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PROPOSAL FOR A μSR FACILITY AT BNL[*]

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Abstract

By implanting positive muons in a substance (either gas, liquid or solid), their magnetic moments can be used to sample the magnetic properties of the material. The precession rate gives the magnetic field strength, and the field direction is given away after the muons decay into positrons that are detected. The information obtained from μSR is complementary to that from other methods such as NMR, ESR, and neutron scattering. Only four user facilities exist in the world but none in the US. We explore the possibility of using the AGS complex at BNL for a μSR facility for the production of positive surface muons.

INTRODUCTION

Muon spin rotation, relaxation and resonance (μSR) is a powerful technique for studying local magnetic fields in samples. When a positive pion decays at rest into a positive muon, the muon has a kinetic energy of 4.119 MeV and its spin is opposite to its direction (negative helicity). If the pion decays near the surface of a target the resulting muons lose little energy and the result is a beam of muons with a narrow energy distribution and almost 100% polarization. When these positive muons are implanted in matter with a magnetic field the muons precess at a rate proportional to the local field. When the muon decays the positron momentum is preferentially along the direction of the muon spin. A muon with 4.119 MeV has a typical range of 150 ± 20 mg/cm^2 [1, 2] so that such muons are useful to study bulk properties of fairly small samples.

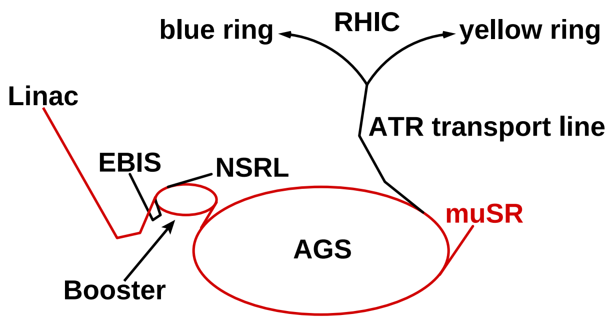

Figure 1: Schematic of BNL Linac, Booster and AGS within the RHIC complex. Proton path in red.

Table 1: Parameters for AGS Booster, AGS, target, and surface μ^+ user stations.

parameter	**unit**	**value**
AGS Booster (accelerator for pulsed proton source)		
circumference	m	201.773
injection energy E_{kin}	MeV	200
repetition rate	Hz	6.67
AGS (stretcher ring for DC proton source)		
circumference	m	807.092
injection energy E_{kin}	MeV	1500
parameters for pulsed and DC proton source		
extraction energy E_{kin}	MeV	1500
proton per pulse/spill	10^{12}	15
average beam current	μA	16
average beam power	kW	32
target for π^+ production		
material	...	carbon
shape	...	rectangular cuboid
dimensions ($l \times h \times w$)	cm	$20 \times 5 \times 0.3$
cooling	...	edge (top, bottom)
μ^+ flux/side	10^7/s	≈ 200
surface μ^+ user stations		
number of stations	...	2
modes	...	6.67 Hz / DC
μ^+ flux/station	10^7/s	≈ 2

There are four μSR user facilities in the world, two pulsed sources at RAL (10^6 μ^+/s [3]) and J-PARC (1.5×10^7 μ^+/s [4]), and two DC sources at TRIUMF (10^6 μ^+/s [3]) and PSI (3×10^8 μ^+/s [5]). Material studies using μSR were done at the BNL AGS already in the 1970s and 1980s [8]. We investigate a positive surface muon source at the existing Linac/Booster/AGS complex (Fig. 1), which can be either pulsed with the Booster repetition rate, or DC when the AGS is used as a stretcher ring. In the following we outline possible accelerator, target, and transfer line configurations. The main parameters of such a facility are presented in Tab. 1.

LINAC, BOOSTER AND AGS

Since 2000 the complex has served as an injector for RHIC. The Linac is also supplying protons for medial isotope production (BLIP) and the Booster has supplied a variety of ions to the NASA Space Radiation Laboratory. Before and during the 1990s the Linac, Booster and AGS delivered high intensity proton beams for fixed target experiments [6]. For μSR the beam parameters are close to those used for fixed targets experiments.

The 200 MeV Linac will deliver pulses of 20×10^{12}

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negative hydrogen ions at 6.67 Hz, the Linac repetitioan rate for BLIP. This also sets the fundamental repetition rate for μSR. The Linac pulse is charge exchange injected for about 300 turns into the Booster while the magnetic field is ramped to get optimal momentum spread for capture.

