μSR Facility Users Guide

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Revised: February 24, 1999

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1 Introduction to TRIUMF

TRIUMF (Tri-University Meson Facility) is Canada's largest national accelerator facility for research in subatomic physics. The facility is located on the campus of the University of British Columbia and is operated as a joint venture by the University of Alberta, Simon Frasier University, the University of Victoria and the University of British Columbia.[1]

1.1 A Brief History

TRIUMF is one of three medium-energy (0.5 to 0.8 GeV), high-current accelerator facilities built in the early 1970's primarily for fundamental meson physics experiments. The other two are at the Paul Scherrer Institute (PSI) in Switzerland and Los Alamos National Laboratory (LAMPF) in the U.S.A. Each is a different design, with characteristics that are generally complementary. Although the TRIUMF cyclotron is third in terms of raw beam power, which is important for meson production, other characteristics, such as large duty factor compared to the LAMPF LINAC and variable proton beam energy compared to the PSI cyclotron, maintain TRIUMF at a front-rank position in the international competition.

TRIUMF was conceived in the mid-1960's in discussions at the UBC Physics Department. It was intended to be a university-based and university-managed facility primarily for fundamental scientific studies. The potential user scientists

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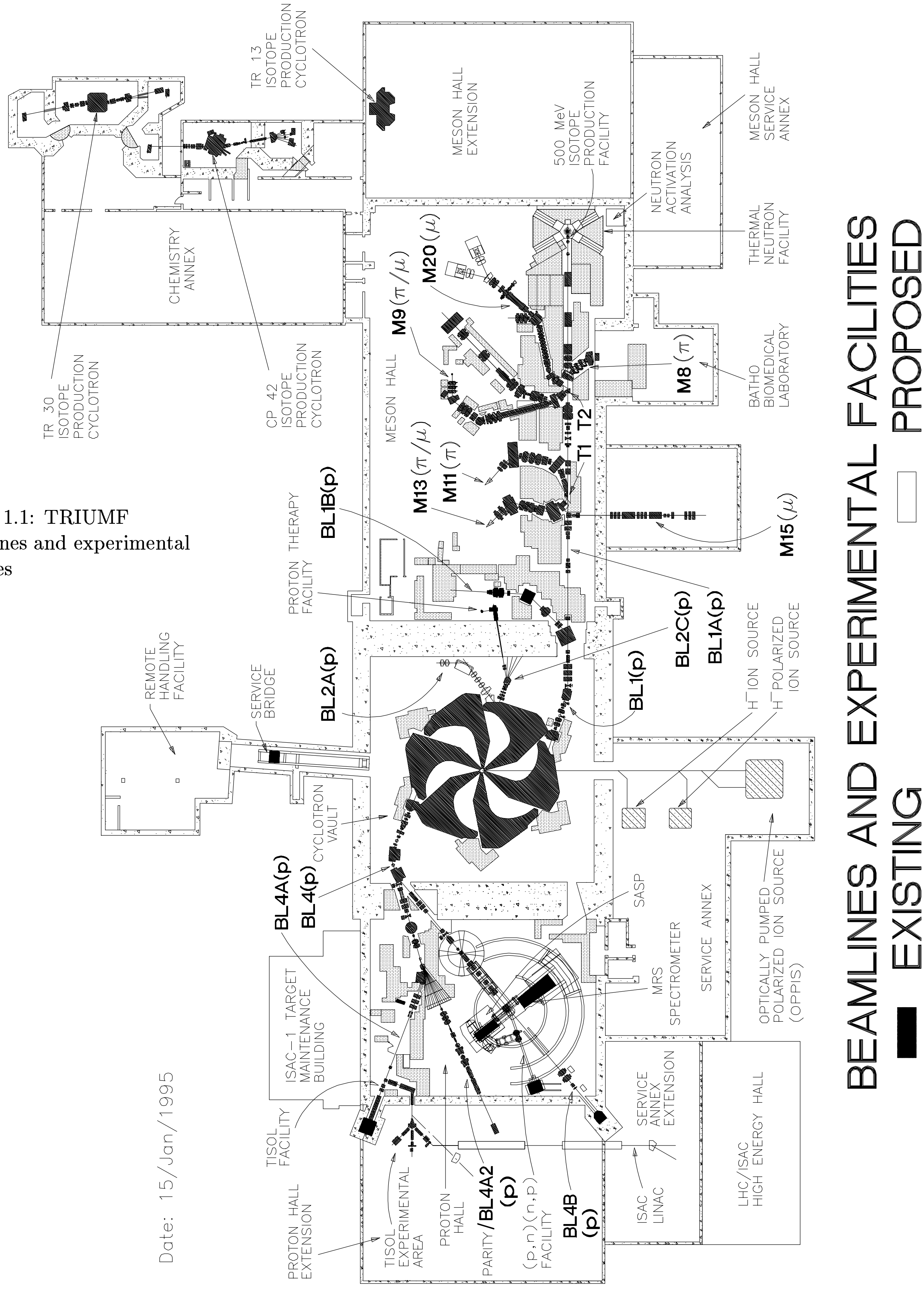
[1] This chapter has been adapted from the introduction of *The TRIUMF Five-Year Plan.*

Figure 1.1: TRIUMF beamlines and experimental facilities



from the other departments of UBC, as well as from Simon Frasier University and the University of Victoria, were also involved in defining the project. It received final approval in 1968 on the basis that the federal government, through the Atomic Energy Control Board (AECB), would fund the construction of the equipment and operation of the facility, with the Province of B.C. funding the construction of the buildings, and UBC contributing the site. Immediately following this final approval, the University of Alberta joined the three B.C. universities in the consortium to manage the construction and operation of the facility. The Province of Alberta also contributed some building construction funding.

The first maximum-energy beam was extracted from the main cyclotron in December 1974. The beam intensity specification of 100 μA was not routinely achieved until 1979. Since then, however, the facility has run reliably at beam power levels approximately 50% above the original design specification. In 1976 NRC took over the role of funding TRIUMF from the AECB. They put in place a reliable and predictable funding mechanism that allowed TRIUMF to make the necessary upgrades and to develop experimental facilities that kept the laboratory competitive with the comparable international facilities cited above.

Recently, TRIUMF funding has been renewed until the year 2000. Its program will focus on three pillars, i) the ongoing proton, pion, and muon program; ii) the building of ISAC-1, and iii) contributing to the LHC.

1.2 The Facility

The TRIUMF laboratory is located on a 6.1 hectare site on the south campus of the University of British Columbia. The facility is centred on a large 6-sector isochronous cyclotron capable of accelerating negative hydrogen ions (H^-) — a proton surrounded by two electrons—to energies up to 520 MeV. The extraction of a beam from the cyclotron involves intercepting the H^- beam with a thin carbon foil which strips off the two electrons while the much heavier proton passes through, and, having the opposite electric charge, is bent out of the cyclotron and transported to the experimental areas. The TRIUMF cyclotron is one of the four accelerators in the world capable of providing high-intensity proton beams in the energy range which is needed for producing intense secondary beams of mesons and leptons (pions and muons). TRIUMF is unique amongst the four in accelerating H^- ions, which allows simultaneous extraction of several proton beams of differing energies and intensities.

Figure 1.1 shows the layout of the cyclotron and experimental areas. At the present time three proton beams are extracted from the cyclotron — a high-current beam for meson production into six secondary channels, a lower-intensity beam for nuclear and particle physics research, and a low-energy beam for isotope production and proton therapy. The proposed ISAC-1 project will use beam line

4A (BL4A) and will occupy the area where the present developmental facility TISOL is located. ISAC-1 will be able to run at 10 μA or higher at the same time that BL1A is operating at 150 μA or higher. BL4B provides a high-quality polarized or unpolarized beam to the dual spectrometer system made up of the Medium Resolution Spectrometer (MRS) and the more recently commissioned Second Arm Spectrometer (SASP). On BL2C, protons with energies from 65 to 120 MeV can be extracted to target areas within the cyclotron vault for isotope production and studies, or can be transported into a treatment area being set up to use protons for cancer therapy.

BL1A directs protons through two meson production targets and finally to an isotope production target area and beam dump. From the first, thin production target three secondary channels emerge: M15, a high-quality surface muon beam for research in chemistry and solid state physics; M13, a general-purpose low-energy pion or muon beam line; and M11, a high-energy, high-resolution pion beam where the large-acceptance CHAOS spectrometer is located. The second, thicker production target also feeds three secondary channels: M9, a high-flux muon beam with an rf separator for particle physics research; M20, a high-flux muon line for μSR research; and M8, the biomedical beam line which provides negative pions for cancer therapy. M9 has a second leg which makes use of a large superconducting solenoid (a gift from the University of Tokyo) to provide a high-intensity beam of polarized negative muons.

The TRIUMF cyclotron has an excellent history of reliable operation, typically delivering the scheduled 4,500–5,500 hours of beam per year with 90% availability. Although the cyclotron was commissioned in 1974, it continues to operate reliably at high intensity due to a number of upgrades and developments made over the years. At the present time two systems are being refurbished, the central control system and the radio-frequency amplifiers.

TRIUMF management has placed a high priority on making the laboratory a "user-friendly" facility. This means providing space and equipment for experimenters to develop or test their detectors prior to running experiments, general-purpose data acquisition systems, an electronics pool, a detector facility to design, develop or fabricate components for detectors, an electronics group for assisting experimenters with instrumentation, and an engineering group and on-site manufacturing capability for producing complex pieces of experimental equipment. There are also close ties with local and Canadian industrial companies to assist in the manufacturing process. This infrastructure support has proven to be important for TRIUMF and Canadian scientists to meet their commitments to off-site experiments.

These factors have made TRIUMF an attractive facility for conducting research by an international user community, not only in subatomic physics but also in chemistry, materials science and the life sciences. TRIUMF's location on the campus of the University of British Columbia in Vancouver has been an important reason for the success of the applications research programs. The presence of the University Departments of Medicine, Chemistry, Plant Sciences, Engineering, and Physics provides research groups interested in making use of the beams.

1.3 The Basic Science Program

The current basic research program at TRIUMF spans nuclear and particle physics, materials science and life sciences; all of which make use of particle beams and nuclear techniques. This section briefly describes the current experimental program approved by TRIUMF's scientific evaluation committees, except for the science of ISAC (isotopic beams). TRIUMF provides beams to about 70 experiments annually and caters to a large, international user community (with 739 users registered in the TRIUMF Users' Group). The experimental program is complemented by a small, but very effective, theory group which provides guidance for the experimenters and does forefront research in topics of interest to the community.

1.3.1 Subatomic Physics

Subatomic physics is the branch of science that tries to understand the fundamental constituents of matter and their interactions. A unified picture known as the Standard Model, which has emerged in the last two decades, identifies two families of elementary constituent particles (leptons and quarks) interacting via three types of forces (strong, weak and electromagnetic). Gravity has yet to be included in this unified description. While quarks are subject to all three types of forces, leptons interact only via the weak and electromagnetic forces. Leptons can be produced and studied by themselves while quarks do not exist in their free states and can be produced only in aggregates of two (mesons such as pions, kaons, c- and b-mesons) or three (hadrons such as protons and neutrons) with very specific properties. Both strong and weak interactions can be studied at TRIUMF.

At TRIUMF the strong-interaction experiments have two principal themes.

- The quark model description of the structure of pions, protons and neutrons, and of their interactions via the weak and strong forces. Results are treated within the framework of the recently developed Chiral Perturbation Theory.
- Understanding properties of nuclei and modifications to the strong force in a nucleus. The emphasis is on questions like: "How does an excited-state nucleon propagate through nuclear matter?", "What are the collective modes of nuclear motion?" and "How is the weak interaction modified in a nucleus?"

Within the past year, two large new magnetic spectrometers, CHAOS and SASP, have been commissioned to address some of the above issues.

Weak interaction studies can be conducted with leptons and/or quarks at the fundamental level. Pion decay, parity violation and rare-decay experiments are examples of such studies which can be performed at TRIUMF. For example, the parity experiment is being assembled to measure a parity-violating asymmetry in proton-proton scattering, to a precision of 2 parts in 100 million. It seeks to measure the weak force between strongly interacting particles.

1.3.2 Material Science Program

Material science studies are carried out with muons from the secondary beam lines. They are used to probe the electromagnetic properties of a wide range of materials, from gases and liquids to semiconductors and superconductors. Muons are produced from pion decay with their spins perfectly aligned; the μ^+ (or μ^-) spins precess (rotate) in a magnetic field until the muons decay into positrons (or electrons) and neutrinos, a process which reveals the muon spin orientation at the instant of decay. Thus muon spin rotation (μSR) measurements can reveal, with unparalleled sensitivity, the local magnetic fields at the sites in crystals where implanted muons stop.

Another tool used by both condensed matter physicists and chemists is the analogue of the hydrogen atom called muonium: an atom made of a positive muon and an electron. Muonium (Mu) presents all the characteristics of a hydrogen (H) atom except for its mass, and can be traced in crystals or chemical compounds through the positron which is emitted when the muon decays. This permits studies of the mass dependent behaviour of the simplest of all atoms, which in turn have led to precise measurements of hydrogen atom chemical reactions in situations where those of hydrogen itself cannot even be observed. In solids, μSR has contributed significantly to what is known about the electronic structure and impurity-passivating properties of the hydrogen atom in commercially-important semiconductors such as Si and GaAs.

Advantages of μSR:

- μSR does not require high magnetic fields, low temperature or rf fields like NMR (μSR can work at zero field at any temperature, without any rf or during an rf irradiation);
- equivalent hydrogen–NMR experiments require $>10^{17}$ protons for a detectable signal, imposing solubility requirements and making probe–probe interactions an important complication; a μSR experiment needs only $\sim10^6$ muons implanted one at a time into any sample;
- the time scale over which μSR is sensitive is shorter than that of NMR and longer than that of neutron scattering;
- μSR does not require large samples like neutron scattering.

Applications of μSR include the study of:

- magnetic properties of superconductors (especially high-T_c);
- structure and dynamics of magnetic materials;
- hydrogen-like impurities in semiconductors;
- chemical reaction rates of hydrogen atoms and radicals;
- radiolysis and charged-particle thermalization.

A good example is provided by recent μSR studies of fullerenes (C_{60} "buckyballs") in which the Mu atom sometimes reacts chemically (attaching at a C=C double bond) to form the $C_{60}Mu\cdot$ radical and sometimes penetrates the buckyball and remains inside its "cage" where it provides an incomparably sensitive probe of the electromagnetic properties of solids composed of fullerenes, such as the high-temperature superconductor Rb_3C_{60}.

TRIUMF has developed a comprehensive suite of μSR facilities which are used on the secondary beam lines that produce intense muon beams. Nearly 50 μSR experiments are currently active, representing the research activities of some 130 users. There are plans to improve the efficiency for mounting experiments by providing semi-permanent setups. The coordination of μSR operations is the responsibility of a TRIUMF μSR Facility Manager, with technical support provided by an NSERC Infrastructure grant.

2 The μSR Technique

This section is intended as a practical introduction to μSR for newcomers; however, "experts" are invited to peruse it for errors or just to enjoy the familiar scenery.

2.1 Introduction to μSR

The acronym "μSR" was coined in 1974 for the inaugural issue of the *μSR Newsletter*, an informal medium used for exchange of preliminary data and ideas among the then-small community of users of the techniques described by the acronym. The definition and explanation offered on that occasion are still apt:

> *μSR stands for Muon Spin Relaxation, Rotation, Resonance, Research or what have you. The intention of the mnemonic acronym is to draw attention to the analogy with NMR and ESR, the range of whose applications is well known. Any study of the interactions of the muon spin by virtue of the asymmetric decay is considered μSR, but this definition is not intended to exclude any peripherally related phenomena, especially if relevant to the use of the muon's magnetic moment as a delicate probe of matter.*

By the way, μSR is pronounced 'Myoo-Ess-Arr'.

The sensitivity of the muon's magnetic moment to local magnetic fields makes μSR a powerful method for probing the microscopic magnetic properties

Table 2.1: Some properties of the Electron, Muon and Proton.

Physical Properties	e$^-$	μ^+	p$^+$
Mass (MeV)	0.51100	105.66	938.28
Spin	1/2	1/2	1/2
Gyromagnetic ratio γ (s^{-1} T^{-1})	1.75882×10^{11}	8.516154×10^{8}	2.675221×10^{8}
$\tilde{\gamma} = \gamma/2\pi$ (MHz T^{-1})	27992.48	135.54	42.58
Lifetime τ (μs)	Stable	2.19703	Stable

of materials, the electronic structure of hydrogen isotopes in matter and the quantum diffusion of light interstitials. For example, the utility of μSR for characterization of high-T_c superconductors and their parent compounds has become widely recognized since 1987.

In addition, because the muonium (μ^+e^-) atom is a light isotope of hydrogen whose chemical reactions can be investigated with ease, μSR has found important applications in the study of chemical reaction kinetics. (Avoided) level-crossing resonance μSR spectroscopy techniques have also begun to play an important role in the study of free radicals. Table 2.1 compares some properties of the muon, electron, and proton. Although the muon is a lepton, it is much closer to the proton in all the properties listed, which are the properties relevant to μSR.

2.2 Muon Decay

Parity non-conservation in $\pi \to \mu \to e$ decay provides beams of 100% polarized muons and cause the muon decay positron [electron] to be emitted along [opposite to] the spin of the μ^+ [μ^-]. The latter effect allows us to "read out" the information encoded in the evolution of an initially polarized muon spin ensemble. The information is delivered to the experimenter in the form of rather high energy (up to 52 MeV) positrons or electrons, which readily penetrate sample holders, cryostats or ovens and the detectors used to establish the time and direction of the muon decay.

The decay probability of the muon depends upon its own spin direction, the direction of $e^\pm$ emission, and the $e^\pm$ energy $x \equiv \varepsilon_e/\varepsilon_{\max}$ (where $\varepsilon_{\max} = 52.83$ MeV is the maximum possible energy of the $e^\pm$) according to

$$dP(x,\theta) \;=\; E(x)\,[1 + a(x)\cos\theta]\,dx\,d(\cos\theta) \qquad (2.1)$$

where θ is the angle between the muon spin direction and the direction of $e^\pm$ emission. The "asymmetry" factor a depends upon the $e^\pm$ energy, with the higher energy emission being most asymmetric, but the energy average is $\langle a\rangle = 1/3$. In practice, higher energy positrons are detected more easily while low energy ones may not even get out of the target, the beam is somewhat less than 100%

polarized, and the polarization may decrease with time (relaxation) so a is always treated as an empirical factor multiplied by a relaxation function $G(t)$ which describes the loss of polarization over time. Moreover, θ may also be time-dependent (precession).

2.3 A Specific Minimal μSR Experiment

It is useful to begin with a qualitative phenomenological description of a specific type of experiment — time-differential transverse-field (TF-TD-μSR) just to establish some terminology. Afterwards we will define some more terms, and then describe the various types of experiment in more detail.

A crude apparatus for TF-μ^+SR (μSR using positive muons precessing in a transverse magnetic field) is pictured schematically in Fig. 2.1. The μ^+ arising from π^+ decay at rest is perfectly spin-polarized as it enters the sample; later, it decays asymmetrically with the decay positron emitted preferentially along the muon spin direction. After stopping $\sim 10^6$ muons in the target sample one obtains a time histogram like that shown in Fig. 2.2 (top), which ideally has the following form:

$$N(t) \; = \; B \; + \; N_0 \, e^{-t/\tau_\mu} \, [1 + A(t)] \tag{2.2}$$

where N_0 is an overall normalization, B is a time-independent background, $\tau_\mu = 2.197$ μs is the muon lifetime, and $A(t)$ is the corresponding "asymmetry spectrum" shown in Fig. 2.2 (bottom), which can be extracted numerically from $N(t)$ as

$$A(t) \; = \; \left[\frac{N(t) \, - \, B}{N_0} \right] e^{+t/\tau_\mu} \; - \; 1 \tag{2.3}$$

Except for an empirical multiplicative constant, $A(t)$ represents the time evolution of the muon polarization, much like a free induction decay (FID) signal in NMR.

2.4 Notational Conventions

Ideally (and often in reality) the μSR experimenter has control over the orientation of the detectors, the applied magnetic field and (within some range) the muons' spin polarization. In order to consistently designate different orientation choices, we have adopted the labelling conventions defined in Fig. 2.3 specifically for μSR experiments using surface muons, which are originally polarized opposite to their momentum but whose spins can be rotated 90° by a Wein filter in the beamline.[1] The 'standard' detector array consists of six counters aligned with the positive and negative coordinate axes and labelled F (forward), B (backward), U

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[1] Such flexibility is not generally available for backward $\mu^\pm$ beams, which will be neglected in this section partly for that reason.

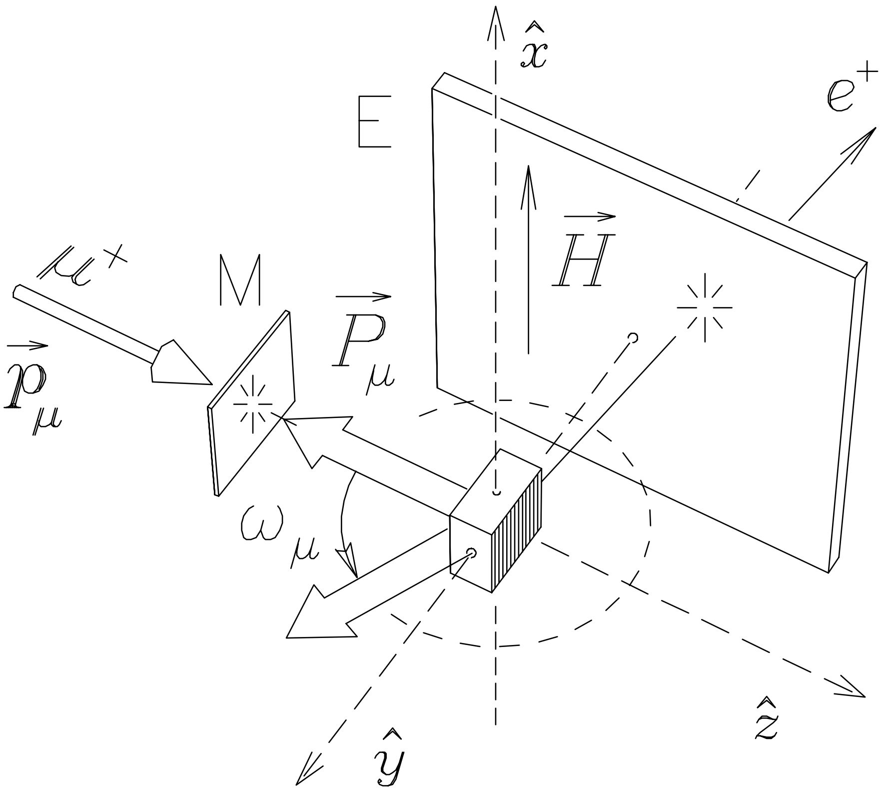


Figure 2.1: A simple time-differential transverse-field (TF)-μ^+SR experiment: the μ^+ beam enters from the left with its polarization ($\vec{P}_\mu$) antiparallel to its momentum. A magnetic field H is applied vertically, causing the μ^+ spins to precess at the Larmor frequency $\omega_\mu = \gamma_\mu H$, where $\gamma_\mu/2\pi = 0.01355342$ MHz/G. An incoming μ^+ triggers the M counter, generating a "start" pulse for a fast time digitizer ("clock"), and an outgoing decay positron later stops the clock with a pulse from the E counter; for each such event the time interval is digitized and the corresponding bin in a time histogram is incremented.

