Instrument suite cost optimisation in a science megaproject

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Abstract
This article presents a cost optimisation study of neutron scattering instrumentation at the European Spallation Source (ESS) in Lund, Sweden. This is done by focusing on the main cost drivers for almost half of the instrument hardware—optics and shielding—and trading detailed cost functions against beam transmission functions in a multi-dimensional, yet simple, parameter space. A cost saving of almost 30% is identified. The method is demonstrated in a worked example on a mature instrument design, and there are no reductions in performance. The proposed solution is shown to correspond to a Nash equilibrium of simultaneous shielding and optics strategies, versus the baseline which is trapped by working through sequential strategies. Finally, this cost analysis is benchmarked against, and found to be in agreement with, the costs of operational facilities of a similar class.

1. Introduction

MW spallation neutron sources, such as the European Spallation Source (ESS) currently under construction in Lund, Sweden, are a class of science megaproject according to Flyvbjerg’s definition [1]. The business end, or front line, of a spallation source are the suite of instruments that serve the scientific community, upon which the entire productivity of the facility rests.

Modern neutron scattering instruments at spallation sources are a relatively expensive form of scientific equipment. They each cost in the region of 10–20 M€, and are usually financed in whole or in part from public funds. Typically, an instrument has a working lifetime of approximately 10–20 years, although some are known to continue for 40 years with rework and upgrades. At the time that this study was completed, the budget for the instrument suite of 16 instruments at the European Spallation Source (ESS) in Lund, Sweden, including ramping up all of the support functions, was around 211 M€, from a total facility budget of 1 843 M€. It is imperative that facilities of this scale strike the appropriate balance of cost and performance, to maximise the return on investment to taxpayers and create as large a scientific benefit as possible with the available resources.

A costing workshop was held early in the ESS project [2], and found that almost half of the instrument cost is shielding and optical components, and that shielding is the largest cost item, as shown in figure 1. There are good reasons that the ESS is focusing urgently on detector technology, since the use of ³He gas is unsustainable and an immediate solution is required [3]. Nonetheless, at 13% of instrument cost, detectors are less than 1/3 of the combined optics and shielding costs, and it would be a mistake to overlook early opportunities in these areas also.

Shielding is also directly coupled with the fraction of useful information that is produced by an instrument, since it directly affects instrument background noise level. Whilst it would require a considerable upgrade to increase the source power by a factor of 10, in the design phase it is relatively easy to put in place a series of strategies to decrease the instrument backgrounds by multiple orders of magnitude—an important consideration for techniques that use logarithmic scales so extensively in data analysis. Shielding is also directly coupled to user safety and time-consuming regulatory processes.

It is therefore quite surprising that shielding is often an uncomfortable afterthought in instrument design strategy, when compared to the early effort spent simulating neutron guides, for example. This is an error of strategy, as is clarified in section 7. It will be shown that successful cost reduction, along with proportional reductions in risk and complexity, are considerably easier if the whole optics and shielding system is designed...
and optimised simultaneously, around an architectural concept. This is somewhat similar to Brooks’ idea of conceptual integrity in software development [4].

Achieving this requires co-located personnel, using a common set of tools, and with thorough cross-checking in place, performed by a dedicated team. The suggestion to do this is not taken without a solid basis in existing excellence, since the NIST Center for Neutron Research [5] at NIST (USA) and SINQ [6] at the Paul Scherrer Institut (PSI, Switzerland) both followed this model to some degree.

One might expect that a cost reduction carries some sacrifice of scope or performance. This idea is reinforced by many public ‘austerity’ measures that have taken place since the financial crisis in 2008, but these were often achieved not via efficiency gains but instead from huge budget cuts in critical areas, with proportional reductions in scope. Instead, a simultaneous and architectural shielding and optics strategy will be derived to reduce the costs of these main areas without reducing performance. The other four main cost drivers—choppers, staff, detectors and ‘other’ that covers admin and overheads, review meetings etc—these are not completely fixed, but they are somewhat less easily optimised architecturally compared to optics and shielding.

The savings in the present study come from an expert understanding of the interplay between neutron optics and shielding, and taking a holistic, architectural approach to designing both of those systems in harmony, according to best current practice. As the ESS is an in-kind project, with 15 instruments contributed by foreign partner laboratories, the status-quo approach would be to design each system independently on each project. This would create a duplication of labour, and unnecessary interfaces in the project: both internally between the groups working on optics and shielding, who in some projects are physically located in different countries, and between the project’s and its neighbours’ shielding activities. Shielding design interfaces in a regulated, nuclear setting are a major risk to any project, let alone a facility attempting to reach new heights in data rates, and hence radiation levels.

To proceed, this article will briefly describe what spallation sources are and how they work. Then the main cost drivers will be described, before analysing the key parameters relating cost to geometry and defining the optimum strategy of matching these parameters to the requirements. Next, this strategy will be worked through for every instrument type in the ESS suite. A detailed example will be given with full instrument simulations, and this will be compared with the baseline to demonstrate that the methodology is sound. Finally, the results will be cross-checked against the costing workshop data of existing facilities, and shown to be consistent.

