EUROPEAN SPALLATION SOURCE

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An Initial Cost-Benefit Analysis for Instrument Optics and Shielding

Executive Summary

Following from the first Annual Review, Q3 2013, it was apparent that a cost optimisation of the instrument suite was timely, which trades performance, optical and shielding costs. The purpose of this initial study is to identify potential savings across the suite by applying strategic optimisation of cost:benefit ratios rather than a tactical, case-by-case optimisation weighted more strongly on performance.

A maximum initial potential saving is identified in the vicinity of 28 M Euro, with negligible costs on instrument performance and bandwidth, by trading minimum λ against optical costs and shielding costs. These cost savings are commensurate with a detailed cost:benefit analysis performed at JPARC, and eventually realised on the JPARC instrument suite [2].

To achieve these savings, it will be necessary to approach each instrument construction project individually in phase 1 and phase 2 with a strategic mindset and strong oversight on the design work.

Contents

1 Introduction

During 2012, Uwe Filges from PSI, Switzerland was hired as a nuclear engineer consultant to perform an initial study of possible shielding specifications for the ESS and a performance evaluation of "$T0$" or "t-zero" choppers: these are heavy choppers that attenuate the high-energy particles during proton illumination of the spallation target. The cost of these T0 choppers was estimated roughly and somewhat optimistically by the ESS Chopper group, assuming some economy of scale by manufacturing multiple units and minimising development costs.

Also requested was a rough cost estimate for an enhanced concrete instrument cave for straight beamlines, based on the PSI instrument "BOA", increased in thickness to 2 metres, and accomodating $5 \times 5 \times 5$ m^3 of instrument space. These specifications were for a generic instrument, based partly on calculations and partly on measurements at PSI and SNS on fast neutron transmission and prompt pulse backgrounds in 2013.

A market survey was performed later in 2012 that provided costs for various neutron guide units across a range of specifications and radiation resistance. In 2014, this was enhanced by the provision of cost functions from two vendors, that allowed the Neutron Optics and Shielding group to scan the potential cost of a large area of parameter space for guide benders of different types, m-values, curvatures and sizes. These cost functions are provided commercial in confidence, under trust to P Bentley not to disseminate them.

In 2013, during the study of high energy neutron backgrounds at PSI, Switzerland and SNS, USA, it became apparent that the best instrument cave for a curved beamline would be quite similar to the LET and OFFSPEC instruments on TS2 at ISIS, in the UK. These are hollow steel cans filled with borated paraffin wax.

Also in 2013, an engineering study was performed on different shutter options for beamline regions with direct line of sight to the source. Part of this study involved a conceptual design and cost study for a heavy shutter outside the target monolith. The decision was made that the ESS would not have heavy shutters inside the target monolith, so these heavy external shutters are seen as necessities for straight neutron beams. Without them, it will not be possible for a human access to the sample area during neutron production.

Initial estimates were made for *thermal* beamlines at ESS, i.e. the parts that are out of line of sight of the source. The worst-case scenario was used, that a chopper or vacuum system is broken and blocking the beam completely with carbon steel. An approximate thickness of 60 cm of regular concrete was found via GEANT4 calculations to attenuate the radiation sufficiently to safe levels (1.5 μSv/h total simulated dose rate). 60 cm of concrete is slightly thicker than other lower power facilities but not excessive. For example, on TS2 at ISIS, 35 cm of concrete shielding is sufficient, although in that case a heavy shutter can be closed if there is a safety hazard on a beamline. It may be possible to further reduce the ESS beamline shielding thickness for thermal beams by relaxing this design principle.

For line-of-sight shielding, and indeed the transition from line-of-sight to out of line-of-sight, we use the BASIS beamline at the SNS as an example concept. This is upgraded from 1.5 metres of concrete to 2 metres of concrete for ESS. This number will be refined during 2014-2015, and some tapering is possible if our continued research at PSI, SNS and ISIS would support this.