(up), D (down), L (left) and R (right) according to a "beam's-eye view" naming convention. Note that the unrotated muon polarization points toward the B counter and in the spin-rotated mode toward the U counter; the latter depends, of course, on the orientation of the fields in the Wein filter; at TRIUMF, all rotated spins point up. Detector arrays might instead be situated in 'nonstandard' directions such as BL (Bottom-Left), TR (Top-Right) *etc.*)

2.5 Time-Differential μSR (TD-μSR)

There are two main classes of μSR experiment: Time-Differential and Time-Integral. In time-differential μSR each muon, or each 'bunch' of muons for a pulsed beam, starts a clock, and both the time and direction of each decay $e^\pm$

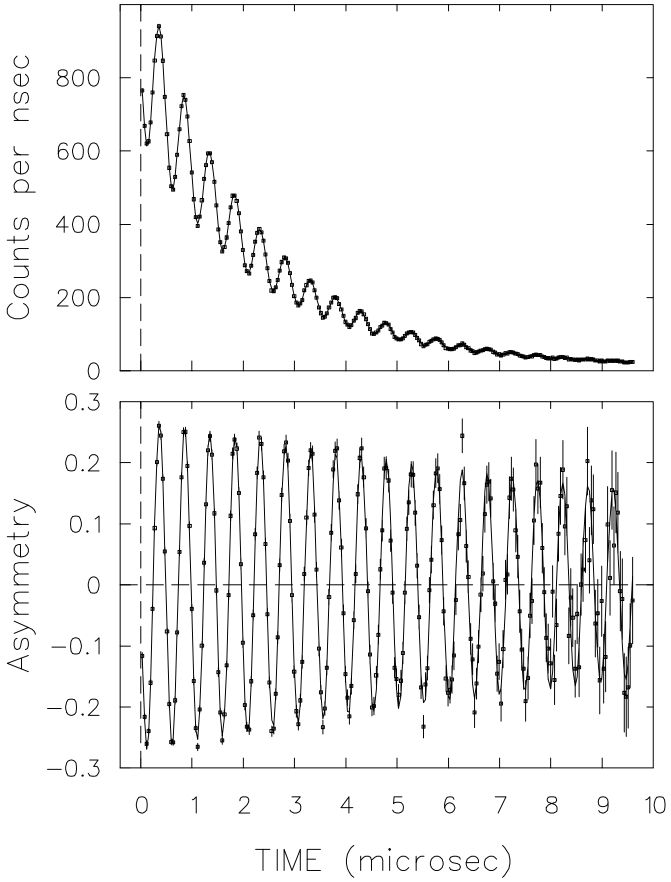


Figure 2.2:
TOP: “Raw” time histogram from a simple TF-μ^+SR experiment: the overall exponential decay reflects the muon lifetime and the precession of the μ^+ spins is manifest in the superimposed oscillations as the muon polarization sweeps past the positron detector.
BOTTOM: TF-μ^+SR “asymmetry spectrum” obtained from the raw time histogram by subtracting any time-independent background and dividing out the exponential distribution of muon decay times.

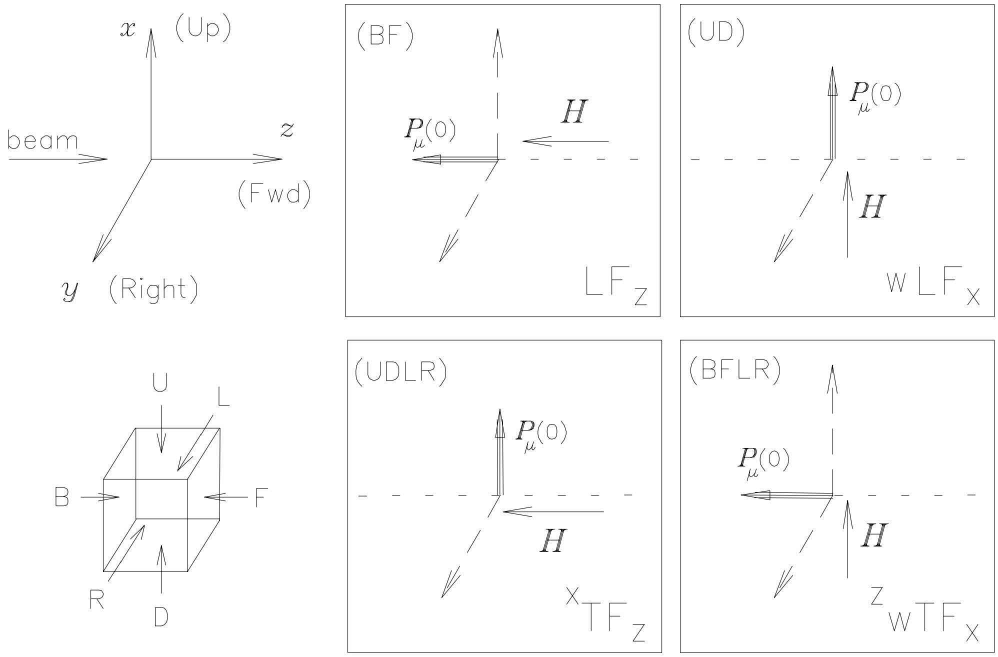


Figure 2.3: Coordinate system and labelling conventions for surface muon μSR experiments. Note that the superscript on the left indicates the direction of the incoming muon polarization while the subscript on the right indicates the direction of the applied field (if any); for longitudinal field (LF) and by continuation for zero field (ZF) both will always be the same, but for TF there are in principle two possible arrangements for each choice of super(sub)script. (For instance, $^z w\mathrm{TF}_y$ *vs.* $^x w\mathrm{TF}_y$.) "Weak" transverse field (wTF) means "not strong enough to deflect the muon beam appreciably."

is recorded (by incrementing a bin in a particular histogram of decay-times). All the $e^\pm$ must be unambiguously correlated with a particular muon or muon pulse. For a pulsed beam, with milliseconds or seconds between pulses, this comes naturally—all the muons have decayed before the next pulse comes. For a continuous beam facility like TRIUMF, the muons must be taken one-at-a-time, and individual decays correlated with individual muons. This necessarily limits the useful data rate because 'events' involving more than one muon or more than one decay must be entirely rejected by the electronic logic modules for the experiment (see section 3.2 on page 32).

Time-integral μSR makes no correlation between muon arrival and decay, but simply tallies decays in opposing directions, which allows it to use as many muons as can be delivered. Nevertheless, TD-μSR is suited to a wider range of experiments, and if you hear an unqualified "μSR", it usually means TD-μSR.

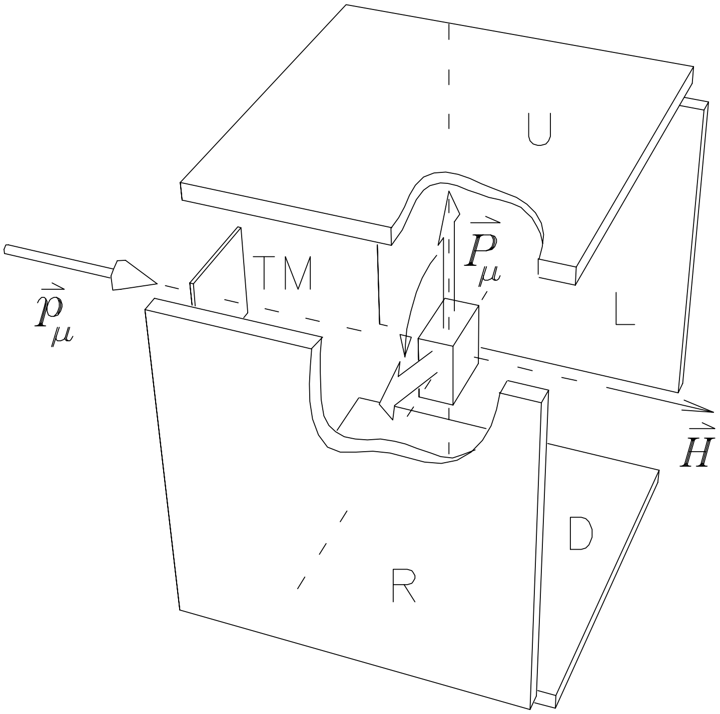


Figure 2.4: ^{x}TF$_z$-μSR, in which the muon beam has been passed through a Wein filter to rotate the muon spins until they are perpendicular to their momenta. The momentum $\vec{p}_\mu$ is undeflected in the magnetic field $\vec{H} = H\hat{z} \parallel \vec{p}_\mu$ but the polarization $\vec{P}_\mu$ precesses in the x-y plane.

2.5.1 TD-μSR in Transverse Field

The simplest and most familiar time-differential (TD)-μSR technique is the transverse field (TF) muon spin *rotation* experiment, in which an external magnetic field $\vec{H}$ is applied perpendicular (transverse) to the muon polarization, causing the muon spins to *precess* (rotate) about the field. This arrangement varies from the primitive version depicted in Fig. 2.1 to the 4-counter, spin-rotated ^{x}TF$_z$-μSR arrangements shown in Figs. 2.4 and 2.5 but the individual time spectra from individual counters all have the qualitative appearance shown in Fig. 2.2, and they share various features of scientific interest:

Frequency: The most obvious observable in a TF-μSR spectrum is the *muon precession frequency* $\omega_\mu = \gamma_\mu B$, which (thanks to our precise knowledge of γ_μ) is equivalent to the local magnetic field B at the muon. Since B may be affected by diamagnetism, paramagnetism and contact hyperfine interactions with polarized electrons (Knight shifts) in the medium, B is generally different from the applied field H; this difference is often the main focus of the TF-μSR experiment.

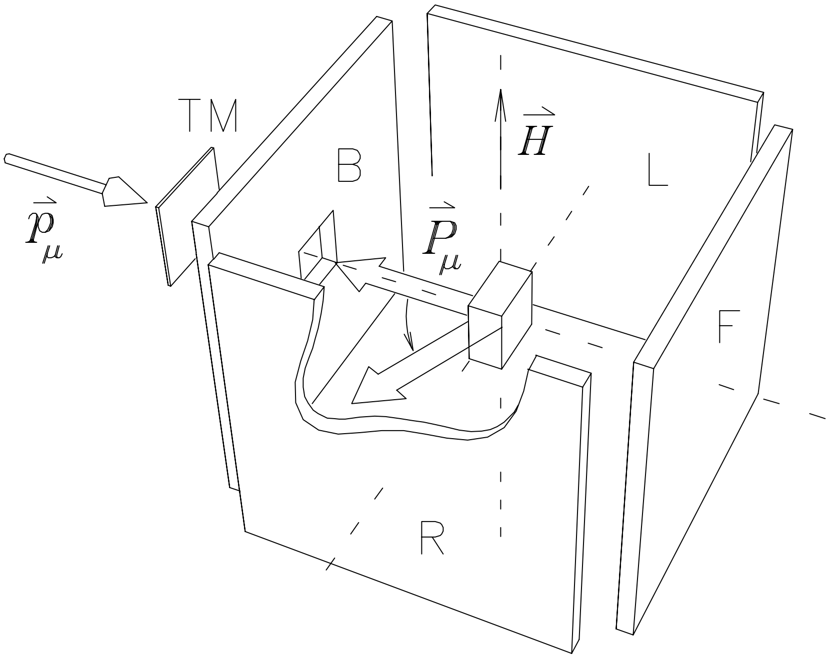


Figure 2.5: ${}^{z}w\mathrm{TF}_x$-μ^+SR, in which the μ^+ beam still has its polarization antiparallel to its momentum. The field must therefore be perpendicular to both $\vec{p}_\mu$ and $\vec{P}_\mu$ which restricts use with surface muon beams to weak fields $H \lesssim 100$ G.

Asymmetry: The second obvious parameter characterizing muon precession in a transverse field is the amplitude or *asymmetry* of the precession signal. As mentioned earlier, the absolute calibration of this amplitude is tricky but one can usually convert the initial amplitude into a polarization with an accuracy of a few percent. In metallic samples the initial polarization is generally consistent with 100%, but in insulators or semiconductors, liquids or gases, some fraction of the muons (ranging from 0 to 100%) either form muonium (Mu) or experience some other form of depolarization in the early ($\lesssim 1$ ns) stages of thermalization in the sample.

The effect of Mu formation in wTF is to cause the muon polarization to precess in the opposite sense to that of muons in diamagnetic environments, roughly 103 times faster; this results in dramatic "dephasing" if the Mu atoms subsequently "react" at exponentially distributed times to enter diamagnetic states. If all this takes place within a few ns, all one can observe is the net effect on the subsequent "diamagnetic" μ^+ precession signal, namely a reduction of asymmetry and a simultaneous shift of the apparent initial phase of precession. If the magnetic field is in the $\hat{z}$ direction and the initial μ^+ polarization is in the $\hat{x}$ direction, we may define the *complex* muon polarization $\tilde{P}(t) \equiv P_x(t) + iP_y(t)$, in terms of which the overall polarization of an ensemble of muons starting as Mu atoms and reacting at a rate Λ to form some diamagnetic species is given in the low-field limit (ignoring high-frequency "hyperfine oscillations" which are usually unobservable) by

$$\tilde{P}(t) = \frac{1}{2} \, \frac{\omega_{\rm Mu} + \omega_\mu}{\omega_{\rm Mu} + \omega_\mu - i\Lambda} \, e^{-(i\omega_{\rm Mu}+\Lambda)t} + \frac{1}{2} \, \frac{i\Lambda}{i\Lambda - (\omega_{\rm Mu} + \omega_\mu)} \, e^{i\omega_\mu t} \qquad (2.4)$$

where the diamagnetic precession frequency is ω_μ and the muonium precession frequency is $\omega_{\rm Mu} \approx 103\omega_\mu$ in the opposite sense. This simple *residual polarization* picture also describes many *delayed formation* scenarios, not just muonium chemistry.

Initial Phase of precession: A more subtle aspect of the residual polarization picture is the shift of the apparent initial phase of the μ^+ precession due to (*e.g.*) the formation of short-lived Mu atoms precessing in the opposite sense. Measurement of such *phase shifts* has often proved valuable in sorting out "fast chemistry" effects and measuring thermalization times of muons in gases.

'Relaxation': Following thermalization of translational degrees of freedom, which may take as little as 100 ps in solids, the muon precession signal may still decrease in amplitude due to dephasing (T_2 effects) or true irreversible relaxation processes (T_1 effects). The latter are more often studied in longitudinal field (LF) where the distinction between T_1 and T_2 is not subject to so much semantic debate. (See later section on "relaxation" in LF-μSR.)

Muonium Precession: All the features just described for muon precession at the "diamagnetic" Larmor frequency $\omega_\mu = \gamma_\mu B$ are also often seen for *muonium precession* in *w*TF-μSR experiments. The main differences are

- that $\omega_{\rm Mu} = \gamma_{\rm Mu} B$ is roughly 103 times larger than ω_μ in the same field B (due to the huge magnetic moment of the electron "locked" to the muon spin by the hyperfine interaction),
- that the sense of *w*TF Mu precession is opposite to that of the "bare" μ^+ (due to the opposite sign of the dominating e^- moment),
- that half the muon polarization appears "lost" in most experiments due to the fast (4463 MHz for Mu in vacuum) "hyperfine oscillations" between the $|\Uparrow\downarrow\rangle$ and $|\Downarrow\uparrow\rangle$ states,
- and that $\omega_{\rm Mu}$ "splits" into two frequencies for $B \gtrsim 20$ G because the hyperfine interaction is finite.

2.5.2 TD-μSR in Longitudinal and Zero Field

Referring again to Fig. 2.3, consider now the time evolution of the muon polarization in a magnetic field parallel to its initial direction (longitudinal field or LF). If the muon polarization initially has no components perpendicular to the local field then none will develop and only the polarization along the initial direction needs to be measured.

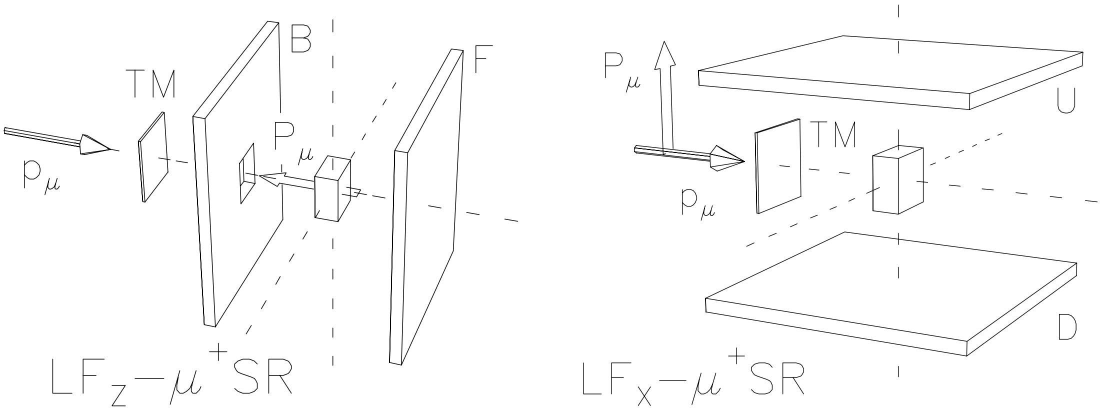


Figure 2.6: Longitudinal-field μSR counter arrangements:
LEFT: LF$_z$-μ^+SR, in which the μ^+ beam is polarized antiparallel to its momentum. As $\vec{H} = H\hat{z} \parallel \vec{p}_\mu \parallel \vec{P}_\mu$ any magnetic field strength may be utilized.
RIGHT: LF$_x$-μSR, in which the muon beam arrives spin-rotated by a Wein filter. Since the field is now perpendicular to $\vec{p}_\mu$, use with surface muon beams is restricted to weak fields $H \lesssim 100$ G.

2.5.2a Two-Counter Asymmetry

Converting single LF-μSR histograms to asymmetry spectra using Eq. (2.3) is not usually practical because neither N_0 nor B can be extracted numerically from the data without some model of the time dependence of the longitudinal polarization. What is done instead is to combine the time spectra from two detectors on opposite sides of the sample, such as "F" and "B" or "U" and "D" in Fig. 2.6 in the way outlined in section 3.6

2.5.2b Zero Field

By extension, the magnetic field may be zero (ZF-μSR) in which case all the same arguments hold as for LF-μSR and one measures the time evolution of the muon polarization along its original direction. In μSR this is just a routine extension of LF, but it bears emphasis since ZF is not so simple (though not impossible) in other magnetic resonance techniques.

2.5.2c "Relaxation"

One consequence of the ease with which one can reduce the field to zero in a LF-μSR experiment is that conventional notions of "longitudinal" (T_1) *vs.* "transverse" (T_2) relaxation processes often become confused and subject to bitter semantic arguments. In NMR, longitudinal relaxation generally occurs in a strong LF so that a change of polarization requires unambiguous transitions between Zeeman energy eigenstates of the probe spin. It is then easy to define the "longitudinal relaxation rate" T_1^{-1} in terms of such "spin-lattice relaxation" processes. Moreover, in strong transverse fields where the Zeeman energies are much greater than any local couplings (such as dipole-dipole interactions between the probe spin and nearby magnetic moments) it is easy to define a "transverse relaxation rate" T_2^{-1} in terms of the *dephasing* of probe spins precessing at slightly different frequencies due to small differences in the local field strength at different sites.

As noted by Kubo and Toyabe, these distinctions are blurred and the terminology becomes less useful as the applied field becomes comparable to the local fields and eventually goes to zero. Basically, if the components of local fields transverse to the applied field are non-negligible in the vector sum forming the total field at the probe, then even in this classical picture the relaxation phenomena become quite complicated and are still being worked out today.

2.5.2d True Relaxation

In a strong longitudinal field the muon's "spin up" and "spin down" states are good eigenstates of the Zeeman hamiltonian and so the muon polarization will remain static ("locked" by the applied field H) unless some magnetic perturbation drives them in resonance at their Larmor frequency $\omega_\mu = \gamma_\mu H$. Such perturbations with finite spectral density at the muon's Larmor frequency can cause its spin to "flip" as in magnetic resonance and lead to "true relaxation" (involving irreversible transitions between energy levels) at a rate T_1^{-1}. For a simple "spin-lattice relaxation" process with a characteristic correlation time τ_c for fluctuations of local fields of strength δ/γ_μ (whether caused by fluctuations of the fields themselves or by "hopping" of the muon between sites with different fields) the longitudinal relaxation rate is given by

$$T_1^{-1} = \frac{2\delta^2\tau_c}{1+\omega_\mu^2\tau_c^2} \tag{2.5}$$

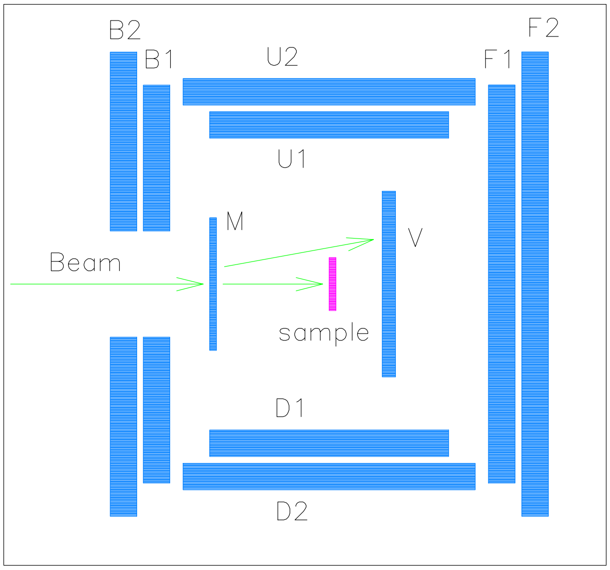
which leads to a "T_1 minimum" $T_1(\mathrm{min}) = \omega_\mu/\delta^2$ at $\omega_\mu\tau_c = 1$.

2.6 Special TD-μSR Applications

2.6.1 Low Background with Small Samples

Although a muon beam can be focussed and/or collimated down to a narrow diameter, it becomes impractical to go below about $\sim$ 1 cm because (a) the muons fill a large phase space, so they can't be focussed indefinitely; (b) the rate is too low if they are collimated ruthlessly; and (c) even for a small collimator, the beam will diverge between the collimator and the sample as there must be some appreciable distance between them (for cryostat vacuum *etc.*) The alternative of having most muons miss the sample is also undesirable because their "background" signal would overwhelm the sample signal. For these reasons, very small or very thin samples require a veto of muons which do not stop in the sample.

Simple Muon Vetos: The most straightforward method of rejecting muons that do not stop in the sample is to place a scintillation counter downstream from the sample and reject all muons that hit this veto counter, as shown schematically in Figure 2.7. Here the definition of a 'good' muon is $\mu(\text{start}) = \text{M} \cap \overline{\text{V}}$.



$$\begin{aligned}
\mu(\text{start}) &= \text{M} \cap \overline{\text{V}} \\
e_{\text{U}}(\text{stop}) &= \text{U}_1 \cap \text{U}_2 \\
e_{\text{D}}(\text{stop}) &= \text{D}_1 \cap \text{D}_2 \\
e_{\text{F}}(\text{stop}) &= \text{F}_1 \cap \text{F}_2 \\
e_{\text{B}}(\text{stop}) &= \text{B}_1 \cap \text{B}_2 \\
\text{Pileup} &= \text{M}
\end{aligned}$$

Figure 2.7: A simple muon veto low background apparatus for moderately small samples.

