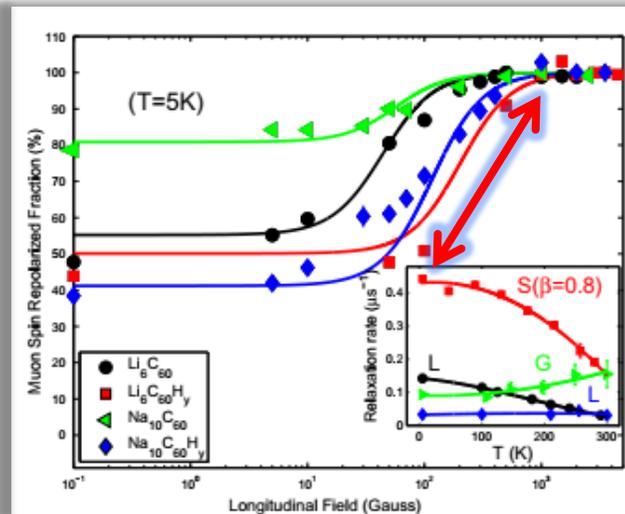
Muon spin repolarization in a longitudinal field

Topical review by L Nuccio et al.



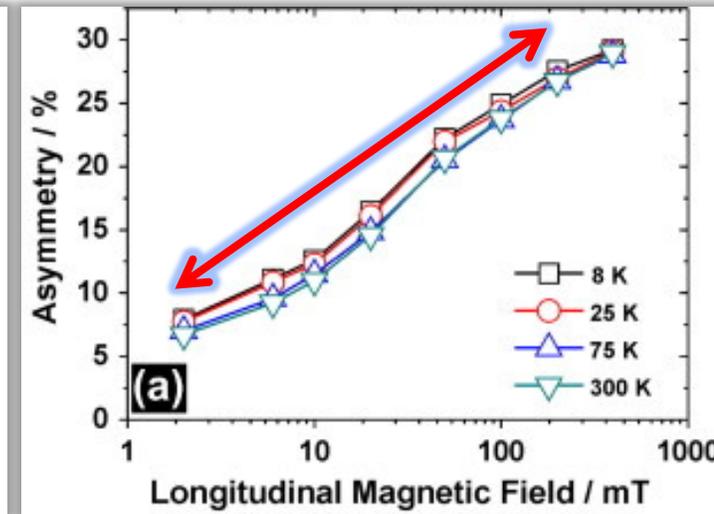
J. Phys. D: Appl. Phys. 47 (2014) 473001

