COMPARISON OF NEUTRON EFFICIENCY OF REACTOR AND PULSED SOURCE INSTRUMENTS

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ABSTRACT

A global comparison of the luminosity of various types of neutron scattering instruments on reactors, traditional type short pulse spallation sources and a new type of long pulse spallation source show that with adapted instrumentation spallation sources outperform reactor sources of equal costs. Instrumentation ideas adequate for long pulses are described and an optimal combination of the two spallation source approaches is proposed.

INTRODUCTION

Current common wisdom regards reactor and pulsed spallation neutron sources as "complementary" facilities. This statement is justified in the following sense: Over the spectrum of various applications a pulsed spallation (PS) source can provide some two orders of magnitude poorer luminosity (data collection rate) in some applications, and at the same time prove an order of magnitude brighter than a given reactor in other applications. (This actually roughly applies to ISIS and ILL.)

On the surface, this suggests that in order to cover all scientific opportunities offered by neutron scattering, both types of sources are needed. However, the argument of "complementarity" is incomplete: It does not include the costs aspect. What should really be compared is the "value for the money", i.e. how facilities of roughly equal costs compare in the various applications.

It is the purpose of this paper to show that an extremely simplified PS source design, (a kind of a pulsed version of the c.w. source under construction at PSI near Zurich) using a single proton linac and applying a few new instrumentation ideas can offer a very cost efficient source with a performance superior to reactors of similar price tag across the board in virtually all kinds of applications. It has to be emphasized that the new design proposed here is not an optimal PS source and that its performance can be dramatically boosted in two thirds of the applications by adding (rather expensive) storage or accelerator rings, but that it clearly outperforms reactor sources. The implication of these ideas for the design of an advanced optimized PS source facility such as ESS is that a possible way is suggested to enhance the power of the *10 Hz* target from *1 MW* to *5 MW*. This enhancement of power is necessary to make ESS a superior source compared to ILL in applications such as small angle scattering (SANS).

In what follows, the concept of a high power PS source will be described, which uses a modern linac as the only accelerator and its neutron luminosity will be compared to reactor and conventional type spallation sources. In doing this, a few new instrumentation ideas will be introduced in order to make best use of the long pulses available from a linac. These considerations will lead to the unavoidable conclusion that there is no room left for reactors in the next generation of neutron sources.

FUNDAMENTALS

In Fig. 1 the relative luminosities of various sources [1] are compared, based on the following assumptions

a) The time averaged thermal flux from an optimized coupled, unpoisoned "slow" moderator on a *5 MW* beam power target is equivalent to that of ILL (conclusion of the SNQ project confirmed within a factor of two by other studies). Furthermore the cold neutron flux on a spallation source compares to reactors a factor of two more favourably than the thermal one because the cold moderator can be placed closer to the core than on a reactor.