In a cryostat, the sample must be mounted on a narrow support or on thin mylar at the center, and the wrappings on the M and V counters must also be very thin, so that (surface) muons that scatter from the M counter and miss the sample will not stop before triggering the V counter. The M counter should be as close to the sample as possible to minimize the scattering. (Two cryostat inserts are available with this arrangement, having both the M and V counters inside the cryostat.)

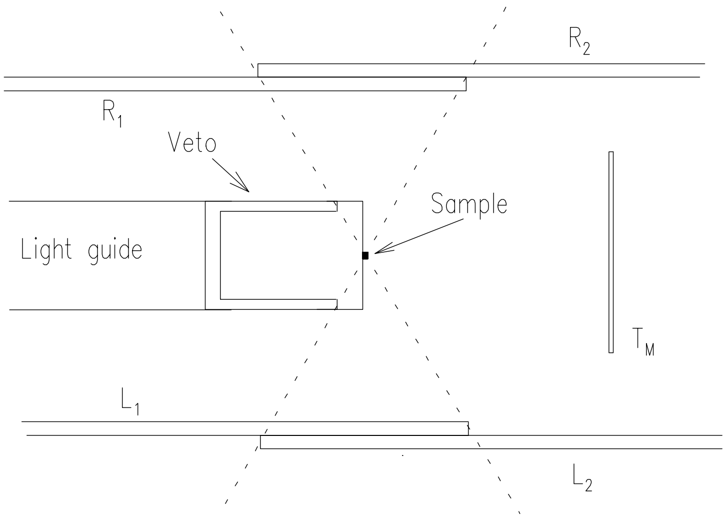
Since normal decay positrons also tend to trigger the V counter, there will be a 'hole' in the Forward histogram at time $t = 0$ due to the V counter accidentally vetoing the corresponding muons. A more refined definition of 'Start' is

$$\text{Start clock} = (\text{M} \cap \overline{\text{V}}) \cup (\text{M} \cap \text{F1} \cap \text{F2})$$

or the equivalent

$$\text{Start clock} = \text{M} \cap \overline{(\text{V} \cap \overline{(\text{F1} \cap \text{F2})})}$$

This is not perfect, though, because then the 'hole' is filled with un-vetoed data. The best approach is to adjust the coincidence times carefully so that the hole at early times is only a few nanoseconds wide.



$$\begin{aligned} \mu(\text{start}) &= \mathrm{T_M} \cap \overline{\mathrm{V}} \\ e_{\mathrm{L}}(\text{stop}) &= \mathrm{L_1} \cap \mathrm{L_2} \cap \overline{\mathrm{V}} \end{aligned}$$

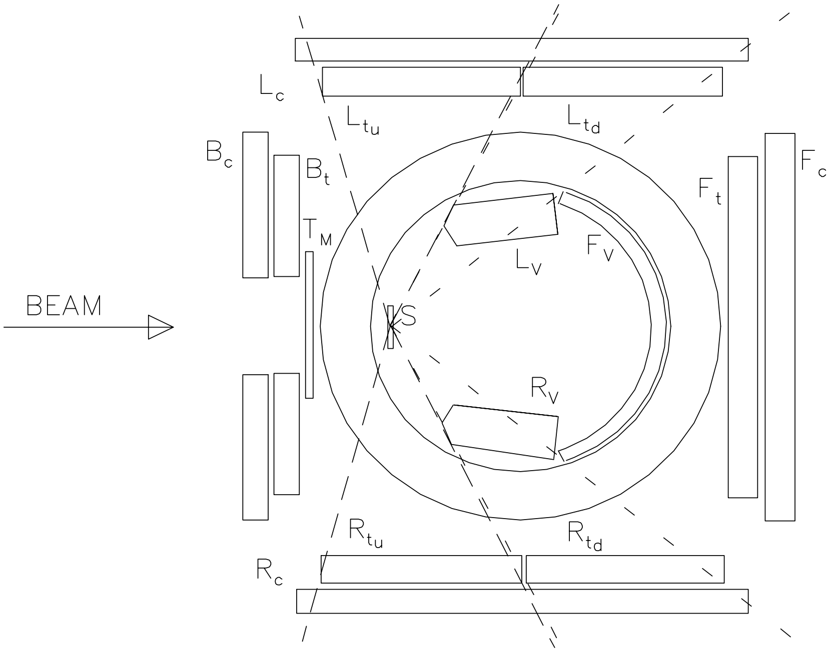
Figure 2.8: The axial (or 'horizontal') low background apparatus. The sample and veto counter fit in a horizontal gas flow cryostat and the external side counters illustrated are those of Helios. The beam enters from the right.

A variation on the vetoing is to combine the functions of the V and F counters. This is usually done with high momentum (backward) muons which are able to penetrate cryostat walls and thick counter wrappings.

Unfortunately, the decay positron from a rejected muon is detected just as well as one from a good muon, but time-differential μSR relies on matching each decay with each muon, so a rejected muon must be allowed to decay before another muon is accepted. This is accomplished by using the M counter without veto to start a pile-up gate.

Vetoing muons that pass through a thin sample is more problematic. It works in principle, and works to some extent in practice, but there is always some fraction of muons that traverse the sample with little energy to spare. When these stop in the veto scintillator, they produce little or no pulse and are not detected; they may even stop in the thinnest counter wrapping. Careful set up and modest expectations are required.

Veto Cups: A simple muon veto works well for moderately small samples, but for very tiny samples the allowable rate of 'good' muons would be unacceptably low because the total incoming muon rate is limited by 'pile up'. The answer to these difficulties is to reject both the *incidence* and the *decay* of the errant muons so they generate neither a 'start' nor a 'stop' signal to the experiment, thus ignoring them totally.



$$\begin{aligned} \mu(\text{start}) &= \mathrm{T_M} \cap \overline{(\mathrm{L_V} \cup \mathrm{R_V} \cup \mathrm{F_V})} \\ e_{\mathrm{L}}(\text{stop}) &= [\,(\mathrm{L_{tu}} \cap \mathrm{L_c}) \cap \overline{(\mathrm{L_V} \cup \mathrm{F_V})}\,] \;\cup\; [\,(\mathrm{L_{td}} \cap \mathrm{L_c}) \cap \mathrm{L_V} \cap \overline{\mathrm{F_V}}\,] \end{aligned}$$

Figure 2.9: The vertical-access low background apparatus. Shown are the sample (S), internal veto counters ($\mathrm{F_V}$, $\mathrm{R_V}$, and $\mathrm{L_V}$), inner and outer cryostat walls, and external counters.

Figures 2.8 and 2.9 illustrate two such “low background” apparatuses at TRIUMF; one for axial access, and one for side access. Both are installed in narrow-tail cryostats. The much simpler axial version will be described first.

The small sample is mounted on a very thin Mylar sheet, which is unlikely to stop any muons. Muons that miss the sample stop in the bottom of the veto cup, and trigger both the $\mathrm{T_M}$ and Veto counters, which is not a valid “start”. Muons that stop in the sample, however, trigger only the $\mathrm{T_M}$ counter and thus start the clock. The Veto counter also serves as a veto to decay events: Muons in the sample have an unobstructed view of the positron counters on either side, and their decays will be duly recorded; but when muons in the cup decay, their positrons must trigger the Veto if they are to trigger the L or R counters—such vetoed events are not accepted. At TRIUMF, this arrangement is used for an insert to the (Cryo Industries) horizontal gas flow cryostat, and on the DR.

The veto system for the vertical low background apparatus (Fig. 2.9) is made more complex by the restricted geometry. There are *three* veto counters and two sections on each side counter. The upstream (u) and downstream (d) segments of each side counter may be used to produce separate histograms or combined for a single histogram. (The common coincidence counter $\mathrm{L_c}$ or $\mathrm{R_c}$ reduces random counts.) Any of the three veto counters, Left ($\mathrm{L_v}$) Right ($\mathrm{R_v}$) or Forward ($\mathrm{F_v}$), will serve to indicate that a muon has missed the sample. They all veto the muon $\mathrm{T_M}$ counter. The upstream segment of the left or right counter is vetoed in much the same way as above: A stop signal requires counts in both external counters, but not in the veto counter(s) $(\mathrm{L_{tu}} \cap \mathrm{L_c}) \cap \overline{(\mathrm{L_V} \cup \mathrm{F_V})}$. The downstream segment is treated quite differently: the side 'veto' counters ($\mathrm{L_V}$, $\mathrm{R_V}$) are used as *coincidence* counters while $\mathrm{F_V}$ provides the sole veto: $(\mathrm{L_{td}} \cap \mathrm{L_c}) \cap \mathrm{L_V} \cap \overline{\mathrm{F_V}}$.

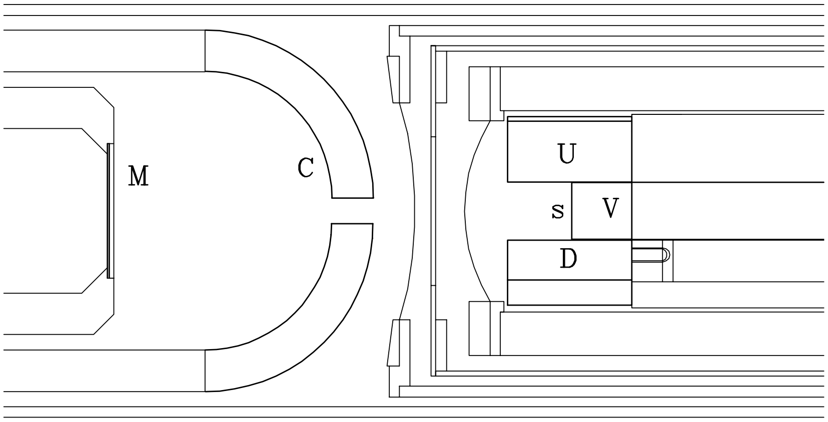
Although forward and backward positron detectors are shown in Figure 2.9, it is not possible to run such forward–backward spectra in low background mode.

Active Collimator: A different type of veto is an 'active collimator' which rejects muons that are *going to* miss the sample after scattering from the thin muon counter. Its effectiveness depends critically on correctly distinguishing between muons that miss and those that hit, so it would work best when placed just before the sample. A good active collimator also rejects the decays of these muons so the data acquisition rate is not limited by pile-up. An example of such an arrangement is the high-timing counter array dedicated to the Belle spectrometer, shown in Figure 2.10. In this specialized high-timing counter arrangement, the sample (S) is mounted at the center of the cryostat indicated by the intersecting lines. Muons must pass through the thin muon counter M and a hole in the thick scintillator of the active collimator C; then they traverse two windows and a heat shield in the cryostat before reaching the sample.

If a muon misses the sample, it would strike the muon-veto counter V or a positron counter (U, D, L, R) and be rejected. (Rejection by the positron counters leaves a hole in the data at $t = 0$.) These rejected muons cannot have their decays vetoed, so they must trigger the pile-up gate just like good muons.

The muons which strike the active collimator stop in its upstream edge, triggering it and vetoing the muon counter. The veto is complete: neither the clock nor the pile-up gate are started, and the experiment is ready for another muon immediately. When those muons decay, the positron may fly harmlessly away from the sample without being detected, or it could go 'downstream' and hit one of the positron counters. For the latter, it must pass through the active collimator counter C which vetos all the stop signals.

In a way, the Belle insert is a bad example of active collimation because its active collimator is effective only at low magnetic field. At high fields, which is the specialty of the instrument, the field focussing makes the active collimator redundant, and even harmful. Extra vetos are also employed between adjacent positron counters to allow for positrons spiraling in the high magnetic field. The implementation of all these vetos is shown in the Belle wiring diagram, in Figure 3.3 on page 36.



$$\begin{aligned}
\mu(\text{start}) &= \text{M} \cap \overline{(\text{C} \cup \text{V} \cup \text{U} \cup \text{D} \cup \text{L} \cup \text{R})} \\
e_{\text{U}}(\text{stop}) &= \text{U} \cap \overline{\text{C}}\ [\cap \overline{\text{L}}] \\
e_{\text{D}}(\text{stop}) &= \text{D} \cap \overline{\text{C}}\ [\cap \overline{\text{R}}] \\
e_{\text{F}}(\text{stop}) &= \text{F} \cap \overline{\text{C}}\ [\cap \overline{\text{U}}] \\
e_{\text{B}}(\text{stop}) &= \text{B} \cap \overline{\text{C}}\ [\cap \overline{\text{D}}] \\
\text{Pileup} &= \text{M}
\end{aligned}$$

Figure 2.10: The counter arrangement in the dedicated Belle apparatus, showing the muon counter (M), the active collimator (C) in the bore of the magnet under vacuum, the simple (forward) muon veto (V), two of the four positron counters (U and D), and the sample (S).

2.6.2 High Frequencies in High Transverse Field

Since the period of muon precession is 7.38 ns in a field of 1 T and is inversely proportional to B, it is not difficult to achieve a magnetic field strong enough to challenge the time resolution of most μSR spectrometers. Moreover, the radius of decay positron orbits shrinks with increasing field until experiments in $B \gtrsim 5$ T require small detectors within 1–2 cm of the sample. Nevertheless, the effort of miniaturization and state-of-the-art time resolution is often justified by the improved resolution for Knight shifts and/or access to intrinsically high-field phenomena.

Another difficulty with high magnetic fields is the effect the fringe field has on the muon before it reaches the sample. The obvious problem with ordinary transverse field, in the absence of spin rotation, is that the muon will never reach the sample, but turn back down the beamline. This has long been solved by using longitudinal fields and rotating the the muon spin to be transverse to the momentum. A second effect of a very strong fringe field, is the dephasing of muons as they precess in flight. If all muons spent the same time in the fringe field (i.e., for a monoenergetic beam) the effect would be seen as a phase offset. But there is a range of momenta in the muon beam, and slow muons will precess further than fast muons, resulting in a loss of phase coherence. This can be solved, or at least alleviated, by starting the μSR clock while the muon is still in the fringe field; by placing the muon counter where the field is about half of its maximum value. For a simplistic example, suppose the field falls off abruptly, and the counter is placed at the step. Faster muons trigger the clock ($t = 0$), and reach the sample at time τ; slow muons reach the sample at time $\tau + \delta$, having precessed by an angle $\omega\,(\tau + \delta)$. Nevertheless, at time $\tau + \delta$, the fast muons have been precessing in the sample for time δ for a total phase angle of $\omega\tau + \omega\delta$, and are still in phase. This method presupposes that ω is the same in the sample as in vacuum, which is a good approximation for diamagnetic samples, but fails for paramagnetic (muonium, anomalous muonium, radicals) or ferromagnetic environments.

At TRIUMF there is an older set of small, tight-fitting counters with large parabolic reflectors as light guides which were used for high-TF studies in the Helios superconducting magnet. This system is now superseded by the Belle spectrometer, dedicated to high transverse field, high timing experiments. The system consists of:

- Oxford Instruments split pair superconducting magnet reaching 7.5 T.
- Oxford Instruments cryostat.
- Beamline snout with collimator, muon counter and active collimator.
- Cryostat insert with four positron counters and a veto counter.

The muon counter is placed as described above (see Figure 2.10) and the light guides are all short to give the best possible timing. Critical for the design are the small sizes of the Belle magnet and cryostat, and the availability of mesh dynode photomultipliers with good timing resolution even in high magnetic fields.

In high fields, a standard TD-μSR time spectrum consists of a large number of small time bins, each of which may have a rather low number of counts and a correspondingly large statistical uncertainty; this circumstance makes the usual "lab frame" asymmetry plot rather uninformative to the eye and expensive to fit by χ^2 minimization, motivating new methods of data analysis such as RRF transforms (see §3.6 and Fig. 4.11).

2.7 Time-Integral μSR

In time-integral μSR, I-μSR, one simply tallies the total $e^{\pm}$ count rate in some direction with no regard for the time of arrival of the muons. Discarding all details of the time dependence of the muon polarization may appear to be a regressive step. Indeed, at a *pulsed* μSR facility, where all the muons arrive at once (within some δt), there is little motive for ignoring the time dependence.

However, most muon channels at Meson Factories are able to produce at least an order of magnitude more muons than can be accommodated in a conventional TD-μSR experiment because of the "pile-up" ambiguity alluded to in section 2.5. Thus I-μSR trades off detailed information for higher sensitivity by accepting the full muon stop rate.

As for TD-μSR there are both TF- and LF- versions of I-μSR.

2.7.1 Transverse Field I-μSRotation

The TF- version is known as *stroboscopic* μSR and was developed at SIN (now PSI) to make a precise measurement of the muon's magnetic moment. This technique has since been adapted to muon Knight shift measurements, where its unlimited rate gives it an advantage over TD-μSR methods. "Strobo-μSR," as it is called, is best suited to situations where the muon precesses at a single well-defined frequency and where any relaxation is either uninteresting or fast enough ($\gtrsim 0.454\ \mu\mathrm{s}^{-1}$) to be easily unfolded from the "natural linewidth." Splittings of less than this linewidth cannot be unambiguously resolved by strobo-μSR.

Since strobo-μSR has not been implemented at TRIUMF, no more will be said about it here.

2.7.2 Longitudinal Field I-μSRelaxation

In ZF and LF the I-μSR technique is much simpler, consisting of simply scaling decay counts in the forward (+) and backward (−) directions separately, and measuring the resultant asymmetry as a function of independent variables like magnetic field or temperature. The relevant terms are defined below.

R:	rate of arrival of muons
$\epsilon_\pm$:	efficiency of e detector along(+) or opposite(−) μ polarization
$B_\pm$:	background rate in said e detector
$A_\pm$:	"intrinsic" asymmetry of said e detector [Count rate $\sim (1 \pm A_\pm)$ when muons are fully polarized along (opposite) detector axis of symmetry.]
$G_{zz}(t)$:	longitudinal relaxation function

The number of counts in time $T \gg \tau_\mu$ is

$$N_\pm \quad = \quad B_\pm T + RT\epsilon_\pm \pm RT\epsilon_\pm A_\pm \mathcal{L}(G_{zz}) \tag{2.6}$$

where

$$\mathcal{L}(G_{zz}) \quad \equiv \quad \int_0^\infty e^{-t/\tau_\mu} G_{zz}(t) \frac{dt}{\tau_\mu} \tag{2.7}$$

is the *Laplace Transform* of $G_{zz}(t)$.

Experimental Asymmetry:

$$\mathcal{A} \equiv \frac{N_+ - N_-}{N_+ + N_-} \tag{2.8}$$

or

$$\mathcal{A} = \frac{b_- + (1-\alpha) + (1+\alpha\beta)A_+\mathcal{L}(G_{zz})}{b_+ + (1+\alpha) + (1-\alpha\beta)A_+\mathcal{L}(G_{zz})} \tag{2.9}$$

where $b_\pm \equiv \dfrac{B_+ \pm B_-}{R\epsilon_+}, \quad \alpha \equiv \dfrac{\epsilon_-}{\epsilon_+}, \quad \beta \equiv \dfrac{A_-}{A_+}.$

Approximations: $B_\pm \approx 0$, $A_\pm \approx A$, $\epsilon_+ \approx \epsilon_-$, giving $\alpha \approx \beta \approx 1$, $b_\pm \approx 0$, and

$$\mathcal{A} \approx \frac{(1-\alpha)}{(1+\alpha)} + \frac{2}{(1+\alpha)} A_+\mathcal{L}(G_{zz})$$

where $(1-\alpha)$ / $(1+\alpha)$ is the "baseline" asymmetry for totally unpolarized muons.

Modulation: Sometimes I-μSR is performed measuring the asymmetry just as described for equation 2.9, but there is often a problem: the baseline asymmetry is quite sensitive to magnetic field due to solenoid focussing, and also to small changes in beam intensity or position. One way to combat this problem is to modulate the sweep parameter (magnetic field) between two discreet values and generate a field-differential time-integral-μSR spectrum. The experimental asymmetry $\mathcal{A}$ defined in Eq. (2.9) is measured for short time intervals (seconds) with a "toggle field" $\pm\delta B$ applied alternately along (+) or opposite (−) the main longitudinal field B_0 and the difference between these two asymmetries

$$\mathcal{A}^+ - \mathcal{A}^- = \frac{N_+^+ - N_-^+}{N_+^+ + N_-^+} - \frac{N_+^- - N_-^-}{N_+^- + N_-^-}$$

is recorded as a function of B_0. This produces a signal analogous to a true differential resonance ($d\mathcal{A}/dB_0$) for a small finite difference ($\pm\delta B$) but if δB is larger than the natural width of the resonance, there will be a "bump" followed by a mirror-image "dip" $2\delta B$ later.

2.7.3 Avoided Level Crossing Resonance

I-μSR is particularly useful when one is looking for *conditions of enhanced relaxation* without measuring the detailed shape of the relaxation. For example, at some magnetic field the muon Zeeman splitting matches a transition between energy levels of the nuclear spins, leading to a resonant "flip-flop" of nuclear and muon spins. Such conditions are referred to as either "level crossing resonance" (LCR) or "avoided level crossing" (ALC) depending mainly upon one's laboratory affiliation; the two acronyms refer to the same phenomenon but one emphasizes the fact that levels never actually cross in quantum mechanics. In ALCR spectroscopy, the nuclear spin energy levels are revealed as the magnetic field is swept.

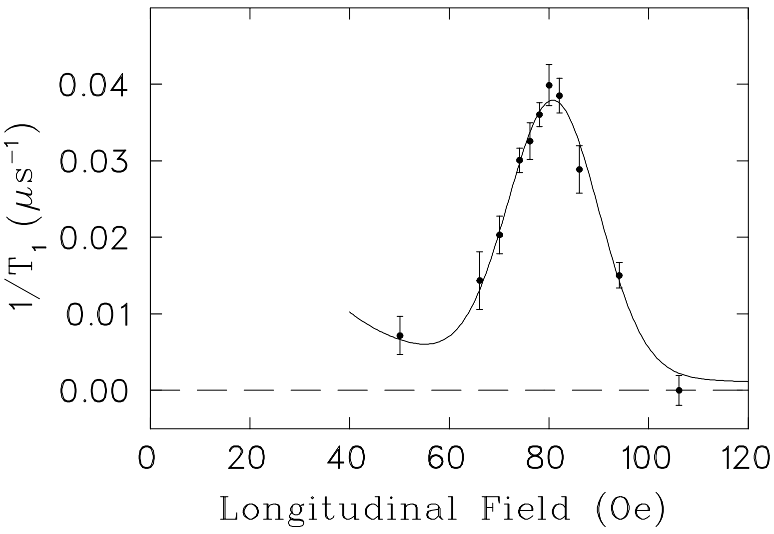


Figure 2.11: Longitudinal relaxation rate of muons in a single crystal of copper with the applied field (and the muon polarization) along the ⟨111⟩ crystalline axis.

