# Fermilab LDRD Proposal

## Project Title: High-Intensity Multi-slice Target Development

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**Lead Division/Sector/Section:** AD/Muon Dept/Simulations
**Co-Investigators (w/institutions):** M. Kiburg (PPD, Fermilab), B. Kiburg (PPD, Fermilab), C. Loss (TRIUMF and AD, Fermilab)

**Proposed FY and Total Budgets:** (summary of budget page (in dollars))

| | SWF | SWF OH | M&S | M&S OH | Contingency | Total |
|---|---|---|---|---|---|---|
| **½ yr FY21** | **199,212** | **122,096** | **246,000** | **10,652** | **202,286** | **780,246** |
| **FY22** | **158,318** | **97,033** | **10,000** | **433** | **98,131** | **363,915** |
| **FY23** | **0** | **0** | **0** | **0** | **0** | **0** |
| **½ yr FY24** | **0** | **0** | **0** | **0** | **0** | **0** |
| **Total** | **357,530** | **219,129** | **256,000** | **11,085** | **300,626** | **1,144,161** |

SWF: Salary, Wages, Fringe SWF OH: overhead on SWF
M&S: Material and Supplies M&S OH: overhead on M&S
Contingency (estimate of additional funds that might be required with justification: Contingency justification is in the Budget Table section)

**Initiative:** 2021 Broad Scope

## Project Description

The present Fermilab 400-MeV and the future PIP-II 800-MeV $H^-$ beams have the potential to produce precision, single-species secondary beams at record intensities including very low energy intense $\mu+$ AND $\mu^-$ beams. Low-energy $\mu^-$ beams are not generally available at any accelerator facility (only Mu2e and the future COMET experiments). Low-energy muon beams can support world-class new physics experiments such as charged lepton flavor violation (CLFV), HEP R&D such as analyses of surface damage in SRF cavities, and a recent DOE-directed initiative in muon catalyzed fusion. Intense $\mu^+$ beams are currently produced through intense bombardment of a low-Z target (graphite or Be) with protons to achieve the highest production rate while minimizing multiple scattering blowup in the outgoing primary proton beam. However, pion/muon total production cross sections increase as $Z^{1/3}$ for $\mu+$ and $N^{2/3}$ for $\mu^-$. Higher mass targets such as tantalum potentially increase low-energy $\mu+$ and $\mu-$ rates by factors of 3 and 8, respectively. Additionally, the muon yield is highly sensitive to the target surface/volume geometry and the secondary beamline solid angle and orientation. The objective of this work is to study higher Z and novel multipole target slice geometries which decrease pion mean-free escape paths, combined with strategic optimization of secondary beamline direction and transport to support a wide range of experiments. This proposal advances a unique opportunity to test heavy, novel targets in a new secondary beamline in the Muon Test Area (MTA) leveraging recent infrastructure upgrades and an independent DOE-funded experiment that will measure muon production data. Deliverables will include a physics study and beam test of novel targets, improved low-energy production models and an MTA beamline for R&D. These deliverables provide critical input to the Snowmass planning process especially in considering future PIP II facilities.

## Significance

The 800-MeV PIP-II Linac beam provides a unique opportunity to develop world-leading muon beams, especially low-energy and surface muons, with unparalleled intensity to drive the next generation of precision muon physics experiments and muon beam facilities; experiments that follow Fermilab's g-2 and Mu2e experiments. The 400-MeV $H^-$ beam available in the Fermilab MTA area further provides an opportunity for a test area for developing and testing production target concepts and optimization of collection and transport of low-energy muon beams, including both polarized surface muons (~4 MeV $\mu$+) and low energy decay-in-flight, "cloud" muons (~4 –100 MeV, $\mu^+$ and $\mu^-$). A short list of experiments and future facilities that would benefit from this research include:

- Charged Lepton Flavor Violation experiments ($\mu^+$ *and* $\mu^-$) [1–6]
- Muon EDM measurements ($\mu^+$ *proposed*) [7–10],
- Muonium and antimuonium transitions, gravity and spectroscopy ($\mu^+$), [11–17]
- a world-leading MuSR facility ($\mu^+$)[18]
- Muon catalyzed fusion experiments ($\mu^-$)[19–22].

