Preliminary Considerations for a Muon Spin Rotation/Relaxation/Resonance (µSR) Facility at the Fermilab MuCool Test Area (MTA)

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Preamble

Due to a backlog of µSR experiments desiring to use the existing facilities at TRIUMF, PSI, ISIS, and J-PARC, the manager of the DOE/HEP/Accelerator Stewardship subprogram has asked whether the existing MuCool Test Area (MTA) at Fermilab can be economically transformed into a µSR facility. Other requests from the muSR community include desire for more intense muon beams (# muons/hour) to reduce sample exposure time and at the pulsed muon sources, shorter proton beam pulse widths to study higher magnetic fields and higher muon precession frequencies.

Before starting on conceptual designs and cost estimates, the first question to be asked is whether such a facility based on the Fermilab LINAC can be competitive with the existing facilities in terms of time integrated muons/hour fluxes and preservation/dilution of the muon polarizations available from surface muon beams. For these notes, I will use the current operations of the Fermilab LINAC with simple, minimum cost, technically feasible enhancements, which I will explicitly state are being assumed. There are also many factor of 2 tweaks or optimizations which could be implemented. These will sometimes be mentioned, but not included in the overall flux comparisons.

Two Approaches – continuous and pulsed muon beams

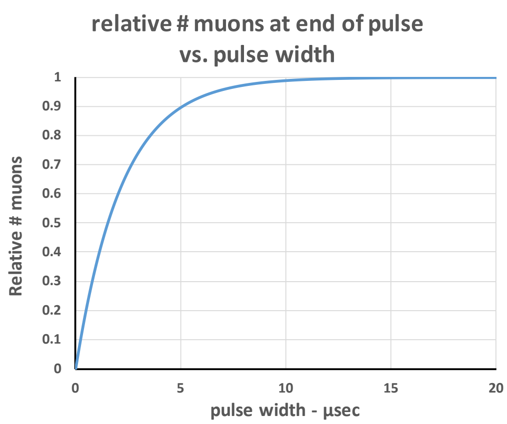
The cyclotron-based muSR facilities at PSI and TRIUMF deliver continuous muon beams to the experiments. These high beam duty factor machines allow each incident muon striking the experimental target to be detected one-at-a-time and to precisely start the clock to time the relative angle of the muon's precession. To maximize the time integrated detected muons/second, ideally, the next muon should arrive as close to 10-12 muon lifetimes after the previous muon, allowing sufficient time for the previous muon to decay to minimize event pile-up in the muon spectrometer. muSR experimenters want more muons/second from both TRIUMF and PSI.

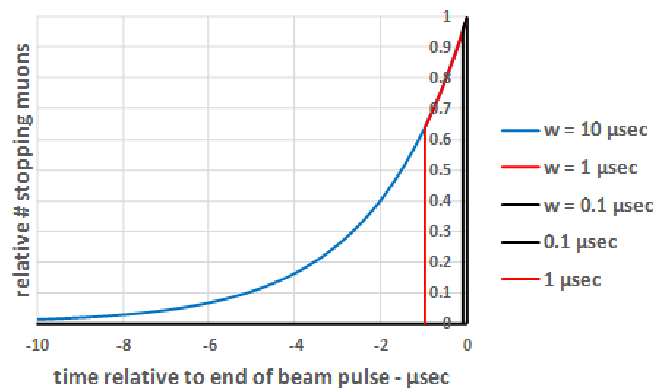
The synchrotron-based muSR facilities at ISIS and J-PARC (3 GeV Rapid Cycling Synchrotron RLS) are much lower beam duty factor and rely on much shorter width proton pulses (70 nsec and 100-140 nsec) at 50 Hz or 25 Hz, respectively. The instantaneous muon rates during these short pulses are too high to clock the precession start times for individual muons. All muons are assumed to arrive simultaneously and the finite beam time smears the start clocks and limits the precession frequency and, thus, the magnetic field which can be studied.

Where does the Fermilab LINAC fit in these schemes?

