Design of the First μSR Spectrometer at China Spallation Neutron Source

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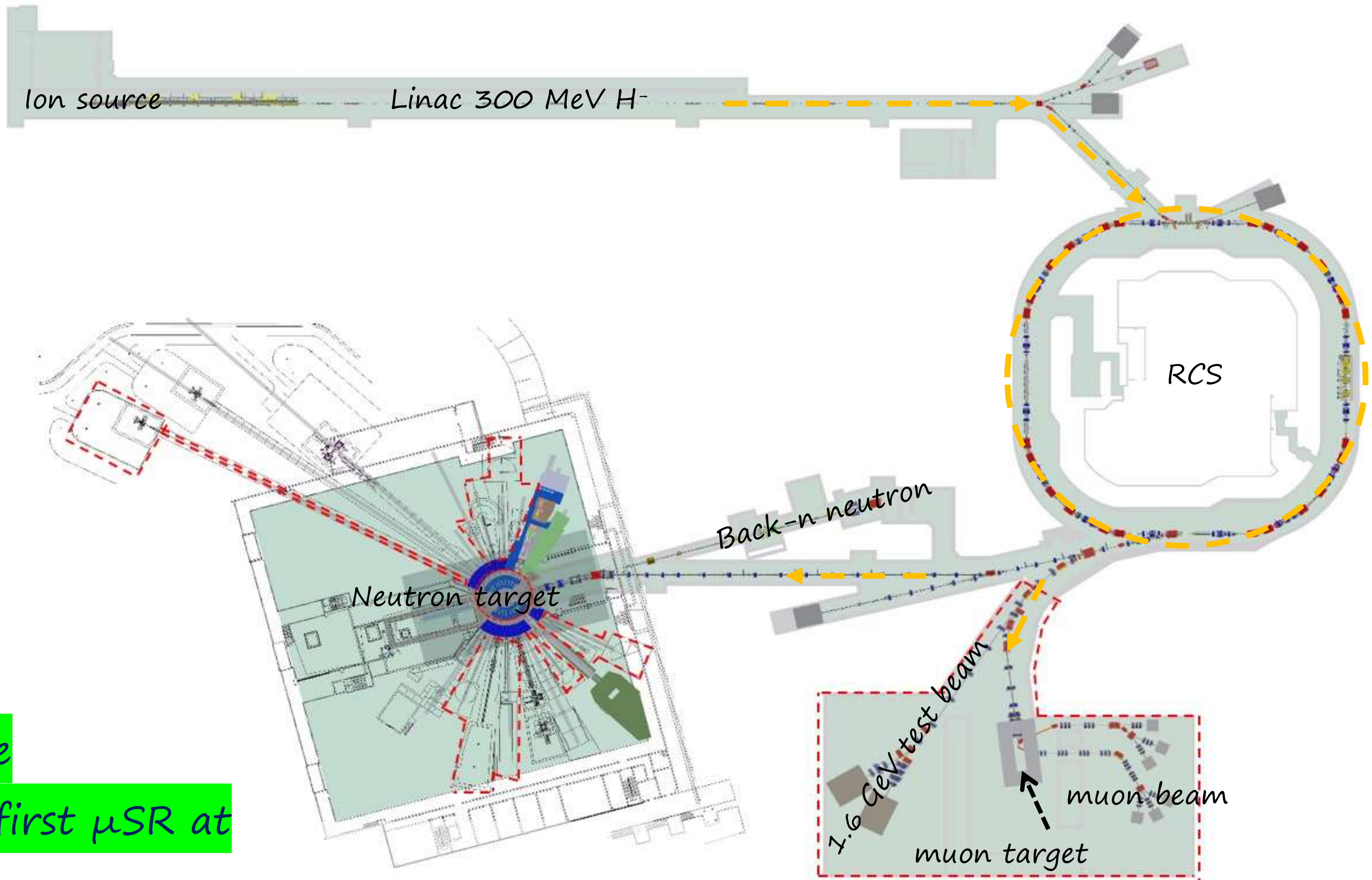
Phase II upgrade project of the CSNS：(2023.01-2028.09)

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



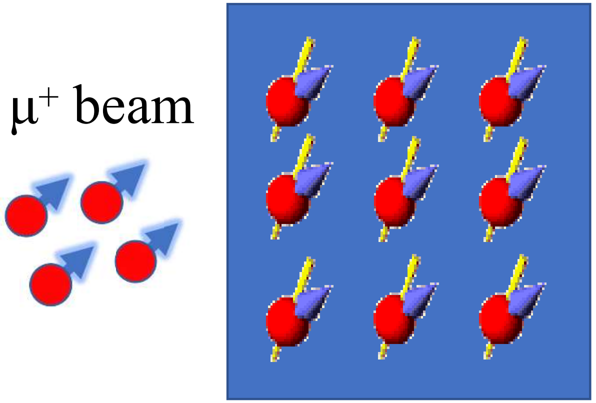
Talk content:

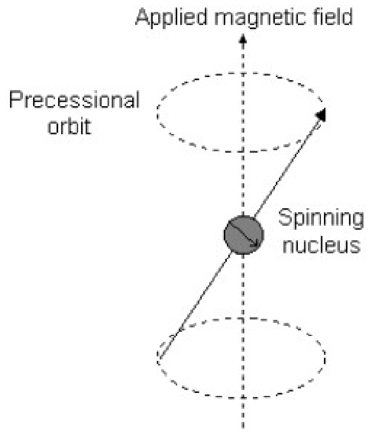
I. The μSR technique
II. The design of the first μSR at CSNS
III. Summary and prospects

I. The μSR techniques

μSR (muon spin rotation, relaxation and resonance), is a technique that uses the spatial asymmetry of positrons generated by polarized μ decay to study the magnetic properties of materials.

Larmor precession

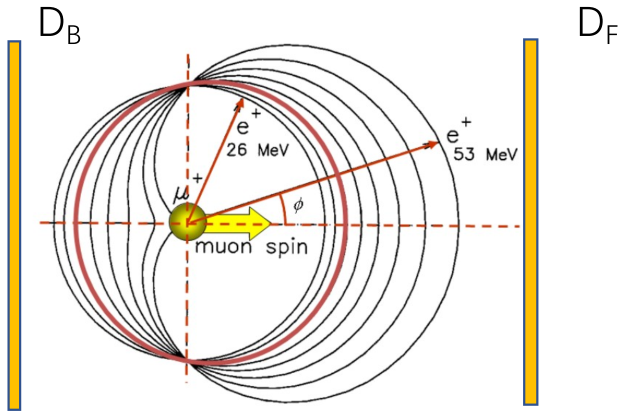




The frequency ω $\gamma_\mu B$

$$\gamma_\mu = g_\mu \frac{e}{2m_\mu} = 851.615\ MHz/T$$

Asymmetric decay



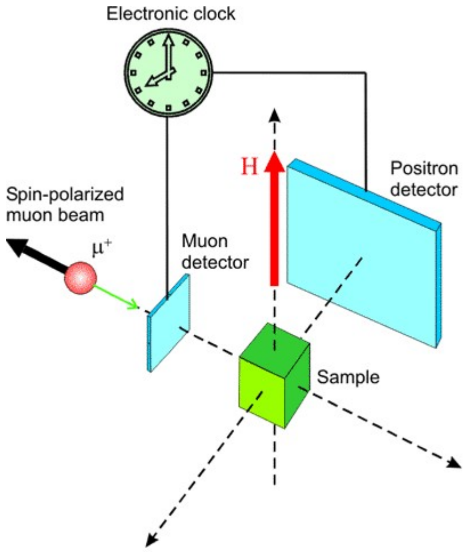
$$\mu^+ \rightarrow e^+ + \vartheta_e + \overline{\vartheta}_\mu$$

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

Positrons emit preferentially along the muon spin!