Nuclear Quadrupolar μLCR: The first such resonance studied in μSR was actually observed with TD-μSR methods following a suggestion by A. Abragam. In that experiment, the μ^+ Zeeman splitting at 81 G matches the (mostly) electric quadrupolar splitting between $m_I = \pm\frac{3}{2}$ and $m_I = \pm\frac{1}{2}$ levels of the spin-$\frac{3}{2}$ Cu nuclei, causing the resonant relaxation shown in Fig. 2.11. This measurement and its later improvements allowed a precise determination of the electric field gradient produced by the μ^+ at the Cu sites; similar experiments have since revealed nuclear quadrupolar μLCR's in solids containing ^{17}O, ^{14}N and other nuclei. The main application is to determination of the muon site in crystals.

"Muonated" Radicals: Shortly after the discovery of nuclear quadrupolar μLCR it was realized that a much stronger resonance could occur through the hyperfine interactions of unpaired electrons with both the μ^+ and the nuclear spins. The quantum mechanics of this system is considerably more complicated, but the notion of level-matching is still applicable: when the energy difference between two states in which both the muon and the nuclear spins have "flipped" approaches zero, resonant muon depolarization can occur.

The first application of this principle to *paramagnetic* systems was in the case of the $C_6F_6Mu\cdot$ radical, a paramagnetic molecule formed by addition of a Mu atom to the unsaturated hexafluorobenzene ring. Many such radicals have now been studied using this method, resulting in much detailed information about both the structure and the dynamics of these molecules, whose difference from the analogous radicals formed by H atom addition is often insignificant. Several new species never observed in any other way have been discovered using μALCR spectroscopy.

Muonium in Semiconductors: Another paramagnetic system amenable to study by these methods is the muonium-like center in semiconductors, where the unpaired electron may have hyperfine interactions not only with the μ^+ but also with neighboring nuclei of the lattice. The resulting spectroscopy can be very rich and allows positive identification of the muonium site as well as a great deal of information about its electronic wave-function.

2.8 Muon Spin Resonance

Traditional magnetic resonance techniques involve intentional irradiation of the probe spin system with photons of energies equal to transitions between its eigenstates. None of the μSR techniques so far described have involved such irradiation, but true *resonance* techniques are also used in μSR, as outlined below. As in NMR, ESR, ENDOR *etc.*, the variety of irradiation schemes is huge and constantly growing; only a few simple generalizations are possible in limited space.

2.8.1 RFI-μSResonance

The first and most familiar form of muon spin *resonance* uses an RF field in the frequency range of about 5-500 MHz to drive the polarization of muons in diamagnetic states (*i.e.*, "bare" muons) in resonance at fields of 300 G to 4 T. The RF field may be generated in a simple coil at the lower frequencies or a cavity at the higher. In some cases the RF frequency can be swept through resonance, but most often the main field H_0 is swept, as in NMR.

For the higher frequencies, the same apparatus may be used at lower fields to study paramagnetic species such as muonated radicals.

The time scale for muon spin resonance is restricted by the muon lifetime; to be observed, a resonance effect must affect the muon polarization in $\lesssim 10$ μs, implying an RF field $H_1 \gtrsim 2$ G, which is not difficult to achieve but represents fairly high RF power. Because of power supply limitations and Ohmic heating, such irradiations are less efficient at CW facilities than at pulsed-beam facilities, where all the muons can be irradiated simultaneously with timed bursts of RF power; nevertheless, RF-μSR is quite feasible at CW facilities and has enjoyed a rapid growth of applications virtually everywhere.

One advantage of RF-μSR is that it can identify *final states* of muons in situations where stochastic processes have dephased the muon spins for a typical TF-μSR experiment. An example is the *delayed formation* of diamagnetic molecules following initial formation of Mu atoms: in TF-μSR the early Mu precession quickly dephases the muon polarization so that no signal can be seen from the diamagnetic final state unless the reaction times are short compared to the Mu frequency; in strong LF, however, not only is the Mu polarization "held" by the applied field but the population of the final state as a function of time can be determined by delaying the RF pulse (at the diamagnetic resonance frequency) relative to the time of arrival of the muons.

Perhaps the most exciting feature of RF-μSR is its ability to reveal the time evolution of the muon polarization *during* the RF irradiation, a capability denied to conventional magnetic resonance techniques which detect the same sort of electromagnetic signal as they use to drive the probe spins. This is a consequence of the fact that μ^+SR detects high energy positrons whose registration by the counters is unaffected by the RF fields.

2.8.2 Muon Spin Echoes

Many modern NMR techniques involve *pulses* of RF power designed to rotate the probe's polarization through various angles in the rotating reference frame. This is more difficult for muons because of their short lifetime—to be useful in μSR a $\pi/2$ pulse must be no more than $\lesssim 1$ μs long, which means an RF magnetic field of $H_1 \gtrsim 75$ G. This is barely possible with today's RF techniques. It is particularly difficult at CW facilities, where the RF pulse must be *asynchronously triggered* by the arrival of individual muons, in order to occur at the same time (relative to "$t = 0$" when the muon arrives in the sample) for each. Nevertheless, such "spin echo" techniques (nicknamed "μSE") were first successfully demonstrated at TRIUMF, a CW facility.

As mentioned earlier, μSR detection techniques allow observation of the time evolution of the muon polarization *during* the RF irradiation. This can be especially informative in the case of μSE pulse sequences.

3 The Tools of μSR

Because μSR requires muons, which are produced by large, high-intensity accelerators, such facilities must be considered the most important "tool" of μSR. Access to these facilities will probably always be a scarce commodity for which users will compete fiercely; Chapter 6 should prepare you for the fray. A general introduction to the TRIUMF facility is the subject of Chapter 1 and descriptions of the muon beamlines at TRIUMF are given in Chapter 4.

More tangible tools are the magnets, particle detectors, target vessels, cryostats, ovens, power supplies, electronic logic & timing modules. There are computers too, but just as important are the programs they run and even the techniques needed to get the most from them. Detailed descriptions for all of these are, or will be, given in the *Operation Manual for μSR at TRIUMF.*

3.1 Detectors

The workhorse of μSR is the plastic scintillation counter, in which a flash of light (generated as an ionizing particle passes through the scintillating plastic) is transmitted down clear plastic light guides by total internal reflection to a photomultiplier tube that in turn emits an electrical pulse which is transmitted down a coaxial cable to a fast timing discriminator module in the "counting room" outside the experimental area. The result is a logical timing pulse whose arrival time corresponds within $\sim$ 1 ns (and a fixed delay) to the time the particle passed through the detector. The M and E detectors in Fig. 2.1 would normally be plastic scintillation counters for the incoming muon and outgoing positron, respectively, and would normally provide a resolution of 0.5-2 ns on the corresponding time interval. With careful design of the counters, special photomultiplier tubes, cables and fast electronics it is possible to achieve time resolutions $\sim$ 100 ps, but this is not yet common.

While scintillation counters are simple, reliable, versatile and have excellent performance in the time domain, they have a number of frustrating features: First, even if the scintillator itself is small the light guides are bulky and inflexible (flexible fibre optics can be used but so far only at the expense of timing degradation and/or loss of light collection efficiency); this becomes increasingly inconvenient as increasing stopping luminosity reduces the scale of μSR samples and experiments. Second, most photomultiplier tubes are very sensitive to magnetic fields and must be magnetically shielded and/or removed to field-free regions by long light guides which again reduce time resolution. Third, scintillation counters have only crude position sensitivity, which is generally of secondary importance to μSR experiments, but could be useful. For example, by distinguishing one incoming muon from another and matching the outgoing positrons to the muons from which they arise, one may overcome the "pile-up" rate limitation normally imposed by allowing only one muon in the sample at a time; this technique has been demonstrated but never widely applied.

Potentially promising alternatives include modern proportional counters and solid-state barrier detectors, but neither of these have the required time resolution in their standard configurations; more development work is needed.

3.2 Electronics

Raw counter pulses are fed to fast discriminators — usually constant fraction discriminators (CFDs) — which generate uniform timing logic pulses if the raw pulse height is above a set threshold. The logic pulses are processed by a simple "fast electronics" circuit; a TD-μSR set up for the longtime standard Le Croy 4204 TDC is shown schematically in Fig. 3.1.

The incoming muon generates a pulse in the M counter which ultimately sends a "start" pulse to a fast time digitizer ("clock"); later the muon decays, triggering a "stop" pulse in the E counter, which stops the clock; the time interval is digitized and the corresponding bin in a time histogram is incremented. The additional logic modules ensure that events with "second muons" are rejected with uniform efficiency throughout the "gate" T, lest rate-dependent distortions spoil the resultant time spectra (histograms) which are the final output of the experiment.

Similar care must be taken to reject "second E" events in which a (possibly accidental) count in an E counter renders the identity of the "stop" pulse ambiguous. This function is handled internally in the LRS 4204 TDC, which has

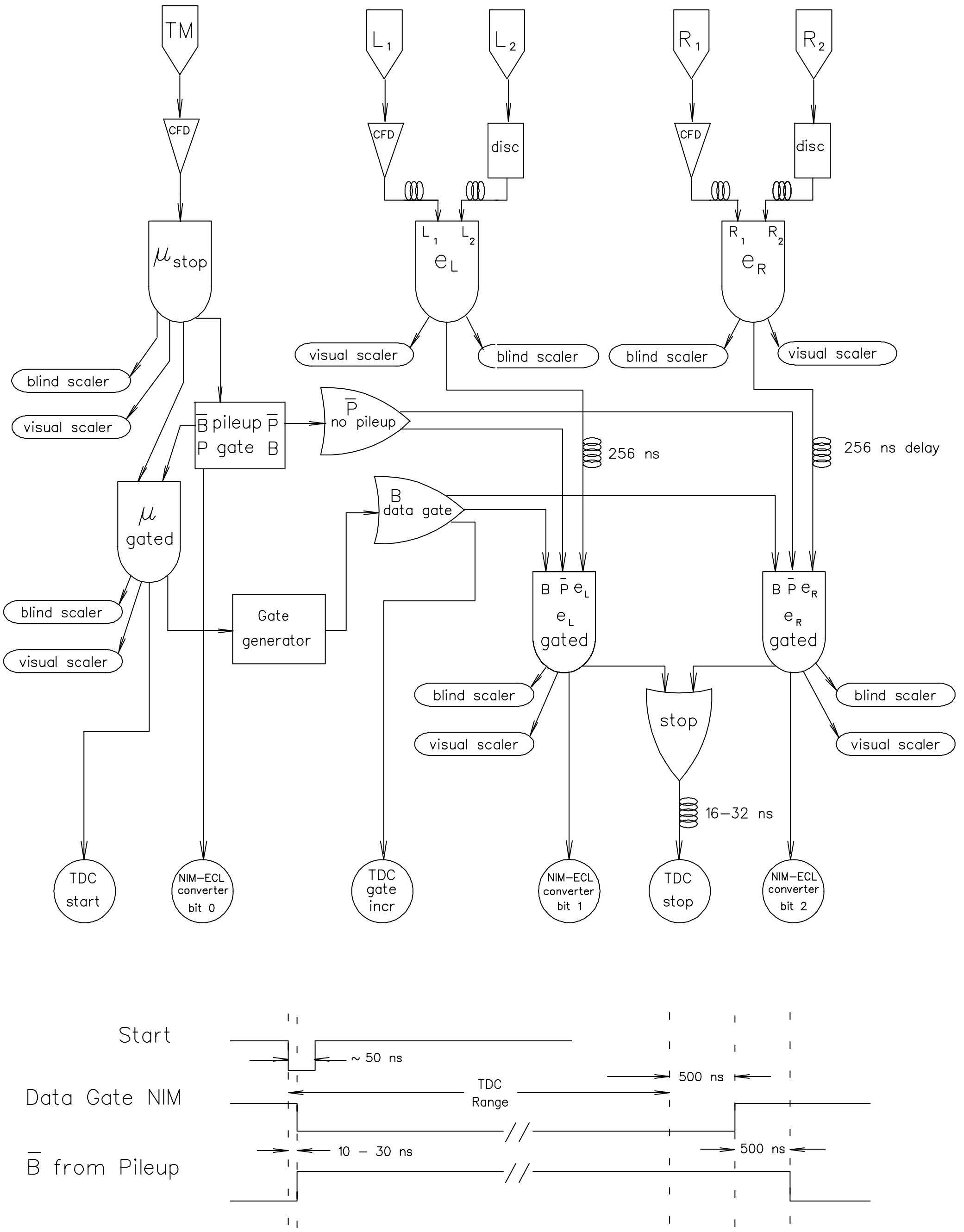


Figure 3.1: Schematic electronics logic diagram for two “channels” of a typical time-differential (TD)-μSR experiment using the Le Croy 4204 TDC (see Fig. 2.1).

long been the standard μSR "clock" primarily because it provides this function, along with good time resolution and the ability to directly increment time bins in a CAMAC histogramming memory, thus relieving the data acquisition computer of all event-processing duties except periodic histogram and scaler readout.

The 4204 TDCs have served well, but are showing their age. Many of them give a spurious signal near 310 MHz, which can be reduced by avoiding the clock's internal 'or' unit for the stops (see Figure 3.1), and they suffer from a host of other sporadic failures. Its replacement is the B980 TDC from BNC. This TDC has been configured for μSR by Highland Technology, the TRIUMF data acquisition group, and the μSR users' facility, with microcode to perform multi-hit rejection in the TDC before events are read and histogrammed by a VME processor. The (tentative) basic wiring for acquisition with the B980 TDC is shown in Figure 3.2.

There are numerous improvements and adaptations of this basic TD-μSR arrangement, of course, as well as several entirely different electronics setups for time-integral I-μSR techniques. The TD-μSR setup for Belle, with its active collimation, muon vetos, and spiral positron vetos, is shown in Figure 3.3. The usual I-μSR wiring is shown in Figure 3.4).

3.3 μSR Spectrometers

The TRIUMF μSR facility supplies a choice of several μSR spectrometers, whose function is to control the magnetic field at the sample and to provide mountings for the various counter arrays, cryostats or other paraphernalia. Often a standard set of counters are an integral part of the spectrometer as well. Table 4.3 on page 58 lists the various μSR spectrometers and their properties, followed by more detailed descriptions on page 46.

3.4 Target Vessels and Cryostats

Since the muon's initial polarization is independent of the state of its environment, μSR samples may be gases, liquids or solids at any temperature, pressure, magnetic or electric field. This versatility is reflected in the variety of sample environments (target vessels) used in μSR experiments, ranging from large "gas cans" (for studying hydrogen gas at low pressure and high temperature) to miniaturized cryostats (for studying small crystals at low temperature and high magnetic field). The most common use of μSR is currently in low-temperature condensed matter physics, so that most μSR spectrometers have general-purpose cryostats built in (but removable).

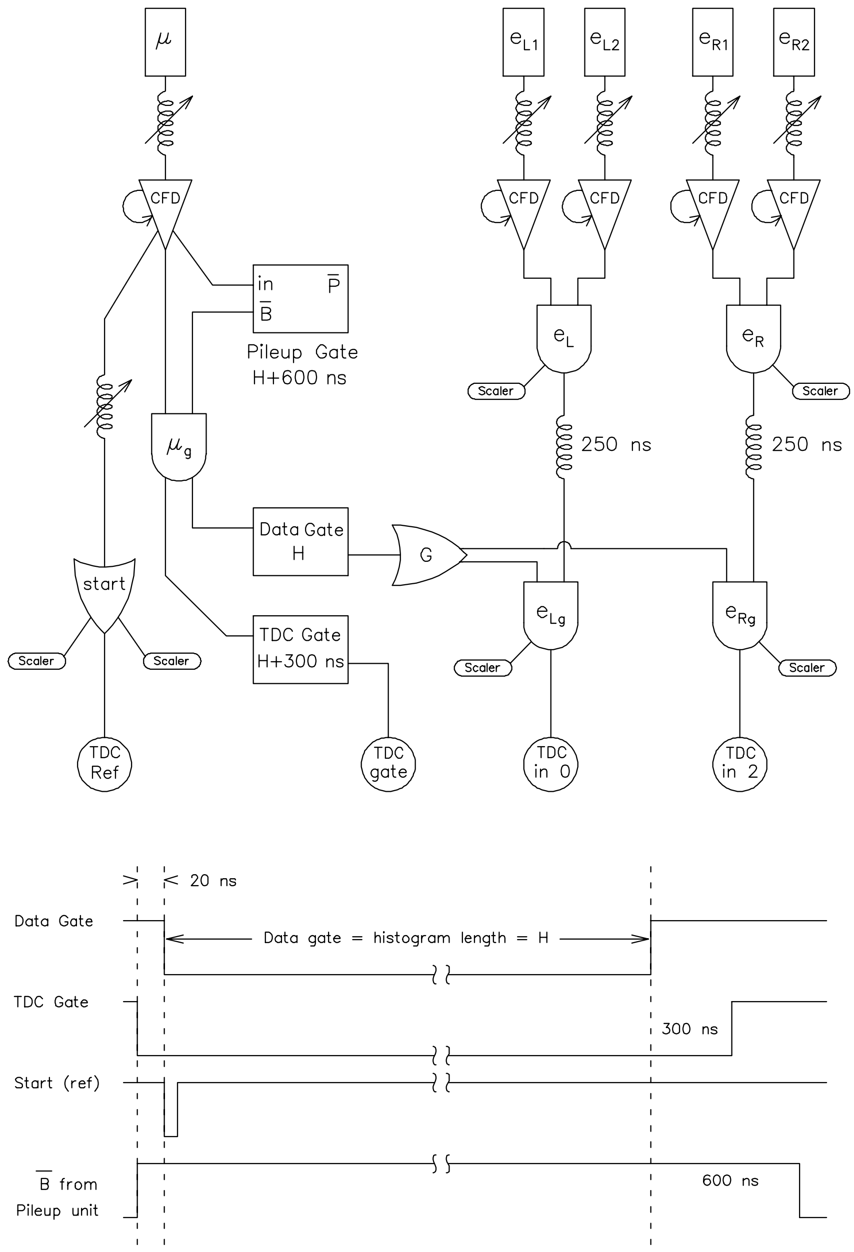
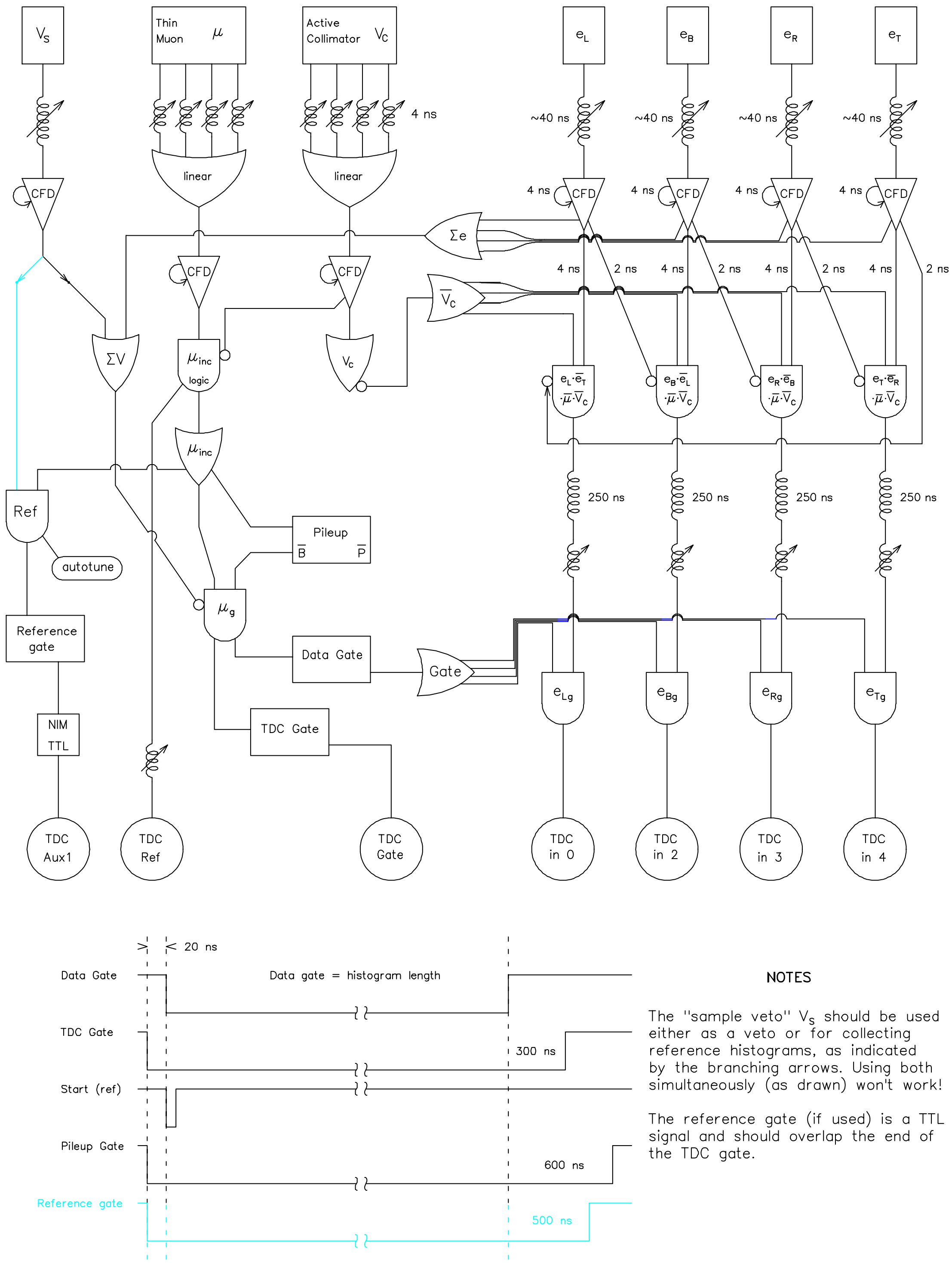


Figure 3.2: Schematic electronics logic diagram for two channels of a typical TD-μSR experiment using the BNC B980 TDC.



NOTES

The "sample veto" V_S should be used either as a veto or for collecting reference histograms, as indicated by the branching arrows. Using both simultaneously (as drawn) won't work!

The reference gate (if used) is a TTL signal and should overlap the end of the TDC gate.

Figure 3.3: Wiring diagram for Belle with B980 TDC, and many interrelated vetos.