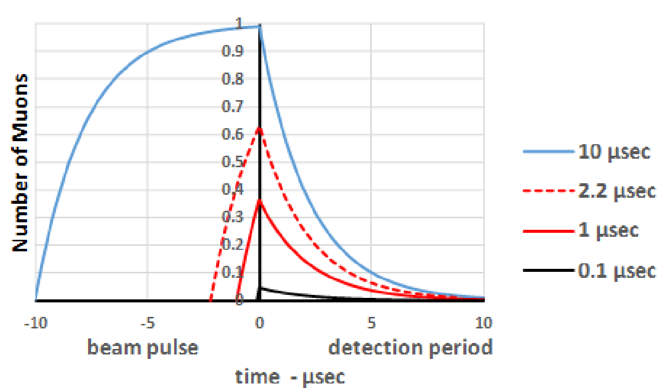
Today, the Fermilab LINAC is delivering (time averaged) 11 µA current of 400 MeV Kinetic Energy protons to the Fermilab Booster synchrotron to service the short baseline, NOvA, and Muon Campus experimental programs. This beam is delivered in 15 Hz pulses of length 36 µsec with average beam current of 21 mA over this short beam pulse. The LINAC can relatively easily be increased to a pulse width of 60 μsec and 27 mA current over this short beam pulse [WP]. In the following, I will assume lengthening of the LINAC pulse to satisfy a possible muSR program, but not assume the current is increased by 30%, since at this time, the Booster cannot accept more than 21 mA instantaneous current. There are considerations to increase both the LINAC and Booster repetition rate to 20 Hz for PIP-1+. In any case, in order not to have unfilled Booster cycles, the LINAC must operate at an integer multiple of the Booster repetition rate, e.g. 15 Hz, 30 Hz, 45 Hz… Increasing the LINAC repetition rate to 30 Hz would involve major upgrading of the RF power generation and cooling, and so is not considered a practical path for consideration.

As can be easily shown, extending the LINAC pulse from 36 μsec (Booster only) to 60 μsec = 36 μsec (Booster) + 24 μsec (muSR) in impractical since 24 μsec is much longer than the 2.2 μsec muon lifetime. Unless the experiments can simultaneously accept new muons, time the precession, and detect the decay positrons, they will have to wait until after the completion of the proton beam pulse to start detecting muons. After 24 μsec of muon beam, the earliest arriving muons will have all decayed, and the number of useful muons saturates as a function of the proton beam pulse width.

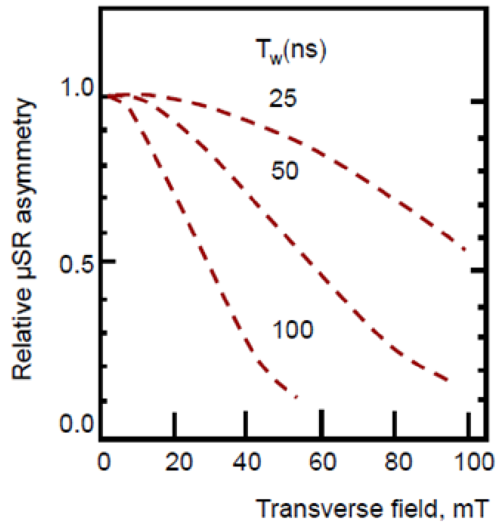




So, the entire available 24 μsec residual proton beam pulse is not useful for muSR studies.
How much of this residual proton beam pulse is useful?
That depends on what muSR science one wants to do.
Up to a muon pulse width of about 2.2 μsec, the muon's average lifetime, the number of useful muons is approximately proportional to the proton beam width.

