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# TRIUMF MuSR and βNMR Research Facilities

S.R. Kreitzman*, G.D. Morris

*TRIUMF, Vancouver, Canada*

**E-mail: syd@triumf.ca*
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The TRIUMF Centre for Molecular and Materials Sciences (MMS) supports a MuSR user facility and a βNMR research program. An overview of this infrastructure, and its future prospects, are presented.

**KEYWORDS:** MuSR, βNMR, βNQR, muon $^{8}$Li beam lines,

## 1. Introduction:

TRIUMF[1] is an accelerator based Canadian National Laboratory focused on the support of nuclear and particle physics, rare-isotope beams, nuclear medicine, accelerator physics, and MMS. Its MMS infrastructure, comprised of three[2] muon and two β-active isotope secondary beam lines, forms its core program in condensed matter physics and physical chemistry. Similar to other MuSR facilities, the range or research encompasses a very broad spectrum, *viz.* magnetism, superconductivity (high Tc, conventional and exotic), hydrogen in semiconductors, radicals and radical reactions, gas phase dynamics, diffusion, battery materials, quantum phase transitions, topological states, spintronics, frustrated systems, reactor moderators, heavy fermions, interface and surface states, super-critical fluids. The muon beams at TRIUMF are bulk matter probes whereas the low energy spin polarized[3] radioactive ion beams (RIB) delivered for βNMR are designed to study ultra-thin films and surfaces[3]. The MMS facility is directly

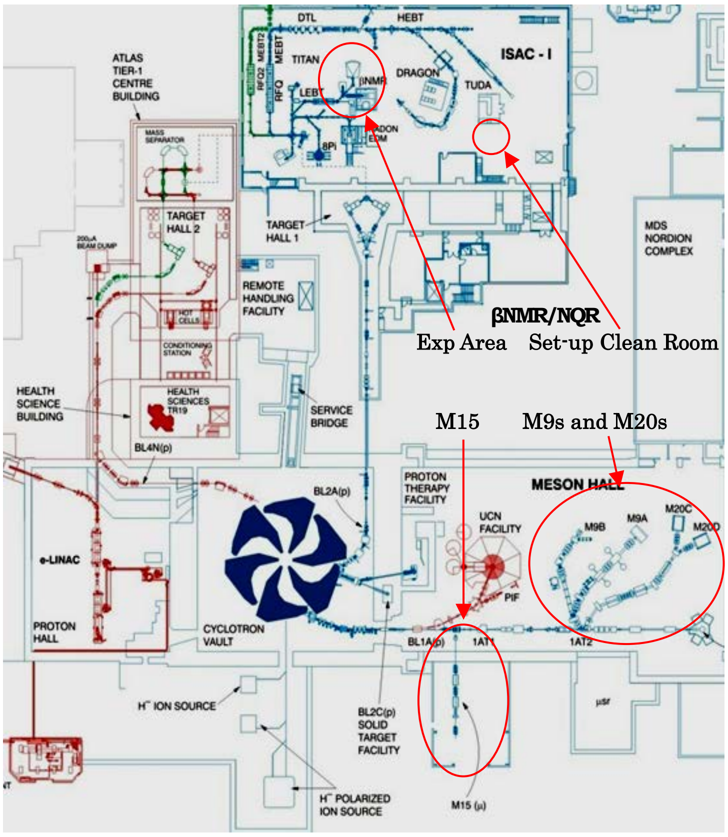


Figure 1: CMMS beam-lines at TRIUMF

supported by a dedicated staff of five resident scientists and three technicians. Access is governed by biannual submissions to an Experimental Evaluation Committee (EEC) which recommends beam allocations to the Science division head. TRIUMF is a safety focused environment and as such safety and building access training is required prior to a user engaging in activities on site. Further onsite training is provided for beamline access and interaction with specialized equipment.

The MuSR beam lines have historically operated for 8 months/yr. Beam time is generally allocated into weekly blocks. The βNMR beam lines operate for 5 weeks/yr and tight experimental scheduling with typical duration of 1-2 days. TRIUMF does not levy fees for utilizing its MMS research facilities but nor does it support user travel and/or accommodation costs. If liquid He is needed for the experiment a charge of $C1.75/liter is levied for the L-He consumption during the beam delivery period.

