Applications of SiPM based detectors in muon spin spectroscopy

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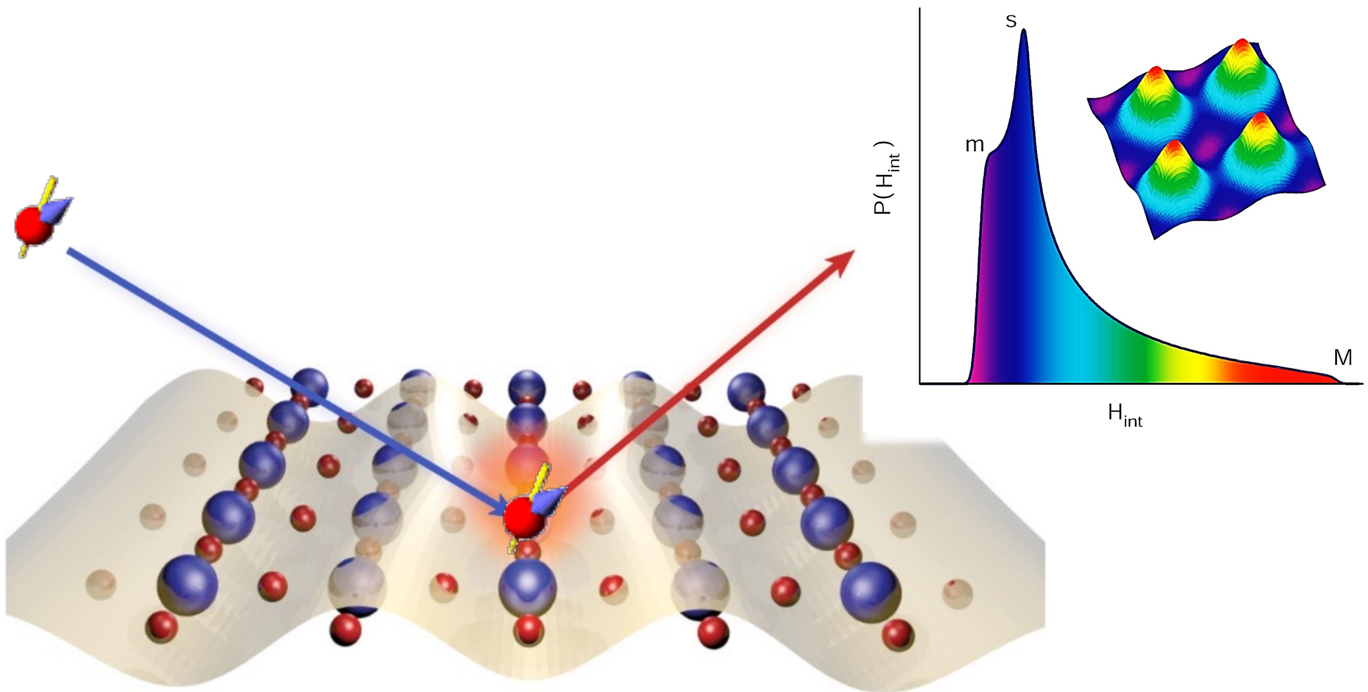
第三届半导体辐射探测器研讨会|巢湖中庙

目录

1. 研究背景

μSR: muon spin rotation/relaxation/resonance
缪子自旋旋转/驰豫/共振



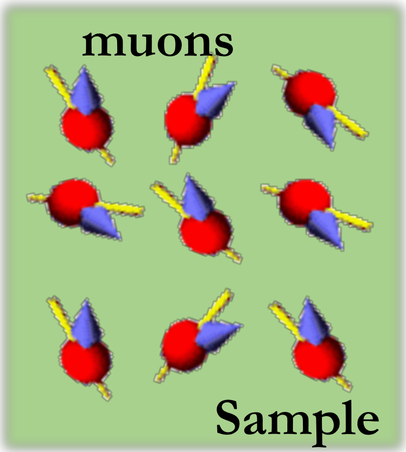
A quantum magnetism probe

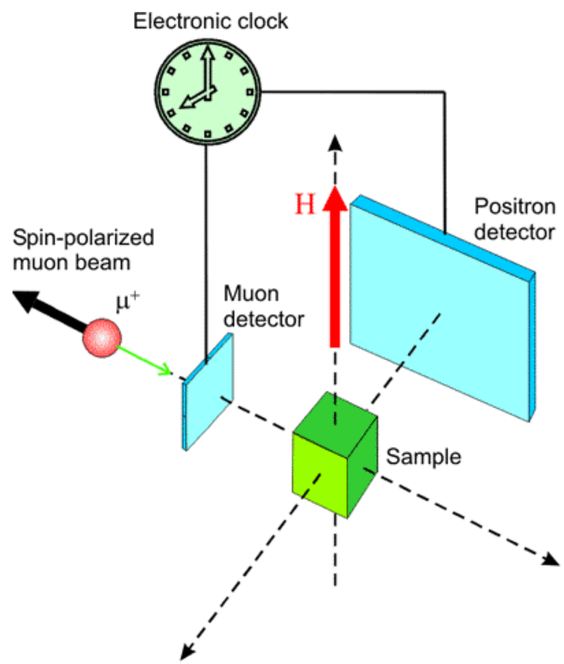
1.1 Principles of μSR spectroscopy

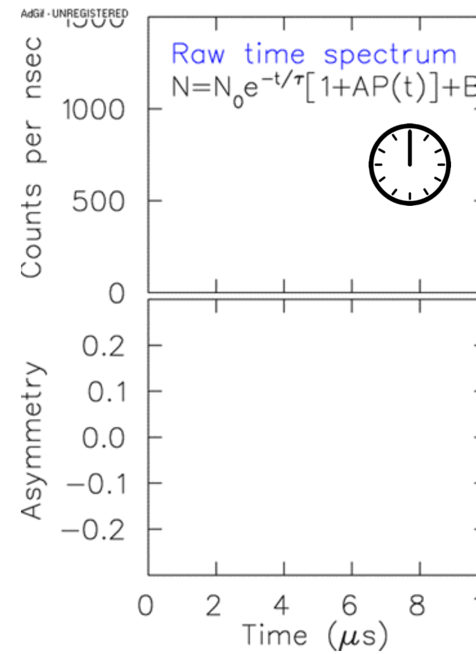
拉莫进动
(自旋相互作用)

非对称衰变
(正电子探测)

μSR谱
(解谱分析)







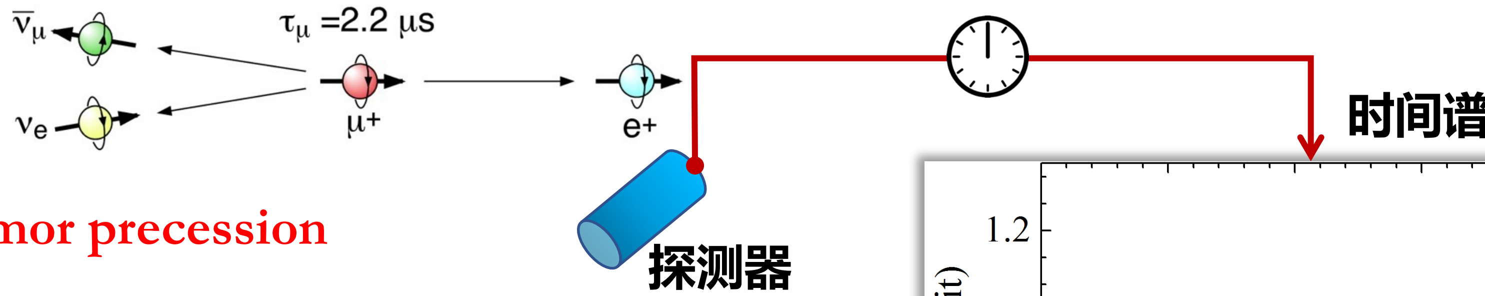
$$\frac{\mathrm{d}\boldsymbol{S}_\mu(t)}{\mathrm{d}t} = \gamma_\mu \boldsymbol{S}_\mu(t) \times \boldsymbol{B}_{\mathrm{loc}}(\mathrm{t})$$

$$\boldsymbol{P}(t) = \frac{\boldsymbol{S}_\mu(t)}{\boldsymbol{S}_\mu(t=0)}$$

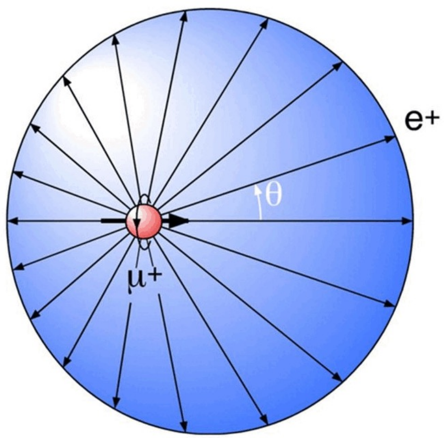
$$\mu^+ \rightarrow \boldsymbol{e}^+ + \nu_e + \bar{\nu}_\mu$$

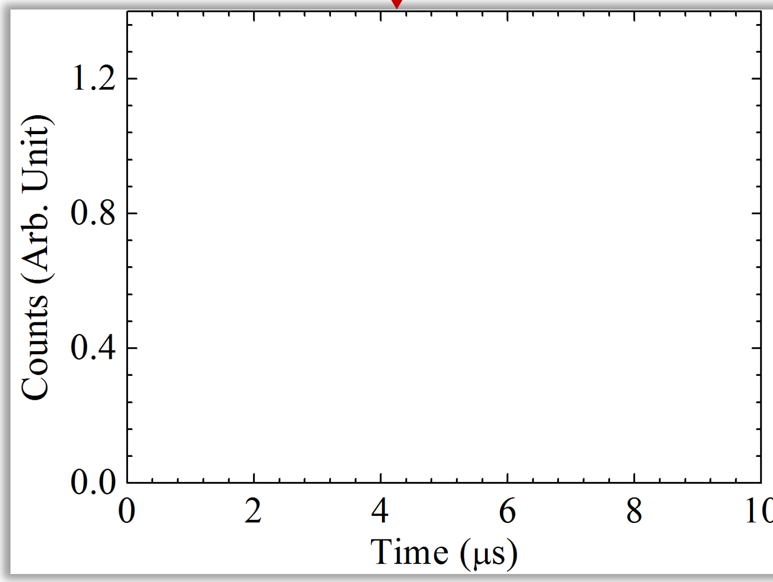
$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = A\boldsymbol{P}(t)$$

