# EXPLORING THE FEASIBILITY OF A STAND ALONE MUON FACILITY FOR MUSR RESEARCH

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*Abstract*

The current paper discusses possible designs for a high intensity stand alone muon source for muSR studies of condensed matter. In particular we shall focus upon the potential implementation of a new generation of high power but relatively compact and cost effective proton drivers based on non-scaling fixed field alternating gradient (ns-FFAG) accelerator technology. The technical issues which must be addressed are also considered.

## INTRODUCTION

Muon spin rotation, relaxation and resonance ($\mu$SR) are powerful techniques in the study of condensed matter science [1], and the increasingly large and broad-based global community of $\mu$SR scientists are currently well served by the excellent continuous muon beam facilities at PSI (Switzerland) and TRIUMF (Canada) and the pulsed muon beam facilities at ISIS (UK). A second pulsed facility at J-PARC (Japan) is currently being commissioned.

However, each of these muon sources could be said, at best, to be in symbiotic coexistence with, or at worst parasitic upon, other users of the powerful proton drivers necessary for pion, and hence muon, production. In this respect the design of each of the muon facilities, and in particular the geometry and efficiency of the pion/muon target, is essentially a compromise which leads to a sub-optimal muon delivery rate to the $\mu$SR spectrometers. The concept of a stand-alone dedicated muon source therefore appears extremely attractive not only as a means of satisfying the growing demand for muon beam time, but also as a route to advanced $\mu$SR techniques capable of addressing problems of increasing complexity in condensed matter science and fundamental physics.

Historically, such a dedicated source has generally been considered to be prohibitively expensive: the required accelerator drivers must be capable of delivering protons with energies substantially greater than the pion production threshold of 350 MeV, with currents of the order of hundreds of microamps. However, the promise of new, cheaper and more compact, yet also appropriately powerful, accelerators based upon the fixed field alternating gradient (FFAG) principle may well present the opportunity of designing and constructing a a fully optimised dedicated muon source at a reasonable cost [2, 3].

In this paper we briefly present our views of how such an FFAG-driven muon source might be configured.

## MUON FACILITY BASELINE PARAMETERS

The $\mu$SR spectrometers at both the PSI and ISIS muon facilities detect similar count rates (25-40 $10^3$ $s^{-1}$) of positrons resulting from the decay of implanted muons within the sample. These are the highest rates currently available. However, at a continuous (CW) source such as PSI only a single muon can be allowed in the sample at a time. A potential increase in count rate is therefore limited not by the muon production rate but by the CW SR technique itself. It thus appears that substantial gains (eg two orders of magnitude) in experimental count rate can be achieved only in pulsed mode.

In comparison with ISIS, a gain factor of at least 3 could be achieved simply by increasing the thickness of the graphite target, an expedient that would cause unacceptable proton beam losses for other users of the accelerators at existing muon facilities. A further factor of 10 could be obtained by appropriate optimisation of the solid angle acceptance of muons from the pion/muon production target. Coupling these modifications with a proton driver with a power of at least 500 kW would provide a total count rate gain of at least 100. Ideally the accelerator driver should operate at 1 GeV in order to take advantage of double pion production beyond the 600 MeV threshold.

The 50 Hz pulsed operation of ISIS is sub-optimal for $\mu$SR studies. It offers a duty cycle of only 0.16% because time resolved $\mu$SR spectra are typically measured over no more than 32 $\mu$s (ie $\sim$ 15 muon lifetimes). It is therefore preferable that a muon source for $\mu$SR experiments should operate at 25 kHz, thereby also alleviating dead time corrections at the muon spectrometers.

Pulsed source operation unfortunately places significant limitations on the frequency response of the muon spectrometers as convolution of a finite muon pulse width (which is itself a convolution of the incident proton pulse

| | Cyclotron | FFAG | Synchrotron |
|---|---|---|---|
| Energy ~ 1 GeV | No | Yes | Yes |
| Current > 1 mA | Yes | Yes | No |
| Frequency | CW | 0.1 – 2 kHz | 30 – 60 Hz |
| Pulse length | Continuous (~ 1 ns) | 10 ns – 1 $\mu$s | 100ns to ~ 1 $\mu$s |
| Beam size ~mm$^2$ | No | Yes | No |
| Extraction efficiency | Good | Good | Good |
| Operation | Easy | Easy | Not easy |
| Maintenance | Hard | Normal | Normal |
| Static fields | Yes | Yes | No |
| Size | Moderate | Compact | Very large |
| Mult. beam extraction | Difficult | Yes | Difficult |
| Construction cost | High | Moderate | Very high |
| Existing technology | Yes | Almost | Yes |

Figure 1: A comparison of the principle features of cyclotron, FFAG and synchrotron drivers for a dedicated muon facility.

width and the pion lifetime of 25 ns) with the precessional rotation of muons in a coherent (internal or external) magnetic field rapidly reduces the measured muon decay asymmetry with increasing field. However, effectively narrow muon pulse widths can be achieved by electrostatically trimming the pion decay tail, and by electrostatic shaping of the muon pulse post-production. A sufficiently high muon production rate therefore affords the opportunity of almost instantaneously trading absolute muon count rate against the frequency response (ie resolution) of the muon spectrometer via suitable pulse shaping. At the extreme, quasi-CW operation with a count rate similar to that at PSI could be achieved by deploying muon-on-request techniques as already implemented at PSI, or by closing the incident beam collimation to allow, on average only one muon per pulse to reach the sample.

