A Proposal for a Next Generation European Neutron Source

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Abstract. We argue that it is not too early to begin the planning process for a next generation neutron source for Europe, even as the European Spallation Source is being constructed. We put forward three main arguments. Firstly, nowadays the period between the first scientific concept of a new facility being proposed and its actual realisation is approaching half a century. We show evidence for this. Secondly, there is a straightforward development of the short pulse/long pulse spallation concepts that will deliver gains in neutron brightness of more than a factor 30 over what the ESS will soon deliver and provide the optimum balance between resolution and intensity. We describe our concept, which is a spallation source where the proton pulse length is matched to the moderating time of slow neutrons. Thirdly, when we look at our colleagues in astronomy and high energy physics, we see that they have a totally different, more global and more ambitious approach to the coming generations of large facilities. We argue that it is time for the neutron community not simply to rest upon its laurels and take what is given but to be proactive..

1. Introduction

Peter Egelstaff gave talks (unpublished) in the 1980s demonstrating that the period of gestation of large scientific facilities had been increasing by one year for every year that had elapsed since the end of the second world war. He supported this assertion by comparing the gestation period of the Dido and Pluto reactors at Harwell (~5 years) with the ISIS pulsed source (~15 years), amongst other examples. Nowadays to see the truth of his statement we need look no further than the elapsed time between the original proposal for the ESS at Simonskall in Germany in 1991 [1] and its projected attainment of full specification with a complete instrument suite in 2028, a period which will approach 40 years – a scientific lifetime. We indicate this in Fig. 1 where a clear linear relationship can be discerned as a function of calendar year, whose slope falls somewhat short of Egelstaff's prediction in that the slope is nearer to 8 months per calendar year elapsed rather than 12 months. Nevertheless this would still mean that a next generation neutron source, which we refer to as NGENS, would be ~47 years in gestation if conceived and embarked upon now and would only arrive at full specification in 2062. If, on the other hand, we waited until ESS was fully functional in 2028 before approaching the matter it would then, according to Egelstaff's Law, take 55 years to complete, and would not be at full specification until 2083! Egelstaff's Law can be seen as being equivalent to Moore's Law, but in reverse gear, and it is a clear warning to the community, recalling that ESS is slated to close down in 2065 under current plans

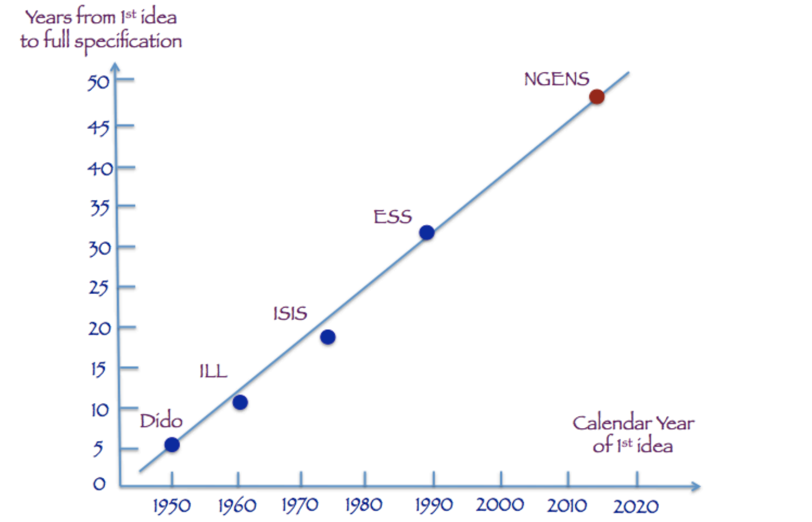

Figure 1. A graphical representation of Egelstaff's Law showing the time to realise a given neutron source as a function of the calendar year when it was first proposed. The numbers are necessarily approximate. Assuming this trend continues we have plotted the position of a next generation neutron source NGENS were it to be proposed now, as we suggest. It would take almost 50 years to reach full operations with a meaningful user programme. Data taken from Jacrot 2012 [2] and Hance 2006 [3]

Therefore it is timely, if not in fact urgent, to contemplate the idea of a next generation neutron source for Europe if neutron scattering is to progress beyond the middle of the century. We propose, as a viable candidate, a high power pulsed spallation source where the incoming proton pulse is matched to the moderating time of slow neutrons.