Test @ EMU, ISIS



Carbon 67 (2014) 92 - 97

Test @ RIKEN-RAL, ISIS



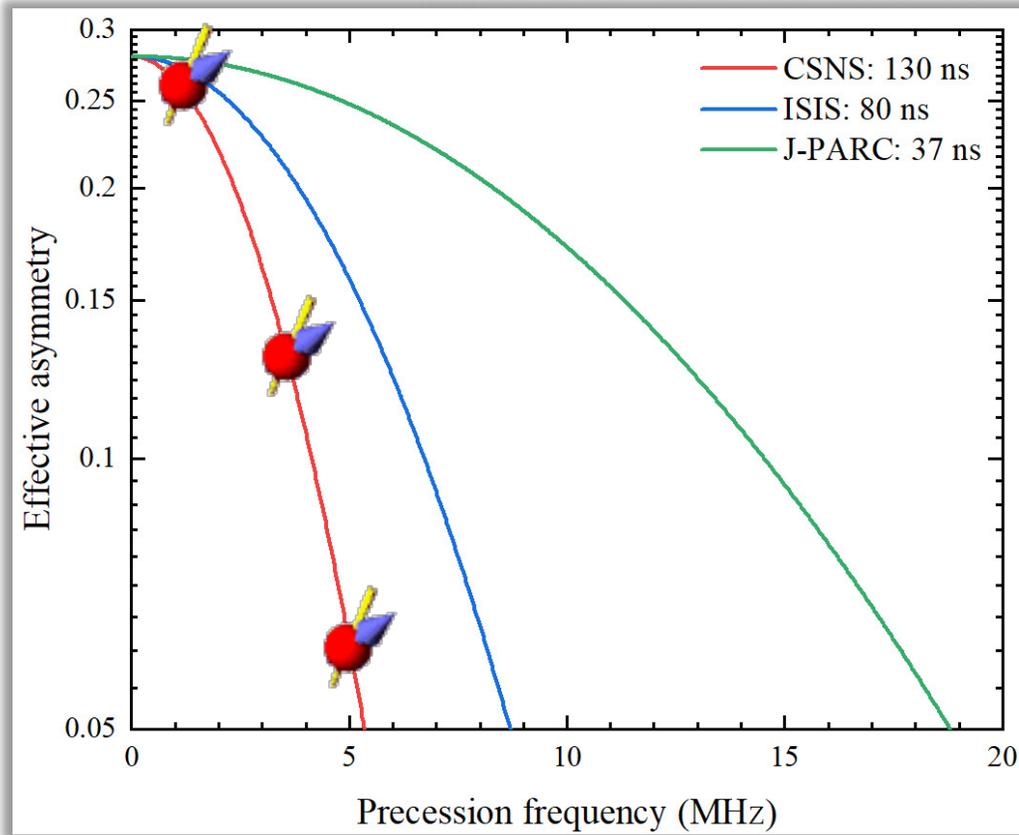
Organic Electronics, 14 (2013) 62 - 66

Longitudinal field: 0 – 5000 G

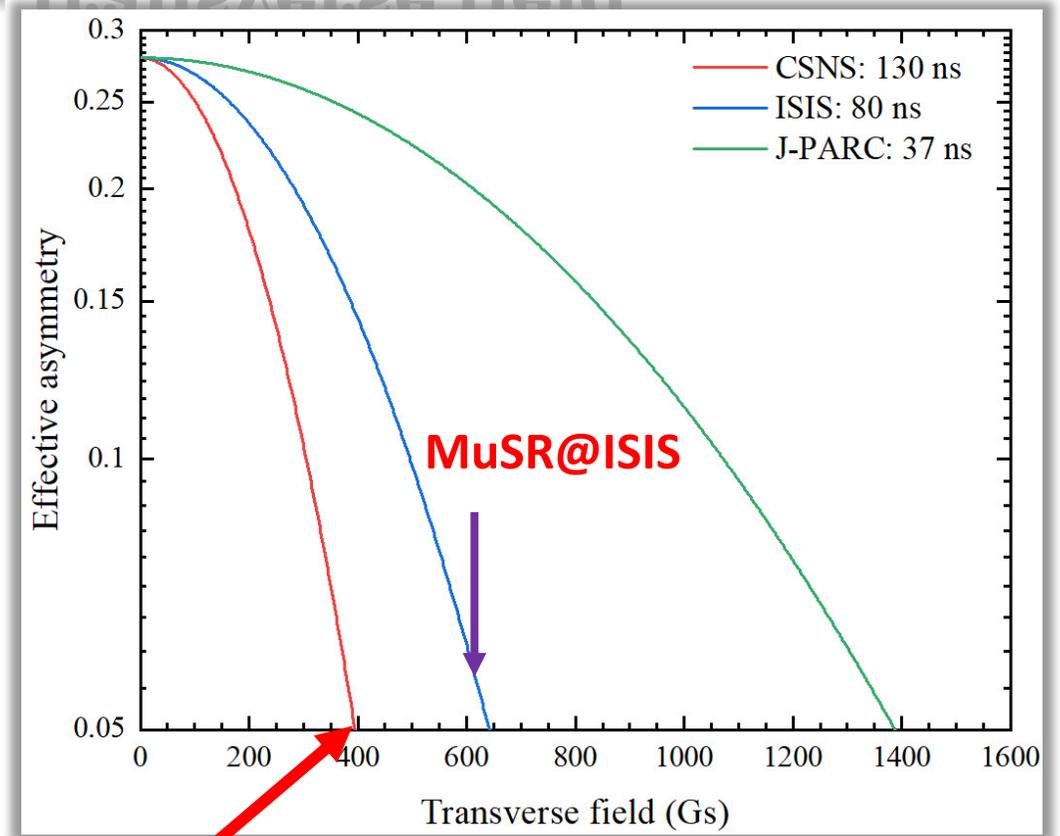
Details in [Muon Spectroscopy: An Introduction](#)