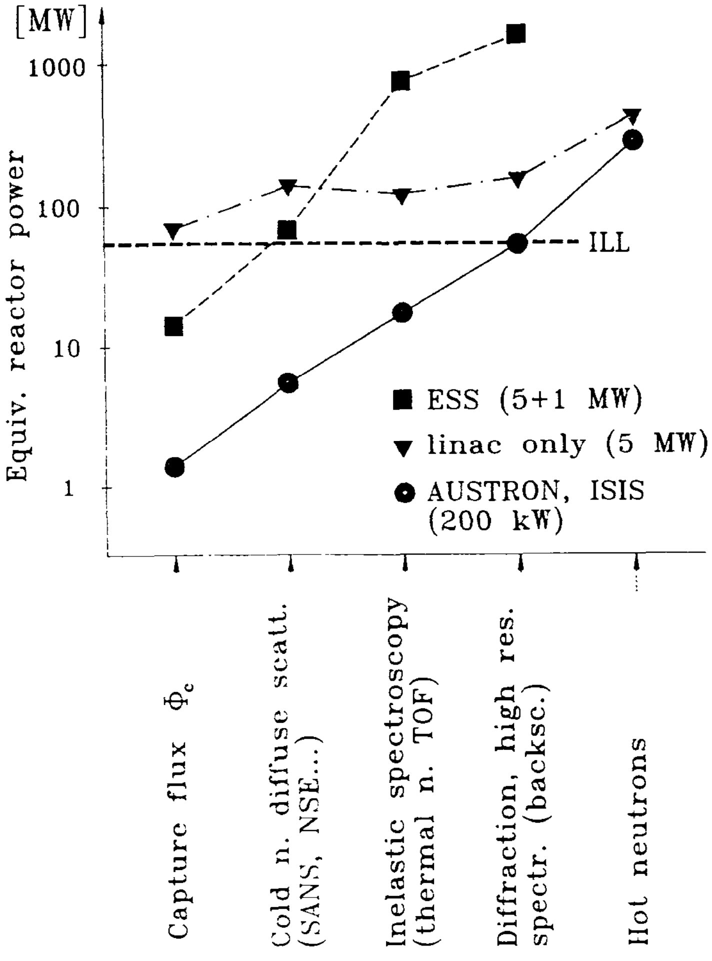

Fig. 1. Comparison of neutron efficiencies (typical data collection rates) in various types of instrument applications on various neutron sources.

b) The time averaged flux of a decoupled, poisonded "fast" moderator (actually most frequently used on current spallation sources) is about 10 times smaller than that of the "slow" moderator of point a).

The basic point in a comparison of the data collection rates I on reactors and various types of moderators on spallation sources is to evaluate the effectively utilized fraction of the total time averaged flux $\bar{\Phi}$. Thus in scattering experiments

$$I \propto \bar{\Phi}\delta\lambda \quad (1)$$

where $\delta\lambda$ is the wavelength band usefully contributing in a given experiment. On a reactor source $\delta\lambda$ is determined by the resolution required while on a pulsed source it is most often defined by the frame overlap conditions, i.e. by the requirement to stop the fastest neutrons from catching up with the slowest ones from a previous pulse. For example at a pulse rate of *50 Hz* and a *20 m* moderator–detector distance the maximum wavelength band is *4 Å* . Thus in a powder diffraction experiment effectively using the *1 - 3 Å* wavelength band with 0.5% required resolution the wavelength band gain on PS source compared to a reactor amounts to a factor of 200 at the average flux of the "fast" moderator b). In a similar diffuse scattering experiment with a wavelength resolution of 20% the same gain factor only amounts to 5, however with respect to the 10 times more intense "slow" moderator. For neutron capture work (parity violation studies, activation analysis, in beam NMR, etc.) the whole spectrum can be used, thus simply the average (cold) flux matters.

Triple axis type spectroscopy is a rather complex case. If information has only to be collected from a single wavenumber $\vec{q}$ in a single crystal, the PS source has no wavelength band benefit, and the average fluxes have to be compared. On the other hand, if the energy scans have to be performed in the whole two-dimensional $\vec{q}$ domain (say *20* × *20 q* pixels), the simultaneous data collection on a time-of-fligth (TOF) instrument can provide a gain factor of up to 400 compared to the time-averaged flux of the "fast" source. Thus, in comparing pulsed and c.w. sources concerning typical applications of triple axis spectroscopy the average slow moderator flux ("capture flux" in Fig. 1) can be taken as the worst, and 10–100 times this value as the best estimate for the pulsed source.

Fig. 1 shows the comparison of the luminosity of a number of existing and planned sources for a selection of typical applications evaluated along the lines of the examples just discussed. Clearly, the gain of PS sources becomes stronger with increasing wavelength resolutions requirements. The comparison for hot neutrons is just indicative and not considered in any detail, since in this field most applications are just not available at reactor sources. The point dashed line corresponds to the proposed "linac only" concept which is described below.

THE BASIC CONCEPT

As shown in Fig. 1 the two first types of applications – neutron capture and diffuse scattering (such as small angle scattering and Neutron Spin Echo) studies with cold neutrons – are those in which PS sources compare less favourably to reactors. This is largely due to the fact that here the wavelength band gain factor is 1 – 5 only. Thus, the only way to go is to increase the average power. In order to maintain a reasonable sample size, optimized small angle scattering devices have to be rather long and a low repetition rate (*10 Hz* in the ESS preliminary specifications) is required in order to maintain an adequate wavelength band. The power is than limited by the energy the ring accelerators (which typically compress the about *1 msec* long injector linac pulse into *1 μsec*) can handle in a single pulse. This leads to an expected limitation of the *10 Hz* target to about *1 MW*.