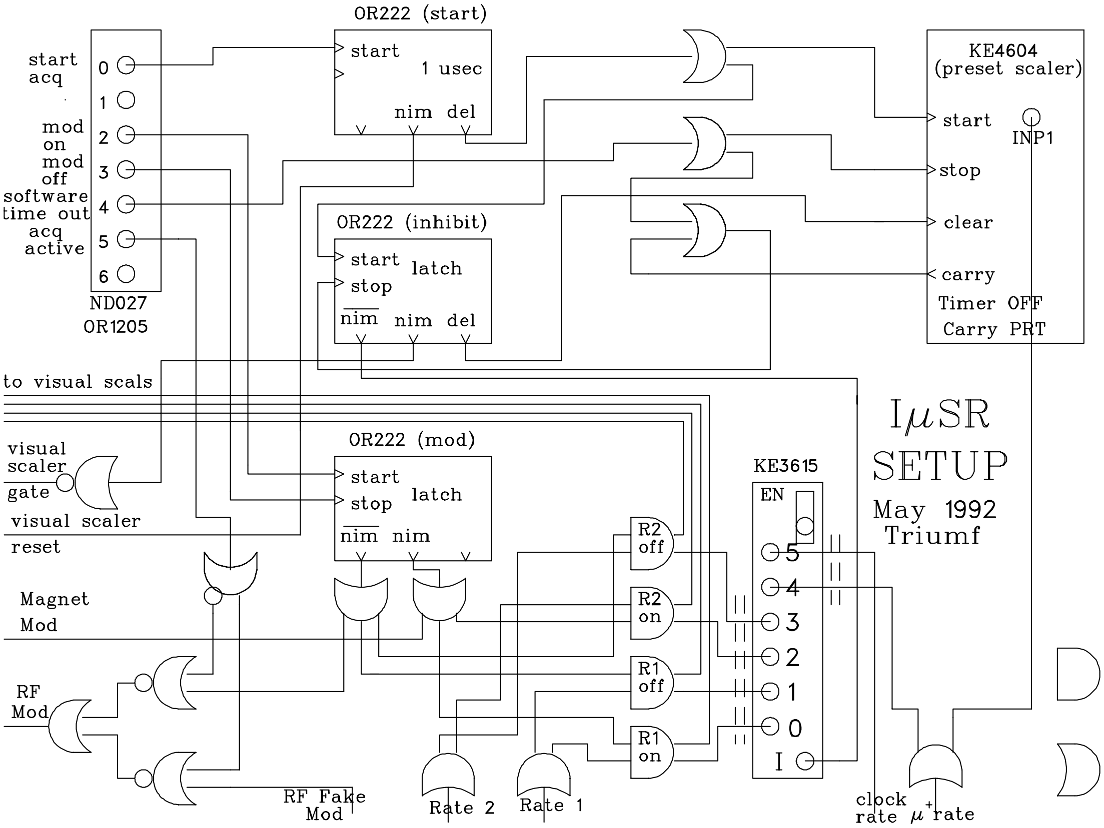


Figure 3.4: Electronics logic diagram for I-μSR experiments, with RF modulation.

3.5 Data Acquisition Software

The two largest μSR facilities (TRIUMF and PSI) now use a common data acquisition system called "MODAS" based on CAMAC and Digital's VAX-VMS computers. This system may be ported to other platforms in the future but the cooperation between laboratories will certainly continue.

For descriptions of the data acquisition software at TRIUMF, both time-differential and integral, see the *Operation Manual for μSR at TRIUMF*.

3.6 Data Analysis Techniques

There is no clear distinction between "on-line" and "off-line" data analysis in μSR. As soon as an experiment starts taking data there is an urgent need to 'chew', if not quite digest, the results so that the experimenter may continue with further "runs" in the most profitable way. The same analysis tools may be used years later to reexamine the same runs with new phenomena in mind. At both times the user will perform fits of the data to some model function or other theory to extract the phenomenological parameters which generally are thought of as "results." This information is also generally required on an hour-by-hour basis to ensure that a complete set of data (phenomenological parameter as a function of independent variables under the experimenter's control) are produced; it may be many months (if ever) before any missing points can be filled in.

For these reasons the power and convenience of data analysis software is one of the most important aspects of an effective μSR facility. Of course, there is no limit to the number of general-purpose fitting routines which may be applied, or special-purpose analysis tools that may be needed, but one may list a few are particularly useful in any TD-μSR enterprise.

Background Subtraction Virtually all μSR time spectra contain some time-independent "background" signal B [see Eqs. (2.2) and (2.3)] due to random triggers, even if only from cosmic rays. The most versatile and reliable method of determining the value of B is to delay the timing signal from the "E" counter by several hundred nanoseconds, so that a "good event" can be formed from an E that arrives physically *before* the M pulse from the incoming muon; such events can only be random noise, so that the average number of counts in such "$t < 0$ bins" is a measure of B.

Single-Counter Asymmetry In the case of high-field TF-μSR spectra there are some advantages to extracting the *single-counter asymmetry* $A(t)$ from a single raw time spectrum using Eq. (2.3). This requires foreknowledge of both B and N_0; fortunately, even if B is not measured using $t < 0$ bins, both constants can be easily extracted numerically from the data as long as the period of the muon precession is a negligible fraction of the muon lifetime. Treating $N(t)$ as a continuous function (the actual discrete sums can easily be deduced from the integrals below) we may write

$$N_0 = \frac{S\tau_\mu E_+ - RT}{\tau_\mu^2 E_+ E_- - T^2} \qquad B = \frac{R\tau_\mu E_- - ST}{\tau_\mu^2 E_+ E_- - T^2} \tag{3.1}$$

where $S \equiv \int_{t_i}^{t_f} N(t)\, dt$, $R \equiv \int_{t_i}^{t_f} N(t)\, e^{t/\tau_\mu}\, dt$, $E_\pm \equiv \pm(e^{\pm t_f/\tau_\mu} - e^{\pm t_i/\tau_\mu})$ and $T \equiv t_f - t_i$, the time interval over which the integrals are evaluated.

Two-Counter Asymmetry Suppose the counter arrangement is for LF$_x$-μSR, as in Fig. 2.6, with a pair of e counters in the $\pm x$ directions; then there will then be two "opposing" time spectra given by

$$N_\pm(t) = B_\pm \; + \; N_0\, \epsilon_\pm \left[1 \pm A_\pm P_y(t)\right] \tag{3.2}$$

with

N_0: a common normalization.

$\epsilon_\pm$: efficiencies of the e detectors in the $+x$ or $-x$ direction

$B_\pm$: background in said e detector (measured using "$t < 0$" bins).

$A_\pm$: "intrinsic" asymmetry of e detector [Count rate $\sim (1 \pm A_\pm)$ when muons are fully polarized along (opposite) detector axis of symmetry].

$P_x(t)$: muon polarization along axis.

The two opposing spectra are combined to form the "experimental asymmetry" according to

$$a(t) \equiv \frac{[N_+(t) - B_+] - [N_-(t) - B_-]}{[N_+(t) - B_+] + [N_-(t) - B_-]} \tag{3.3}$$

or

$$a(t) = \frac{(1-\alpha) + (1+\alpha\beta)A_+P_x(t)}{(1+\alpha) + (1-\alpha\beta)A_+P_x(t)} \tag{3.4}$$

where

$$\alpha \equiv \frac{\epsilon_-}{\epsilon_+} \quad \text{and} \quad \beta \equiv \frac{A_-}{A_+} . \tag{3.5}$$

Thus $(1-\alpha)$ / $(1+\alpha)$ is the "baseline" asymmetry for totally unpolarized muons.

Although this construction introduces a "baseline shift" as well as more subtle distortions, it is easily generated for on-line display, it is model-independent and works equally well for all types of TD-μSR spectra, it reduces to $A(t) = A_+P_y(t)$ for $\alpha = \beta = 1$ (an ideal counter arrangement) and the corrections can easily be made as part of a model fit. It is also a factor of two more efficient to fit one asymmetry spectrum than the two raw spectra from which it is formed.

"Corrected" Asymmetry To completely remove these distortions one must somehow independently determine α and β (usually by fitting data taken in wTF with the same geometry) and then apply the correction

$$A_+P_y(t) = \frac{(\alpha-1) + (\alpha+1)\,a(t)}{(\alpha\beta+1) + (\alpha\beta-1)\,a(t)} . \tag{3.6}$$

These corrections apply equally to TF-μSR asymmetry spectra formed from opposing pairs of detectors; in fact these are usually used to fit for α. on the other hand, β must be determined from simultaneous fits to the opposing "raw" spectra $N_\pm(t)$ in TF. It is not unusual to assume $\beta = 1$, although in principle one should always determine this empirical parameter as accurately as possible.

Fourier Transforms For a time spectrum containing oscillatory signals (as in TF-μSR) it is often useful to convert it to a frequency spectrum by means of a fast Fourier transform (FFT). Fourier transforms are useful for showing the *frequency spectrum* for muon precession in such complex spin systems as organic free radicals, *e.g.*, C_{60}Mu·, illustrated in Fig. 3.5. They also show *lineshapes*, implying field distributions, in condensed matter, *e.g.*, high-T_c superconductors, Fig. 3.6.

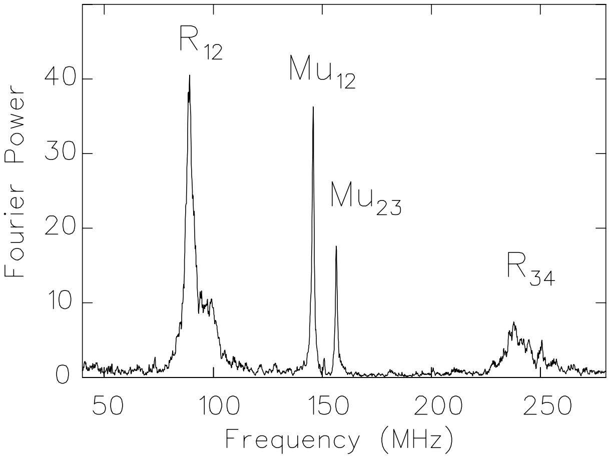


Figure 3.5: Frequency power spectrum for positive muons in powdered buckminsterfullerite (crystalline C_{60}) at room temperature and 108 Oe showing simultaneously the signals from muons in the C_{60}Mu· radical (R_{12} and R_{34}) and the endohedral muonium (Mu@C_{60}) atom (Mu_{12} and Mu_{23}). In paramagnetic molecules with nuclear moments, such radical signals cannot be seen in low field due to nuclear hyperfine broadening.

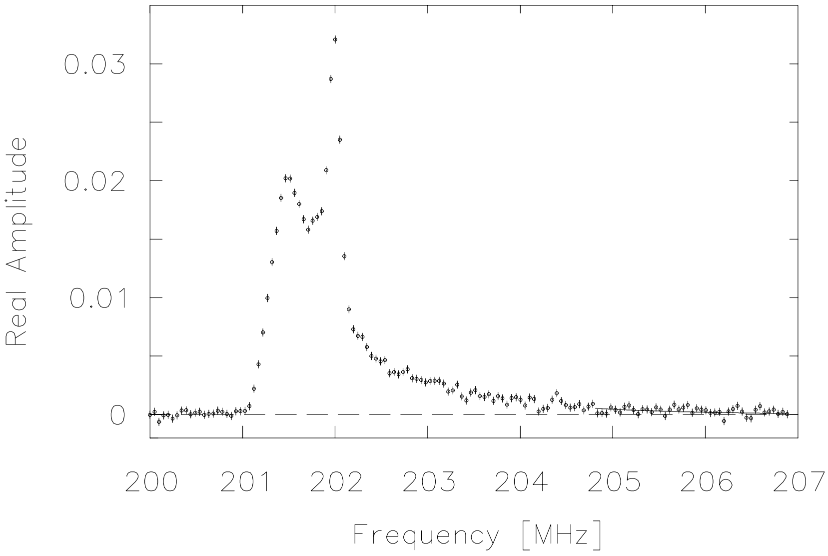


Figure 3.6: Real part of frequency spectrum taken at a temperature of 6 K for positive muons in a single crystal of superconducting $YBa_2Cu_3O_{6.95}$ (a type II superconductor with $T_c = 92\,K$) cooled in a field of 1.489 T applied along the crystalline c axis. The sharp peak at 202 MHz is due to muons missing the superconductor and stopping in a normal region where the field distribution is not broadened by the vortex lattice.

Every μSR facility provides FFT algorithms as part of data analysis facilities. There are many variations and adaptations of these algorithms, and there are many incompatible opinions regarding the correct or optimal preparation of the time spectra before transforming. Some notes on Fourier transforming TF-μSR data are presented here with the hope that no one holding contrary opinions is offended.

First, The fact that the time range of a μSR spectrum necessarily starts at $t = 0$ means that the complex (odd in t) part of the resultant frequency spectrum is dramatically broadened by the tacit presence of the Heaviside function; this has nothing to do with either the muon lifetime or the finite range of positive time. Thus the real part of the amplitude (the proper objective of our FFT) may be quite narrow but the square root of the power spectrum (the sum of the squares of the real and imaginary parts) will still be very broad. Various tricks are available for "unmixing" the real and imaginary parts.

Second, because of the finite muon lifetime there are less statistics in the bins at late times and consequently the "error bars" in the asymmetry spectrum grow exponentially with time as $\exp(+t/2\tau_\mu)$. (See Fig. 2.2.) This introduces noise in an annoyingly non-uniform way, which may in principle be corrected for using not-so-fast fourier transform methods. These "noise effects" are always subject to suppression *without limit* (except the patience of the experimenter) by simply taking more statistics; although the finite muon lifetime is responsible, is does *not* fix any absolute limits on precision — only practical ones.

Third, because experimenters' patience is indeed finite, most μSR time spectra only extend to 10–20 μs; thus the FFT is "cut off" abruptly at some time limit, introducing the "ringing" effect. This can be suppressed by "apodization" — multiplying the raw time spectrum by an *envelope function* that causes the product to go to zero "gently" before the abrupt end of the time range. Well-chosen apodization removes the "ringing" caused by FFT on a finite time interval but introduces a broadening effect that must be taken into account in the interpretation.

Rotating Reference Frame For TF-μSR in high magnetic field (HTF-μSR), another essential tool is the *rotating reference frame* (RRF) transformation. Here we will gloss over the details of transforming discrete spectra and give only a simplified description in terms of an idealized continuous time spectrum. Figure 4.11 on page 57 displays a RRF spectrum for a run taken at 7.5 T.

RRF transformation works best on *orthogonal pairs* of spectra—as for instance when the magnetic field acts in the $\hat{z}$ direction and detectors are situated in the $\pm\hat{x}$ and $\pm\hat{y}$ directions defining the plane of precession of the muon polarization— where a *complex* asymmetry spectrum $\tilde{A}(t)$ can be defined as, *e.g.*, $\tilde{A}(t) \equiv A_x(t) + iA_y(t)$. In this case the RRF transformation is simply

$$\tilde{A}_{\mathrm{RRF}}(t) \;=\; \tilde{A}(t)\, e^{-i\Omega t} \tag{3.7}$$

where Ω is the RRF frequency — chosen arbitrarily to produce a transformed $\tilde{A}_{\rm RRF}(t)$ with the desired characteristics. For instance, if the muons precess at a high frequency ω_μ, one may select Ω slightly smaller than ω_μ to produce a $\tilde{A}_{\rm RRF}(t)$ which varies relatively slowly with time; the resulting complex spectrum can be "packed" (n_p original time bins $\rightarrow$ one coarser time bin) in which the statistical uncertainties of individual bins are reduced by a factor roughly equal to $\sqrt{n_p}$.

There are several advantages to such a transformation: first and most obvious is the reduction (by a factor of n_p) of the number of bins to be fitted in analysis programs, a straightforward improvement of efficiency; second and probably more important is the transformation of a large number of narrow time bins (with statistical uncertainties often larger than the signals under scrutiny) into a small number of well-defined bins representing the signal in a form that allows convenient visual display and inspection.

In the event that a single spectrum contains several signals at drastically different frequencies ω_i, separate RRF transformations at frequencies $\Omega_i \approx \omega_i$ can be used to isolate each signal for easy fitting.

It is also possible to perform a RRF transformation on a pure real spectrum (*i.e.*, one without orthogonal detector axes) if care is taken to select Ω and n_p so as to "bin out" the spurious signal at the RRF frequency.

4 Selecting Beamline and Apparatus

TRIUMF has several muon beamlines used for μSR which together provide a wide range of beam energies, polarization, and intensity. The μSR facility has several 'μSR spectrometers' (magnets and particle counters) plus many sample holders or 'spectrometer inserts' (mainly cryostats) which make possible a wide range of experiments. In order to help the experimenter plan an experiment well, this chapter describes and tabulates the various options for selecting beam properties, spectrometer, and insert. The tables should give enough information in most instances, but more detailed descriptions, including pictures and/or diagrams are given in many cases. The experimenter should choose combinations which are suitable for a measurement, and list the choices when submitting a beam request to the experimental evaluation committee.

4.1 Muon Beamlines at TRIUMF

This section gives a short description of the beamlines at TRIUMF used for μSR. The characteristics of these beamlines are listed in Table 4.1 on the following page. More complete descriptions of the beamlines are to be found in the *TRIUMF Users Handbook*.

Table 4.1: Muon Beamlines at TRIUMF

Characteristic	M15	M20	M13	M9B
Momentum Range (MeV/c)	19–40	20–200	20–30	20–100
Spin Rotation	$\surd$	$\surd$	x	x
μ^+ flux (1000/sec)	1900	2100	180	
μ^+ central luminosity 1000/(cm^2 s)	500	102	30	
μ^- flux				1400
Momentum bite, $\Delta p/p$				
slits open	10.6%	7.4%	7%	11%
slits closed	3.5%	3.8%	0.75%	3.4%
spins rotated		4.6%	–	–

4.1.1 M15

The M15 beamline is dedicated to surface μ^+ taken from the 1AT1 proton target, which is usually 1 cm graphite or beryllium. Beam is collected by a permanent quadrupole doublet located very close to 1AT1. This gives good muon collection, but limits the momentum range of the channel from about 19 MeV/c to 40 MeV/c. Although designed primarily for μ^+, M15 will work with μ^- also (but M9B would be a better choice).

After transporting the beam up above the level of most other beamlines, M15 produces a high-luminosity focus in the M15 experimental area, which is not actually in the meson hall.

M15 is equipped with dual spin-rotators (Wein filters) which serve both to separate positrons from the beam and to rotate the muon spin to be perpendicular to the beam direction. They may be operated at low voltage to remove positron contamination without rotating the spins much. These dual rotators retain more beam flux than the single rotator in M20 because the dispersion from the first rotator is partly counteracted by the second.

M15 has slits for selecting the beam momentum acceptance and adjusting the final spot size.

4.1.2 M20

The M20 channel is both a (low momentum) surface muon and a (high momentum) decay muon beamline with a long history; and its present form reflects that history. The original (1975) M20 was rebuilt in 1982 as a split beamline (M20A&M20B) with the capacity to run ‘forward’ (173 MeV/c) and ‘backward’ (86.5 MeV/c) beams simultaneously into separate experiments, or to run ‘surface’ muons (29 MeV/c) with spin-rotation into the B-leg alone. After M9B was built the M20A leg was dismantled to make M20(B) a dedicated surface-muon channel, albeit with a long 'decay' section of 10 quadrupole magnets. It is, in principle, still usable for high-momentum backward-decay muons (~80 MeV/c) and even higher-momentum forward muons (~170 MeV/c), but it has never been used that way; M20 is, *de facto*, a dedicated surface-muon channel.

As with all surface muon beams, the flux of μ^- is disappointing.

M20 takes muons from the 1AT2 target, typically 10 cm beryllium, and delivers a high flux of surface muons, but with a large final focus imaging the large production target. The beam flux is nearly doubled if a bare carbon target is used, but there have been problems with durability. In Table 4.1, fluxes for a 10 cm Be production target are listed.

The spin rotator can provide clean beam with longitudinal or transverse (spin-rotated) polarization by operating at 50 or 140 kV/plate, respectively. Slits limit the final spot size and the momentum range transmitted. The spin rotator also selects momentum, and therefore reduces total flux, at full 90° rotation.

4.1.3 M13

M13 is a low energy π/μ beamline, taking particles from 1AT1, and having a good final spot, but lower rate and less versatility than M20 or M15. When used for μSR, M13 is fitted with a small beam separator and an extra quadrupole triplet which give a fairly positron-free muon beam but only with longitudinal polarization.

4.1.4 M9B

The M9 beamline has two legs coming from the 1AT2 target, both specializing in negative muons. Leg A has an RF beam separator and is dedicated to rare-event experiments, like radiative muon capture. M9B, built by the University of Tokyo, is a backward μ^+/μ^- channel with a superconducting solenoid for the decay section. It delivers a high flux beam over a momentum range approximately 20–100 MeV/c; both ends are limited by dropping intensity: an intrinsic lack of low energy pions at the low end, and the current limits on some beam elements at the high end.

4.2 The μSR Spectrometers

The μSR 'spectrometers' are magnets plus an array of counters to detect incoming muons and decay positrons. The magnets can often be paired with a range counter arrays to meet the needs of an experiment; some counter arrays are general-purpose and will meet the needs of most any experiment.

The magnets are of various types—Helmholtz, solenoid, or solid pole electromagnet; superconducting or not—as indicated in Table 4.3 on page 58. In fact, most spectrometers have more than one magnet. The main magnet of an apparatus is usually oriented so the field is along the beam axis ($\hat{\mathbf{z}}$ direction) which allows surface muons to enter the sample without being turned away. Other coils provide weaker fields in perpendicular directions either for zeroing the field or for applying weak fields ($< 10\,\mathrm{mT}$) transverse to the beam direction. The latter capability allows experiments in weak transverse field without spin rotation (on M13 & M9), and ZF/LF experiments with spin rotation ($\hat{\mathbf{x}}$ counters). There are no spin rotators that can cope with high momentum muon beams, but backward muons can be injected transverse to the field. The Gas Cart and SFUMU can be positioned either axially or transverse to the beam; Varian is oriented transverse; and all the others have the main magnet axial to the beam.

All apparatuses rest, and roll, on standardized rails so they can be reproducibly positioned in any beamline. They can be rolled back from the beam snout (to access collimators *etc.*) at any time and accurately rolled back into position by one person. The four beam lines, M15, M20, M9B and M13 which are used for μSR have such rail systems.

The magnet type is important for choosing which sample insert will fit: The Helmholtz magnets allow complete access ($\hat{\mathbf{x}}$,$\hat{\mathbf{y}}$,$\hat{\mathbf{z}}$); the Helios solenoid allows only axial ($\hat{\mathbf{z}}$) access, and the Varian magnet allows only horizontal access (near $\hat{\mathbf{z}}$). The exception is the DR, which is a combined magnet and dilution refrigerator, and takes no separate inserts. Belle also has a dedicated cryostat and counters, but it would be possible to remove them and run something else.

In Table 4.3, the counter arrays are distinguished by their solid-angle coverage (4π means full coverage is possible, although sample holders usually reduce that), and by the directions the counters cover: $\hat{\mathbf{z}}$ means along the beam direction (which is also the axis of the muon spin with unrotated beam), $\hat{\mathbf{x}}$ means up (which is the direction of the muon spin when rotated), and $\hat{\mathbf{y}}$ means to the right. The 'backward' $\hat{\mathbf{z}}$ positron counters have holes to allow the muon beam to pass through. Most of the counter systems are movable in various ways, and many follow a uniform standard design of multi-counter modules mounted on tracks on tables attached to the spectrometer.

Some counter arrangements are partially built into the sample inserts. These are the low background apparatuses for small or thin samples which have veto counters to reject counts from anything but the sample itself. The Belle counters also fit inside the small Oxford cryostat and incorporate a simple muon veto. There is a low-background veto cup built into the Dilution refrigerator outside the 80 K shield.