In all beamlines, it is anticipated to use at least three laminate collimation blocks within the shielding bunker and/or curved sections, to reduce the streaming of fast neutrons into the guide system downstream. These may be conceptually similar to the collimator on the CHIPIR beamline at ISIS, but for the purposes of this study it can be assumed to be 1m ^{3} of copper or brass with a small channel cut through the centre, which would offer excellent performance in any case.

The cost of concrete comes from ESS Conventional Facilities, and is the price for reinforced concrete, cut and shaped and installed.

The cost of raw metals come from the London Metal Exchange.

An initial shopping list of components can be now assembled for a generic neutron instrument, described in section 2 on page 6. This price list will of course be refined during the next few years as engineering details are developed.

Nonetheless, using this shopping list in its present state, it is possible to perform an initial estimate of costing *ranges* for the ESS suite, using a number of beamline options. The options considered are as follows:

Baseline – this is the instrument cost as described in the proposal, with some adjustments. The proposals have varying degrees of information on pricing of items, so the proposal scope was costed using the same items as the rest of this study, and compared with the proposal cost. If there were significant discrepancy between the NOSG estimate of the cost and the stated proposal cost, then we use the NOSG cost estimate based on the defined scope.

Homogenised – this replaces the neutron guide system in the proposal with a "standard" ESS beamline that we currently feel has the greatest bang-for-buck value. Elliptic guides with m 3-6 are replaced with ballistic guides, with a maximum cross section of 200 mm in horizontal and vertical directions, and a typical m value of 1-1.5 for the wide sections, and m=3 for the compression and expansion sections nominally. The divergence and spatial dimensions of the beam can be fully tailored to the instrument in the final 10-15 metres of guide, and the design of the compression and expansion sections is done so as to guarantee phase space homogeneity.

Curved – the homogenised guide concepts are used, except that in this option there are no guides that are straight with a line of sight back to the source. All beams are curved. The m-values are optimised to transport the minimum wavelength efficiently and cheaply as specified for each instrument.

Bender – The same guide concepts are used, except now we use benders to get out of line of sight within the beam extraction guide bunkers. This means that the shielding outside the bunker has specifications based on the Ni/Ti capture radiatoin rather than spallation source radiation, and is much cheaper. Conversely, the benders can be more expensive than a regular curved guide.

Note that in some cases (Estia) a neutron guide is not used, and so no cost adjustment was made since the Selene optics concept is already expected to be excellent in terms of a cost benefit ratio, background suppression and avoiding line of sight inside the bunker shielding.

2 Cost Breakdown

2.1 Shielding Costs

The cost breakdown for shielding is as follows:

ISIS-TS2 Wax Cave based on LET and OFFSPEC, for thermal beams out of line of sight. Cost: 950 kGBP several years ago, rounded to 1.5 MEuro.

PSI Concrete Cave based on BOA, for beams with direct line of sight: 2 MEuro.

Heavy beam shielding for beam areas within line of sight: approx. 7770 Euro per metre.

Light beam shielding for thermal beams out of line of sight: approx. 2600 Euro per metre.

Laminate collimation blocks initially costed as 100% copper: 47 kEuro per unit, 3 units per beam.

T0 Chopper : only necessary for straight beamlines with line of sight of source, 750 kEuro.

Heavy shutter : only necessary for straight beamlines with line of sight of source, 750 kEuro.

2.2 Optical Component Costs

The guide and bender costs were provided commerical in confidence and are not recorded here.

2.3 Optical Component Specifications

In this section, the requirements and specifications of low cost beam components will be explored.

2.3.1 Requirements

The minimum wavelength band of the instrument suite is shown in figure 1 on page 7. Here we can see that there are three categories of instrument: those who are interested in wavelengths at and just below 1 Å and above; those interested in 2 Å neutrons and above, and those interested only in cold neutrons of 4 Å wavelength and longer.

Subdividing into long (150 m) and medium (60 m) instruments is informative. The minimum wavelength band of the long instruments is shown in figure 2 on page 7. Here we see that the long instruments are split almost half:half into 2Å and $\sim$1Å instruments.