3.4 Field range selection

Muon spin rotation in a transverse field



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

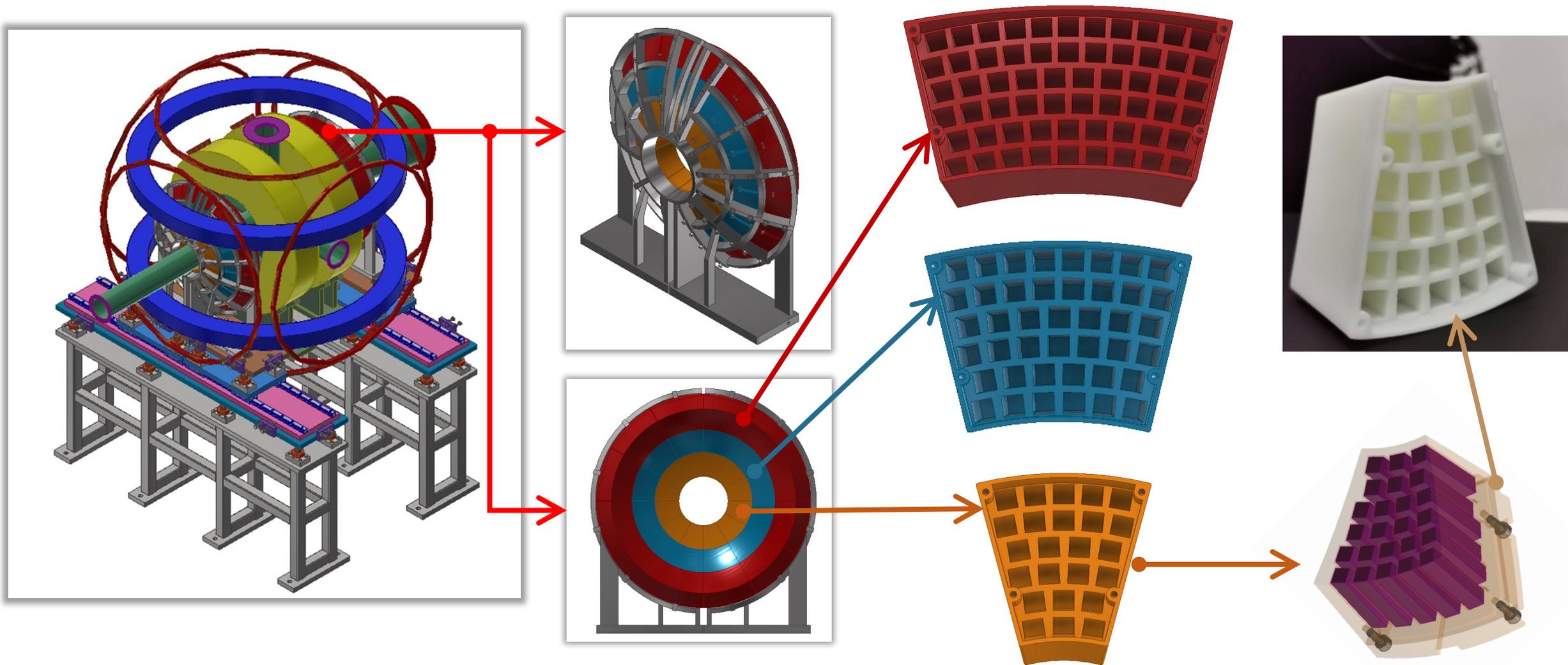


Transverse field: 0 – 400 G

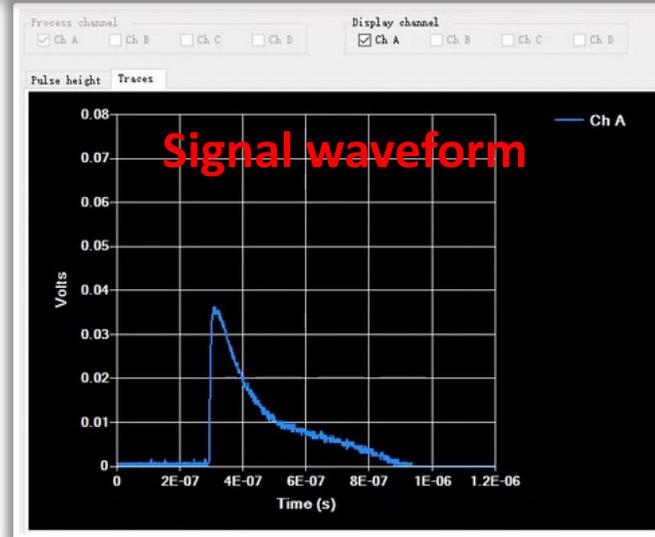