CLFV is a powerful approach to explore new physics beyond the Standard Model and muon CLFV has specific noted advantages with projected orders of magnitude improvement in sensitivity for many processes[23]. Muon CLFV are either decay searches[24] ($\mu+\rightarrow e\gamma$ and $\mu+\rightarrow 3e$, MEG, Mu3e at PSI) or muon to electron conversion in the field of a nucleus ($\mu^- N\rightarrow eN$, Mu2e at Fermilab and COMET at JPARC[2–5]). Decay searches use surface (<4 MeV) $\mu^+$ beams which decay in stopping targets[6] and muon conversion experiments require low-energy (100 MeV or less) $\mu^-$ beams. Both types of experiments are required to resolve the type of the physics amplitude responsible for lepton flavor violation; i.e. a four fermion and a dipole amplitude [23]. Development of intense low-energy $\mu^-$ beams have become a priority for muon conversion CLFV experiments. The proposed PSI muon EDM experiment utilizes a low-energy 50 MeV $\mu$+ beam and the funded muon catalyzed fusion experiment requires a variable energy, 10-50 MeV, well-focused $\mu^-$ beam.

Muon Spin Resonance involves embedding polarized, positively charged surface muons in a sample material which allows the properties of the material to be measured and characterized at the microscopic atomic-structure level. The spin of the muon couples to the local magnetic field of the material, making them sensitive probes of the magnetic environment. The $\mu^+$ decays within a short time ($\tau_\mu$ = 2.197 μs) to a positron and two neutrinos, with the positron emitted preferentially in the direction of the initial $\mu^+$ spin. Detection and measurements of the positrons reveals evolution of the $\mu^+$ polarization in the sample material, from which the properties of the target material can be determined. A MuSR facility at Fermilab has been proposed in the past to advance superconducting R&D by studying SC surfaces after breakdown or quenches and also general characterization of material damage from high radiation environments.[25]

At present, there are four operating accelerator μSR facilities in the world, with TRIUMF hosting the only North American center. At ISIS, PSI, and J-PARC the proton beams are optimized for production of neutron beams for neutron scattering experiments, not muon production. Muon production runs parasitically with strict limits on the degree to which the primary proton intensity for the neutron program can be reduced – with reduction reflecting a combination of target interaction length (IL) and outgoing primary beam loss (due to beam blowup). TRIUMF is the exception but its primary role is to service a wider nuclear community and the facility is not optimized for muon production.

Intense low-energy muon beams are currently produced through intense proton bombardment of a low-Z production target. Positive pions are produced in nuclear reactions and those that decay "at rest" near the surface of the production target generate low energy muons with polarization as high as 100% (a $\pi^+$ at rest decays into a 4.120 MeV, or 29.792 MeV/c, $\mu^+$ and a neutrino). Only muons formed close to the target surface, or surface muons, escape and these are positive because low-energy negative muons are captured by the target nuclei. Pions that decay in flight are called cloud muons and have a lower net polarization because of the large uncertainty in parent momentum. Either surface or low-energy muons are transported via a low-energy beamline to an experimental target. Low energy negative muon beams are currently experiment specific (Mu2e and the future COMET experiment at JPARC) and are not available outside of the experiment.

Low-Z materials, graphite or Be, have been used for all MuSR targets to date to achieve the highest production rate that minimizes the contribution of multiple scattering to the properties of the outgoing primary proton beam – a critical condition for the downstream spallation targets at PSI, RAL, and J-PARC. TRIUMF utilizes a Be target to increase the radiation length vs nuclear interaction length ratio over graphite, again to control the primary proton beam transport through downstream systems, ultimately to a beam absorber. Even the COMET experiment notes that higher Z targets favor muon production, yet chose graphite from primary beam loss considerations[5]. All current production schemes are compromised by limiting the target impact on the outgoing primary beam considering downstream programs, or low-loss transport of primary beam to an absorber.