For the medium-length instruments, the wavelength bands are shown in figure 3 on page 8.

From this very brief survey, we can begin to construct a *minimum-cost* standard transport system to compare with the baseline. There are four curved guide systems to consider: two sets of curved guides for the 150 metre instruments

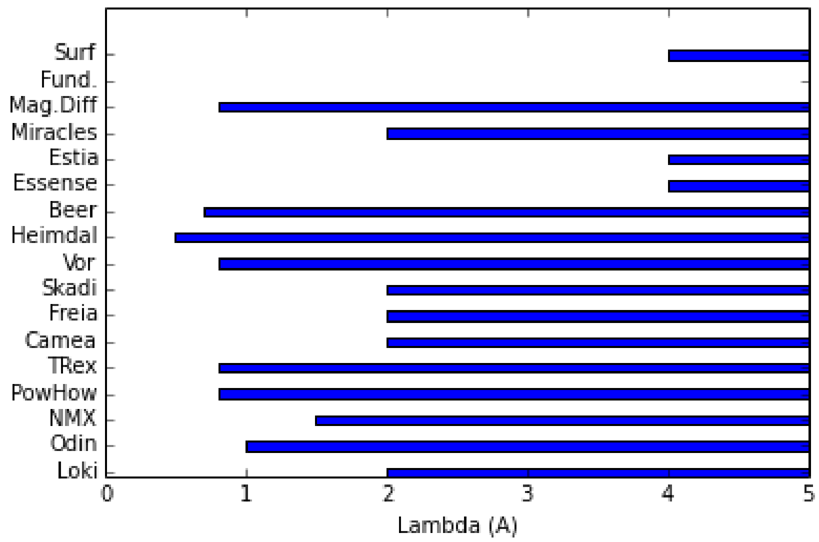

Figure 1: Wavelength range of each instrument in the suite. Fundamental physics needs colder wavelengths than this.

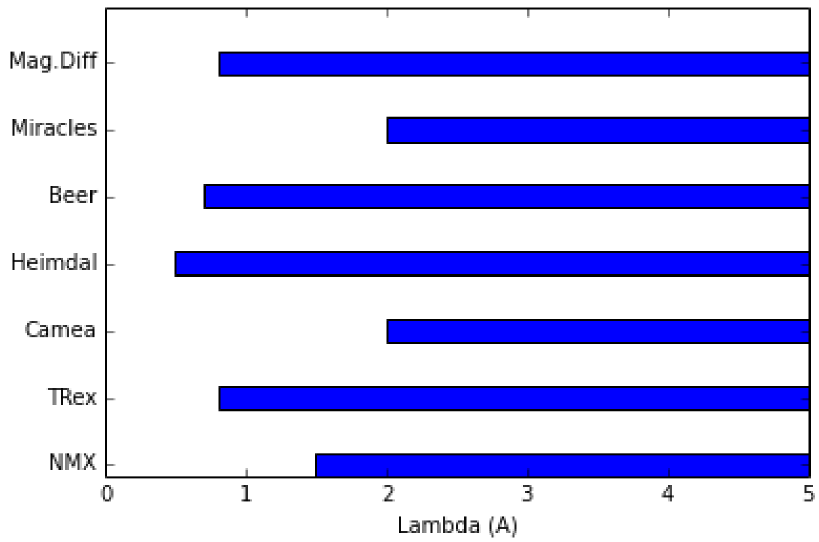

Figure 2: Wavelength range of the long, 150 m instruments in the suite.

