Proposal to Use the Fermilab PIP-II Linac to Support a Low Energy Muon Program

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Abstract

This note explores the potential for a low energy muon program based on the 800 MeV PIP-II proton accelerator, which is planned to built at Fermilab within the next decade. There are currently no such facilities in the US, and existing international facilities are badly oversubscribed. One advantage of the PIP-II linac would be the extremely flexible bunch structure, which could emulate both pulsed machines, like ISIS or JPARC, and CW machines, like PSI or TRIUMF. The total power available would be around 3 kW when emulating ISIS operation, and up to 800 kW in CW mode, making it very competitive with existing facilities of both types.

1 Introduction and Motivation

Muon spectroscopy for condensed matter research has become a mainstream technique since its inception from an applied particle physics method only practiced by a small number of specialists. It is now utilized by a wide user-base of scientists across the world. There are only four centers in the world, TRIUMF (Vancouver, Canada), PSI (Villigen, Switzerland), ISIS (Didcot, UK) and J-PARC (Tokai, Japan) and with two new possible sources at the CSNS (China) and RAON (S. Korea). The muon technique involves implanting spin-polarized positive muons into a material where they act as a local probe. Muons are short-lived particles, decaying after an average lifetime of 2.2 μs to produce positrons, which are emitted preferentially along the muon spin direction. The positrons that emerge from a sample after muon implantation are detected revealing information about the muons' behavior inside the material particularly about how the muon polarization changed within the sample. This, in turn, enables us to deduce information about the properties of the material on an atomic scale, and to probe the system on a unique timescale. Muon spectroscopy has provided invaluable information in a wide range of research areas such as:

- **Superconductivity:** Probing the vortex state, determining the mechanism for superconductivity and measurement of spontaneous fields within an exotic superconducting state.
- **Magnetism:** Probing static magnetism and dynamics, investigating novel ground states such as: spin-liquids, low dimensional magnetism and spintronic materials. The muon is ideally suited studying weak magnetism and materials that have challenges by other techniques.
- **Semiconductors:** A muon can pick-up an electron and form muonium, which can be considered a light isotope of hydrogen. This can be used to study the effects of Hydrogen in semiconductors, providing useful information for the electronics community.
- **Battery materials:** By measuring the diffusion rates of say Li in a battery material can lead to improvements in battery design.
- **Molecular dynamics:** Muons offer unique probe for electron spin relaxation and molecular dynamics, investigations into potential spin based technologies have proven extremely useful.
- **Chemical reactions:** Proton transfer can be modeled using the results from muon experiments.
- **Cultural heritage:** By using a negative muon, elemental analysis can be conducted which allows non-destructive analysis deep inside the material. This might be expanded into areas such as engineering, batteries, biomaterials, etc.
- **Electronic irradiation:** The effects of some radiation on electronics are well known, primarily the effects of neutrons and heavy elements; however, as the electronic components become smaller the effects of muons are becoming an increasing concern. There is therefore growing industrial interest in performing radiation damage tests with muons.

It is not feasible for the current Fermilab accelerator complex to support such a facility; however, the lab is currently planning a set of upgrades to increase the power to the 120 GeV neutrino program to 1.2 MW. These upgrades are organized as the "Proton Improvement Plan II", or PIP-II[1]. The centerpiece of this plan is an 800 MeV H^- linac, which will increase the injection energy and therefore reduce space charge effects in the 8 GeV Booster synchrotron, as shown in Figure 1. The linac will consist of a H^- source, followed by a 162.5 MHz RFQ, and a superconducting linac with an ultimate frequency of 650 MHz.

It is planned that the PIP-II linac will have significant excess capacity, which could be used for a complementary 800 MeV physics program, possibly including a low energy muon program, as described below.

Table 1: Beam parameters of the PIP-II Linac (second column) and the proposed slow muon beam line (third column). The maximum current available to the slow muon line would depend on the bunch structure, as described in the text.