Since pion/muon total production cross sections increase as $Z^{1/3}$ for positive muons and $N^{2/3}$ for negative muons[26], higher mass targets such as tantalum can potentially increase low-energy μ+ and μ- rates by factors of 3 and 8, respectively. However, the muon yield is highly sensitive to the details of the target geometry and coupling to the secondary beamline collection design and orientation – low energy pion production is predominately backward and increasingly isotropic the lower the energy as shown in Figure 1. At proton energies lower than a GeV, a low energy muon production peak is realized between a 90-135° backward angle relative to the primary proton direction for both $\pi^+$ and $\pi^-$ and is reflection symmetric (Figure 1). The backward angle increases with energy and approaches 180° for multi-GeV proton energies. For example, PSI, TRIUMF, and RAL use beamlines directed within the angle range above, while J-PARC/COMET and Mu2e use 180° collection.

TABLE XII. Total cross sections for $\pi^+$ and $\pi^-$.

| Element | $\sigma^+$ | $\sigma^-$ | Ratio |
|---|---|---|---|
| H | 13.50±0.73 | 0.03±0.01 | 45 |
| D | 11.42±0.55 | 1.12±0.06 | 10.2 |
| Be | 27.30±1.40 | 6.49±0.37 | 4.3 |
| C | 35.00±1.80 | 6.64±0.41 | 5.3 |
| Al | 53.10±2.90 | 13.17±0.90 | 4.0 |
| Ti | 67.00±3.60 | 21.20±1.60 | 3.2 |
| Cu | 77.30±4.30 | 25.20±2.0 | 3.1 |
| Ag | 91.60±5.10 | 35.00±3.0 | 2.6 |
| Ta | 101.00±5.60 | 51.40±4.70 | 2.0 |
| Pb | 104.20±5.80 | 53.70±4.90 | 1.95 |
| Th | 107.90±5.90 | 60.40±5.50 | 1.9 |

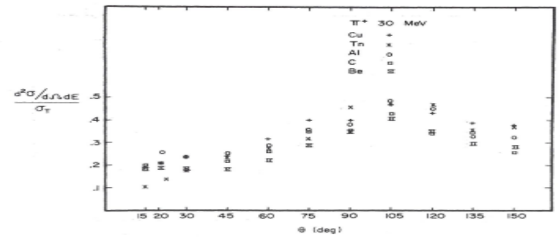


FIG. 22. $(d^2\sigma/d\Omega dE)/\sigma_T$ for 30-MeV $\pi^+$.

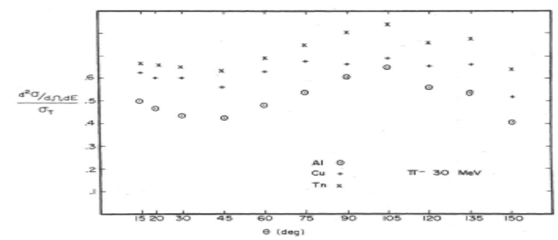


FIG. 23. $(d^2\sigma/d\Omega dE)/\sigma_T$ for 30-MeV $\pi^-$.

Figure 1. Table of total cross sections[26] for production of charged pions by 730-MeV protons as a function of target (left) and angular distribution of differential cross sections for 30 MeV $\pi^+$ (top right) and $\pi^-$ (bottom right); both show a production peak at ~105°.

This work proposes a completely new approach to advance state-of-the-art muon production by investing in R&D that entail and combine three primary innovations 1) heavy Ta target to increase production by a factor of 3(8) in $\mu^+(\mu^-)$ rates over current graphite production targets, 2) a large-acceptance primary beam absorber just downstream of the production target to avoid restrictive primary beam transport losses due to heavy targets, and 3) increase surface to volume ratio by using multiple target slices and angling the target relative to the incident direction (this reduces the mean-free path of pions in the production target allowing them to escape for a given IL). Ta has essentially the same heat capacity as graphite and the slice innovation increases convective cooling and simplifies conduction cooling designs. Such target innovations could potentially also impact the design of $H^-$ stripping foils for the PIP-II beam, improving heat deposition, cooling, and operational lifetime. Heavy targets play an additional role in optimization of secondary beamline capture and transport rates simply by longitudinally shorter targets – centimeter vs many centimeters for Ta vs graphite improving the phase space density and solid angle acceptance of the secondary beamline capture solenoid.