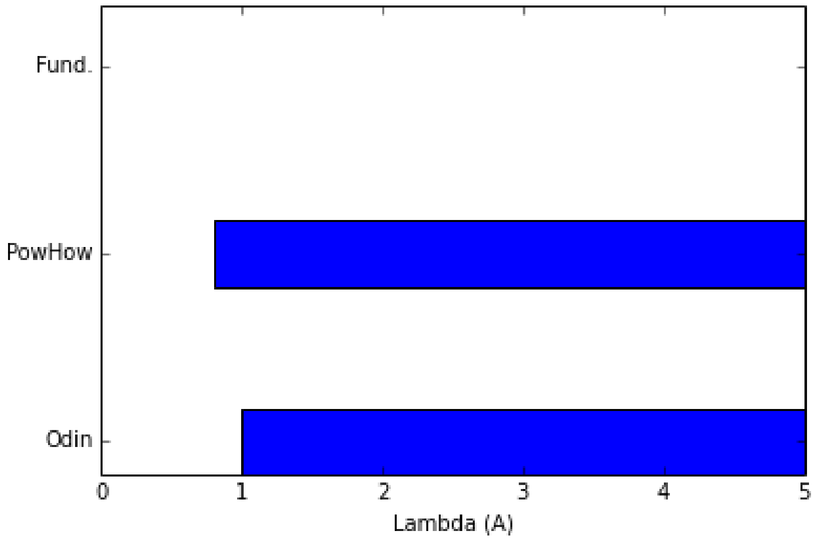

Figure 3: Wavelength range of the medium-length, 60 m instruments in the suite.

for the two wavelength ranges; two sets of curved guides for the 60 metre instruments for the two wavelength ranges. Similary, there are four types of benders for the two lengths and two wavelength ranges. The 150 metre instruments can have a 20 metre long bender within the bunker, and the 60 metre instruments can have a 15 metre long bender, and each of these is designed for different wavelength bands.

2.3.2 General Guide Considerations

In this section, a number of curved guide options will be considered. The performance estimates follow the work of Mildner [1] which is reliable for the low-divergence parts of the guide systems with low-m values, which is the strategy in this case.

All the guides in the low cost options will be considered to have a maximum size of 200 mm in horizontal and vertical extent. The curved guides have an additional constraint that the curved parts have a width of 4 cm.

The parallel section of the guides is capped at m=1.5. If we restrict ourselves to guarantee the phase space homogeneity at 1.5Å, then with 12 metre long compression/expansion sections we only require m=4 coatings. This still provides a maximum beam divergence of 1°. The transmission of this guide system is shown in figure 4 on page 9.

For the 60 metre guides, a higher m is required to get out of line of sight in a shorter distance. The transmission of this guide system is shown on page

2.3.3 Benders for 150 metre Guides and 1Å Beams

The specifications of this example bender are shown in table 1 on page 10. The transmission curve is shown in figure 6 on page 10.

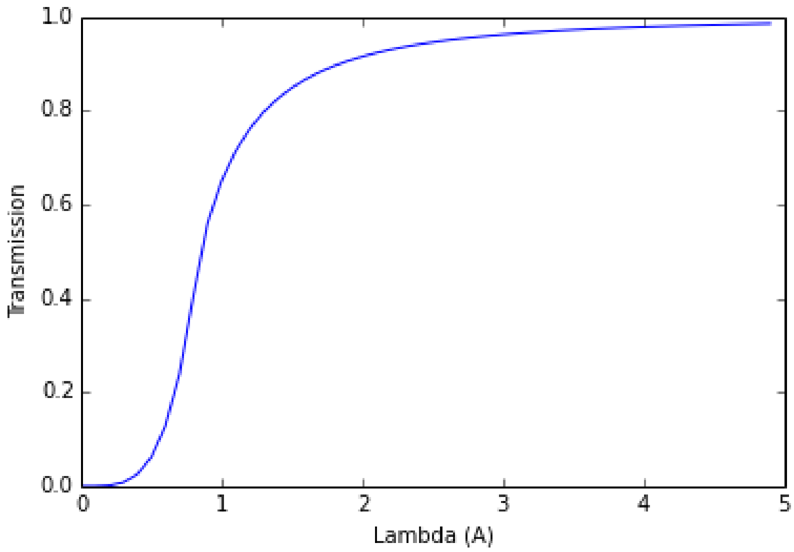

Figure 4: Transmission of a generic, curved 150 metre guide system as described in the text compared to a straight one, neglecting reflectivity losses.