2. Spallation neutron sources and instrumentation

Spallation neutron sources generate neutrons by high energy particle interactions. Typically, a heavy metal target is illuminated by a beam of relativistic protons. Continuous sources, such as the SINQ source in Switzerland [6], provide a steady beam of protons with almost no time variation of intensity that can be resolved by the
The instrumentation concepts are similar to those at nuclear reactor sources such as the Institut Laue-Langevin in Grenoble, France; the main difference is the extra shielding required for spallation source neutron energies. Reactors typically produce neutrons with kinetic energies below 20 MeV, whilst modern spallation sources operate with upper-limit energies in the range 500 MeV–3 GeV.

At pulsed sources, such as the Spallation Neutron Source (SNS) [7] in Tennessee, USA, the proton beam arrives in temporally narrow, coordinated bunches. We will focus our attention on this class of facility, since the ESS uses this pulsed source concept, albeit with some changes to the details of the timing. The arrival of the driving proton beam pulses are used as a time reference. All neutron detection events are recorded in time relative to the source timing signal, by which it is possible to quantify physical phenomena with respect to variations in the kinetic energy of the neutrons [8].

The process by which neutrons are liberated at such facilities, known as spallation, occurs when a quark in the proton beam and a quark in the target material exchange a gluon. The subsequent particle shower produces a cascade of particles and relaxation processes that result in free neutrons escaping over a wide energy range, up to the incident proton beam energy [9]. The particle charge (protons) or lack thereof (neutrons) is irrelevant as far as spallation is concerned, and daughter neutron particles of sufficient energy are able to induce spallation processes wherever they interact with matter. The particle range in matter does of course differ between charged and uncharged particles [10].

Whilst it is the neutrons that are of interest, other hadrons and photons are also produced over the same energy range. Most of these hadrons are short-lived, and they do not escape from the target shielding due to a combination of half life and electric charge. The instrument designers mainly have to concern themselves with the high energy neutrons and photons.

The aim of neutron source design is to maximise the probability that the high energy neutrons undergo a series of inelastic processes, and reach temperature-controlled baths of carbon-rich and/or hydrogen-rich substances, known as moderators. Moderators have, by design, large inelastic scattering cross sections and relatively low absorption cross sections (ignoring poisoned moderators for high resolution work, which are not used at ESS). The end result is a powerful source of neutrons, radiated with a well-defined and controlled energy spectrum, from a small volume [11].

The radiated neutrons are channelled to the instruments by neutron guides that are aimed directly at the moderator assemblies. Neutron guides are glass or metal tubes, coated with a high contrast, low absorption metal films. At small grazing angles, the neutrons undergo total external reflection at a nickel surface, similar to the process of total internal reflection for photons. There is a critical angle for this process, which is dependent on the de Broglie wavelength of the neutron. The standard angle is quantified in a parameter known as ‘m value’, where $m = 1$ is defined as being the critical grazing angle for total external reflection of neutrons on a surface of atomically smooth nickel with natural isotopic concentrations. This single nickel layer is often augmented to increase the critical grazing angle by diffractive effects. Such mirrors are known as supermirrors. By adding multilayers of Ni-Ti, it is possible to increase the effective critical angle in the range $1 < m \lesssim 4$ for reasonable cost, and up to $m = 8$ have been demonstrated [12]. However, the diffractive processes produce a significant imaginary component of the wavefunction, so the process becomes increasingly lossy as $m$ increases. It is the design of these guides, and the shielding around them, that forms the focus of this work.

The main gamma shielding effects to consider are the absorption of neutrons in the guides, which emit low energy photons $\lesssim 10$ MeV, and the high energy photons from the source. The neutron shielding must account for stray neutrons due to scattering and misalignment of the guides; and fast neutrons of energies in the range keV–GeV. These come directly from the source, or via $(\gamma, n)$ photo-nuclear processes.

### 3. Main cost drivers and methodology

There are two beam concepts to consider in this initial study, which are described in the following subsections. The first concept is a straight neutron beam with direct line-of-sight to the source, and the second concept is a curved neutron beam that blocks the view of the source from the instrument sample position.

The instruments described in [13] allowed for an indicative cost estimate, which is part of the total ESS construction cost of €843 M€ established in 2013. Then, in order to refine the cost estimates in more detail, a workshop was held in early 2014 [3], which involved partners from ISIS in the UK, PSI from Switzerland, and JCNS from Germany.

The workshop focused on a list of around 20 components, drawing on recent experience such as the second target station project ‘ISIS TS-II’ [14] and the spin-echo instrument on at SNS [15]. The list also included services for installation and labour costs. Although the scope of the instrument programme was still indicative and not fully defined at that time, the component cost listings were used to:
• Better estimate the costs of the ESS Technical Design Report (TDR) reference suite,
• To gradually refine costs as instrument concepts became better defined, and
• To independently assess costs to obtain the best ‘value-for-money’ for all the partner countries involved in the instrument build programme, and consequently the tax payers within the partner countries.

We will now consider two concepts that are frequently used at neutron instruments:

(i) A straight instrument in section 3.1, where there is a direct line of sight from the moderator and sample.
(ii) A curved instrument in section 3.2, where line of sight between the source and sample is blocked by curving the guides—the cold and thermal neutrons can follow the curve like photons in a fibre optic cable, whereas the high energy radiation passes through the guides and into the bulk shielding.