Parameter	**PIP-II (full)**	**Slow Muon Line**	**Comments**
Kinetic Energy [MeV]	800	800	
protons/bunch	1.5×10^8	1.5×10^8	
Max bunch frequency [MHz]	162.5	40.625	
Min bunch Spacing [ns]	6.2	24.6	
Bunch length [ps]	4	4	
Instantaneous Current [mA]	4	1	
Instantaneous Power [kW]	3200	800	
Average Available Current [mA, max.]	2	1	
Average Available Power [kW, max.]	1600	800	depending on bunch structure

2 PIP-II Bunch Structure

One very attractive feature of the PIP-II linac is its extremely versatile bunch structure, which could be configured to emulate either pulsed machines, such as ISIS, or CW machines, such as PSI or TRIUMF, with intermediate or even hybrid modes of operation being possible.

The parameters of the PIP-II linac are shown in Table 1. The source produces 162.5 MHz bunches of 1.5×10^8 protons each, for an instantaneous current of 4 mA. During acceleration, these are transfered to a 325 MHz RF system and finally to a 650 MHz RF system, which accelerates them to 800 MeV kinetic energy, for a final instantaneous power of 3.2 MW. The maximum average power is planned to be about 1600 kW (2 mA average current), of which about 100 kW are tentatively allocated to for a rare muon decay experiment, such as a second generation of the Mu2e Experiment[2].

Within this total power limit, the source can provide an arbitrary bunch structure. The primary motivation for the new linac is to increase the injection energy for the Fermilab Booster, thereby reducing space charge effects and allowing more protons to be loaded for acceleration. During the PIP-II era, the Booster will run at 20 Hz and accelerate about 6.5×10^{13} protons per cycle, corresponding to an injected power of about 17 kW. The bunch train will will be chopped to match the Booster RF, so it will take about 1 ms to inject every 50 ms (2% duty factor). This switching will will be done with an ordinary kicker, leaving a 98% duty factor available to other users.

Although the source can arbitrarily populate 162.5 MHz bunches, there is no technology to arbitrarily switch such bunches to multiple beam lines. An attractive solution has been proposed, which is illustrated in Figure 2. A deflecting cavity is run at one quarter of the bunch frequency, or 40.625 MHz. The loading of bunches in time can thus be used to select one of three beam lines,

Table 2: PIP-II muon line parameters in CW mode, as well as a mode chosen to emulate the ISIS bunch length with a 32 μsec relaxation time. ISIS parameters are shown for comparison.

Parameter	**PIP-II (CW)**	**PIP-II (ISIS-mode)**	**ISIS**	**Comments**
Kinetic Energy [MeV]	800	800	800	
Circumference [m]	N/A	N/A	163	
f_{RF} [MHz]	40.625	40.625	3.099	
Protons per Bunch	1.5×10^8	1.5×10^8	1.4×10^{13}	
Bunches per Cycle	1	5	2	ISIS bunches sent to two sub-lines
Bunch Length [ns]	.004	98.5	100	
Bunch Spacing [μsec]	.0246	32	20000	
I [μA]	1000	3.9	224	
Total Power [kW]	800	3.1	180	
Target Station 1 Power [kW]	N/A	N/A	143	4 out of 5 ISIS cycles
Muon Production Power [kW]	800	3.1	3.4	1 cm Carbon target in ISIS beam line

up to a maximum of 81.25 MHz for the central (null) line and 40.625 MHz for each of the two peripheral lines. While Mu2e does not need a great deal of beam power, they do benefit from small bunch spacing, so we assume they will use the central line, while one of the peripheral lines can be dedicated to a slow muon program, as shown in the second column of Table 1.

The maximum power available to this line would be 800 kW, which would still leave roughly 700 kW available for the other peripheral line after accounting for the 100 kW going to Mu2e. The actual power would depend on the bunch structure, as described in the next section.

It must be mentioned that this beam line switching system is not currently part of the PIP-II scope; however if there is enthusiasm for such a program, the incremental cost of adding it would not be large.

3 Low Energy Muon Configurations

In general, there are two types of slow muon experiments: those involving continuous beams and those involving pulsed beams. At present, these different classes experiments are done at different labs: cyclotron-based facilities like PSI and TRIUMF deliver continuous beams, while synchrotron-based facilities like J-PARC and ISIS deliver pulsed beams. The PIP-II facility has the capability of emulating, as well as other bunch structures.

Table 2 shows the operation of the proposed PIP-II muon line. The first column shows the parameters for CW opeation, which would make it the most powerful dedicated muon line in the

Table 3: An example of researchers from the US who are active users at the ISIS muon facility.