2. Matching proton and neutron times

The incoming proton pulse widths of the third generation MW-class spallation sources around the world (SNS, J-PARC and ESS) are all mismatched to the neutron moderating times by significant factors, either too short or too long. The moderator response for cold neutrons to a delta-function burst of protons to a spallation target is shown in Fig 2 [4]. Effectively SNS, JPARC and ISIS deliver delta function proton pulses (actually ~600ns) to their targets. The mismatch at this wavelength for a short pulse facility is very obvious. At shorter wavelengths the mismatch is less, but it is still one order of magnitude. When contemplating higher brightness sources employing narrow pulses we are limited by the instantaneous energy deposited into the target; no target is likely to survive the stresses imposed beyond a proton power of ~1MW. The forte of short pulse sources is that they are intrinsically high resolution facilities which is ideal for some applications but in many cases such as neutron spin echo, reflectometry ,small angle scattering and cold-neutron chopper and crystal-analyser spectroscopy, the resolution can be too high and hence instrument performance is below the optimum.

At the other extreme we have the long pulse concept, which ESS employs. In this situation a proton pulse of length ~3ms is used to generate the slow neutron beams and the moderating time of the neutron plays little part in the final pulse width. The moderating time of the neutrons can therefore be allowed to be much longer than in a short pulse source. In this situation increased intensity is the driver behind the source design and high resolution is achieved by chopping the pulse in time at each individual instrument. This however is at the expense of intensity. In many ways a long pulse source behaves like a quasi-continuous source.

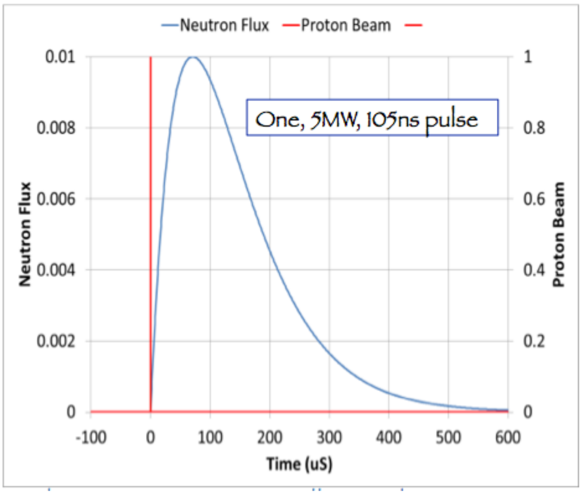

Figure 2. A monochromatic slice taken from the neutron pulse (blue) resulting from a quasi-delta-function (105ns) proton pulse (red) with the fast rise time and slow decay time clear in the neutron pulse. A useful rule of thumb for such sources is that the FWHM of the neutron pulse is approximately 7λ(Å)μs in the epithermal region and 22λ(Å)μs in the thermalised region.

In the case of a continuous source there is full flexibility to trade intensity for resolution and to be able to build a diverse set of instrumentation. Equally well continuous sources can be pulsed, with the advantage that the pulse length can be varied and the pulse repetition rate can be chosen as required, rather than being dictated by the parameters of the source itself. The design parameters of a pulsed source have a far greater consequence for the performance of the instrument suite than do the design parameters of a continuous source where spectral range and intensity are the only relevant factors.

If we consider the more or less accepted practical limits in pulsed source power today we see that short pulse sources such as SNS or J-PARC do not have ambitions beyond 1.4MW and the only long pulse source, ESS, is targeting 5MW. It is therefore appropriate to ask what would be the maximum power achievable were the pulse length to be varied away from the two extremes. Current expertise [5] suggests that, provided a solid target were used, then the full 5MW power of the ESS could be employed. The Goldilocks solution – just right - would therefore be to have the proton and neutron time constants as nearly equal as possible over the desired range of neutron wavelengths. In such a case both the peak and time-average slow neutron brightness can be simultaneously maximised for a given accelerator power. Gain factors of between one and two orders of magnitude in terms of intensity for a given resolution would accrue at the neutron instruments and would represent a very significant increase in sensitivity for neutron scattering investigations - a technique which benefits from a range of unique advantages for studies of condensed-matter science, but nevertheless facing fierce competition from the inexorable rise in intensity of photon sources. It is often stated that neutron and synchrotron sources are complementary but such complementarity begins to wane if the comparative source intensities diverge too much. Whilst pulse matching cannot be achieved at all wavelengths one could envisage a number of complementary regional sources which are optimised for different spectral ranges and hence for different ranges of scientific investigations rather in the way that different designs of telescope are diverse, being focused upon sky surveys or pin-point observations and operating in a specific wavelength band such as the UV, optical, IR or radio ranges, thus optimally serving science.

Our proposal is for an H- linear accelerator feeding into a compressor ring that generates proton pulses of some tens to hundreds of μs width [4] feeding into a rotating tungsten target similar to that of the ESS.