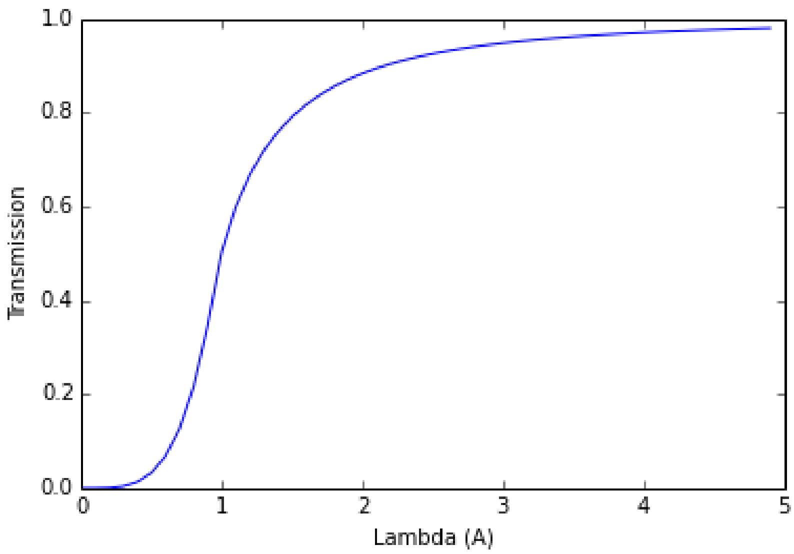

Figure 5: Transmission of a generic, curved 60 metre guide system as described in the text compared to a straight one.

Parameter	Value
150 m bender width	4.0 cm
150 m bender length	20 m
150 m channel width	0.5 cm
150 m bender m	3.0
150 m nchannels	8.0
150 m bender radius	1250.0 m
150 m transmission at 1Å	52%
150 m Cost	1444 k Euro

Table 1: 150 metre bender for 1Å neutrons.

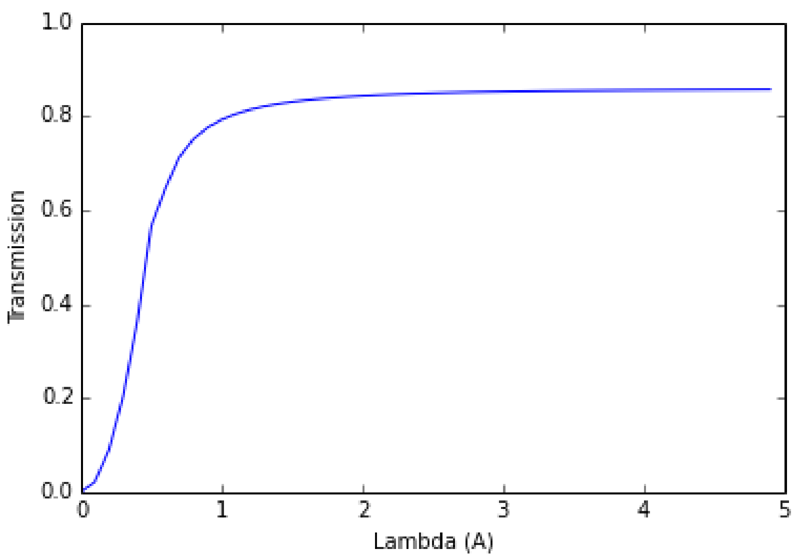

Figure 6: Transmission curve of an example bender for 150 m instruments to transmit 1Å neutrons.

2.3.4 Benders for 150 metre Guides and 2Å Beams

The specifications of this example bender are shown in table 2 on page 11. The

Parameter	Value
150 m bender width	4.0 cm
150 m bender length	20 m
150 m channel width	2 cm
150 m bender m	2.5
150 m nchannels	2
150 m bender radius	1250.0 m
150 m transmission at 1Å	78%
150 m Cost	341 k Euro

Table 2: 150 metre bender for 2Å neutrons.

transmission curve is shown in figure 7 on page 11.