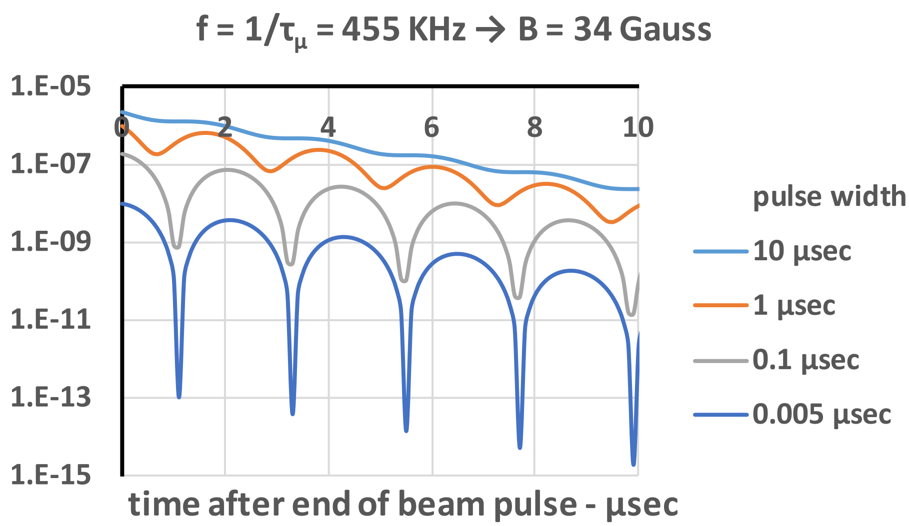


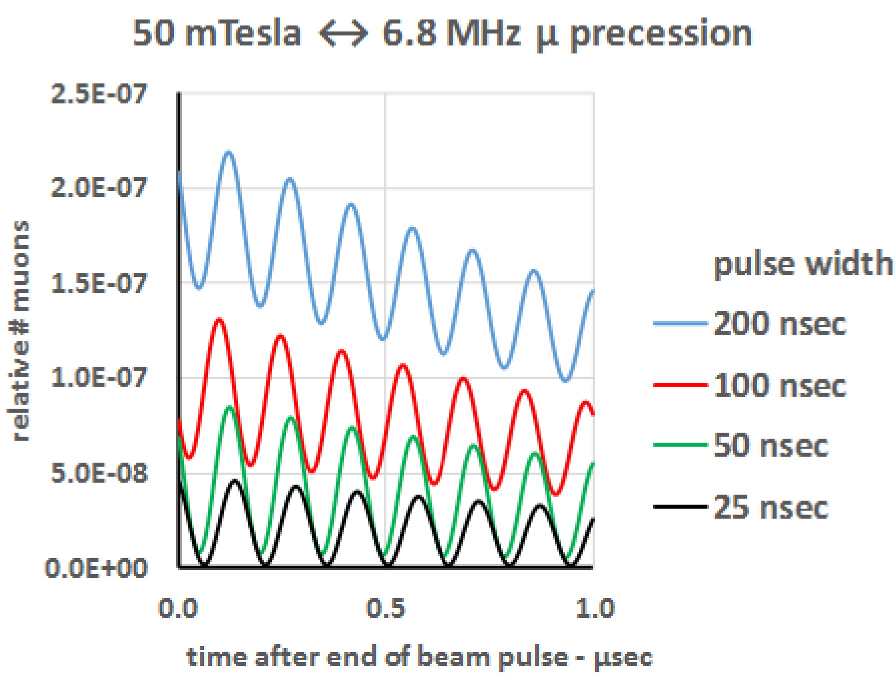
However, such long incident proton pulses will smear the t=0 clock start for timing the muon precession, leading to a dilution of the asymmetry in the positron decay angles, diluting the resolution on precession frequency and magnetic fields. B. Cywinski and A. Bungau [PX] show the dilution of the Relative muSR Asymmetry as a function of the beam pulse width Tw and transverse magnetic field.