In summary, a wide spectrum of future and world-leading muon beam facilities and experiments can be developed at Fermilab complementing and following the g-2 and Mu2e experiments. The MW-scale 800 MeV PIP-II beam is ideal to drive next-generation low-energy muon beams to higher intensities. MTA proves to be an invaluable resource to research optimal target and secondary line configurations to prepare for the PIP-II era.

## Research Plan

## Pre-LDRD Research Plan (Dec 2020 – March 2021)

Pre-LDRD background studies supported by PPD/FTBF dept and AD/Muon Dept will begin in November. Radiation studies and shielding assessment compliance will be performed on varying interaction length (10%-50%), solid rod Ta and Ni targets first and then followed by more sophisticated target geometry radiation studies; i.e.: dividing the target into slices and rotating the target configuration relative to primary and secondary beam directions (rotating the target increases primary beam IL while maintaining surface to volume ratio). In parallel, a secondary beamline will be designed for 10-50 MeV muons (both signs) with an appropriate pion decay length, chicane for momentum spread control and elimination of backgrounds. Once target simulation studies and beamline design studies are sufficiently complete, preliminary engineering design and drafting of target assembly, absorber assembly and beamline will begin, projected to start in January.

*Deliverables from pre-LDRD work*

1) Radiation and shielding studies including particle type and levels in MTA hall and counting house (previously MTA cryogenic service building) initially with solid rod Ta and Ni targets. Compliance with shielding and radiological controls will be verified.
2) Study of $\pi^+$ and $\pi^-$ production rates as a function of target material, energy, slice and rotational geometry. Finalize target geometry.
3) Secondary beamline optics and physical transport design with identified components (available original Booster correctors, and a PXIE solenoid, in storage). Assess and optimize transmission rates at experiment and estimates of background contamination.
4) Preliminary engineering including drafting of retractable target, housing, stand, actuator, plus thermal and mechanical analysis. Target assembly will be based on a modified PIP-II retractable beam scraper assembly and housing.
5) Preliminary engineering including drafting of an in-air absorber, actuators, housing and stand. (A steel in-air standalone absorber was used for the MuCool cavity beam tests).
6) Preliminary engineering including layout of secondary beamline vacuum system, components and component stands.

Studies from a previous shielding assessment for the MTA facility forecast a promising outcome for the proposed innovations and for establishing a test muon beam in the MTA experimental hall. Figure 2 (left) shows the directionality (~135°) of muon production from a MARS model of the 400-MeV primary beam striking 1" steel windows of a test gas-filled RF cavity. The histogram on the right in Figure 2 shows the muon spectrum extends from surface muons (<10 MeV) to cloud muons (~10-100 MeV). Also included here are a dimensional layout in Figure 3 (left) of the MTA experimental hall (right) alongside pictures of showing the area available for the low-energy secondary beamline (at least 30').