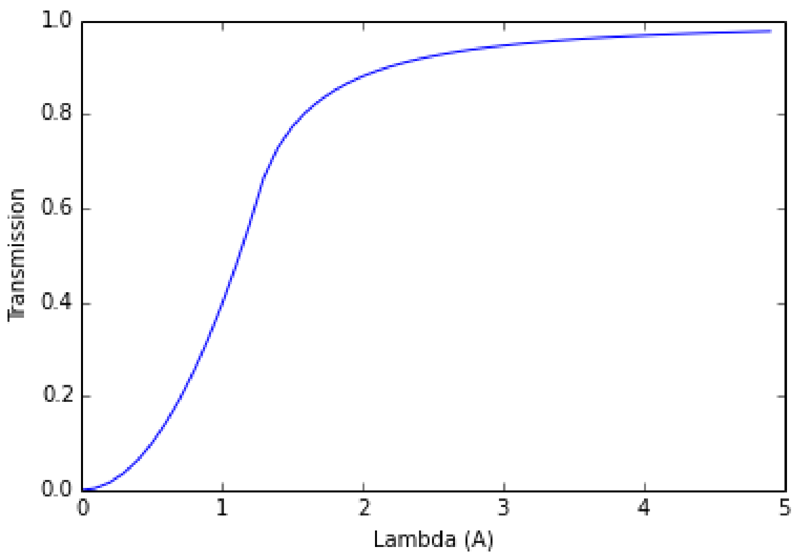

Figure 7: Transmission curve of an example bender for 150 m instruments to transmit 2Å neutrons.

2.3.5 Benders for 60 metre Guides and 1Å Beams

The specifications of this example bender are shown in table 3 on page 12. The transmission curve is shown in figure 8 on page 12.

2.3.6 Benders for 60 metre Guides and 4Å Beams

The specifications of this example bender are shown in table 4 on page 12. The transmission curve is shown in figure 9 on page 13.

Parameter	**Value**
60 m bender width	3.0 cm
60 m bender length	15 m
60 m channel width	0.5 cm
60 m bender m	3.0
60 m nchannels	6.0
60 m bender radius	937.5 m
60 m transmission at 1Å	51%
60 m Cost	742 k Euro

Table 3: 60 metre bender for 1Å neutrons.

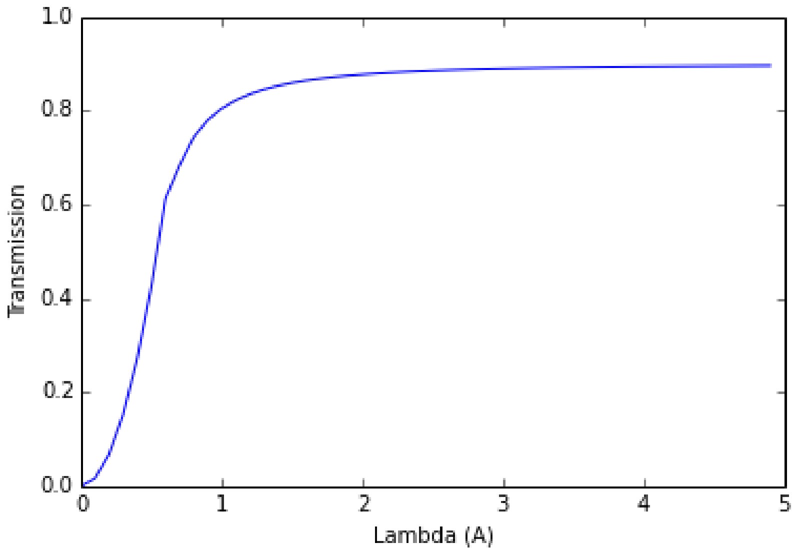

Figure 8: Transmission curve of an example bender for 60 m instruments to transmit 1Å neutrons.