Name	**Institution**	**Interest**
B.L. Bhuva	Vanderbilt University	Electronics Irradiation
S. Disseler	NIST	Magnetism
M.J. Graf	Boston University	Magnetism
R.L. Lichti	Texas Tech University	Semiconductors
D.E. MacLaughlin	University of California, Riverside	Superconductivity
R. Mengyan	Texas Tech University	Semiconductors
H. Tom	University of California, Riverside	Semiconductors
Y. Uemura	Columbia University	Magnetism and Superconductivity
D.E. MacLaughlin	University of California, Riverside	Superconductivity

world. The second column shows a mode configured to emulate the ISIS bunch length with a 32 μsec relaxation time, as explained below.

The ISIS muon areas[3] are shown in Figure 3. The synchrotron runs at 50 Hz, with two 100 ns bunches in each cycles. Four out of five cycles are sent to the muon production beam line, which uses a 1 cm Carbon target to intercept 2-3% of the beam for production of muons for the slow muon program. The total effective power going to muon production is about 3.4 kW.

In the case of the PIP-II linac, the bunch intensity is much smaller, but we benefit from the much higher repetition rate, as well at the fact that 100% of the protons in the line can be used for muon production. A string of five 40.625 MHz bunches every 32 μsec would emulate the 100 ns ISIS bunch with a sufficient relaxation time for most experiments. We see that in this mode, the total power is about 3 kW, or roughly equivalent to ISIS. Of course, more power could be achieved at the cost of a longer bunch length and/or shorter relaxation time.

Unlike existing facilities, which are tied to a particular mode of operation, the PIP-II muon facility could easily switch modes, or provide intermediate modes, if desired.

We have not yet discussed the details of the low energy muon experimental area. If this program as seen as worthwhile, the details of these areas would be designed in collaboration with interested scientists.

4 Domestic Interest

There is a sizable community in the United States who are interested in doing research at a slow muon facility, and these researchers are currently forced to conduct their research outside the country. The muon facility at ISIS has received requests from investigators at numerous US universities and labs. Particularly active researchers and their interests are shown in Table 3