From a shielding perspective, the difference between these two concepts is that (ii) requires lighter shielding after the loss of line of sight, which is cheaper, and (i) requires heavy shielding, which is expensive. The straight instrument also must have a heavier instrument cave, since it must protect against scattered high energy (MeV–GeV) neutrons and gamma rays.

3.1. Straight / line of sight option
We use a rough cost estimate for an enhanced concrete instrument cave for straight beam-lines, based on the PSI instrument ‘BOA’ at the SINQ source, increased in thickness to 2 metres, and accommodating $5 \times 5 \times 5$ m$^3$ of instrument space. These specifications were for a generic instrument, based partly on calculations of minimum thickness for a MW spallation source with a GeV proton beam, and partly on measurements at PSI and SNS on fast neutron transmission and prompt pulse backgrounds, which usually adversely affects instrument performance. This cave is a minimum specification item meeting the basic requirements, and has not been optimised for instrument backgrounds at pulsed sources.

A completely straight beam-line may also require a heavy chopper—commonly known as a ‘$T_0$’, ‘t-zero’, or ‘Prompt Pulse Suppression’ (PPS) chopper: these items are heavy choppers that attenuate the high-energy particles during proton illumination of the spallation target. The cost of these $T_0$ choppers was estimated at the aforementioned workshop.

Finally, a straight instrument also requires a heavy shutter, capable of blocking the high energy beam and allowing access to the sample area. A study performed by the ESS engineering department for an SNS-style cylindrical drum shutter was completed in 2013, which provided the cost estimates for this item [16].

3.2. Curved / out of line of sight option
This option has a similar cost of guide shielding as that of an instrument at a reactor source. A thickness of 60 cm of regular concrete was found via preliminary Monte-Carlo calculations to attenuate the radiation sufficiently to safe levels (1.5 $\mu$Sv/h 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.

For the instrument cave in this latter geometry, we assume an enclosure similar to those at the ‘LET’ and ‘OFFSPEC’ instruments on the second target station at ISIS, in the UK. These are hollow steel cans filled with borated paraffin wax, and are optimised for low instrument backgrounds.

3.3. Concept-neutral costs
There are costs that are common to all designs, irrespective of the concept that is used. The cost of concrete per unit volume comes from ESS Conventional Facilities Department, and is the price for reinforced concrete, cut, finished and installed. The prices of raw metals come from the London Metal Exchange.

In all beam-lines, 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 beam-line at ISIS, or indeed much smaller, and spread between multiple units. Other names for these devices could include ‘horse-collars’ or ‘fast neutron scrapers’. For the purposes of this study, we assume these to be three units of 1 m$^3$ of copper with a small channel cut through the centre.

3.4. Summary of shielding costs
A summary of the shielding costs is given in table 1. We can see that just from the cave, $T_0$-chopper and heavy shutter we arrive at a shielding cost difference of 2 Me$^3$ between a curved instrument and a straight one.

However, this does not take into account the details of the guide shielding and the optics cost. The fast neutron
shielding load decreases as $R^{-3}$ [17], so even the straight guide shielding gets thinner with distance. On the other hand, increasing the supermirror $m$ value increases the prompt gamma shielding requirement [18], so whilst the table shows the ranges the precise number must be calculated in each case.

Not included in this budget estimate are the centrally-provided ESS guide bunker and target shielding, which absorb a large fraction of the radiation. We only include shielding items outside the common shielding areas, in the budget control of the instrument projects. This has a potential cost-saving from the perspective of the instrument project, since—if the geometry loses line of sight within the bunker—the instrument only needs thermal beam shielding in its budget.

3.5. Optics performance envelope and costs

Previous sections have described the itemised shielding costs of straight and curved instruments. Now one must turn to the cost and performance of the neutron optical systems themselves.

The optical system costs are evaluated for the full length of the beam-line. Curving out of line of sight quickly, with a radius of 1.5 km for example, increases the optical cost compared to a straight guide or a gentle curvature of several km, because the neutron supermirrors need to be engineered to reflect at larger grazing angles. At still tighter radii, of a few hundred metres, the neutron guides are normally divided into several thin channels known as ‘multi-channel benders’. These require more precision manufacturing, with a greater surface that needs to be coated with supermirrors. It should be clear that, whilst curving out of line of sight quickly can reduce the shielding cost, it drives up the cost of the optical components. These two costs are traded against each other in the optimisation.

Optical component cost equations were provided to ESS as part of a market survey, and these are commercial details that cannot be published. However, they are comparable to costs of items at similar facilities, and can be rapidly recreated for any future study of this kind by requesting the same information from the small number of manufacturers in this niche market. Perhaps of more practical relevance is the assessment of commercial tenders over several years. What one notes there is consistent with the price $p$ of neutron optical components following a simple empirical relation:

$$ p = a + m^z $$

where the fixed price per metre $a$ is typically €1000s, and $z$ is a power between 2 and 4. Both $a$ and $z$ are calculated on a per-contract basis, and depend on the size of the order and market conditions. The only variable in (1) under the designer’s direct control is $m$. The first objective in this paper is to identify the optimal $m$ value that meets, but does not exceed, the requirements.