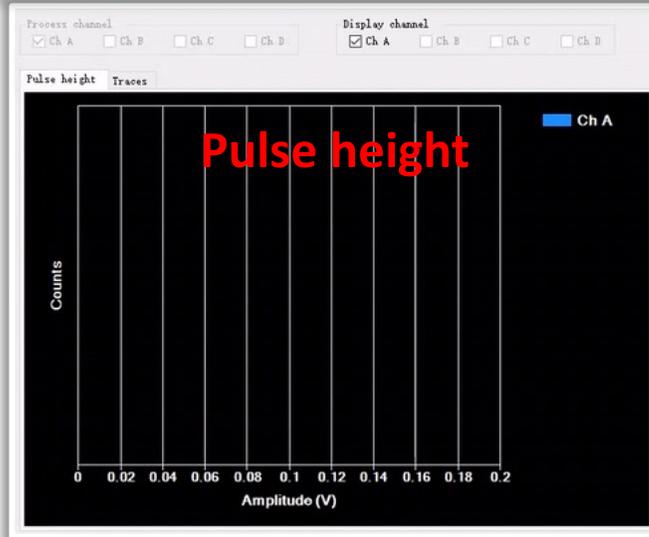
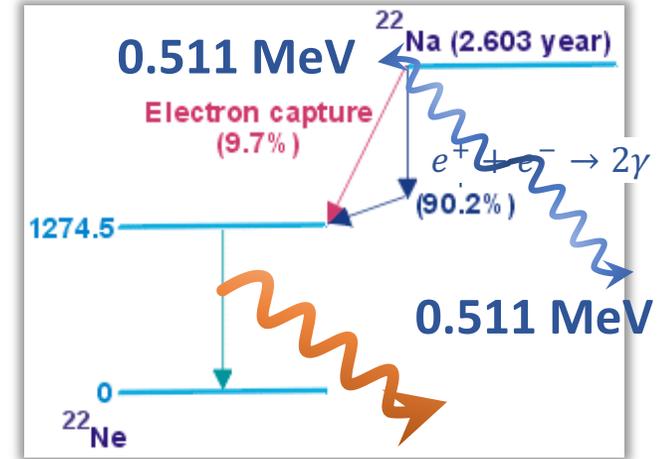
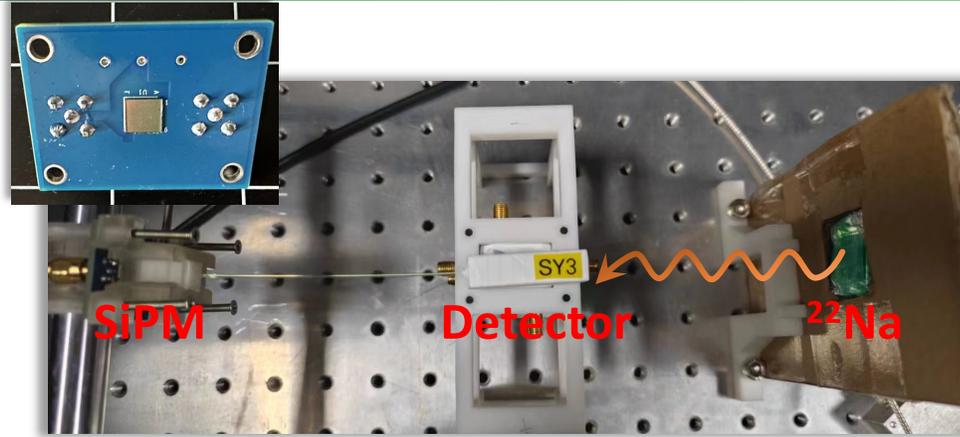
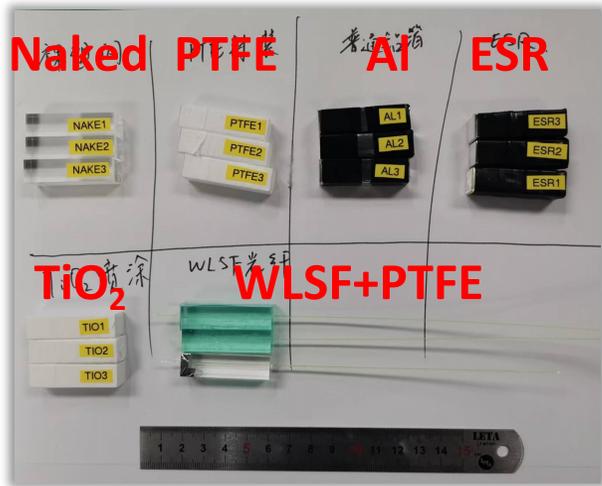
Z Pan et al., NIM A 1024 (2022) 166121;