References

[1] http://pip2.fnal.gov/

[2] http://mu2e.fnal.gov/

[3] http://www.isis.stfc.ac.uk/groups/muons/

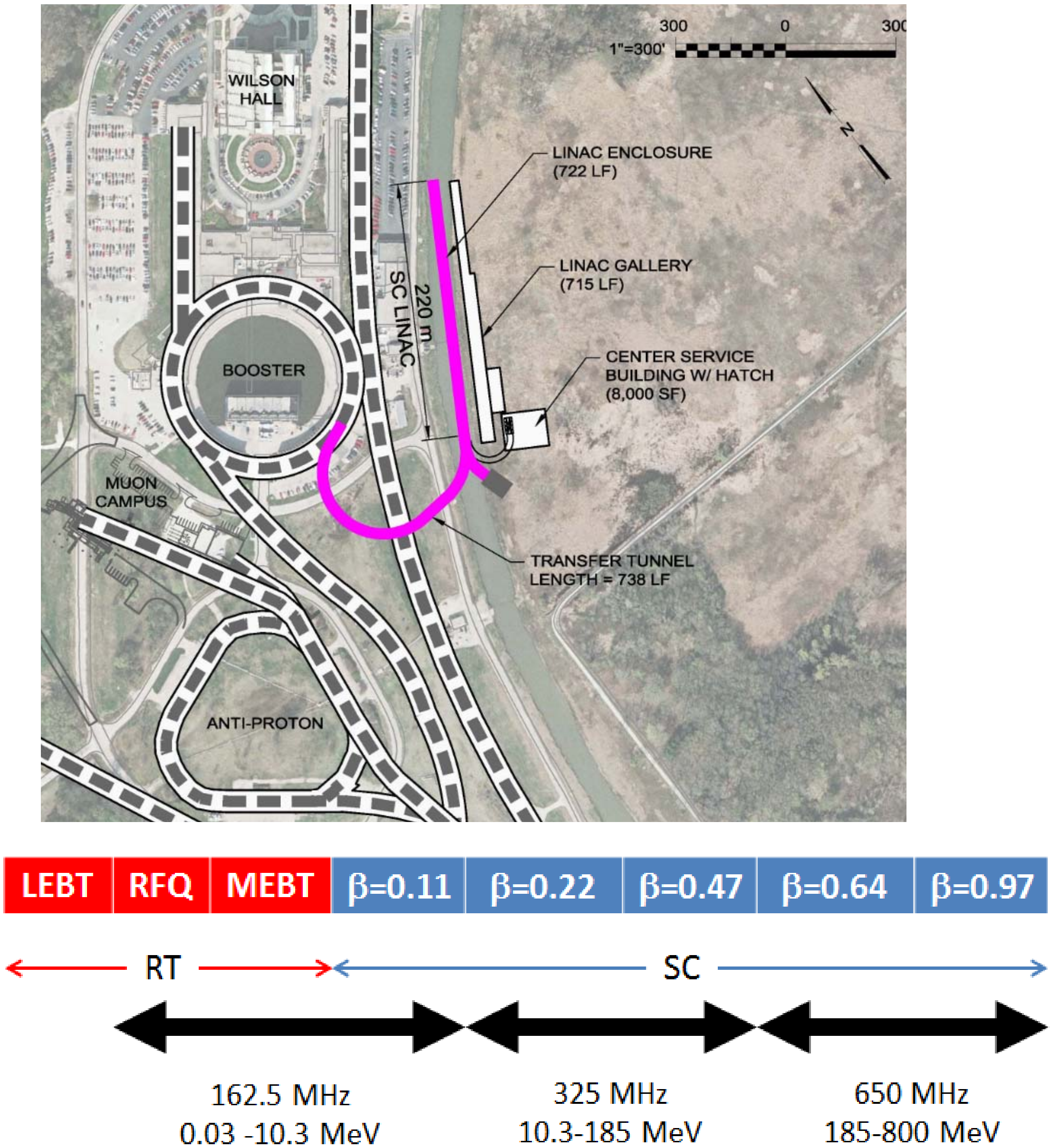

Figure 1: Proposed PIP-II linac. The linac will replace the existing 400 MeV linac, to reduce space charge effects in the Booster synchrotron.

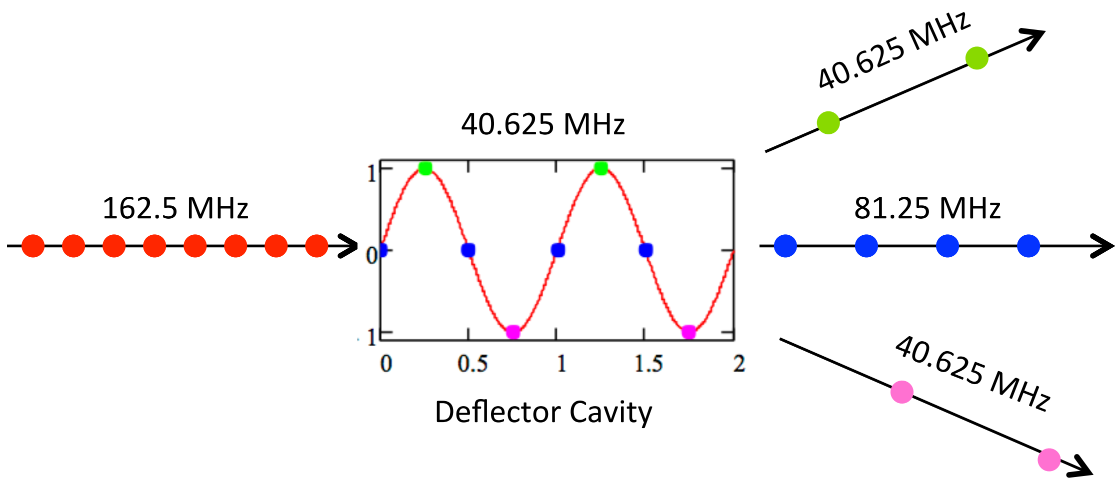

Figure 2: Proposed bunch switching scheme for the PIP-II linac. The source can produce arbitrarily populated 162.5 MHz buckets, for a minimum instantaneous bunch spacing of 6.2 ns. A proposed deflecting cavity would operate at one quarter of this frequency and divert individual bunches to one of three beam lines, based on their timing. The central (null) line would receive a maximum of 81.25 MHz bunches (12.3 ns spacing). It's assumed the the low energy muon program would use on of the two peripheral lines, which would each receive a maximum of 40.625 MHz (24.6 ns spacing).