3. Evolution of neutron source strength

The rise in source intensity since the discovery of the neutron by Chadwick in 1932 is frequently represented by variations of the plot shown in Fig 3 [6] which takes its data from the quoted source fluxes which are often not actually useable by the instrument suite.

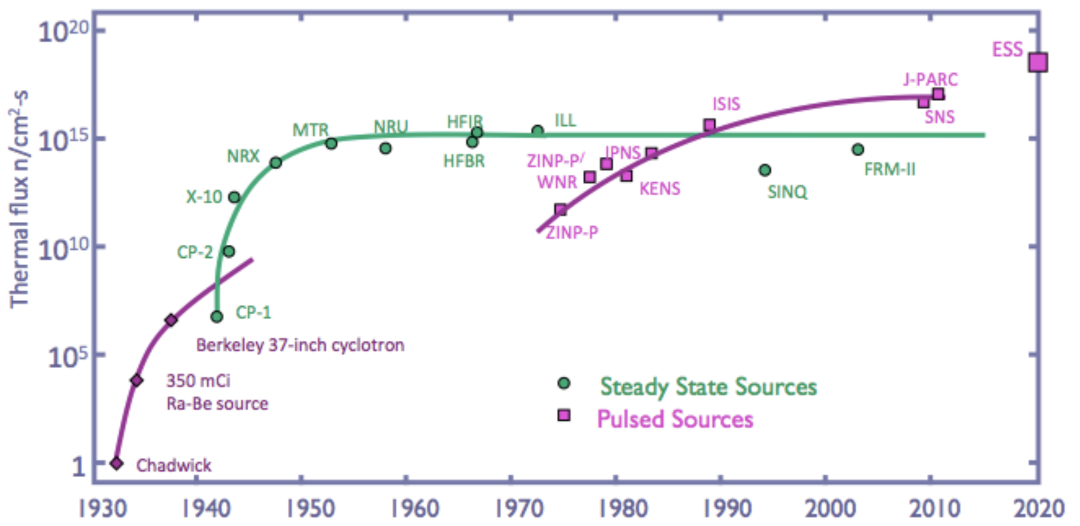

Figure 3. A representation of the effective thermal flux of various different neutron sources since the discovery of the neutron in 1932 by James Chadwick, adapted from [6]. Early sources are shown as red diamonds, reactor sources as green circles and spallation sources as red squares. An estimated flux for ESS is indicated by the larger red square.

Instead we have re-examined the data and express the same information in terms of neutron intensity available to the instruments. The results are shown as a scatter plot in Fig 4. Here we have made the distinction between reactor sources and spallation sources only and have fitted the data to straight lines in this logarithmic representation. This allows an average rise in useable effective source brightness over the past 5 decades to be derived and compared for the two kinds of source. In addition we have put upper and lower trend lines in the diagram. We find that whilst reactor facilities have risen in brightness by a modest 20% per decade on average, spallation sources have risen in brightness by a factor of 4 per decade on average. From this we can conclude that, of the two kinds of source, spallation has the most potential to deliver further gains in brightness when we come to consider possible source options for a next generation neutron source.

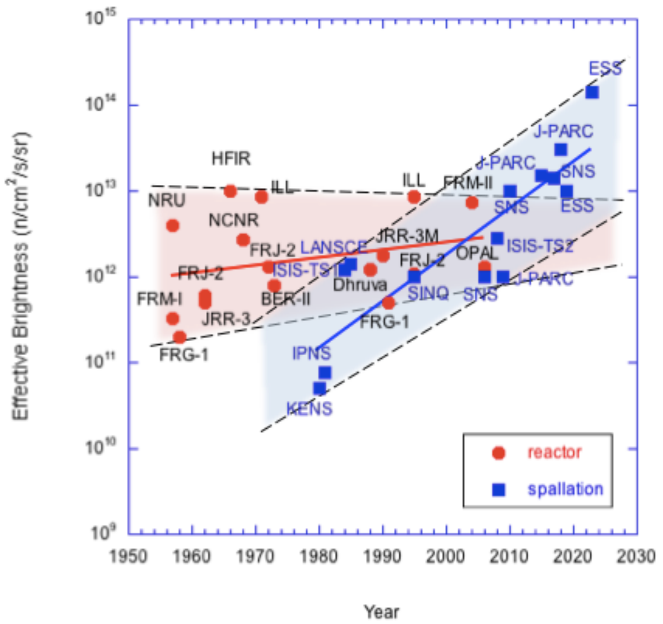

Figure 4. A scatter plot of source brightnesses where reactor sources are plotted in blue and spallation sources in red. The sources are those referred to in Tables 1 and 2.

