



# Muon Target Simulations

Adriana Bungau (Bob Cywinski)







....an FP6 NMI3 funded workshop at the Cockcroft Institute, Daresbury, in April 2008

## Towards a Next Generation **European Muon Source**



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ARTICLE INFO

29.25.-1 29.25.-1 29.20.-5 76.75.+1

1. Introduction

Towards a dedicated high-intensity muon facility R. Cywinski 4. R. Cywinski 4. R. Edgecock 4. P.J.C. King 4. J.S. Lord 4. S. Smith 5. P. Dalmas de Reotier 4. R. Barlow 4. School 9 Applied Sciences University of Huddersheld Hild Bendels Hild 2004, UK A. SUBERION, S. FJAN, MING, J. S. LUNG, S. L. ITAL, "FALL ITAL", N.N. School of Applied Statements (Journaus) of Historistical Holderschole Hold 2000 (J. Applied Statements), Warraum, October 101, 2000 (J. CASHIG, S., Rate and Mannaeu, J. Mannaeu, October 101, 2000 (J. CASHIG, S., Rate and Mannaeu, J. Mannaeu, Cashida, "Mannaeu, Mannaeu, Applied Statements Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Fall Schorter Instance, Cashida, Salanaeu, Mannaeu, Mannaeu, Applied Schorter Instance, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Fall Schorter Instance, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Salanaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Mannaeu, Cashida, Mannaeu, ABSTRACT We discuss possible designs for a high-intensity, stand-alone truum source dotter optimized for JSR studies. In puriticular, we frous upon the potential implement generation of high-power, but relatively compact and cost effective, proton drives base optimised for uss studies. In putricular we new studies the potential implementation of high-money to be relatively compared with the potential implementation of the studies of the studi Ledings with multiple optimised pion takets, each anoming position order or magnitude higher than existing pulsed non success, more accompatible coge, at comparison exact comparable for the best constanting successful to the relative mergin pulsed non-accessing so faultices which operate is synthesic mode with other uncertaing so outstanding networked leagers which more he south other uncert of the pi e dedicated to and fully suggest that a The production of high-intensity, spin-polarised muon beams is intrinsically related to the availability of recordary plan beams the generation of which, in turn, requires the use of high-homobeams proton accelerators. The high costs related to accelerator con-

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2. Optimal proton driver parameters for a dedicated muon Any stand-alone muon facility must be based upon sufficiently how day, arouting the forest on afford onlinear training of the Any stand-slone muon facility must be based upon sufficiently flexible accelerator technology to afford optimal tuning of the in detail below and to better illustrate the advantages are considered the new paradigm, we compare these requisites with the the new paradigm, we compare these requisites with the parameters of two representative mon sources. ISS and PSD objects in pluse power and cinegy. Both curves, ISS and PSD and arrive power and cinegy. Both curves, ISS and PSD for the source as only one muon (with half life of 2.2 µS) can detail below and, to better illustrate the advantages offered by e-new\_paradigm, we compare these requisites with the reameters of two reomsonitative much courses (second the This have similar muon count rates  $(25-d0 \times 10^{+} \text{s}^{-1})$ . At a since source, as only one muon (with half life of  $2.2 \, \mu\text{s}^{-1}$ ). At a blowed in the sample at a time, the remembrand (restrict) (restricted) continuous source, as only one muon (with half life of <...(is) on be allowed in the sample at a time, the experimental (position)

NMI3, Zurich, 30 March '09

A stand-alone optimised muon facility could deliver x100 intensity gains in pulsed mode and comparable intensity to PSI in CW mode

A 1Gev, 0.5mA Fixed Field Alternating Gradient proton accelerator at KHz frequencies would be an appropriate and cost effective driver

	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 µs	100ns to ~ 1 µs
Beam size ~mm²	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	No	Yes	Difficult
Construction cost	High	Moderate	Very high
Existing technology	Yes	No!	Yes

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#### Towards a dedicated high-intensity muon facility

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<sup>a</sup> School of Applied Sciences, University of Huddersfield, Huddersfield HD1 3DH, UK <sup>b</sup> ASTeC, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK <sup>c</sup> CEA/INAC, 17, rue des Martyrs, 38054 Grenoble cedex 9, France <sup>d</sup> School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK <sup>e</sup> ISIS Facility, STFC Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK <sup>f</sup> Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

ARTICLE INFO	ABSTRACT	
PACS: 29.25t 29.20c 76.75.+i Keyward: Stand Johne muon sources Non-scaling FACA accelerators Muon spin spectroscopy	We discuss possible designs for a high-intensity, stand-alone muon source dedicated to and fully optimised for JSR studies. In particular, we 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-FRG) accelerator technology. Initial considerations suggest that a facility with multiple optimised pion targets, each affording positron count rates approximately two orders of magnitude higher than existing pulsed muon sources, logether with the potential of steady state operation at count rates comparable to the best existing sources, should be achievable at reasonable cost. The relative merits of a stand-alone muon facility with respect to those of current facilities which operate in symbiotic mode with other users of the proton driver are highlighted. The outstanding technical issues which must be addressed by both muon scientists and accelerator technologists are also considered.	