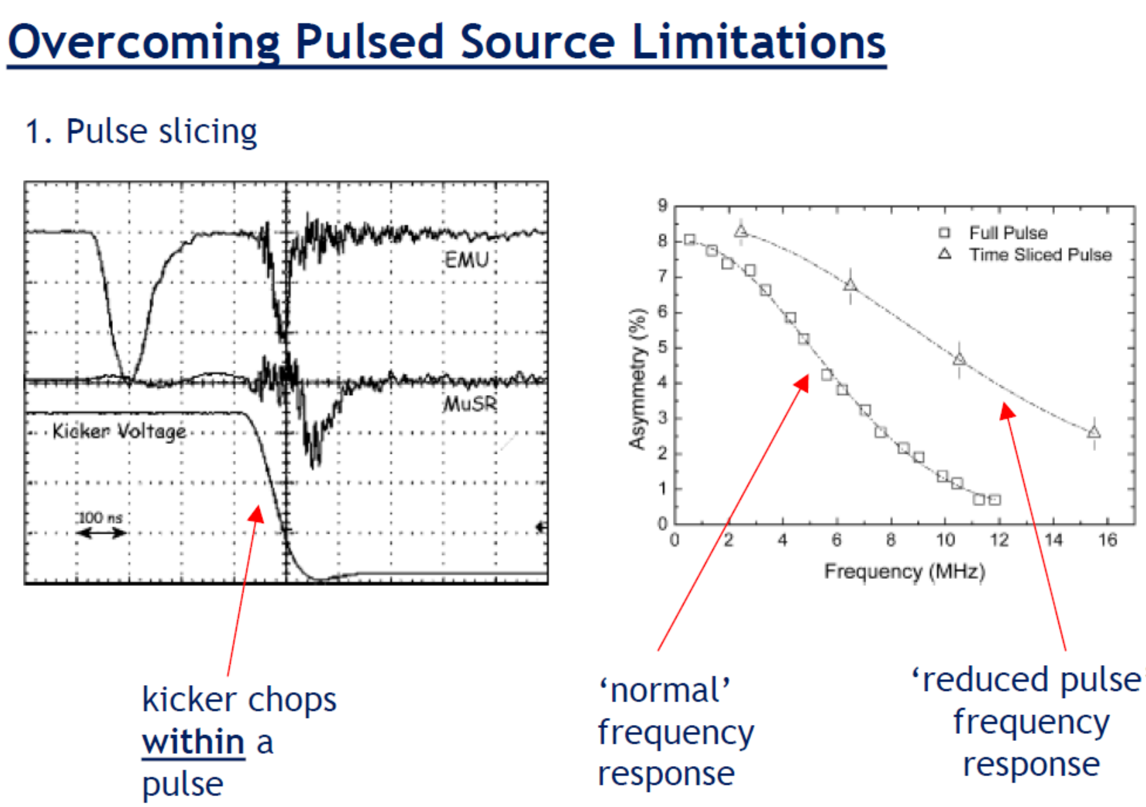
Note that 100 mTesla corresponds to a precession frequency of 13.5 MHz or a period of 74 nsec. The beam pulse at ISIS has an approximate FWHM of 70 nsec. Note also that the effective pulse width is also ultimately limited at the lower end by the lifetime distribution with average lifetime of τ_π = 26 nsec for the stopped pions, which are the parents of the decay muons.

Examples of this dilution of the observed Asymmetry (peak to valley ratio) are also illustrated in my Asymmetry simulations for various incident proton beam widths, below.