4.2.1 Omni

Omni is, as its name implies, a multi-purpose spectrometer with flexible counter arrangements which accepts most inserts, transverse or axial. It was the first spectrometer at TRIUMF to have its main Helmholtz coil oriented longitudinally,

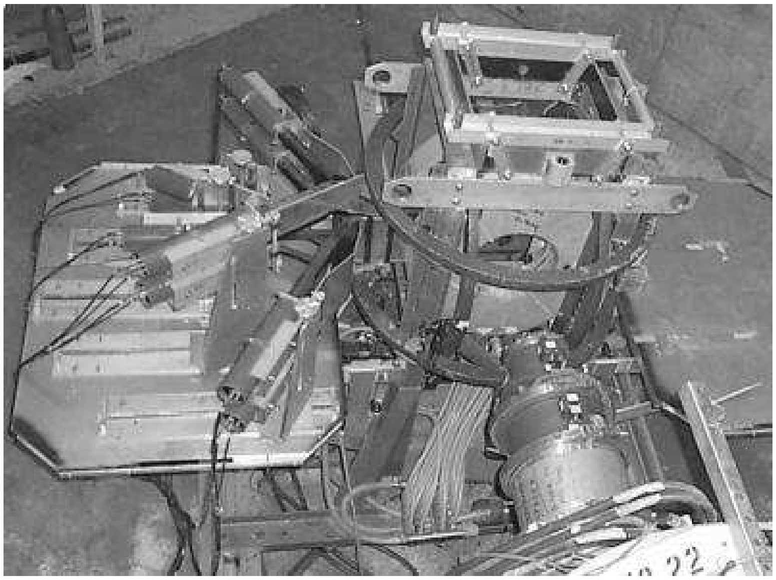


Figure 4.1: Omni in M20. Noteworthy in this picture are the counter stands and tracks (at left), the three-axis Helmholtz magnets, the vertical cryostat stand at top, and the variable beam collimator ("Sydimator") on the beamline.

taking advantage of spin rotators on M15 and M20. It also has lighter coils in the two other directions, and an axial shim coil, with a convenient pivoting bus bar to switch the main power supply to any of the three directions. The main coils are separated by a 5.25-inch gap.

Over the years, Omni has undergone several changes to its counter mounting system, and now features the μSR facility standard tables and THK tracks on which the counters (and side-access cryostat) ride. Less appealing are the changes to its main magnets. Originally, Omni gave 4 kG (0.4 T) at 750 A, but one of its main coils short-circuited, and a new pair was purchased, leaving one (original) spare coil. A new coil short-circuited soon thereafter, but the spare seems to have vanished, so at present, Omni provides 3 kG (0.3 T) at 750 A, or 4 G/A.

4.2.2 Omni′ (Omni-Prime)

Omni was so successful that there was demand for a copy of it, and less demand for an existing spectrometer named Eagle. Eagle was stripped of its main coils which were used to build another Omni apparatus, Omni′. The main coils are spaced a generous (and un-Helmholtz) 6.25 inches apart, providing 3.2 kG (0.32 T) axially with 750 A (4.25 G/A). There is a second pair of coils for 150 G vertical field and axial shim coils for active feedback field control.

A system of arms for the counters was, and is, very versatile, but never had the rigidity to preserve counter alignment, so beware: the counters can move

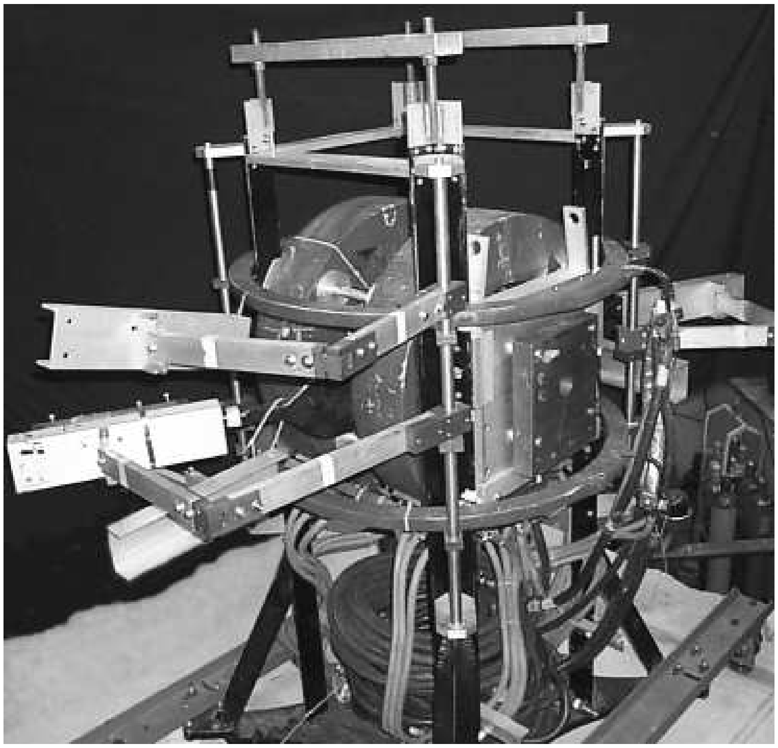


Figure 4.2: Omni′. This picture shows the counter holder arms (two of which are empty), the lead and brass walls, the coils which give field in two directions, and the mounting platform for the vertical cryostats Janis and VGC at top.

even in the middle of a run if a high magnetic field pulls on the iron shield of a phototube.

For the last three years, Omni′ has been used exclusively for higher energy backward muons (on M9B). To this end it has a lead collimator wall, 3 inches thick, upstream of the coils; a 2-inch thick brass collimator block, borrowed from the gas cart, attached to that; and two 1-inch copper collimator walls sliding in a channel within the coils. This arrangement may need some explanation. For backward muons, it is desirable to use two muon counters, in coincidence, to avoid counting x-rays and positrons, and, preferably, there should be collimation between the two counters. In the case of Omni′, the first counter, M0, is inserted between the lead and brass walls while the second goes after all collimation, just before the sample. Note that all collimators take tungsten inserts to select the size of hole.

4.2.3 Omni-Lampf

Omni-Lampf, Lampf Omni, or just “Lampf”, is the third Omni apparatus. When the Omni magnet short-circuited a second time, R. Heffner kindly provided the

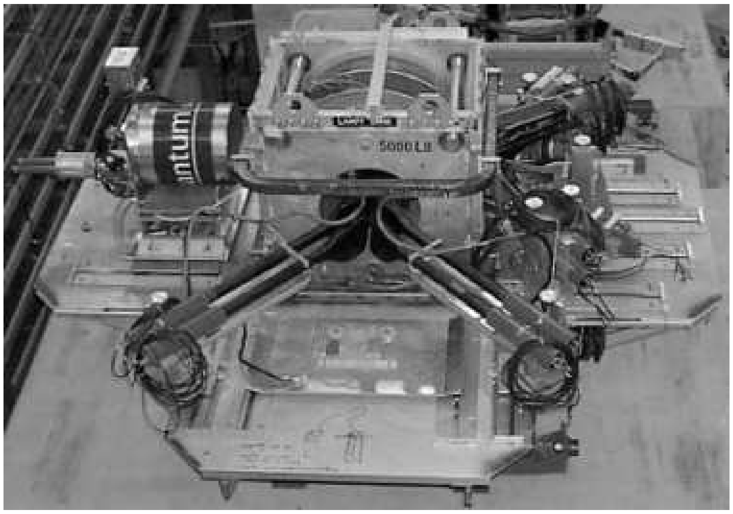


Figure 4.3: Omni-Lampf in storage. In the center are the magnet coils: the heavy main coils and the large square vertical coils; the side transverse coils are smaller and hidden inside the main bore. To the right is the typical array of counters on tracks. In front (downstream) are axial counters and the platform for mounting an axial cryostat (or oven). To the left is the Quantum gas flow cryostat (Miss Piggy) with the muon veto insert installed.

magnet and stand which had already enjoyed a career in μSR at LAMPF. It has since been fitted with transverse coils and three standard tables for counters and cryostats. The available gap between the coils, inside the support frame, is 4.75 inches. The maximum field provided is 4.0 kG (0.4 T) at 1000 A (4.0 A/G), but 1000 A are available only in M15, with 750 A provided to other beam areas allowing a field of 3.0 kG (0.3 T). Using 1000 A in M15 is problematic as well; it depends on the cooling water flow, and thus on the load all around TRIUMF (and only 950 A is possible with decent regulation).

4.2.4 SFUMU

The SFUMU apparatus has recently been converted from its original guise as a dedicated backward muon spectrometer to a dual-orientation device: with its coils transverse to the beam it fulfills its original role, but when turned axial to the beam it is another Omni. This makes it the most omni-purpose of the Omni apparatuses, but with some compromises. The prime motivation for this conversion was the magnet: It delivers 6 A/G allowing experiments at 4.5 kG (0.45 T) on any beamline. The coils can run at 850 A if necessary, so in M15 SFUMU could deliver 0.5 T. The drawback is the small spacing of the coils—only 3 inches—preventing side access for most counters and cryostats, and giving a quite small region of homogeneous field.

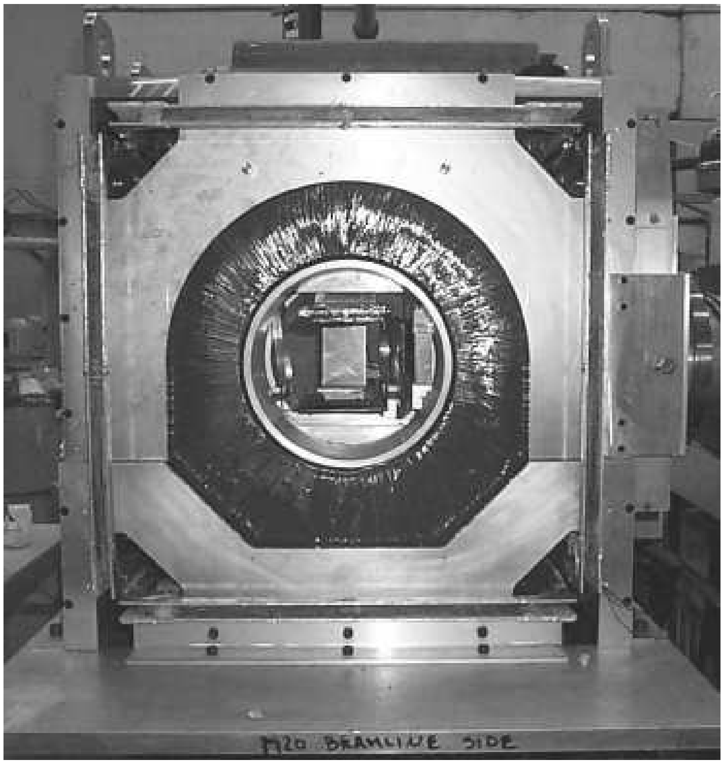


Figure 4.4: The upper half of SFUMU in M9B. This view down the field direction shows the main coils partially covered by aluminum support structure. To the right, where beam enters is a lead wall; in the center are the counters, which emerge on the far side. The M0 counter is just visible above the main coils. Tri-axial shim coils, useful for field control and achieving zero field surround the main coil. For backward muons, the beam enters transverse to the field, as illustrated, but for surface muons the apparatus is rotated so the beam enters from the viewer's direction (as indicated by the written notation on the base plate).

For backward muon studies, SFUMU is fitted with a 3-inch thick lead wall with collimator; an M0 counter is behind the wall, followed by more heavy collimation between the coils.

4.2.5 Helios

Helios is the workhorse superconducting magnet with a 6-inch diameter, 24-inch long warm bore. It provides 6.7 T at its maximum current of 70 A; that's 961 G/A. The main counter array is for solid state work in narrow cryostats, and there is another set of counters for larger samples such as gas cells. Both sets have long light guides and poor timing resolution (> 1 ns).

Of course all access is axial, but the large bore makes this a versatile magnet.

There is no persistence switch so the magnet must be driven constantly. That is actually an asset, because the field tends to be changed frequently in μSR experiments, and a switch heater would boil away a lot of helium.

4.2.6 DR

The DR 'Pandora' hides a superconducting Helmholtz magnet, a dilution refrigerator, and a veto cup within its tall black box. Externally, there are field adjustment coils and counters, including the phototube for the veto cup built into the 80 K shield. The main magnet runs in persistent mode and up to 5 T. The dilution refrigerator reaches 10 mK (and has reached 8 mK) but can be used as an ordinary cryostat up to 30 K.

4.2.7 Gas Cart

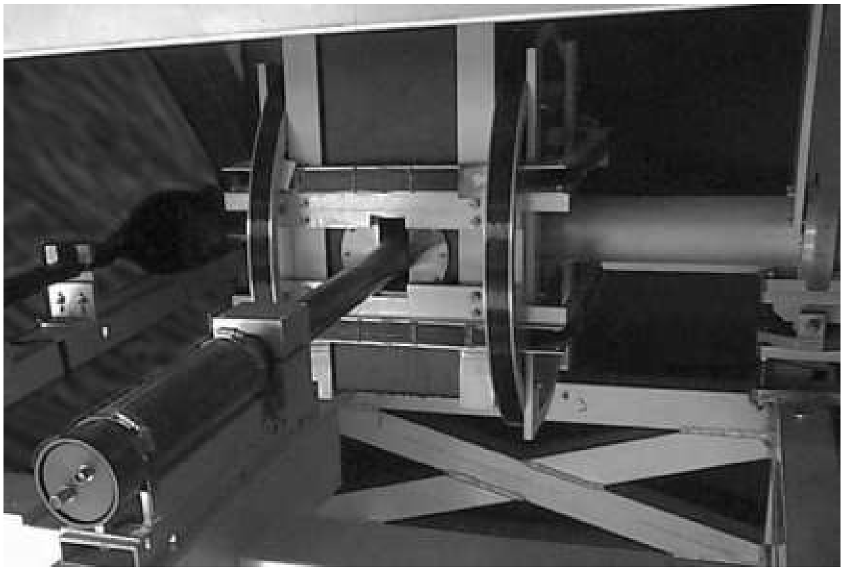
The Gas Cart, with its big coils and counters, is specifically designed for large gas targets. The main 1.5 m diameter Helmholtz coils provide magnetic fields up to 330 G (33 mT) directed horizontally along or across the beam direction, and homogeneous to $\sim 1\%$ over a 5 litre volume. There were also two other pairs of coils, capable of generating a few gauss, which were used to accurately zero the field and to provide a weak vertical field when necessary.

Arrays of counters (25×45 cm) are mounted above and below the center, with the top set movable vertically. The gas pressure vessels roll on aluminum rails to position the muon stopping distribution in the center of the magnet and between the counters.

Although there are no facilities for solid state experiments, such as cryostat mounting, the roomy design will facilitate unorthodox setups and could be useful for zero-field experiments.

4.2.8 Varian

The Varian magnet is a solid pole electromagnet providing fields of 10 kG (1 T) vertically with 90 A; that indicates 111 G/A overall, but the response is non-linear depending on the saturation of the iron yoke and poles. Since the field is transverse to the beam direction, only high momentum backward muons may be used; and Varian is the only way to get such high transverse magnetic fields for backward muons, in the absence of spin rotators. Even with energetic muons, the beam is bent considerably, so the magnet slews sideways to catch the beam. Cryostat access is axial.



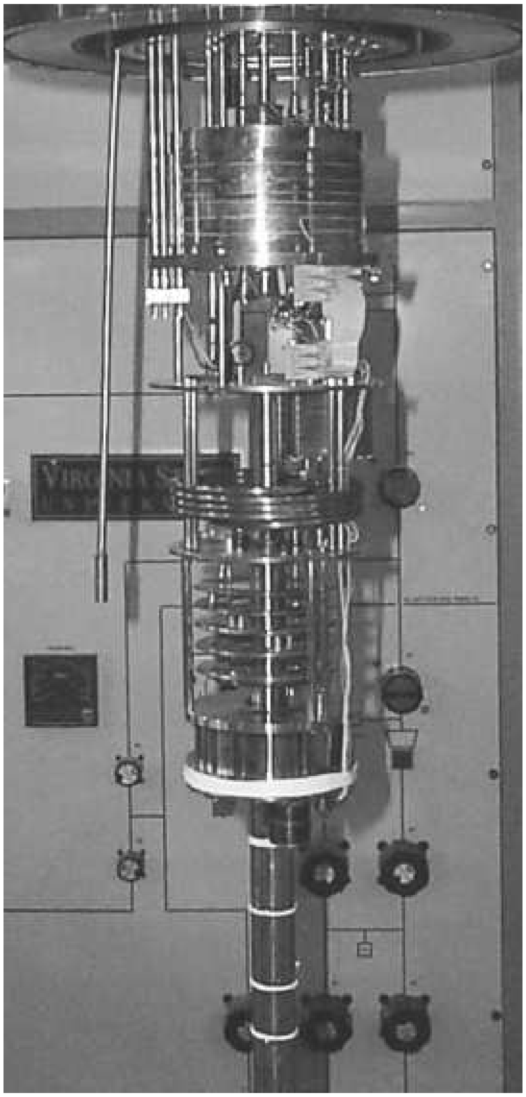


Figure 4.5: The Dilution Refrigerator. Visible externally are the weak field coils and the counters; there is much more detail internally. Note that the internal view is of the VSU DR destined for ISAC.

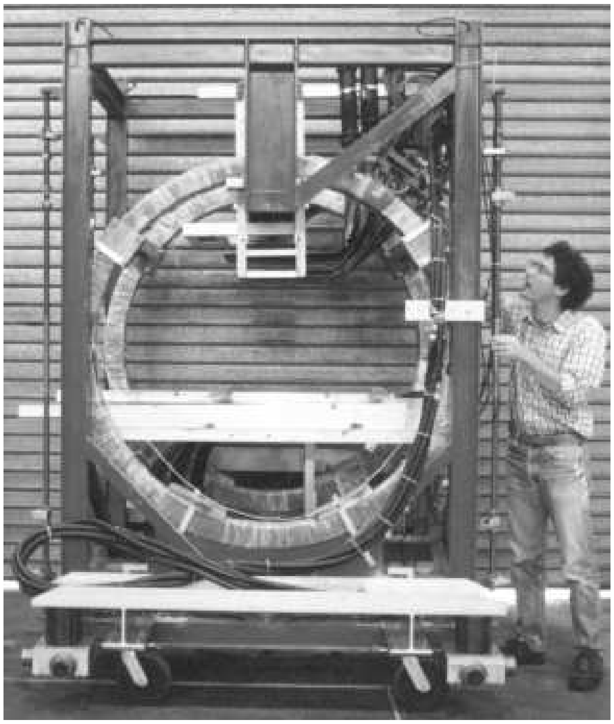


Figure 4.6: The Gas Cart, with the light correction coils dismounted.

4.2.9 Belle

The Belle spectrometer is built around an Oxford Instruments superconducting magnet provided by Physikon[1] dedicated to studies with high transverse fields and high frequencies. To this end, its counters all have short light guides with high-field mesh dynode phototubes: the muon counter and active collimator each have four phototubes, and are mounted in the the beamline vacuum; the four positron counters and the muon veto are form a cryostat insert and sample holder. Figure 4.8 shows the overall apparatus, and Fig. 4.9 shows the functional region of the magnet, cryostat and counters; Fig. 2.10 on page 24 shows a more detailed view of the scintillators and the sample region.

The magnet is a superconducting split solenoid delivering 7.5 T (75 kG) from 100 A (750 G/A) and which runs in persistent mode.

The Oxford Instruments cryostat is a hybrid between a gas flow and cold finger cryostat as the helium flow is through a ring around the sample area—the sample is cooled by helium exchange gas surrounding it. (This system has the benefit of not having the gas become very dense at low temperatures.) There is a phase separator on the inlet and counterflow cooling in the transfer line, allowing the cryostat to reach 1.7 K.

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[1] It was originally brought to TRIUMF when owned by Bell Labs; thus the name.

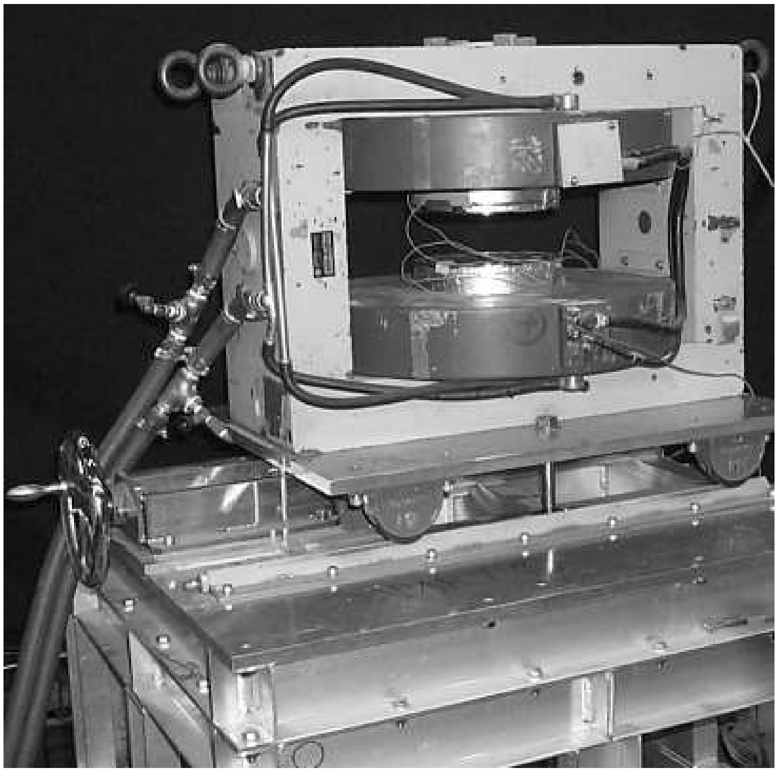


Figure 4.7: The Varian Magnet. The magnet rolls sideways on wheels, under control of the hand crank, to intercept the beam. Extra windings around the pole tip are for field correction.

Figure 4.10 shows the performance of Belle at high fields: the measured precession amplitude decreases from its low field maximum by 37% at 7.5 T.

Although the counters are optimized for high transverse fields (with spin-rotated muons), Belle can be used for longitudinal field experiments by using the muon veto counter as the forward counter and the active collimator as the backward.

4.3 The μSR Inserts: Cryostats and Other Sample Holders

Into each apparatus go a number of sample-holding inserts. Most of these are cryostats, but there are ovens, pressure vessels, and RF resonance cells. Each has various modes of operation. When planning an experiment, you should look at Table 4.3 on page 59 for which insert will provide the experimental conditions desired, and specify possible options with your beam request.

The characteristics of an insert include:

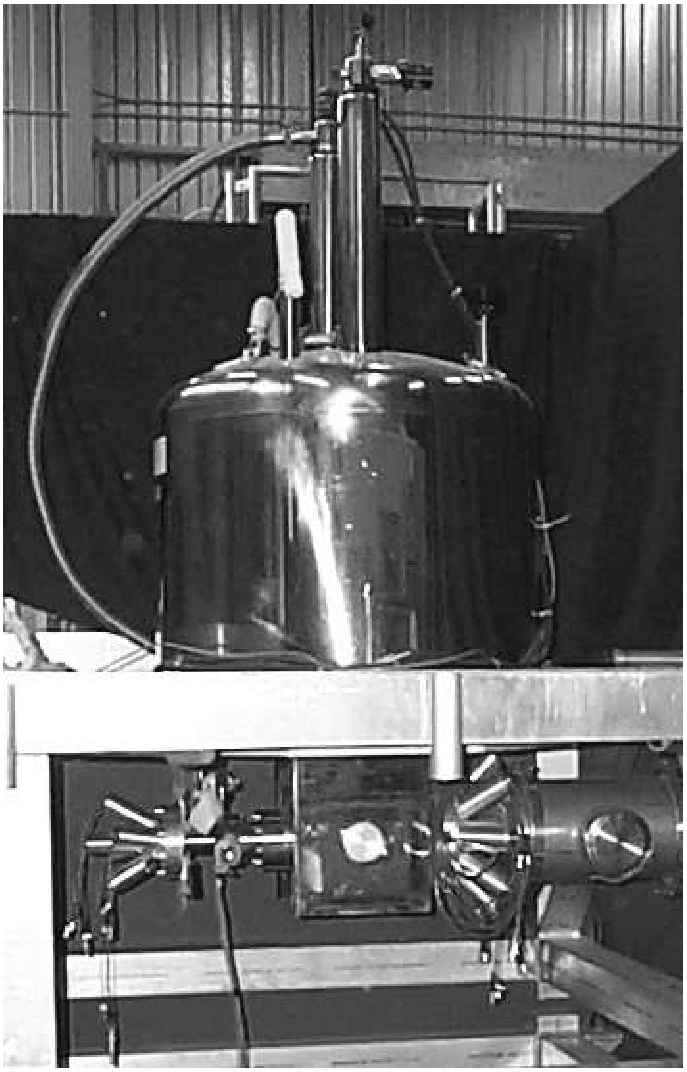


Figure 4.8: The Belle spectrometer. The upper portion contains the cryogens (He and N_2) while the magnet, cryostat and counters are all below the platform.