#### 1 Introduction

The production of high-intensity, spin-polarised muon beams is intrinsically related to the availability of secondary pion beams. the generation of which, in turn, requires the use of high-intensity proton accelerators. The high costs related to accelerator construction and operation have resulted in the so-called multipurpose facility model, where muon, neutron and particle physics experiments are carried out at the same facility, typically running a medium energy (~800 MeV) accelerator.

This co-existence, at best symbiotic and at worst parasitic, was understandable in the early days of uSR, when the technique was still in its infancy and the user community rather small. However, the resulting paradigm is a compromise in which many muon beam parameters are far from optimal, thereby limiting the potential of the µSR method and often precluding developments which could be realised at a dedicated source.

Today, when µSR has a wide user base and is a well established and powerful tool in condensed matter science which complements, and in some cases competes with neutron scattering [1,2], there are good reasons to investigate other models of muon beam

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delivery. Indeed there is a growing consensus that the concept of a stand-alone muon source is most certainly worth pursuing [3].

The current paper discusses possible designs for a highintensity, stand-alone muon source dedicated and fully optimised for µSR studies of condensed matter. In particular, we shall focus upon the potential implementation of a new generation of highpower, but relatively compact and cost effective, proton drivers based on non-scaling fixed-field alternating gradient (ns-FFAG) accelerator technology.

#### 2. Optimal proton driver parameters for a dedicated muon source

Any stand-alone muon facility must be based upon sufficiently flexible accelerator technology to afford optimal tuning of the proton driver parameters. The necessary requisites are considered in detail below and, to better illustrate the advantages offered by the new paradigm, we compare these requisites with the parameters of two representative muon sources: ISIS and PSI. operating in pulsed and continuous (CW) mode, respectively.

Proton driver power and energy: Both current European muon facilities have similar muon count rates  $(25-40 \times 10^3 \text{ s}^{-1})$ . At a continuous source, as only one muon (with half life of  $2.2 \,\mu$ s) can be allowed in the sample at a time, the experimental (positron)

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<sup>\*</sup> Corresponding author, Tel.: +44 1484 473013 E-mail address: r.cywinski@hud.ac.uk (R. Cywinski).

A stand-alone optimised muon facility could deliver x100 intensity gains in pulsed mode and comparable intensity to PSI in CW mode

A 1Gev, 0.5mA Fixed Field Alternating Gradient proton accelerator at KHz frequencies would be an appropriate cost effective driver

Simulations of (multiple) pion/muon production targets and accelerator/target/collection/beam optics combinations are necessary

.....But first the codes have to be benchmarked - against the ISIS target?

.....could the ISIS target geometry/muon collection system be optimised as part of the same programme?



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<sup>4</sup> School of Applied Sciences, University of Huddersfield, Huddersfield, HDI 3DH, UK ASTC, STK Densbury, Iaboutory, Wurnigton, Cheinlen Wei 44D, UK <sup>6</sup> CEA/INKC, Tr. nue des Martyrs, 38054 Grenoble cedex 9, Pance <sup>6</sup> School of Physica and Astronomy, University of Manchester, Manchester M13 9FL, UK <sup>8</sup> ISS Facility, STK? Rutherford Appleton Laboratory, Chilton, Ddot OX11 0QX, UK <sup>7</sup> Mau Scherrer Institut, CH-522 Willen PLS, Switzerland

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0921-4526/\$-see front matter © 2008 Elsevier B.V. All rights reserved, doi:10.1016/j.physb.2008.11.203 delivery. Indeed there is a growing consensus that the concept of a stand-alone muon source is most certainly worth pursuing [3].

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<sup>\*</sup> Corresponding author, Tel.; +44 1484 473013, E-mail address: r.cywinski@hud.ac.uk (R. Cywinski).

# **GEANT4**

Geant4 is a toolkit for the simulation of the passage of particles through matter

Developed and maintained at CERN

Originally intended for high energy physics experiments (eg LEP)

Now wide range of uses including medical, nuclear, and space science

Distributed as a set of C++ libraries

GEANT4 is already used in simulations of µSR experiments *eg, Prokscha, Shiroka, Lancaster, Sedlak ......* 

# Can GEANT4 accurately simulate proton/target interactions ?



#### GEANT4 as a simulation framework in $\mu SR^{\star}$

T. Shiroka <sup>a,b,\*</sup>, T. Prokscha <sup>a</sup>, E. Morenzoni <sup>a</sup>, K. Sedlak <sup>a</sup> <sup>a</sup>Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland <sup>b</sup>Dipartimento di Fisica, Università di Parana & CNR-INFM, Viale C.P. Usebriti 7, 4, 4500 Parma, Italy

#### Abstract

GEANT4 is a Monte Carlo radiation transport toolkit which includes a complete range of functionalities required to build flexible simulation frameworks. Taking advantage of its open architecture and object-oriented design, we could develop a software suite, able to simulate  $\mu$ SR experiments and instrumentation. The versatility offered by this new tool has permitted us to model the existing instruments, thus allowing a fuller understanding of their operation. It has guided also the design and construction of new types of spectrometers, as those equipped for high-field  $\mu$ SR, where numerical simulations proved decisive in understanding the complex behaviour of the incoming muon beam and of the outgoing positrons in a high magnetic field environment. The developed  $\mu$ SR simulation framework, with its fully flexible and customizable design, will allow potential users not familiar with programming to focus exclusively on physics, by building and running their own applications without the need to modify the source ocde.