The critical grazing angle for reflection of the mirror depends on $m$, relative to natural nickel, and follows empirically:

$$ \theta_c(m) = \theta_{Ni} \lambda m $$

where $\lambda$ is the wavelength of the neutron (Å), $\theta_{Ni} \approx 0.1^\circ$ is the critical angle for total external reflection for nickel, measured using neutrons with a wavelength of 1 Å.

For $\theta$ in the range $0 \leq \theta \leq \theta_c(m = 1)$, total external reflection occurs from the upper nickel layer of the supermirror. Thereafter, in the range $\theta_{Ni}(m = 1) \leq \theta \leq \theta_c(m)$ the reflectivity decreases almost linearly, and at $\theta = \theta_c(m)$ the reflectivity $R_c$ is given by the empirical equation:

$$ R_c \approx 0.98 - 0.008 m^{2.06} $$

This is illustrated graphically in figure 2.

So we see that, with increasing $m$, whilst the critical angle $\theta_c$ does increase, the critical reflectivity diminishes with the square of the $m$ value whilst the costs increase faster than the square of the $m$ value.

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### Table 1. Main cost drivers in shielding-related instrument components for regions in line of sight (LOS) of the neutron source, and curved out of line of sight (OLOS).

| Item                           | Unit cost (€) |
|--------------------------------|---------------|
| Cave                           | 2 M           |
| Guide shielding                | 7–18k €/m     |
| Cu collimators                 | 47 k€         |
| $T_{1/2}$ chopper              | 750 k€        |
| Heavy shutter                  | 750 k€        |
| Guide shielding                | 3–9 k€/m      |
| Guide shielding (OLOS)         | 1.5 M         |

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$\lambda$ is the wavelength of the neutron (Å), $\theta_{Ni} \approx 0.1^\circ$ is the critical angle for total external reflection for nickel, measured using neutrons with a wavelength of 1 Å.
The performance only increases up to a point. For many reflections in a long guide, no matter what \( m \) is chosen the reflectivity losses at large grazing angles cause the beam characteristics to match that of \( m = 1.5 \). Moreover, the divergence of the beam given by (2) must be less than or equal to the divergence requirements for the angular resolution of the instrument. Any increases in \( m \) beyond that point only contribute to instrument background.

One therefore has to be careful not to oversimplify phase space arguments. Nonetheless, we could continue under ideal assumptions—that the divergence does not exceed the resolution envelope and we are dealing with a single reflection. A fundamental economic principle of a profit-seeking business, the ‘Theory of the Firm’ \[19\], offers a perspective on this cost optimisation. The choice in company output \( Q \) and the choice in supermirror \( m \) value may be treated as being somewhat analogous. Similarly, one might draw parallels between the marginal cost \( MC = \delta C/\delta Q \) and the incremental guide cost with \( \Delta m = 1 \) brings. The optimum output is found at the intersection of the marginal cost and marginal revenue curves \[19\]. The difference here is that, unlike in economics, the ‘units of cost’ are not the same as the ‘units of revenue’: \( 1 \text{ €} \) = 1 neutron s\(^{-1} \!\)!

Instead, we can compare the relative changes. The relative incremental/marginal increases (for \( m \) relative to \( m = 1 \) for \( m \geq 1 \)) in phase space and in price, for a single mirror section with one reflection, is shown in figure 3. The incremental performance increases can be approximated by essentially taking the ratio of the integrals of the curves in figure 2. Neglecting losses, the incremental gain curve follows:

\[
g(m) \approx \begin{cases} \frac{m}{m-1} & m \leq 2 \\ \frac{m}{m-1} & m > 2 \end{cases}
\]

The piece-wise nature of this curve follows from the fact that we are comparing the performance at \( m \) with that at \( m = 1 \), with an integration window that is 1 \( m \) unit wide. Comparing \( m \) spacings with different widths would give slightly different shaped curves, but the conclusions would be the same: the decreasing performance gains follow a shifted \( 1/m \) shape at higher \( m \) values. This is the expected behaviour, because the neutron current is ultimately some complex equation involving an integral of the supermirror reflectivity curve up to the critical reflectivity defined in (3), and if one integrates \( f'(m) \propto -m^{-2} \) one obtains \( f(m) \propto m^{-1} \).

This figure shows that increasing from \( m = 1 \) to \( m = 2 \) carries a 30% cost increase but almost \( 2 \times \) performance. Increasing from \( m = 2 \) to \( m = 3 \) costs an extra 50% and provides an additional performance a
little below 50%. Thereafter, each increment of $m$ brings a costs increment in the vicinity of 50%, but the relative performance increment follows $\propto 1/m$: diminishing returns indeed. The optimum point is the crossing of these two curves, just above $m = 3$, where the cost increment exceeds the performance increment. For focusing mirrors or short benders, a slightly higher $m$ value is needed, and this can be capped at $m = 4$.

There are a number of effects that will make these diminishing returns even less relevant than they appear. In the derivation, a single reflection was considered, but in a real guide system with a spatially extended source and target and imperfections, there will be multiple reflections. This is especially true for cold wavelengths, as demonstrated in independent numerical studies—e.g. Klønø et al figure 4 [20], showing a cold guide optimisation under more forgiving conditions, so their critical performance region is at lower $m$ values.