1.1 Principles of μSR spectroscopy



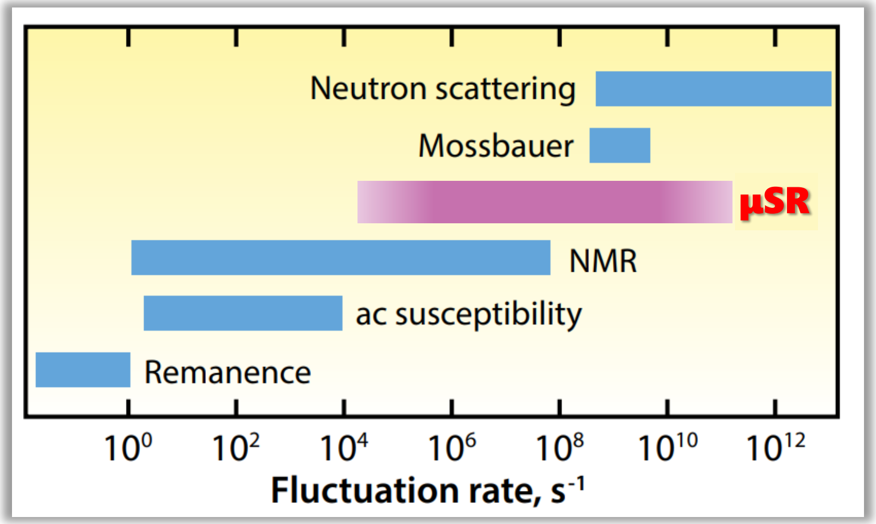
Larmor precession

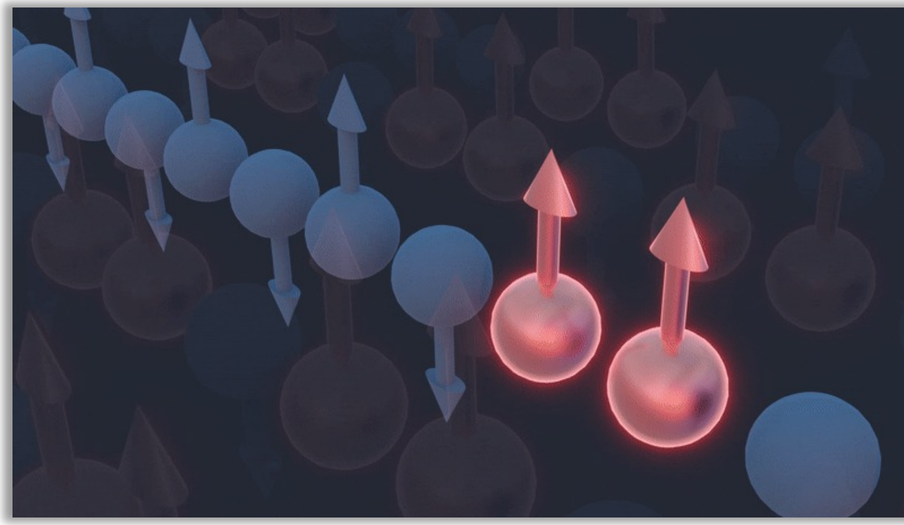




缪子自旋取向在局域场中随时间变化 → 正电子空间分布随缪子自旋取向变化 → 探测器正电子计数随时间变化 → 拟合解谱提取极化函数AP(t)，表征材料磁性

1.2 Advantages of μSR spectroscopy





- **独特的时间窗**(complementary to NMR/neutron scattering)
- **弱磁性灵敏**(small moment magnetism ~ 10^{-3} μ_B/Atom)
- **随机/不均匀磁性分布**(e.g. spin glasses)
- **短程有序**(where neutron scattering is not sensitive)
- **高度极化，可零场实验**(independent of temperature, unique measurements without disturbance of the system)
- **单粒子探测**(with extremely high sensitivity)
- **样品状态无限制**(in choice of materials to be studied)
- **局域量子磁探针**(no need to search reciprocal space)

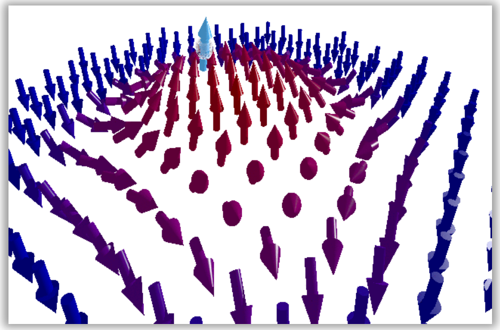
1.3 Application fields

● Passive probe
(lepton)

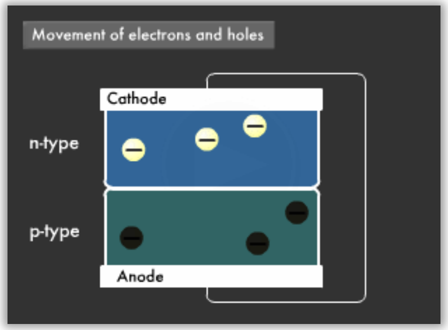
● Active probe
(light proton)

Superconductor

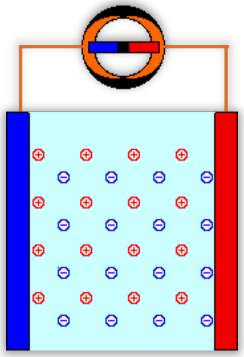
Magnetism



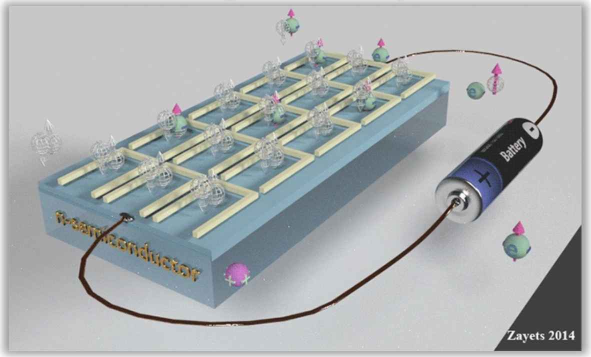
Semiconductor



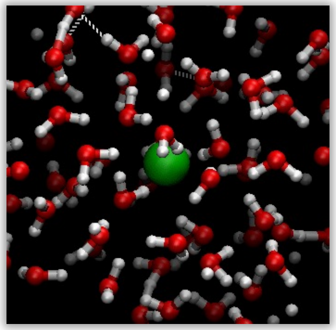
Ionic conductor



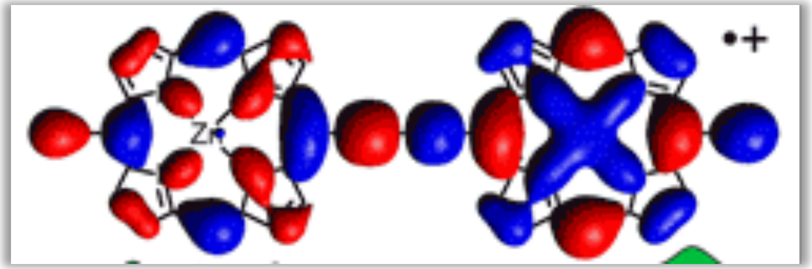
Charge transport



MD



Polaron motion



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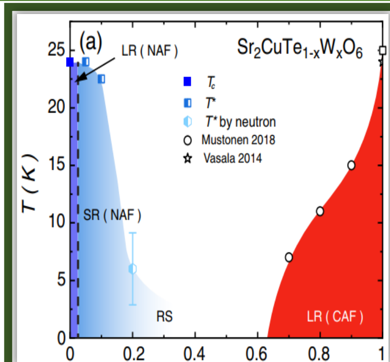
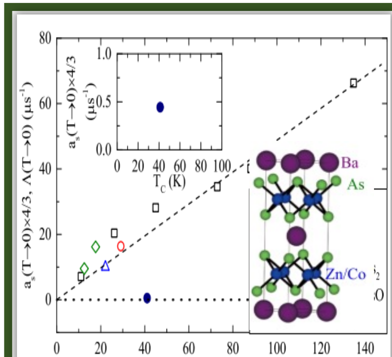
1.3 Application fields



李世亮课题组 @ 中科院物理所

Extreme Suppression of Antiferromagnetic Order and Critical Scaling in a Two-Dimensional Random Quantum Magnet, **Physical Review Letters** *126, 037201 (2021).*

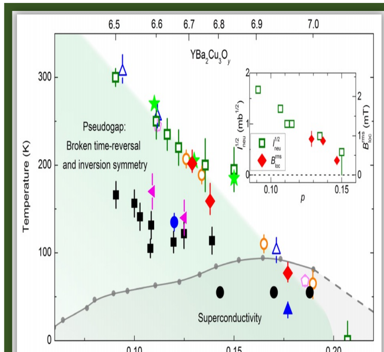
二维量子反铁磁体掺杂演化机制得到部分澄清



宁凡龙课题组 @ 浙江大学

Ba(Zn,Co)$_2$As$_2$: A diluted ferromagnetic semiconductor with n-type carriers and isostructural to 122 iron-based superconductors, **Physical Review B** *99, 155201 (2019).*