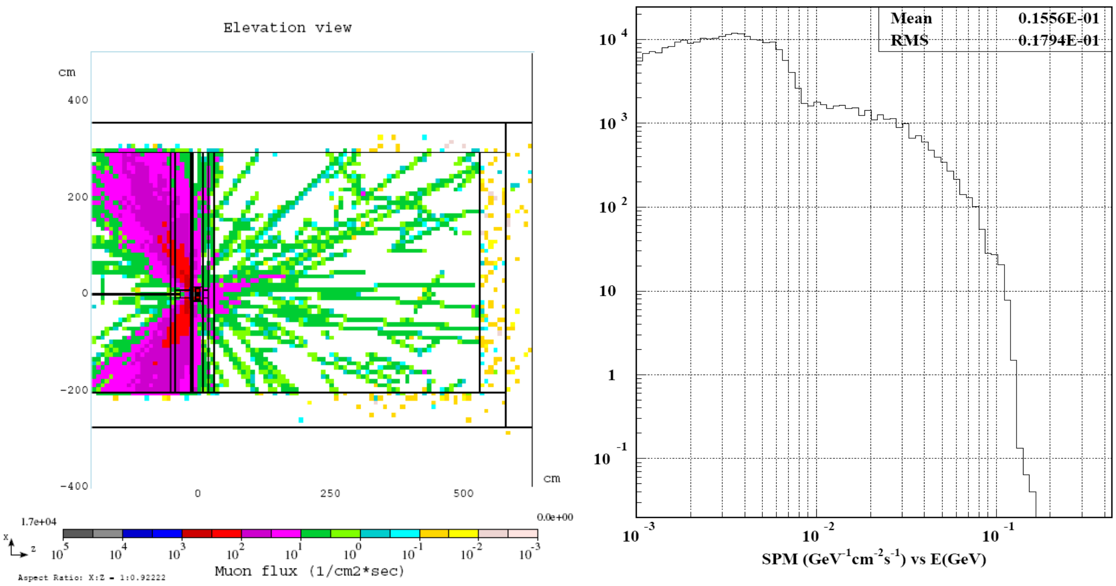


Figure Muon flux in the experimental hall for 2.67 x $10^{11}$ p/sec (1.6 x $10^{13}$ p/pulse and 1 pulse/minute in Experiment mode) on a gas-filled RF test cell with thick (>100% Interaction length) walls. Muon energy spectrum (right) from 400-MeV protons incident on a gas-filled RF test cell for 2.67 x $10^{11}$ p/sec (1.6 x $10^{13}$ p/pulse and 1 pulse/minute)

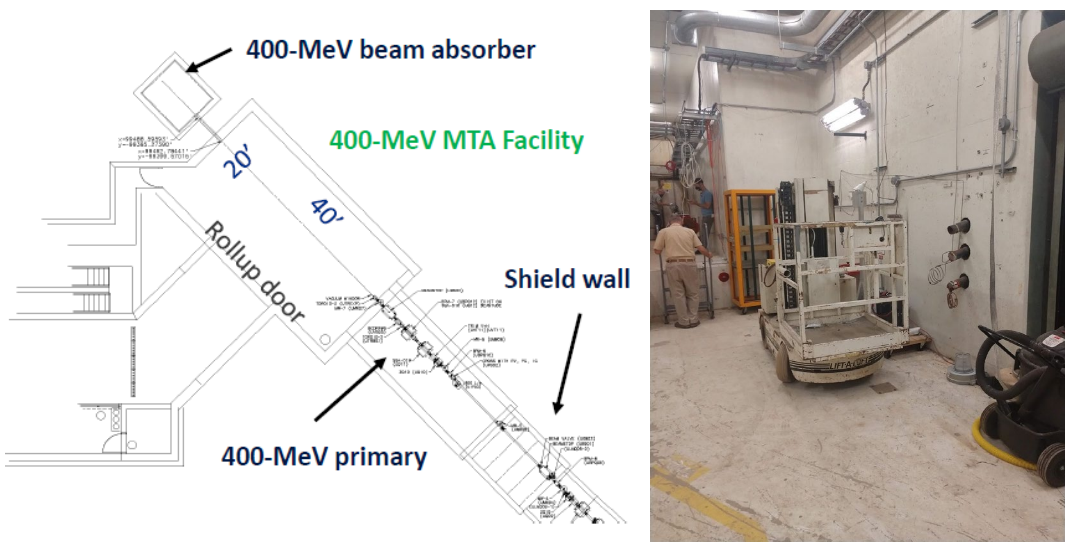


Figure 3. Layout of the MTA experimental hall and primary beamline (left). Area running alongside rollup door for secondary beamline installation. Secondary production target would be just upstream of the ITA experiment cave. Beamline height is ~6' from floor so access to primary beamline and other infrastructure is not an issue.