Moreover, when one considers that the experimental uncertainties scale with the square-root of the neutron current ($\propto\text{performance in these figures}$), it makes little sense generally using $m$ values higher than these, except where the short neutron transmission of a curved section requires it, and in the design of the curved section we should choose an $m$ value in this cost effective range.

The time-independent transmission $T(\lambda)$ of a curved neutron guide does not need to be fully simulated until one wishes to begin minimising second order effects, or to introduce temporal correlations. In practice, $T(\lambda)$ can be computed analytically following the work of Mildner [21] and Copley [22]. Specifically, the transmission of a curved guide system relative to a straight guide system of the same length is given by:

$$T(\lambda) = \frac{2}{3} \left(\frac{\lambda}{\lambda_c}\right)^2$$

for $\lambda \leq \lambda_c$ and

$$T(\lambda) = \frac{2}{3} \left(\frac{\lambda}{\lambda_c}\right)^3 - \left[\left(\frac{\lambda}{\lambda_c}\right)^2 - 1\right]^{3/2}$$

for $\lambda > \lambda_c$.

(5) and (6) are intended to calculate the relative transmission of a curved guide relative to a straight guide of identical cross section, ignoring reflectivity losses, and as such one might expect the approximation to hold only
to first order. However, in extensive comparisons with Monte-Carlo simulations, it holds for almost all geometries that one might consider, and the effect of reflectivity losses are usually less than one percent. The reason for this is that the neutron wavelengths with the lowest reflectivity, i.e. the short wavelengths, also have the lowest beam divergence and therefore the fewest reflections. One may therefore work within this lossless approximation without a noticeable impact on the results.

The critical wavelength \( \lambda_c \), width \( w \), radius of curvature \( R \), \( m \) value, and length required to lose line of sight \( L_c \) are all related via the well known equations:

\[
\lambda_c = \frac{575}{m} \left( \frac{2w}{R} \right)
\]

\[
L_c = \sqrt{8wR}
\]

where \( \lambda_c \) is the shortest wavelength that the science case of the instrument requires for routine measurements, and \( L_c \) is the distance at which line of sight of the source is closed. It is important to note that the two \( w \) values might not be the same, hence the subscripts \( s \) for streaming paths inside the shielding, and \( g \) for the guide opening. For large \( L_c \), \( w_s \approx w_g \). For short \( L_c \), the assumption \( w_s \approx w_g \) needs to be ensured through good engineering of the shielding, and adding shimming around the guides to close streaming paths. We will proceed under this assumption, and use a single value of \( w \) for (7) and (8) in the remainder of this article.

It is fairly obvious that, with 5 degrees of freedom and two equations, the design work is to specify at least three of the variables based on a logical concept. For example, we could choose \( L_c = 20 \) m to fit inside the bunker for the long instruments, and have a nominal guide width of \( w = 0.04 \). Thus, we obtain \( R = 1250 \) and \( m = 4.6/\lambda_c \). This is quite a large \( m \) value for short wavelength neutrons, so we can consider the possibility of relaxing \( L_c \), or artificially reducing \( w \) by using guides with multiple channels—known in the community as ‘benders’—which in turn will reduce \( m \). This is because the value of \( w \) in (7) is modified to the channel width rather than the full guide width. However, the value of \( w \) in (8) remains the full guide width to achieve a full deflection of the beam out of line of sight. In that case, there is a small additional loss of efficiency using benders that can be taken into account according to:

\[
T_{\text{bender}}(\lambda) = T(\lambda) \left[ 1 - (n - 1) \left( \frac{L_c}{w} \right) \right]
\]

where \( T(\lambda) \) is the transmission calculated using (5) and (6); \( n \) is the number of open channels; \( t \) is the substrate thickness for the wafers separating the channels (often a silicon sheet, \( \leq 1 \) mm thick); and \( w \) is the total thickness of the bender system. (9) is a small correction that can usually be ignored in the conceptual design phase. If we assume \( w = 0.04, t = 0.0005 \), and \( n = 5 \) then the additional loss due to this phase space shadowing of the wafers amounts to only 5%.

One should bear in mind that the phase space from curved guides can be asymmetric, and the standard methods to mitigate this are to either curve with an S-shaped geometry rather than a C-shaped geometry, as discussed by Mildner [21], or to add a straight section with sufficient length for subsequent reflections to rehomogenise the phase space. The minimum length of the straight section depends on the required neutron wavelength and phase space volume at the sample position, and tends to be manually optimised.

### 3.6. Summary of the optimisation strategy

The previous sections are fairly deep and technical, and it may not be obvious on the first reading precisely how they translate into a cost optimisation. What has been shown, effectively, is that there are substantial savings to be made by curving an instrument out of line of sight (section 3.4) if this is realistic; and that there is a most cost effective \( m \) value to aim for in the optical design (section 3.5).