成功合成一种新型稀磁半导体并由μSR确证

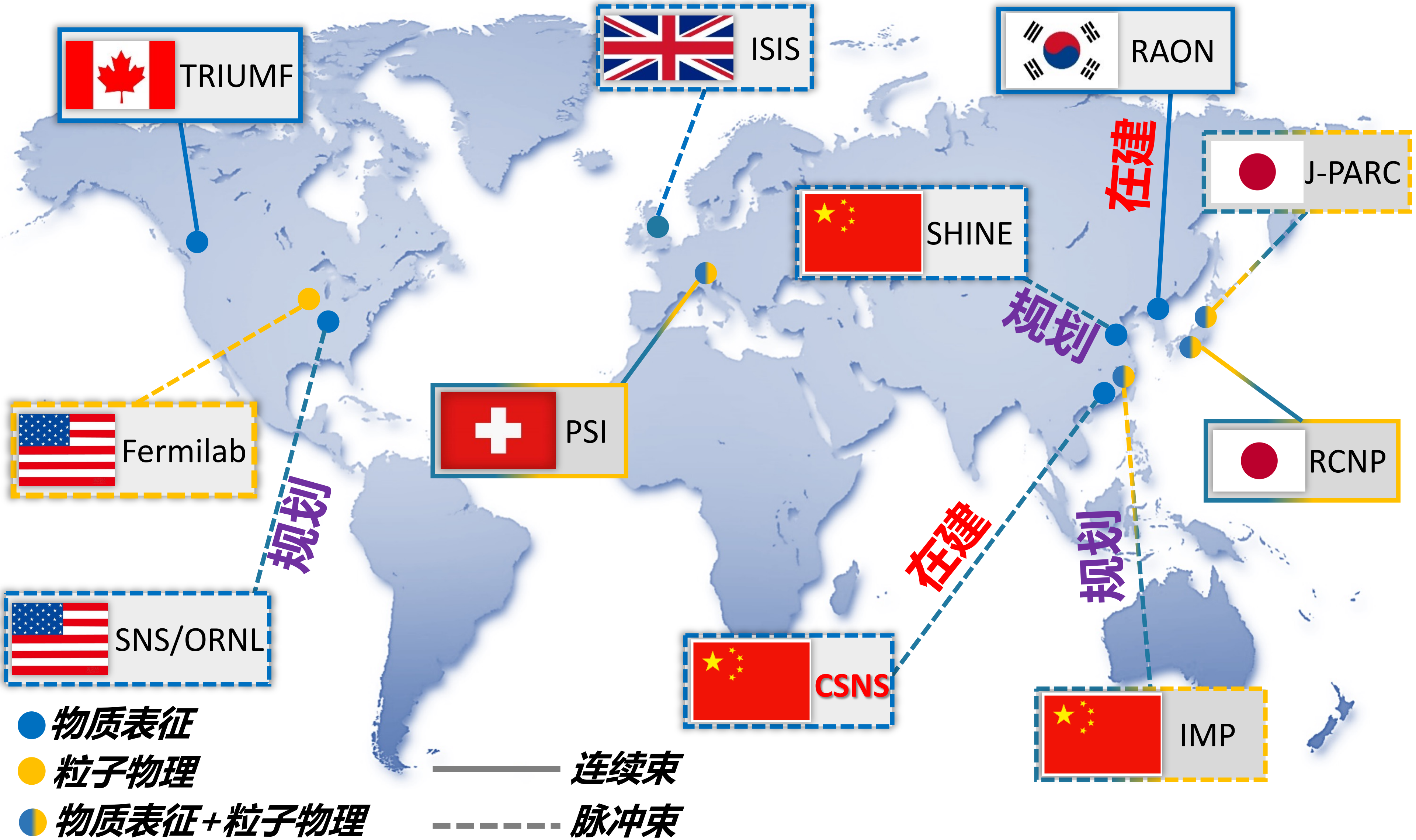


殳蕾课题组 @ 复旦大学

Discovery of slow magnetic fluctuations and critical slowing down in the pseudogap phase of YBa$_2$Cu$_3$O$_y$, **Science Advances** *4, eaao5235 (2018).*

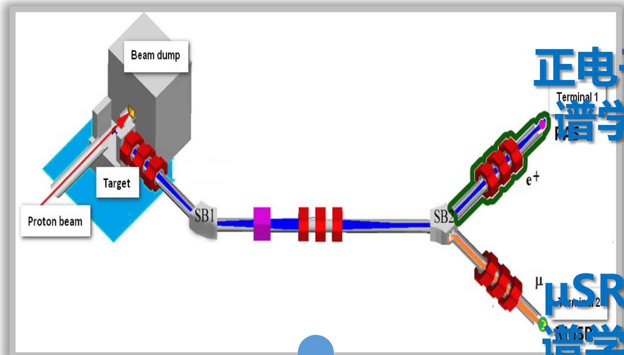
高温超导体赝能隙研究取得突破

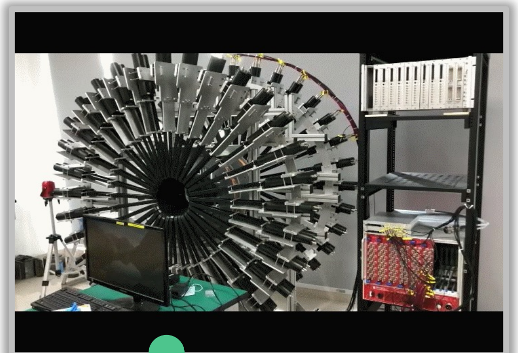
1.4 Worldwide muon sources

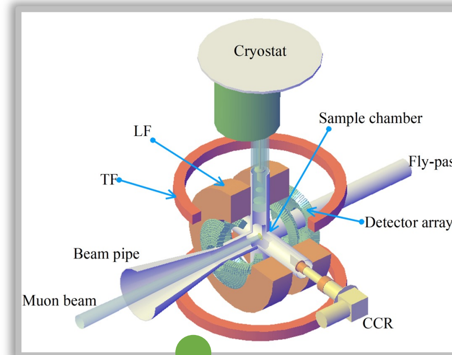


1.5 Instrumentation @ USTC muon group

Particle Beam Application Laboratory **(PI: 叶邦角教授)**





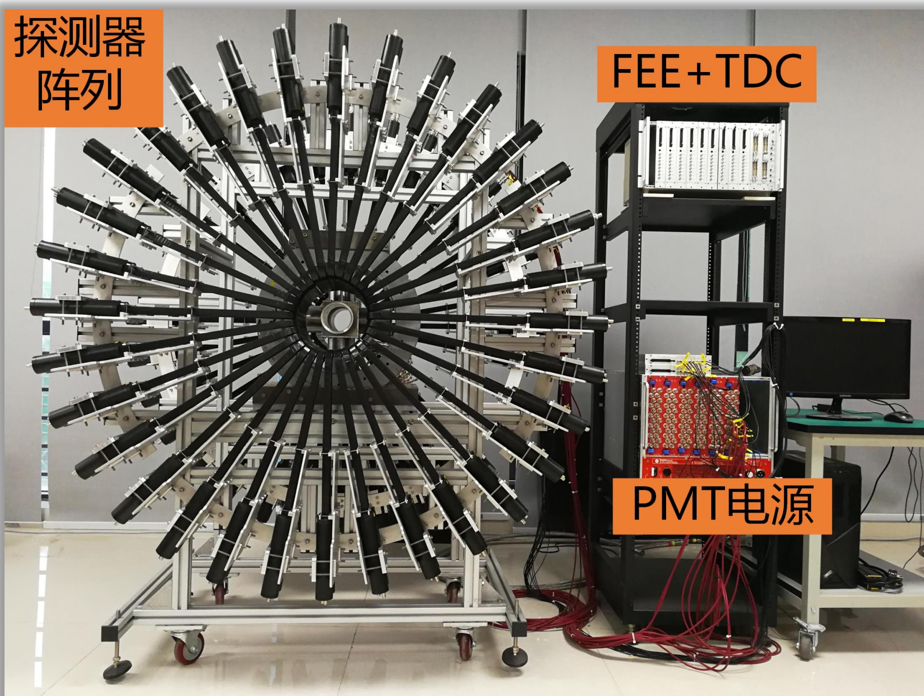


Pre-study (2007-2014) — 束流设计

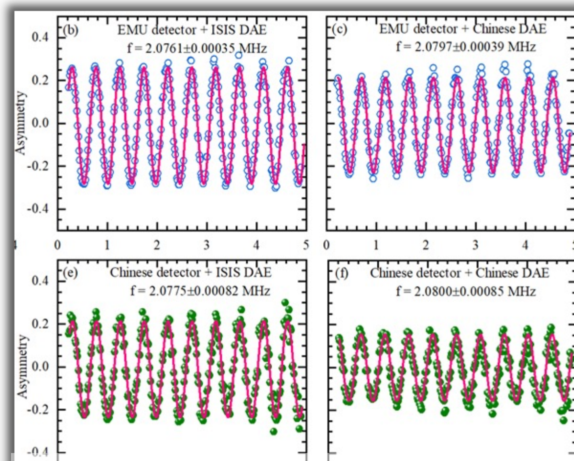
Prototype R&D (2015-2020) — 1st generation 128路样机(PMT)

Construction (2023-2028) — 2nd generation 工程谱仪(SiPM)