Parameter	**Value**
60 m bender width	4.0 cm
60 m bender length	15 m
60 m channel width	2 cm
60 m bender m	1.5
60 m nchannels	2
60 m bender radius	703.0 m
60 m transmission at 1Å	73%
60 m Cost	193 k Euro

Table 4: 60 metre bender for 4Å neutrons.

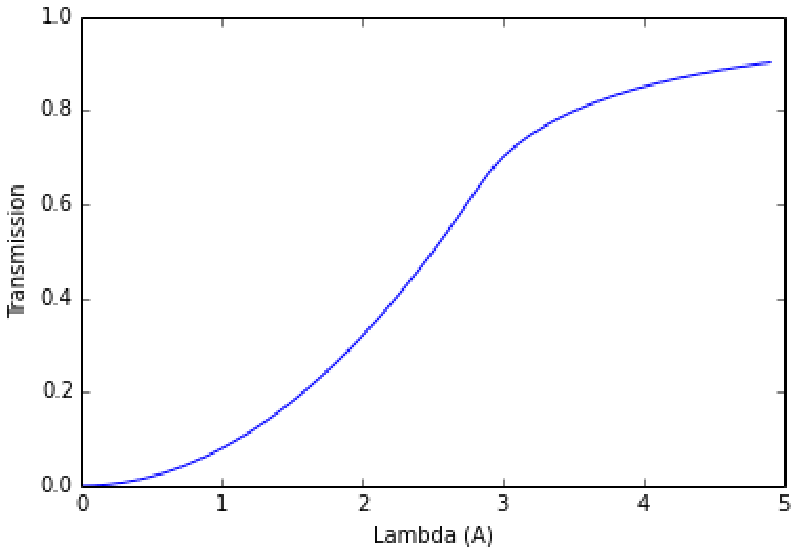

Figure 9: Transmission curve of an example bender for 60 m instruments to transmit 4Å neutrons.

3 Suite Cost Totals

The cost per instrument as a function of instrument length is shown for the standard instrument options in figure 10 on page 14. Here, we see that a general strategy of curving all the guides is cheaper overall than using benders, even though with benders no heavy shielding would be needed outside the bunker.

Furthermore, we also see that the total cost delta for a straight guide *vs* a curved guide is one or two million Euros. This seems approximately correct, considering the components in the cost-δ, namely a $T0$ chopper, heavy shutter, and enhanced instrument cave.

The total instrument suite cost for the full suite is shown in figure 11 on page 14, and the potential savings in figure 12 on page 15. Here we see that with the specifications described in this report, a suite cost optimisation of $\sim$23 M Euro may be found. These numbers are approximately in line with the findings at JPARC, once a cost-benefit analysis had been performed there then optics and shielding cost fraction was reduced to 25% of the total instrument suite budget [2].

4 Conclusions

An initial exploration of potential cost:benefit ranges has been performed. It appears that for reasonable reductions in specifications, with low expected impact on performance, that cost reductions in the mid-to-high 20 M Euros could be expected. The ESS is therefore invited to consider further exploration of this kind of optimisation.

To achieve these cost savings overall, it will be necessary to engage in such studies for each instrument project individually, with a strategic mindset despite working on individual instrument projects. In other words, too much fragmenta-