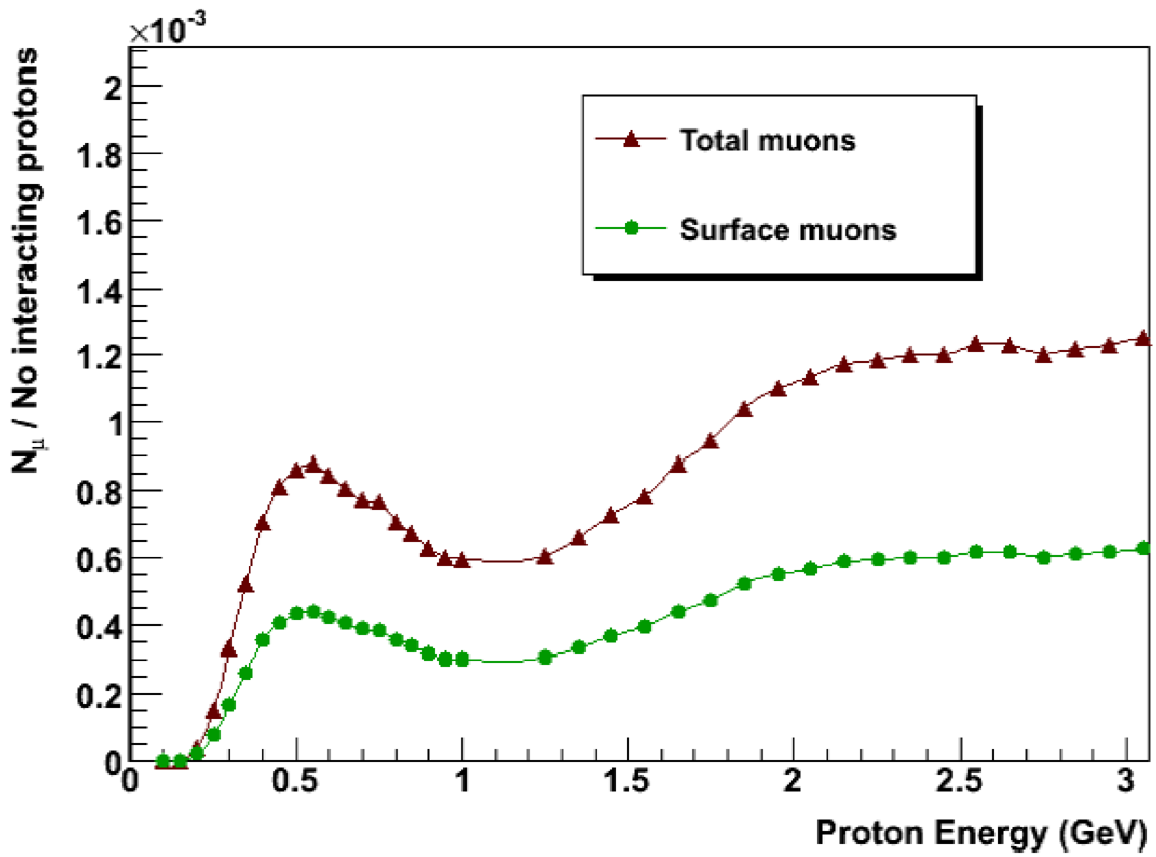


In fact ISIS "chops" the proton pulse to the muSR production target to approximately half this width to increase the sensitivity to higher magnetic fields [AH], or for some applications, uses a 90-degree RF pulse to remove the time structure of the pulsed beam, analogous to pulsed NMR [AC],[RF]. From S. Kilcoyne [PX]:



Comparison of the Fermilab LINAC with other Existing muSR Facilities (with 30 years' experience)

Since we do not have designs or acceptances for the muon beamlines, I assume that the Figure of Merit for these comparisons will be number of protons available per second for the muSR facility, assuming the same proton targeting for muon production, and the same surface μ^+/proton production ratio. B. Cywinski and A. Bungau [PX] provided this ratio (seems to be a Monte Carlo simulation). The μ^+/proton at the Fermilab LINAC (400 MeV) and ISIS (800 MeV) is ~ 0.35 x 10^{-3}, at TRIUMF (520 MeV) and PSI (590 MeV) is ~ 0.45 x 10^{-3}, and at J-PARC (3 GeV) is ~ 0.62 x 10^{-3}, showing less than a factor of 2 variation with proton beam energy over this range.



Comparison of Fermilab LINAC with Existing muSR Facilities

all use protons a.	ISIS synchrotron	J-PARC RCS	Fermilab LINAC	TRIUMF cyclotron	PSI cyclotron
Kinetic Energy	800 MeV	3 GeV	400 MeV	520 MeV	590 MeV
Repetition Rate	50 Hz	25 Hz	15 Hz	continuous	continuous
Pulses/Cycle	2 b.	2 c.	1 d.		
time averaged proton Current	200 μA	333 μA	7 μA e.	166 μA	2.2 mA
protons/pulse	2.5×10^{13}	8.3×10^{13}	2.9×10^{12}		
pulse width	70 nsec	120 nsec	24 μsec		
time averaged protons/second	1.25×10^{15}	2.1×10^{15}	4.4×10^{13}	1.0×10^{15}	1.4×10^{16}
figure of merit f. for pulsed beam	29	48	1		
figure of merit f.,g. for continuous beam			1	24	314
chopped pulse width			100 nsec		
protons per chopped pulse	2.5×10^{13}	8.3×10^{13}	1.3×10^{10}		
protons/sec for chopped pulse	1.25×10^{15}	2.1×10^{15}	2.0×10^{11}		
figure of merit f. for chopped beam	6,250	10,500	1		

Notes:

a. Only part of the total beam is available for muSR

b. ISIS direct alternating pulses to the two muSR target stations

c. This is per pulse for J-PARC

d. The Fermilab LINAC could deliver 3 short pulses per cycle.

e. Based on 24 μsec to muSR after 36 μsec pulse to Booster

f. Based only on protons/second, assuming same targetting, μ+/p ratio, acceptance

g. Assuming Fermilab LINAC beam stretched from 24 μsec to 67 msec (1/15 Hz)

A similar comparison of the projected capability for low energy muons of PIP-II, both CW and Pulsed, is presented by Prebys, Hillier, and Sheehy [EP].