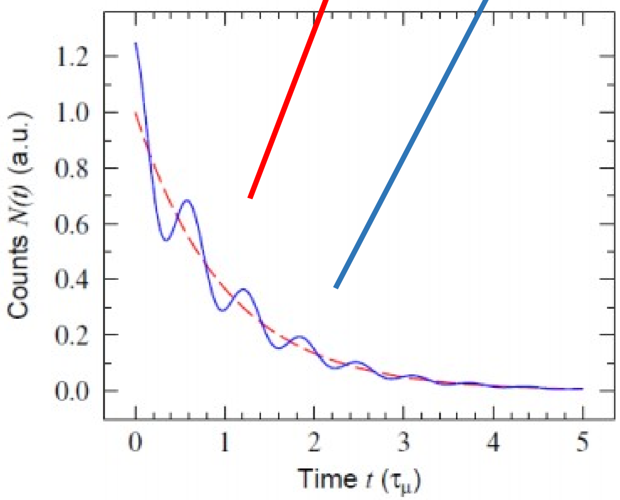
average factor A = 1/3

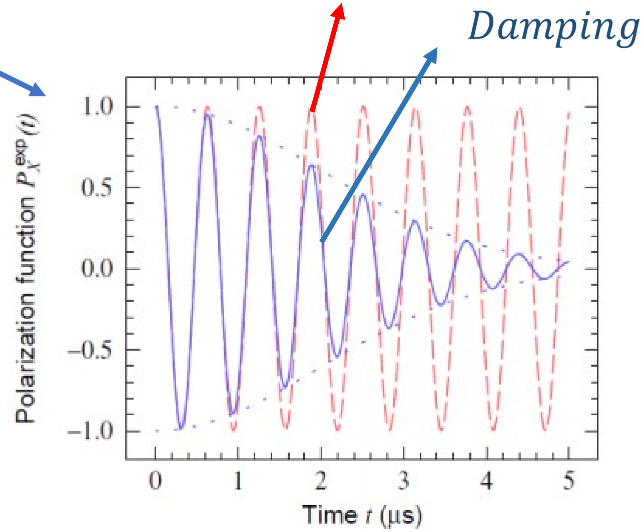
Depolarization function P(t)

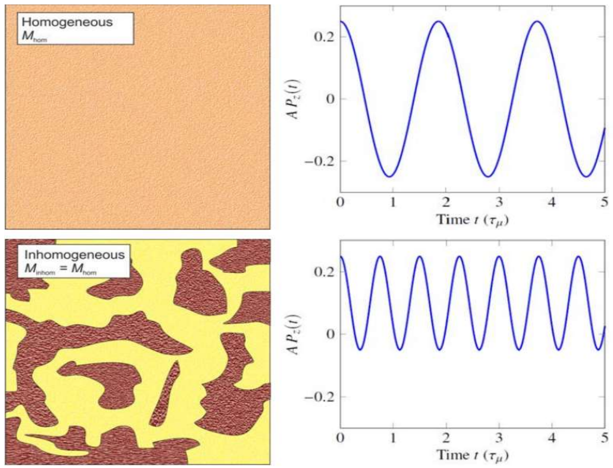


$$N(t) = N_0\, exp\left(-\frac{t}{\tau_\mu}\right)[1 + AP(t)] + B$$

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







P(t) oscillation frequency: magnetic strength

P(t) depolarization: polarization relaxation with magnetic

Moreover, the local magnetic distribution

… …

μSR applications

Magnetism

Magnetically ordered systems

Spin-glass systems

Colossal magnetoresistance

Low-dimensional systems

Molecular magnets & clusters

Superconductors

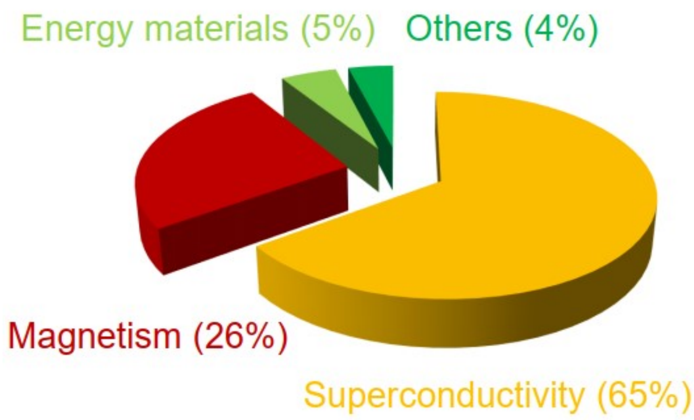
Magnetic phases & phase separation

Weak magnetism

Characteristic length scales

Pairing properties

MuSR



Transport

Quantum diffusion

Electron transport in non-metals

Conducting polymers

Semiconductors

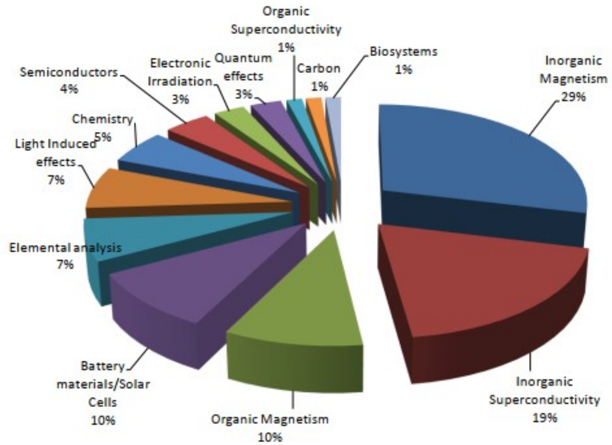
Chemistry

Chemical reaction kinetics and H isotopes

Free radical systems

Biological applications

ISIS Muons



μSR Advantages

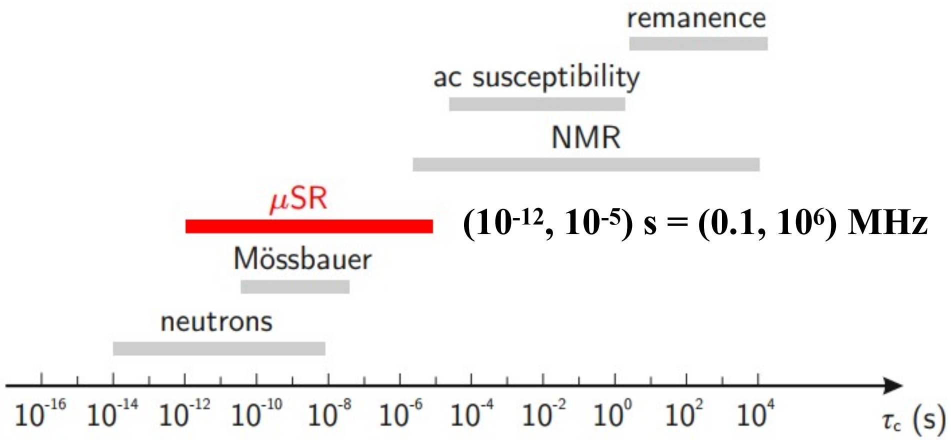
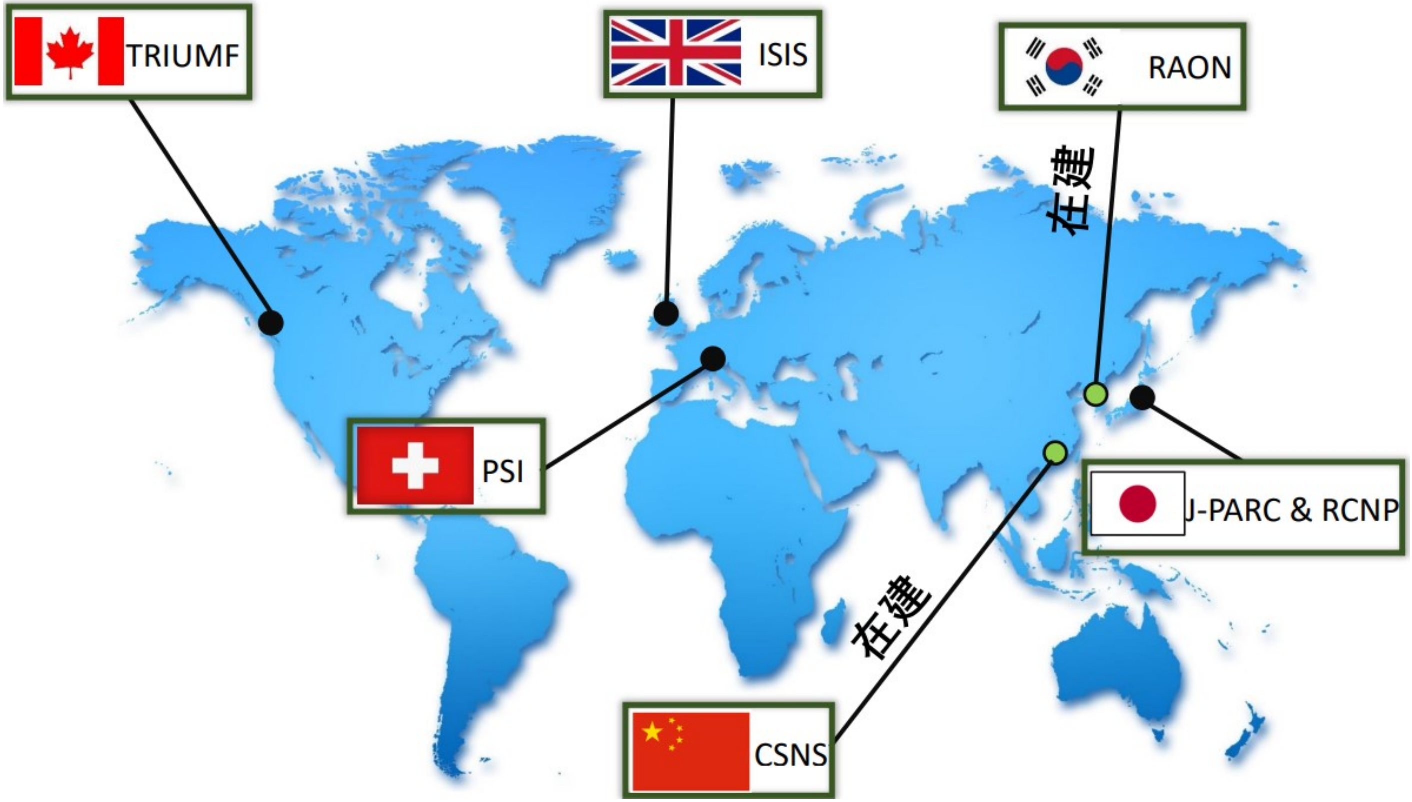