Access: Either side access, axial access, or vertical access. This determines which spectrometers each insert will fit into, and, to a lesser extent, affects how counters are arranged. For many inserts, there is only one access direction, but for others the access direction is specified as a qualifier to the insert's acronym. For inserts with only one access direction, the name ("vertical…") gives the direction; Table 4.3 lists both the unique access directions and the multi-directional qualifiers for inserts.

Sample size: The sample size will determine the size of the sample holder required, and whether a low background configuration is necessary. The standard holders for the gas-flow cryostats take samples up to 3 cm in diameter, and up to

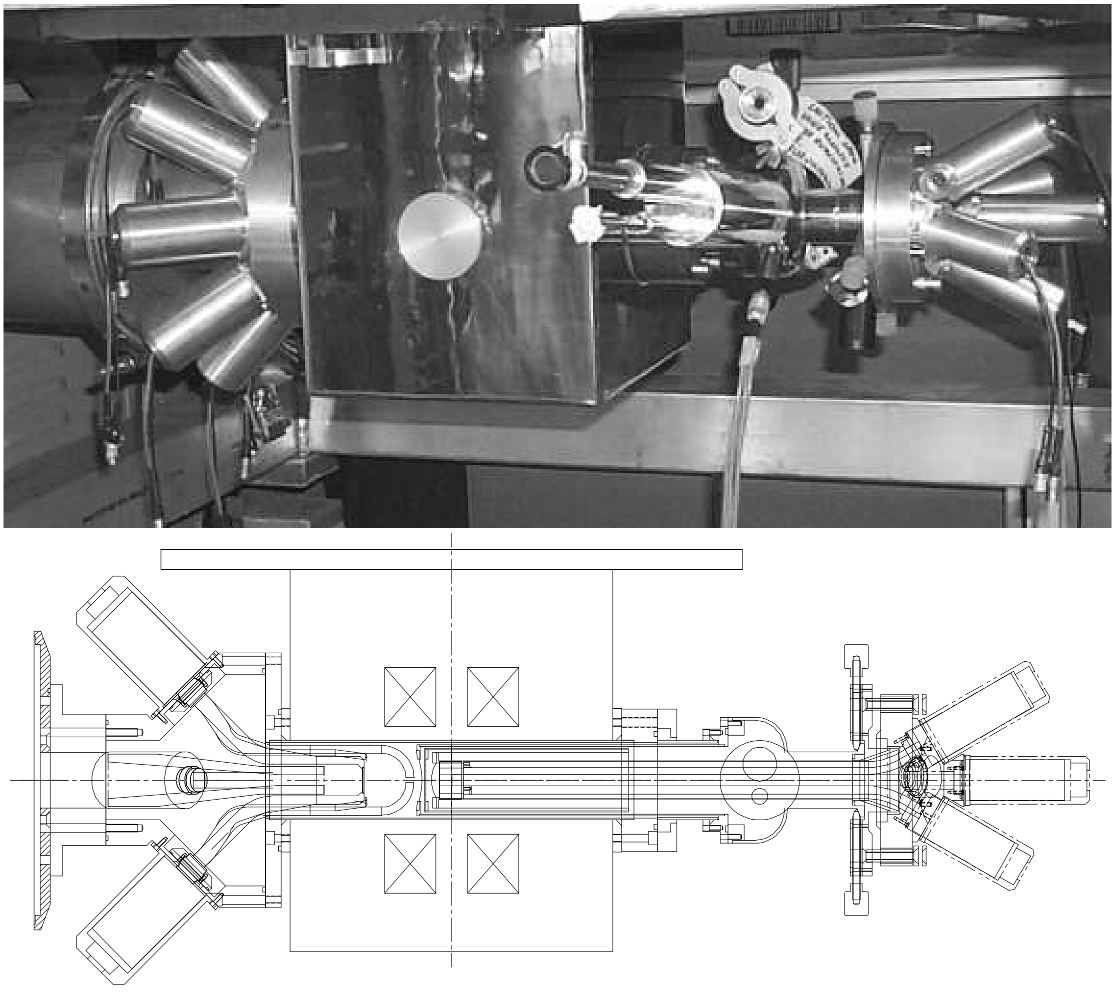


Figure 4.9: Photograph and diagram of Belle. From left to right are shown: the phototubes for the muon counter and active collimator; the collimator; the muon counter; the active collimator; the cryostat windows; the sample region with positron counters inside the cryostat; the light guides; the cryostat phase separator (in photo); the positron counter phototubes.

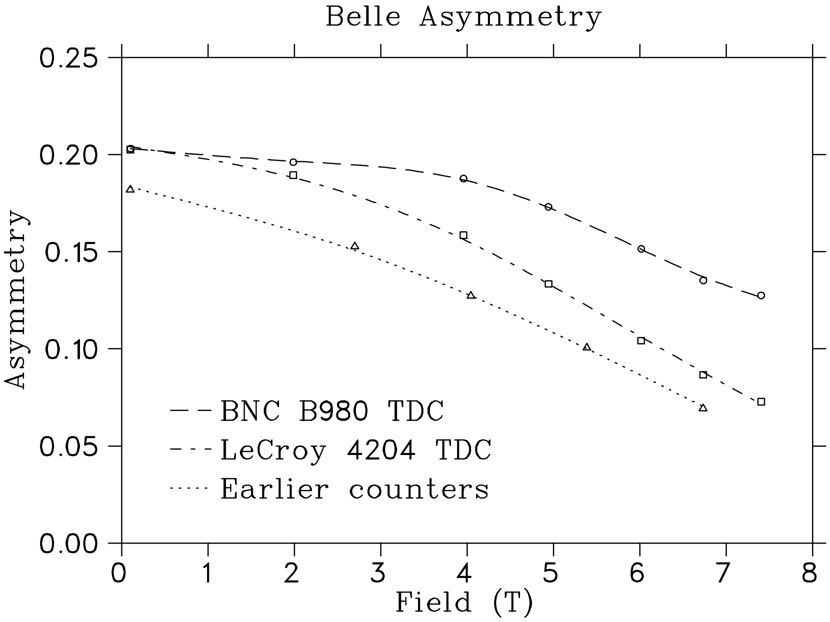


Figure 4.10: The precession amplitude, or asymmetry, measured in a silver sample over the field range of Belle.

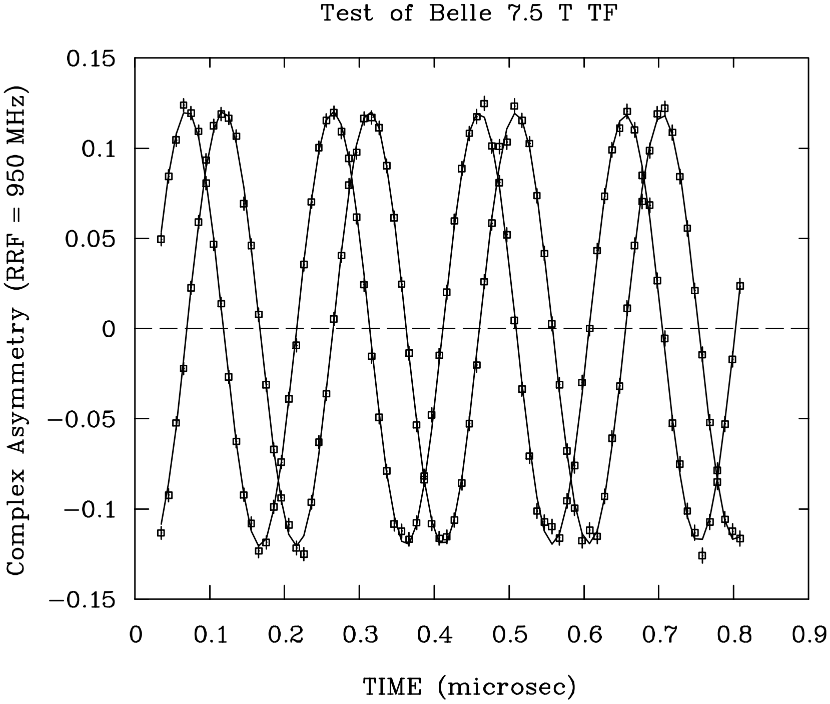


Figure 4.11: Four-counter asymmetry in a silver sample measured at 7.5 T with Belle and displayed in the rotating reference frame.

Table 4.2: The Spectrometers

Spectrometer	Characteristics			Experiment
Name	Type	Field	Counters	Types
Omni	3×Helmholtz	0.3 T $\hat{\mathbf{z}}$, 20 mT $\hat{\mathbf{x}}$-$\hat{\mathbf{y}}$	4π	LF, TF, LTF, ZF, RF-μwave
Omni′	2×Helmholtz	0.32 T $\hat{\mathbf{z}}$, 20 mT $\hat{\mathbf{y}}$	4π	LF, TF, LTF, ZF, RF-μwave, bwμ
Lampf	3×Helmholtz	0.38 T $\hat{\mathbf{z}}$(M15) 0.30 T $\hat{\mathbf{z}}$(other) 10 mT $\hat{\mathbf{x}}$-$\hat{\mathbf{y}}$	4π	LF, TF, LTF, ZF, RF-μwave
Helios	SC solenoid	7 T $\hat{\mathbf{z}}$ 2 mT $\hat{\mathbf{x}}$	1–3π	LF, TF, HTF, RF-μwave, bwμ
DR	SC Helmholtz	5 T $\hat{\mathbf{z}}$ 5 mT $\hat{\mathbf{z}}$,$\hat{\mathbf{y}}$	0.1–1.5π	LF, TF, ZF, HTF
SFUMU	TF Helmholtz	0.45 T $\hat{\mathbf{y}}$	3π	TF, ZF, LTF, bwμ
	LF Helmholtz	0.45 T $\hat{\mathbf{z}}$	4π	LF, TF, ZF
Gas Cart	3×Helmholtz	33 mT $\hat{\mathbf{z}}$,$\hat{\mathbf{y}}$	$1\pi\,\hat{\mathbf{x}}$	TF, LTF, ZF
Varian	Electromagnet	1.0 T $\hat{\mathbf{y}}$	1–2π	TF, bwμ
Belle	SC Helmholtz	7.5 T $\hat{\mathbf{z}}$	3π	HTF, TF, LF

SC = Superconducting. LF = Longitudinal Field. ZF = Zero Field (with a flux gate magnetometer and ZF controller available).
TF = Transverse Field (usually requiring spin rotation).
LTF = Low Transverse Field (without spin rotation, $\lesssim$ 10 mT).
HTF = High Transverse Field (spin rot. and fast-timing counters).
RF = Radio Frequency. μwave = Microwave. bwμ = can be used with high momentum backward muons
$\hat{\mathbf{z}}$ = The beam direction. $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$ = Perpendicular directions.

Table 4.3: The Inserts

Acronym	Full Descriptive Name of Insert	Characteristics
VGFC:Janis /SC /KT /V /LB	Vertical Gas Flow Cryostat: Janis standard configuration separate spectra configuration simple muon veto counter low background configuration	2.4–330 K [va] large sample Knight shift, *etc.* large or small sample small sample
VGFC:Cryo /SC /KT /V	Vertical Gas Flow Cryostat: Cryo Industries standard configuration separate spectra configuration simple muon veto counter	2.4–330 K [va] large sample Knight shift, *etc.* large or small sample
HGFC:Cryo /SC /KT /LB /RFss /RF300 /μwave	Horizontal Gas Flow Cryostat: Cryo Ind. standard configuration separate spectra configuration low background configuration RF solid state configuration RF 300 MHz configuration μwave solid state configuration	2.8–330 K [ax] large sample Knight shift, *etc.* small sample 10–220 MHz, 1kW 300 MHz 1–2 GHz, 2W
HGFC:Quant /SC /V /LB	Horizontal Gas Flow Cryostat: Quantum Ind. standard configuration simple veto counter low background configuration	1.5–330 K [va,sa] large sample large or small sample small sample
HGFC:Ox /HiTime	Horizontal Gas Flow Cryostat: Oxford Inst. High timing resolution (dedicated)	1.7–330 K [ax] ≤7 mm sample
CFC:20cm /ax /sa	20cm Cold Finger Cryostat (20 cm tail) axial or side access	2.8–330 K
CFC:40cm /ax /sa	40cm Cold Finger Cryostat (40 cm tail) axial or side access	2.8–330 K
HO /2cm /3cm	Horizontal Oven 2 cm or 3 cm sample holder	330–900 K [ax]
HPCell /16 /60 /500	High Pressure Gas Cell 16, 60 or 500 atm pressure	150–450 K [ax]
GasCan	Various High Volume Gas Targets	90–850 K
RFchem /160 /185/205/305	RF Apparatus for Liquid Chemistry Targets Resonant Frequency Specification	280–325 K [ax] 300 W
DR	Dilution Refrigerator: Oxford Inst.	10 mK–30 K [va]

Table 4.4: Spectrometer & Insert Compatibility Guide

INSERTS	SPECTROMETERS								
	DR	Omni	Omni′	Lampf	Helios	Belle	SFUMU	Varian	GasC
DR	√								
HGFC:Ox						√			
VGFC:Janis		√	√	√					
VGFC:Cryo		√	√	√					
HGFC:Cryo		√	√	√	√		√	√	
VGFC:Quant		√	√	√			√		
CFC:20cm		√	√	√					
CFC:40cm/ax		√	√	√	√		√	√	
CFC:40cm/sa		√	√	√			√		
H Oven		√	√	√	√		√		√
HPCell		√	√	√	√		√		√
GasCan									√
RFchem		√	√	√	√		√		

1 cm deep. Samples smaller than 1 cm require a low-background configuration; the vertical low background insert has no room for large samples, only small samples. For an illustration of the 'horizontal' low background configuration, see Fig. 2.8 on page 21, and for the 'vertical' configuration see Fig. 2.9. A simple muon veto counter is used for intermediate size samples, or for flexibility in running various sizes of samples in succession, but gives a reduced acquisition rate for small samples.

Temperature: Different inserts handle different temperature ranges, and you may require more than one insert to cover the whole range desired.

RF frequency: For resonance experiments, the desired frequency should be specified.

Pressure: For gas samples, the pressure should be specified also.

The (Oxford Instruments) dilution refrigerator is not actually an 'insert' because it is a stand-alone spectrometer ("Pandora"). It takes samples up to 1.2 cm × 2 cm in size, and temperatures from 10 mK to 30 K.

Table 4.4 summarizes which spectrometers can be used with which inserts, for the set of spectrometers and inserts that is currently available for μSR exper-

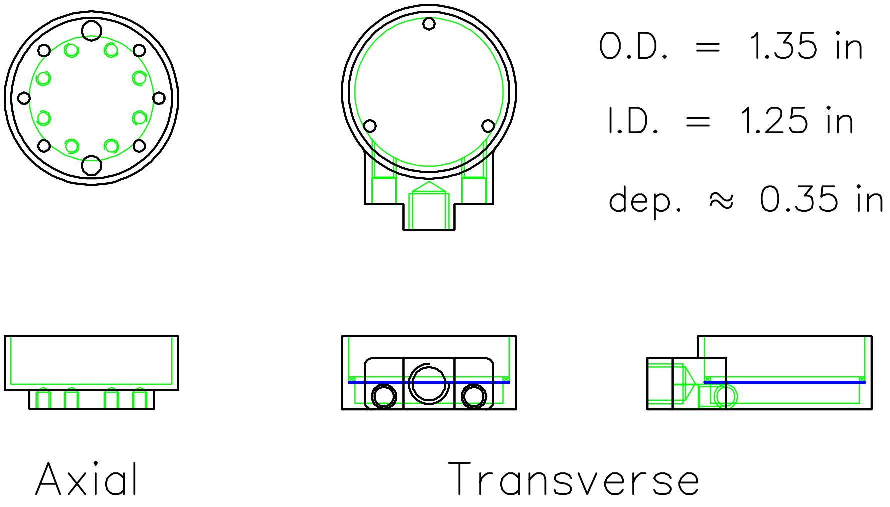


Figure 4.12: Standard sample cups for both axial and transverse cryostats.

iments at TRIUMF. Note that almost all inserts fit into Omni and Omni′; only the long axial inserts fit in Helios (*i.e.*, excluding CFC:20cm/ax and HGFC:Ox).

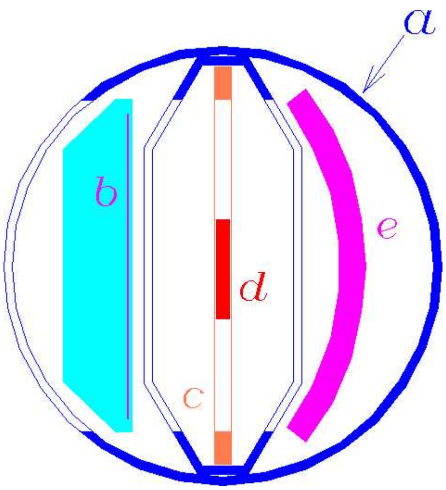
4.4 Sample Holders

Within the cryostats and ovens, there can be a variety of sample holders as diverse as the samples to be run. However, there are a few standard sample rods that are used in the majority of solid state experiments.

First, there are the standard simple sample cups used in both the horizontal and vertical cryostats when samples are large and vetos unnecessary. The inside diameter of the cup is 1.25 inches, which sets the maximum sample size. The cup on the transverse version is divided by a silver disc, held in place by rings, and the thermometer (GaAlAs diode) resides in the space behind the disc. The thermometers (CGR and GaAlAs) for the axial version are in the sample rod. The sample is attached to the disc by grease.

For somewhat smaller samples, there are the standard muon veto inserts for the transverse cryostats containing an integral thin muon counter and a veto counter (Fig. 4.13). The insert has a fiberglass shell that separates the sample rod from the counters (it is cut away in the sample region to allow free muon passage). The sample chamber limits the size of the sample as listed in Table 4.5. The sample rod itself ends in a thermometry block to which can be attached different sample holders; the two holders currently in use are shown in Fig. 4.14. The usual holder is a rectangular copper frame on which small samples are mounted with thin Mylar tape. The other is a holder for a round powder cell.

Sample holders for the other low background apparatuses and the Belle insert are shown in section 2.6.1.



- *a* Fiberglass shell (outlines indicate where it is cut away)
- *b* Thin muon scintillator and light guide
- *c* Copper sample frame
- *d* Sample, attached by Mylar tape
- *e* Veto scintillator

Figure 4.13: Sample region of the standard muon veto cryostat insert.

Table 4.5: Sample size limits with the open frame sample holder in the standard muon veto insert.

	width × thickness	
Smallest sample:	~0.5 cm × 0.2 cm	(A ‘soft’ limit indicating where the good event rate becomes noticeably low. It becomes intolerably low at about 0.3 cm width.)
Widest sample:	3.1 cm × 0.75 cm	(Width limited by sample frame, thickness by compartment.)
Thickest sample:	2.2 cm × 1.3 cm	(Width and thickness limited by widest part of sample compartment.)
Intermediate sample:	2.6 cm × 1.0 cm	(Maximum sizes interpolate linearly between the previous entries; this entry gives the maximum width for a 1.0 cm thick sample.)

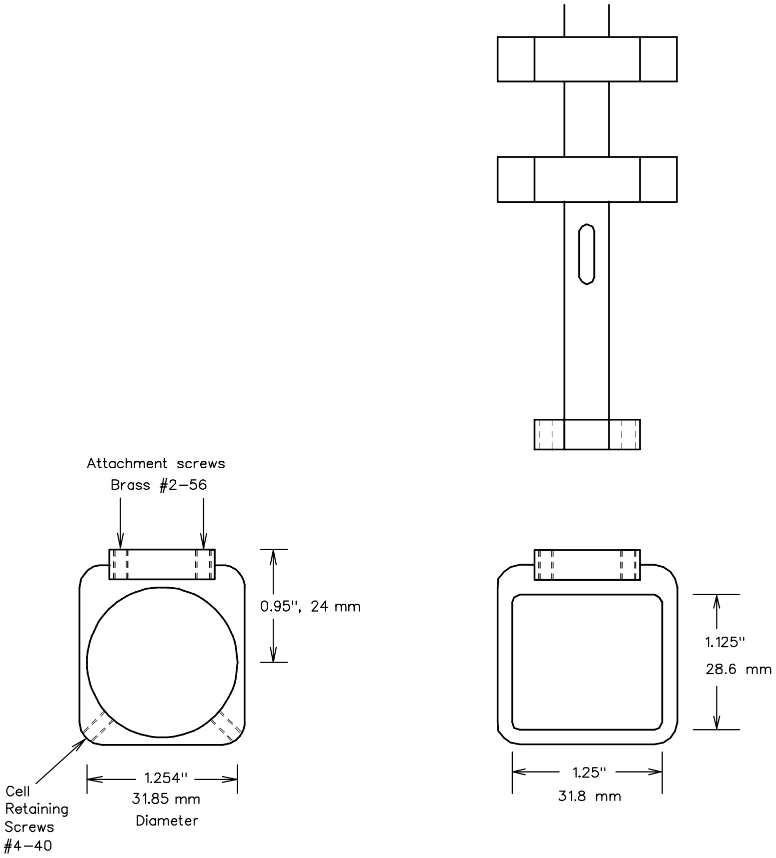


Figure 4.14: Sample holders for the muon veto insert.

5 Facility Resources

5.1 Equipment

Most of the major equipment belonging to, or available to, the TRIUMF μSR Facility consists of magnets (spectrometers), detectors, cryostats, ovens, *etc.* which are tabulated in Chapter 4, and the lists will not be repeated here. There is a lot of minor equipment in addition to the major apparatuses, and a good sample of these smaller devices is listed below:

6	LakeShore Autotuning Temperature Controllers.
2	Oxford Instruments Dilution Refrigerator Temperature Controllers.
3	Resistance Bridges.
1	High Precision Metrolab NMR Teslameter.
2	Group3 Hall Probe Digital Teslameters.
1	Lakeshore 450 Digital Gaussmeter.
1	Hand-Held Gaussmeter.
3	Zero Field Flux-Gate Magnetometers with dedicated feedback-controlled magnet power supplies.
1	Oxford Instruments Superconducting Magnet Power Supply.
1	Cryogenic Consultants Superconducting Magnet Power Supply.
3	HP Bipolar Power Supplies.