Hyperfine Interact. 65 (1991) 1113-1119

3.5 Technical considerations



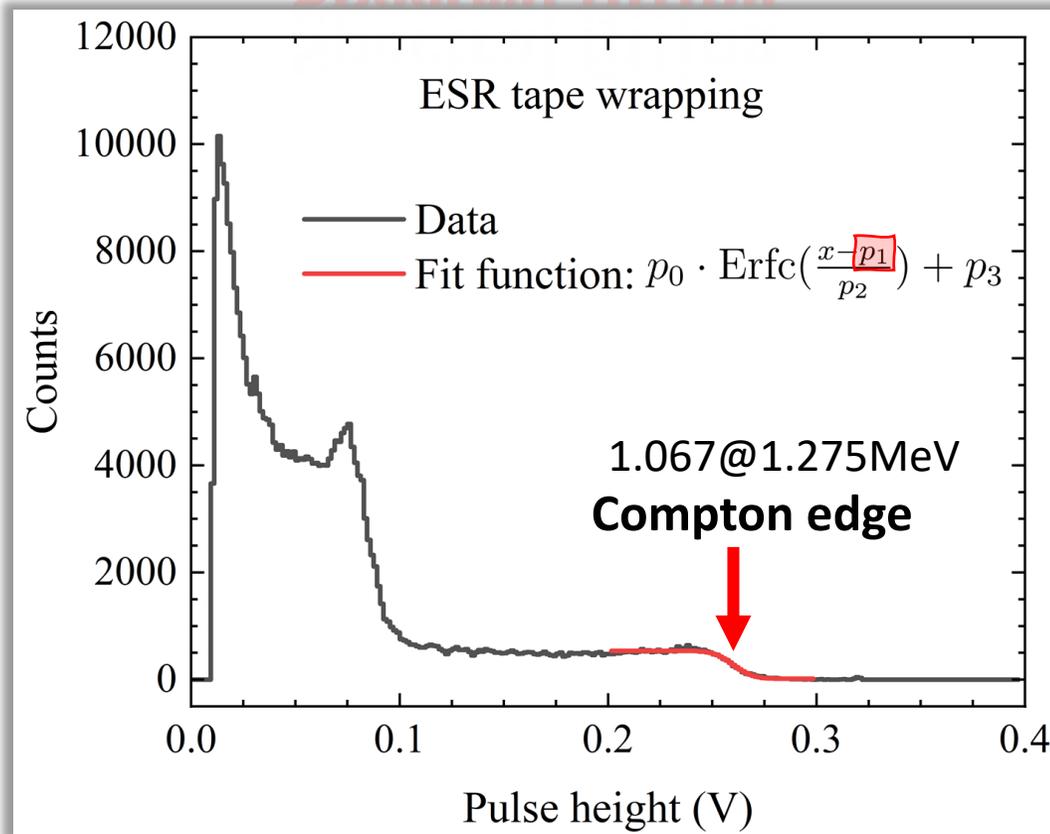
3.6 Preliminary scintillator tests



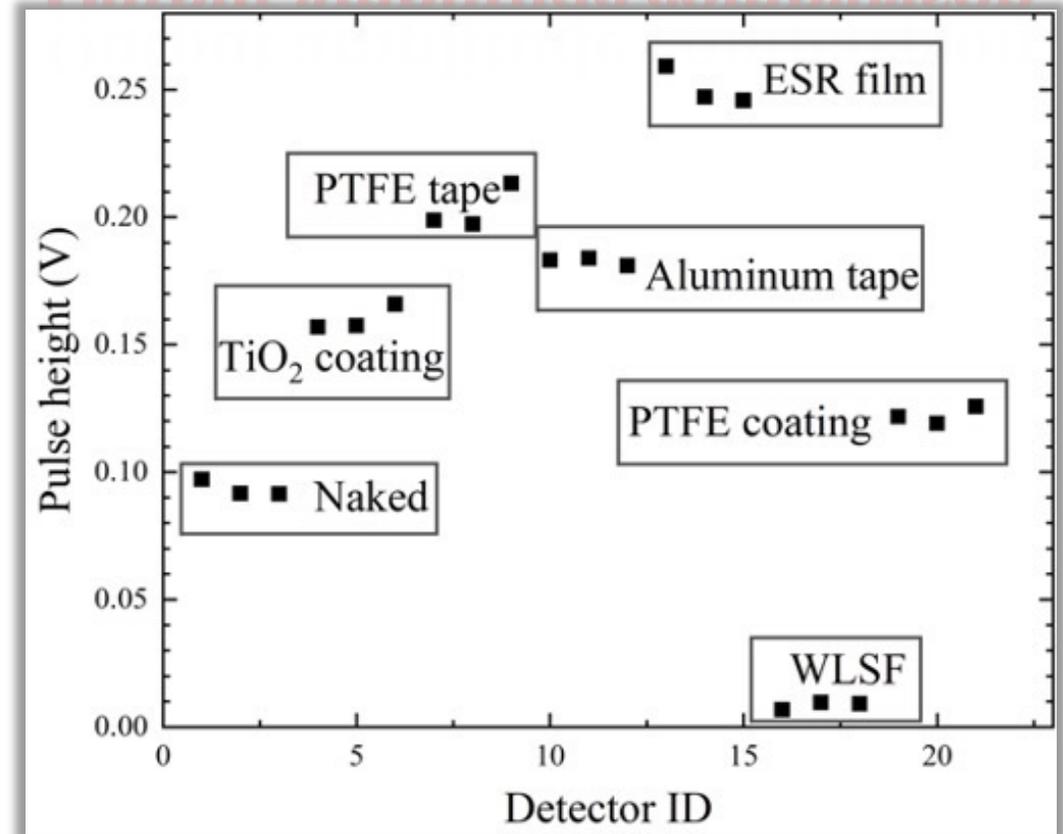
Courtesy of Dr. Erik Schooneveld (STFC ISIS Detector Group) for providing DAQ software!

3.6 Preliminary scintillator tests

Spectral fitting



Output amplitude comparison



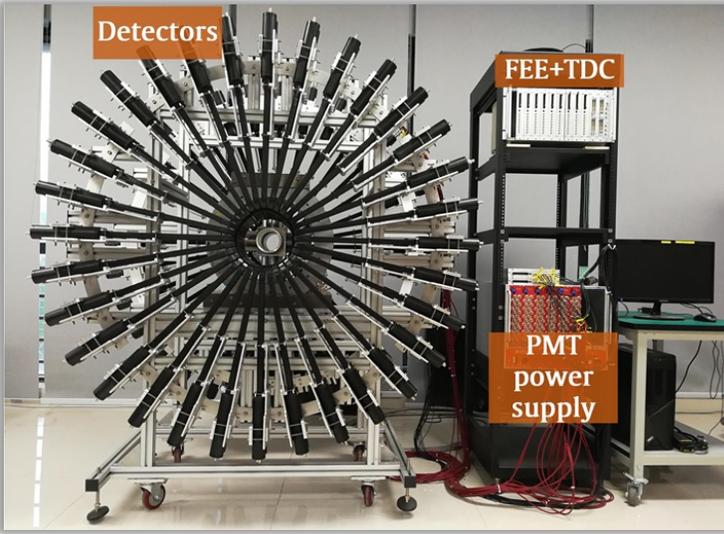