<u>What would be needed to implement a minimal muSR facility at MTA</u>

400 MeV Proton beam: switching between Booster and MTA and on/off kicker capability
which could be based on the existing Einzel Lens [JL]

Proton beam transport: John Johnstone has a simple design [JJ] and magnets seem to exist,
but will need power supplies, vacuum, instrumentation, and installation

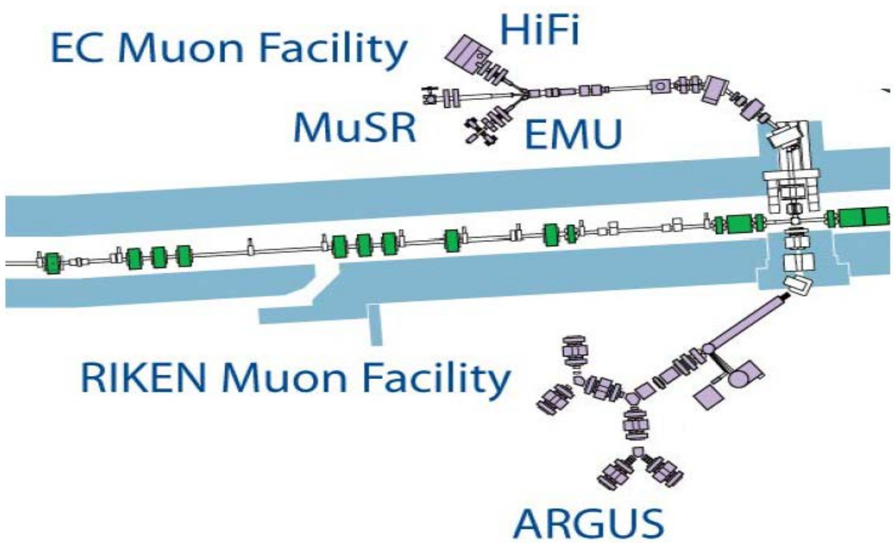
Radiation Shielding: both prompt neutrons and ground water activation
Depends on beam conditions (100 nsec pulses at 15 Hz, 30 Hz, 45 Hz) or 24 μsec pules at 15 Hz)
Can this be made safe from a radiation safety viewpoint? How do you assure $\leq$ 100 nsec pulse?

Civil considerations:
- Cleanout of what's presently installed.
- Accessibility for larger components, magnets, shielding blocks – there is no crane in the MTA hall.
- At the present MTA, small equipment can be transported through the stairwell and personnel access labyrinth. Moving of larger equipment requires the rental of a costly mobile crane with 100 foot reach to unstack/restack the external shield block wall. This situation would need to be improved to make MTA a more useful facility.
- If needed, increase the radiation shielding berm and/or groundwater contamination prevention, could be big $ if needed
- Room for beamline(s)
- Experimental target station – accessible without accessing primary beam area

Local shielding of experiment and components

Muon production target: not a big deal mechanically, but Bob Zwaska (Head, AD Target Systems Department) says residual radiation/activation could be an issue.

Muon beamline to select given momentum of muons – will be big $
Muon moderator to stop muons in experimental target
Considerations to reduce prompt backgrounds from production target, muon/electron separation.
Example of the complexity of ISIS muSR beamlines:



Muon decay spectrometer(s) with good timing and positron energy resolution to detect positron decays with Asymmetry precessing in magnetic field of sample. Will be big $

Maximum positron momentum (52.5 MeV/c) has maximum decay asymmetry. Need to integrate over decay angular distribution of positron.

Experimenter expectation:

- Magnetics: cancel earth's local magnetic field, external fields (how high? SC magnets?)
- Thermal: at least mK^{O} facility, ovens for high temperatures
- Are exposure rates for each reasonable? 1 hour runs, not 1 week runs
- Variable rotation of muon polarization?

<u>Dreams and Schemes</u> – how to improve LINAC performance for muSR

3 short pulses per LINAC cycle – at t=0 before pulse to Booster, at t = 36 µsec after pulse to booster, and at t = 60 µsec at end of (extended) LINAC pulse.

If you can do 1 short pulse per Booster cycle for muSR, then 3 pulses should be straight forward.

Since a muSR facility at MTA would be the final user of LINAC protons, a thicker muon production target could be used than at the other muSR facilities where the number of protons targeted for parasitic muon production is limited to preserve protons for downstream neutron spallation targets.

Stretcher Ring for ~ 100% duty factor – problem is that you can only have a maximum of ~ 11 µA time averaged beam available (can't be greater than LINAC output current) to compare to 160 µA at TRIUMF and 2.2 mA at PSI (although not all of these beams are devoted to muSR).

