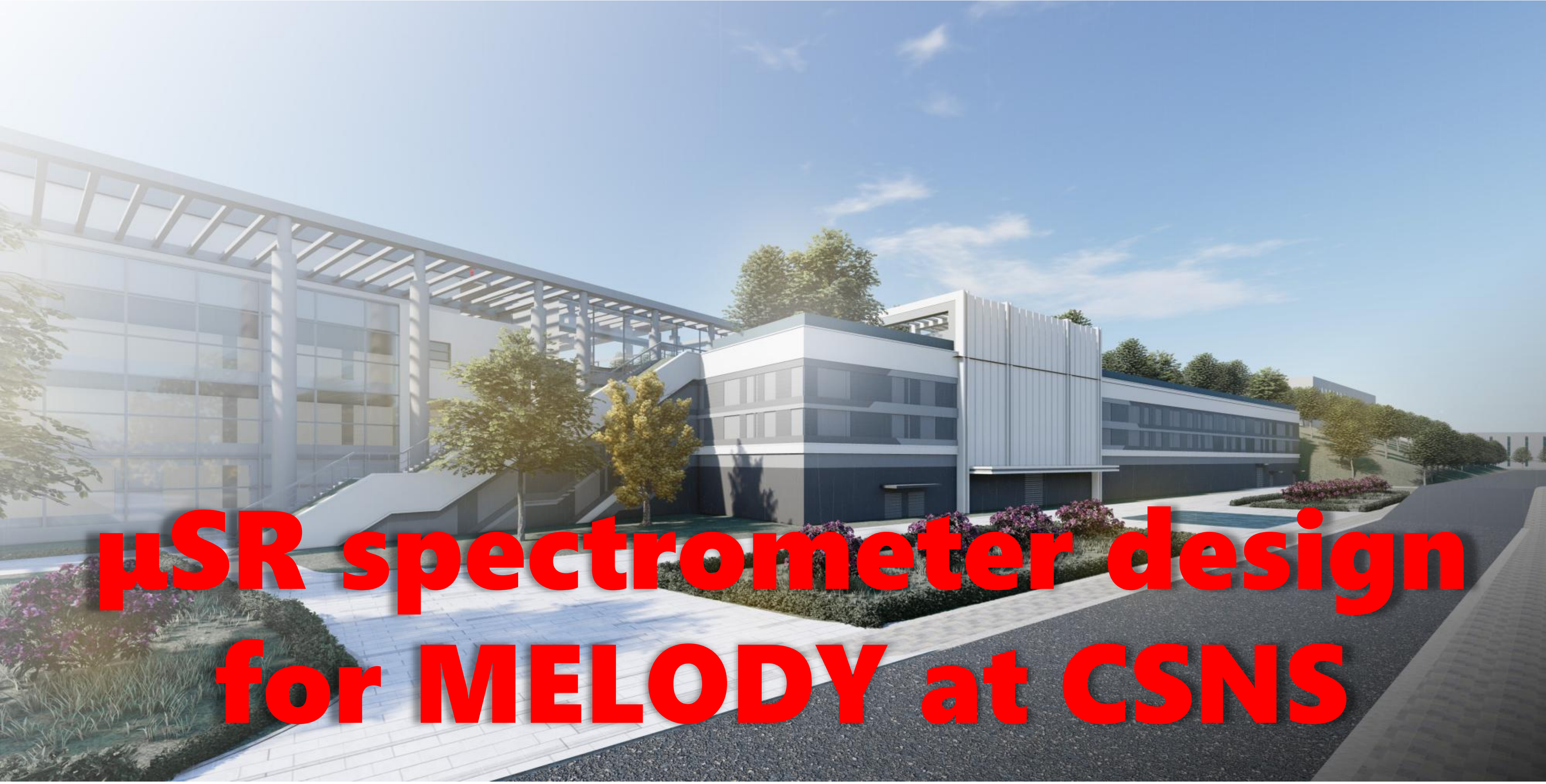

μSR spectrometer design for MELODY at CSNS

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Content:

I. Basic Principles of μSR Spectrometer

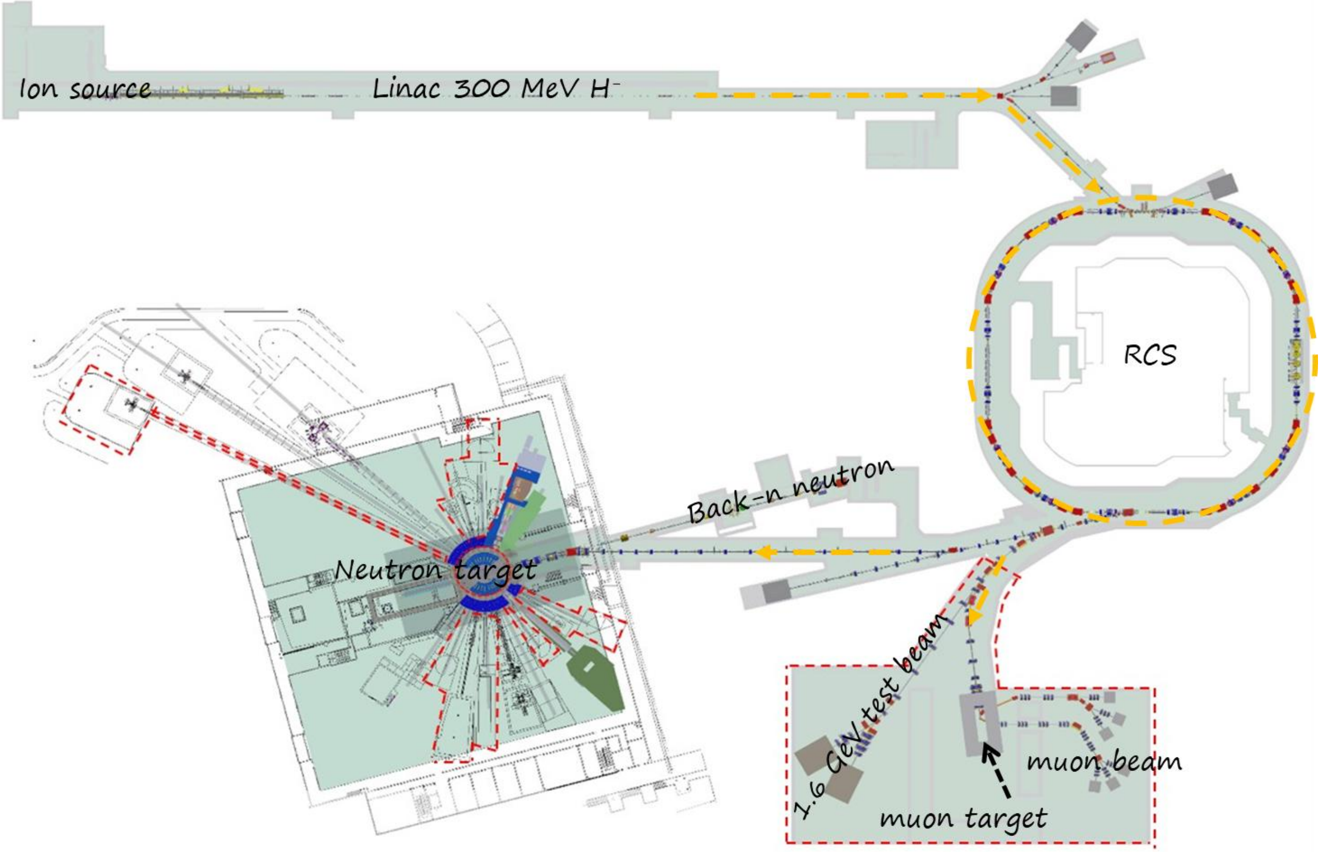
II. Overall Design of the MELODY μSR Spectrometer