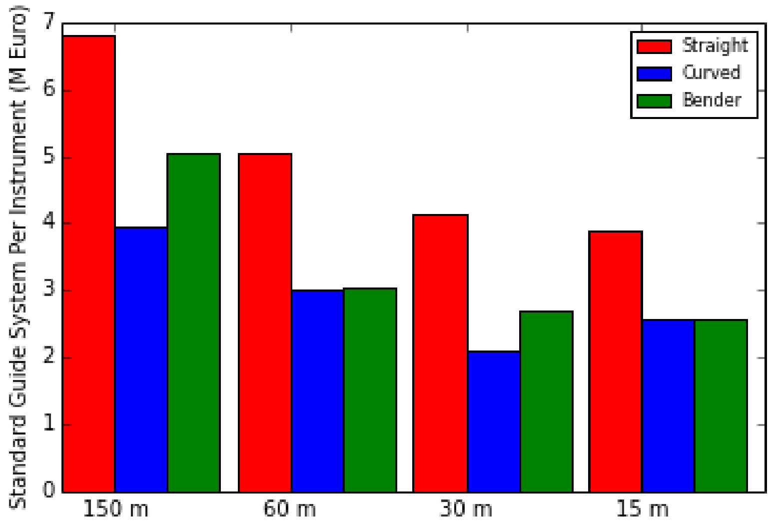

Figure 10: Cost of each instrument using the standard ESS guide concept, to isolate the cost delta for the different curving options (therefore omitting the baseline suite).

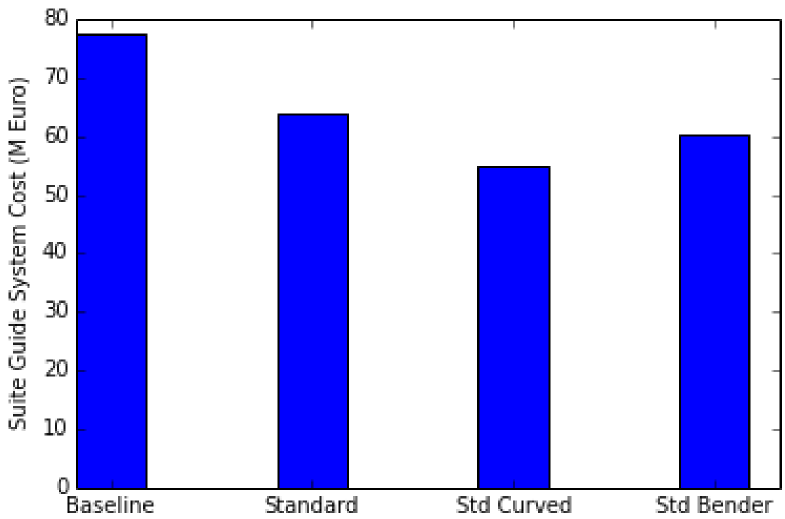

Figure 11: Total cost for the instrument suite cosidered.

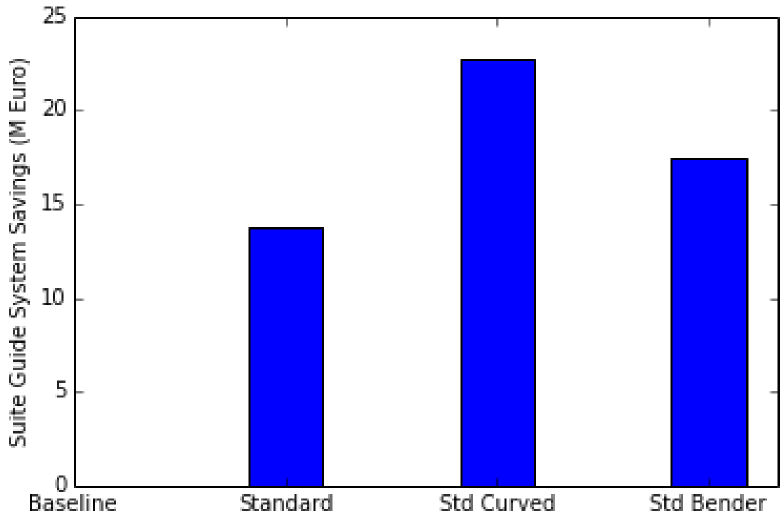

Figure 12: Total cost saving for the instrument suite cosidered, for each of the options, relative to the baseline of as-proposed optics geometry.

tion of the effort augments the risk of cost increases across the suite, though the cost delta in each individual project would appear to be minor. If this effort is expanded further — namely into procurement stages — then yet more cost reductions should be realised due to economies of scale and bulk manufacture across all the vendors.

References

[1] D.F.R. Mildner. Acceptance diagrams for curved neutron guides. *Nuclear Instruments & Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment*, A290:189, 1990.

[2] M Arai. Private communication. *SAC discussions, 2014*.