During high intensity operations typical losses of 15% occurred during the first 10 ms of the 75 ms Booster cycle. With continuous running the Booster will need a main magnet power supply upgrade to reduce perturbations to the local power grid. It is likely that 2 bunches running rf harmonics 2 and 4 will be the final choice for two reasons. First, all longitudinal coupled bunch modes are stable with two bunches, but not with more. Second, the synchrotron frequency is a factor of 2 larger than for one bunch with the same momentum spread. This allows adiabatic capture to proceed twice as fast as with one bunch.

After capture the beam is accelerated to 1.5 GeV. The extraction energy is chosen to increase the aperture in the Booster, the transfer line and the AGS. For muon production an energy of 600 MeV would be sufficient (see below). An upgrade to the aperture limiting elements would allow for a reduction in the Booster extraction energy. At a kinetic energy of 1.5 GeV, 17×10^{12} protons remain. At high intensity roughly 10% of the beam is lost in the transfer between the booster and AGS. In the AGS we can proceed with either fast extraction for a pulsed muon source, or slow extraction for DC muon source.

For fast extraction we can use the AGS as a transfer line. In this case the entire 15×10^{12} protons would be extracted to the target in one shot. For slow extraction we envision using the machinery employed during high intensity operations, but modified for the larger beam size and faster repetition rate.

TARGET

Muon production targets used in the present μSR facilities are located upstream of spallation neutron targets. With this configuration the surface muon target length is limited in order to minimize proton beam losses upstream of the neutron spallation targets, with typically $> 90\%$ proton transmission to the neutron spallation target. The μSR facility at BNL will use the entire incident proton beam allowing for a long target and a higher surface muon to proton ratio than at J-PARC and RAL.

A `g4beamline` [7] simulation was used to compare surface muon production at RAL, J-PARC, and PSI targets to a longer target at BNL, and to optimize the target material and dimensions as well as the proton energy. Figure 2 shows the surface muon yield as a function of target width for a carbon target 20 cm long and 5 cm high, and 600 MeV proton energy. Figure 3 shows the yield as function of the proton energy for a number of target materials.

Platinum targets were used with 24 GeV beam in previous μSR studies at the AGS [8]. We studied targets from carbon up to tungsten but the heavier targets did not yield more muons for proton energies up to 3 GeV and 20 cm long targets. For a 10 cm target both tungsten and copper yielded more muons than carbon for proton energies above 1.5 GeV.

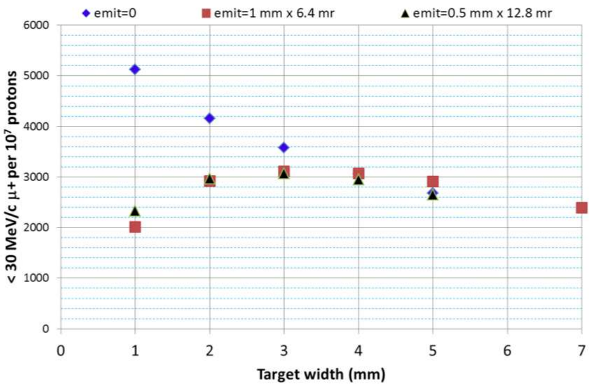

Figure 2: Surface muon yield as a function of target width for a carbon target 20 cm long and 5 cm high, and 600 MeV proton energy.

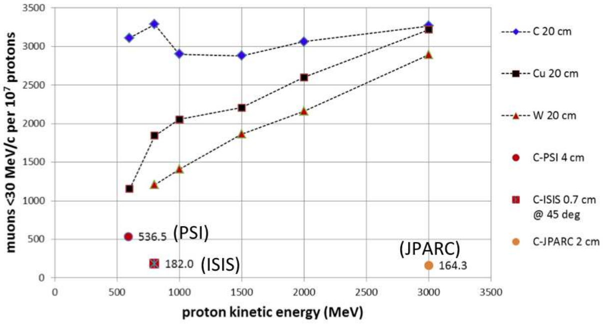

Figure 3: Surface muon yield as a function of proton kinetic energy for a carbon target $20\times5\times0.3$ cm.

The result of the optimization is a carbon target 20 cm long, 5 cm high and 0.3 cm wide, and a further optimization may be possible [9]. The proton energy of 1.5 GeV is only chosen to maximize the aperture in the Booster extraction and AGS injection and extraction elements although at this energy the muon yield is 7% lower than at 600 MeV. The `g4beamline` [7] simulation shows that 15×10^{12} incident protons at 1.5 GeV give 2.2×10^{9} positive surface muons per side.

MUON BEAM LINE

We have done a TURTLE [10] study of the μE4 beam line at PSI [5] with nominal settings. If we were to copy the existing beamline at PSI that could also accept the 20 cm long target, we expect about 2×10^{7} surface muons to reach the end of the beamline. We have begun to investigate a line with a better horizontal acceptance.

