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OPTIONS FOR A NEXT GENERATION NEUTRON SOURCE FOR NEUTRON SCATTERING BASED ON THE PROJECTED LINAC FACILITY AT JAERI

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Japan Atomic Energy Research Institute (JAERI) has a project to construct a high intensity proton accelerator to promote wide basic science using neutrons and nuclear power technologies such as radioactive nuclide transmutation. One of the most important field for utilization of neutron beam is neutron scattering.

The energy and the averaged current obtained by the proton accelerator are 1.5 GeV and 4-5.3 mA, respectively and these provide 6-8 MW power. The repetition frequency is 50-60 Hz. Evaluation of options for the use of accelerators for neutron production for neutron scattering research and investigation of the neutron research opportunities offered by sharing the superconducting linac planned at JAERI were discussed.

There are two ways of the utilization of proton beams for neutron scattering experiment. One is for long pulse spallation source (LPSS) and the other is for short pulse spallation source (SPSS). Quantitative evaluation of instrument performance with LPSS and SPSS was examined in the intensive discussion, calculations, workshop on this topics with Prof. F. Mezei who stayed at JAERI from October 24 to November 6, 1996.

A report of the collaborative workshop will be also published separately.

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Keywords: Spallation Neutron Source, Long Pulse Neutron, Short Pulse Neutron, Neutron Scattering, Proton Linac

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原研線形加速器計画における中性子散乱用次世代中性子源の選択

日本原子力研究所先端基礎研究センター
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（1997年2月20日受理）

原研は中性子を利用する広範な基礎科学と高レベル放射性廃棄物消滅処理技術開発を推進するために，大強度陽子加速器の建設を計画している。この陽子加速器によって得られるビームエネルギー，平均電流，出力は各々1.5 GeV，4～5.3 mA，6～8 MWであり，くり返しは50～60 Hzである。中性子散乱研究用中性子源として考えられているロングパルス核破砕中性子源とショートパルス核破砕中性子源について，それらの建設費用相対比，中性子強度比，各種の中性子散乱装置に対する性能比を定量的に検討し，表にまとめた。この検討結果は，中性子科学研究計画を推進する上で，極めて重要な基礎データとなる。

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The options of a short pulse and a long pulse spallation source (SPSS and LPSS, respectively) have been examined assuming the availability of a 30 mA peak current, 1.5 GeV linac accelerator for both H^+ and H^- beams. For the LPSS option the maximum reasonable duty factor leads to a projected beam power on target of 4.5 MW, while, for SPSS, 2 ms injection time into a single storage ring at 60% proton beam chopping rate gives 2.7 MW projected average proton beam power. The underlying assumptions for the accelerator-target system are

a) Injection: in other current project studies about 0.6 ms long linac pulses are assumed for injection in a storage ring. In view of the relatively low linac peak current, 2 ms was assumed here in order to achieve 2.7 MW average SPSS power per storage ring. Achieving this would considerably reduce linac requirements for SPSS design and it is a crucial R&D subject in the present considerations.

b) Target stations were assumed to be able to handle average power of up to 5 MW, up to 200 kJ energy per pulse for LPSS operation (no shock waves) and up to 100 kJ/pulse for SPSS operation(with shock waves). International studies are in progress in order to establish feasibility.

c) The tentative construction costs are derived from the preliminary values cited for the European ESS study of a 5 MW 50 Hz SPSS with two target stations.

The total costs of this facility is estimated to 940 M ECU about \$ 1200 M (1996 value).

d) The following moderators were assumed:

LPSS target station:	coupled H_2O and H_2
SPSS target station:	decoupled H_2O, decoupled CH_4 pebble-bed or H_2+ZrH_2, grooved coupled H_2 & flat coupled H_2

The performance of coupled moderators is estimated on the basis of Ferguson et al. and Pitcher et al. ICANS-XIII. These estimates are conservative, and further R&D is in progress to establish the optimal design of target stations with coupled moderators both for LPSS and SPSS (e.g.H_2 with premoderator).

In comparing expected instrument performance to that available at ILL, two basic assumptions were used.

a) The finite efficiency of the instrument components (neutron guides, detectors, monochromator crystals, collimators, velocity selectors etc.) effects both sides of the comparison on the whole equally.
b) Equally optimized instruments were assumed for both the projected pulse source options and ILL. Thus in particular for cold neutron inelastic scattering the possible (and planned) improvements for IN5 were assumed (cf. the performance of NEAT at HMI) or for diffuse scattering a velocity selector instrument is considered instead of D7.

A few cases are worth mentioning in an explicit fashion.

a) Most of the optimized LPSS instruments have to use neutron guides both for thermal and cold neutrons in view of the required some 30-120 m length between moderator and sample.
The transmission of Ni or ^{58}Ni coated guides of this length is expected to be above 80%, eventually by using novel guide design ("ballistic guides").
Many cold neutron ILL instruments use similar length of guide.
b) Beam focusing/divergence.
By using beam "compressor" focusing optical devices, the beam divergence at the sample can be increased up to $6\times\theta_c^{Ni}$ with commercially available supermirrors. This divergence is sufficient horizontally (e.g. 0.6° at 1Å wavelength). On the other hand, crystal monochromators on reactor sources can make typically 2° vertical divergence available. Supermirror beam compressors only provide this divergence for wavelength longer than 2Å, however the finite reflectivity of the monochromator crystals used at shorter wavelengths can be considered to off-set the intensity gain by the vertical focusing.

c) Detectors were assumed to have adequate x-y resolution, if required, in order to give sufficient resolution for the scattering angle. For time-of-flight (TOF) operation only the newly developed image plate detector has to be ruled out from the usual choice of detectors. For. e.g. Laue diffractometry, where only moderate TOF resolution is required, it can be efficiently replaced by x-y resolution multiwire or microstrip detectors.

d) For TOF inelastic spectroscopy the full use of "repetition rate multiplication" (F.Mezei, in Proc. ICANS-XIII) was assumed, both in the LPSS and SPSS cases i.e. identical repetition rate of the sample-end chopper for both pulsed and CW sources.

By the growing practice of using several different resolution (wavelength) runs on CW-sources in a complete series of experiment, the assumption of equal data collection efficiency on average for single wavelength and multiple wavelength data collection appears to be well justified. The disc choppers currently operating on CW sources and spallation sources (ISIS) provide a satisfactory technical basis for the projected chopper instruments for pulsed sources. By proper choice of instrument design parameters in particular source to sample distance, one can achieve that no chopper has to be placed inside the about 6 m thick bulk shielding (neither for wavelength band definition nor for pulse length definition) in both projected options, LPSS or SPSS.

e) For triple axis spectroscopy (TAS) the use of a usual crystal monochromator instrument was assumed for the pulsed source. The time structure of the pulse provides for some intensity gain compared to the time averaged flux due to the elimination of the need for higher order filtering and assigning the background to time channels. More than one incoming neutron wavelength could also be simultaneously used in connection with the RITA(Risϕ) multiple analyzer crystal approach which would give further relative advantage to the pulsed technique. Another possible alternative to constant q spectroscopy is being developed on existing pulsed sources by refining TOF spectroscopic methods.

The results of the comparison of the two options for the projected JAERI source are summarized in Table 1-3. These results show that both options offer a large improvement compared to the best existing facilities worldwide. The LPSS option would basically equal the performance aimed at by the ANS superreactor project at Oak Ridge, abandoned by now because of too high costs. The LPSS facility has the characteristics of an improved CW reactor source. The SPSS option offers a 14 fold improvement compared to the world leading pulsed source ISIS with, in addition, improved efficiency for cold neutrons due to the projected use of coupled cold moderators.

Table 1. Tentative estimate of construction costs for the LPSS and SPSS options

	Linac	H^+ or H^-	Beam transport	Ring	Target	~40 spectrometers	Sum
LPSS	1	0	0	0	0.3	0.22	1.52
SPSS	1	0.05	0.05	0.3	0.3	0.2	1.90
				0.6 (2 rings)	0.6 (2 targets)		2.5
For comparison: ESS (SPSS)	1	0.05	0.25	0.625	0.625	0.2	2.75

Costs for basic linac are taken as 1. This is currently estimated to be $500M.

Table 2. Comparison of projected neutron fluxes relative to ILL

	E (GeV)	I_{peak} (mA)	Proton pulse duration	Rep. (Hz)	Average beam power (MW)	Φ_{peak}	Φ_{av}
LPSS	1.5	30 (H^+)	4 msec	25	4.5	all coupled moderator (cold) 10 (thermal) 7 (slowing down) 50	1 0.7 5 *1
			2 msec	50			
SPSS	1.5	30 (H^-)	1 µsec	50	2.7	(coupled, cold) 30*2 (decoupled, thermal) 140 at 0.1nm wavelength (slowing down) 30000	0.6 0.05 *3 3
			1 ring, 2 msec injection time, chopping factor 0.6				

*1 : if compared to the hot source at ILL, then ~1/5

*2 : fig.5, E. J. Pitcher et al, Proceedings of the Meetings ICANS-XIII AND ESS-PM4, p327. Note : from improved design, up to ×2 is expected

*3 : pulse length (µsec) = 70×λ(nm)

Table3. Examples of projected instrument performance relative to ILL

	SANS	Medium resolution diffraction	High resolution powder diffraction	Inelastic scattering thermal neutron	Inelastic scattering cold neutron	Cold TAS	Reflectometry
LPSS (4.5MW)	8 (25Hz) 4 (50Hz)	7	7	7	10	2	8 $\Delta q/q \sim 3 - 5\%$
SPSS (2.7MW)	2.4	1.2 (thermal)	60 $\Delta d/d \sim 1 \times 10^{-3}$ $d > 0.07$nm	10～20 $\Delta E/E \sim 2\%$	30	1.2	11
		2 (0.2nm), cold moderator with premoderator	140 $\Delta d/d \sim 1 \times 10^{-4}$ $d < 0.07$nm	35～40 $\Delta E/E \sim 0.5\%$			
			(14×ISIS)	(14×ISIS)			

In brackets : comparison to ISIS in cases where ISIS provides superior performance to ILL

SANS inculdes Neutron Spin Echo and low resolution ($\delta\lambda/\lambda \sim 10\%$) Diffuse Scattering

Appendixes

F. Mezei

Berlin, 3.5.1996

SPALLATION SOURCES: TECHNICAL ASPECTS

1. Heat production limit

Conventional short pulse spallation sources (SPSS) and continuously operating (CW) reactor sources are regarded as complementary facilities. For example, comparing ILL, the best existing CW source to ISIS, the most powerfull SPSS in operation, complementarity means that the time averaged thermal or cold flux of ILL (relevant for neutron capture or inherently fixed wavelength experiments such as neutron interometry) is about 20 – 30 times higher than that of ISIS, while the peak flux is in the epithermal neutron range (relevant to many high resolution powder diffraction experiments optimally performed by the time–of–flight (TOF) method) 30 – 100 times higher at ISIS than at ILL. The relative performance of the two sources lies between these extremes for other types of applications.

This example illustrates the point that pulsed time structure makes it possible to use the total number of neutrons produced over the time of a neutron scattering data collection (time average flux) more efficiently by in monochromatic beam experiments. This more efficient use of the time average flux is crucial, since the flux on reactor sources is ultimately limited by the heat production in the core, which practially cannot be increased much beyond the level achieved at ILL (i.e. 1.5 MW/l). Additionally it is interesting, that in spallation the heat production per available fast neutron is nearly an order of magnitude lower than in fission. These two factors, pulsed time structure and lower heat production per neutron allow us to envisage a vast improvement of neutron fluxes delivered on a sample in neutron scattering experiments once proton accelerators in the MW or 10 MW power range of reactors become available.

2. High power accelerators

With current technology powerful proton beams are most favourably accelerated by linear accelerators, and the most powerful existing linac (Los Alamos) reaches about

20 MW peak and 1 MW average power. The linac power is fundamentally determined by the current capability of the ion source. At the present state of the art one can envisage 60 MW average power in continuous operation (Brookhaven project, assuming superconducting cavities in order to reduce electricity consumption and beam spill; cost estimate $\sim$ 200 MECU) or 150 - 300 MW peak power for H^+ ions (less for H^- ions) at final proton energies 1.2–2.5 GeV, respectively. These linac performances are far from the space charge limit. Consequently, in order to achieve average beam powers in the range of several MW, the linac has to operate with substantial duty cycle (3–10%) which for the pulse repetition rates reasonable for neutron scattering applications (10–50 Hz) implies linac pulse lenths 0.6–10 msec.

Pulse lengths within this range are adequate for taking full advantage of the pulsed structure of the beam in an important classes of neutron scattering work (small, angle scattering, neutron spin echo, diffuse scattering, amorphous materials) but do not provide sufficient TOF wavelength resolution for other applications over fligth paths of reasonable length. Using crystal monochromators as on CW sources can solve this problem, however this approach only allows for taking partial (but still essential) advantage of the source time structure (so–called multiplexing).

3. Alternatives for short neutron pulse production

Optimal efficiency in the use of the produced neutron flux is achieved in high resolution applications by making the neutron pulses adequately short. This goal can either be achieved by compressing the long proton pulses by storage rings into pulses of sub μs length (SPSS concept) or by using the long proton pulses directly for neutron production and producing the desired short pulses by mechanical neutron choppers familiar from TOF spectroscopy on CW sources (Long Pulse - LPSS - concept). After a detailed analysis of the advantages and drawbacks of both methods one arrives to the conclusion that the LPSS approach to the production of short neutron pulses is largely superior to the conventional SPSS approach for cold neutrons (higher flux, better resolution, better flexibility) and significantly superior for thermal neutrons. On the other hand, the SPSS approach is only superior for hot and epithermal neutrons, i.e. in not more than 25% of current neutron scattering research and in none of the work currently performed on CW reactor sources (see appendix I.). The main reasons for this situation are

a) The costs for adding storage rings to a linac doubles the investment volume for the same average beam power. (Additional costs: ring accelerators, the need to have two target stations for optimal use instead of one, and the modifications of the linac with respect to the injection: H^- source instead of H^+, necessity of linac beam chopping, output beam shaping). At constant investment this implies a lowering of the average beam power by a factor of about 4 on a SPSS. The higher electricity bill of the LPSS will possibly be compensated for by the lower maintenance and operating costs due to the smaller number of components in the facility. In addition the storage rings operate at the space large limit, and so there is little room for further improvements even in the more distant future.

b) The neutron moderation times in an optimal reflector ensemble are several 100 μsec long.Thus the compression of the proton pulse does only implies the compression of the neutron pulse to this limit. The production of shorter neutron pulses by introducing neutron absorbers into the moderator–reflector ensemble reduces the time average neutron flux.

c) Modern choppers can provide pulse lengths comparable to the shortest ones obtainable on thermal moderators on a SPSS (about 20 μsec) and shorter than those which can be achieved for cold neutrons on a cold moderator (about 70 μsec).

d) Hot and epithermal neutrons are not thermalized in a spallation source (except if one would install a hot source). They are produced by direct collision slowing down with typical time constant in the range of a few μsec. Therefore the neutron pulse compression is much more efficient here than for thermalized beams. On the other hand, in the same energy range the time averaged thermalized flux is an order of magnitude superior to the slowing down flux, e.g. for thermal neutrons from a thermal moderator (thermalized regime) compared to thermal neutrons from a cold moderator (slowing down regime).

Thus the rationale behind the LPSS approach is entirely accelerator physical, and it is due to the up to date inevitable use of coupled cavity linacs for beam acceleration. Other accelerator concepts are aimed at accelerating the short pulse beam directly, but the rapid cycling synchrotrons are only competitive below 1 MW average beam power and the induction linac and fixed field alternating gradient synchrotron proposals are not well establishled yet.

4. Limitations of the energy per pulse

Adding pulse compression storage rings to a linac not only reduces the beam power at constant total expenses by the necessity of sharing the investment between the linac and the additional expensive accelerator equipment, but the current technical limits on proton beam energy per pulse are much lower for short pulses than for long ones.

The three factor limiting the energy in short pulse sources are: space charge limitations in the rings, the use of more current limited H^- ion source in order to allow for the stripping at injection and the shock waves in the target. The reference value, 100 kj per pulse in the ESS study has been shown to be eventually feasible leaving still some questions open on the shock waves. The energy limiting factor in long pulse sources is the heat deposited in the target in a single pulse and the peak linac power since an upper limit of the pulse length is desirable. For the heat capacity of heavy metal target materials the temperature increase of the target in a single pulse attains a potential upper limit of 300 °C at 600–1200 kj per pulse, for a proton beam energy between 1 and 2 GeV, respectively. This pulse energy can be achieved at currently envisaged linac proton currents of about 4 msec pulse length.

5. Options for next generation neutron sources

In contrast to SPSS long pulse spallation sources (LPSS) perform rather similarly to CW reactors in various applications. An LPSS can in fact be considered as a CW source, which is only switched on for about 10% of the time (at pulses 1–3 ms long). Thus compared to the ILL a 1 MW average power LPSS (such as proposed by Los Alamos) will provide 4–6 times lower average flux than ILL, while in comparable resolution TOF experiments its flux will be 2–3 times higher than that available at ILL (see first assessment from the Berkeley LPSS workshop, April 1995, appendix II). Note, that a LPSS cost equivalent to ILL would provide about an average power of 4 MW, i.e. performances in the range having been expected from the abandoned ANS reactor project. This similarity between the LPSS performance spectrum and that of a reactor implies that the same kind of complementarity exists between SPSS and LPSS sources as the well known complementarity between SPSS and CW reactors. The performance of a cost equivalent pair of LPSS and SPSS will be complementary very much in the same way as ILL and ISIS relate to each other.