III. Summary and prospective

Phase II upgrade project of the CSNS：
(2023.01-2028.09)

MELODY:
1 Hz of proton pulses (1.6 GeV, 20 kW) to hit the muon target

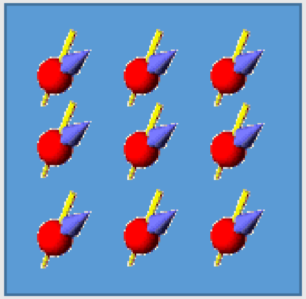
a surface muon line and a μSR spectrometer will be first built

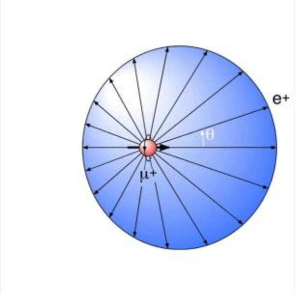


I. Basic Principles of the μSR Spectrometer

μSR (muon spin rotation/relaxation/resonance)

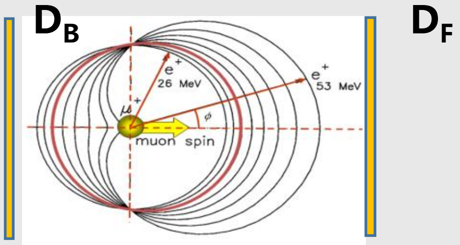
A technique that uses the spatial asymmetry of positrons generated by polarized μ decay to study the magnetic properties of materials.



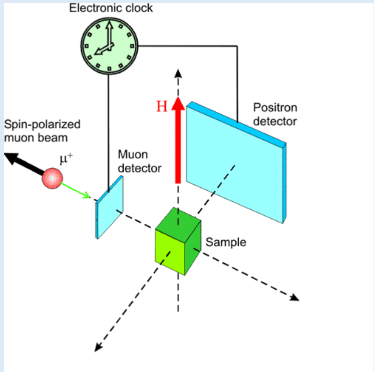


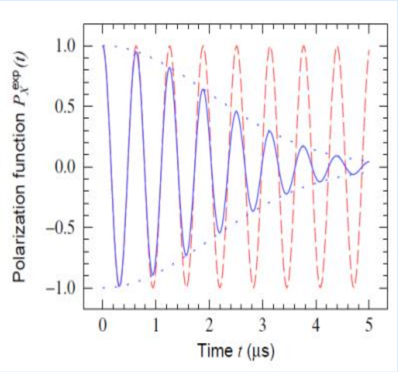
$$\omega = \gamma_\mu B$$

Positrons emit tend to along the muon spin



$$Asymmetry\ A = \frac{N_F - N_B}{N_F + N_B}$$





$$N(t) = N_0\, exp\left(-\frac{t}{\tau_\mu}\right)[1 + AP(t)] + B$$

P(t) frequency → magnetic strength

P(t) depolarization→ polarization relaxation

→ magnetic distribution

P(t) deviation → local magnetic distribution

…

µSR

High-temperature superconductivity

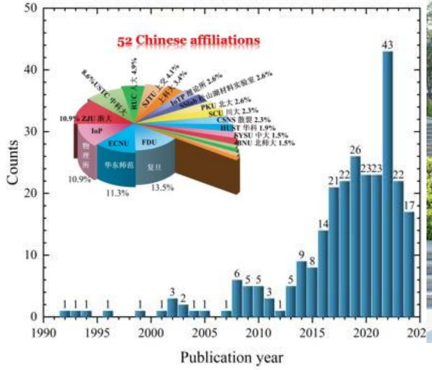
Magnetic materials

New energy materials (lithium batteries)

Organic semiconductor

Chemistry

…



Domestic users and achievements continue to grow (2025 2nd User Conference)

Features or Advantages:

- **Pure magnetic probe:** point particle, no volume effect
- **Measure extremely weak magnetism:** ~0.1 G or 10^{-3} μ_B/Atom
- **Very short magnetic order:** exceeds neutron scattering
- **Fluctuation compensation:** the gap between neutrons and NMR
- **Non-destructive measurement technique**

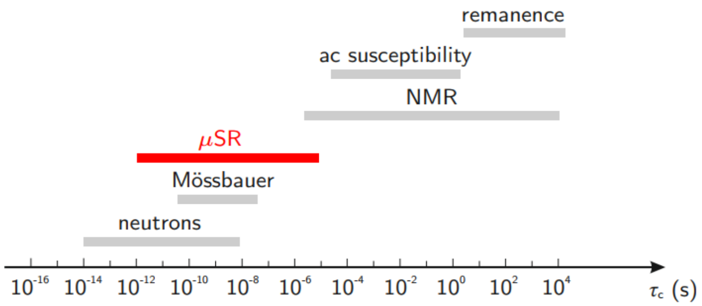
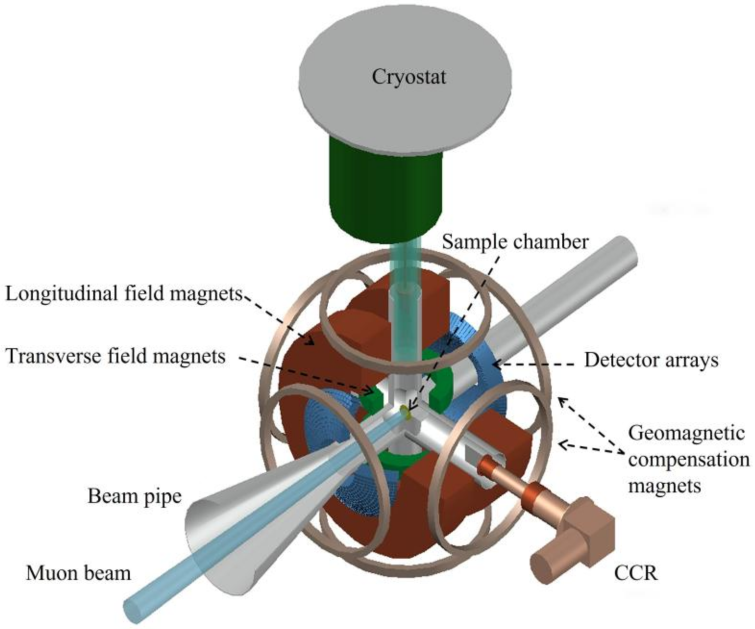