## LDRD Research Plan

a. **Objective**: The objective of this LDRD is to design, build, and beam test combined innovative concepts for low-energy secondary muon production using the 400-MeV MTA proton beam. Demonstration of concepts facilitate economical and intense sign-selectable muon beams that can support world-leading physics experiments and R&D detector and material research on an economical platform with multi-capabilities in terms of research. This objective is best broken down into deliverables.

b. **Hypothesis and technical concepts**. This LDRD addresses the advantage of heavy targets for muon production with production increasing as $Z^{1/3}$ for positive muons and $N^{2/3}$ for negative muons – predicting increases in low-energy μ+ and μ- rates by factors of 3 and 8, respectively, relative to the standard graphite production target (even higher relative to Be targets). Innovative technical concepts however need to be applied in combination to realize this advantage. The concepts to be tested include 1) multi-slice target geometry to maximize surface to volume and minimize pion mean-free-path to surface thus minimizing reabsorption, 2) increased capture density arising from smaller longitudinal target dimensions for a fixed IL, 3) secondary beam orientation optimized for collection of backward pion production peaks, 4) target rotation angle to increase IL without impacting surface to volume ratio, and 5) a local, large-acceptance downstream primary beam absorber insensitive to the emittance blowup through multiple scattering of the primary beam by the heavy target. Production models in GEANT4 and G4Beamline and MARs will be compared with production rates in this simple proposed implementation.

c. **Methods, materials, facilities, data, validation.** Conventional methods applied are MARS and GEANT production models to study and optimize target geometry and study particle production characteristics and overall radiation environment in the MTA experimental hall. G4Beamline will be applied to optimize collection and transport design of the secondary beamline, production beam composition and its energy spectrum (G4Beamline was successfully applied to the g-2 beam downstream of production which was composed of secondary protons, pions and muons). The beam test will be performed in a secondary production beamline installed in the MTA experimental hall with LDRD funding. Major components are available and the installation leverages infrastructure upgrades to the MTA hall and available space within a new counting house (renovated cryo service building). This LDRD also takes advantage of a unique opportunity – production rates and backgrounds will be measured by an independent, DOE-funded muon catalyzed fusion experiment[27] to be installed in the hall at the end of the secondary beamline in the summer accelerator shutdown, 2021. Data rates will be compared with simulation results and predictions and comparisons with other facilities to validate enhanced muon production rates. Production models in existing codes (GEANT4 and MARS) can be potentially benchmarked, possibly improved. Engineering and design of target, absorber, and beamline use standard engineering software, materials, components and in-house facilities for fabrication and assembly. When appropriate (Ta target, for example) manufacture will be bid out. All secondary beamline components that are required for the secondary beamline have been identified and are available (original Fermilab Booster correctors – quadrupoles and dipoles – and the PXIE solenoid for capture) and most power supplies, controls are also available. Two including the solenoid are costed to be purchased.

**d.** **Expected Results and Impact.** Confirmation of enhanced muon production in an economical implementation is a groundbreaking and enabling technology that facilitates a wide range of world-leading new physics experiments and R&D test beams for detector and material science.

**e.** **Deliverables:** The LDRD Research Plan will build on past work and the described pre-LDRD studies and preliminary design work. Final design, engineering, fabrication, installation, and operation – culminating in beam testing of targets to provide and confirm projected high muon production rates form the deliverable list below for this proposal, in addition to technical design reports on the different systems. Comprehensive final report on results and publications will complete this LDRD.

**Year One Deliverables***:*

1) *Retractable Ta target, housing, and stand*
2) *Beam absorber and motion table assembly.*
3) *Secondary Beamline Final Revisions, Fabrication, and Installation*
4) *Technical design report including simulations and models*

**Year Two Deliverables***:*

1) *Commissioning and Optimized Operation of production & secondary beamline*
2) *Data Acquisition and analysis of Production rates.*
3) *Comparison with models and production rates at other muon facilities*
4) *Final report on results and publications*

## **Future Funding** (~1/2 page):

**a.** The results are eminently publishable as the interest in new physics experiments and R&D based on muon production is international (see references on EDM, muon decay and conversion experiments such as g-2, Mu2e, and COMET). There are numerous publications on progress in particle production and experimental designs to effectively utilize low-energy muons. A broad sample of appropriate venues can be viewed in the references provided.