1.5 Instrumentation @ USTC muon group



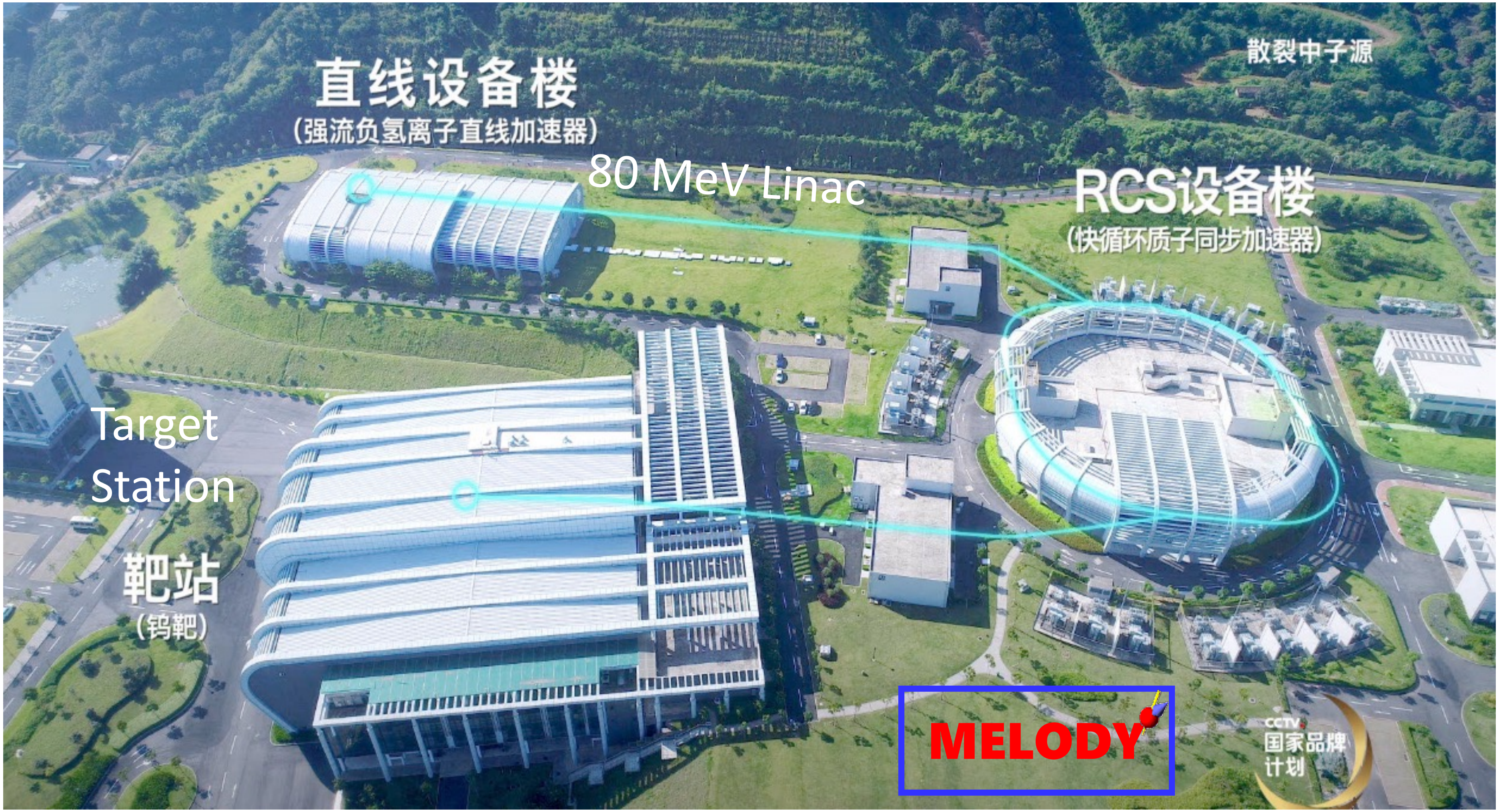
专家组验收



Z. Pan, et. al., IEEE TNS 2021

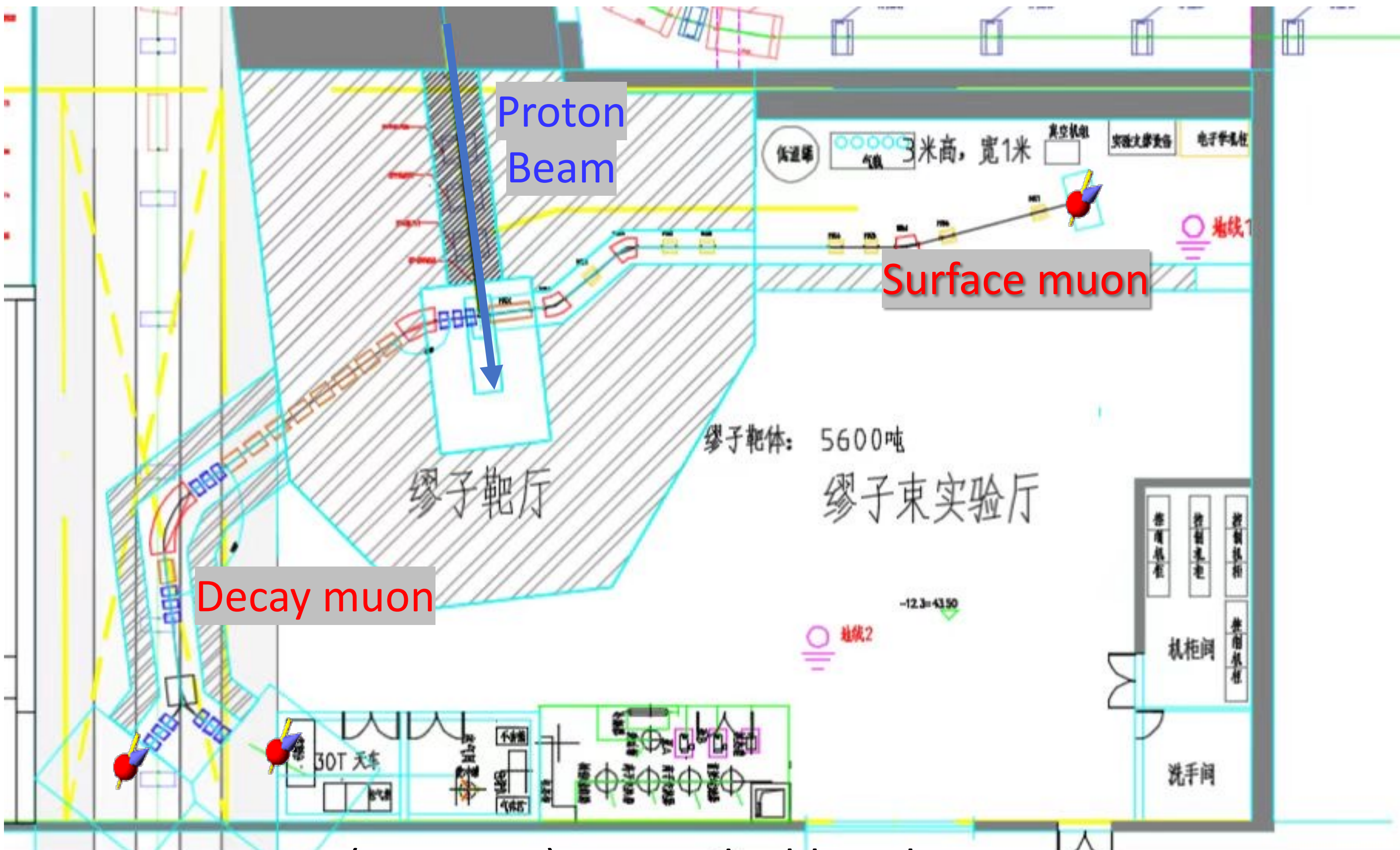
- ✓ 样机探测系统计数性能优于ISIS谱仪
- ✓ 可以精确测量样品局域磁场
- ✓ 基金委结题评价为亮点工作

Muon station for sciEnce technoLOgy and inDustrY (MELODY)



1.6 MELODY @ CSNS II

Muon station for sciEnce technoLOgy and inDustrY (MELODY)

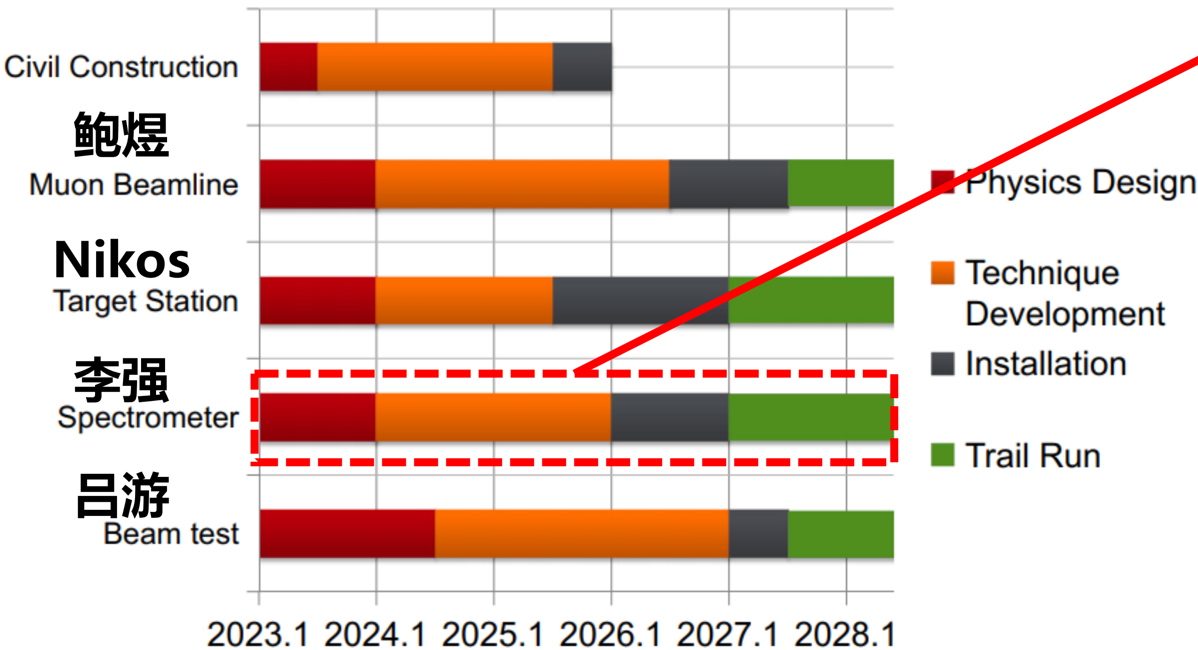


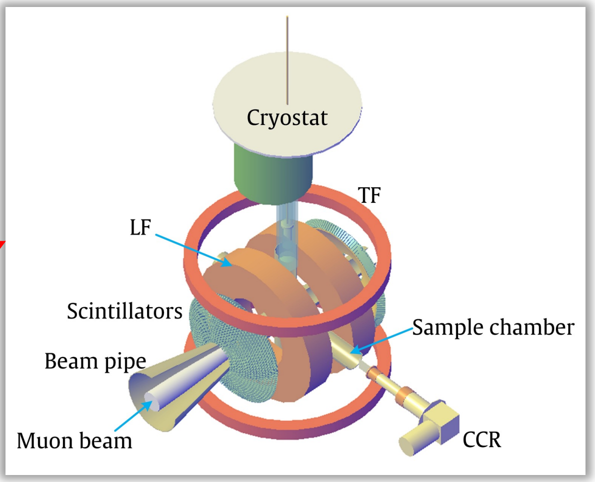
- Protons: 1.6GeV, 1 Hz (up to 5Hz), 130ns double pulses
- Muon beamlines: one **surface muon** and one decay muon beam
- Spectrometers: **1 μSR spectrometer** and more…

Proceedings @ MuSR2020

1.6 MELODY @ CSNS II

负责人：鲍煜





Detection system: (潘子文)

2868 plastic scintillators
Sensl sipm
FEE+TDC readout

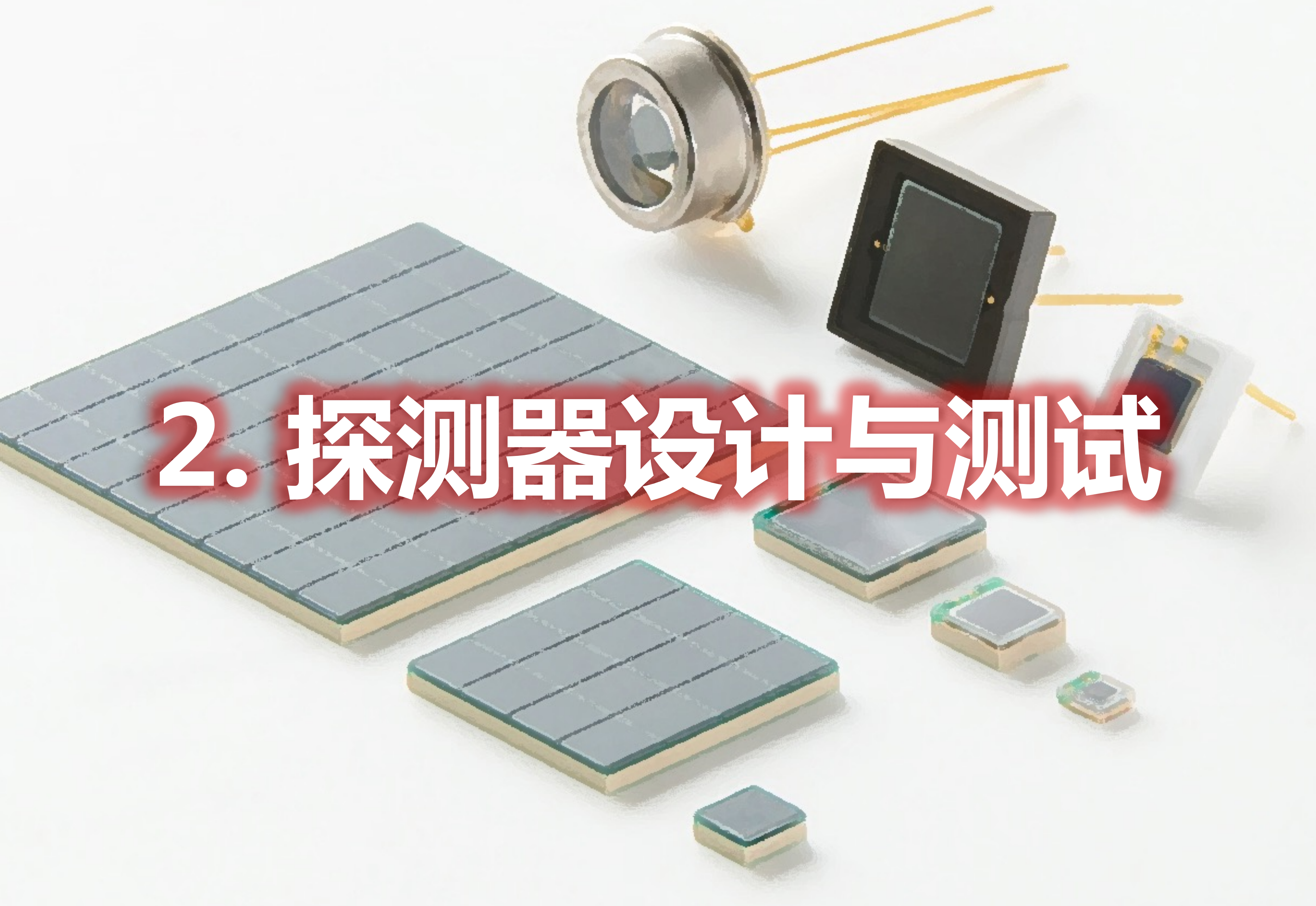
Sample environment: (程辉、胡海韬)