Muon beam size is yet a further experimental parameter which is ultimately imposed by the primary proton driver. At PSI and ISIS the beam size is typically between 100 and 1000 mm$^2$. Smaller beams, for example for single crystal studies or for spot scanning, can only be achieved at the expense of beam intensity by narrowing collimation. A dedicated accelerator capable of delivering proton beams of significantly smaller cross sections would in turn facilitate delivery of significantly smaller muon beams.

Finally, removed from the restrictions imposed by other demands on the proton driver, a dedicated muon source would provide the possibility of incorporating multiple (sequential) muon targets, each with the material, thickness, geometry and transmission fully optimised for specific requirements (eg for surface muons, low energy cryogenic muon production, and decay muon channels).

## TOWARDS A DEDICATED MUON FACILITY: FFAG DRIVERS

From the previous discussion it is clear that a dedicated muon source could indeed offer significant gains in intensity over existing facilities, but only in pulsed mode operation. However it is possible to compete favourably with the currently most intense CW muon source at PSI, whilst also offering some improvement to certain beam parameters (eg beam size) and providing the opportunity for deployment of multiple muon targets.

We have seen that a dedicated world-leading next generation muon source should be based upon a proton driver of at least 500 kW power, and should be able to deliver three modes of operation:

- A pure pulsed mode (ideally operating at 25 kHz) with am integrated positron count rate at each muon spectrometers of at least two orders of magnitude higher than that at ISIS, whilst also offering an improved frequency response (ie a pulse width of 30 ns or less)
- Provision for electrostatically tailored muon pulses (eg ~5 ns at 25 kHz) with a count rate approximately an order of magnitude higher than ISIS, but with a significantly improved frequency response
- The possibility of operating in a quasi-CW mode which at least matches the experimental count rate of the best existing CW sources.

The question remains as to which kind of accelerator could best deliver these characteristics. In an attempt to answer this question we list and compare the relevant features of synchrotrons, cyclotrons and FFAGs in Fig.1. It is apparent that FFAGs fulfill most of the requirements of a proton driver for a dedicated muon source, although current estimates of the operational frequency of FFAG accelerators fall an order of magnitude below the optimal 25 kHz.

Nevertheless it is worth exploring whether higher frequencies operation can be achieved with FFAGs, for example through single injection and slow extraction. To summarise FFAG accelerators appear to combine the ease of use, and proton current capabilities, of a cyclotron with the high energies generally achievable with a synchrotron.

Unfortunately, FFAG technology is not yet at the stage at which it can be readily deployed, particularly at the high energies and currents demanded by a muon facility. Scaling FFAGs have been prototyped and demonstrated (eg [4]) at energies of up to 150 MeV, and there is little doubt that more powerful FFAGs will soon be developed. However, we consider that non-scaling FFAGs may offer a more suitable and cost-effective solution.

Non-scaling FFAGs have a much smaller variation in orbit radius, and a magnetic field profile which has a significantly simpler variation on the orbit radius. They also have unique optical features: small orbit excursions giving large momentum compaction, rapid tune changes leading to multiple resonance crossing and asynchronous acceleration. Whilst scaling FFAG accelerators attempt to minimise the effect of resonances, the non-scaling FFAGs do not. However, recent calculations carried out as part of the UK's CONFORM project [5] indicate that acceleration takes place so rapidly, and particles cross the resonances so quickly, that the associated instabilities will have little effect on the beam. Tests on CONFORM's EMMA [6], the world's first non-scaling FFAG currently being constructed at the UK Science and Technology Facilities Council's Daresbury Laboratory, should soon show whether this supposition is correct. A successful demonstration of the non-scaling FFAG principle will undoubtedly open the way for more compact and significantly cheaper FFAG technology

## CONCLUSIONS

There is little doubt that condensed matter science studies of phenomena as diverse as superconducting vortex lattices, spin glasses, magnetic fluctuations, hydrogen passivation in superconductors, diffusion, surface magnetism and catalysis and muonium chemistry would greatly benefit from the construction of a fully optimised and dedicated next generation muon beam facility. Such a facility would not only enable existing muon science to be performed more efficiently, allowing more detailed multidimensional parametric $\mu$SR studies across temperature, magnetic field and pressure space, but would also open the way for new muon science and technology.

A non-scaling FFAG operating at 0.5 mA and 1 GeV, with a pulse width of 30 ns,a pulse frequency of several kHz and a small cross section proton beam would provide an almost optimal driver for such a facility, offering multiple target and multiple beam experimental facilities with count rates some two orders of magnitude higher than those available at present. Indeed, the non-scaling FFAG may be the only viable and cost-effective driver for a next generation muon facility.

As part of the wider CONFORM project, we are at present exploring the design of such a non-scaling FFAG driven muon facility in a programme which involves a close collaboration between members of the international accelerator and muon science communities. In particular pion/muon target materials and geometries, and muon collection geometries are being studied using GEANT4 simulations [7].

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