Figure 3.5.: *Comparison of dynamical ranges accessible to different techniques.* *$\tau_c = 1/\nu_c$ is the characteristic fluctuation time associated with the magnetic fluctuations. Adapted from Pierre Dalmas de Réotier.*

II. Design of µSR Spectrometer

Basic components of a pulsed-surface muon-µSR spectrometer:



Detector arrays:

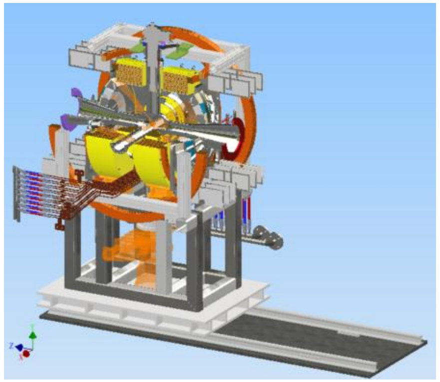
High granularity
Cover large solid angles
Scintillator + SiPM
No T0 detector required

Temperature conditions:

Cryogenic: Cryostat CCR
High temp: Furnace

Magnets:

LF: Longitudinal field is parallel to the µ spin
TF: Transverse field is perpendicular to the µ spin



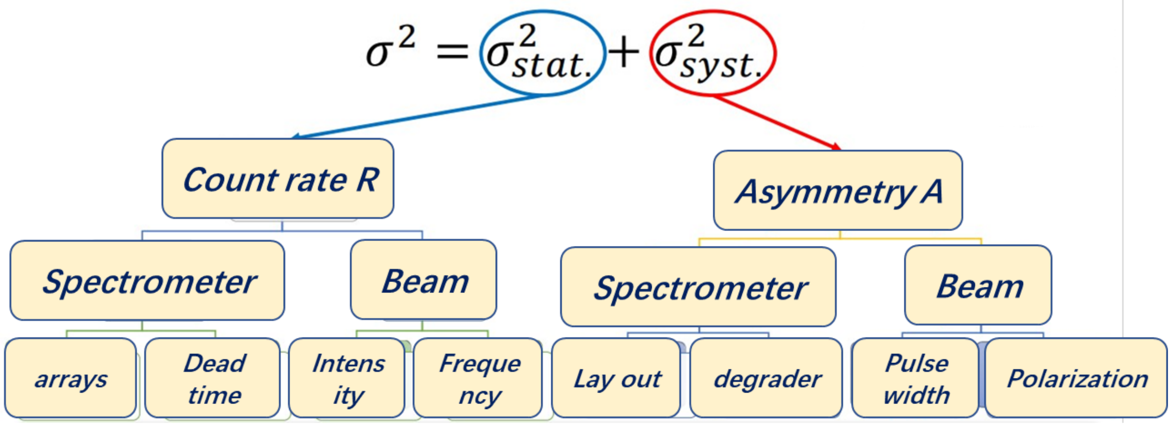
Sample chamber:

Provides vacuum environment for CCR
Provides fly-past for the muons out off sample

More: Pressure, laser, RF field, etc.

How well a spectrometer performs?

Performance: The quality of the experimental data



$$\sigma^2 = \sigma^2_{stat.} + \sigma^2_{syst.}$$

Count rate R

- Spectrometer
  - arrays
  - Dead time
- Beam
  - Intensity
  - Frequency

Asymmetry A

- Spectrometer
  - Lay out
  - degrader
- Beam
  - Pulse width
  - Polarization

Figure of merit:

F = A^2 × R

The higher the F,
the better the μSR performance

Usefulness: What physical problems can be studied using the spectrometer

Environmental conditions: temperature, magnetic field, pressure, laser, etc.,

The beam : pulse width determines the limit of magnetic dynamic range that can be measured

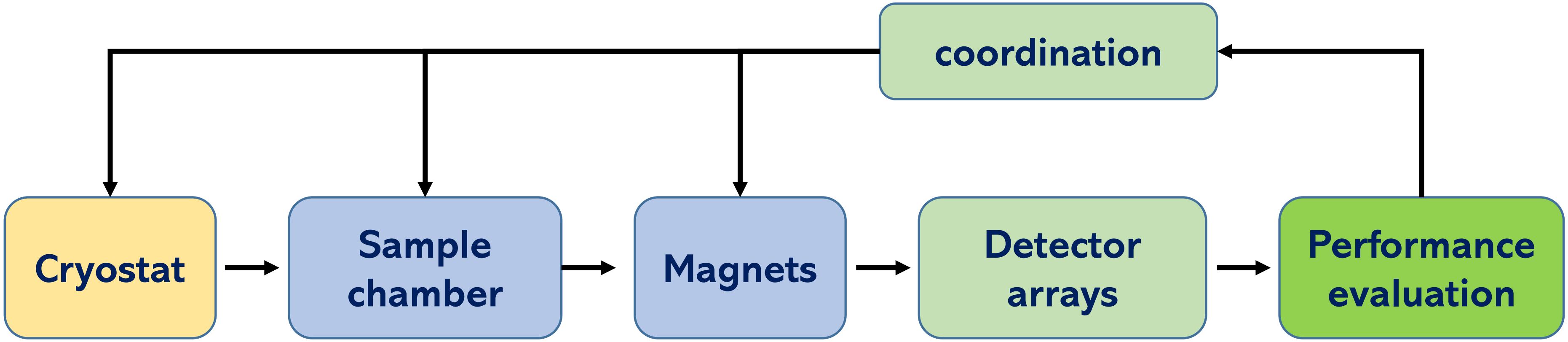
The most important factors that define a spectrometer:
1. **beam conditions**, 2. **sample environments**, and 3. **detector arrays**

Beam conditions

rigid boundary conditions for spectrometer design

Beam Condition	Impact on Design	Current Parameter
Pulse Intensity	Detector granularity	**2×10^5 /pulse @Φ20mm**
Pulse Length	Maximum transverse magnetic field	**~130 ns**

More: Beam profile (beam spot size), Polarization(> 95%), Positron background, etc.

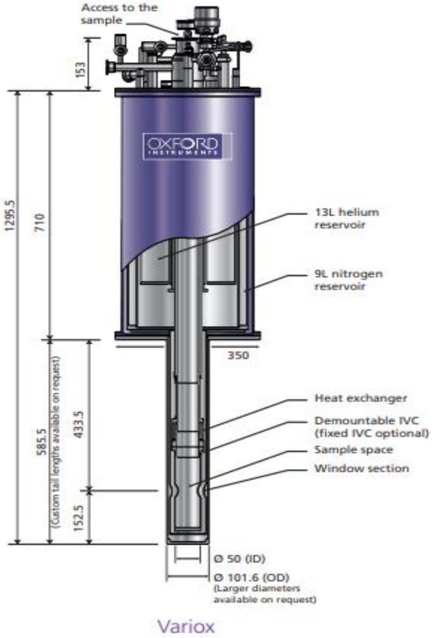


to make full use of the "good" positrons of each pulse!

Temperature conditions

consider in the first place:

1. customized devices with many sizes can't be changed.
2. spatial boundary of the sample chamber and magnets.