Cryostat: 2 – 600 K
CCR: 10 – 600 K
ZF/LF/TF magnets

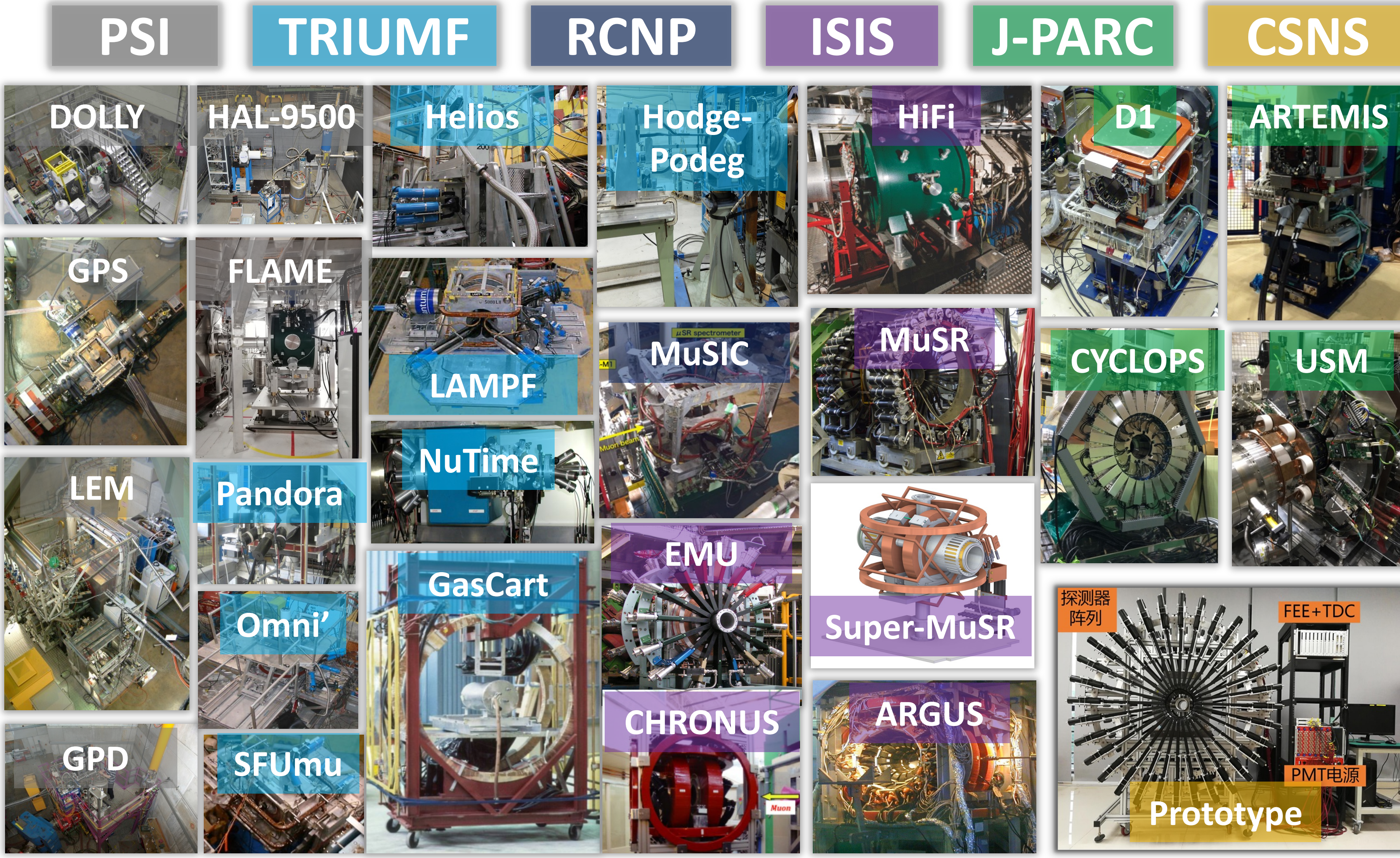
Data analysis software: (李样)

Proceedings @ MuSR2020

2. 探测器设计与测试



2.1 Spectrometer development trend



2.1 Spectrometer development trend

Facilities	Time mode	Spectrometer	Light sensors	Amount
PSI	Continuous	DOLLY、 GPS、 GPD、 HAL-9500、 LEM、 FLAME	SiPM/PMT	6
TRIUMF	Continuous	Helios、 DR、 NuTime、 Omni Prime、 LAMPF、 SFUmu、 Hodge-Podge、 Gas Cart	PMT	8
MuSIC	Continuous	Reused from KEK	PMT	1
ISIS	Pulsed	MuSR→SuperMuSR、 EMU、 HiFi、 ARGUS、 CHRONUS	PMT/SiPM	5
J-PARC	Pulsed	D1、 ARTEMIS、 USM、 CYCLOPS	SiPM	4
		In total:		**24**

- ◆ 早期建设的谱仪(如TRIUMF、ISIS)使用PMT，后期建设的基本使用SiPM
- ◆ 使用PMT的谱仪也逐步升级到SiPM
- ◆ μSR谱仪逐步SiPM化

2.2 Technical challenges

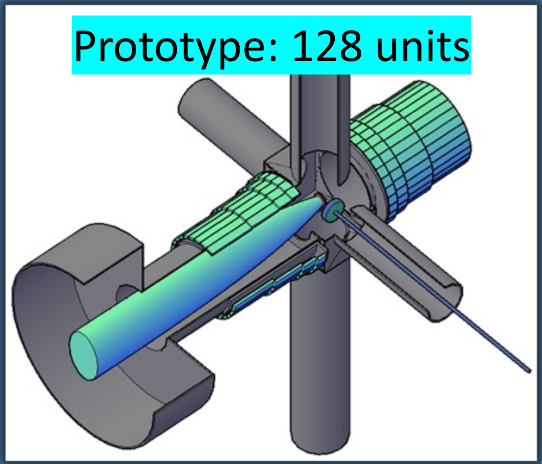
缪子源	J-PARC			ISIS	CSNS
谱仪	DΩ1	D1	ARTEMIS	EMU	-
流强(μ^+/pulse)	$< 10^{11}$ (需准直)			$< 7.5\times10^4$	$> 10^5$
频率(Hz)	25			40	1
通道数	128	640	640	96	
总计数率 (Mevents/h)	40	180	180	140	-
单路计数率 (e^+/pulse/ch)	3.47	3.13	3.13	10.13	-
传感器	PMT	SiPM	SiPM	PMT	SiPM
死时间(ns)	-	~ 100	50	8	-