**b.** Future funding sources are predicted to be extensive based on international interest in muon beams. These would include DOE HEP programs and other agencies (Nuclear, Basic Science), and the private sector – such as the muon catalyzed fusion experiment[27], funded by a Small Business Initiative Research award; the experimenters were referred by the DOE to Fermilab.

**c.** The HEP DOE will likely fund follow-on muon-based physics experiments to g-2 and Mu2e. Other DOE agencies (nuclear and SBIR programs) also fund muon-based applications. Material science and biology are users of MuSR techniques. Contacts with DOE sponsors and tracking proposal calls will be an important activity to realize additional future MTA and PIP-II funding resulting from the LDRD work. SBIR Phase II funding is typically over a million and a number of precision muon physics experimental proposals are being formed for Snowmass.

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## Qualifications

The extensive beamline design experience is documented in the attached CV of Carol Johnstone, an AD Senior Scientist and PI. She has designed all of the secondary production beamlines at the Fermilab Test Beam Facility and a number of fixed target experimental lines including the MTA beamline, g-2 and Mu2e. For reference, the MTEST beamline was designed, installed and operational in 6.5 months.

## Resource Availability and Recent LDRD Funding

**a.** Investigators and key personnel have all been contacted and are available for the budgeted hours and workload including the lead engineer. Research for Snowmass initiatives are the dominant research activity. A generous assignment of 0.2 FTE represents potential obligations to contributions and white papers for Snowmass for key investigators. The PI is the beam physicist for E1039 which is pending; earliest run period is projected to be in FY22 with integrated commitment anticipated to be 0.2 FTE in FY22 as the NM beamline has standardized operations. All aspects of external beam support fall under the PI’s lab responsibilities so hours budgeted reflect oversight of LDRD project. Implementation of the MTA test beam and experiment support is also part of M. Kiburg’s role as department head of the FTBF. Precision muon beams and physics are supported by Brendan Kiburg research as a scientist in PPD. Additionally, TRIUMF is providing and supporting a fulltime a senior experimental post-doc (Chris Izzo, Ph.D. from MSU) for the pre-LDRD work. He will transition to the LDRD budget full time as an experienced resource and will be local and available for onsite work for the duration of the LDRD (through FY22). His salary has been budgeted at full time.

**b.** Investigators with budgeted hours currently have no active or pending LDRD commitments.

## Budget Table

Tables 1 gives the contingency estimates for FY21 based on individual work categories. Design and Installation hours were based on the recent beamline and ITA experiment installation at MTA – hence the reduced contingency which is dominated by the estimates provided by TD for magnet tasks. An electrical contractor is costed to pull power and signal cables as required by Davis-Bacon. Table 2 gives the contingency estimates for FY22 which as we move into conventional operations. The PAMs budget is submitted has additional details.

Table1. Total hours for each category of labor associated with this LDRD. Contingency labor hours were estimated by lead engineers and scientists for individual tasks. A 35% average contingency is assigned to labor consistent with a preliminary simulations and preliminary engineering design status at the beginning of the LDRD. M&S corresponds to a preliminary design rate of 35% also.

| Category | FY21 Base Labor (hrs) | FY21 Contingency hrs | Contingency % | M&S | Contingency % |
|---|---|---|---|---|---|
| ***Simulations*** | **1004** | **384** | **38%** | **-** | **-** |
| ***Design and Installation*** | **1118** | **390** | **35%** | **$208k** | **35%** |
| ***Operation*** | **148** | **-** | **-** | **-** | |

Table 2. Total hours for each category of labor associated with this LDRD for F22. Contingency labor hours were estimated by lead engineers and scientists. Contingency is for operational tuning studies, maintenance and repairs is based on other beamlines.

| Category | FY22 Base Labor (hrs) | FY21 Contingency hrs | Contingency % | M&S | Contingency % |
|---|---|---|---|---|---|
| ***Operation*** | **772** | **288** | **37%** | **$10k** | **35%** |