Custom-made windows:

Windows	thickness	diameter	Material
outer	125µm	50mm	Mylar
middle	15µm	50mm	Al
inner	125µm	46mm	Aluminized mylar

With sample chamber the outer layer can be removed

Custom-made tail length:

Due to LF magnet size,

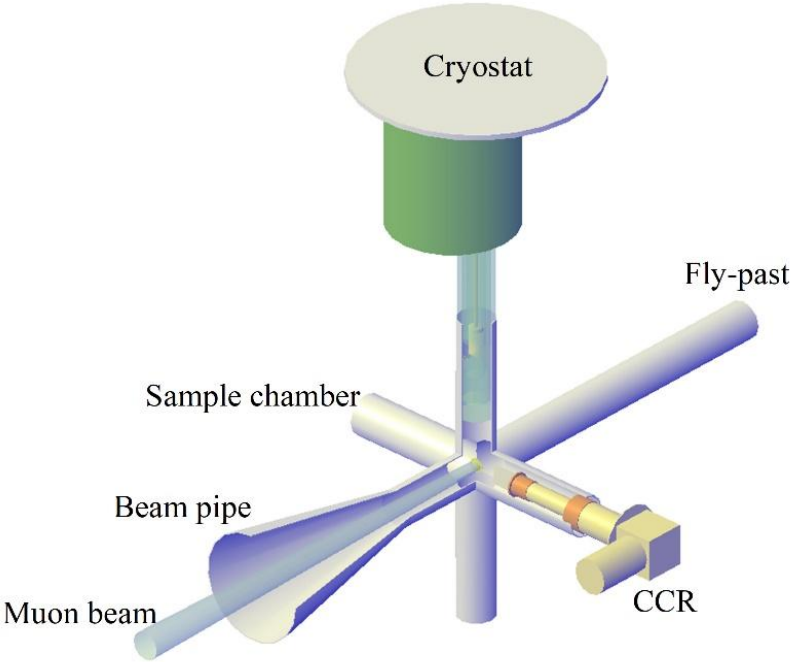
The tail: **500 mm** from sample to the flange

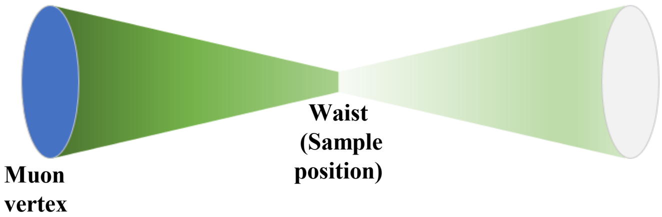
First stage: Cryostat **2- 300 K**

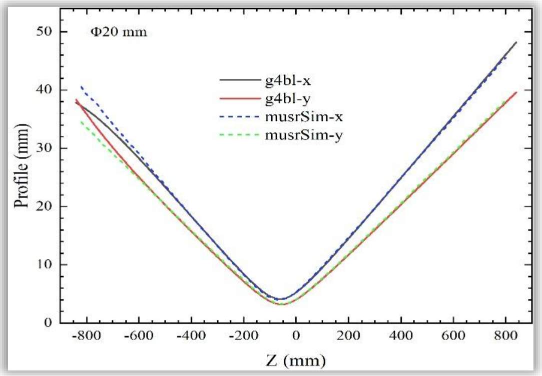
Future: Extend to **30 mK**

Sample chamber

1. Allow the tails of the cryogenic devices to enter
2. Allow almost all muons to reach the sample position, and then,
3. as small as possible to allow enough space for the detector arrays







Reduce the total window layers from 4 to 2

No window between the chamber and beamline

A plug-in valve on beamline for change samples

With a Horn type,

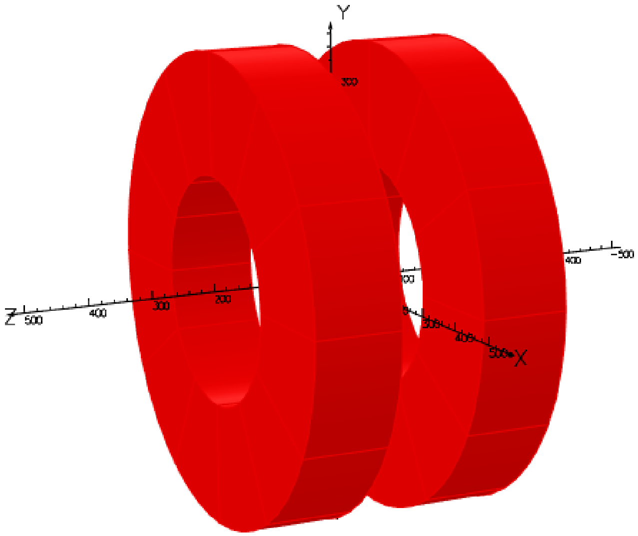
muons pass rate >99%

The magnets

Longitudinal field magnets (LF)

Boundaries of the detector arrays:

enlarge inner diameter and reduce thickness of coils, leave most space for detector arrays



Some important parameters:

Inner diameter	580 mm
Outer diameter	920 mm
Coil thickness	208 mm
Coil gap	178 mm
Current density	11.5 A/mm^2
Max power	205 kW

0-5000 G, the upper limit of magnetic field that we designed.

15 ppm for field uniformity at the sample region (requires < 100 ppm)

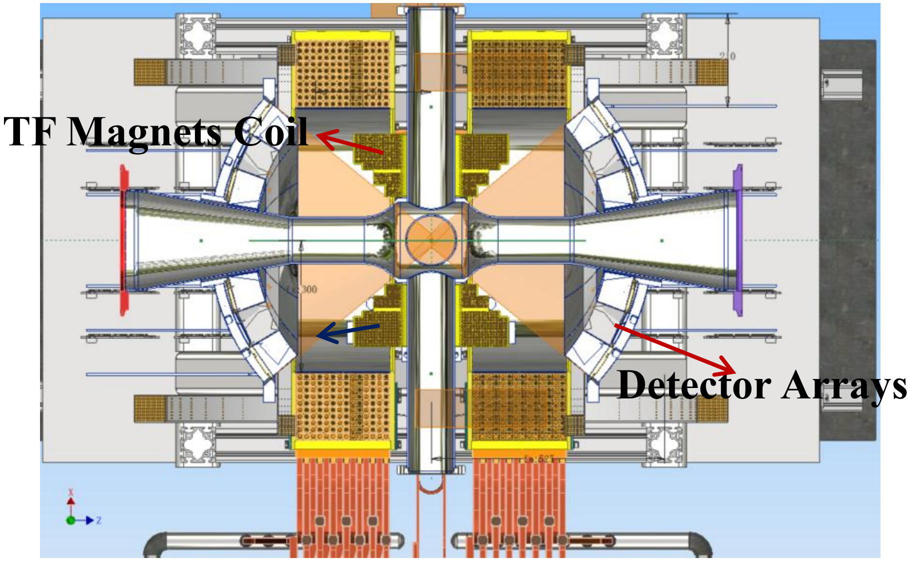
Transverse field magnets (TF)

Physical design parameters:

0~400 G, limited by muon beam pulse width 130 ns

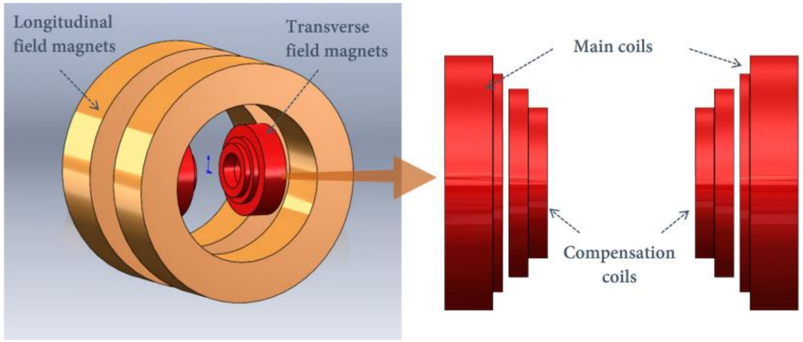
Sample space uniformity: requirement < 100 ppm

Small Coil Compensation Scheme Design



Top view: detector space optical path

Internationally first adoption of this scheme



Small coils: 160 mm inner diameter

Advantage: small spot deflection **(~1.5 mm)**

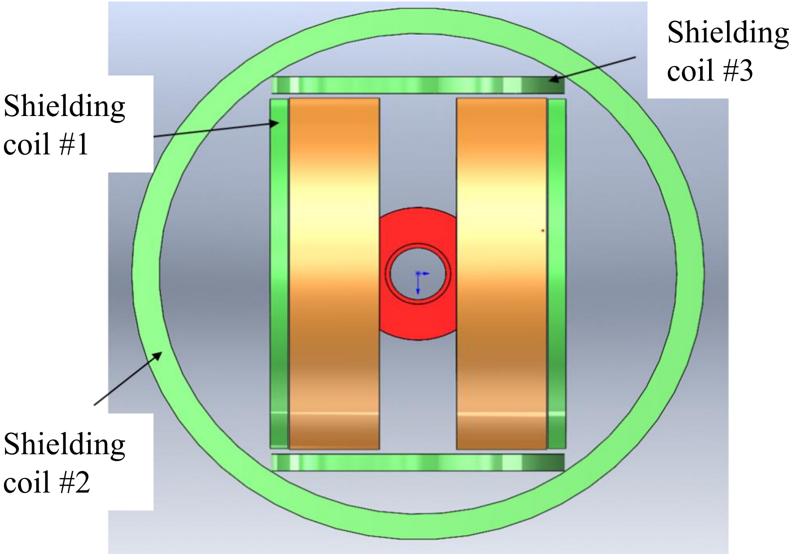
disadvantage: bad field uniformity ~1000ppm

compensation coils: back to **~ 32 ppm**

Geomagnetic compensation coils (zero filed, ZF)

Small coils: inexpensive, but blocking positrons

Large coils: Large, relatively expensive, but no impact on others



Some main parameters:

Inner diameter	940 mm
Outer diameter	960 mm
Coil thickness	10 mm
Coil gap	1020 mm

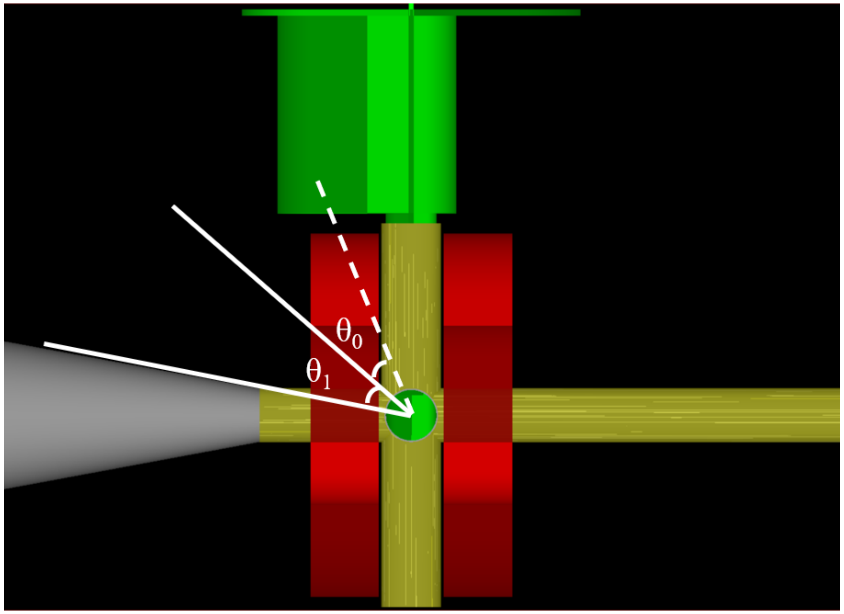
Three independent pairs of large coils are selected:

- **0-50 G,** sometimes it can be used as a small TF field.
- It can be used to compensate for the leakage field from beamline solenoids

~10 G at the sample with an uniformity of ~0.1%. The accuracy of ZF will be about **~10 mG**

Detector arrays

1. The space left for the detector layout is:



$\theta_0 + \theta_1$: 10° ~ 70°

2. Re-raise the beam conditions:

high pulse intensity: 2×10^5 /pulse

Very low repetition rate: 1Hz

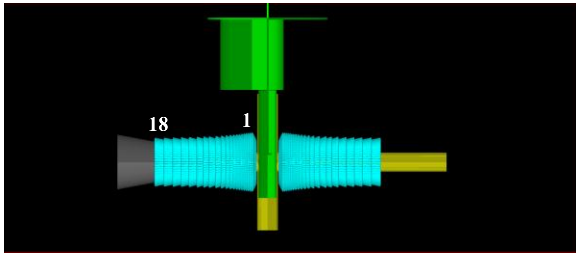
detector arrays with **high granularity** is required to obtain a sufficiently high **R**

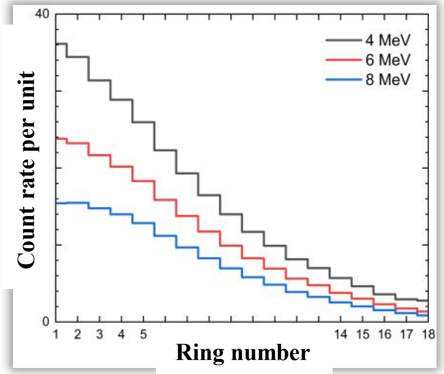
The **plastic scintillator-matched SiPM** was selected as the detector unit

The possible configurations that we considered:

Calorimeters

36 rings with a total of 3204 units

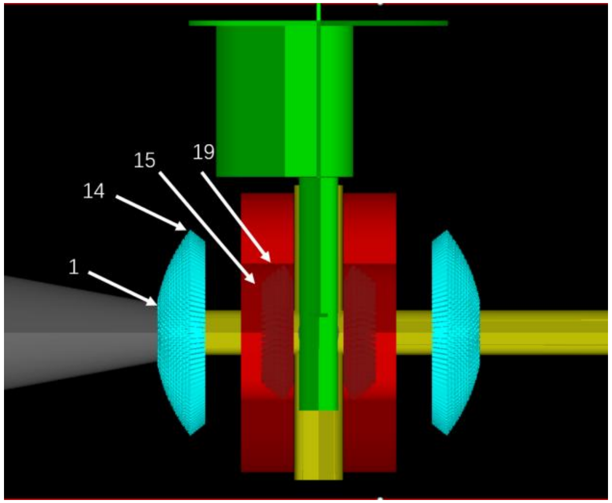




The inner the rings, the higher the count rate and the granularity

Double spherical shells

38 rings with a total of 2782 units

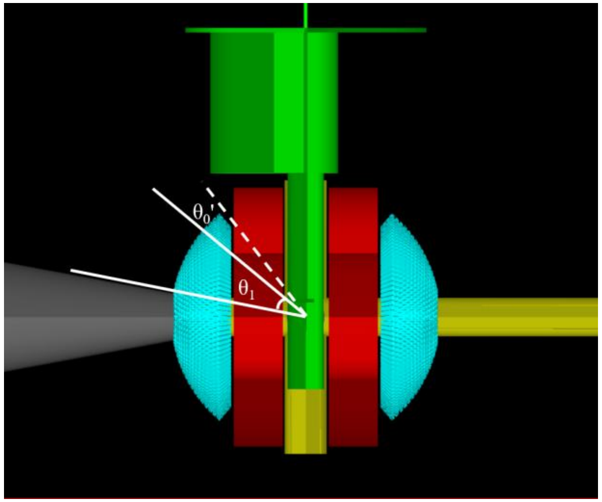


The units in the inner diameter of the magnet are so crowded

that it is difficult to match the electronics and output the signal

Large-angle spherical shells

32 rings with a total of 2626 units



units within the θ_0' angle have a very low count rate due to the positrons being blocked by the magnet

The type of final selection

We don't have to take advantage of positrons in the θ_0 angle because:

$\sim 4.5 \times 10^4$ /pulse within the θ_1 angle **and**

very sufficient for ~3000 detector units

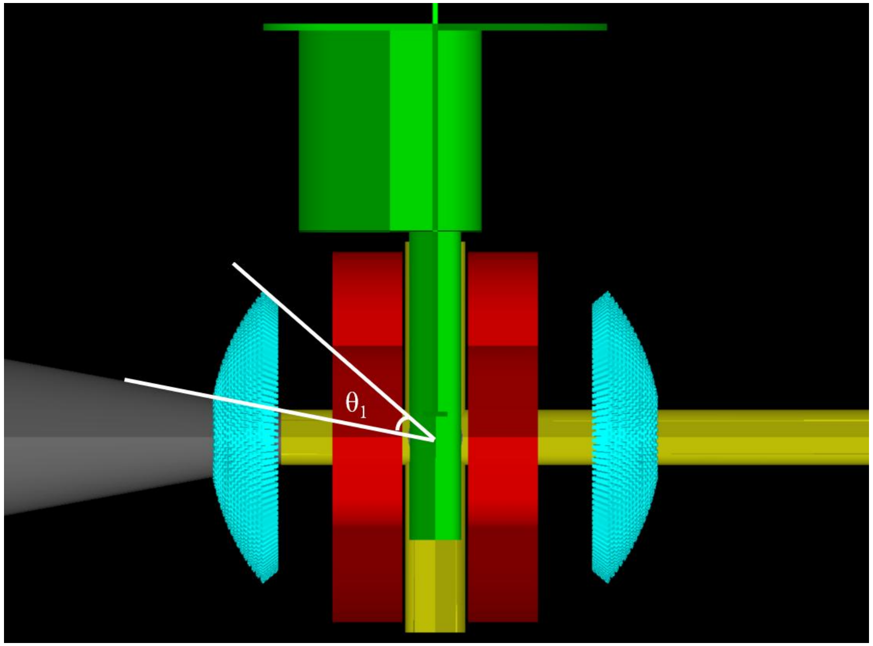
Design enough units fill up the θ_1 solid angle

Count rate does not decrease

and A will increase properly

Double spherical shells

36 rings with a total of 3024 units

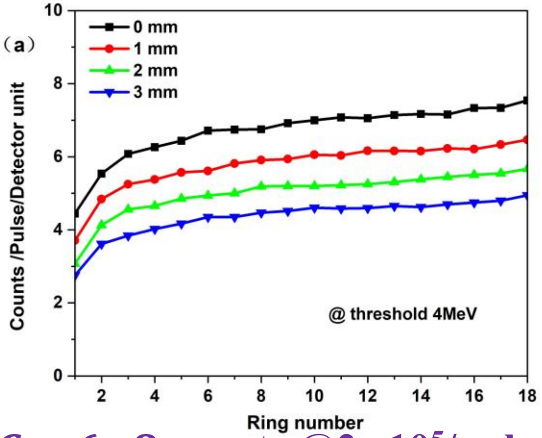


θ_1: 10° ~ 40°

Units: 8×8 mm plastic scintillators + 6×6 mm Sensl SiPM

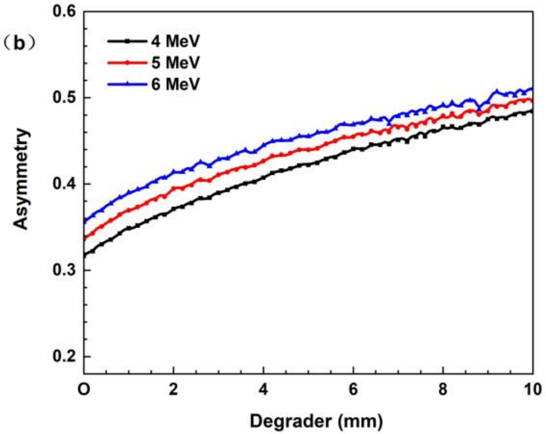
Spectrometer Performance (After engineering optimization design, with module housing)

Detector counts (/det/pulse)