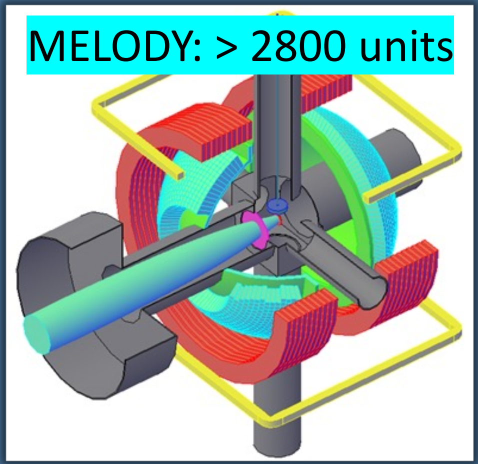
用户需求: 多样品多条件快速测量（一次测量需要2×10^7 events）

技术难点:
- MELODY束流重复频率低
- 每脉冲流强高
- SiPM死时间长

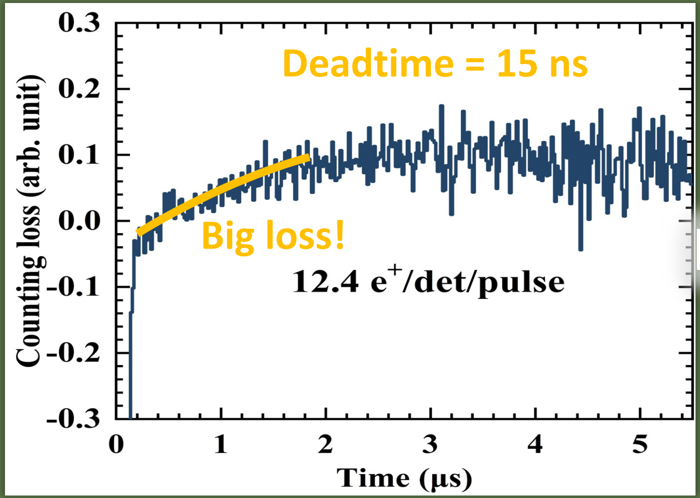
2.3 Solutions

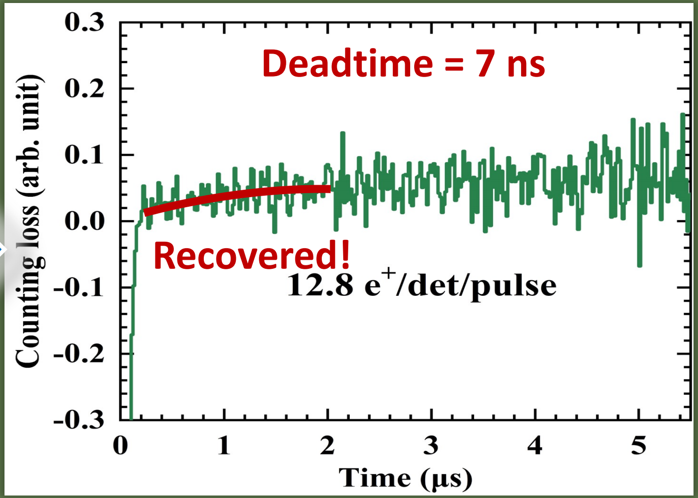
高度
阵列化





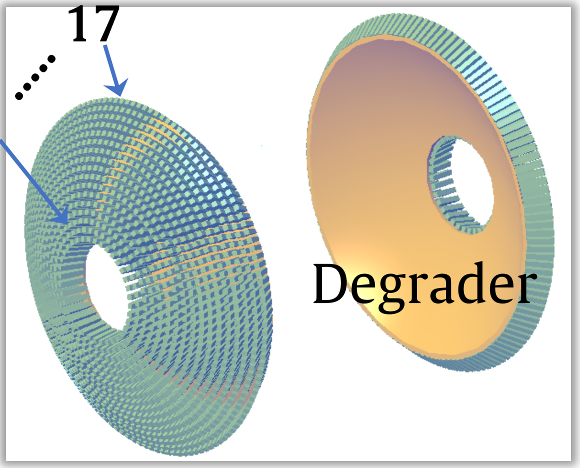
信号
窄化



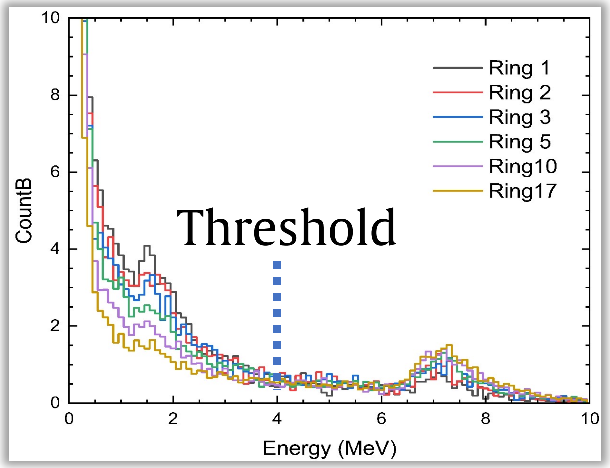


2.3 Preliminary design

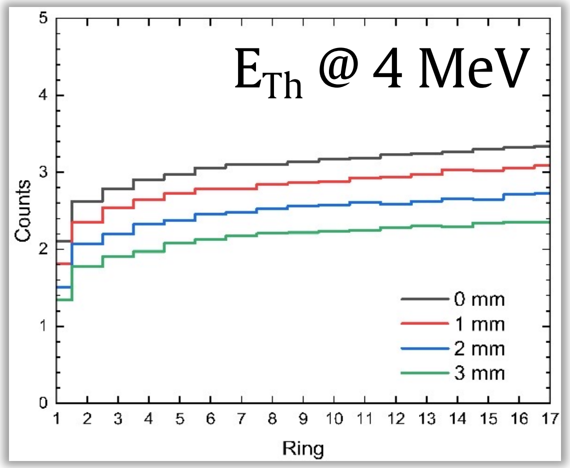
Detectors



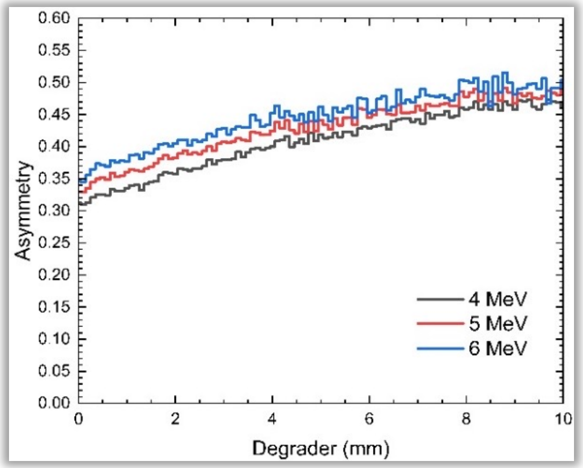
Energy deposition



Counting rate (/det/pulse)



Asymmetry



Detection rate

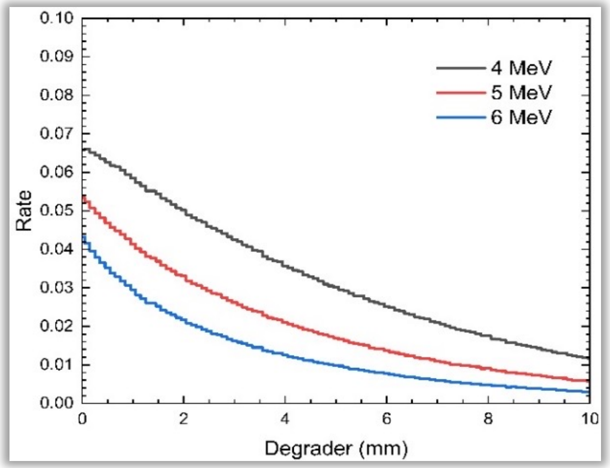
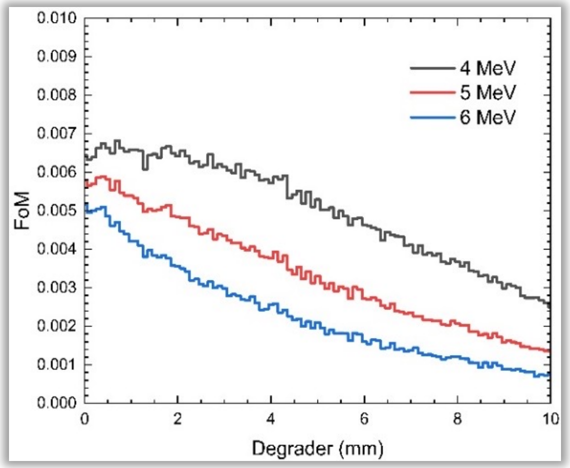
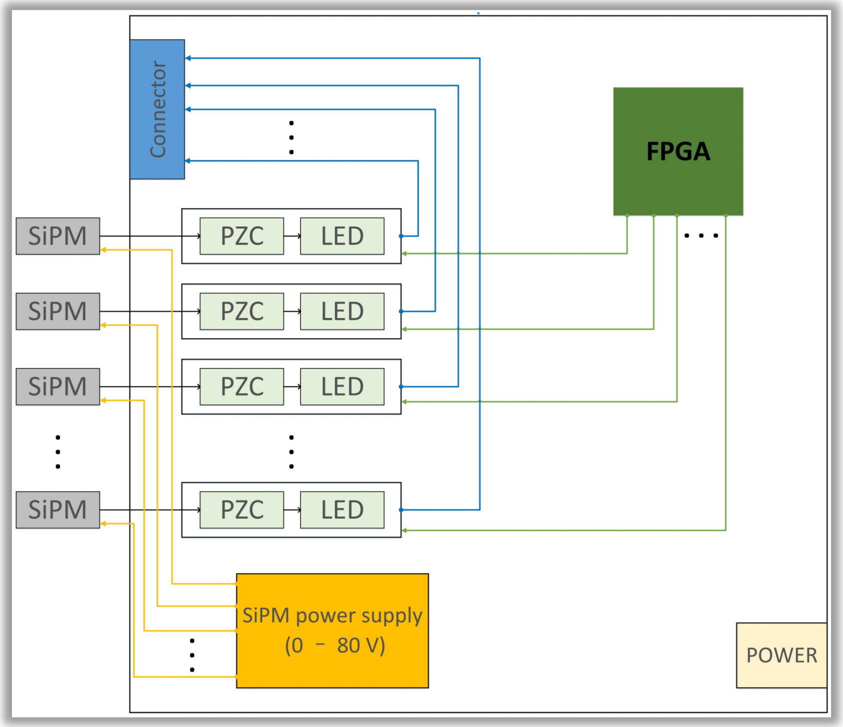