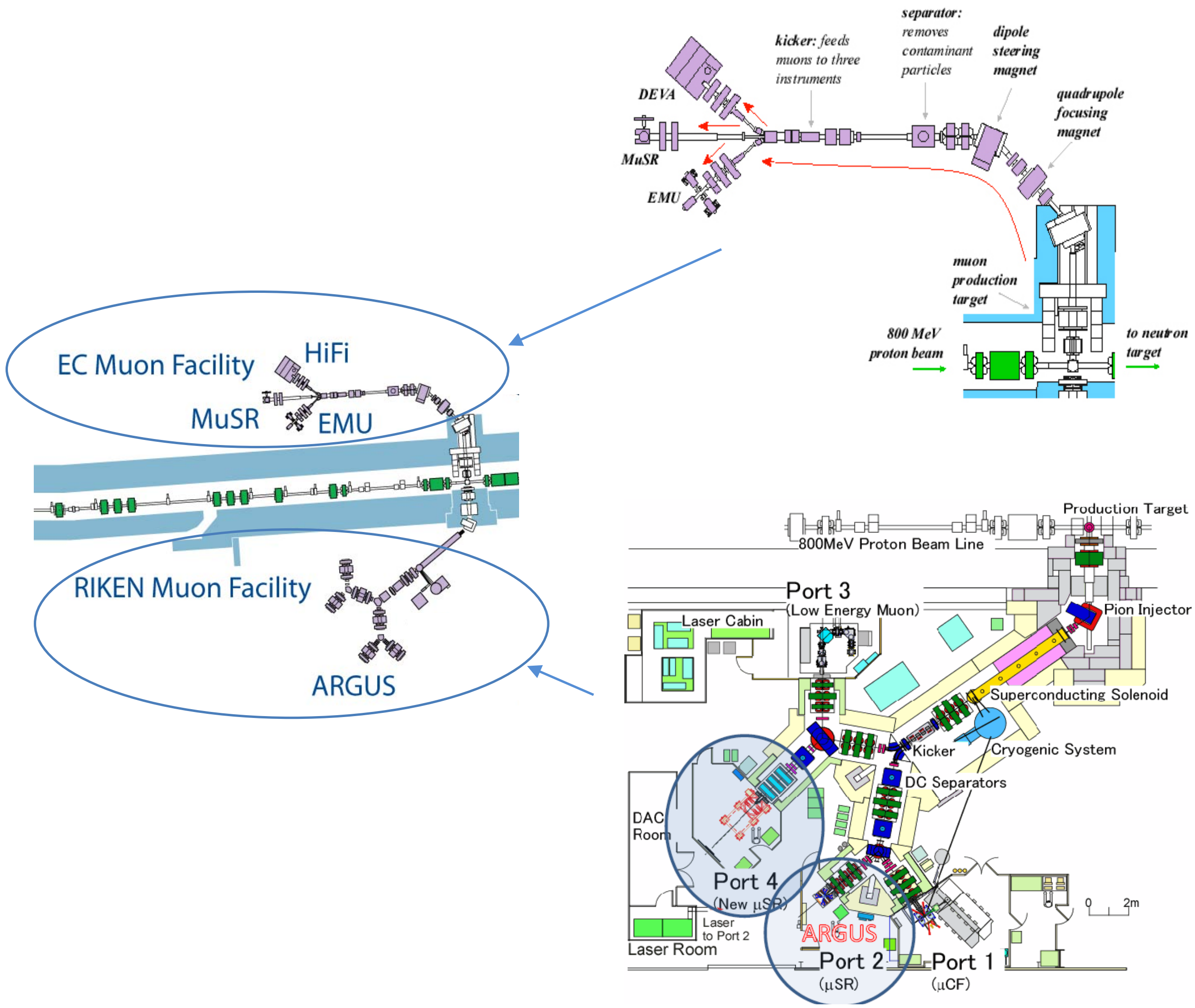

Figure 3: Muon facilities at ISIS. A parasitic 1 cm Carbon target (2.4% interaction length) is placed in the Target Station 1 beam line, supporting numerous experimental areas in the EC and RIKEN areas on either side.