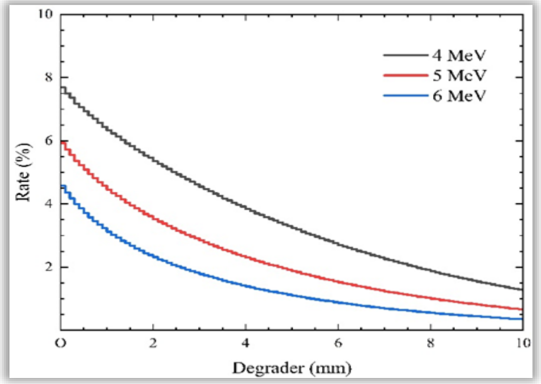
$C \approx 6\sim8$ counts @2×10^5/pulse

Asymmetry



$A > 0.3$

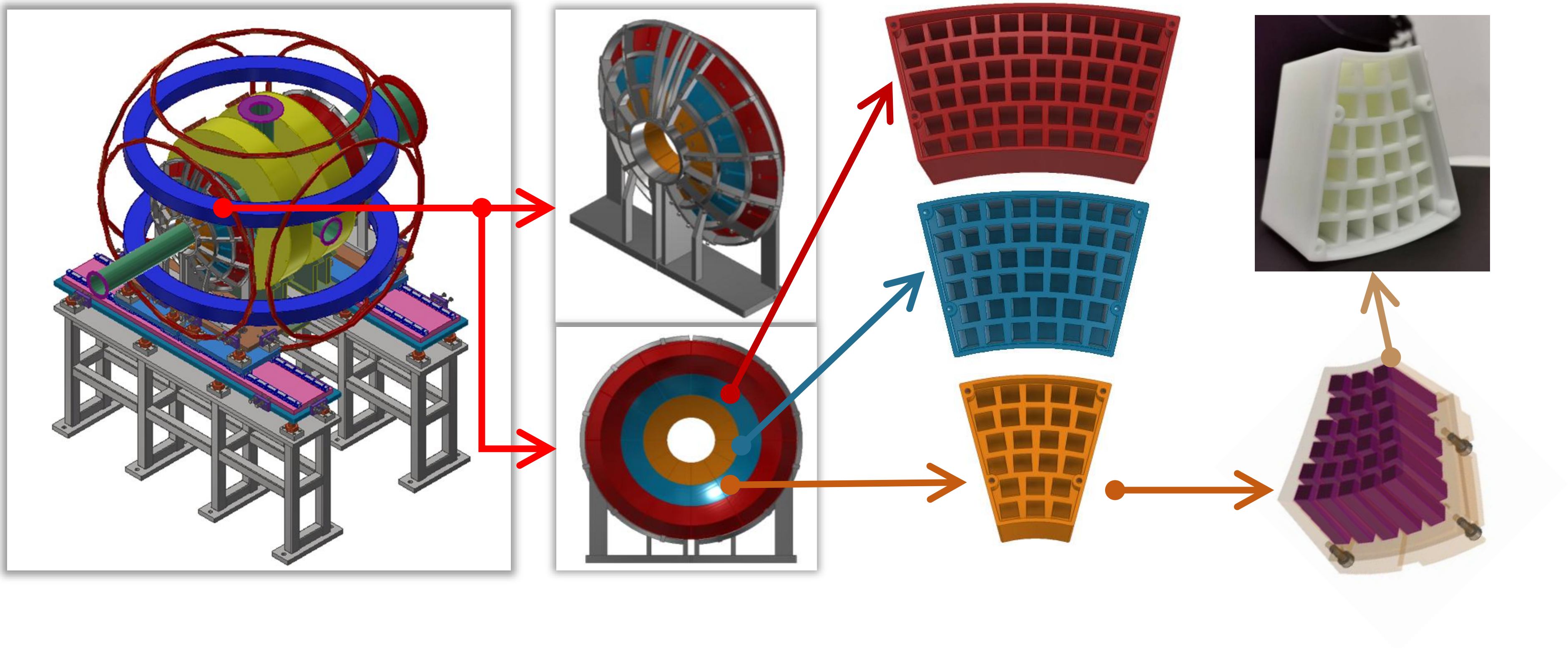
Total event rate



$R \approx 7.6 \times 10^7\ e^+/hour$

	ISIS					J-PARC			CSNS
Beam intensity	~3.3×10^3 μ^+/pulse					~4.4×10^4 μ^+/pulse			**~2×10^5 μ^+/pulse**
Repetition rate	40 Hz					25 Hz			**1 Hz**
Spectrometer	MuSR (1987)	EMU (1993)	HiFi (2009)	ARGUS	CHRNOUS	DΩ-1 (2005)	Kalliope (2013)	ARTEMIS (2015)	**MELODY**
detector	Single-anode PMT			Multiple-anode PMT			SiPM		**SiPM**
Segments	64	96	64	192	606	256	1280	1280	**3024**
Asymmetry	~0.28			---		~0.16			**> 0.3**
Counting rate	40~200 Million/hour			55~80 Million/hour		90~300 Million/hour			**~76 M/h**
Relatively FoM	3~15			---		2.3~7.8			**~5.8**

The Technical consideration:



The overall layout of the spectrometer is designed

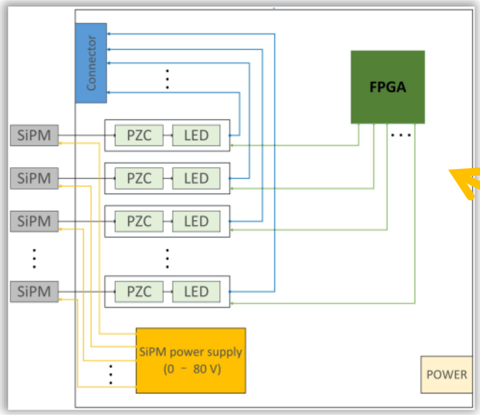
The detector arrays are divided into three types with a total of 72 modules, for easy management and maintenance

One of the inner modules has been prepared and tested on muon source at ISIS

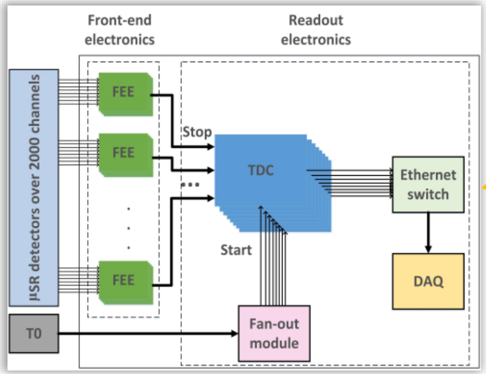
Electronics Design:

Leading-edge discrimination + TDC

Front-End Electronics

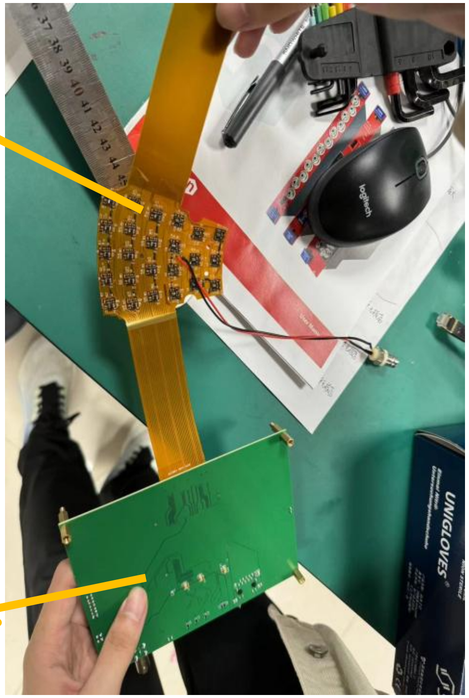


TDC Readout



T_0 signal input to TDC as time start signal

Detector event signal input to TDC as time stop signal



Front-end board: carries SiPM and comparator, outputs digitized time signals

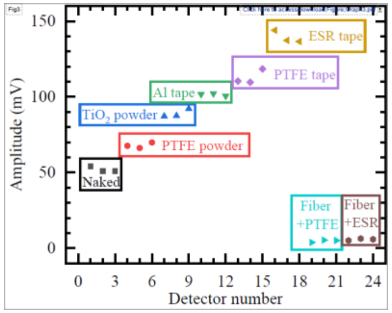
Readout board: outputs time information for each event