The data shown in Fig. 4 are based on a literature search, resulting in the neutron facility list shown in Table 1.

Table 1. Neutron sources which are part of the present study

Source	Dates	In-pile thermal flux ($n/cm^2/s$)	B_{eff} ($n/cm^2/s/sr/Å$)
BER-II Berlin	1973 10MW 2019 shutdown	1.2e14 [8][9]	8e11 [a]
FRJ-2 Jülich	1962 10MW 1967 15MW 1972 23MW 1990 shutdown 1995 20MW 2006 shutdown	1.7e14 [8]	1.1e12 [a]
FRG-1 Geesthacht	1958 5MW 1990 CS added 1991 core size reduced 2010 shutdown	8e13 [8]	5e11 [a]
ILL Grenoble	1971 57MW 1992 shutdown 1995 57MW	1.3e15 [9]	8.7e12 [10]
FRM-I Munich	1957 4MW 2000 shutdown	5e13 [8]	3.3e11 [a]
FRM-II Munich	2004 20MW	8e14 [8][9]	7.4e12 [11]
Dhruva Trombay	1985 start 1988 100MW	1.8e14 [7][9]	1.2e12 [a]
NCNR	1967 10MW		

NIST	1985 20MW 1987 CS	4e14 [9]	2.7e12 [a]
HFIR Oak Ridge	1966 100MW 1986 shutdown 1990 85MW	1.5e9 [9]	1.0e13 [a]
NRU Chalk River	1957 200MW ^{nat}U 1964 60MW HEU 1991 135MW LEU 2018 shutdown	3e14 [12]	4e12 [a]
JRR-3(M) Tokai	1962 10MW 1983 shutdown 1990 20MW 2011 shutdown	2.7e14 [9]	1.8e12 [a]
OPAL Lucas Heights	2006 20MW	2.4e14 [9]	1.3e12 [a]
SINQ PSI	1995 1.5mA 600MeV	1.5e14 [9]	1.0e12 [a]
Lujan LANSCE	1985 120uA 800MeV 2015 shutdown		1.4e12 [b]
IPNS Argonne	1981 1.5uA 450MeV 2008 shutdown		7.7e10 [b]
KENS KEK	1980 7uA 500MeV 2006 shutdown		5.1e10 [b]
ISIS-TS1 RAL	1984 start 1990 160uA 800MeV		1.2e12 [b]
ISIS-TS2 RAL	2008 40uA 800MeV		2.8e12 [b]
SNS Oak Ridge	2006 start 2010 1MW 2017 1.4MW		1.0e13 [b]
J-PARC Tokai	2009 start 2015 500kW 2018 1MW		3.0e13 [b]
ESS Lund	2019 start 2023 5MW		4.1e14 [b]

[a] Rescaled from the value of the ILL effective brightness B_{eff}, assuming same ratio between B_{eff} and in-pile thermal flux. This will occasionally be an overestimate, as it assumes good beam-tube access to the region of peak thermal in-pile flux and an efficient cold source. Hot sources are not taken into account.

[b] Calculated from the spectral brightness values shown in Table 2, using equation (2).

Such a cross-facility comparison is fraught with difficulty. The first is conceptual; there is no simple correlation between the flux on the instruments and their scientific productivity, which ultimately is the metric against which large-scale facilities are measured [13][14]. Even if we somehow reach agreement on displaying what will inevitably be interpreted as "scientific productivity" or "usefulness to society" in terms of the neutron flux available on the instruments, there are a number of technical issues which stand in our way: the correlation between source brightness and instrument performance depends entirely on the efficiency of the neutron optics and other critical instrument design features. The availability of sample environment and data reduction and analysis software is similarly critical. These considerations, however, are somewhat beyond the scope of the present paper and we will instead focus our efforts on making the best possible comparison between individual steady-state and pulsed neutron sources. It is important that a comparison is made in order to arrive at an informed evaluation of the current and possible future developments in neutron facilities.

The time-average source brightness of pulsed sources is typically orders of magnitude below that of the steady-state sources. A claim frequently made however is that the performance of instruments on a pulsed source scales with the peak brightness, thereby redressing the balance in favour of pulsed sources.