High power SPSS and LPSS need a powerful linac. It is technically feasible for the two facilities to share this linac (and this is actually planned at Los Alamos). Beyond savings related to the same site, this solution is more economic than building two equivalent independent sources. The optimization of the common performance of a combined facility will lead to sharing the linac power in about a ratio of 80%–20% between LPSS and SPSS use, respectively, which reflects the proportions in the use of cold, thermal and hot/epithermal neutrons and also the current technical limitations of the energy delivered per pulse in both cases.

The capabilities of the next generation spallation sources based on current technological potentials can be summarized by the following rather conservative options:

1) An enhanced power SPSS can provide more than 10 times higher neutron fluxes than ISIS for all applications.

2) A high power LPSS can provide more than 10 times higher neutron fluxes than ILL in all neutron scattering experiments. (i.e. with the exception of irradiation type work). These two sources, 1) and 2), are roughly cost equivalent.

3) A combined SPSS and LPSS facility with a common linac allow for achieving both performances 1) and 2) at a cost level lower than the sum for two seperate facilities.

6. LPSS use of the ESS reference linac

The linac design worked out in the framework of the ESS study is optimized for SPSS use, i.e. H^- instead of H^+, and beam parameters optimized for injection. Nevertheless, by simply supressing the proton beam chopping and prolongating the linac pulse from 1.2 msec to 2 msec, the energy per pulse can be increased from 100 kj to 270 kj. A LPSS target station with optimized target–reflector design will provide a peak neutron flux in the pulse (135 peak power) which is about 20–25 times superior to ILL. At a repetition rate of 50 Hz (10% duty factor) this corresponds to 13.5 MW and 2–2.5 times the average flux of ILL. In order to optimize for the fully moderated neutron production, Hg cannot be used in the target because of its high absorption of thermal neutron. A Ta or W target could be envisaged instead, for which this power level should be feasible with about 20% of the volume occupied by the D_2O coolant. For LPSS operation a single target station with two moderators, one cold and one thermal, are sufficient for at least 40 beam ports (most of them guides, placed at an angle of about 5 ° from each other). Compared to the short pulse ESS reference design, the average flux in the LPSS will be about 4–5 times higher at equal repetition rate than the short pulse high intensity moderators (factor 2.7 from the larger power, the rest from the optimization for maximum average flux, e.g. absence of Hg, two moderators per target station instead of 4, stronger reflectors) and a peak flux, which is about equal to that of the short pulse high resolution moderators. The overall performance will correspond to a flux of 10–20 times of ILL in neutron scattering work with a pulsed time structure gain factor of 4–8 over the average flux in various kinds of experiments.

7. Optimization of ESS using long pulses

A sizable fraction of instruments considered for the ESS in its reference version (cf. appendix III.), i.e. SPSS with two target stations, A: 4 MW at a repetition time of 20 msec and B: 1 MW at a repetition time of 100 msec, would perform only equally or marginally better than existing instruments at ILL. This kind of planning can be justified if ESS is intended to be used in a complementary way to an ANS class reactor or a high power LPSS, although in this case it is questionable to include these instruments at all. The worst served instruments will be those planned for the high intensity cold moderators on target station B. These instruments could directly benefit from the integrated flux increase per pulse achievable by replacing this target station by a long pulse one fed directly by the linac by 2 msec non–chopped pulses. Furthermore nearly all instruments planned for the 1 MW target station could benefit from a higher repetition rate. If the linac pulses are shared by a 25 Hz 2.5 MW SPSS and a 25 Hz 6.75 LPSS target station, the instruments on the 4 MW target will loose neutron flux by a factor of 1.6 at worst. For some of the diffractometers this loss will be lower, due to the fact that they can accomodate a larger wavelength band at a repetition time of 40 msec than at 20 msec. All instruments using neutron wavelengths longer than 1.5 Å could actually be improved by lowering the repetition rate. State of the art neutron guides allow to increase the moderator to sample distance on these instruemnts by a factor of two without reducing the beam divergence. This would either be beneficial for the resolution or (if all instruemtns on the cold, high resolution moderator are pulled back) the moderator pulse length can be enhanced and hence the beam flux per pulse can be increased by a factor of two at equal resolution. Together with the gain in background this would more than compensate for the loss of 3 pulses out of 8. This loss will ultimately only apply to isntruments using hot/epithermal neutrons.

All instruments planned for the high intensity cold moderators on the SPSS 1 MW source will gain essentially in proportion of the time average flux gain, i.e. by a factor of 10–12. The 20 to 40 Å wavelength band obtained in the 10 Hz operation is not fully useful, and the 8 Å band obtained at a distance of 20 m and 25 Hz is sufficient. Of course, slow, 25–50 Hz choppers defining the wavelength band are requied here in the spirit of LPSS instrumentation, which will have to be placed outside the bulk shielding. The three μeV resolution spectrometers (backscattering) will require choppers for pulse shortening. These choppers will limit the wavelength band to about 1.8 Å if placed at a distance of 4 m from the moderator, and to about 1 Å, if placed outside the bulk shielding. This kind of band is sufficient for most high resolution studies. With equal peak flux on the LP target these instruments will gain flux in proportion to the increase of the repetition rate (2.5) and also gain resolution capability due to the shorter pulses achievable by disc choppers and the increased flexibility because the pulse lengths of the choppers are tunable.

All cold neutron instruments for spectroscopy planned for the 4 MW SP target station will gain resolution capability and tunability (and eventually also intensity if repetition rate multiplication can be used) by switching to the 25 Hz LP target station. This leaves room for moving the high resolution powder diffractometers to the 25 Hz SP target station, which will still provide a sufficient wavelength band for fully efficient operation, i.e. improve performance by the increase of the repetition rate.

In Appendix III instruments expected to gain in flux by replacing the two SP target stations by one 25 Hz (2.5 MW) short pulse target station and one 25 Hz (6.7 MW) long pulse target station are marked by two stars for an expected gain larger than 5 fold, and by one star for a gain of more than 2 fold. No instrument stand to loose more than a factor of 1.6. Thus one concludes that sharing the linac pulses between one SPSS and one LPSS target station, without any further optimization of the linac design, improves the overall performance of ESS even for the set of instruments projected for the SPSS use only.

8. Combined long pulse – short pulse facility

In chapter 6. we have seen that an LPSS, even with a non–optimized linac designed for SPSS use can boost neutron fluxes in scattering experiments to more than 10 times higher levels than available at the best current reactor source. In chapter 7. we found that sharing the ESS linac beam between a 25 Hz SPSS and a 25 Hz LPSS target station considerably improves the overall neutron scattering performance of the facitlity for the planned suite of instruments compared to the reference SPSS only use. Both of these lines of arguments stress the potentials of combined LPSS – SPSS facilities.

The economy realized by the common use of a linac is substantial, but not overwhelming. The reason for this is that different optimizations are required for the two cases. The complete realization of a cost equivalent pair of high power LPSS and SPSS on a common linac (i.e. LPSS average power 4 times higher than that of the SPSS) would come to about 85% of the total costs of the two facilities realized independently of each other, without considering the economics resulting from the common site (cf. ILL–ESRF).

Furthermore, if one takes consequent advantage of the complementarity of the LPSS and SPSS approaches (i.e. putting all instruments on the best suited type of source and not trying to set–up a complete suite of instruemnts on each of the two sources) the combined approach becomes much more attractive and economic. Thus the SPSS part would be built with a single target station optimized for high resolution moderators operating in the slowing down regime (both thermal and cold) and the LPSS part would be optimized for fully thermalized thermal and cold moderators providing optimal average flux and at least equal peak flux compared to the SPSS target station for cold and thermal neutrons. The LPSS power should be about 4 times that of the SPSS power and about 2/3 of the instruemnt (of a total of about 60 possible) should be on the LPSS. Instruments on the LPSS target will cover the type of experiments currently doing best on a reactor source, while the SPSS will provide for the work currently done best at a spallation source like ISIS. The following relative cost estimates for the various combinations of ESS system components are based on the costs quoted for various ESS items in percentage of the total project.

	Source design	Relative costs
a)	ESS reference design: SPSS 40 p/sec, 4 MW SPSS 1 Hz, 1 MW	100 %
b)	ESS linac only: LPSS 50 Hz, 13.5 MW	80%
c)	ESS linac shared: SPSS 25 Hz, 2.5 MW LPSS 25 Hz, 6.7 MW	115%

Note: The reduction of the repetition rate at equal energy per pulse (option c) does not systematically reduce performance proportionally. Some power loss is compensated for by the improved wavelength band at constant source – sample distance (cf. also chapter 7). Option b) and c) are not optimized, i.e. the linac is assumed to stay identical to the design optimized for option a).

Literature:

— Proceedings of the Workshop on Neutron Instrumentation for a Long–Pulse Spallation Source (Lawrence Berkeley Laboratory, University of California), April 1995

— Proceedings of ICANS–XIII, Paul–Scherrer–Institut, Villigen, Switzerland, October 1995.

Appendix I.

F. Mezei, 15. 12. 1995

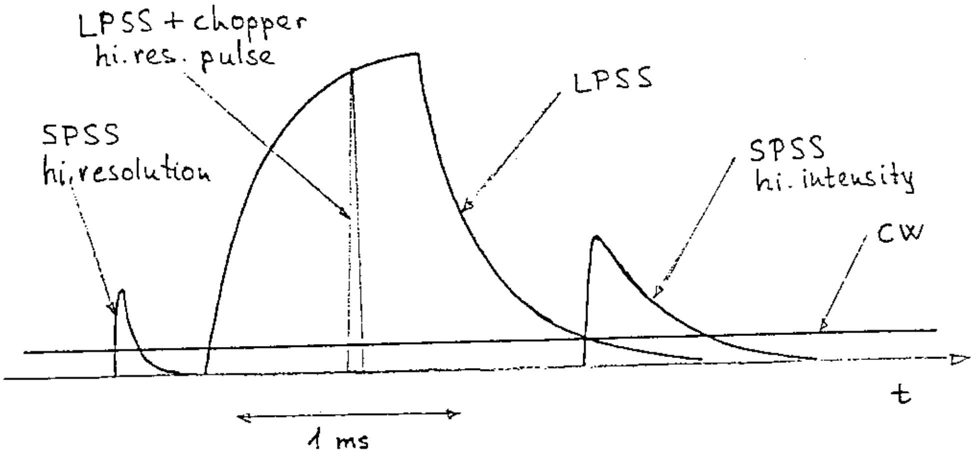
Comparison of neutron fluxes of cost-equivalent sources

CW: reactor source 60 MW (ILL)

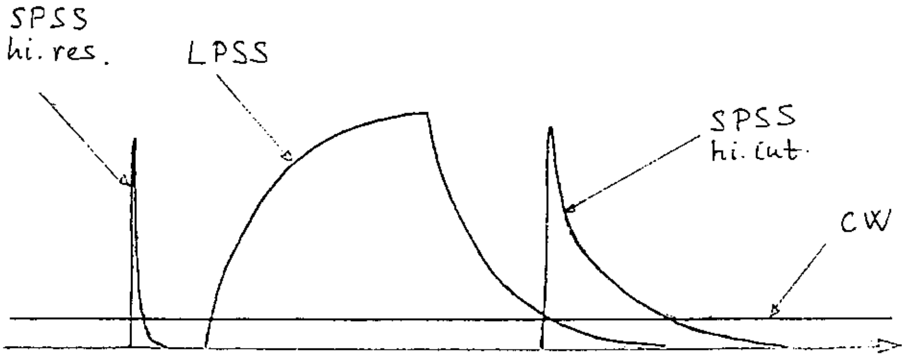
SPSS: 0.67 MW short pulse spallation source: one of the two target stations of a 1 MW, 60 Hz source

LPSS: 4 MW long pulse spallation source, 60 Hz, 6.7 % duty factor

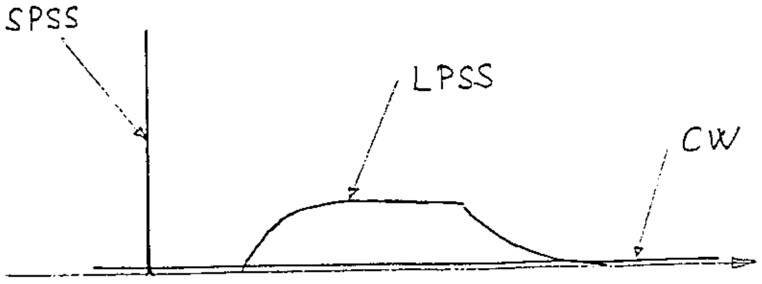
Cold neutrons



Thermal neutrons



Hot neutrons (~0.5 A) hot moderator assumed for CW and LPSS (guessed performance), without hot source: ~10 times smaller flux for CW & LPSS



Appendix II. From Berkeley Workshop Proceedings (April '95).

Spectrometer Type	Typical Science	Equiv ILL Instr.	Equiv ISIS Instr.	Neutron Energy	1 MW LPSS Performance*	Comments
Small Angle Scattering	structure of macromolecular assemblies					
- 20 m flight path; 10 Å wavelength		D22	LOQ	cold	0.6 x ILL	
- 20 m flight path; 6 Å wavelength		D22	LOQ	cold	1 x ILL	
Reflectometer	density profiles of layered structures	D17	CRISP	cold	3 - 5 x ILL	
Powder Diffraction	atomic structures of polycrystalline materials					
Low Resolution Powder Diffraction		D7		cold	0.5 - 1 x ILL	For powder diffraction, gains over ILL
Medium Resolution Powder Diffraction		D16		cold	6 x ILL	performance are already available at
High Resolution Powder Diffraction		D2B	HRPD	thermal	3 - 4 x ILL	existing short-pulse spallation sources
Amorphous Material Diffraction	atomic coordination in glasses	D4	LAD	hot	0.6 x ILL	for thermal and hot neutrons.
Single Crystal Diffraction						
Laue Diffraction	protein crystallography			thermal	1 x ILL	comparison is with Laue instr. at ILL. Gains
4-circle (small unit cells)	crystal structures for small unit cells	D8	SXD	thermal	1 x ILL	relative to traditional instr. are higher
Diffuse Scattering	lattice distortions, defects	D7		cold	3 - 4 x ILL	
Crystal Analyser Spectrometer	high energy molecular spectroscopy	IN1B	TFXA	hot	not feasible	Use conventional SPSS
High Energy Spectroscopy	high energy collective excitations	IN1	HET, MARI	hot	not feasible	Use conventional SPSS
High Resolution Inelastic Scattering	diffusion, tunnelling, magnetic excitations, 3-He					
- multi-chopper spectrometer		IN5		cold	2 - 4 x ILL	gain depends on useful dynamic range
- time focussed TOF spectrometer		IN6		cold	1.6 x ILL	
- backscattering (1 μeV resolution)		IN10		cold	0.25 - 4 x ILL	gain depends on useful dynamic range
- backscattering (10 μeV resolution)			IRIS	cold	2.6 x ISIS	
- backscattering with MUSICAL mono.				cold	2.5 - 4 x ILL	
Neutron Spin Echo	diffusion; polymer & spin glass dynamics	IN15		cold	1 x ILL	better dynamic range & Q resoln. for LPSS
S(Q,E) Spectroscopy	magnetic excitations; glassy dynamics	IN4C	HET	thermal	0.4 - 5 x ILL	gain depends on resolution required
Conventional Three Axis Machines	limited scans of collective excitations					
Cold Neutron TAS		IN14		cold	0.4 x ILL	Detector gating reduces background and
Thermal Neutron TAS		IN8		thermal	0.2 x ILL	increases performance at an LPSS by a
Hot Neutron TAS		IN1		hot	0.2 x ILL	further factor of 1 to 7 for all TAS.
Augmented Three Axis Machines	extended scans of collective excitations					
Multi-Analyser TAS (RITA)			PRISMA	cold	0.7 - 5 x ILL	gain depends on resolution required

* Compares count rates for "optimal" spectrometers at existing sources and the benchmark 1 MW LPSS for equal resolution in the important dimensions of (Q,E) space

Appendix III.   J L Finney 13.3.95

Target A : 4 MW

Instrument type	Moderator	Flight Path (m)
Diffraction:		
High intensity diffractometer	A HR	10
High intensity diffractometer	A HR	15
Strain measurement diffractometer	C HR	15
Liquids and amorphous diffractometer	A HR	10
Liquids and amorphous diffractometer	C HR	15
Single crystal diffractometer	C HR	15
Special sample environment instruments		
- High pressure diffractometer	A HR	10
- High (pulsed) magnetic field diffractometer	C HR	10
Diffuse & critical scattering diffractometer	C HR	10
Polarised neutron diffractometer	C HR	10
Spectroscopy:		FP1, FP2
Single crystal spectroscopy:		
Chopper spectrometer	A HR	10, 6
Chopper spectrometer	C HR	10, 4
Crystal analyser spectrometer	C HR	10
Polarised chopper spectrometer	A HR	10, 4
Polarised crystal analyser spectrometer	C HR	10
Spectroscopy in polycrystalline materials:		
Chopper spectrometer	A HR	10, 4
Chopper spectrometer	C HR	10, 4
Polarised chopper spectrometer	C HR	10, 4
Molecular spectroscopy instrument	A HR	20
Nuclear Physics		
High Resolution Beamline	A HR	50

Total : 20   AHR - 9   CHR - 11   Elastic - 10   Inelastic 9   NP - 1.