ESR wrapping outperforms, while PTFE wrapping has less difficulty in manufacturing .



IV. Summary and prospects

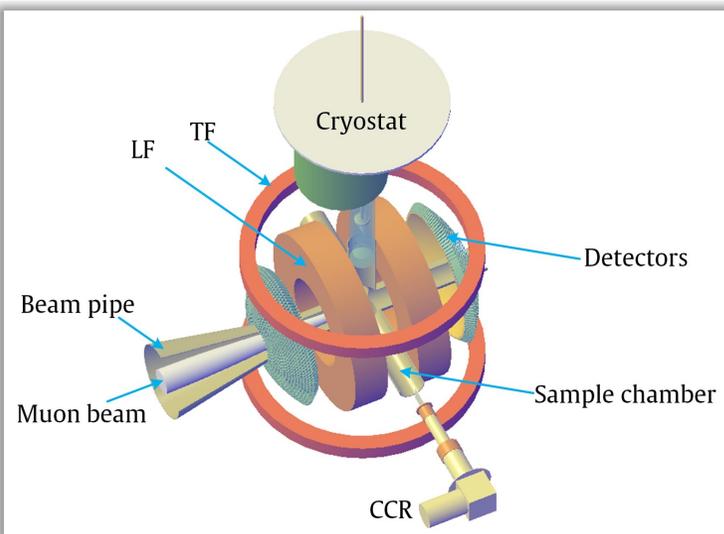
Spinning toward future

4.1 Summary: μ SR spectrometer development



First μ SR spectrometer demonstrator

- 128 plastic scintillator + PMT **2015 - 2020**
- Good counting capability (short deadtime)
- Multiple beam tests