Figure 3.5.: *Comparison of dynamical ranges accessible to different techniques. $\tau_c = 1/\nu_c$ is the characteristic fluctuation time associated with the magnetic fluctuations. Adapted from Pierre Dalmas de Réotier.*

1. **Pure magnetic probes**: Only magnetic fields are probed
2. **Arbitrary magnetism**: especially dilute magnetism, spin glass, etc.
3. **Extremely high sensitivity** : ~0.1 G or 10^{-3} μ_B /Atom
4. **nondestructive**
5. **Very short magnetic order**: exceeds the neutron scattering sensitivity
6. **Any sample form**: block, powder, liquid, etc
7. **Uniqueness**: The measurable magnetic field compensates for the gap between neutrons and NMR

μ sources for μSR in the world



In operation :

Pulse beam : ISIS、J-PARC

Continuous beam: PSI、TRIUMF

Under construction:

Pulse beam : CSNS

MORE:

CiADS and HIAF (Hui Zhou)

SHINE facility (Shang Hai)

II. Construction of the first μSR at CSNS

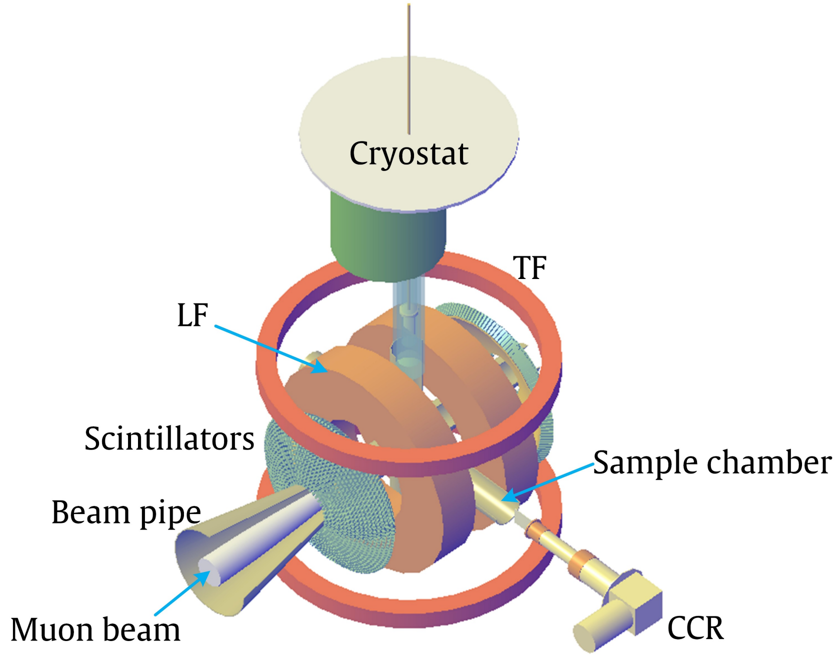
1. Basic components of a pulsed-surface muon-μSR spectrometer:

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.

2. How well a spectrometer performs?

Performance: The quality of the experimental data

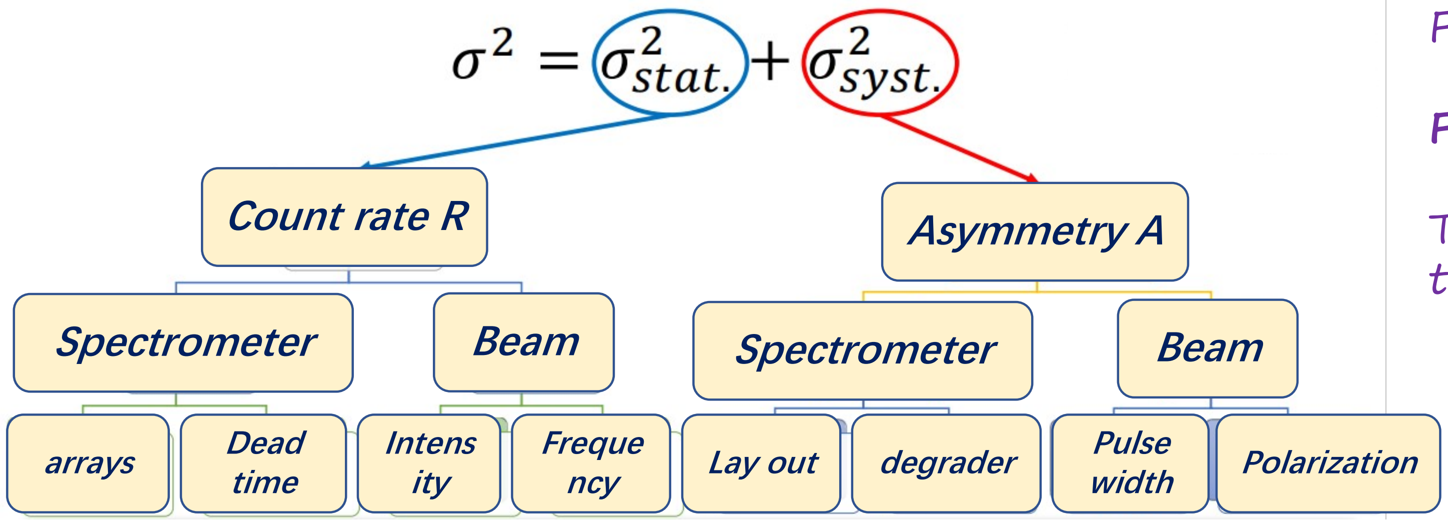


Figure of merit:

$F = A^2 \times R$

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 : The **pulse width** determines the upper limit of the magnetism that can be measured