The design of the beam line is similar to the μE4 beam at PSI, but uses quadrupole doublets rather than triplets for focusing. A proton beam hits a thin long carbon target placed midway between solenoids -1 and 1 (Fig. 4). Surface μ^{+} are collected by solenoids 1, 2 and 3. To eliminate coupling from the three solenoids, we require that

$$B_{s1} + B_{s2} + B_{s3} = 0. \quad (1)$$

The solenoid -1 is used to continue the field lines with $B_{s-1} = B_{s1}$ and may also be used for beginning of a second beam line, although it is not all that necessary. Parameters of the solenoids are listed in Tab. 2.

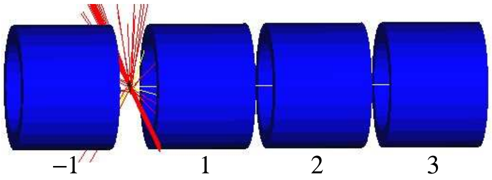

Figure 4: Target, solenoids, and incoming beam (red).

solenoid	**field** [T]	**aperture** radius [cm]	**length** [cm]
S1	-0.335	24	50
S2	0.280	24	50
S3	0.055	24	50

Table 2: Solenoid parameters ($B_{-1} = B_1$).

Starting from the target, the beamline is about 21 m long and consists of three 1 m long sector bends of $-40°$, $34°$, and $-34°$, and quadrupole doublets as shown in Fig. 5. A 70 cm-long Wien filter (yellow) separates positrons vertically from the μ^+ beam and is placed before the 7th quadrupole with two vertical scrapers (black) located between quadrupoles 8 and 9.

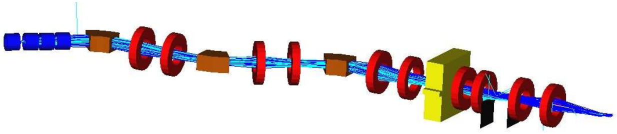

Figure 5: Layout of muon beam line.

The beam line has been modeled with `g4beamline` [7]. Since the production rate for surface muons is quite small compared the required number of protons, we generated a beam of 29.792 MeV/c muons with an rms opening angle of 100 mrad just downstream of the carbon target to tune the beam line. For tuning the separator we generated positrons of the same momentum. Fig. 6 shows the separation of e$^+$ from μ^+ at the second scraper for a $\pm 5\%$ momentum spread. Monochromatic μ^+ were transported down the line with a 66% efficiency as shown in Fig. 7, but dropped to 44% for $\sigma_p/p = 5\%$. The beamline work is still ongoing.

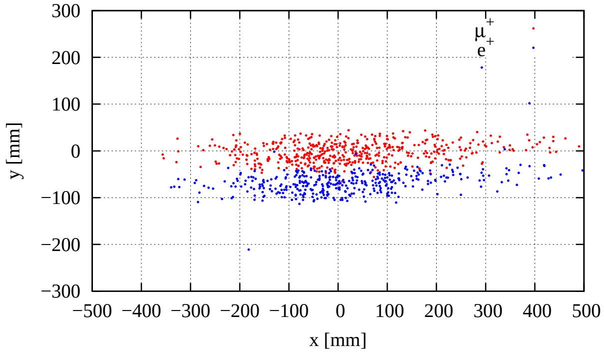

Figure 6: Separation of generated μ^+ and e$^+$ just upstream of the second scraper for $V_{\text{sep}} = 350$ kV across a 20 cm gap with a perpendicular magnetic field of 215 G.

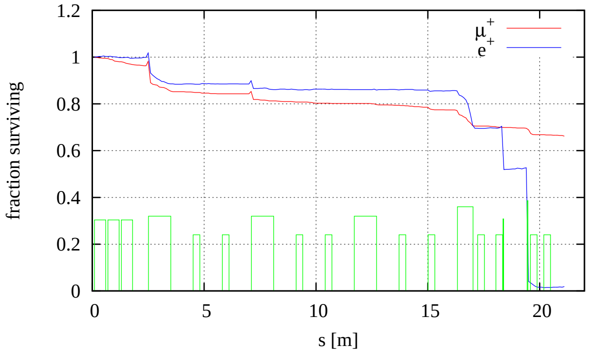

Figure 7: Fraction of generated 29.792 MeV/c μ^+ and e$^+$ surviving down the beam line.

SUMMARY

With the existing BNL hadron complex a 6.67 Hz pulsed positive surface muon source can be constructed with the Linac and Booster. Using a long target and all accelerated protons for the muon production, fluxes of approximately 2×10^7 μ^+/s in each of 2 user stations can be achieved, comparable to the existing pulsed sources. By using the AGS as a stretcher ring the same flux can also be delivered in DC mode.

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