Target B : 1 MW

Instrument type	Moderator	Flight Path (m)	
Diffraction:			
* High resolution diffractometer	C HR	75	g*
Ultra-high resolution powder diffractometer	C HR	150	g
* Magnetic structure powder diffractometer	C HR	50	g
* Magn^c structure SX diffractometer (polarised)	C HR	20	g
Large unit cell single crystal diffractometer	C HR	50	g
** Small angle scattering instrument	C HI	20	g
** Small angle scattering instrument	C HI	20	g
** Polarised small angle scattering instrument	C HI	15	g
** Reflectometer	C HI	10	
** Reflectometer	C HI	15	
* Reflectometer	C HR	15	
** Polarised reflectometer	C HI	10	
* Polarised reflectometer (e.g. thin films)	C HR	15	
Spectroscopy:			
* µeV resolution spectrometer	C HR	40	g
* µeV resolution spectrometer	C HR	100	g
* Polarised µeV resolution spectrometer	C HR	40	g
** Neutron Spin echo	C HI	40	g
Nuclear Physics			
** Interferometer	C HR	10	
* Nuclear Physics Beam	C HR	50	g
** Nuclear Physics Beam	C HI	7	

*g = guide

Total : 20. CHI - 8; CHR - 12; Guides- 13; Elastic - 13; Inelastic 4; NP - 3;

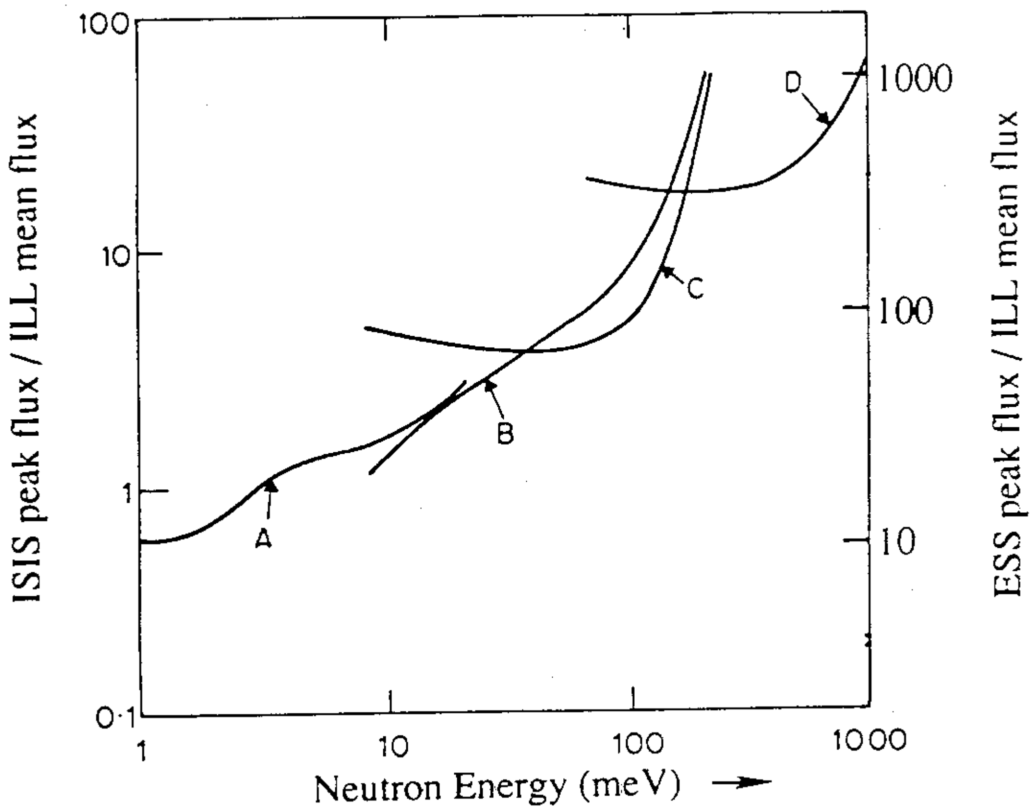


Figure 1. *A plot of the ratio of the peak flux of a pulsed source to the average flux of a reactor as a function of neutron energy. The left hand abscissa refers to the ISIS peak flux at 180 µAmp and the ILL average flux at 57 MW. Curve A is the ISIS liquid* H_2 *moderator and the ILL cold source. B is ISIS liquid* CH_4 *and ILL ambient. C is ISIS* H_2O *and ILL ambient. D is ISIS* H_2O *and ILL hot source. The right hand abscissa illustrates the ratio of the ESS peak flux to the ILL average flux with a similar set of moderators.*

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COMPLEMENTARITY OF LONG PULSE AND SHORT PULSE SPALLATION SOURCES

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ABSTRACT

The complementarity of short pulse spallation sources (SPSS) and steady state (CW) reactors is a widely accepted concept. SPSS and long pulse spallation sources (LPSS) are complementary in two ways: a) in their performance in neutron scattering experiments LPSS closely emulate CW reactors. In this respect two facets of the time–of–flight (TOF) monochromator method adequate for LPSS will be discussed: the superiority of the TOF approach to the crystal monochromator method in high resolution powder diffraction, and the novel technique of repetition rate multiplication in TOF spectroscopy. b) LPSS combined with adequate chopper systems can also emulate SPSS in a number of applications. It will be shown that the LPSS method of producing short neutron pulses is more efficient for cold and thermal neutrons (below an energy of about 100 meV), while SPSS is the more favourable approach for hot, epithermal neutrons, i.e. in the slowing down regime in contrast to the moderated regime. These two aspects of complementarity of LPSS and SPSS lead to the conclusions that for about 75% of the spectrum of neutron scattering experiments as known of today the LPSS approach is the most advantageous one with a feasible neutron intensity exceeding that available at ILL by a factor of about 30, while for the remaining 25% of applications the SPSS technique is superior with a well–known potential of a similar gain over present day performances.

1. Introduction and Overview

The complementarity of SPSS and CW reactor sources can be illustrated by comparing two facilities of roughly the same costs. The FRM-II 20 MW reactor project (Munich) and the AUSTRON 200 kW spallation source project (see report given at this meeting) happen to represent such a pair. The projected time averaged flux in the epithermal (slowing down) neutron range is equal for both facilities, while FRM-II should provide

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Keywords: long pulse source, complementary, powder diffraction
TOF- spectroscopy

a moderated thermal and cold average flux which is an order of magnitude higher than that of longest pulse length moderators (some 150 μs for thermal and 1 ms for cold neutrons) at AUSTRON. On the other hand, AUSTRON at a repetition rate of 25 Hz and with a pulse width of less than 10 μs in the slowing down regime should outperform FRM-II in respect of the peak flux by a factor of more than 4000, while for thermal and cold neutrons independently of the moderator type the gain "only" amounts to a factor of 30 and 4, respectively. These flux relations, as well known from several studies (cf. Abingdon workshop on ESS), make AUSTRON about an order of magnitude inferior for white beam irridiation and fixed wavelengths experiments (such as interferometry) and comparable or vastly superior to FRM–II in the rest of neutron scattering work (e.g. small angle scattering and short wavelength powder diffraction, respectively). This complementary performance in various utilizations is primarily due to the huge variation of the ratio of the peak fluxes of both facilities with the neutron energy.

In contrast, for a LPSS facility, due to the fact that the pulse length (which is in the ms range) is constant, the neutron wavelength dependence of the peak flux follows that of the average flux, i.e. it is rather similar to a reactor (with an enhanced slowing down range though). The difference between a CW and long pulse source resides in the potential for *more efficient utilization* of the average flux of the latter. The clue to this efficiency is to use a neutron monochromatization technique which only needs the source to be on for a limited time, i.e. some 10% of the total time. By the TOF wavelength band monochromatization technique a quasi–continuous monochromatic beam can be produced on the sample, which has about the same time averaged intensity as that on a CW source with a flux equal to the peak ("on") flux of the LPSS. However, there is one major difference: At the CW source we have a constant wavelength all the time, while on a LPSS we will have a well defined wavelength at any given time, which changes periodically within a more or less narrow band. The width of the wavelength band can be adapted to the various types of experiments, but it has to be at least $\delta\lambda/c$, where $\delta\lambda$ is the wavelength resolution aimed at, and c the duty factor of the source. The efficiency of the use of LPPS is thus determined by the relative merits of performing a given experiment with a series of adjacent wavelengths for the same total period of time instead of using a single wavelength all the time. If several different wavelengths, i.e. different intensities and resolutions, are used the experimental procedure requires an adequate combination of the information obtained at various wavelengths, and not only the simple summation of raw spectra. This kind of *information processing*, as opposed to *input data processing*, is usual in high energy physics experiments, and it is getting more and more common in the work at SPSS facilities, but it is still quite unusual at CW sources. The two examples of employing TOF monochromator techniques instead of the usual single wavelength approach at CW sources discussed below show, that the multiple wavelength approach can a) be largely superior in some, rather obvious cases or b) still be favourable or competitive in other cases, where this would not be expected on the basis of conventional wisdom.

The example for a) is high resolution powder diffraction, where the larger acceptable solid angle of the detector in the TOF approach is clearly advantageous. The case study for b) concerns TOF spectroscopy. The straightforward transfer of CW source TOF spectroscopy to pulsed sources is known to be disadvantaged by being tied to the repetition rate of the source, which is too low in most cases. If one accepts to use more than one wavelength (repetition rate multiplication), the same freedom of choice as on a CW source is regained in respect to the choice of the repetition rate. It will be shown below for a specific example that the multiple wavelength approach can offer a competitive (and actually better) information collection rate than the conventional single wavelength method. In most cases this new proposal of multiplying the repetition rate removes one last technical disadvantage that pulsed sources (short or long) were perceived to have in comparison to CW sources. Thus, with LPSS sources with an average power of 10 to 20 MW now appearing well within reach (cf. the 135 MW "on" linac power without proton beam chopping of the ESS reference design) the LPSS approach offers a capability to achieve average neutron intensities on the sample, which are 20 to 40 times higher than that of ILL for all neutron scattering applications.

Beyond the complementarity between LPSS and SPSS, which is due to the similarity of LPSS and CW reactors, there also is a technical complementarity in another respect: It turns out that it is more efficient to produce short pulses of cold and thermal neutrons by fast choppers on a LPSS than by a SPSS. The fundamental reason for this are the long moderation times for maximum time averaged flux moderator–reflector ensembles. Quite similarly to mechanical choppers the pulse length can only be shortened by taylored, short pulse moderators at the expense of the total neutron flux and to some extend also at the expense of the peak flux. If we thus consider a pair of a SPSS and a LPSS, which represent about the same investment, the technically less demanding LPSS will display some four times higher average power, mainly due to the higher "on" power of the linac operating without beam chopping and eventually with H^+. Beyond substantially higher peak fluxes for cold neutrons and comparable ones for thermal neutrons, the LPSS approach with choppers also offers more flexibility in the choice of pulse lengths, leading to improved resolution for cold neutrons in view of the shortest SPSS moderator pulse of 100 μs. Furthermore, present instrumentation concepts for SPSS favour short target to sample distances, and thus lead to the necessity to split the accelerator power between two target stations, which amounts to a flux reduction on all instruments. The TOF monochromator approach for LPSS instrumentation often calls for the use of neutron guides of substantial length (20–100 m), so that there is room for many instrument positions on a single target station. In sum, SPSS offer the most efficient way to produce short neutron pulses in the epithermal neutron energy range via the slowing down mechanism. (On a cold moderator the slowing down regime extends somewhat into the thermal energy range.) This mechanism provides pulse lengths $\lesssim$ 10 μs. LPSS complement SPSS performances by providing the most efficient way of producing variable length thermal and cold neutron pulses with pulse lengths ranging from 20 μs to several hundreds of μs using state of the art chopper technology.

In what follows various points mentioned in this chapter will be discussed in more detail.

2. Neutron monochromators and the principle of time-of-flight wavelength band monochromatization

In all neutron scattering experiments on a CW source a small, more or less precisely monochromatic fraction of the Maxwellian spectrum of the moderator is selected by eliminating the rest. Actually the precision of this monochromatization determines in nearly all cases the resolution of the experiment. The exceptions are Neutron Spin Echo (NSE) and TOF Fourier Diffraction. The clue of these Fourier methods is exactly the intensity gain achieved by the poor monochromatization required compared to the resolution offered. Unfortunately, such "simultaneous" methods, in which the signal from various wavelengths is detected at the same time and sorted out by signal processing methods standard in other modern experimental techniques (such as Fourier transformation e.g. in pulsed NMR) can only be used in a few special cases with neutrons, due to the inherent quantum noise of neutron signals. Namely neutron scattering spectra contain a very small number of quanta (neutrons) compared to microwave or light signals, for instance, so that the statistical Poisson noise is inevitably large. In simultaneous data processing this leads to masking the low intensity part of the spectra, which contain the hard-to-observe pieces of the information. (This was the reason of the practical abandoning of neutron correlation spectroscopy, a promising idea from the 1960's).

There are basically three types of successful monochromator devices used on CW sources, none of them without substantial drawbacks though. Crystals transmit not only the desired wavelength λ, but higher orders $\lambda/2$ and/or $\lambda/3$ etc. too, which has to be most often removed by a filter. Furthermore, the reflectivity of many crystal monochromators is considerably lower than 100% and the resolution curve shows up long tails. The optimal adjustment of the resolution, requiring a set of exchangeable crystals, is of limited flexibility. Last but not least, crystals also display other scattering processes than Bragg reflection. This often leads to "spurion" signals, which are time consuming and not always easy to be sorted out. Helical slot velocity selectors suffer from none of these drawbacks of crystal monochromators, but they cannot provide comparable resolution due to mechanical limitations of the speed of rotation. They are actually limited to some 5% best resolution and this holds for cold neutrons only. In contrast to these two continuous beam, (CW) monochromators, disc chopper systems of the type of IN5 at ILL provide a clean, tunable beam and to crystals comparable resolution, but only for a fraction of the time with duty factors around 1% or less.

In a neutron scattering experiment on a CW source one starts with choosing an optimal incoming neutron wavelength. This choice is never a unique, single value, it is rather one of many equivalent ones within a given more or less broad wavelength band. Conventionally a single wavelength within this "useful band" is selected for extended data collection periods. In many cases the best compromise between intensity, resolution and dynamic range requirements is, however, achieved by dividing the beam time between runs with several incoming wavelengths within the useful range.

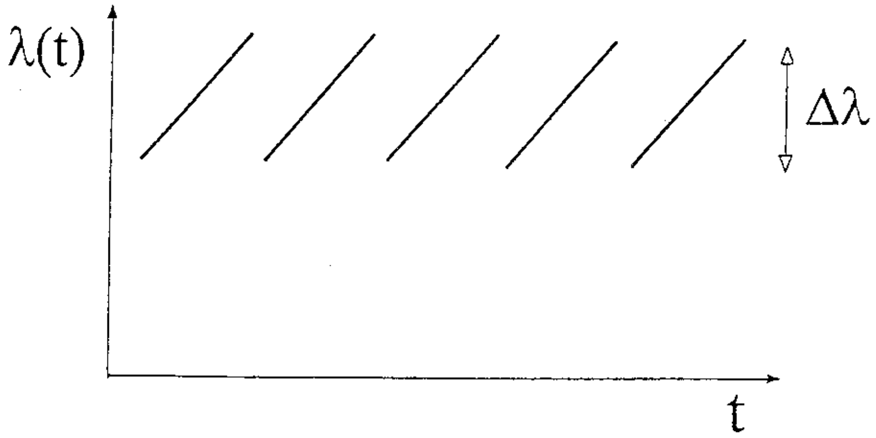


Fig. 1: Time dependence of the wavelength of the monchromatic beam in a TOF monochromator.

The basic idea of the approach of time-of-flight wavelength band monochromatization (TOF-monochromators) is to produce a set of monochromatic wavelengths (within a suitable range) one after the other with an appropriate periodic repetition. A TOF-monochromator provides a monochromatic beam at any instant of time t with a wavelength $\lambda(t)$ and a resolution $\delta\lambda(t)$, with $\lambda(t)$ and $\delta\lambda(t)$ periodically changing in time. Actually $\lambda(t)$ follows a sawtooth pattern within a band $\lambda_{max} - \lambda_{min} = \Delta\lambda$ (Fig. 1). Thus instead of using one single wavelength the measurement is performed with a set of wavelengths stretching over a range $\Delta\lambda$ which is chosen to be fully within the "useful range" so that each wavelength $\lambda(t)$ provides roughly equally useful information. Fig. 2 illustrates how this can be realized with a set of disc choppers [1].On this distance vs. time TOF-diagram the trajectory of an incoming neutron is a straight line with the slope corresponding to the velocity $v = h/m\lambda$.

The essential point is that the TOF monochromator delivers useful neutrons for nearly all the time onto the sample and maintains all the advantages of chopper systems compared to crystals (no higher orders, clean, well defined lineshape without tails, tunable resolution, 100% transmission at the center of the line). The price to be paid for is the more complex data collection (i.e. adding the additional parameter t which labels the various wavelengths $\lambda(t)$ used and combining the information content of data sets corresponding to a set of single wavelength bins $\lambda_1, \lambda_2, ...\lambda_n$). This complexity is, however, rather small compared to state-of-the-art methods in e.g. nuclear physics, and to a large extent well under control on existing spallation souces.