## 2. Beam Lines:

During the last 5 years TRIUMF has rebuilt its M20 channel, and added a new surface muon channel at M9. The M9 beamline is undergoing a refurbishment of its front end connection to the T2 target station and its anticipated operation will commence in 2019.

**Table 1: CMMS Beam Lines and their Beam Properties**

| **Beam-Line Properties** | **Flux** (/s) | **Luminosity** (/s-mm$^2$) | **Momentum (or Energy)** | **Spin Polarization** T: **P**⊥ **z** ; L: **P** ∥ **z** |
|---|---|---|---|---|
| M15 | 7.5e5 | 6e3 | 28.5+/-1 MeV/c | 1@T, 95@L |
| M20 c & d | 5.5e5 | 7.1e3 | 28.5+/-.5 MeV/c | 1@T, .99@L |
| M9a | 7.5e5 *(est)* | 1e4 *(est)* | 28.5+/-.5 MeV/c | 1@T, .95@L |
| βNMR | 1e7 ($^8$Li) | 1e7 ($^8$Li) | .1-40keV $^8$Li, $^9$Li, $^{11}$Li, $^{11}$Be, $^{31}$Mg | -.7→+.7 ($^8$Li) @L |
| βNQR | 1e7 ($^8$Li) | 1e7 ($^8$Li) | .5-40keV $^8$Li, $^9$Li, $^{11}$Li, $^{11}$Be, $^{31}$Mg | -.7→+.7 ($^8$Li) @T |

The muon beams use high voltage dual achromatic Wien filters capable of fully rotating the $\mu^+$ spin by $90^0$ to create a fully (100%) transverse (T) spin polarization. βNQR transmits the beam through an electrostatic $90^0$ bend to reorient the initial longitudinal (L) polarization into a transverse orientation.

## 3. Spectrometers, Sample Environments & Specialized Inserts:

To date, MMS facility beamlines do not have fixed spectrometers and the requirements of a specific experiment usually dictate the most appropriate instrument. Efficient MMS operations require that the spectrometers be scheduled in large contiguous blocks of time.

**Table 2: CMMS Spectrometers and their Characteristics**

| **Spectrometer** | **Field Range** | **Access** | **Experimental[4] Configuration** | **Detector Solid Angle** (π sr) | **Central 1cm Homogeneity** |
|---|---|---|---|---|---|
| DR (M15) | 0-5T | Vert. | ZF,LF, HTF | 1.5 F/B; .1-.02 L/R | 150 ppm (HTF) |
| NuTime (M15) | 0-7T | Horiz. | HTF, LF | 1 HTF | 1.5 ppm |
| Helios (H: M20, M15, M9s) | 0-7T | Horiz. | ZF, LF,TF | 1-2 | 10 ppm |
| LAMPF (L: M20, M15) | 0-.4T | H/ Side | ZF, LF,TF | 4 | 100 ppm |
| SFUMU (SFU: M20s, M15, M9s) | 0-.35T | H/V/Side | ZF, LF,TF | 2 | 200 ppm |

| | | | | | |
|---|---|---|---|---|---|
| OMNI’ (O’: M20s, M15, M9s) | 0-.3T | H/V/Side | ZF, LF,TF | 2-4 | 400 ppm |
| HodgePodge (HP: M20D) | 0-.4T | Radial | B \|\| Sample face | 1 | 500 ppm |
| bNMR (ISAC-I) | 0.1-9T | Axial | LF, B+SF | .1 F | 1 ppm *(effect)* |
| bNQR (ISAC-I) | 0-24mT | Horiz | LF, B\|\| SF | .06 | 100 ppm *(effect)* |

The two beta-NMR spectrometers differ principally in the magnitude and orientation of the applied magnetic field and as a consequence, the layout of the beta detectors. The high field spectrometer has the standard MuSR-like LF geometry with the initial polarization normal to the sample face. The low field spectrometer applies fields transverse to the beam momentum and in the plane of the sample face, a geometry suited for studying superconductors in the Meissner state. Beta detectors in both cases are arranged along the initial polarization and either spin-lattice relaxation or RF induced spectral transitions drive the observable polarization decay. Further details regarding the two instruments' configurations and capabilities are provided in reference [5].