Compressor Ring – can the 24 µsec pulse be compressed into a ~ 50 -100 nsec wide pulse for muSR? These are pulse compression factors of 240-480 compression! How difficult? There could be 3 x 10^{12} protons in this pulse.

Are there other muSR options at Fermilab before PIP-II involving the 15 Hz 8 GeV beam from the Booster [MP]? In order not to steal Booster cycles from the neutrino and Muon Campus programs, these schemes would have to parasitically use these 8 GeV pulses, maybe by using a thin transmission target in the 8 GeV transfer lines, the Antiproton Target Station, or an internal target in the Delivery Ring in the Muon Campus. All of these options would very likely involve new civil construction.

Conversely, are there specific muSR applications and experiments that could use the 3×10^{12} proton beam distributed over the 24 μsec pulse?

Summary and Conclusions

Something could be done using the Fermilab LINAC, but would it be useful for the muSR community?

Would it be competitive or complementary to the existing muSR facilities?
(FoM = Figure of Merit based on time averaged protons/sec delivered to the muon production target)
- If the LINAC beam was chopped to 100 nec width,
  - the ISIS FoM is 3,000 times better, J-PARC FoM is 10,000 times better than Fermilab LINAC
    - going to 3 pulses per LINAC cycle doesn't change the conclusion of this comparison
- If the full 24 μsec LINAC beam were compressed to 100 nsec width,
  - the ISIS FoM is 29 times better, J-PARC FoM is 48 times better than Fermilab LINAC
    - attaining this factor of 240 compression would be complicated and costly
- if a stretcher ring was used to provide a continuous LINAC beam,
  - it would be limited to the LINAC time averaged output current 7 μA and
    - the TRIUMF FoM is 24 times better, PSI FoM is 314 times better than Fermilab LINAC

Although it, hopefully, is only a decade away, the PIP-II CW Linac (2 mA at 800 MeV) [PD] could fulfill many of the desires of the muSR community, but alas, even that doesn't provide substantial improvement over the PSI continuous beam (2.2 mA @ 590 MeV).

Acknowledgements

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References:

[AH] A.D. Hillier, *et al*., Physica **B 326** (2003) 275.

[EP] Eric Prebys, Adrian Hillier, and Susanne Sheehy, "Proposal to Use the Fermilab PIP-II Linac to Support a Low Energy Muon Program", May, 2016, Beams-doc-5489-v1 http://beamdocs.fnal.gov/AD/DocDB/0054/005489/001/pip-II-muons.pdf

[FG] Fernanda Garcia, private conversation: the 400 MeV LINAC beam has a microstructure of a pulse width of ~ 5 psec at 201 MHz, May 31, 2017.

[ISIS] "How ISIS Works – in Depth" http://www.isis.stfc.ac.uk/about/how-isis-works---in-depth4371.html

[JJ] John A. Johnstone, "Prospects for a Muon Spin Resonance Facility in the MuCool Test Area",

FERMILAB-TM-2652-AD-APC.
[JL] J.R. Lackey, *et al*., “A Novel Low Energy Fast Chopper for H- Injectors”, FERMILAB-PUB-12-576-AD.
[KN] K. Nagamine, Introductory Muon Science, Cambridge University Press, 2003.
[MP] Milorad Popovic, private discussions, May, 2017.
[PD] Paul Derwent, private communication, June 1, 2017.
[PX] Project X muSR Forum, Fermilab, October 2012,
https://indico.fnal.gov/conferenceDisplay.py?confId=6025
[RF] RF-muSR techniques are described in
A. Carne, *et al*., “A pulsed surface muon beam and muSR facilities proposed for the UK”,
Hyperfine Interactions **17-19** (1984) 945;
S.R. Kreitzman, “RF Resonance Techniques for Continuous Muon Beams’,
Hyperfine Interactions **65** (1990) 1055;
S.P. Cottrel, *et al*., “The development of a facility for radio-frequency experiments at ISIS”,
Hyperfine Interactions **106** (1997) 251.
[WP] Bill Pellico, private conversation, May 5, 2017.
[YD] A. Yaouanc and P. Dalmas de Reotier, Muon Spin Rotation, Relaxation, and
Resonance, Applications to Condensed Matter, Oxford, 2011.
[YM] Y. Miyake, *et al*., “Birth of an intense pulsed muon source, J-PARC MUSE”,
Physica **B 404** (2009) 957.