Figure of Merit

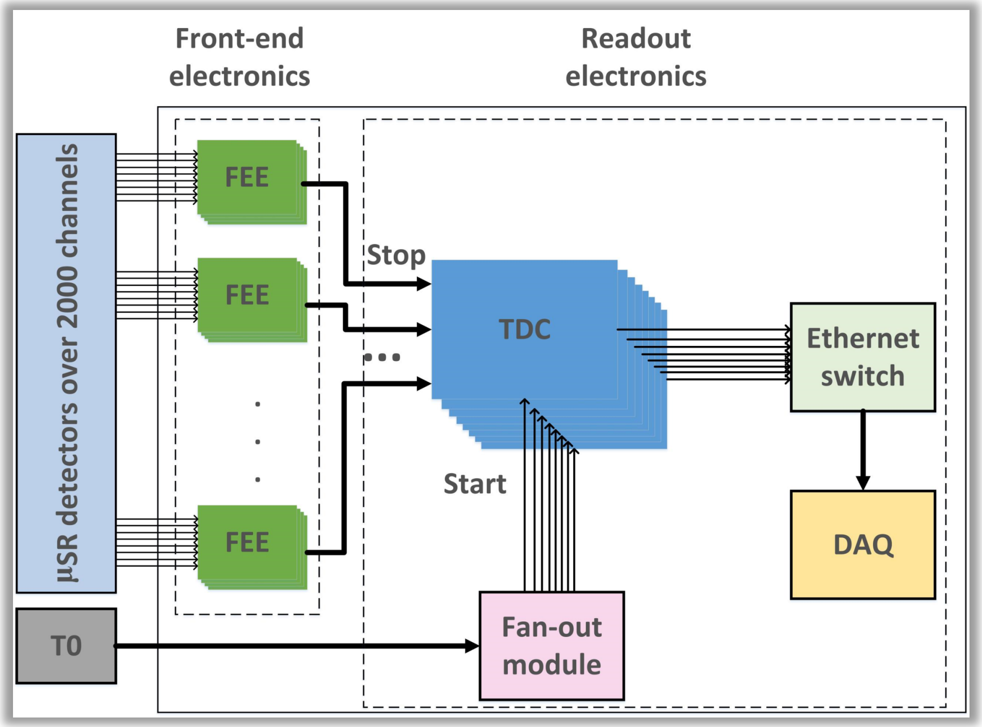


Electronics

Front-End Electronics



TDC Readout

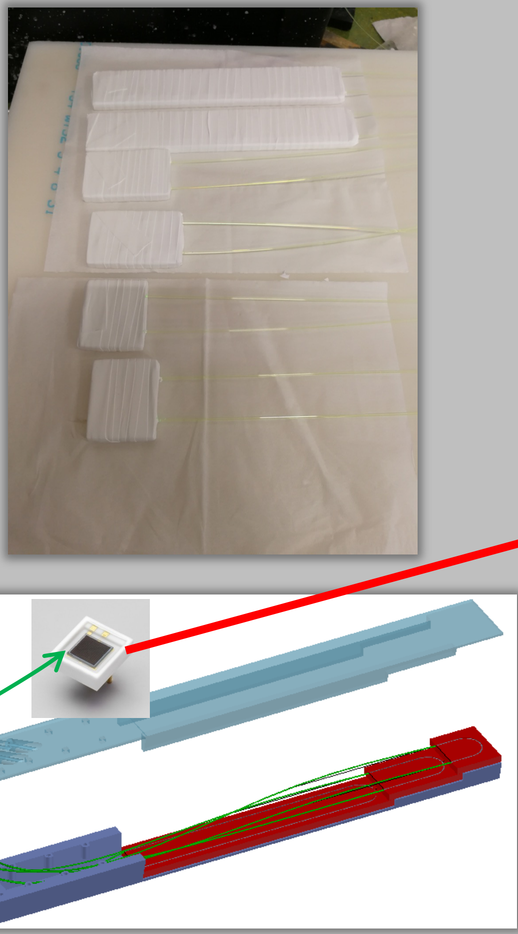


FEE (PZC + LED) + TDC

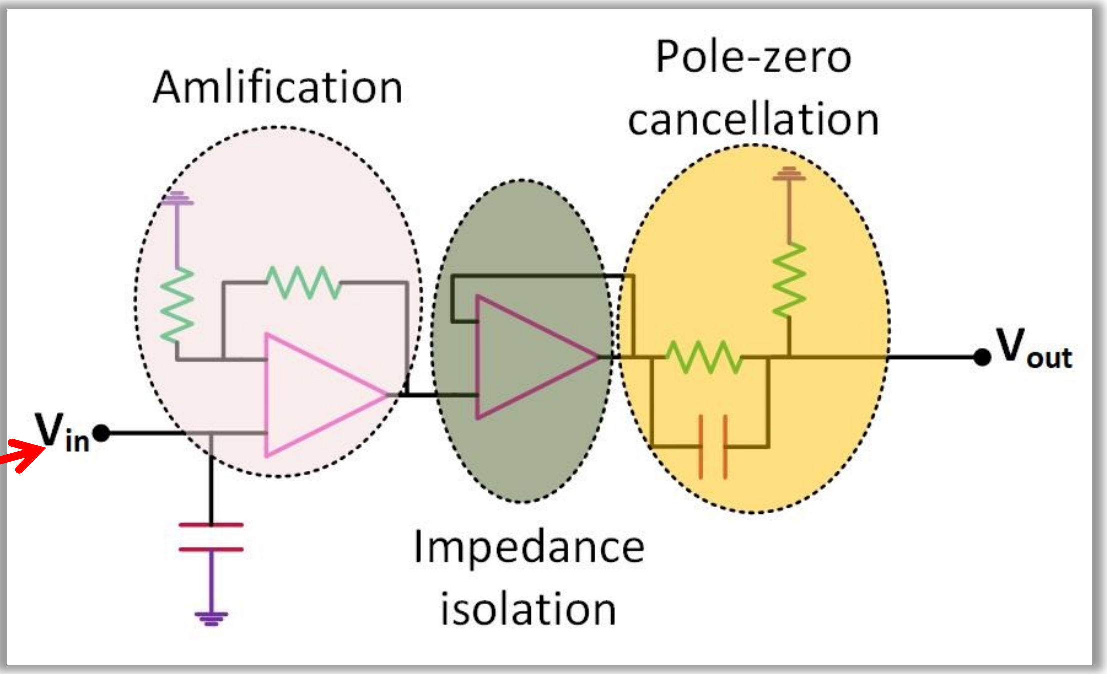
PZC: Pole-zero cancellation, LED: Leading-edge discrimination

2.4 Tests @ ISIS Muon Facility

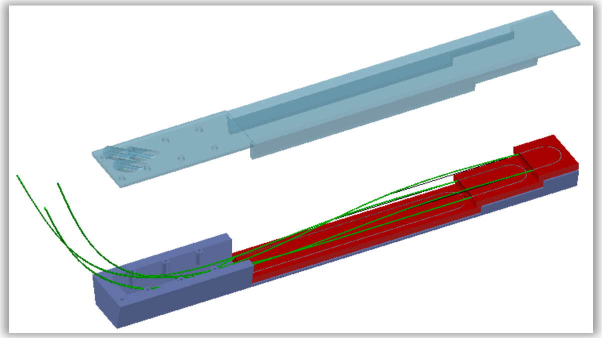
PS + WLSF



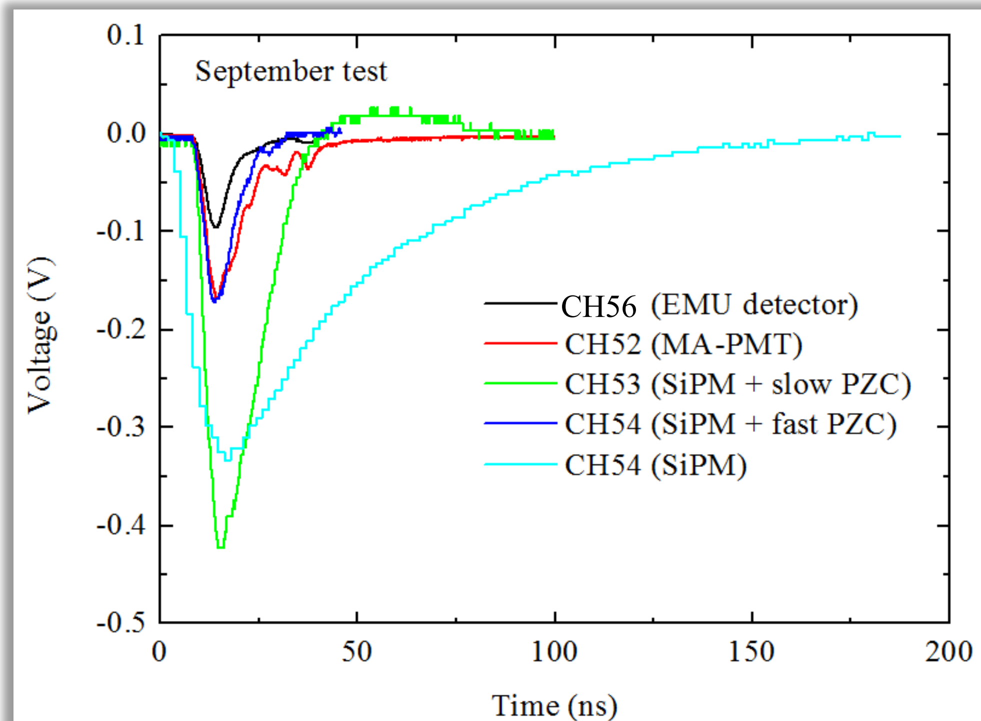
Electronics



2.4 Tests @ ISIS Muon Facility



CH52: MA-PMT
CH53: SiPM + slow PZC
CH54: SiPM + fast PZC
CH56: EMU detector (PMT)



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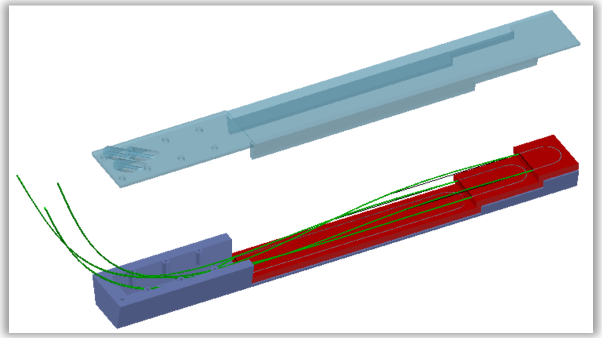