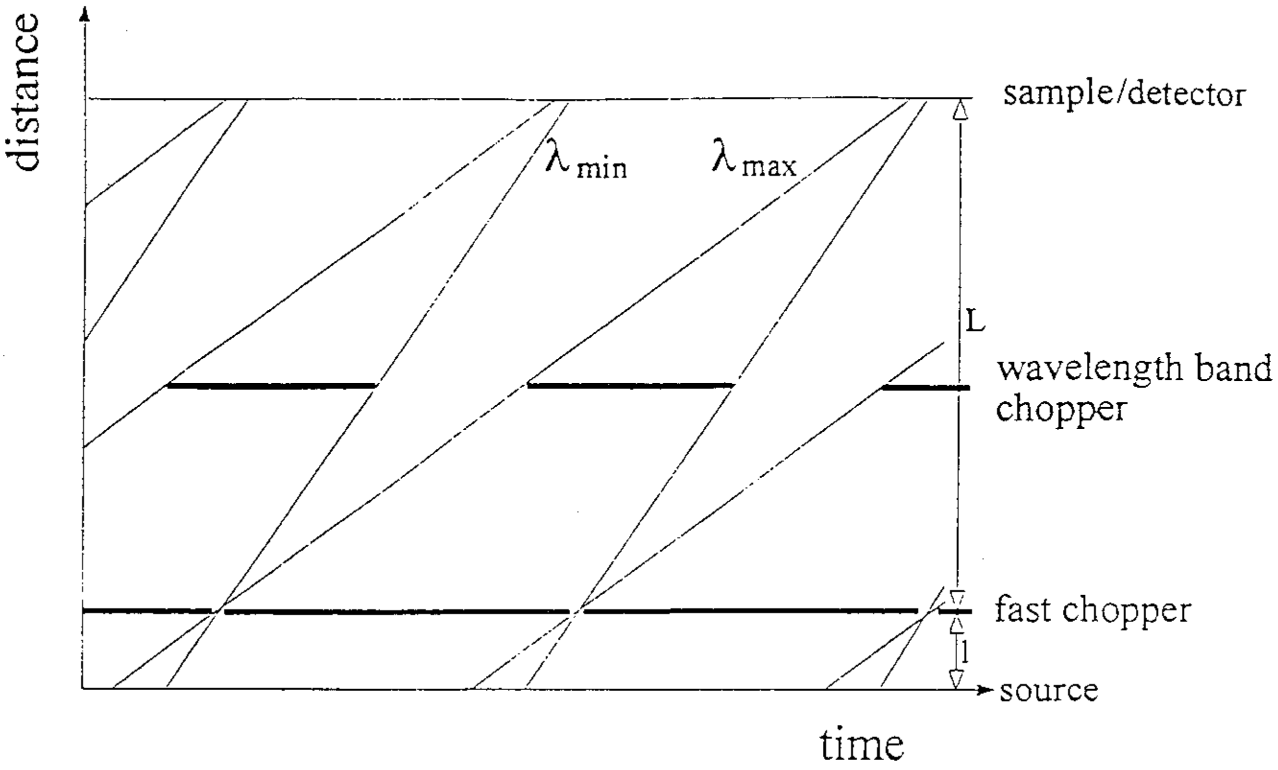


Fig. 2: The principle of TOF monchromators after Ref.[1].

The clue to making the whole wavelength band of a TOF-monochromator uniformly useful is to make it narrow enough. In some cases, e.g. TOF-diffraction as suggested long time ago by Buras [2], this restriction is rather mild since the relevant intensity parameter $\lambda^4\phi(\lambda)$ is flat over a large range of λ (where $\phi(\lambda)$ is the quasi-Maxwellian neutron flux distribution of the moderator). In other cases, such as triple-axis spectroscopy, where one wants to concentrate on a small range of momentum and energy transfer $\vec{q}$ and ω, $\Delta\lambda/\lambda$ might be chosen as small as 10–20%. We will show now, that under the condition of selecting an uniformly useful wavelength band $(\lambda_{min}, \lambda_{max})$ the time averaged flux produced by the TOF monochromator at the sample is equal to that of the CW-monochromator (assuming equal resolution and beam collimations, and neglecting losses such as finite crystal reflectivities, filter absorption etc.) [3]. Indeed:

$$\Phi_{CW} \simeq \phi(\lambda)\delta\lambda \tag{1}$$

and

$$\Phi_{TOF} \simeq c\phi(\lambda)\Delta\lambda \tag{2}$$

where c is the duty factor of the fast chopper in Fig. 2, and it is given as c = δt/t, i.e. the ratio of the chopper opening time δt to the pulse repetition time Δt. On the other hand

$$\delta\lambda = \frac{h}{m}\frac{\delta t}{L}, \qquad \Delta\lambda = \frac{h}{m}\frac{\Delta t}{L} \tag{3}$$

where L is the neutron flight path from the fast chopper to the detector or – in inverted geometry inelastic experiments – to the sample. Thus we find that

$$c = \frac{\delta t}{\Delta t} = \frac{\delta\lambda}{\Delta\lambda} \tag{4}$$

Substituting (4) into (2) and comparing to (1) we get the mean flux (MF) theorem:

$$\Phi_{TOF} = \Phi_{CW} \tag{5}$$

i.e., that the time averaged flux on the sample for the TOF monochromator is the same as that for the conventional CW monochromator of equal resolution (for equal beam collimatimations and neutron transmission efficiencies) if the wavelength band Δλ is narrow enough.

The second half of the previous sentence is the crux of the matter. Without making the band Δλ narrow enough, i.e. working with just one fast chopper and making the repetition rate small enough so that there is no frame overlap between the fastest and slowest neutrons from contiguous pulses (as originally proposed by Buras or actually done on short pulse spallation souces) δλ is not uniformly useful. One reason for this is the strong wavelength dependence of the Maxwellian distribution $\phi(\lambda)$ with eventually the low intensity parts contributing little to the information gathered. Also the strongly λ dependent resolution might limit the usable range. Thus a narrow enough Δλ is a guarantee to make all of it fully useful, which can be achieved by making L long enough and/or Δλ short enough. (This latter choice applies to a CW source, where the chopper system can have any repetition rate mechanically feasible.)

The TOF wavelength band monochromator method can also be applied to generalize conventional TOF-inelastic spectroscopy. Here the difference between CW and pulsed operation is that in the first case the repetition rate is freely chosen as required by the secondary (sample to detector) flight-path. In the spirit of the present approach, however, we can run the monochromator system at a lower repetition rate than that of the analyser TOF system, so that we use instead of one a number of wavelengths in the $(\lambda_{min}, \lambda_{max})$ range, cf. Fig. 2. Thus eq. (5) also holds for this case, meaning that in this approach the flux of a chopper spectrometer is independent of the monochromator/source repetition rate. This solves a longstanding problem in spectroscopy on existing short pulse spallation sources, where the TOF spectrometers are running at the same repetition rate as the source, which is much lower than ideal for this kind of work, e.g. 50 Hz instead of 300 Hz. We will discuss this subject in more detail in chapter 4.

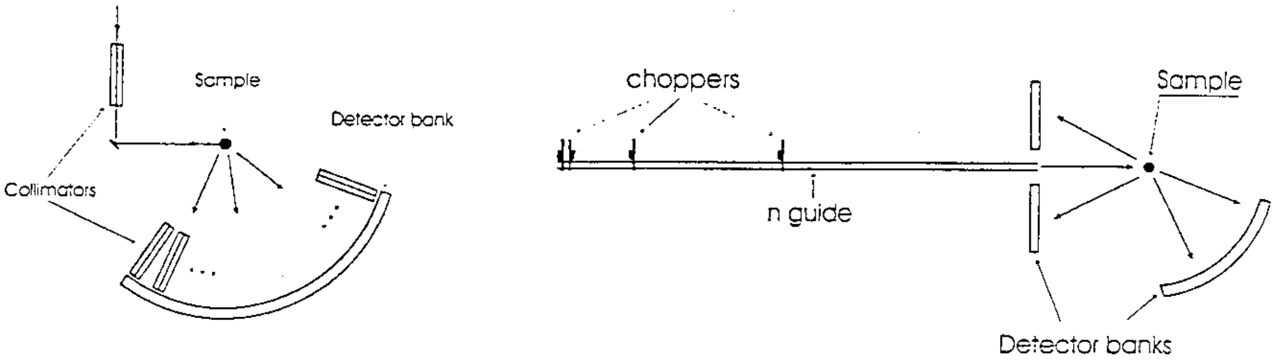
In connection with eq.(5) we used the expression "time averaged flux on the sample". Indeed, what matters for the experiments is the number of neutrons actually hitting the sample at a given angular and wavelength resolution within a given beam time, and not the number of neutrons in the core, target, or moderators. Thus this flux is the relevant number for comparing sources and instruments. In applying these arguments to actual SPSS instruments, we usually observe time averaged fluxes on the sample which are in contrast to LPSS much lower than those corresponding to the peak flux of the source as given by eq.(1), because $\Delta\lambda$ (i.e. L is too small cf. eq.(3)) is much too large. In addition with $\delta\lambda$ determined by the source and moderator ensemble, we sometimes have to work with better than necessary wavelength resolution (e.g. in small angle scattering), which can be avoided on CW and LPSS sources.

3. TOF–monochromator for high resolution powder diffraction on CW sources

High resolution powder diffractometry (HRPD) is one of the most successful ways of utilizing short pulse neutron sources. This is partially due to the excellent peak flux and short duration of the epithermal neutron pulses in the slowing down regime. Although the hot neutron flux on the hot source at ILL is proportionally higher with respect to the thermal flux than on a SPSS, no high resolution monochromatization method is known for hot neutrons on a CW source with a comparable efficiency to the shorter than 10 μs pulses of the SPSS. On the other hand, for thermal and cold neutrons both crystal monochromators and disc choppers give quite satisfactory resolutions on CW sources.

The other clue of the success of HRPD on SPSS has nothing to do with the source: It is due to the advantages of the TOF method itself, as early recognized by Buras [2]. In order to illustrate this point, we consider a detailed quantitative comparison of a crystal monochromator and a TOF monochromator instrument on the same thermal moderator of a CW reactor source. The scheme of the two instruments are shown in Fig. 3.

The crystal monochromator HRPD set–up is assumed to work at a fixed wavelength of 1.5 Å at the monchromator take–off angle of 90°, i.e. giving best resolution due to focussing for the lattice spacing d=1.06 Å. The in–pile collimation is 6' FWHM and the 62 detectors span 7.5°–150° scattering angle in steps of 2.5° with a 6' FWHM collimator infront of each detector. The width of each collimator was assumed to be sufficient to see the whole sample volume. The detectors are 20 cm high and installed at a distance of 1.5 m from the sample. The monochromator has a Gaussian mosaic distribution of 10' FWHM. A natural collimation of 40' FWHM was assumed between monochromator and sample as defined by the beam width and the distance. No losses have been assumed, i.e. the peak transmission of the collimator, the peak reflectivity of the monochromator, the transmission of the higher order filter and the efficiency of the detectors have been taken as 100%. The vertical collimation of the beam impinging on the sample was assumed to be the same as that of the neutron guide of the



Xtal monochromator instrument

TOF monochromator instrument

Fig. 3: Layout of a crystal (left) and a TOF monochromator high resolution powder diffractometer.

TOF instrument specified below, i.e. no vertically curved monochromator assembly has been assumed. We shall discuss this point later.

The TOF monochromator instrument has the following parameters: The pulse length of the counterrotating pair of choppers is 10 μsec, which is achievable for a beam width of 1 cm. The neutron guide follows the "eye–of–the–needle" principle [1] with a beam width of 1 cm at the the entrance and a width of 2 cm towards the sample and for most of its length. The length of the guide is 16 m and it stops 2 m before the sample position. The two single choppers determine the wavelength band which has been choosen to be 1.5–5 Å. At a repetition rate of 50 Hz this implies 12% dead time between successive frames. The detectors are 1.25 cm thick, with an efficiency of 70% at 1 Å. They form banks with a horizontal resolution of 1.25 cm and a hight of 20 cm. (Low resolution banana detectors could be an alternative.) Two banks on top of each other are placed on both sides of the incoming beam in order to cover the scattering angle range of 157°–175°. A third bank covers the low angle range from 15° to 60°. The sample is contained in a flat slab perpendicular to the incoming beam, 0.4 mm thick, 2 mm wide and 10 cm high. No collimators are used, the precision of the scattering angles is determined by the geometry of the set–up.

In Fig. 4 the resolutions for the determination of lattice spacings d and the relative intensities of the two instruments are compared as functions of d. The results were obtained by a complete Monte–Carlo simulation using the above instrumental parameters and the Maxwellian spectrum of thermal neutrons. The dashed lines for the TOF instrument indicate the behaviour for other wavelength bands obtained by shifting the phasing of the third and fourth chopper, e.g. 6.5–10 Å in order to explore

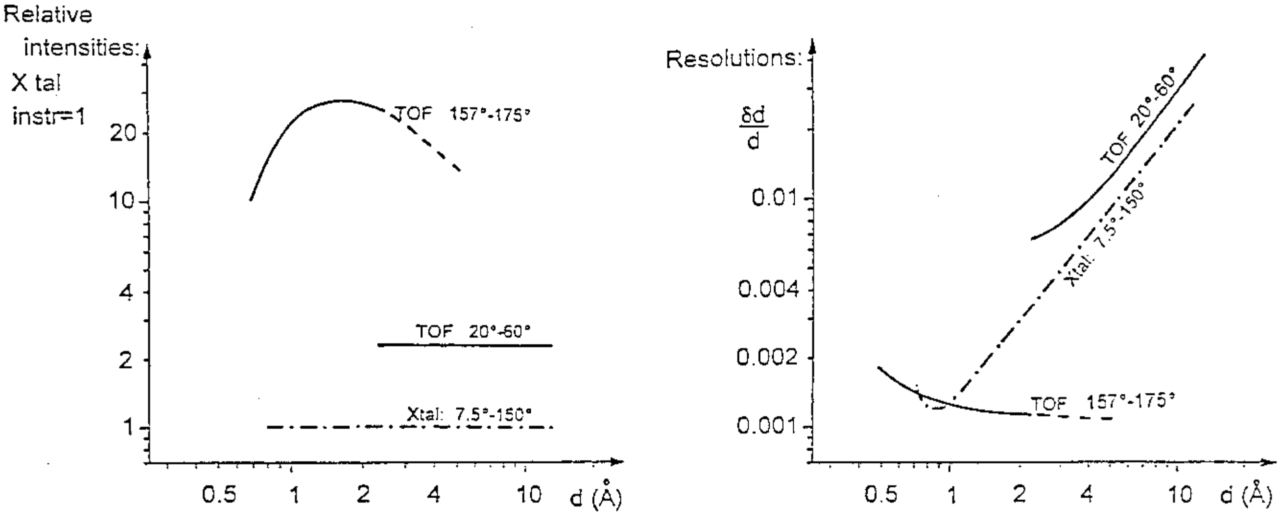


Fig. 4: Comparison of the intensity of the reflections (left) and the resolution as a function of the d–spacing for the crystal and TOF monochromator instruments described in the text.

d spacings in the range of 3.25–5 Å with high resolution. (On the Xtal instrument this would require a change of the monochromator in order to obtain an incoming wavelength of about 5 Å.)

The reason why the intensity offered by the TOF monochromator approach is about an order of magnitude superior can be understood by the following simplified reasoning: The same resolution requires a cruder beam collimation at both, higher scattering angles and longer neutron wavelengths. Therefore it is advantageous to use several wavelengths, since for all reflections data are collected under the best conditions, as opposed to the single wavelength monochromator method which would only allow for the use of the nearly backscattering geometry for an extremely narrow d range (some 2%), compared to 0.75–2.5 Å for TOF. For a given Bragg reflection we have a detector solid angle of 0.16 sterad with a duty factor of $10\mu s/20ms = 0.5 \times 10^{-3}$ with TOF, while the crystal instrument only offers a detector solid angle of 2×10^{-4} sterad with a duty factor of 4% (due to the necessity to scan the detector bank over the 2.5° gap between neighbouring detectors covering 0.1° each).

The intensity offered by the monochromator instrument can normally be improved by using a curved monochromator focussed to the sample. Compared to a flat monochromator without a guide the gain in incoming flux for a small sample (not higher than 2-3 cm) can optimally amount to a factor of 5. However, compared with a TOF monochromator, this gain is largely offset by the finite transmission of the collimators and the higher order filter and the finite reflectivity of the monochromator crystal. In addition by using guides coated with supermirrors on the top and on the bottom or with a vertically converging section in front of the sample some vertical focussing can also be achieved with TOF monochromators, which reach namely some 1° vertical divergence at 2 Å and more at higher wavelengths. Thus, the more efficient vertical beam focussing capability of crystal monochromators on the whole compensates for the higher instrumental losses in this approach compared to the TOF method. This is why in the above comparison both vertical focussing and beam losses were ignored.

4. Repetition rate multiplication and constant $\vec{q}$ TOF spectroscopy

We will now consider in some detail how the main aspects of the TOF monochromator concept can also be applied to IN5 type multichopper TOF spectrometers [4]. The key idea of the TOF-monochromator approach is that the same information can be obtained by using not only a single incoming wavelength, but a set of eventually close wavelengths $\lambda_2 ... \lambda_n$ and combining the information obtained afterwards. Adding a fast chopper to the TOF monochromator set-up just infront of the sample with a repetition rate properly chosen for the TOF energy analysis in the secondary spectrometer and running synchronously with the TOF-monochromator, (i.e. with a frequency being an integer multiple of the that of the monochromator system) we get a set of short pulses with wavelengths $\lambda_1, \lambda_2, ... \lambda_n$, cf. Fig. 5. With each of these wavelengths we obtain a complete TOF spectrum of the sample, and the n spectra will carry essentially identical information if the total wavelength band $\lambda_n - \lambda_1$ is narrow, or eventually – and actually quite often – an improved data collection rate by extending the dynamic range of the data if $\lambda_n - \lambda_1$ is chosen to be substantial. Thus we can also formulate the mean-flux theorem eq. (5) for this case as follows: the mean flux on the sample in a TOF spectrometer of any repetion rate ν installed on a TOF monochromator with a repetition rate ν/n (where n is an integer) is independent of n as long as the wavelength band $\lambda_n - \lambda_1$ is narrow enough

$$\Phi^{(\nu)} = \Phi_{TOF}^{(\nu/n)} \tag{6}$$

This TOF-monochromator – TOF secondary spectrometer combination also offers another new possibility: constant $\vec{q}$ scans on single crystal samples in a single run using TOF technique only, a problem which was deemed to be unsolvable. Instead of phasing the fast chopper in front of the sample to the TOF monochromator system we let it run asynchronously, so that we get TOF spectra with a quasi continuous set of incoming wavelengths (reasonably binned according to the resolution) within the $\Delta\lambda$ wavelength band. The thus obtained 2 dimensional data set $I(\lambda_{in}, \lambda_{out})$ contains many constant $\vec{q}$ energy spectra in an exended 2 dimensional (with detectors covering a large vertical angular range, as usual, 3 dimensional) $\vec{q}$ domain (cf. Fig. 6). The method is mechanically simpler than the TOF monochromator TAS approach described elsewhere [5], although in principle it provides inferior data rates if a single or a small number a constant $\vec{q}$ scans are required due to the additional duty factor loss by the sample-end chopper. This disadvantage could be partially compensated for by the larger solid angles attainable with TOF and by having no reflectivity losses and higher order reflections in the analyser system.