Various sample environments are available, some dedicated to specific spectrometers, but others portable to specific spectrometers for experimental optimization. Additionally, the cryostats can accommodate specialized inserts which provide extended experimental capabilities. Tables 3 and 4 detail the compatible configurations.

**Table 3: Sample Environments**

| **Name or Mnemonic** | **Temp Range** | **Spectrometer Compatibility** | **Sample Size** | **Sample Loading** | **Sample Cycle Time** |
|---|---|---|---|---|---|
| DR (cold finger) | .012-10K | Stand alone | 5x5-15x25mm$^2$ | top / vac. lock | 2 hrs |
| NuTime (NT: gas flow) | 1.5-300K | Stand alone | 2x2 -8x8 mm$^2$ | axial /+ detects | 45 min |
| Miss Piggy | 1.7-300K | LAMPF | See Table 4: | axial | 15 min |
| HGF1 (gas flow) | 2.5-300K | H, L, SFU, HP, O’ | 7-25mm Ø | axial | 30 min |
| HGF2 (gas flow) | 2.5-300K | H, L, SFU, HP, O’ | 7-25mm Ø | axial | 30 min |
| Oven (vac or xch gas) | 295-1000K | H, L, SFU,HP, O’ | 10-30mm Ø | axial | 1 hr |
| Pluto (cold finger) | 2.5-300K | H, L, SFU, HP, O’ | 10-20mm Ø | axial | 1.5 hr |
| βNMR (cold finger) | 3.5-317K | Stand alone | 1x1 - 8x12.5 mm$^2$ | top / vac. lock | 40 min |
| βNQR (cold finger) | 4.2-317K | Stand alone | 2 x 2 - 12x12 mm$^2$ | ladder | 1-40 min |

**Table 4: Inserts**

| | **Compatible Environment** | **Sample Dimensions** | **Experimental Capability** |
|---|---|---|---|
| Low Backgnd | Miss Piggy | 4-20mmØ | μ Veto |
| Ultra-Low Backgnd | Miss Piggy | 2-10mmØ | μ & $e^+$ Veto |
| Knight Shift /Low B | HG1 | 3x3-25mmØ | +/- 3ppm @4T |
| RF-MuSR | HG1 | <15x20 mm$^2$ | 10-250 MHz |
| μWave-MuSR | HG1 | <15x20 mm$^2$ | .8-2.2 GHz |
| HP cell (only M9H) | HG2 | 7mmØ | 2 GPA |
| Light Modulation (Halogen Lamp) | HG1&2 | 45mmØ | 50 Watts @ .03Hz |

## 4. Future Developments and Directions:

Historically TRIUMF has provided a muon-decay channel (M9B) that featured a spin-rotated beam at higher momenta. Reliability issues require that the solenoid, provided by KEK[6], be replaced. This upgrade will re-enable extreme environment MuSR at the MMS. The second major initiative is focused on implementing a new generation of detectors, based on Si-PMs (i.e. Avalanche Photo Diodes), into all spectrometers. On the βNMR side, a rapid switching (~1kHz) kicker is planned to allow fast multiplexing of the beam among the various end stations, decoupling their simultaneous operation. Additionally, a second end station for the βNQR leg will deliver magnetic fields up to 0.2T (parallel to the sample face) and temperatures to 300mK.