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

and 3

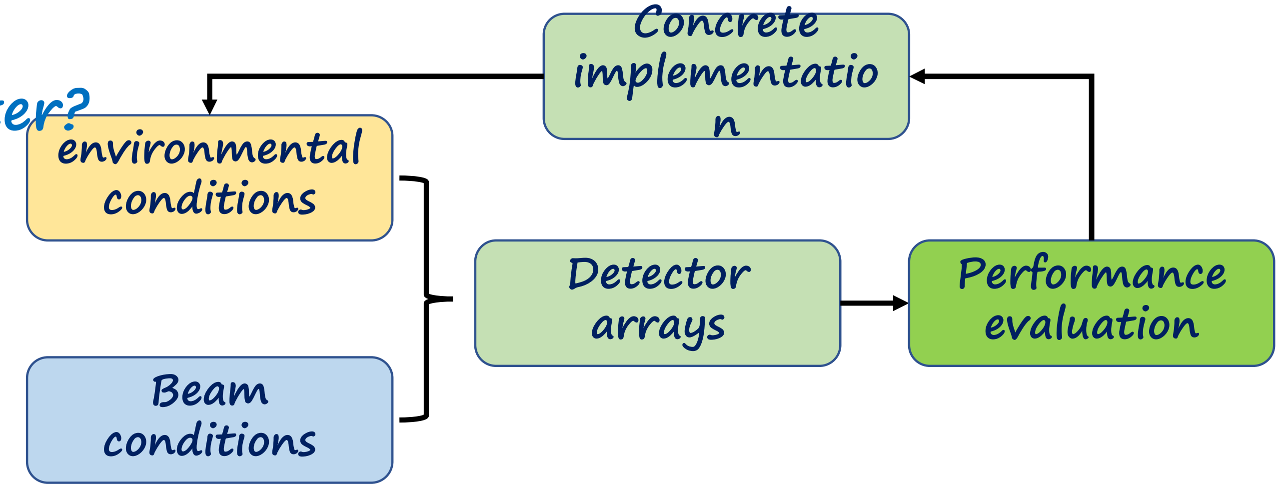
3. Beam conditions: the prerequisite for the μSR spectrometer design. Whi

Beam conditions	Effect on the μSR design	expectation	MELODY parameter
Beam intensity	Detector granularity	The higher the better	**2×10^5/pulse**
Repetition rate	none	Within 10^4 Hz, the higher the better	**1 Hz**
Pulse length	Maximum transverse magnetic field	The smaller the better	**~130 ns**

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

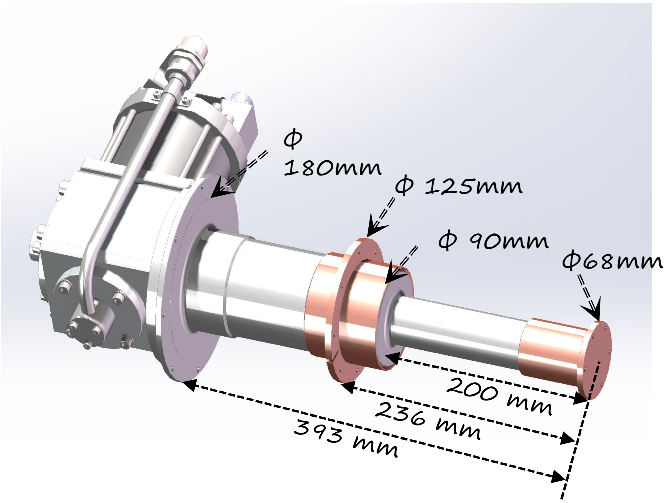
How to design the spectrometer?

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

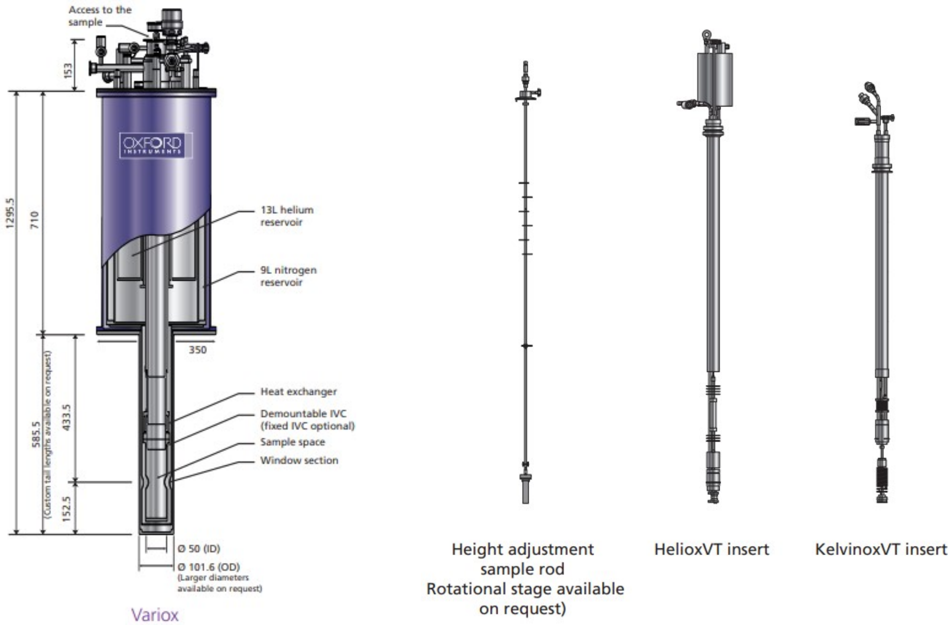


4. Temperature conditions: Why consider in the first place?

1. the cryogenic devices are customized product with standard specifications. A lot of sizes can't be changed.
2. Their tails are at the heart of the spectrometer and affect the spatial boundaries of other equipment such as sample chamber and magnets. For examples:



CCR from Sumitomo, Japan



Oxford Variox cryostat + HelioxVT insert with Custom-made windows

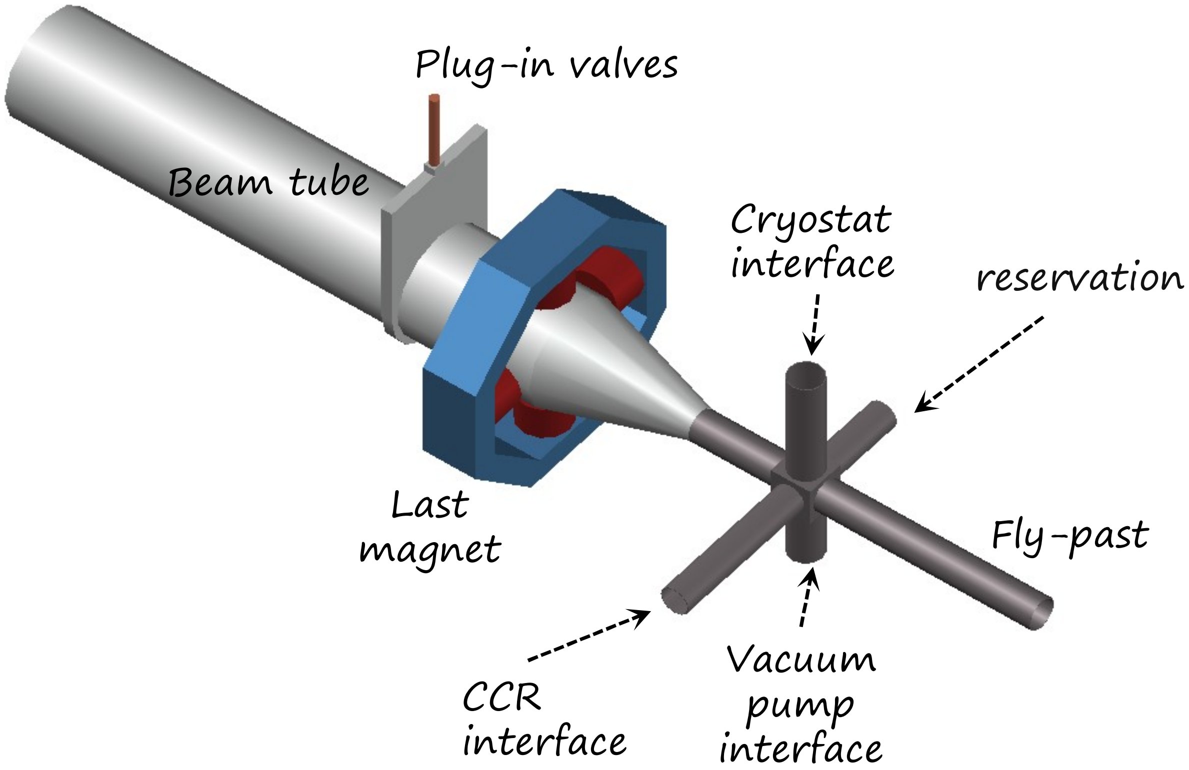
First stage: CCR 10 – 600 K and Cryostat