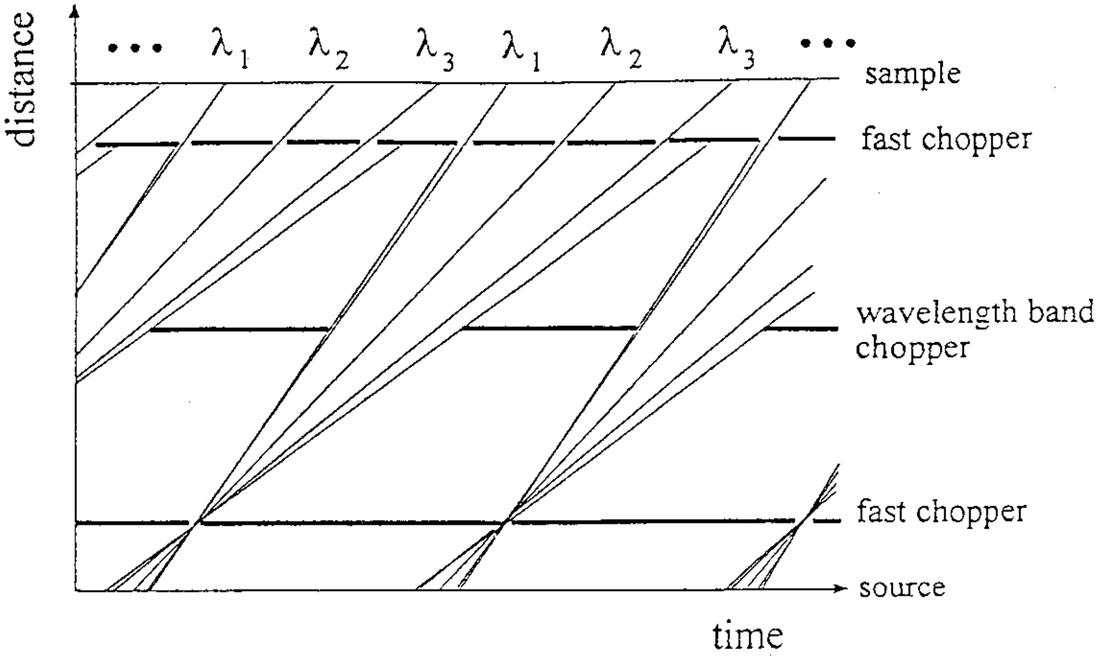


Fig. 5: Principle of TOF monochromator - TOF analyser inelastic spectroscopy with repetition rate multiplication [4].

In order to illustrate the main point of the present approach, i.e. the efficient combination of information obtained with different incoming wavelengths, a model example has been numerically evaluated and the results are shown in Fig. 7. A TOF spectrometer is considered here with a chopper system of the type shown in Fig. 5. The goal of the assumed experiment is to determine the linewidth Γ of quasielastic Lorentzian lines. The continuous line in the Fig. 7. shows the relative statistical error of the determination of Γ obtained in a given measuring time as a function of the ratio of Γ and the width Δ of the triangular resolution function of the chopper system at a chosen reference wavelength λ=2.5 Å, assuming that the two fast choppers in Fig. 5. run at the same repetition rate, i.e. single wavelength conventional operation. The best precision within a given measuring time is obtained at around $\Gamma \simeq 2.7\Delta$, an understandable conclusion. The two dashed curves shows the relative error of Γ obtained by combining (taking the error weighted average of) the Γ values obtained during the same measuring time with the fast chopper near to the source operating at 5 times lower repetition rate (but with the same pulse length), i.e. by taking 5 TOF spectra at 5 different wavelengths. Explicitely these 5 wavelengths were assumed to be 1.5, 2, 2.5, 3 and 3.5 Å. The intensity distribution across these wavelengths was assumed to correspond to a thermal moderator with the peak at 1 Å. The $\delta\Theta$ = const case corresponds to using equal collimations for all wavelengths, in which case the incoming beam intensity changes by a factor of 26 between 1.5 and 3.5 Å. Note, that the information obtained at 3.5 Å is still relevant at small Γ values. In contrast, if

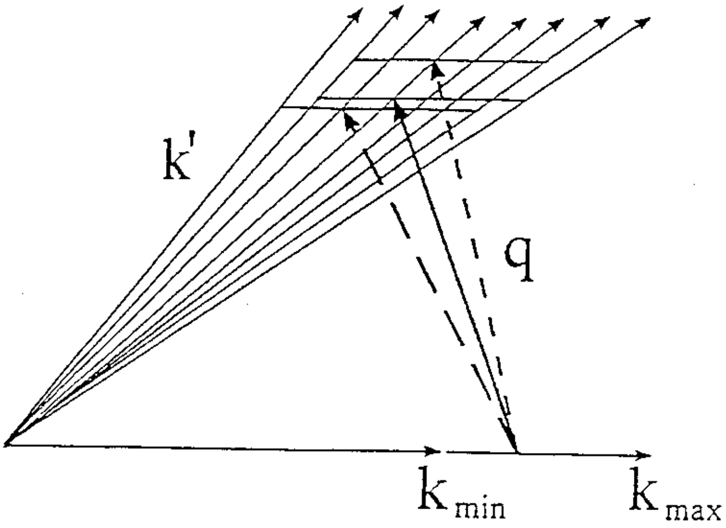


Fig. 6. Constant q scans on a TOF monochromator – TOF analyser inelastic spectrometer. The horizontal bars at the end of the q vectors and equal to the incoming k band represent the constant q cuts across the quasi–continuous set of TOF data at various fixed angle detectors.

constant q resolution is aimed at, a supermirror neutron guide can be envisaged for the incoming beam, and the a matching horizontal angular resolution can be achieved on the detector side by adding the spectra of more or less individual detectors. In this δq = const case (cf. Fig. 7) the incoming flux ratio between 1.5 and 3.5 Å is only 2. The spectrometer resolution in both cases, however, varies by a factor of 13 between the two extreme wavelengths, assuming constant chopper pulse lengths. The results in Fig. 7 clearly show, that the data collection rate on the whole is the same for all 3 cases and that, in contrast to the conventional wisdom, data taken for the same time with very different intensities and resolutions can in a very meaningful way be combined by using proper information processing. (Actually the δq = const curve shows the best characteristics in view of the smaller variation of the precision over a broad range of Γ values.) From the point of view of the time-of-flight wavelength band monochromator concept the fundamental conclusion from Fig. 7. is that quite different wavelengths can be included in a "useful" wavelengths band, which leaves us with a substantial flexibility.

This kind of repetition rate multiplying TOF-spectroscopy offers a new opportunity for the usual short pulse spallation sources too. It allows one to make optimal use of the source flux by being able to use a pulse repetition rate on the sample corresponding to the one optimal for the secondary spectromter, i.e. to the flight path

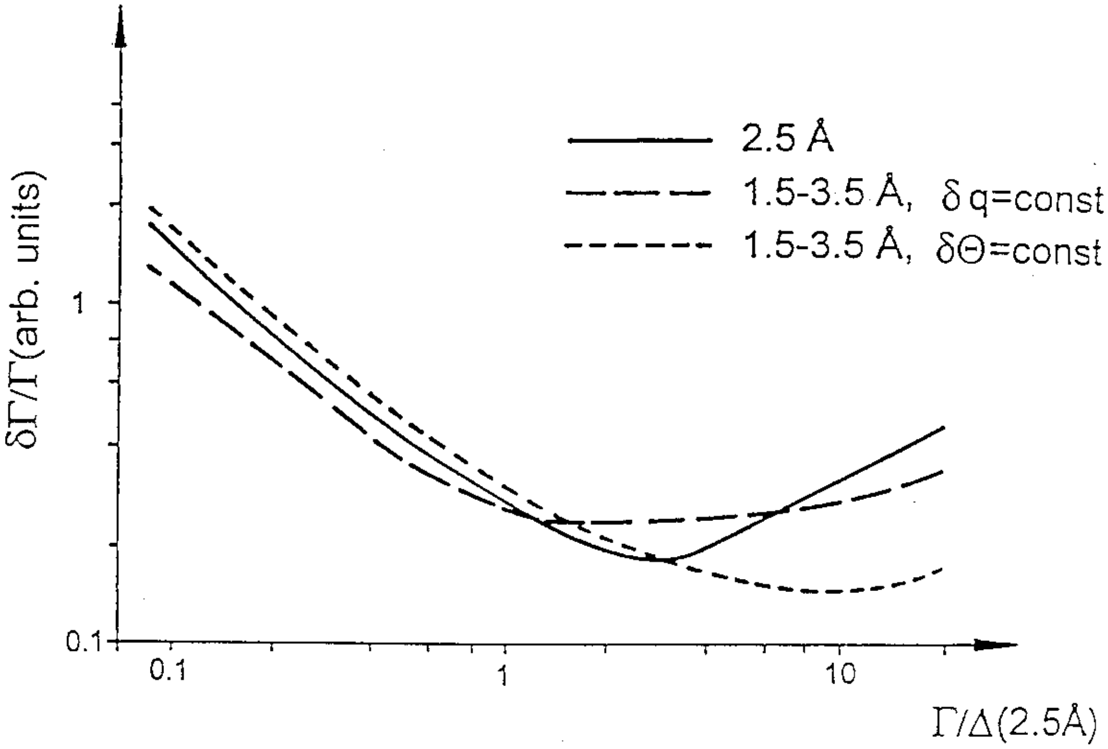


Fig. 7. Comparison of the data collection rates — as characterized by the error of the determination of quasielastic linewidts within a given measuring time — by the use of a single wavelength (continuous line) and five different wavelengths within the limits shown (see text).

of the scattered neutron, as usual on a CW source. The flux gain compared to the conventional use of TOF spectroscopy on SPSS will reach a factor of 5 – 10 in many cases, e.g. by running a spectrometer at 300 Hz on a 30 Hz source.

5. Producing short pulses: SPSS vs. choppers on LPSS

In the slowing down regime, i.e. for hot neutrons the time averaged luminosity of the moderators is to a large extent independent of the type of monochromator: coupled or decoupled, poisoned or not etc. [6]. In this regime the integrated intensity per pulse only depends on the energy per pulse. Thus typical neutron pulse lengths of 10 μs (or less) for sub μs proton pulses mean some 100 times higher peak flux than for an equal energy 1 ms proton pulse. We have to take into account however, that if one works with a linac and a proton storage ring for pulse compression from about 1 ms to 1 μsec, the linac beam chopping necessary for the injection and the injection losses themselves lead to an energy per pulse for the storage ring of about 1.5–1.8 smaller than the one the same linac would produce. Furthermore, if the additional costs for a

H^- source (also necessary for injection) instead of H^+, for the beam chopping device, for the beam preparation for injection, for the ring accelerators and for the two target stations instead of the one sufficient on an LPSS (due to the longer source to instrument distances) are used to build a linac and a long pulse target station of higher power, we will end up with a LPSS of about 4 times higher average power than the more powerful target station of a SPSS of equal costs. This would likely also apply for a 5 MW SPSS vs. a 20 MW LPSS. Thus we can conclude that for a pair of cost–equivalent SPSS and LPSS the peak flux of the epithermal neutron pulses of the SPSS exceeds by a factor of about 25 at low epithermal energies (and more at higher ones) the peak flux of the LPSS. In addition 10 μs FWHM is about the shortest pulse length choppers can produce, so for this neutron energy range the SPSS is clearly superior with respect to both flux and resolution.

The situation is drastically different for moderated (cold or thermal) neutrons. In this range the neutron pulse length on a SPSS becomes dramatically longer due to the moderation time, and the average brightness becomes strongly dependent on the type of moderator and reflector choosen [6]. The integrated neutron flux per pulse increases with the moderator pulse length in a way similar to variable pulse length choppers, and for slow (high intensity) moderators it is typically an order of magnitude higher than for fast (high resolution) ones. With moderation times for high intensity moderators being around 0.5 ms, or more, the peak flux gain achieved by compressing the proton pulse length fom 1 ms to a 1 μs is marginal, and more than off–set by the lower power available at the same costs. Thus the investment in making the proton pulses shorter is counterproductive for cold neutrons, it is more cost effective to produce short cold neutron pulses by choppers on LPSS than by SPSS. In addition, choppers can produce considerable shorter long wavelength pulses than the about 100 μs minimum achievable with tailored moderators. Thus for cold neutrons a LPSS source provides pulses with both superior peak intensity and superior resolution compared to a cost equivalent SPSS.

For thermal neutrons (10 to 100meV) the situation is basically similar to that of cold neutrons, but somewhat more favourable for the SPSS in view of the shorter moderation times. The difference might however be rather small, since time constants in efficient reflectors for thermal neutron production are not much shorter than those for cold neutrons [6]. Although this case has to be studied more in detail, one can expect the peak thermal fluxes to come out about equal for the above defined cost–equivalent LPSS and SPSS sources. The greater flexibility of disc chopper systems, their more favourable lineshape and the higher resolution (shorter pulse lengths) they offer are, however, a clear advantage for the LPSS approach in the production of short thermal neutron pulses, too. (Note that with the exception of TOF inelastic spectroscopy without repetition rate multiplication, chopper systems cannot efficiently be used on SPSS for reducing the neutron pulse lengths).

6. Conlcusion

In comparing the performance of a long pulse spallation source (LPSS) to a complementary pair a CW reactor and a usual short pulse spallation source (SPSS) one finds that: a) LPSS reproduce the utilization characteristics of CW reactors in neutron scattering applications with a LPSS providing time averaged fluxes on the sample which is about 4–8 times superior to that of a cost–equivalent reactor. This opens up the way to emulate by LPSS reactor sources with a flux 20–40 times superior to that of ILL. b) For the production of short neutron pulses a LPSS equipped with disc chopper systems (TOF monochromators) offers both superior peak flux and better resolution for cold neutrons, and equivalent peak flux and superior resolution for thermal neutrons compared to a cost–equivalent SPSS. In contrast in the slowing down regime (hot neutrons) the SPSS is clearly superior to the LPSS in both peak flux and resolution. Points a) and b) amount to conclude that for some 75 % of the neutron scattering work as practiced today the LPSS approach provides the most efficient source and the remaining 25 % is best served by SPSS.

7. References

[1] F. Mezei, Proc. ICANS XII (Rutherford Appleton Lab, 1994) p. I–377.
[2] B. Buras, AEC–ENEA Seminar, Santa Fe, New Mexico (1967); G.E. Bacon, Neutron Diffraction (Oxford, Clarendon Press, 1975), p. 144.
[3] F. Mezei, Neutron News, Vol. **5** issue 3 (1994) p. 2.
[4] F. Mezei, in press.
[5] Proceedings of a workshop on a 1 MW Long Pulse Spallation Source, April 1995 (Lawrence Berkeley National Laboratory).
[6] See G.J. Russell, E.J. Pitcher and P.D. Ferguson, in this proceedings.

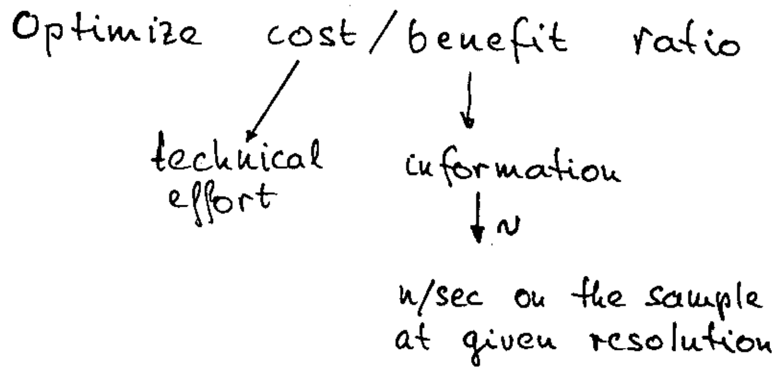
F. Mezei 's OHP Drawings for the Lecture I

F. MEZEI

JAERI, 1996.10.25

LONG PULSE SPALLATION SOURCES (LPSS)

(Quasi-continuous s.)