On the other hand, it turns out that for small angle scattering etc. pulse lengths of even *5-10 msec* are acceptable, since they still provide a wavelength resolution of 10-20% at $\lambda > 4$ Å and a source–detector distance of *40 m* or greater. Within such a long period a linac can provide the energy required for *5 MW* average beam power on the target even at *10 Hz*. This is the starting point of the present concept: to feed a target directly by the

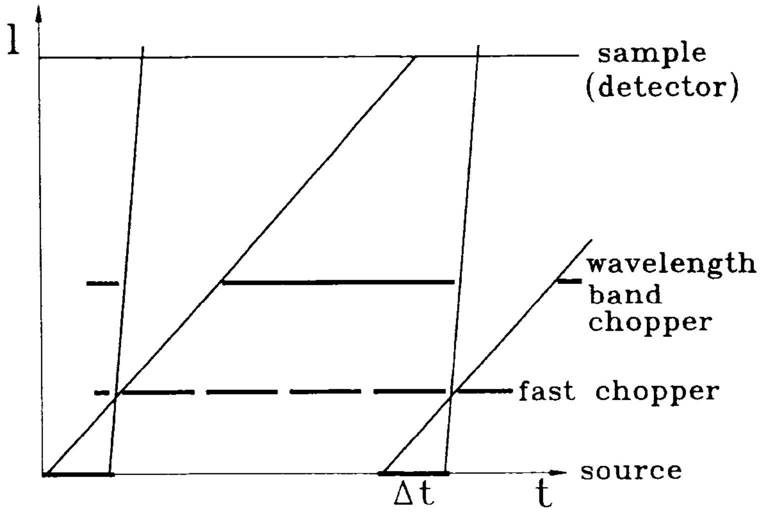

Fig. 2. Principle of using fast choppers for diffraction and inverted geometry inelastic scattering instruments on long pulse sources.

linac beam in order to overcome the energy bottleneck presented by the ring accelerators in the two less favourable type of applications in Fig. 1.

The second part of the proposal concerns the question of how such a long pulse source can be used for other types of experiments, i.e. where good (~ 1% or better) wavelength resolution is required. It will be shown that by the application of pulse shaping choppers the favourable comparison to reactors can be maintained over the whole spectrum of applications, while the optimized (also more expensive) PS source would provide a much superior performance in this end of the application spectrum. The new concept provides very much reactor-like characteristics, because, as it will be seen, it basically treats the source as a stationary one, which just does not have to be switched on all the time for the time-of-flight techniques proposed. Thus it can be regarded as an improved, more efficient version of the PSI c.w. spallation approach. It has, on the other hand, little in common with the SNQ concept of instrumentation, which was based on relatively short, directly utilizable pulses. This is why the present accelerator requirements are much less stringent than those of the SNQ project were.

INSTRUMENTATION WITH LONG PULSES

In order to be more specific and to get a feeling of the orders of magnitude, in the present discussion we shall assume a state of the art H^+ linac with a peak beam power of *50 MW*, which can be operated at 10-15% duty cycle (very much like a possible injector in the ESS project). For SANS type experiments a pulse duration of *4 msec* will be considered with *12.5 Hz* period, i.e. *8 Å* maximal wavelength band *40 m* from the source. This provides *2.5 MW* average beam power, and with a wavelength band gain factor of at least 4 we arrive at the *200 MW* reactor equivalent flux in Fig. 1.