The procedure to design an instrument cost-optimally for a high power spallation source is therefore:

1. Identify the minimum wavelength requirement of the instrument.
2. Try to identify a set of parameters solving the optical equations for this wavelength and a single, curved guide channel using an \( m \) value ideally below \( m = 3 \), and no higher than \( m = 4 \) if possible, knowing that increasing \( m \) brings diminishing performance increases but steady cost increases in both optics and shielding.
3. Identify a second solution using a multi-channel bender and the same boundary conditions as those in step (ii).
4. Calculate the total cost of the guide system and shielding for both design concepts produced by steps (ii) and (iii).
5. Select the cheapest option.
In steps (ii) and (iii) the goal is to lose line of sight of the source half way down the guide and/or in the common shielding bunker. Thereafter, the curved concepts can be tuned to include focusing/de-focusing stages where feasible.

This procedure will now be applied to all the ESS instruments, to identify which output of steps (ii) and (iii) is the most cost effective for different instrument lengths and types, and compared to the baseline designs, which were contributed essentially by crowd-sourced contributions with no common architectural strategy.

4. Requirements and matched optical solutions

Instrument requirements were extracted initially from the ESS Technical Design Report (TDR) \[13\] and gradually refined with requirements described later in the respective instrument proposals and reports.

The minimum wavelength $\lambda_c$ for each instrument in the suite is shown in figure 4. Here we can see that there are three instrument categories based on minimum neutron wavelength: one just below 1 Å; one at 2 Å, and one at 4 Å.

Subdividing into long (150 m) and medium (60 m) instruments is informative. The minimum wavelength band of the long instruments is shown in figure 5, where we see that the long instruments are split almost 50:50 into 2 Å and $\sim$1 Å instruments.

For the medium-length instruments, the wavelength bands are shown in figure 6. In that subset, there are two instruments requiring wavelengths around 1 Å, and a third requiring 5 Å.

The discussion of shorter instruments follows a similar structure, except with the 15 m instruments. These are considered to be so short that the choice is between a straight geometry or a multi-channel bender; and furthermore the baselines have used the bender concept in any case. We therefore do not go into much detail on the short instruments, but use their multi-channel bender designs to inform the current work.

We can now begin to construct a critical performance/cost ratio transport system as a standard, to compare with the baseline systems. There are four curved guide systems to consider: two sets of curved guides for the 150 metre instruments for the two wavelength ranges; two sets of curved guides for the 60 metre instruments for the two wavelength ranges. Similarly, 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.

A somewhat minimalist neutron guide concept was developed at ESS for these kinds of studies to compare with more elaborate designs. This was based on the earlier work of Zendler and Martin Rodriguez \[23\] which stands out against many early ESS optics studies in that it includes real-world effects from the outset such as misalignment and background reduction. Just after that publication, the design strategy outlined in section 3.5 was formulated in a quantitative way. It does not sacrifice any meaningful performance, as will be shown. Since the early work of Böni, where elliptic geometries of neutron guide were demonstrated to offer superior performance.
performance [24], elliptic shapes have become the ‘go-to’ geometry, even in the cases where simpler and cheaper alternatives would offer an improvement in beam characteristics. In the minimalist concept, elliptic geometries with tiny variations of only a few mm over tens of metres are replaced with constant cross section geometries. Wider ellipses are replaced with ballistic geometries.

A frequently-heard criticism of ballistic geometries is that they create phase space shadows, which appear at moderate divergence. This has already been solved, in a cost-neutral way, by a more complete understanding of
coma, phase space mapping and conic sections in general [25], informed by modern telescope design and work on Wolter optics [26]. The elliptic focusing section nearest the sample is simply replaced by a de-focused parabola, and the length of the parabolic section is extended to cover the phase space shadows. The upstream defocussing component continues to use ellipses which, due to coma, produce a large image of the source that exceeds the phase space volume needed by the parabola.

Figure 6. (a) Wavelengths requested by the 60 m medium length instruments at ESS. ‘Fund’ corresponding to ‘Fundamental physics’ requests 5 Å. (b) Transmission of a multi-channel bender designed to transmit 1 Å neutrons to the 60 m long instruments at ESS. The specifications of this bender are given in table 4. (c) Transmission of a multi-channel bender designed to transmit 4 Å neutrons to the 60 m long instruments at ESS. The specifications of this bender are given in table 5.
Supermirror $m$ values are capped at $m = 4$ for 12 m long ballistic focusing sections. Earlier in section 3.5 an optimum $m$ value was derived for a generic mirror, but because of the parabolic focusing section the central $m$ value can generally be decreased to $m = 1.5$. This concept exceeds the required performance envelope, and is a good estimate of potential costs for many instruments. If an instrument can accept the additional divergence from $m = 5$ guides, the higher $m$ values are only needed within a few metres of the sample position, so the costing is still accurate. In practice, some minor tuning of the focusing section is to be expected for correct sample illumination.

The maximum dimensions of the guide are limited to below 4 cm in the single channel curved sections in accordance with (7) and (8). This still has good transmission at 1 Å, due to the large radii involved with such long guides as ESS. Otherwise, the dimensions of the guide are capped at 20 cm.