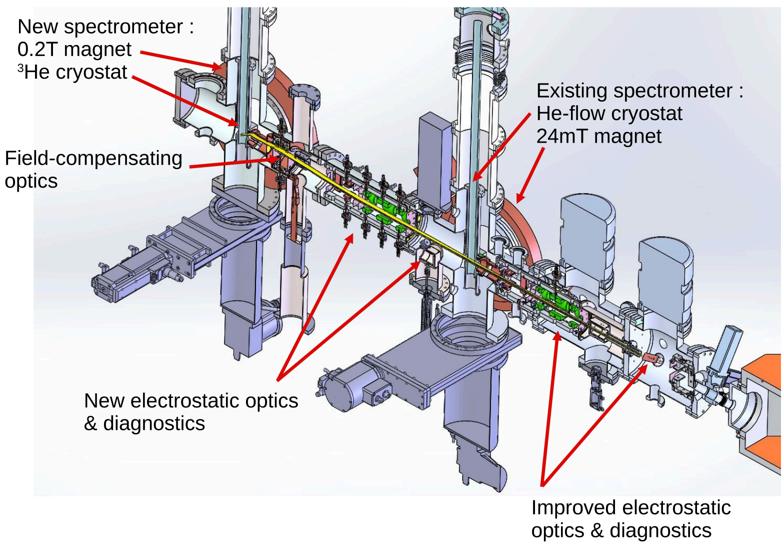


Figure 2: Planned upgrade to the low/zero-field βNMR/NQR beamline adds a second spectrometer for higher magnetic fields and lower temperatures. This down-stream station is accessed simply by removing the sample rod from the existing spectrometer. The bending of the beam in the .2T fringe field is electrostatically mitigated along this part of the trajectory.

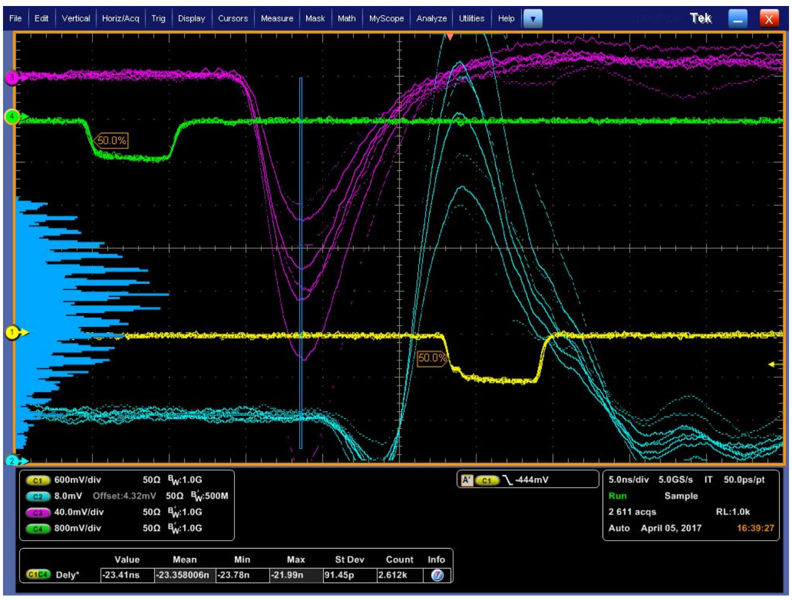

Figure 3: An Si-PM based muon signal produced by a 70ps 405nm laser pulse (green sync ±28ps). The purple / magenta traces are a few samples of amplified signal / CFD output (yellow sync edge) pulses. The blue histogram (left) records the discreet Poisson distribution of the quantized SIPM photo-electrons (PE) signal amplitudes, indicating an average of 16 detected PE given the acceptance trigger of 9 PE. The green → yellow edge RMS timing is ~ 72ps.

## 5. Conclusion:

TRIUMF has formally recognized its MMS facility as a fundamental pillar of its research mission. As such, a positive environment exists to realize the potentialities of its many current MMS initiatives and thereby significantly strengthen and broaden its scope within these research areas.

## Acknowledgment:

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## References:

[1] http://www.triumf.ca/research-program/research-facilities
[2] Two are currently operational.
[3] C.D.P. Levy, M.R. Pearson, R.F. Kiefl, E. Mané, G.D. Morris, A. Voss, Hyperfine Interactions **225,** 173 **(**2014).
[4] ZF=zero field, LF=Longitudinal field, TF=Transvers Field, HTF=High Transverse Field
[5] G.D. Morris, Hyperfine Interactions **225,** 165 **(**2014).
[6] http://www.triumf.ca/galleries/image/5-japanese-delegation-m9-upgrade