For the purpose of higher wavelength resolution applications let us assume 3 other pulses of a duration of *1.4 ms* each, which completes the burst rate to *50 Hz* and the total power on the target to *5 MW*. (These extra pulses will be masked by a frame overlap chopper for SANS type applications.) The instantaneous neutron flux emitted by the slow moderators during the pulses – with moderation times in the *100 μsec* range – is equivalent to the thermal flux of a *500 MW* reactor! In order to achieve the desired resolution, we shall essentially apply continuous source TOF techniques with fast choppers. This requires

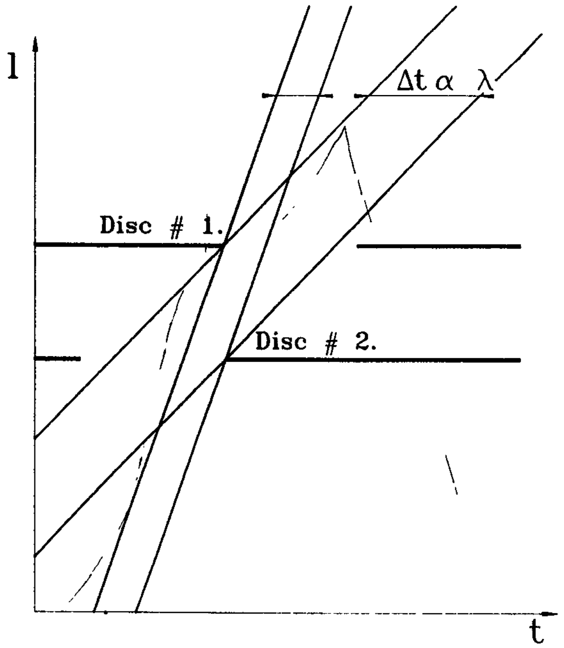

Fig. 3. Producing wavelength dependent neutron pulse length by a pair of chopper discs.

a source switched on long enough to provide a sufficient wavelength band in view of the finite distance between source and fast chopper, as illustrated in the TOF timetable in Fig. 2. With $l = 1.5$ *m* source–chopper distance $\Delta t = 1.4$ *msec* pulse length provides a wavelength band of *3.6 Å* , which will be preserved if the source–detector distance does not exceed a fair limit of *21 m*. Experts' advice differs on the technical feasibility of running choppers at *1.5 m* from the moderators, a somewhat longer distance would reduce the available wavelength band a bit, if the pulse is not made longer.

For applications such as powder diffractometry, single crystal diffractometry, inverted geometry (crystal analyser) time- of-flight inelastic spectrometry we would thus fundamentally end up with a *500 MW* equivalent reactor flux, as long as the full wavelength band allowed can be used. Compared to the TOF method crystal spectrometers occasionally offer advantages when concentrating on short scans, which will be compensated in other cases by the wider dynamic range offered by the TOF method. Nevertheless, in order to remain on the safe side, in Fig. 1 on the average only 40% of the available wavelength band is considered as useful. Note, that in the detailed analysis one often finds that the TOF method is just superior even on a c.w. source. Thus backscattering spectroscopy with a *1 meV* scan width and a resolution of *1 μeV* at a wavelength of about *6 Å* is achieved in a very efficient way by an IRIS [2] type machine at the end of an *80 m* neutron guide following a *30 μsec* pulse length fast chopper.

In direct conventional geometry, inelastic TOF spectroscopy the incoming beam is narrowly monochromatized by a sequence of fast choppers. Thus the first fast chopper does not need to be very close to the source and shorter pulses would also be sufficient. (One could even include further about *0.3 msec* long linac pulses between the *50 Hz* ones considered in order to increase the repetition rate to the *100 Hz* maximum possible for a linac.) The ideal repetition rate for TOF instruments on c.w. sources ranges from *50* to *200 Hz*, and an average of *150 Hz* has been assumed in Fig. 1 in comparison to the *50 Hz* taken for the PS sources.

CHOPPER PERFORMANCE

The use of the TOF method for diffraction and inelastic scattering studies by applying pulse definition choppers on a long pulse spallation source is analogous to the way this could be done on a reactor source. It remains to be shown that these chopper methods are competitive to the presently more usual crystal spectroscopy, although the average flux of the here discussed source is comparable to that of ILL, so that e.g. triple axis spectrometers could be operated right away with some additional bonus from the TOF filtering of higher orders and "spurions".