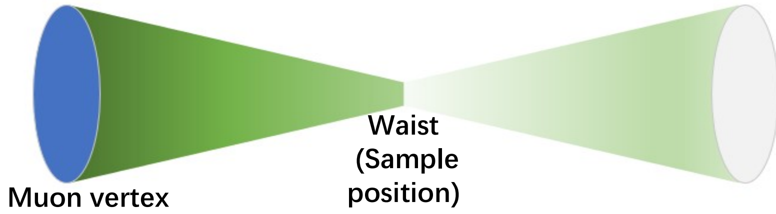
2- 300 K

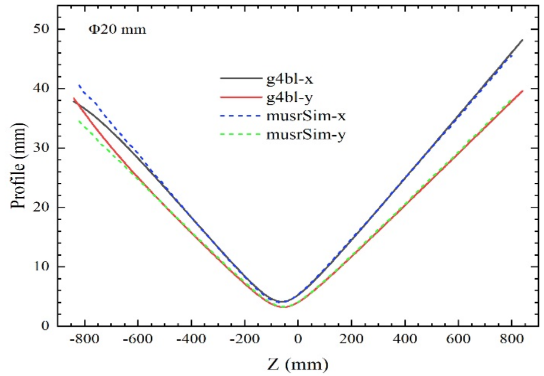
Second stage: HelioxVT insert down to

5. Sample chamber: How should we consider the 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







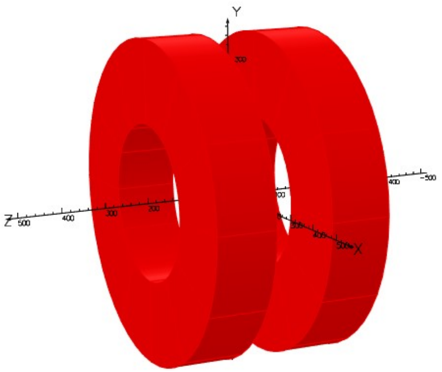
With a Horn type, muons pass rate >99%

6. magnets:

6.1 Longitudinal field magnets

Boundaries that affect the layout of the detector arrays

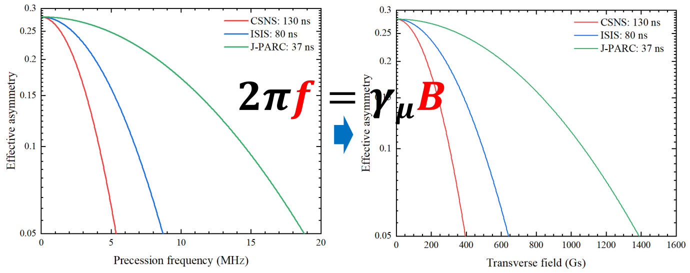
1. Allow the sample chamber to be placed with coil spacing > 135 mm
2. The inner diameter of 370mm and the thickness of 131mm

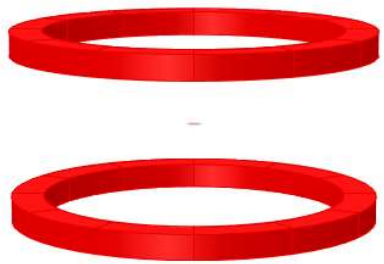


0-5000 G, the upper limit of conventional magnets

The magnetic field uniformity

6.2 Transverse field magnets





0-400 G, The measurable upper limit with the 130 ns

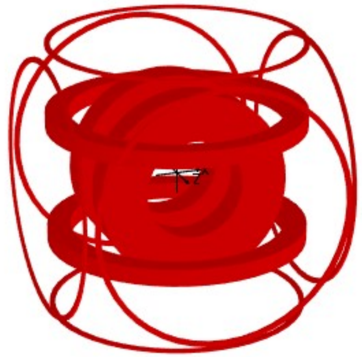
The magnetic field uniformity

6.3 Geomagnetic compensation coils

Is it inside or outside the main magnets?

1. **Inside**: Small, inexpensive, but blocking positrons
2. **Outside**: Large but no impact on others

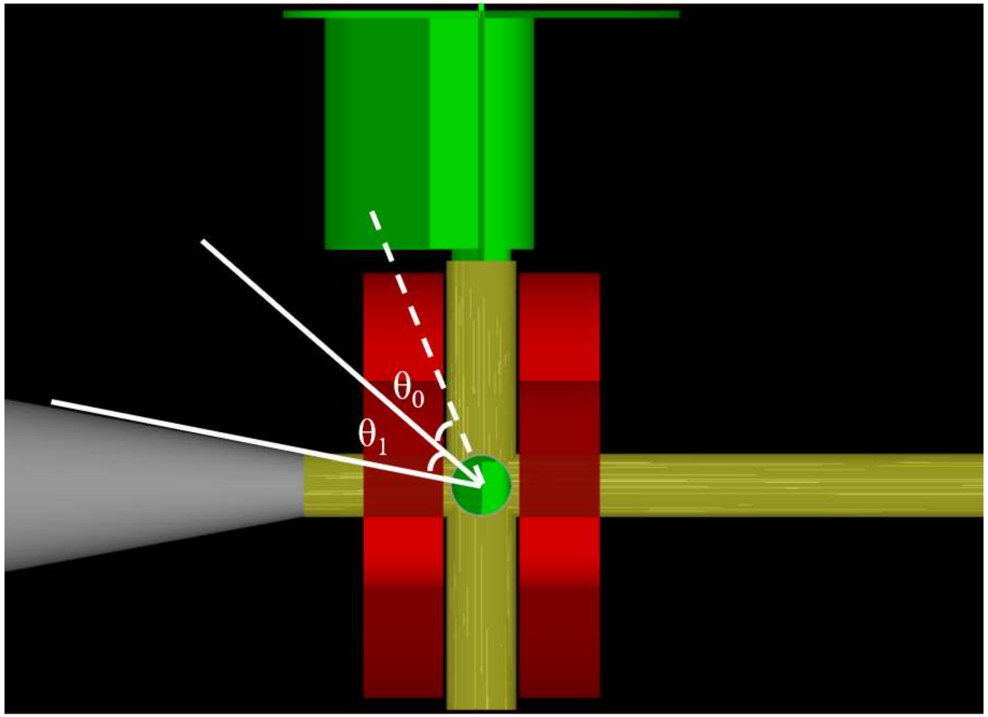
Large coils are selected



The accuracy is as good as possible than 10 mG

7. 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

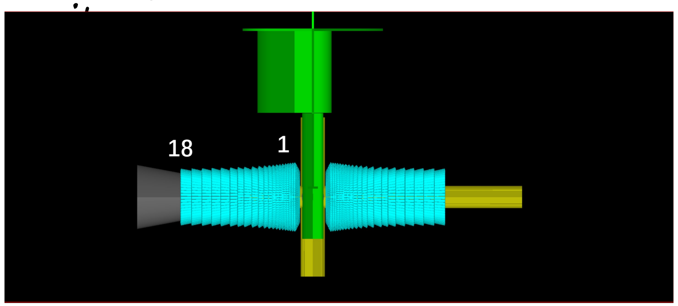
detector arrays with **high granularity** is required to obtain a sufficiently high **R**

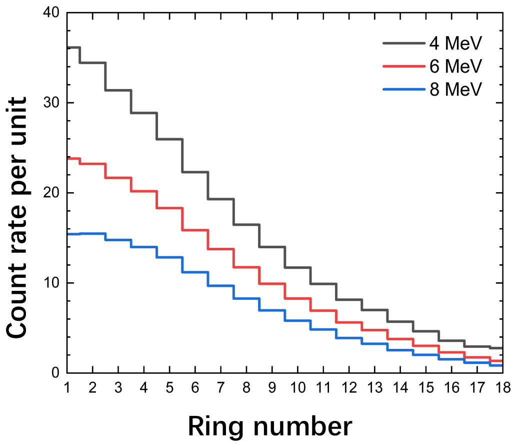
The **plastic scintillator-matched SiPM** was selected as the detector unit

The possible configurations that we considered:

Calorimeters

36 rings with a total of 3204

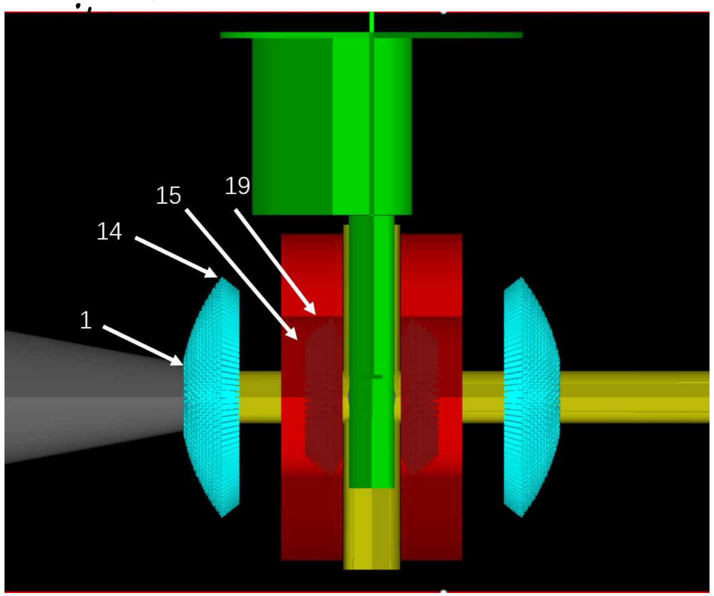




The inner the rings, the higher the count rate or the granularity

Double spherical shells

38 rings with a total of 2782

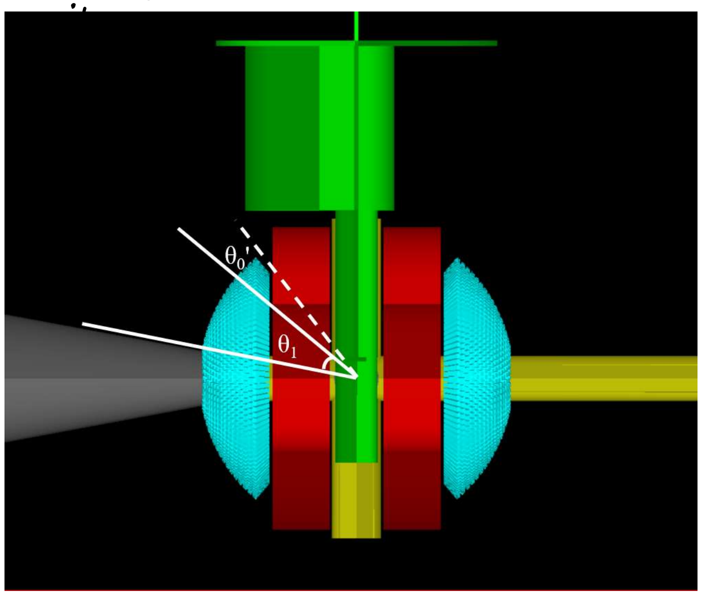


The units in the inner diameter of the magnet are so crowded

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

Large-angle spherical shells

32 rings with a total of 2626



units 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:

What limits the number of detector units?

Pulse intensity is not high: Pulse intensity

Pulse intensity is high enough: Money

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

~4.5×10^4 /pulse within the θ_1 angle **and**

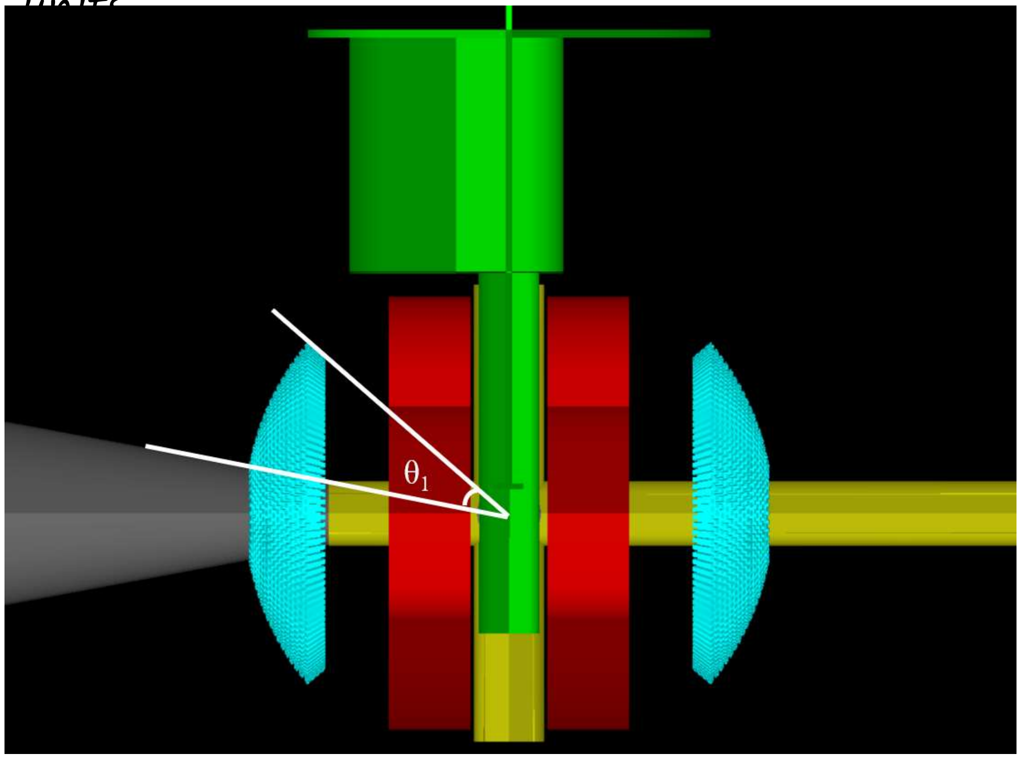
~3000 units is the limit of the funding

Choose the right unit size and fill up the θ_1 solid angle

R does not decrease while A will increase

Double spherical shells

36 rings with a total of 3024 units

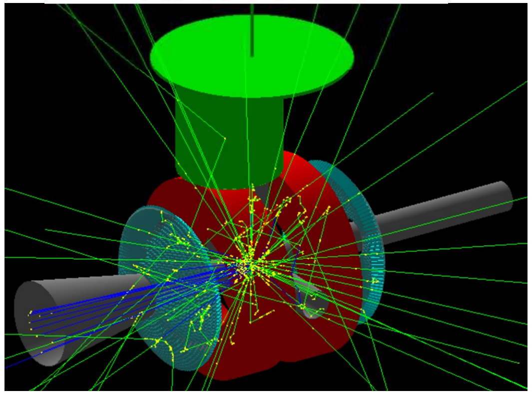


θ_1: 10° ~ 40°

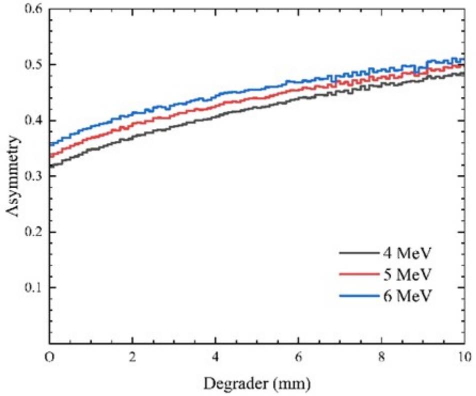
Units: 8×8 mm plastic scintillators + 6×6 mm Sensl SiPM

The performance that we evaluated:

Detectors

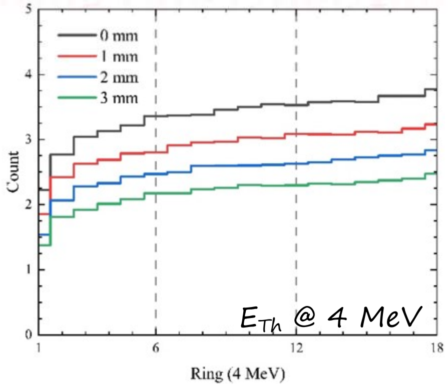


Asymmetry



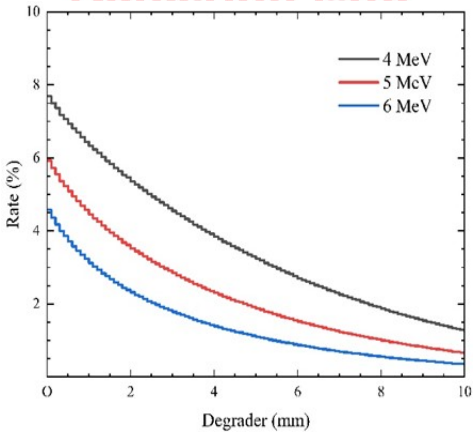
$A > 0.3$

Counting rate (/det/pulse)