Optimize cost/benefit ratio

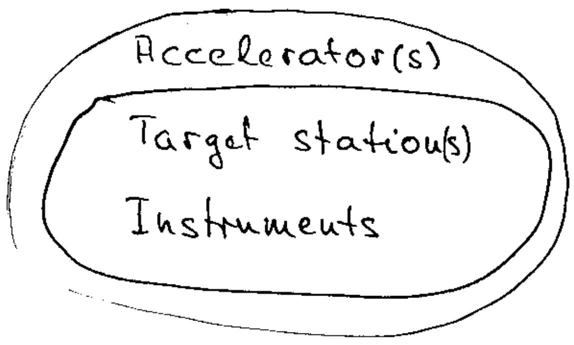
technical effort

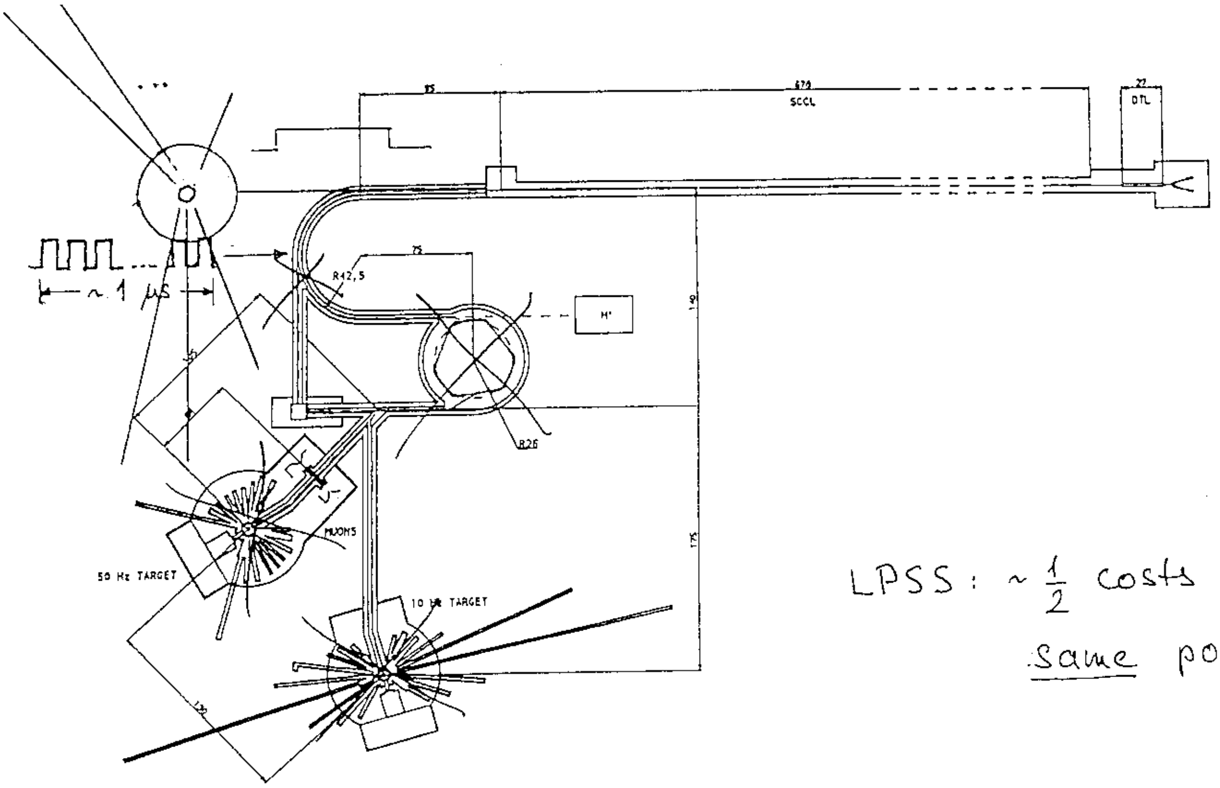
information

↓ ~

n/sec on the sample at given resolution

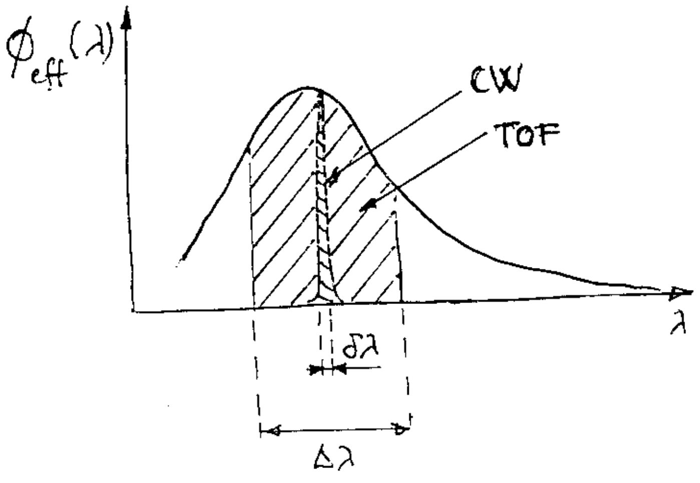
Spallation source:





LPSS : ~ $\frac{1}{2}$ costs at <u>same</u> power

Figure 1.1 ESS Layout



− $\Delta\lambda$ can be relatively small ($\ll \lambda$)

$\lambda_1, \lambda_2, \lambda_3 \ldots \lambda_n$: Information processing

F. Mezei, Proc. ICANS XIII. (PSI, 1955)

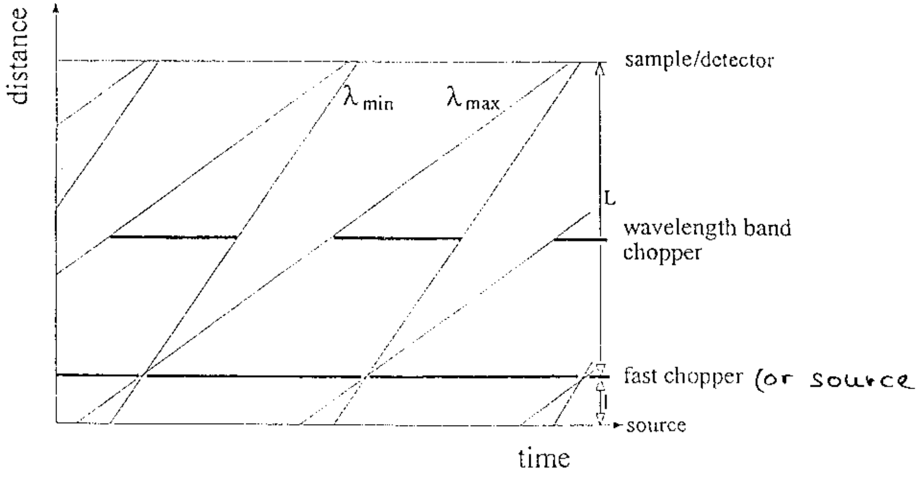


Fig. 1. The principle of TOF monochromators, after Ref. [1].

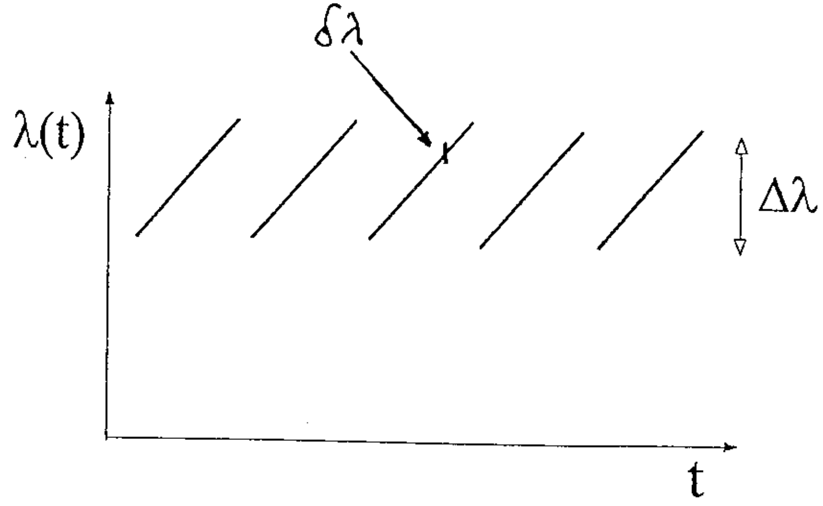


Fig. 2. Time dependence of the wavelength of the monochromatic beam in a TOF monochromator.

$$\delta\lambda = \delta t_{ch} / L$$

$$\Delta\lambda = T_{rep} / L$$

Duty factor:

f. chopper: $c \simeq \frac{\delta\lambda}{\Delta\lambda}$

source $c_s \simeq \frac{\ell}{L}$

Mean flux theorem:

$$\bar{\Phi}_{sample} = g f \bar{\Phi}_{peak}$$

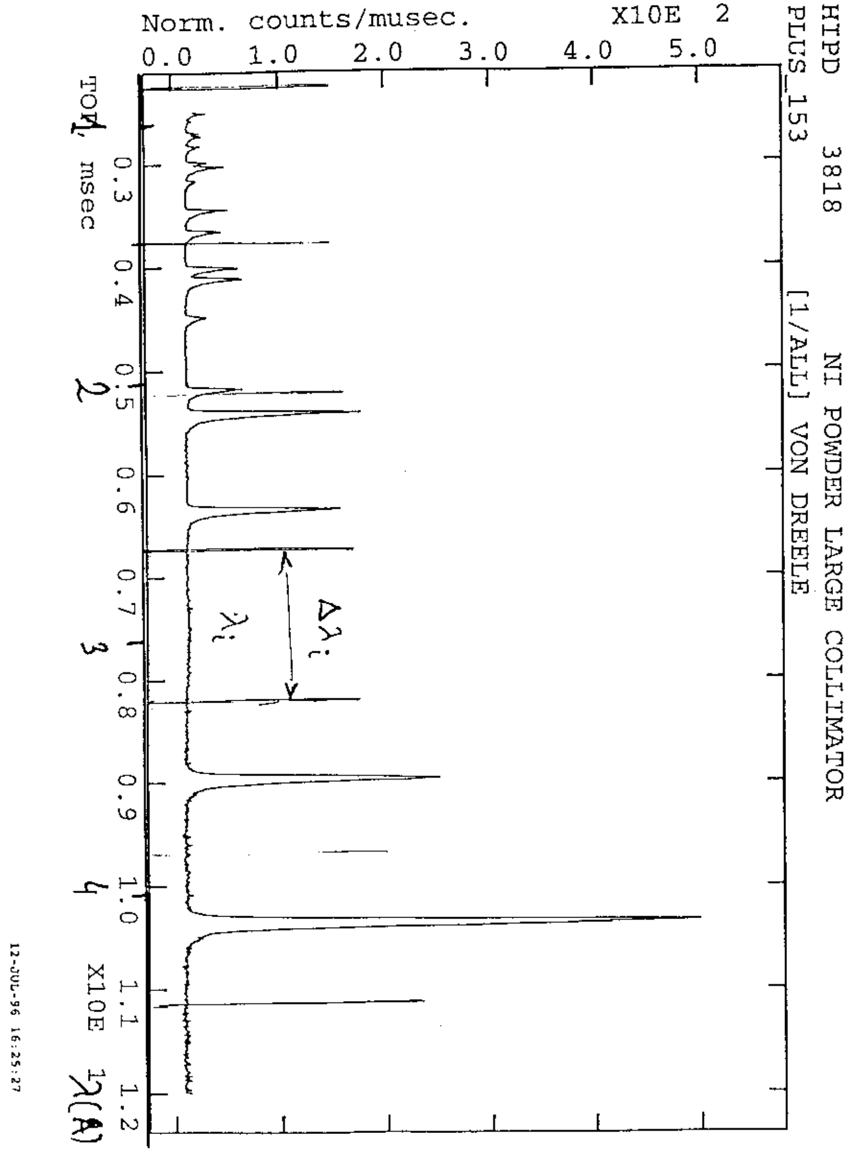
$$g = \begin{cases} 1 & \text{if } \delta\lambda = \delta\lambda_{desired} \\ \delta\lambda / \delta\lambda_{desired} & \end{cases}$$

$$f^{-1} = \frac{n t_i^{max}}{\sum_{i=1}^{n} t_i}$$

"usefulness" of the bandwidth $\Delta\lambda$

t_i = ideal measuring time with wave-length λ_i

$t_i^{max} = max(t_i)$

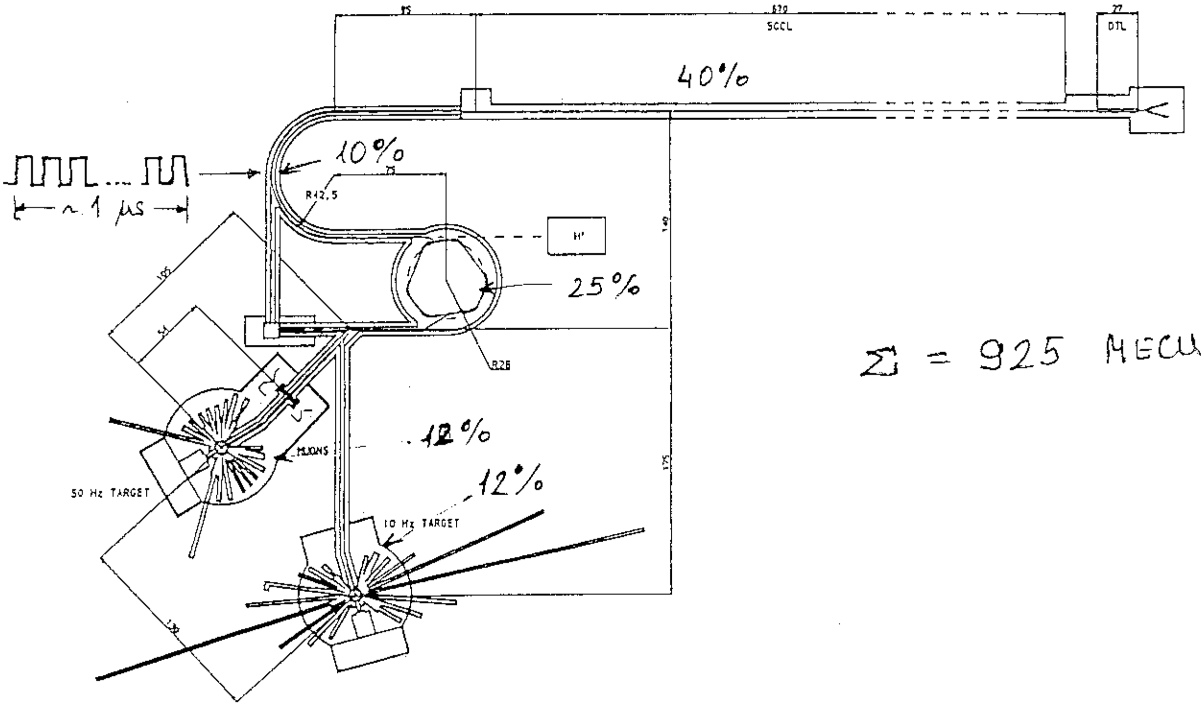


Long neutron pulses:

mederators

Long proton pulses:

linac vs. RCS
↓
high power



Σ = 925 MECU

Figure 1.1 ESS Layout

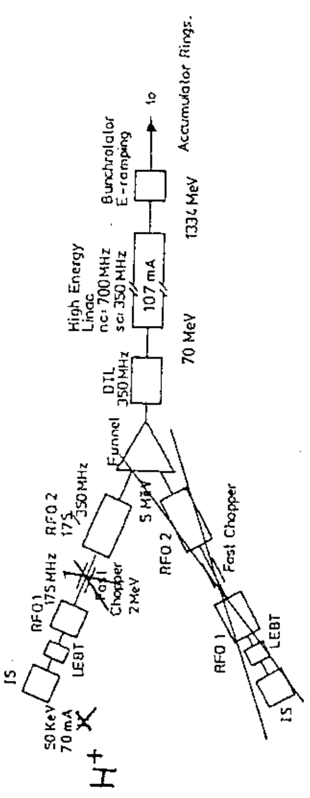


Fig 2.1: Proposed ESS linac scheme.

Injection pulse: ESS 1.2 μs
NSNS 0.5 μs

WHY?

Costs: Linac ≃ injection + ring

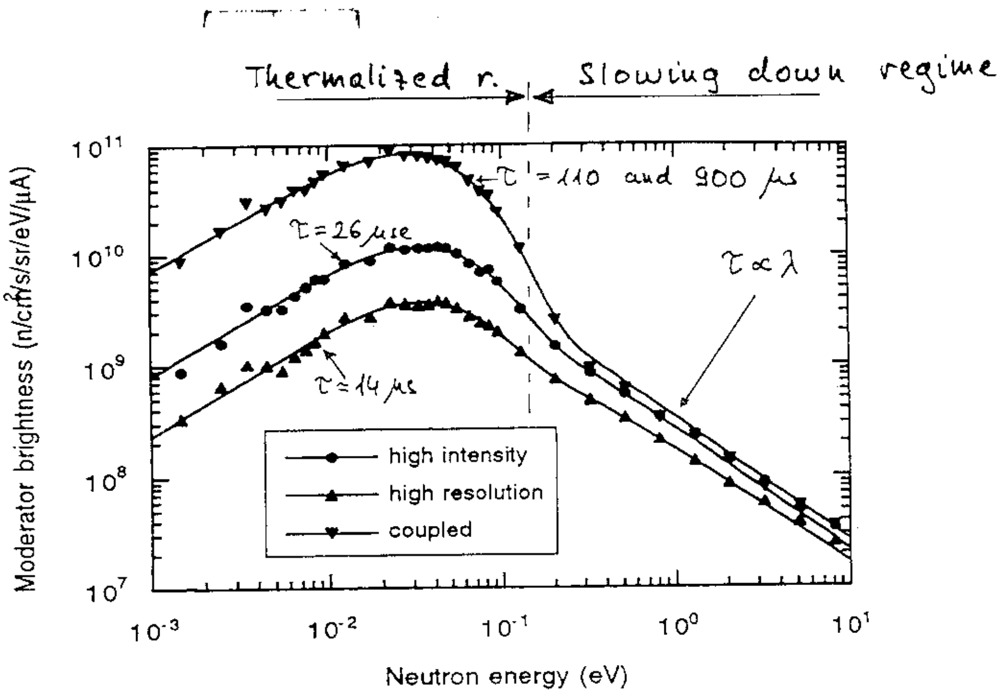
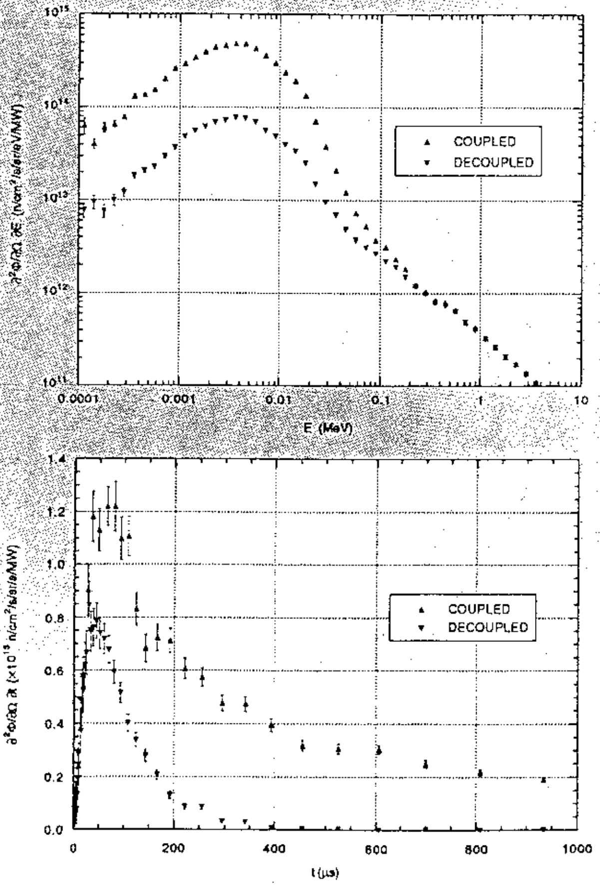


Fig. 2. Average moderator brightness as a function of neutron energy for three water moderators.