6 Single Phase Magnet Power Supplies (Zero Field Coils).
4 He-Pumping Stations.
4 Vacuum-Pumping Stations.
1 Personal Computer 386 with a Multi Channel Analyzer.
2 Personal Computers Pentium.

Plus several small current supplies, Operational amplifier supplies, Temperature sensors, Lead, brass and tungsten beam collimators, Small magnets (‘flip coils’), and more.

5.2 μSR Facility Personnel

Manager TRIUMF BOM appointed employee

Current Holder: Syd Kreitzman (since June 1993)

Found at: Trailer Bb, local 7303, email SYD.[1]

Responsibilities:

- User fee collection
- Facility equipment coordination and allocation
- Maintain contact with μSR user community
- μSR Facility budget preparation
- Setting facility priorities
- μSR facility staff policy and coordination
- Initiation of new μSR facilities
- Liaison with TRIUMF management
- Scientific activities

Condensed Matter Liaison Scientist NSERC μSR Infrastructure position

Current Holder: Bassam Hitti (since Feb. 1995)

Found at: Trailer Bb, local 6295, email HITTI.

Responsibilities:

- Experimental setup support—particularly for condensed matter
- Co-management and development of cryostats, cryogenic inserts, dilution refrigerator, and oven inserts
- Maintenance and development of scintillation counters and electronics M15, M13
- Maintenance and development of RF and microwave μSR spectrometers
- Provision of documentation of co-managed or maintained systems.
- Assisting the documentation of shared facility resources.
- Scientific research utilizing 20% of working hours.

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[1] All email addresses listed are local; for internet mail append “@triumf.ca”; *e.g.*, “syd@triumf.ca”.

Chemistry Liaison Scientist NSERC μSR Infrastructure position

Current Holder: Donald Arseneau (since Jan. 1995)

Found at: Trailer Bb, local 6295, email ASND.

Responsibilities:
- Experimental setup support—particularly for chemistry
- Co-management and development of backward muon facilities
- Maintenance and development of scintillation counters and electronics M20, M9B
- Maintenance and development of data acquisition and analysis systems integration
- Provision of documentation of co-managed or maintained systems.
- Assisting the documentation of shared facility resources.
- Scientific research utilizing 20% of working hours.

Software Systems Programmer TRIUMF and/or NSERC μSR Infrastructure position

Current Holder: Suzannah Daviel (since May 1997)

Found at: Trailer Gg, local 7306, email SUZ.

Responsibilities:
- Maintain data acquisition software for TD and TI experiments
- Develop and implement new DAC software and interfaces
- Integrate new hardware into the software control system
- Maintain software upgrades on DA machines.
- Develop and implement software ports to new hardware platforms

Mechanical Technologist NSERC μSR Infrastructure position

Current Holder: Mel Good (since June 1994)

Found at: Trailer J, M15, local 6200/6456,

Responsibilities:
- Spectrometer and μSR beam line setup
- Support the cool down of superconducting magnets and cryostats
- Provision of technical (AutoCad) drawings and designs
- Maintenance, modification and assembly of facility equipment
- Design of standardized mounting systems
- Technical liaison between μSR facility and machine shop
- Documentation on equipment operation and maintenance

Technician / Machinist NSERC μSR Infrastructure position

Current Holder: Edi Dalla Valle (since July 1997)

Found at: Trailer J, M15, local 6460,

Responsibilities:

- Spectrometer and μSR beam line setup
- Support the cool down of superconducting magnets and cryostats
- Fabrication of new equipment and parts
- Technical liaison between μSR facility and machine shop
- Maintenance, modification and assembly of facility equipment

5.3 TRIUMF site Support

- Machine Shop Support: Roland Roper (head); Machine Shop Building; local 7445.
- Scintillator Fabrication and Maintenance: Chris Stevens (head); Scintillator shop in front office building; local 6373.
- Electronics Support: (NIM and Camac modules) trailer Gg; local 6509. (Repairs) Naomi Shibaoka; trailer Gg; local 6514.
- Main Computer Cluster or Network Access: Russell King, Chemistry Annex, local 3232, email RKING. Hossein Rafighi, Chemistry Annex, local 3233, email HOSSEIN.
- Beamline power supplies: Bill Beck, local 6346. Ron Ginn, local 7407. Chuck Yee, local 6516.
- Beamline Control Hardware: Controls Hardware Group, local 7446. Peter Wilmshurst, local 6518. Tony Tateyama, local 6519.
- Beamline Control Software (TICS): Graham Waters, local 6531.
- Liquid helium: (arrangements are normally handled by μSR Facility personnel) Tom Inglis; Vacuum group office (west of main building) local 6276.
- Beamline vacuum system: George Takacs, Vacuum group office (west of main building), local 6276.
- For anything and everything, call the TRIUMF cyclotron operators; main control room; local 7333.

6 Having an Experiment Approved and Scheduled

6.1 The EEC

All experimental proposals at TRIUMF are screened by the Experiments Evaluation Committee (EEC), a peer review board constituted of distinguished scientists from all over the globe. This EEC convenes to hear formal proposals either twice a year (usually in early December and early July) for condensed matter physics or once a year (July) for chemistry disciplines. It then advises TRIUMF's Director of its recommended priorities in the allocation of beam time and major facilities. The Director is not bound by the EEC's recommendations, but has never ignored them. Proposals are solicited and received from individuals and groups around the world and are judged solely on the basis of scientific merit and feasibility. During their review they are assigned a priority rating that assists in the scheduling of the experiment.

Completed proposals should be *mailed* to the head of the TRIUMF Science division, Jean-Michel Poutissou:

Dr. J.-M. Poutissou
TRIUMF
4004 Wesbrook Mall,
Vancouver, B.C.,
Canada V6T 2A3

The EEC proposals are best submitted in a standard format to ensure that no essential information is omitted; TRIUMF provides for this purpose a LaTeX style file and a sample LaTeX input file, both of which may be obtained *via* e-mail on request. If you do not do text processing with LaTeX, a hard copy blank form and sample output will be mailed to you on request.

Deadlines for new proposals are usually around 6 weeks prior to the EEC meetings. Announcements of these meetings and the corresponding deadlines will normally accompany biannual mailings from the TRIUMF Information Office to registered members of the TRIUMF Users' Group (distinct from the μSR Users Group, which you should also join). Please pay close attention to these deadlines and leave plenty of time to prepare good proposals.

6.2 The Experimental Proposal

The proposal consists of a summary, beam requirements, TRIUMF support requirements, safety, and statement of research (science).

6.2.1 Summary

The summary must be less then one page in order to keep the EEC happy. It should clearly summarize the proposed experiment along with its scientific context and motivation.

Even at this early stage, it is particularly wise to clearly indicate how the proposed work fits into a broader program, and if it does not, why it can stand up as relatively isolated measurement.

Any unique aspect of the experiment should also be mentioned here.

6.2.2 Beam Requirements

Any particular requirements regarding beam properties are detailed here. The following is a list of properties that are commonly associated with various types of μSR experiments and on what secondary beamline they can be accommodated:

In general, the energy of the primary beam is 500 MeV. For all μSR experiments on M20, M15 and M13 the secondary beam line momentum will be 29 MeV/c for a surface beam. For high momentum muons that can be produced on M9B, muon momenta can range from 20 MeV/c to 90 MeV/c; please see Table 4.1 on page 44, and select a beamline and minimum beam current for your experimental requirements according to this schedule:

Experiment	Beam Current	Suitable Beamlines, Targets
Time-Differential – HTF	>40 μA primary >80 μA primary	M15 /w C T1 , M20 /w C T2 M20 /w Be T2
Time-Diff – LTF, LF	>40 μA primary	M15, M20, M13
Low Background	>120 μA primary	M15 /w C T1, M20 /w C T2
Time-Integral	>120 μA primary	M15 /w C T1, M20 /wC T2
High-p $\mu^{\pm}$	>80 μA primary	M9B /w C or Be T2

In some circumstances (where small field changes can be critical) it is required that the crane not be moved at random during an experimental run. If that is the case please indicate.

6.2.3 TRIUMF Support Requirements

Facility staff are responsible for beam line preparation and the mounting (and nominal alignment) of spectrometers, positron detectors, cryostats, ovens, pressure cells and other standard inserts. The standard μSR data acquisition systems are also generally available. During the course of the experiment, and during nominal working hours, experimenters may request that facility personnel assist in the liquid He filling of the SC magnets. The individual experimental groups are responsible for maintaining the cryostats with liquid cryogens.

Beyond this level of support, any further requirements should be indicated here. Some examples where special support might be needed are:

- Mounting of specialized counters.
- When there is an unusual geometry for the experiment.
- Any specialized data acquisition support. As an example, it may be necessary to control and monitor a non-standard piece of equipment (*e.g.*, an x-y table).
- Any specialized needs or equipment regarding sample preparation.
- Unusual restrictions on the operation of our standard systems, *e.g.*, if a magnet needs to be particularly stable.
- Use of additional equipment that goes beyond what is normally associated with a given setup.

It should be mentioned that, in the above situations, the facility will generally not consider building or otherwise providing any specialized hardware that does not have a broad application. This type of hardware should be prepared by the individual experimental groups and its provision should be documented in the Experimental Equipment subsection of the Detailed Statement of Proposed Research.

6.2.4 Safety Issues

Rules regarding the safe operation of an experiment have recently (Sept. 1995) been revised to ensure that

- Adequate planning has been carried out to address any safety issues.
- Responsibility for safety during the experiment is clearly defined by designating a **Safety Project Coordinator** (SPC) for each proposal.

An experiment that does not pass its safety review will not be considered for scheduling. The review is carried out by the Safety Review Committee, and if safety concerns are raised, the TRIUMF Safety Group (TSG) will become involved with the SPC to address the problem. This whole process will be carried out before the call for beam time for those experiments that obtain EEC approval.

To help with the planning for a safe experiment the call for proposals from the user group contains two documents dealing with safety. One is a general (experiment independent) guide that outlines how the safety section of the proposal should be structured, and the other is a μSR specific form that deals with μSR specific safety issues. Filing both of these is mandatory.

The first document, the guideline for preparing a safety report, requires that a proposal provide the following information and safety data:

- Identification
    - Name of experiment leader
      address, email
      telephone, fax
      name of local contact
    - Official EEC name and number of experiment
      name of SPC
      address, email
      telephone, fax
- Description of Experiment
  location
  layout
  conditions
  reference to relevant design codes
- Definition and Estimates of Hazard
    - One can say there is *absolutely* no hazard,
    - but if it is a case of “safe *if* this or that” then the conditions and rules for safe operation must be spelt out in detail.
    - Specify consequences in case of failure.
- Safety Measures
    - Say, in detail, how safety measures will address hazard.

Sample Handling/Disposition and Special Equipment Procedures Form

Sample Handling/Disposition and Special Equipment Procedures Form

  - Results of safety tests.
  - Copies of actual safety instructions for experimenters, should such be desired.
- Responsibility
  Basically, the experiment leader and/or SPC (if different) is responsible for everything.
- Outline plans for decommissioning or disposal.

The second, μSR-specific, form must also be completed. A blank form can be copied (or removed) from the preceding page.

6.2.5 Detailed Statement of Proposed Research

This section tends to occupy the bulk of an EEC proposal. It should contain:

1. Scientific Justification
   - Importance of the Experiment
   - Competitive Measurements
   - Theoretical Calculations
2. Description of the Experiment
3. Experimental Equipment
4. Experimental Readiness
5. Data Analysis
6. Beam Time Required

6.3 Beam Requests and Allocations

There are usually two high-intensity running periods a year at TRIUMF, averaging about 12 weeks each: one from mid-November to late February and one from late May to early August. Beam time is usually allocated in quanta of "weeks"—5–7 days (8–14 shifts) of 24-hour-per-day operation—separated by Maintenance Days during which any apparatus changes are normally completed.

Spokespersons for EEC-approved experiments will be contacted by TRIUMF management approximately 100 days before each beam period and asked to submit beam time requests and safety documents on standard forms or an online html form.

After the completed beam time requests have been returned and collected, they are ordered according to the priority rating given by the EEC and according to the remaining beam allocation available. (Experiments which have not taken beamtime for two years and have not appeared in front of the EEC are no longer eligible.) The head of the TRIUMF science division, with the help of the beamline coordinators, produces a rough outline of the schedule, and then each beamline coordinator provides a possible schedule for the respective channel(s). Experiments are then placed on the schedule according to priority, preferred instrument availability, and preferred period.

With luck, there will be enough beamtime available to satisfy all the outstanding requests, but that is unusual. When conflicts occur, the scince division head makes the final selection of which experiment will get time, taking into account: the past performance (effective use of beamtime, publications); thesis requirements; how much total beamtime is already allocated to that same group; and the possibility of delaying the experiment to the next beam period (when it would be given precedence over other experiments of equal priority).

A draft schedule is circulated to get feedback, in particular for those cases where some of the specific requirements could not be met or conflicting demands could not be resolved. A final scheduling meeting is held at TRIUMF and the schedule is then frozen.

6.4 Timing of Beam Requests and Maintaining Experimental Continuity

In considering the timing of beam allocation, it is important to remember that the EEC meetings, where experiments are approved, take place during a beam period whose schedule is already filled with older experiments. The delivery of beam to an approved new experiment (or one which has exhausted its previously allocated beam) usually proceeds in one of the following scenarios:

1. An experiment may receive approval at a given EEC meeting and be allocated beam time during that very same beam period in which the EEC convened, *i.e.*, to be inserted in the current schedule. This situation is usually manifest for a very high priority experiment on a late breaking system coupled with the circumstance that, during the previous scheduling exercise, there was adequate beam availability to have some of if set aside for this purpose.
2. An experiment that receives approval from the EEC (at some priority) submits a beam request for the following running period—typically 5 months away. If there is adequate beam time available, all requests will be filled. If there is a backlog and/or insufficient beam, requests are filled on a priority basis.
3. An experiment which did not receive a beam time allocation in the next beam schedule after an EEC meeting should receive its allotment in the next schedule after that, but it might be delayed again. In the former case, approximately one year has transpired from the granting of EEC approval. In the latter case the combination of a low priority experiment and inadequate beam availability may allow newer, higher-priority experiments

> to preempt older but lower-priority studies. If an experiment of medium priority finds itself in this situation, the spokesperson should approach the TRIUMF administration and vigorously argue that insufficient beam time is available for the community's needs.

From these scenarios, it can be seen that there is typically a 6-month to 1-year time lag from EEC approval to finding one's experiment on the beam line.

Users should be made aware of another situation that often arises, and that is one of maintaining experimental continuity in the face of intrinsic scheduling delays. This situation is best illustrated by a rather typical example.

Suppose spokesperson/group Unaware proposes an experiment that requires two weeks of beam to do an initial study, and then, contingent on the results obtained, will need additional beam to mount a longer term program. The EEC approves his proposal, and he is allotted two weeks during the next beam schedule; half a year hence. When the time comes for Unaware to run the experiment, another EEC committee is meeting at the very same time—or had even met before Unware's beam. Because there is nothing to report to that EEC, Unware has to wait half a year for the next EEC meeting. Presuming the initial experiment was successful, *that* EEC would allocate more beam time, to begin in the next beam period afterwards—another half year wait. Thus, without doing anything wrong, a year has passed between beam periods for the Unaware group.

To avoid this situation, Prof. Unaware should be aware that if his experiment will use up its allotted beam time during the next running period, he should arrange to have something to report to the EEC which will meet concurrent with that experiment, in order to request additional beam time. For an experiment that is having its first run, it is especially critical to have some beam time before the EEC meeting so that preliminary results can be reported. The situation is not so critical for older experiments that are about to run out of allocation, since they should have previous measurements on which to base any further requests for time.

6.5 μSR Users Time

If demand for access to certain beamlines (commonly M13) is less than the total beam time available, the excess time may be allocated as *μSR Users' Time*. This time will be allocated to experimenters that request it by TRIUMF's Director and the head of the TRIUMF Science Division. This extra beam time gives users the chance to respond rapidly to recent discoveries; to recoup beam lost earlier in the schedule; to make some progress in an experiment when other beam time was not allocated; and to try out new experimental techniques before making a major EEC proposal.

6.6 Proposal Extensions

Often, during the course of an experimental program, the beam time originally allocated is not sufficient to adequately complete an investigation. It it then appropriate for the group leader to present a progress report to the next EEC and request additional beam time under the same experiment number. In these circumstances, the EEC has instructed that some very specific issues be addressed. They are

- The user should reiterate the goal and overall context of what was proposed and done during the original proposal and clearly explain why those are relevant to the requested extension.
- The user must clearly state why the extra beam time is required. For example:
  1. has a relevant but unanticipated aspect of the phenomenon been unearthed, or
  2. have the originally proposed measurements proven to be less sensitive to the phenomena and more time is required
  3. *etc.*...
- The user should detail exactly what will be done with the extension, what samples will be measured, and how much time will be required of each sample.

For the chemistry proposal extensions that occur *via* mail/email during the winter EEC (when the chemistry EEC representatives are not present at TRIUMF), it is particularly important that such requests follow these guidelines. The spokesperson will *not* have an opportunity to defend the extension request personally.

6.7 User Fees

The infrastructure and Major Facilities Access (MFA) grant, under which μSR at TRIUMF operates, imposes strict guidelines as to which costs its funds can and cannot be applied. Specifically, these funds can only be used for operating and maintaining the facility infrastructure. No direct research support, recoverable consumables, or new facility installations are allowed from this grant.

Clearly, these items are needed for the facility to operate smoothly, and the terms of the grant address this need by requiring that direct user fees be assessed to cover those costs.

In practice, the MFA grant does not cover all the MFA-eligible costs of the μSR facility, so not only must the non-MFA costs be made up in user fees, but the user fees must also supplement the MFA-eligible costs.

Therefore, all liquid helium costs are directly passed on to the user and will appear as a liquid He charge against their TRIUMF account. Furthermore, when a group utilizes any of the facility resources, a user fee is assessed. In those cases where high intensity beam is provided to an experiment, the beam delivered will determine the amount of the user fee. On the other hand, when facility resources are used in the absence of beam, an *ad-hoc* assessment will be made by the facility manager.

7 Preparing to Run an Experiment

After an experimental proposal has been submitted and presented to the TRIUMF μSR experimental evaluation committee (μSR EEC) the spokesperson will receive a letter from the head of the science division that includes the recommendation of the μSR EEC, the number of shifts (12 hours of beam) approved and at which priority. The TRIUMF cyclotron currently runs two high intensity production periods every year. Depending on the experiment readiness and demand for beam the approved shifts can be used during one or more beam periods.

7.1 Before Your Visit

Scheduling Before scheduling each period, beam request forms are sent to the spokesperson of each active experiment. It is the responsibility of this person to contact the rest of the group and return to TRIUMF their request which should include the number of shifts, apparatus and beam line they would like to use. The μSR time is then allocated and scheduled among the various users. You can also request to exclude dates when you can not use the beam, however, it is always very difficult to satisfy the demand of all the users and the constrains on our resources so please try be flexible when possible.

Safety TRIUMF is committed to maintaining a safe and healthy working environment for its workers and visitors. To this end each experiment must appoint a Safety Project Coordinator (SPC) and each beam time request form must be accompanied by a safety report signed by the SPC. No experiment will be scheduled to run without safety approval by the science division and the TRIUMF Safety Group (TSG). A guideline for preparing the safety report will be sent with the beam request form.

Technical review The resources of the μSR facility are limited; please be sure to outline on the beam request form the demands your experiment will place on these resources.

The facility maintains a number of cryostats and ovens. The samples you plan to measure should fit in the holder and cryostat that will be used. For information on the dimensions that can be accommodated please refer to the apparatus selection guide in Chapter 4 of this guide.

Accommodations TRIUMF house is a guest house located on the U.B.C. campus about 2.5 km from the laboratory, it provides accommodation to visiting scientists. Room rates vary from $ 25/night for a single room with hall bathroom to $ 35/night for single room with private bathroom. A fully equipped common kitchen, laundry facility, TV room and rental bicycles are some of the amenities available to guests. A limited number of double rooms and rooms with kitchen are also available. For information and reservation contact the housing office during business hours at (604)222-1062 or 222-6733, by FAX (604)222-3576 or by E-mail `housing@erich.triumf.ca`. Make your reservation early as TRIUMF house gets very busy when the beam is on; in particular during the summer.

Transportation Thrifty car rental offers special rates to TRIUMF visitors, reservations can be made by calling Thrifty; their telephone number is (604)276-0800 for the Vancouver International Airport depot. Taxi service from the Airport to TRIUMF house costs about $ 25. Close to TRIUMF house there is only a limited number of shops and restaurants, but bus service to the rest of the city is available.

Shipping Programs are available to temporary import duty free scientific equipment into Canada to be utilized in experiments at TRIUMF. For the best procedure that applies to you and the appropriate documents please contact Andy Decsenyi at Shipping and Receiving (local 7367) well in advance of shipping your goods.

7.2 When you arrive

It is essential that you arrive at TRIUMF a few days before the start of your experiment. You can use this time to become familiar with the TRIUMF environment.

Key and Badge The area inside the TRIUMF perimeter fence is a controlled radiation zone. A temporary key to enter the fenced area can be obtained during office hours from the Personnel Office (Josie Farrell/Dana Rains; locals 7332/7360). If you plan to stay at TRIUMF for more than few days, on arrival contact Christine Unkmeir (local 6450) to obtain a dosimeter badge which must be worn at all times when in the radiation controlled area. For short visits a direct reading dosimeter can be obtained from Stores during office hours or the control room at all other times. You can contact the control room through speakers on the wall next to the entrance.

Under no circumstances may any person enter the radiation controlled area without a badge or dosimeter.

Experimental setup The personnel of the μSR facility maintain all the common hardware and software necessary to carry out μSR experiments. We will mount the equipment in the experimental area, set up the standard data acquisition electronics and make sure beam is delivered to your experimental area. It is very important that you be available during that time to become familiar with the equipment and procedures and to answer question relating to your experiment that might arise during set-up.

Control room It is your responsibility to make sure the control room has a copy of the safety approval form and to fill in a beam properties request form. Without these two, beam will not be delivered to your experiment.

Account It is very useful to open an account at TRIUMF. You can use this account to pay for store items, TRIUMF house charges, Thrifty car rental, phone calls, your liquid helium bill, and the user fee. To open an account contact Shirley Reeve at accounting (local 7391).

Data Analysis Center (DAC) The DAC at TRIUMF has two VAX 8650s available for use by visitors. These machines are on the VAX cluster with the node names Erich and Reg. Registration forms can be obtained from outside the DAC office located in room 206 of the Chemistry Annex (the north-east wing of the main TRIUMF building). The name and signature of your local contact will be needed on this form. Support is provided by the following people: Accounts and network problems: Russell King (local 3232, E-mail RKING), General support: Corrie Kost (local 7365, E-mail KOST, Fred Jones (local 6310, E-mail FWJ), and Joe Chuma (local 6310, E-mail CHUMA). The "TRIUMF VAX Cluster User's Guide" provides a good introduction for new users, the LaTeX sources for this document can be found on ERICH::PRV2:[KOST.TEX.VAX_USERS_GUIDE]VAX. TEX.