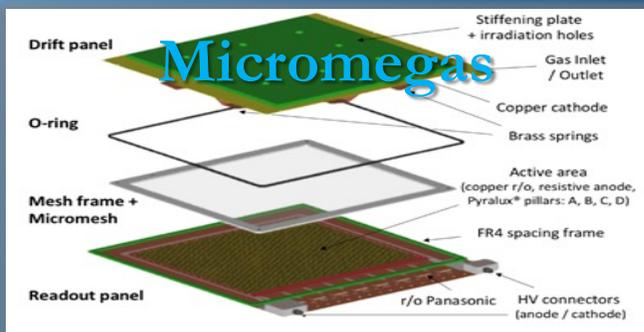
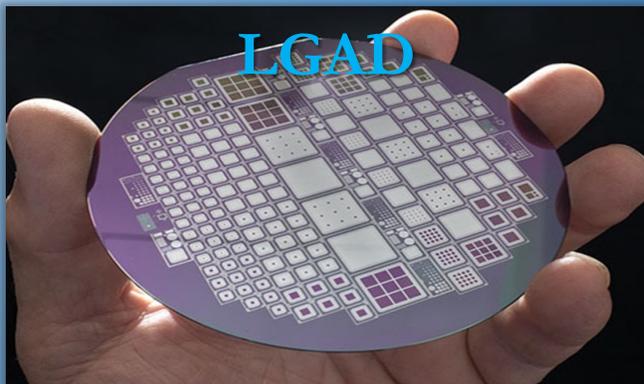
X Spectrometer @ MELODY-CSNS

- 3024 plastic scintillator + SiPM **2023 - 2028**
- Asymmetry: > 0.28
- Counting rate: $8 \times 10^7 e^+/\text{hour}$ @ 1 Hz
- Fast readout

4.2 Prospect: pulsed μ SR spectroscopy

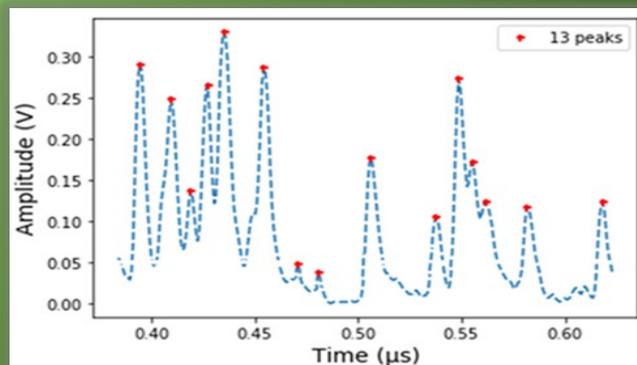
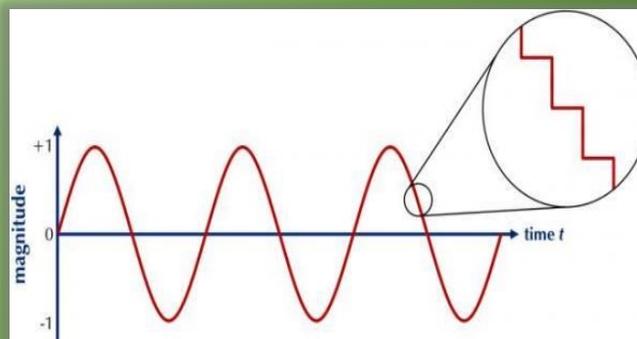
● Detector