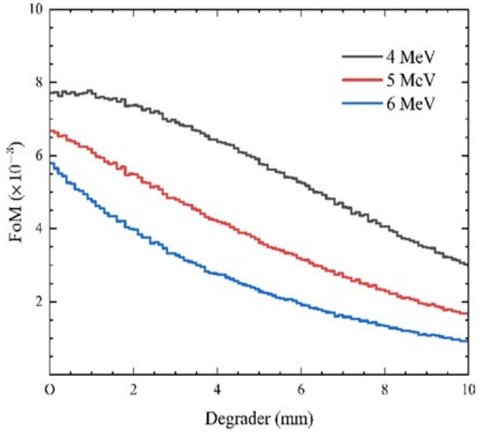
$C > 6$~8 *counts @2×10^5/p*

Detection rate



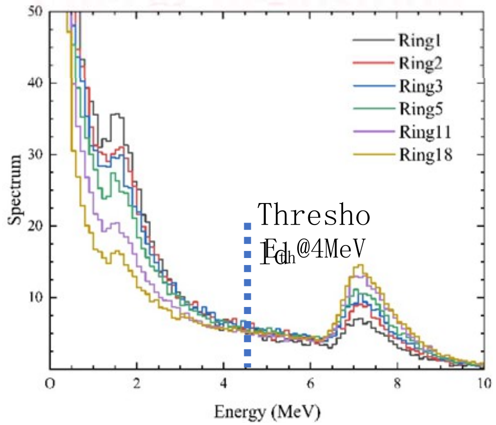
$R \approx 8 \times 107\ e^+/hour$

Figure of Merit



$AR^2 \approx 0.004$~0.008

Energy deposition

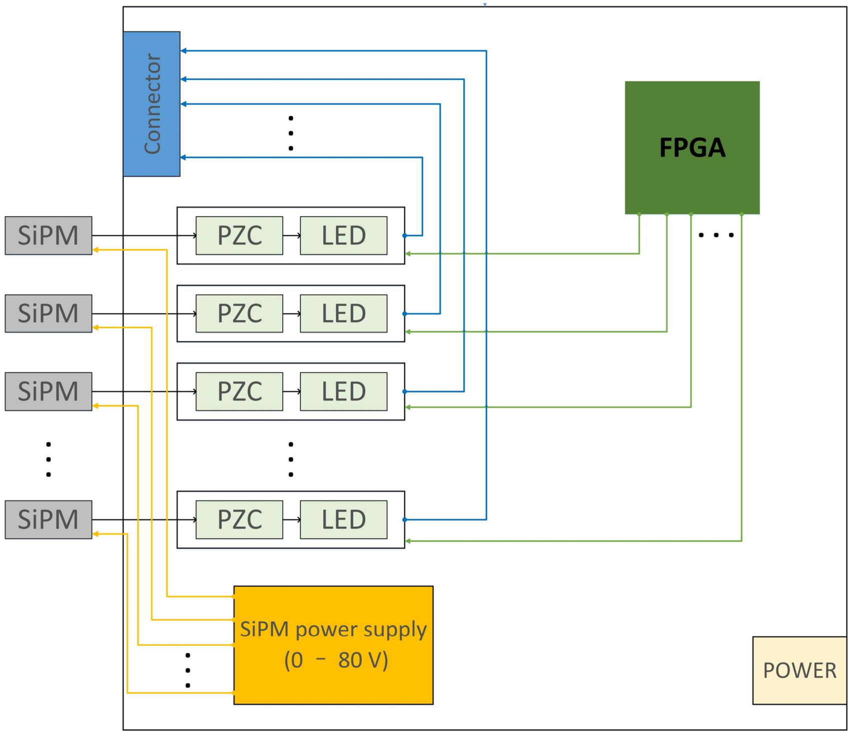


$Double\ hits < 0.5\%$

The Electronics design:

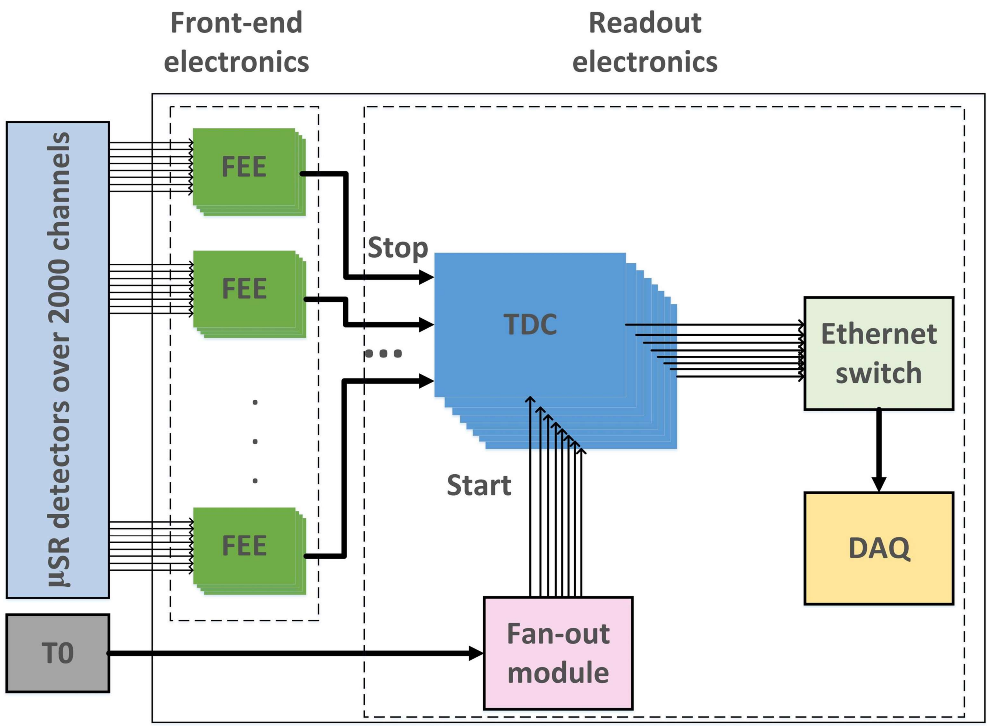
Leading-edge discrimination + TDC

Front-End Electronics



FS Deng, et al., JINST

TDC Readout



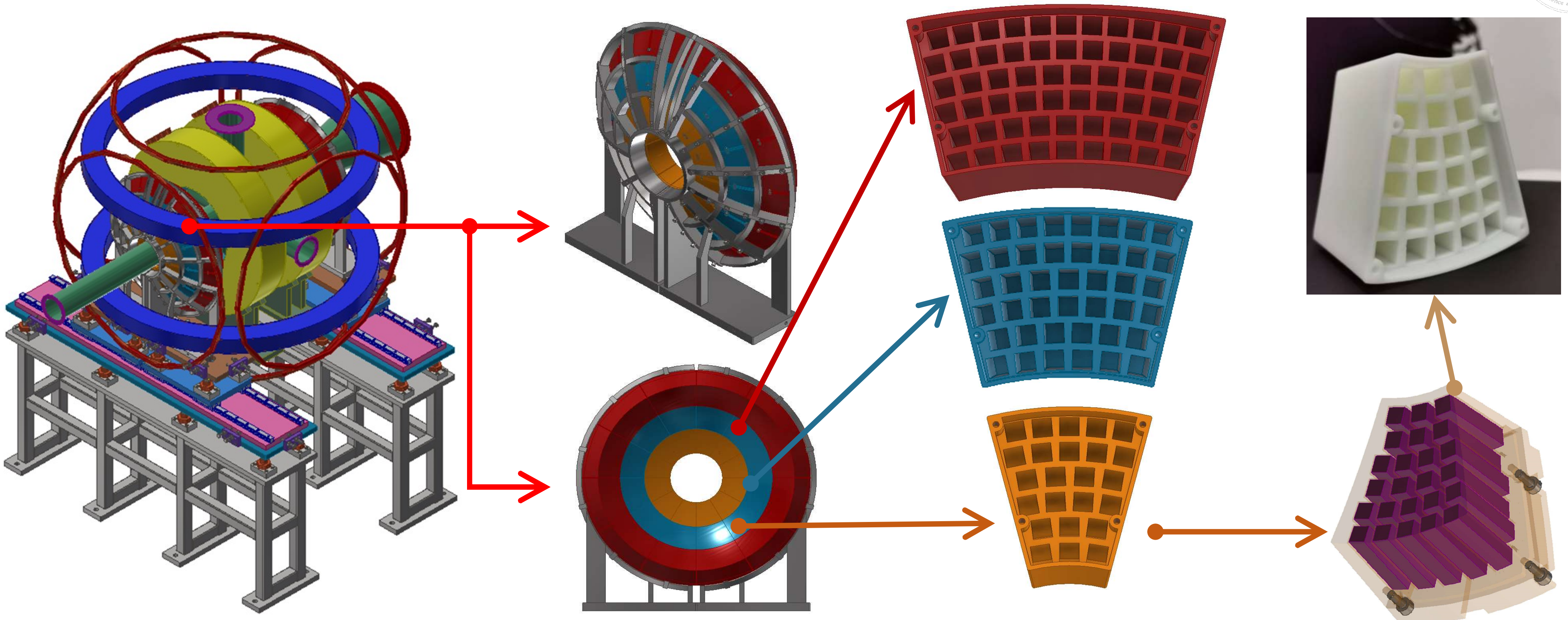
Proceedings @ MuSR2020

The beam start signal input into the TDC as a T_{start}

The detector signals through the FEE into the TDC as a T_{stop}

DAQ software enables data reading, storage, and preprocessing

The Technical consideration:



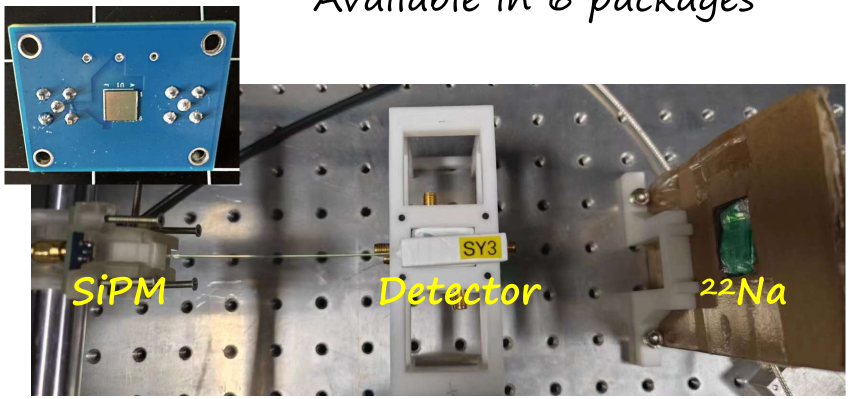
The overall layout of the spectrometer is designed

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

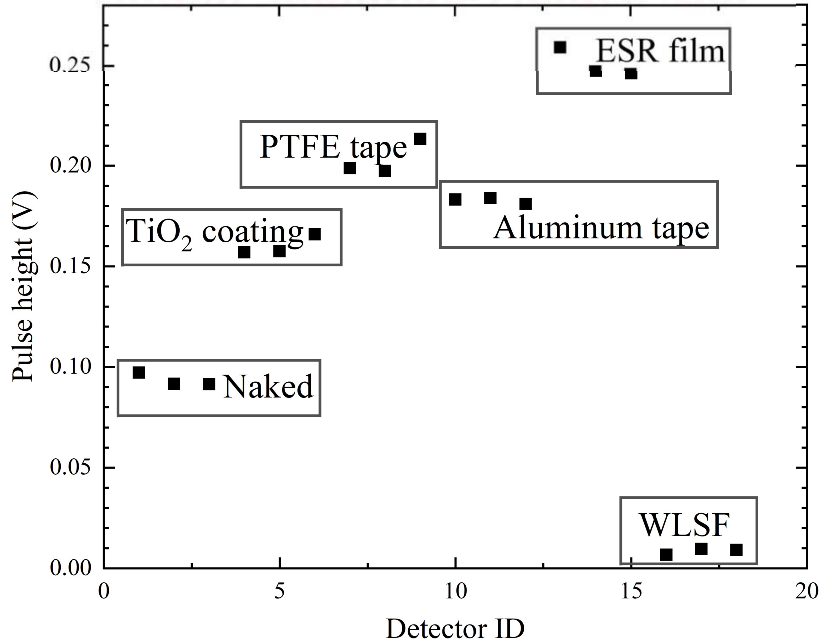
One of the inner modules is prepared for testing on muon source at ISIS

Preliminary scintillator tests :

Available in 6 packages



Output amplitude comparison

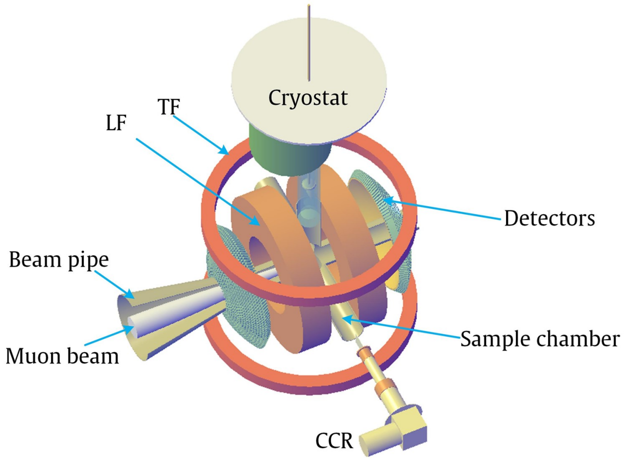


ESR is the best
PTFE works well and is the easiest to operate
Wavelength-shifted fibers can dramatically reduce the efficiency of light collection

What to do next:

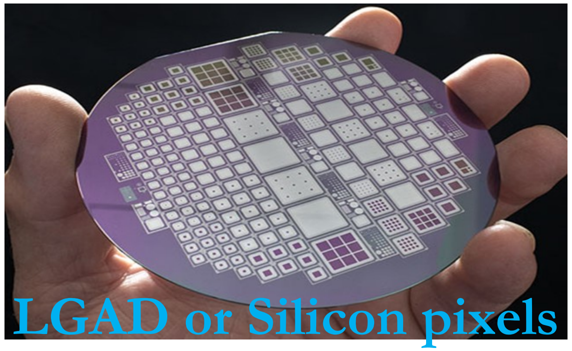
1. Continue testing on the CSNS particle beam
2. Prepare the detector module for testing on the ISIS beam

III. Summary and prospects

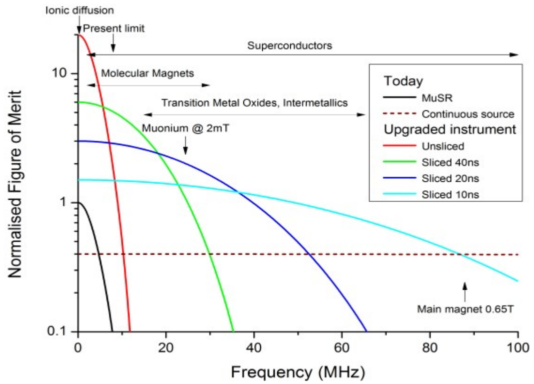


- ~1500 detector units in the first stage (~3024 units in total)
- R: ~ 4×10^{7} e^{+}/hour @1 Hz (~8 MEvent/hour in total)
- Asymmetry: > 0.3
- Pulse length: ~130 ns (consider slicing to 10 ns)
- Temperature: 10-600 K with CCR (2-300 K with cryostat in the future)
- LF: 0-5000 G
- TF: 0-400 G
- Beam spot: Φ10-30 mm

Which are the most important concerns of users? Any suggestions?



1. High granularity
   Fast output
   ⇒ R ↑↑



2. Slice the bunch:
   From 130 ns to ~10 ns

3. More environmental conditions:

   HelioxVT insert ~300 mK

   RF field

   Pressure, etc.

   Welcome to discuss!


Thanks !
CSNS