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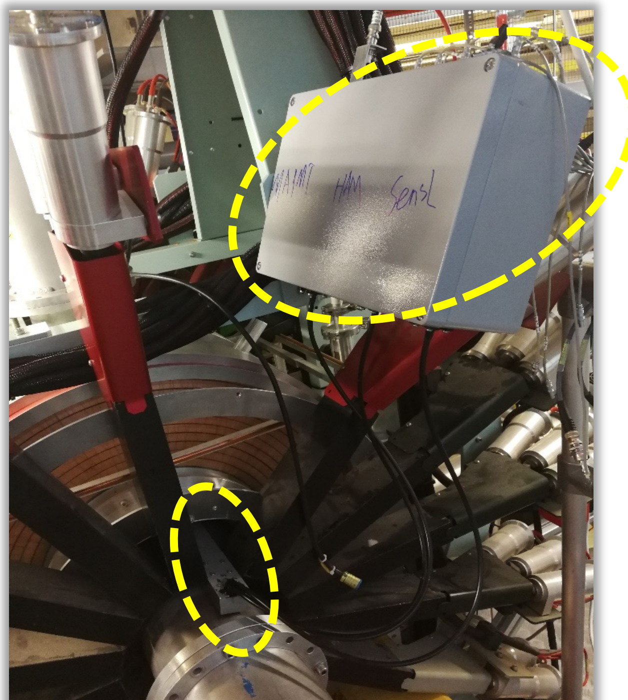
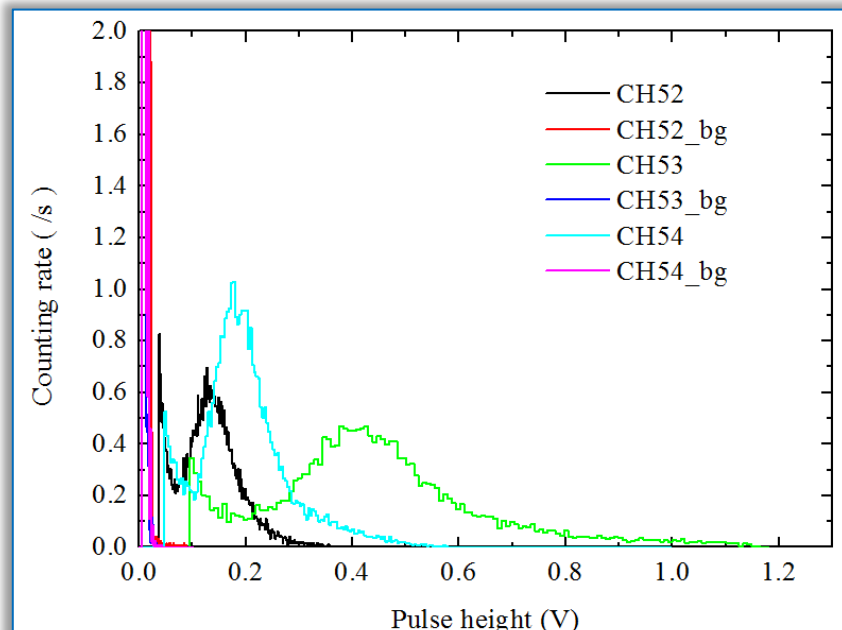
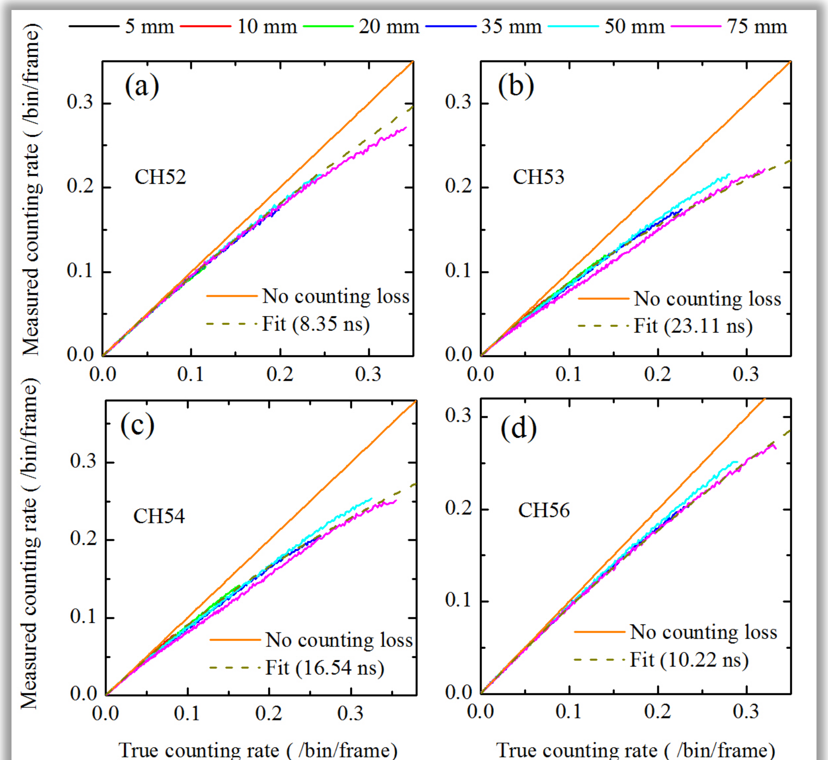
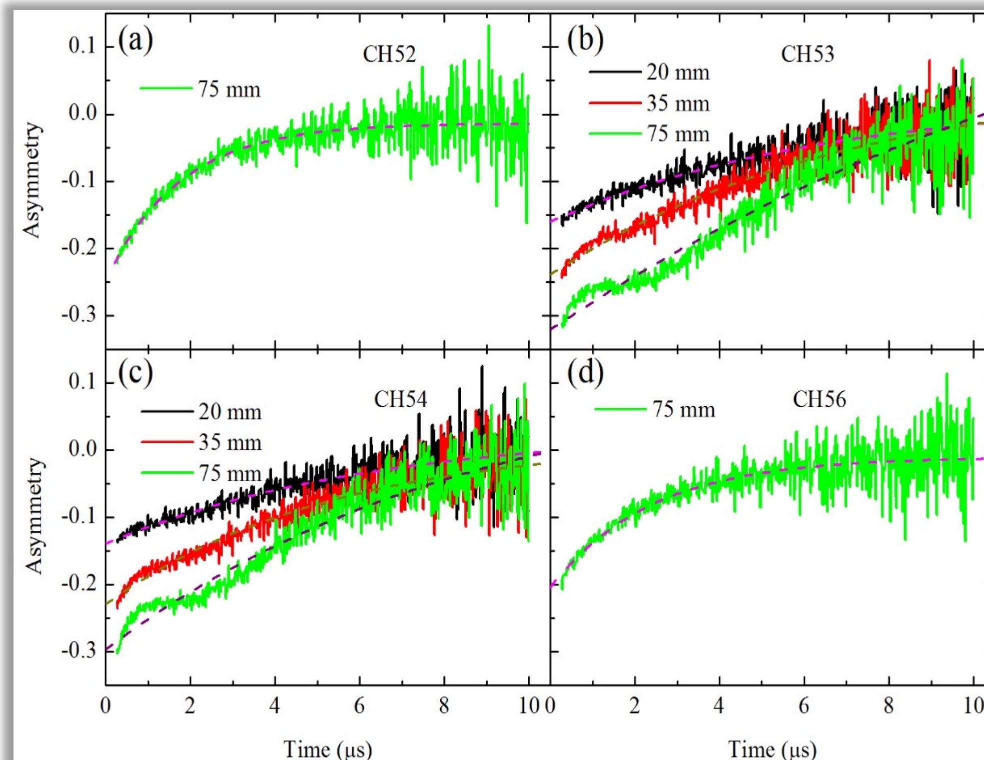




2.4 Tests @ ISIS Muon Facility

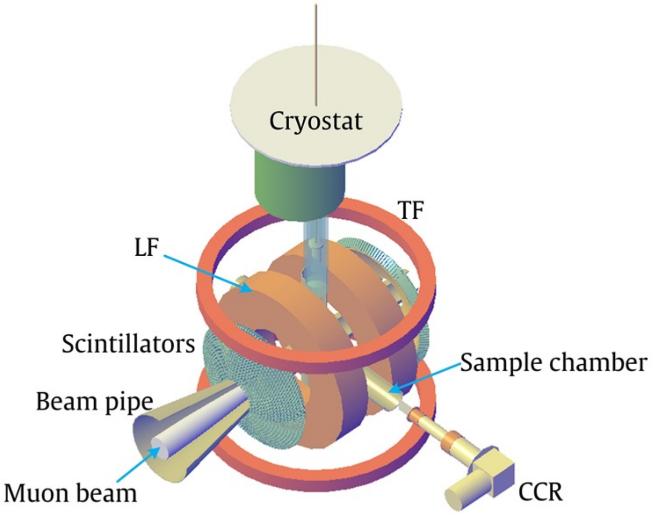




- ◆ MA-PMT和PMT死时间相当
- ◆ SiPM使用极零相消电路（PZC）后，死时间下降至20 ns左右
- ◆ 计数率高于18 events/pulse后，μSR谱出现明显变形

3. 总结与展望

3.1 Summary



Day-One at MELODY

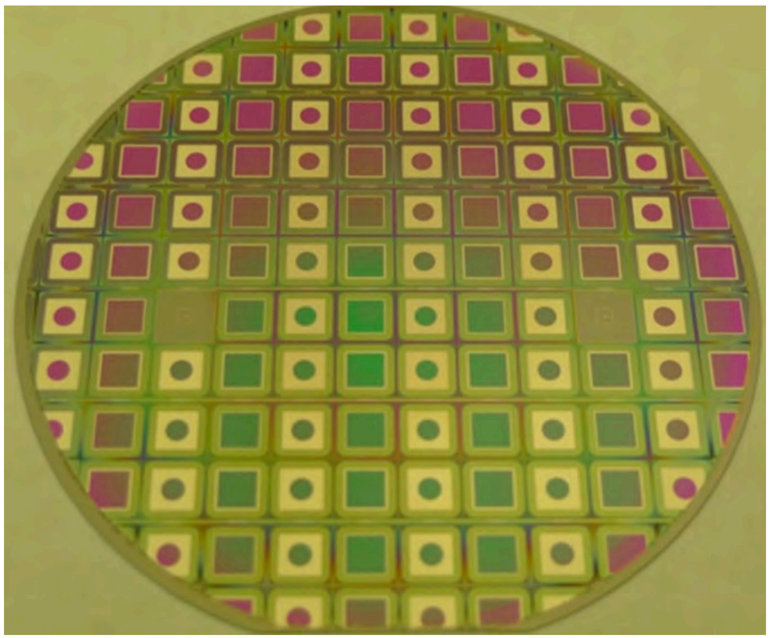
- 2868 PS+SiPM
- Asymmetry : 0.39
- Counting rate : 8×10^7/hour @ 1 Hz

Tests @ ISIS Muon Facility

- SiPM (sensl slow output) + PZC
- Dead time : ~ 20 ns
- Fast output / PZC optimization ?

Next-Generation Spectrometer ?

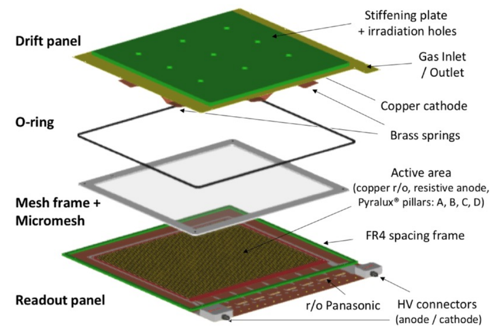
LGAD

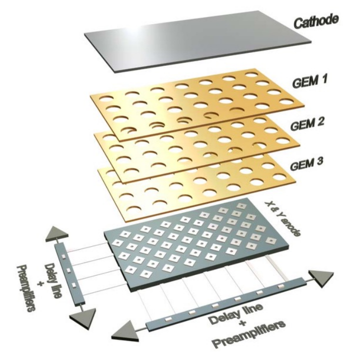


Small size: ~ mm^2

Fast signal: 10s of picosecond

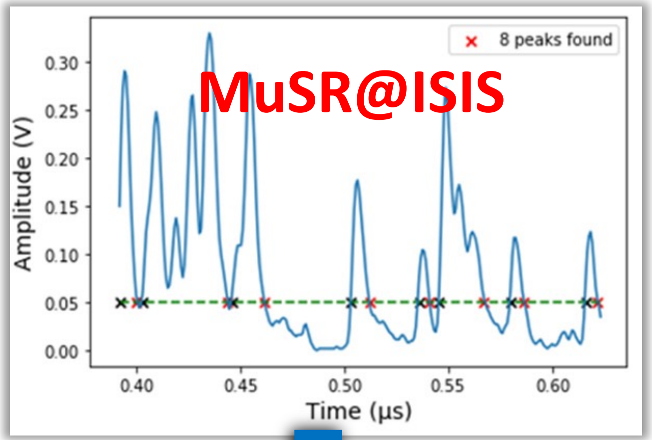
Micromegas or GEM ?

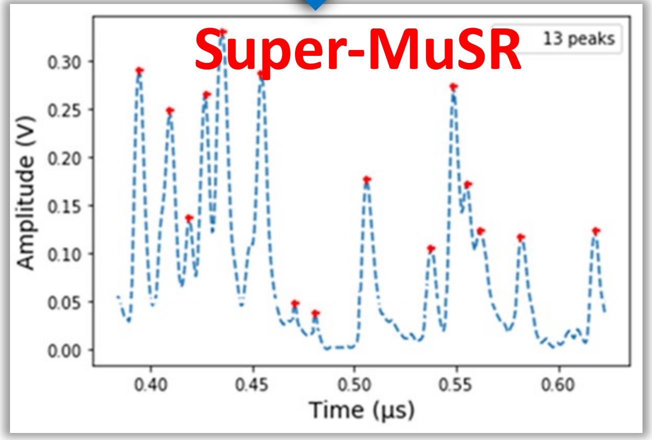




High granularity (almost no pileups under current intensity)

Next-Generation Spectrometer ?





Thanks!