- ✓ High granularity
- ✓ Fast output



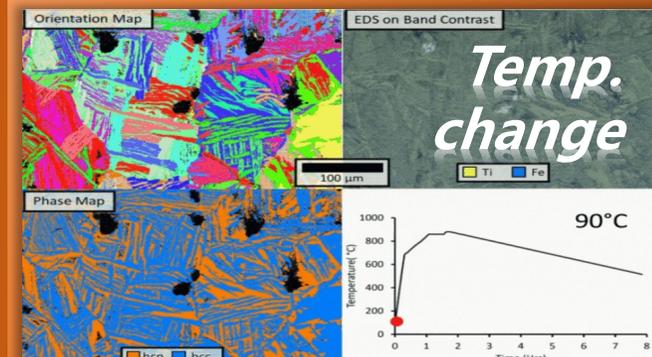
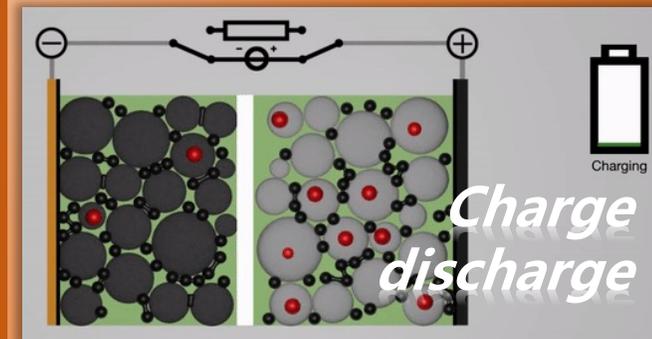
● Electronics

- ✓ Digitization
- ✓ High precision

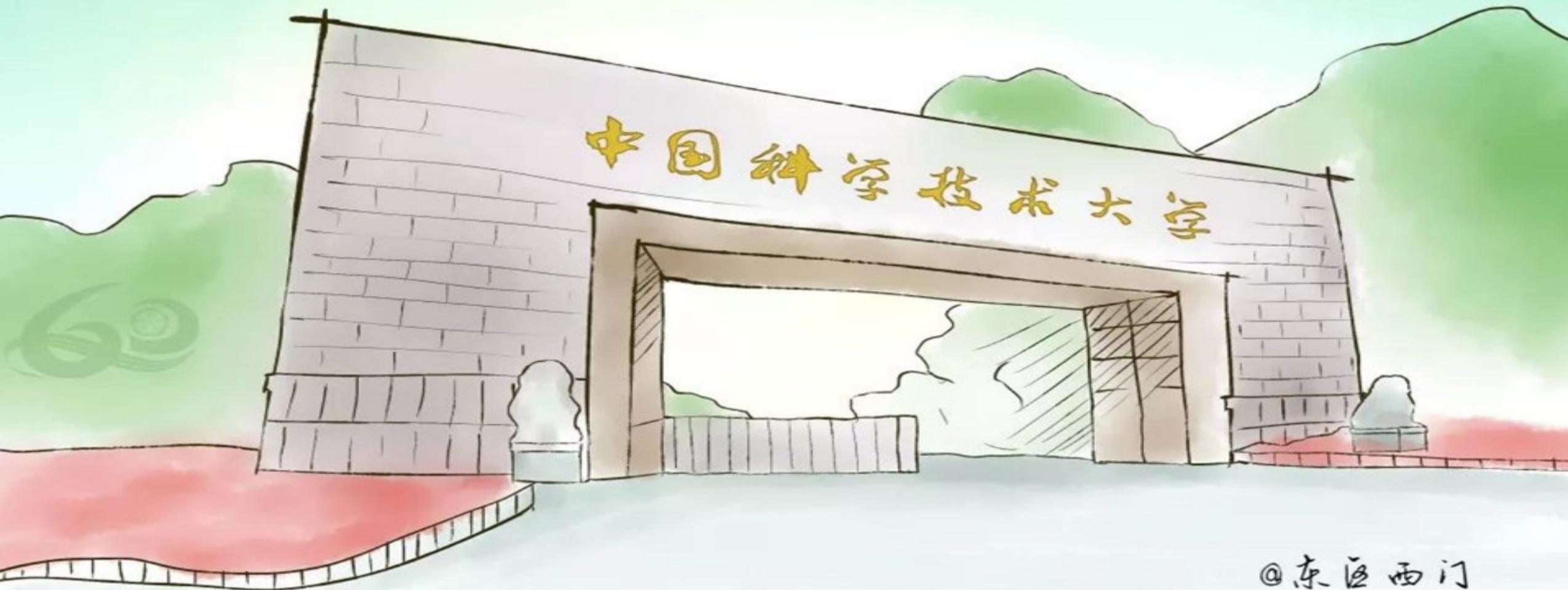


● Measure

- ✓ In-situ
- ✓ Operando



Thanks!



@东区西门

Main Gate of USTC