Flexible cable communication: between front-end board and readout board

Inspection port: each channel can individually output waveform for inspection

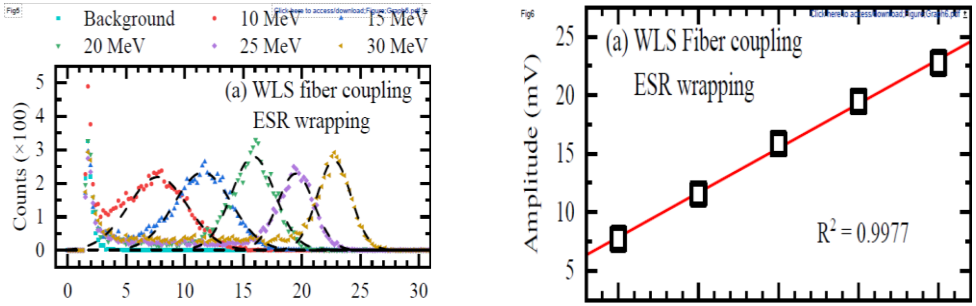
Detector Module + Electronics + Basic DAQ Test

^{22}Na source - detector unit test



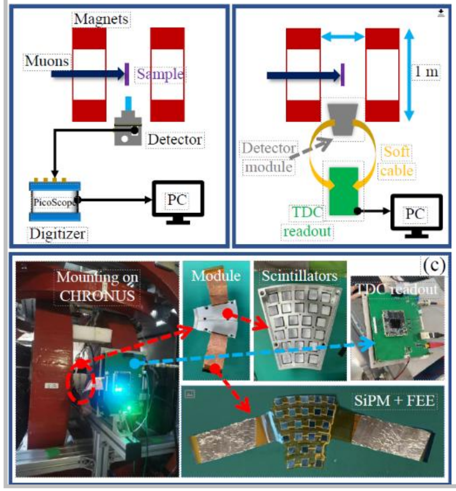
SiPM + scintillator unit: light collection efficiency test

Medium energy proton beam - detector energy response linearity test



10-50MeV deposited energy response linearity test

UK ISIS muon source - μSR spectrometer performance technical verification experiment

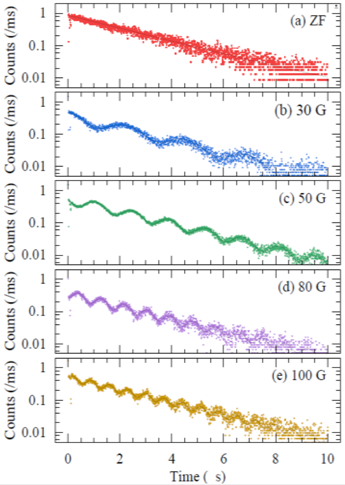


Detector modular design

24-channel module

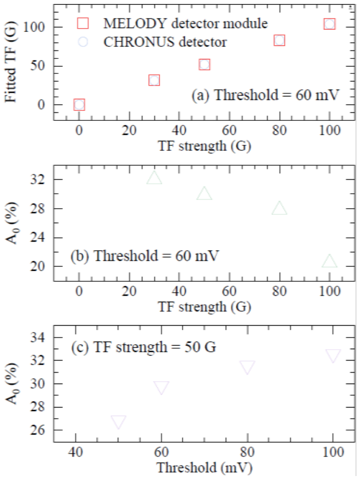
Detector + electronics

DAQ joint test



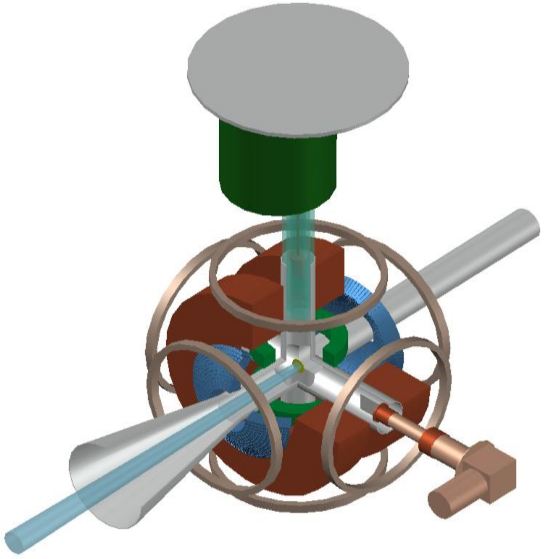
μSR curve changes with magnetic field strength

Measurement results consistent with ISIS spectrometer results, error less than 0.2%



Tianyi Yang, Qi Yuan, Ziwen Pan, **Qiang Li***, et al., Nuclear Inst. and Methods in Physics Research, A 1082 (2026) 170918*

III. Summary and prospective



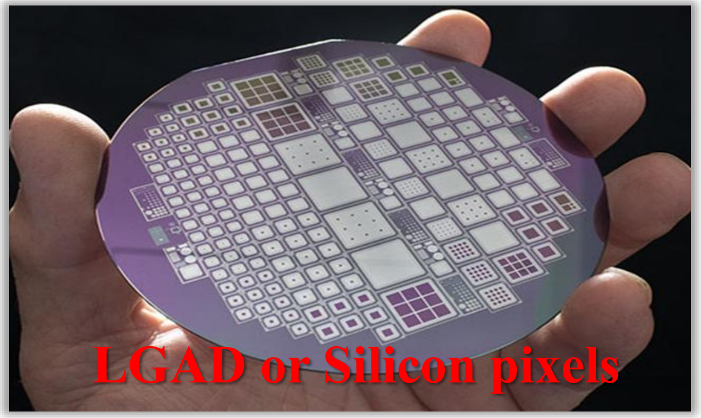
- **~1584 detector units** (~3024 in total)
- **R： ~ 3.8×10^{7} e^{+}/hour @1 Hz** (~76 ME/h in total)
- **Asymmetry： > 0.3**
- **Pulse length： ~130 ns**
- **Temperature: 2-300 K with cryostat**
- **LF: 0-5000 G**
- **TF: 0-400 G**
- **Beam spot: Φ10-30 mm**

Key Time Nodes

Time	**December 2025**	**July 2026**	**May 2028**	**July 2029**
Key milestone	**Experimental station delivery**		**Available beam**	**Final acceptance**
Spectrometer	**detector electronics system**	**Ready for online testing**		**Open to users**

Summary and prospective

1. The μSR spectrometer of MELODY is under construction.
2. Key parameters:
   - Event rate: R=38 MEvents/h and can be upgraded to 76 MEvents/h
   - Asymmetry: $A > 0.3$
3. It is expected to be constructed and open to users in 2029.
4. It will provide support for researches in superconductivity, magnetism, magnetic functional materials, etc., together with other μSR facilities in the world.



High granularity
Fast output
⇨ **R** ↑↑

See the talk given by Feng Meichan

Further: Full detector arrays, Beam slice to 10 ns, LGAD-type detector arrays, etc.

Thanks !