Ferguson et al, ICANS XIII.

Coupled and Decoupled LH_2 Moderator Energy Spectra & Time Distributions



Los Alamos

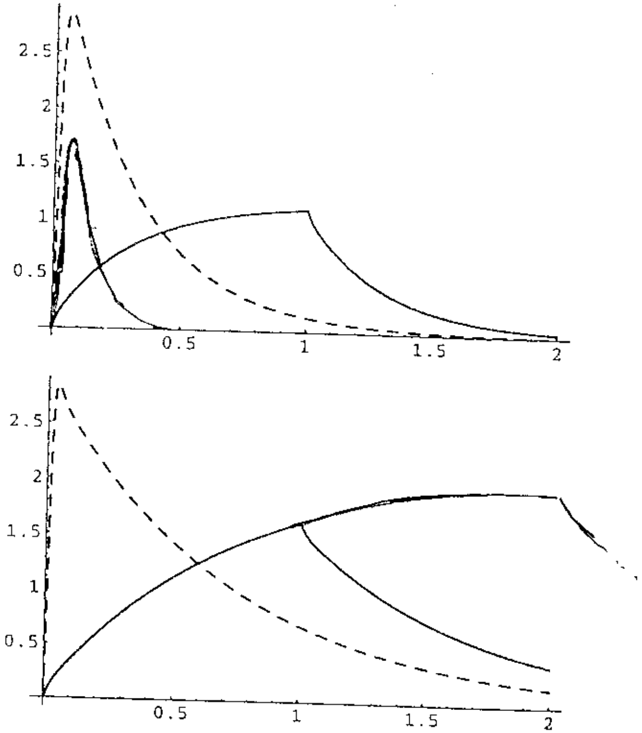
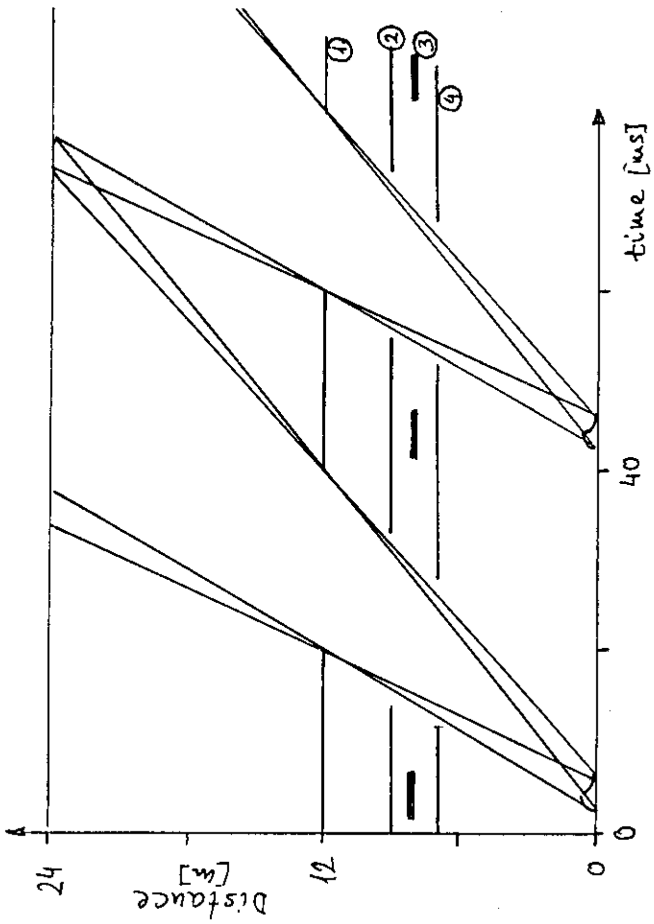


Figure 3: Pulse shapes for SPSS (dotted curve) and LPSS (solid curve) with different time constants. In the upper panel the decay constant is 300 μsec corresponding to a coupled, weakly-reflected target/moderator system (CWR) while in the lower panel the decay constant is 700 μsec, a value more typical of a strongly reflected system (CSR). The integrated intensity of the pulses in the lower panel is twice that of those in the upper panel.

Pynn x Daemen, ICANS XIII.

$\frac{\delta\lambda}{\lambda} \sim 10\%$: outside narrow band approximation



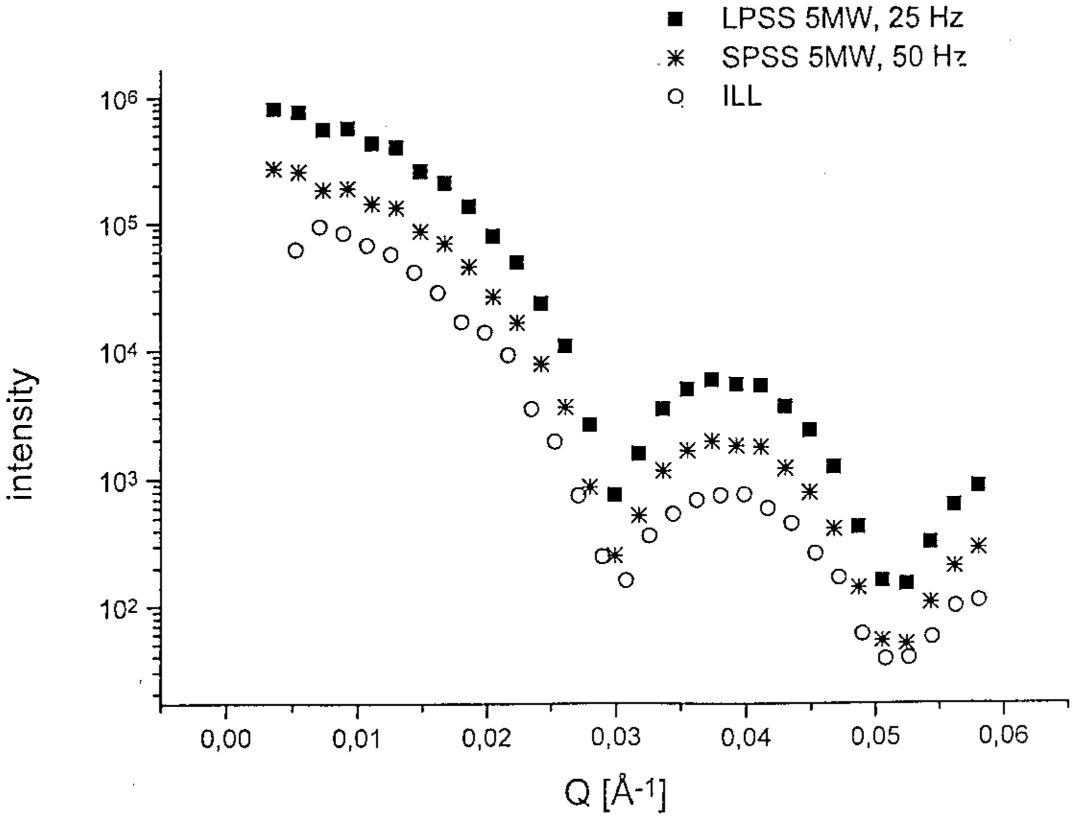
SANS example:
25 Hz
2 ms pulse length
24 m source — detector

③ t_0 chopper (fast neutrons)

① + ④ wavelength band choppers : filters for $\lambda < \lambda_{used} + 27$ Å

① + ② + ④ same but $\lambda < \lambda_{used} + 40$ Å

SANS: hard spheres



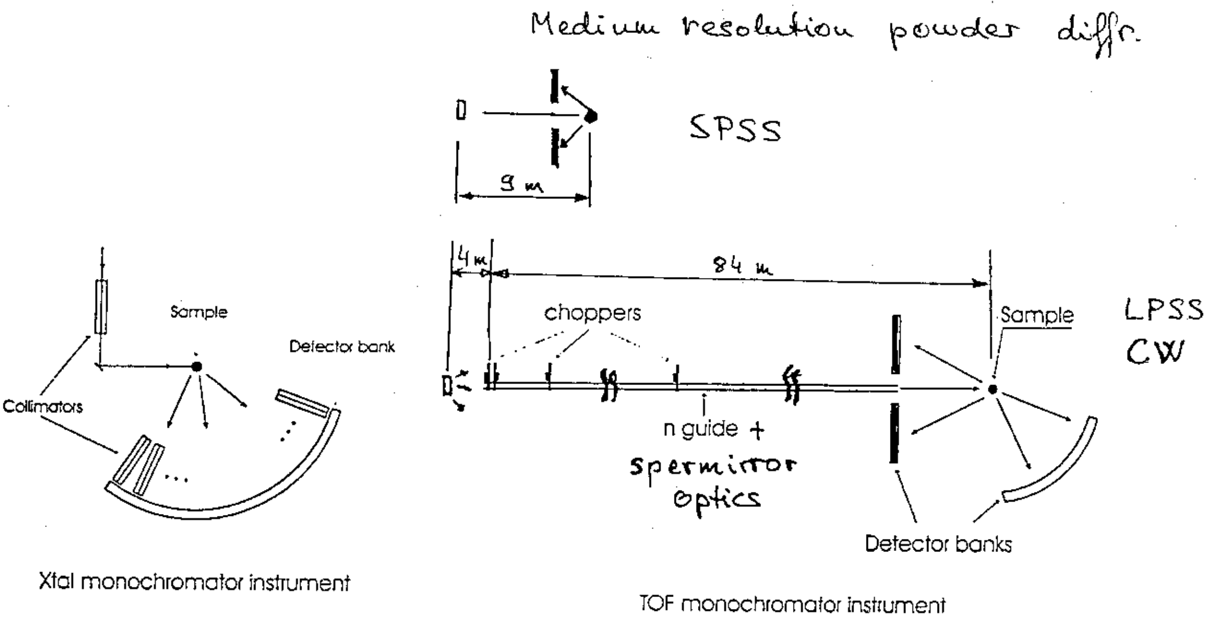
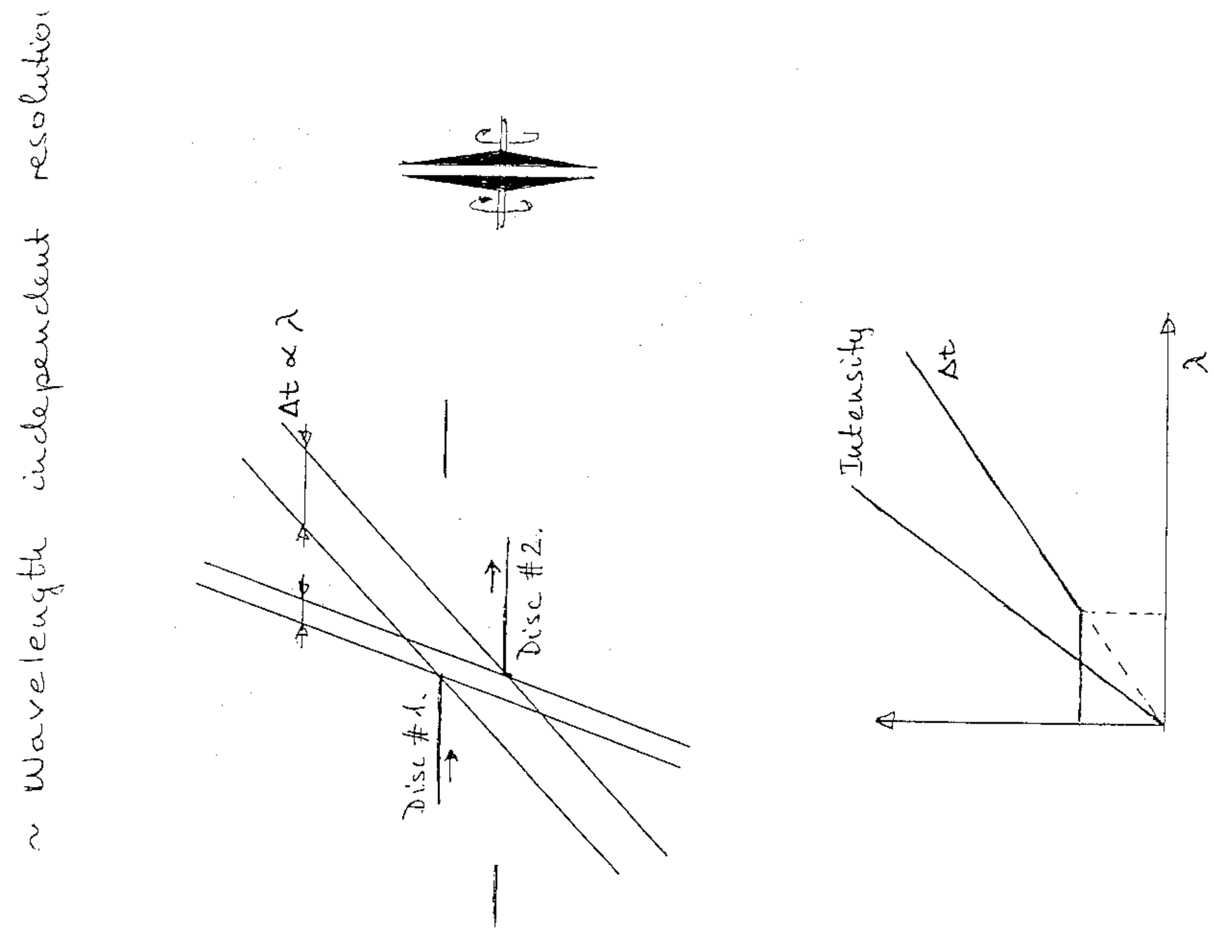
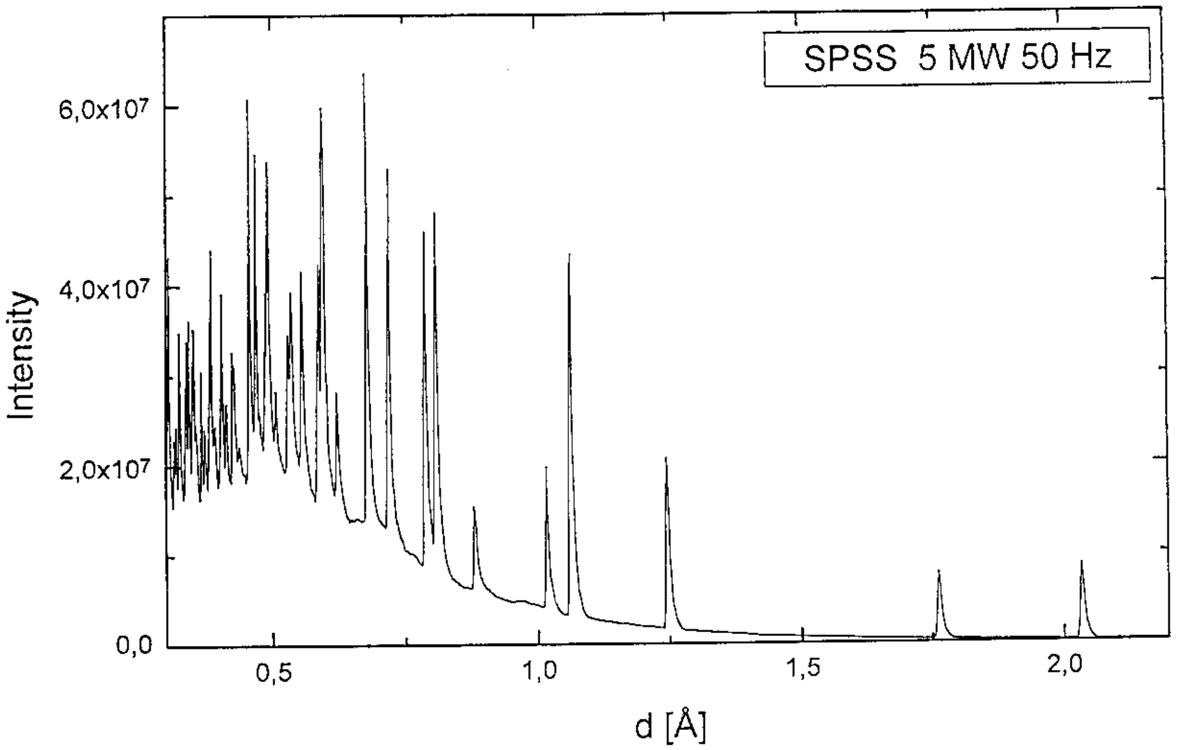
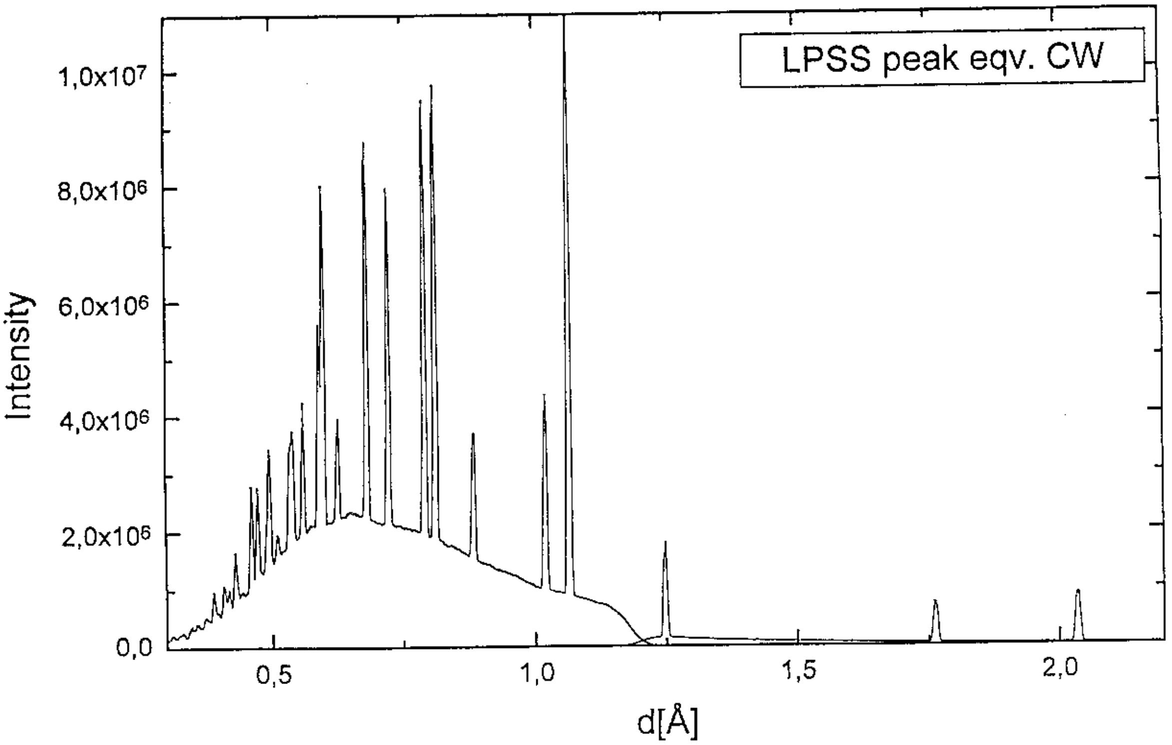
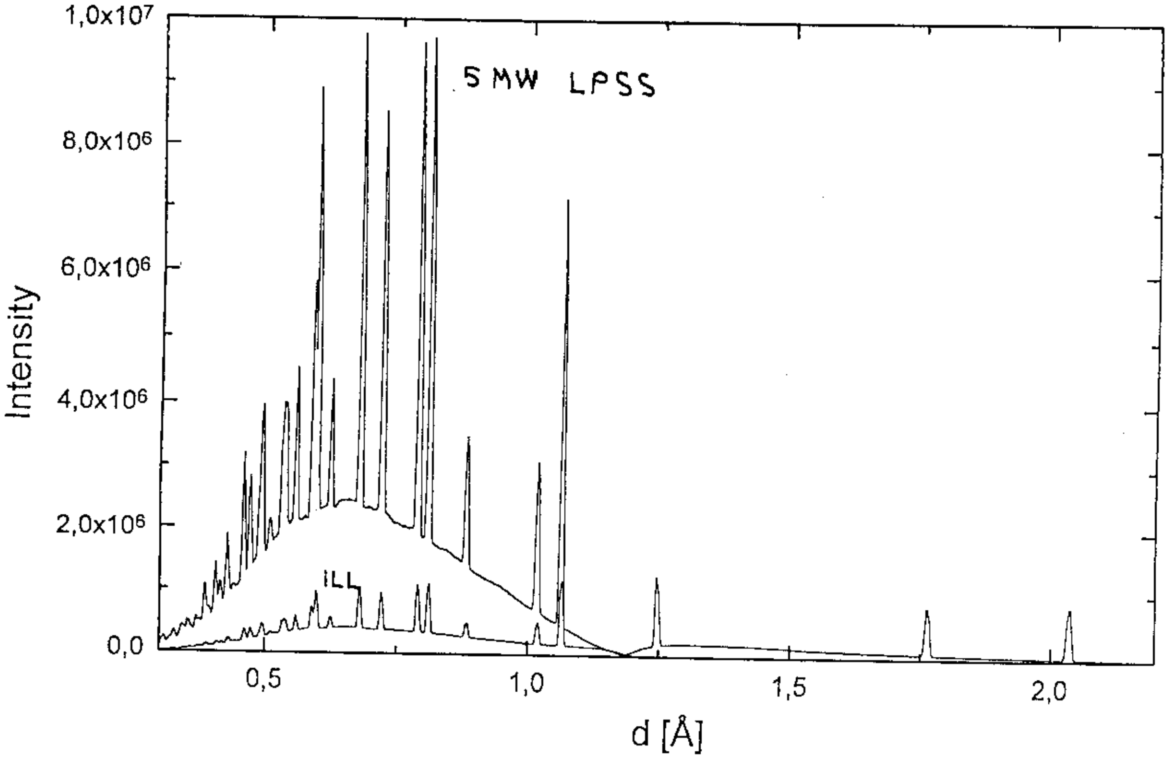