A study [15] has been carried out of the performance of a reference instrument suite for the ESS as a function of the source time structure. At the time, the purpose of the study was to determine the optimal duty cycle of the ESS, resulting in the choice of a pulse repetition period of 14 Hz and a proton pulse length of 2.857 ms. However, one of the key findings of the paper is that, averaged over the full instrument suite, the instrument performance (expressed by flux on the sample) scales very closely to the duty cycle (pulse length divided by repetition period) to the power of 0.30. This leads us to propose a figure of merit (FoM) for all sources which is proportional to the product of the time-average brightness (B_{av}) to the power of 1/3 and the peak brightness (B_{pk}) to the power of 2/3. This corresponds to a geometric average of B_{av} and B_{pk} where B_{pk} is given twice the weight of B_{av}:

$$\mathrm{FoM} = B_{av}^{1/3} B_{pk}^{2/3} \tag{1}$$

For a continuous source, the time-average and peak brightnesses are the same, resulting in an effective FoM equal to the time-average brightness. In order to take into account the neutron wavelength-dependence of the source brightness, we propose to take an equal-weight geometric average of the FoMs evaluated using the highest available source spectral brightness at wavelengths of 1 Å and 5 Å, resulting in the "Effective Brightness" given below:

$$B_{eff} = \left(\mathrm{FoM}(1\text{Å}) \times \mathrm{FoM}(5\text{Å})\right)^{1/2} \tag{2}$$

The data needed for the evaluation of the Effective Brightness are not easily available for all neutron sources. We have therefore made some simplifying assumptions which are stated in the captions of Tables 1 and 2.

Table 2. Moderator spectral brightnesses in units of n/cm^2/s/sr/Å for the pulsed sources in Table 1 at wavelengths of 1 Å and 5 Å. For each facility, the moderator with the highest brightness for that wavelength has been chosen and stated in the table. The corresponding numbers for ILL and FRM-II are shown for comparison.

	Bav (1Å)	Bpk(1Å)	FoM(1Å)	Bav(5Å)	Bpk(5Å)	FoM(5Å)
ESS 5MW	4.4e13	1.1e15	3.6e14	3.8e15	1.5e14	4.6r14
2.5mA 2GeV 14Hz	3cm tall coupled water			3cm tall coupled liquid para-H_2		
J-PARC 1MW	4.5e11	1.2e15	7.6e13	4.4e11	6.8e14	1.2e13
333uA 3GeV 25Hz	coupled liquid para-hydrogen			coupled liquid para-hydrogen		
ISIS-TS1 128kW	9e10	1.5e14	1.1e13	3.5e9	9e11	1.2e12
160uA 800MeV 50Hz	decoupled poisoned water			decoupled liquid hydrogen		
ISIS-TS2 32kW	4.5e10	3.5e14	1.5e13	7e9	5.5e12	5.3e11
40uA 800MeV 10Hz	decoupled solid methane			decoupled solid methane		
SNS 1MW	5e11	5e14	4.5e13	1.2e11	1.1e13	2.3e12
1mA 1GeV 60Hz	decoupled poisoned water			coupled liquid hydrogen		
KENS 3.5kW	2.5e9 [a]	8.2e12 [a]	4.8e11 [a]	9.6e7 [a]	4.9e10 [a]	5.5e9 [a]
7uA 500MeV 20Hz						

IPNS 7kW 15uA 450MeV 30Hz	4.7e9 [a]	1.1e13 [a]	7.3e11 [a]	1.8e8 [a]	6.3e10 [a]	8.1e9 [a]
LANSCE 96kW 120uA 800MeV 20Hz	6.8e10 [a]	2.3e14 [a]	1.3e13 [a]	2.6e9 [a]	1.4e12 [a]	1.5e11 [a]
ILL 57MW [10]	2.8e13	2.8e13	2.8e13	2.7e12	2.7e12	2.7e12
	H2 thermal beamtube			horizontal/vertical cold source		
FRM-II 20MW [11]	3.2e13	3.2e13	3.2e13	1.7e12	1.7e12	1.7e12
	thermal beamtube			cold source		

[a] extrapolated from ISIS-TS1, using the source powers and time structures, assuming similar moderator-reflector performance

4. Conclusions

We conclude that a concerted consideration of the design of a next generation neutron source for Europe should begin in the immediate future. Even so we predict that such a source would not be operational, under the most optimistic scenario, until well into the second half of this century. We put forward as a viable option for such a source a matched neutron-proton pulsed source driven by a 5MW proton accelerator with a proton pulse length of between 50 and 100 μs . In such a case we believe that peak brightnesses a factor of 35 over what ESS is calculated to achieve in the mid 2020s will accrue. This implies brightnesses over what is available now to researchers at SNS and ILL will be almost three orders of magnitude higher. This would be a considerable step forward in terms of scientific investigative power.

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