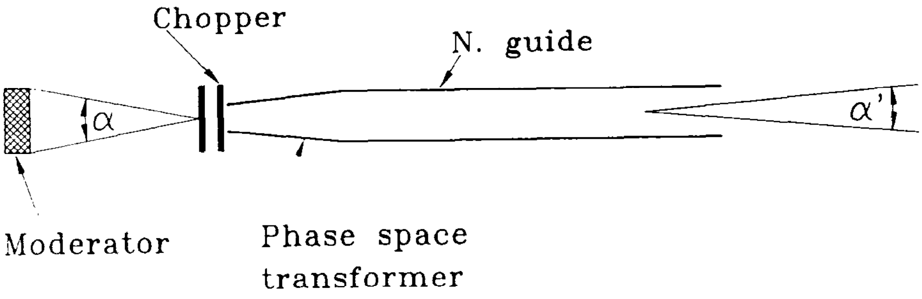

Fig. 4. The principle of the "eye-of-the needle" neutron beam line design, utilizing the large divergence of the beam across the narrow chopper slit.

Indeed, to start with, the resolution comparison turns out to be quite favourable for the TOF method. In diffractometry and inverted geometry inelastic spectroscopy. For example, 1% wavelength resolution at *2 Å* wavelength and *20 m* chopper–detector distance only requires a chopper pulse length of *100* μsec, which is easily achieved by up-to-date disc choppers. Disc choppers are to be preferred here because their transmission is wavelength independent. A further advantage is that with two choppers rotating synchronously in the same direction, at the same speed and at a distance of a few *cm* from each other, one can imitate the wavelength proportional pulse width of fast PS source moderators, offering the attractive feature of constant relative resolution. Indeed, in view of Fig. 3 the FWHM pulse length becomes

$$\Delta t = max(l/v_n, d/v_c) \tag{2}$$

where l is the distance between chopper discs, d the beam width, and v_n and v_c are the neutron and the peripheral chopper velocities, respectively.

In order to achieve high resolutions – actually better ones than available with crystal instruments – some additional tricks can be used. Fermi choppers with broader slits can offer some compromise between pulse length and transmitted wavelength band. Counterrotating disc choppers at a distance of *1–2 cm* from each other give a broad band transmission and short, wavelength independent pulse lengths in the *10–20* μ*sec* range at *500 m/sec* peripheral velocity. This however requires a narrow slit width of *1–2 cm*, which can prove to be a serious restriction. This can be alleviated by the "eye-of-the-needle" beam line design illustrated in Fig. 4. At a narrow slit at the chopper the beam divergence α is considerably higher than the one useful on the sample. Than by a mirror optical "phase space transformer", e.g. widening guide section as a simple example case, the beam is transformed into a spatially wider, but less divergent beam which can feed a neutron guide. This is the inverse of the beam "compressors" such as the one used on