This guide concept is designed to have an analytical transmission efficiency above 70% at the shortest wavelength, and is certain to exceed 50%. It therefore already competes with the 60%–80% range seen in optimised systems (see [20] figure 9). It is to be expected that it is easily within a factor of 2 of the maximum possible performance. As such, exceeding 50% transmission efficiency should be seen as a threshold to success. Some projects have spent multiple years chasing performance gains of ~5%, and this is not useful effort: it is common for such projects as a whole to quantify critical path slippage in the region of millions of euros per week [1], and the ESS is no different in this regard. Objectors to this point should consider that the variance, $\sigma$, scales not with the total neutron current $\Phi$ but $\sqrt{\Phi}$; and that the information obtained via measurements is proportional to the logarithm of $\Phi$ relative to background; and that in de facto technical failure of neutron guides there have been reductions in $\Phi$ of around 70%–80% that persisted for years without detection.

### 4.1. Long Instruments

A simple curve can be used for the long instruments, losing line of sight at the half way point near 75 m, in two $\lambda_c$ groups: one at short wavelengths and one at longer wavelengths. This is shown in figure 5 (a). Also shown in figure 5 are the transmissions of multi-channel benders losing line of sight at 20 m for the same wavelength groups. The specifications of the benders are given in tables 2 and 3 respectively.

### 4.2. Medium length instruments

For the shorter, 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, along with the instruments’ required wavelength bands, is shown in figure 6.
Considering the associated multi-channel benders, there are again 2 $\lambda$: one at 1 Å and one at 4 Å, slightly over-engineered for the requirement of 5 Å. Their specifications are detailed in tables 4 and 5 respectively.

### Table 4. Bender specifications for efficient transmission of 1 Å neutrons to 60 m long instruments.

| 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 1 Å   | 73%        |
| 60 m Cost                  | 742 k€     |

### Table 5. Bender specifications for efficient transmission of 4 Å neutrons to 60 m long instruments.

| 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 4 Å   | 85%        |
| 60 m Cost                  | 193 k€     |

### 5. Short instruments

For the short instruments, there is little choice but to use a multi-channel bender with the appropriate $\lambda$, and set $L_c = 11$ m. We simply use the crowd-sourced designs and costings for those systems with no changes.

### 6. Suite cost totals

#### 6.1. General optimum strategy

The cost per instrument as a function of instrument length and concept is shown in figure 7, where we just examine the minimalist version of the optics to compare like-for-like. There it is clear that a general strategy of curving all the guides is cheaper overall. The cheapest possible method is using simple curved guides, since the additional cost of multi-channel benders is not offset by the cost savings in shielding outside the bunker. On the other hand, these minor differences between the curved guides and benders are a small increment to pay for likely improvements in the instrument backgrounds that result by losing line of sight further away from the instrument cave.

The total cost delta for a straight guide versus a curved guide system is 1–2 M€ per instrument, in agreement with the main cost drivers, namely a $T_0$ chopper, heavy shutter, and enhanced instrument cave, as summarised in table 1.

#### 6.2. Extrapolated to the instrument reference suite

The total optics and shielding hardware cost for the instrument suite is shown in figure 8 for each option, and the potential savings in figure 9. In these figures, the following options are costed:
Baseline which uses the crowd-sourced concepts.

Minimalist which is a reduction of the optical specifications towards the minimalist design, but allowing straight guides where such are used in the baselines.

Minimalist Curved using the minimalist design and forcing all beam-lines to curve out of line of sight with single channel guides for the longer instruments, and benders on short instruments.

Figure 7. Cost of each instrument guide and shielding system, only using the minimalist concept described earlier in the text. 'Free geometry' allows straight guides; 'All curved' means all guides curve out of line of sight of the source; and 'All bender' means all beams lose line of sight in the bunker.

Figure 8. Total hardware cost for the instrument suite considered.

Figure 9. Total cost saving for the instrument suite considered, for each of the options, relative to the baseline of as-proposed optics geometry.

- 'Baseline' which uses the crowd-sourced concepts.
- 'Minimalist' which is a reduction of the optical specifications towards the minimalist design, but allowing straight guides where such are used in the baselines.
- 'Minimalist Curved' using the minimalist design and forcing all beam-lines to curve out of line of sight with single channel guides for the longer instruments, and benders on short instruments.
'Minimalist Bender' using the minimalist design and forcing all beam-lines to use multi-channel benders and lose line of sight in the bunker.

One can see that, relative to the baseline, the minimalist curved guide concept is likely to save 24 M€ across the suite, with negligible impact on the instrument performance.

7. Technical feasibility

It is tempting to interpret this work as a reduction of costs obtained by sacrificing specifications, and thus performance. To quantify these aspects, we will now demonstrate an example of this methodology for one of the instruments in the reference suite, which is in the 1 Å wavelength group. This instrument team expressed the strongest incertitude to the ideas presented here, and firmly held to the straight baseline concept on the grounds that curving out of line of sight or reducing the \( m \) values carried unacceptable performance penalties given their short wavelength needs.

The changes from the baseline are as follows. A focusing-defocussing section of graded \( m \) values with quite large variation in dimensions was replaced with a 20 metre long, 4 channel bender coated with \( m = 2.3 \) supermirrors, and a radius of 1250m, which matches the chopper opening of the narrowest point of the original pinhole. A wide, elliptic section of guide with graded supermirrors in the range \( m = 3–6 \) was replaced with a hybrid geometry \[25\] in the range \( m = 1.5–4 \), and thus a deliberate phase space manipulation to improve homogeneity. The two concepts are compared in figure 10.