Key words: Computer modeling and simulation, GEANT4, Object-oriented design, Muon spin rotation PACS: 07.05.Tp, 41.85.-p, 76.75.+i

#### 1. Introduction

The Monte Carlo method is a computer-based statistical sampling technique for solving complex, nonstandard problems. Due to its general-purpose, numerical approach the method has found a wide range of applications in many which needs to accommodate more elaborate sample environments, the situation has changed. The growing demand to understand the detailed operation of muon spectrometers has been recognized by the FP6 JRA8 program, where the development of software code to enable full instrument simulation has a dedicated work package.



# GEANT4: hadronic model inventory





# GEANT4: eg LEP vs Bertini

### After: Aatos Heikkinen



Gean3.21 based Geant4 LEP model pion production from 730 MeV proton on Carbon.

Bertini cascade model pion production from 730 MeV proton on Carbon.



# The ISIS muon target

### Proton beam:

800MeV with ~1MeV energy spread

Focused to Gaussian "waist" at target with rms half width and rms half height of 5mm:

rms x' = 6mrad rms y'=5mrad

### Target:

Graphite plate 50\*50\*7 mm<sup>3</sup>

Oriented at 45° to proton beam (rotated around vertical axis)

Effective path length through target ~10mm

Graphite muon production target



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# Simulation geometry



Spatial cut: (a) particles emerge from target within ±0.5cm vertically and ±3cm horizontally
(b) particles must be parallel to beamline axis with 180mrad in horizontal direction and 35 mrad in vertical direction

Momentum cut: momentum bite must be between 25.175 and 27.825 MeV/c (ie 10% around 26.5MeV/c)



# **GEANT4** simulations

GEANT4 and three physics models have been used:

Bertini model

Binary Cascade Model

INCL-ABLA model.

Initial simulations of 2x10<sup>13</sup> protons (corresponding to an ISIS double pulse) took a prohibitively long time to run

Shorter simulations of  $4x10^7$  protons resulted in much poorer statistics, but in agreement with the longer runs and experiment, give the equivalent of 20000-40000 µ<sup>+</sup> with the correct momentum and spatial cuts entering the beam window per ISIS double pulse.





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The simulations showed a reasonably isotropic distribution of muons from the target – this was used to speed up the simulation procedures by separating pion production from muon transport



# **GEANT4** simulations

Each model generates the final state for hadron inelastic scattering by simulating the intra-nuclear cascade.

### The Bertini model:

The target nucleus is treated as an average nuclear medium to which excitons (particle-hole states) are added after each collision.

### The Binary Cascade model:

The target nucleus is modelled by a 3-D collection of nucleons, as opposed to a smooth nuclear medium.

### The INCL-ABLA model

The intra nuclear cascade is based upon the Liege cascade model (INCL) and the de-excitation is based on ABLA





## Bertini Cascade Model

- simulations are for 2.5 x 10<sup>11</sup> protons on target
- for 2.5 x 10<sup>13</sup> protons there are 84200 positive muons entering the beam window





## **Binary Cascade Model**

- simulations are for 2.5 x 10<sup>11</sup> protons on target

- for 2.5 x  $10^{13}$  protons there are 62700 positive muons entering the beam window



NMI3, Zurich, 30 March '09

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## **INCL-ABLA Model**

- simulations are for  $2.5 \times 10^{11}$  protons on target

- for 2.5 x 10<sup>13</sup> protons there are 27500 positive muons entering the beam window



# INCL-ABLA: pions at rest in target



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## **INCL-ABLA:** muon production





250



x (mm)



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# **Unwanted particles**

### Background particles entering the muon beam window





## **Target material**



## Next steps

- Composite targets (eg Ni coated Be)
- Complex geometries (eg small xsection pencil/conical target)
- Proton loss calculations
- Thermal load calculations
- Improvement of collimators and collection geometries

With implications for

- Neutrino factory
- Stand-alone dedicated muon facility (protons?)





## Carbon ion beams



Beam	$\pi^+$
р	0.0339
d	0.0337
С	0.190

Pion yield at 30 < E < 230 MeV

Carbon seems a promising projectile

Pion spectra from 400 MeV/A projectiles on an Hg nucleus

Simulations by N. Mokhov (From Shiroka)