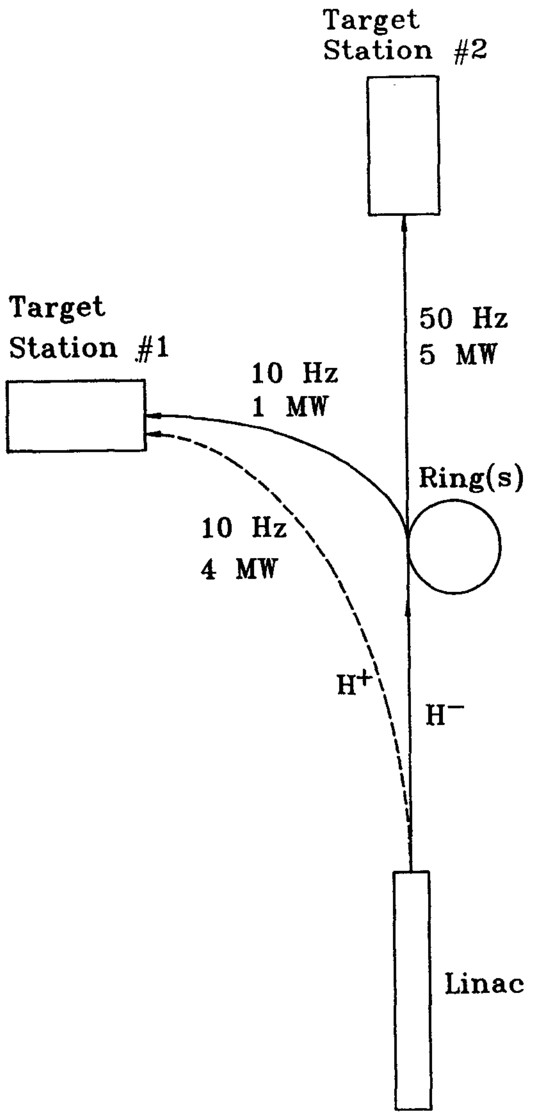

Fig. 5. A combination of the short and long pulse spallation approach proposed to optimize efficiency over the whole spectrum of applications.

IRIS in front of the sample. With currently routinely available supermirrors a 1:2 width compression – or decompression – can be achieved in conjunction with a neutron guide without substantial loss of neutrons [3]. The effective beam width can be further doubled by using the double slit trick for a counterrotating pair of discs, as under construction at NIST. More sophisticated optical focussing methods and improved supermirrors will also increase the flux one can concentrate on the sample downstream to the narrow slit required for the shortest pulse disc choppers.

CONCLUSION

We have shown that a new type of spallation source set-up using a state of the art high power H^+ linac as the only accelerator, directly feeding the target with long pulses of *1 – 10 msec*, offers neutron source characteristics similar to reactors. An ILL equivalent performance in neutron scattering would require a *1.5 MW* total beam power on the target, half of which power concentrated into every 4th pulse in the *50 Hz* basic repetition rate. The reliability of the source should also be excellent, since the delicate problem of stripping at injection into the ring is absent. On the basis of the PSI *1 MW* source budget and various project cost estimates presented at this meeting [1], the price tag of such a source (buildings, beam guides included, instruments excluded) should not exceed $ 150–200 Mio, i.e. it is well below the construction costs of any conceivable research reactor. In the majority of the applications adding compressor or accelerator ring(s) would tremendously enhance the effective luminosity of this source, however at substantial additional costs and technical difficulties.

The most delicate point in the *5 MW* beam power, some *200 MW* reactor equivalent version considered in Fig.1 is the target design. Although the feasibility of a *5 MW* rotating target has been demonstrated in the SNQ study, and it is part of the specification of the ESS study project, concentrating half of this power in a quarter of the pulses adds to the difficulty: It would imply a *100°C* temperature jump during the longest pulses compared to *50° C* for equally distributed pulse power, unless the target used rotates at speeds comparable to that of railway wheels. (During the pulses the cooling helps little, it is only the specific heat of the target material that matters.) This leads to additional stresses, with not yet studied consequences. Nevertheless it is well possible that even at *5 MW* as in Fig. 1 this "linac only" spallation source will not cost more than an ILL type reactor, with the costs primarily determined by the target. (In contrast, e.g. a *100 mA* peak current *500 MeV* H^+ linac can just be considered as state of the art.) Assuming that even higher, power single pulses can be handled in the target, the present approach would allow to improve the performance of an ESS type design in small angle scattering type applications by adding long linac pulses at *10 Hz* and some *4 MW* average power to the *1 MW* delivered in form of short pulses from the ring(s) to the *10 Hz* target (Fig. 5).

In sum, the most cost efficient spallation source variant proposed here together with an adapted novel instrumentation approach offers better neutron flux conditions in virtually all applications in neutron scattering (and possibly also in the shear time averaged flux) than reactor sources of comparable costs. On the basis of current technology, optimal spallation source performance can be obtained by combining the present long pulse and the traditional short pulse approaches.

REFERENCES

[1] The reader is referred to appropriate sections of this proceedings for specific information on the ISIS, Austron, ESS facilities/projects and on accelerator and target performance/problems.

[2] See ISIS user guide.

[3] R.E. Lechner and F. Mezei, ICANS XI Proceedings (KEK, Tsukuba, 1991) p. 919.