Despite these changes, there was no noticeable deterioration of phase space homogeneity as one might naively expect. Instead, the minimalist design offers an improvement, as figures 11 and 12 show quite clearly. Nor was there a reduction in performance: the baseline was published anticipating a total neutron current at the detector of \( 2.5 \times 10^9 \text{ n s}^{-1} \), but we find that the minimalist concept offers \( 4.8 \times 10^9 \text{ n s}^{-1} \), which is almost double the performance.

In the vertical direction, whilst the minimalist concept is still superior to the baseline, the phase space is a little less smooth than in the horizontal plane due to the use of a multi-channel bender. Taking this concept to detailed engineering would obviously require the trivial step of adjusting the beam extraction and bender geometries slightly to arrive at a horizontal beam. That step has been neglected for simplicity, and there is plenty of headroom in the almost 2\( \times \) performance to resolve this minor issue.

At the same time, the estimated total costs decrease from \( 4.4 \text{ M€} \), to \( 2.6 \text{ M€} \), a saving of \( 1.8 \text{ M€} \), which is just over a 40% reduction in cost and consistent with the data shown in figure 7. Note that the gains are not associated with increases in the brightest parts of the phase space, but from the improvements in homogeneity and 'filling in' the lossy parts of the phase space, which should be clear from figures 11 and 12. It is also worth noting that the cost savings come entirely from the shielding. The optics costs in this example have actually increased in price by \( 70 \text{ k} \), due to the use of a multi-channel bender.
Thus we see the trap that ensnared the original designers: there is a Nash equilibrium \[27\] for a sequential application of strategies that start first with optics and then end with shielding, as illustrated in figure 13, but this does not have the maximum possible payoff. Because the performance of the curved optics solution that they considered was inferior to the straight solution, they rejected all curved solutions and instead spent much time fine tuning their chosen solution and waiting for a shielding design.

Table 6, on the other hand, shows a payoff matrix for a wider choice of simultaneous optics and shielding strategies. There one can see that the proposed solution in this paper corresponds to that Nash equilibrium, which has a higher payoff than the sequential solution.

One might argue that this simple game theory analysis is obvious, and the author does sympathise with this point of view; but the counter argument is equally self-evident. If the solution in table 6 is indeed obvious, then one would tend to avoid labouring further with the results of the sequential strategy from figure 13. Anecdotal

Figure 11. Horizontal phase space of the baseline (top) and minimalist (bottom) beam concept evaluated at the sample position. Despite having reduced specifications, the phase space mapping in the minimalist geometry offers a clear improvement in the homogeneity.
observations indicate a split in the neutron community, with half agreeing with the simultaneous approach—to their benefit—and half following the sequential, and thus increasing their costs unnecessarily.

8. Costing validation

At the previously-mentioned costing workshop [2], a breakdown of instrument costs was presented as shown in figure 1.

At the time this work was completed, the scope of the instrument build programme had been reduced to 16 instruments, with a longer term plan to eventually reach the foreseen 22 public instruments described originally [13]). These 16 instruments were costed at €211 M. A bottom-up accounting of the components arrived at a total for optics and shielding in the vicinity of €83 M, which is within 10% of the baseline cost shown in figure 8.
Note that the ESS bunker shielding is not included in the shielding budget in this comparison, so the ESS does appear slightly under-costed.

The instrument caves were costed at €40 M, which would reduce to €26 M if the beams were curved out of line of sight of the source, representing a saving of €14 M. The proportional reductions in the guide shielding costs, indicated in table 1, for the medium and long instruments, of which there are 10, would lead to an average saving of roughly €800 k per instrument, leading to a total saving of €22 M. This suggests that the earlier savings in figure 9 might very well be reasonable, when extrapolated to a real-world deployment scenario.

In any case, it seems clear that an expert understanding of the interplay between two technical areas can unlock finances that are comparable to the cost of one or two entire instruments, or a bunker designed with the best professional practice rather than lowest possible cost. Alternatively, it could be used to obtain a relatively comfortable contingency that such complex projects always require in the latter half of the construction project. It is also worthwhile noting that, at the time this work was completed, no significant de-scoping of the ESS construction project had been discussed.

9. Conclusions

A simultaneous strategy on conceptual design, coupled with a rigorous expert technical analysis, has been shown to offer significant savings on the customer-facing components of a European megaproject. The results are superior in both cost and performance to a sequential strategy, and challenge some of the strategic assumptions held by a large fraction of the neutron scattering community. Whilst this result necessarily dives deeply into some highly technical areas of neutron scattering, this overarching conclusion may serve as an example in strategy to other complex megaprojects.

By optimising two main technical areas, in an architectural way, cost savings above €20 M were identified out of a total of €70 M. To reduce fears that such cost savings bring also a reduction in performance, a worked example was given in applying the optimisation to a mature instrument design. This demonstrated not just the expected cost reductions but, at the same time, an increase in performance through a proper understanding of
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