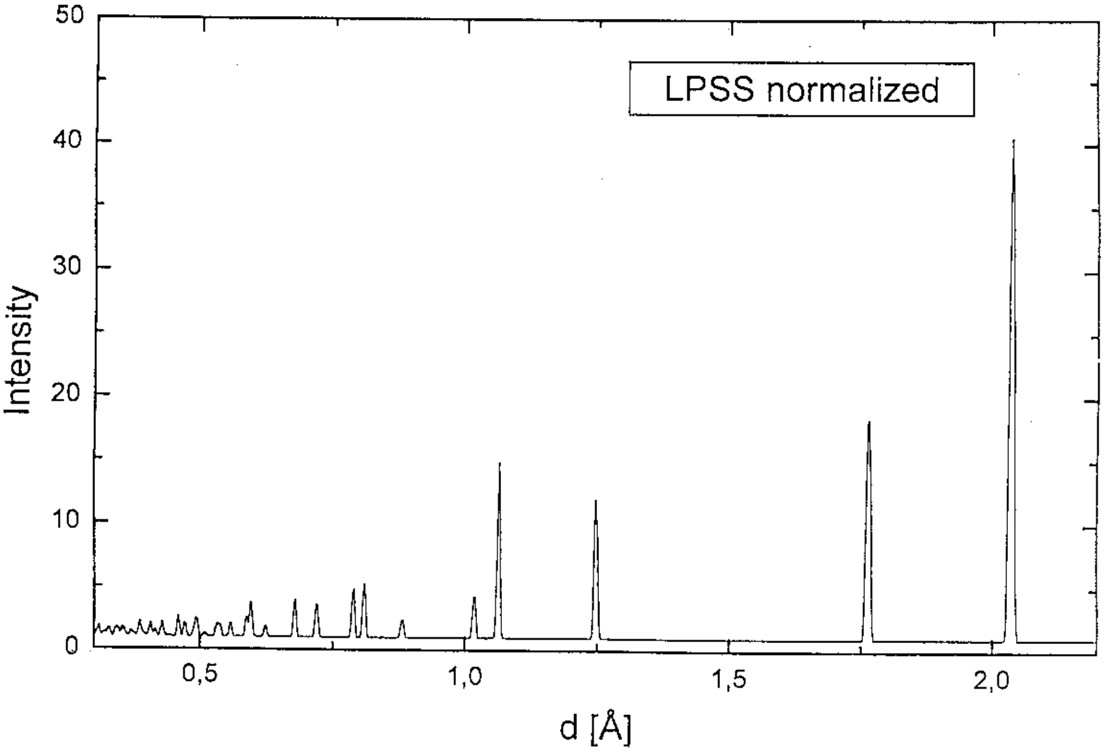
Fig. 3: Layout of a crystal (left) and a TOF monochromator high resolution powder diffractometer.

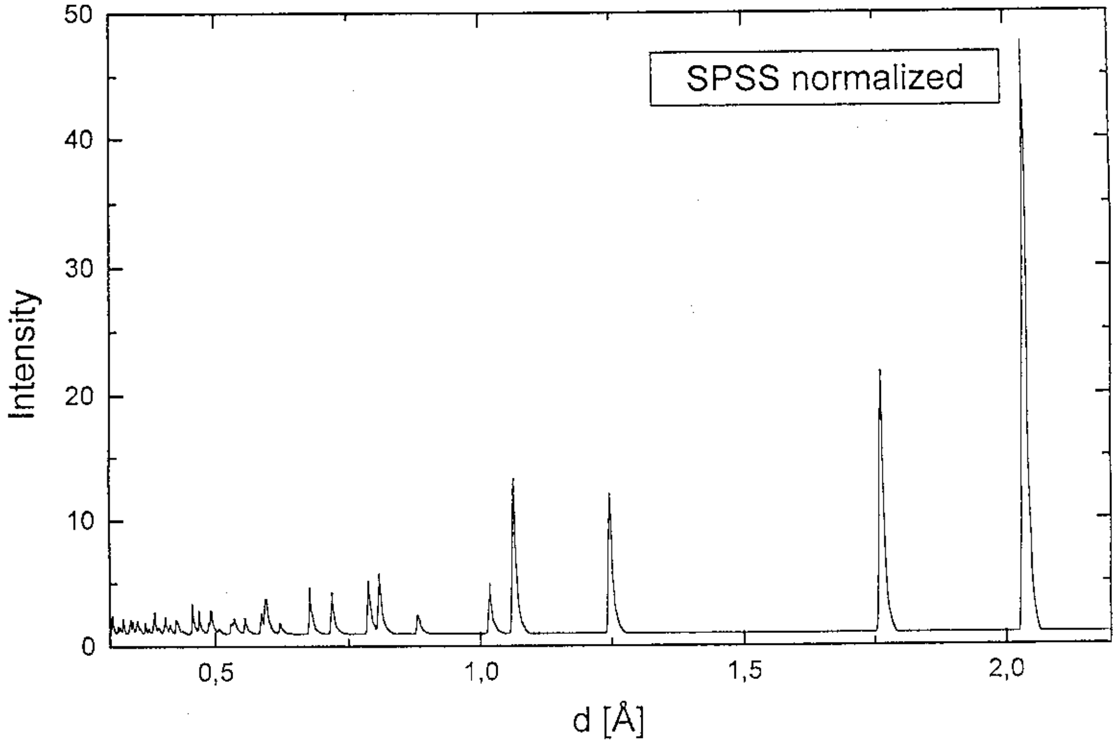


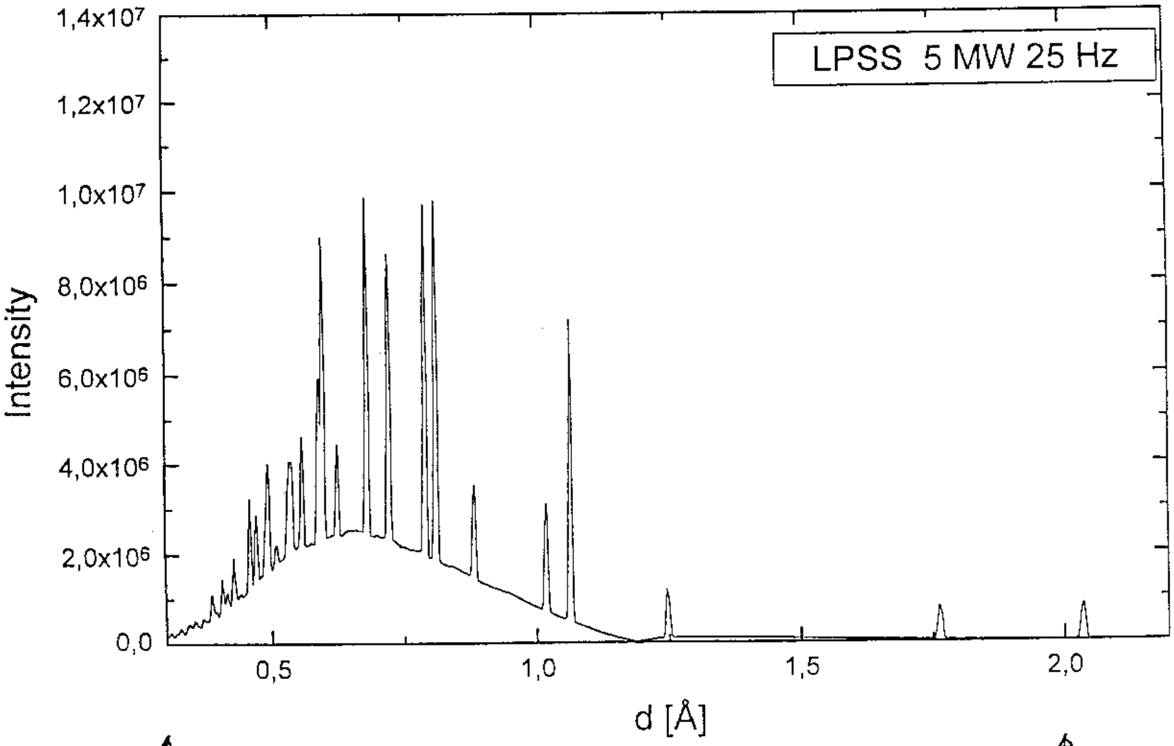

SPSS 5 MW 50 Hz
Intensity
6,0x10⁷
4,0x10⁷
2,0x10⁷
0,0
0,5
1,0
1,5
2,0
d [Å]


LPSS peak eqv. CW
Intensity
1,0x10⁷
8,0x10⁶
6,0x10⁶
4,0x10⁶
2,0x10⁶
0,0
0,5
1,0
1,5
2,0
d[Å]


1,0x10^7
8,0x10^6
6,0x10^6
4,0x10^6
2,0x10^6
0,0
Intensity
5 MW LPSS
ILL
0,5
1,0
1,5
2,0
d [Å]


50
40
30
20
10
0
Intensity
LPSS normalized
0,5
1,0
1,5
2,0
d [Å]


SPSS normalized
Intensity
50
40
30
20
10
0
0,5
1,0
1,5
2,0
d [Å]


LPSS 5 MW 25 Hz
Intensity
1,4x10⁷
1,2x10⁷
1,0x10⁷
8,0x10⁶
6,0x10⁶
4,0x10⁶
2,0x10⁶
0,0
0,5
1,0
1,5
2,0
d [Å]

↑ 250 μs

↑ 400 μs

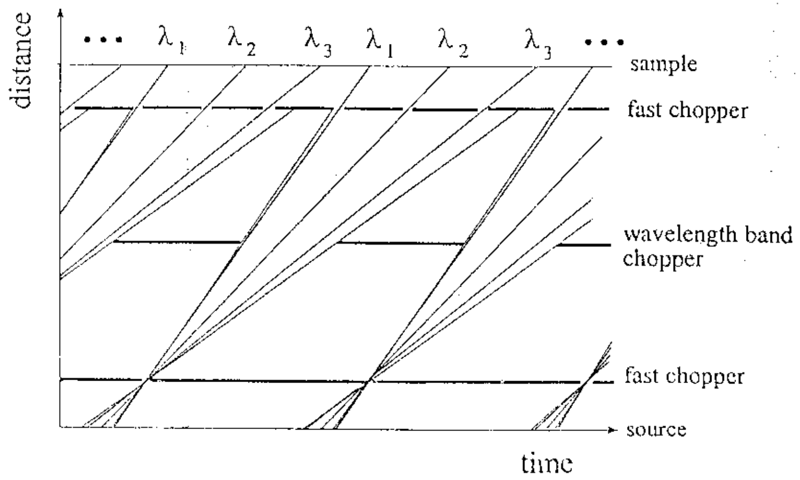


Fig. 6 Principle of TOF monochromator - TOF analyser inelastic spectroscopy with repetition rate multiplication [12].

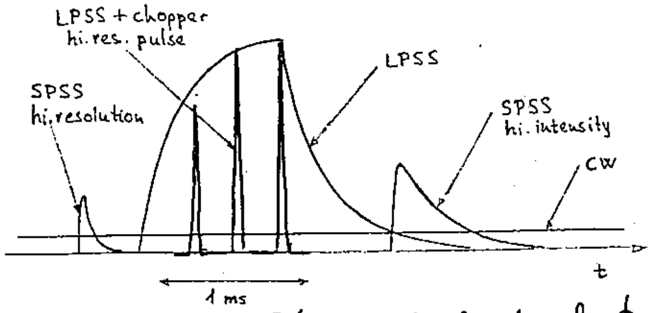
Repetition Rate Multiplication
(FM 1995)

= generalized TOF - monochromator

Comparison of neutron fluxes of cost-equivalent sources

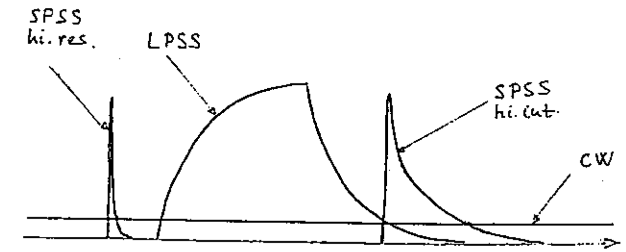
CW: reactor source 60 MW (ILL)
SPSS: 0.67 MW short pulse spallation source: one of the two target stations of a 1 MW, 60 Hz source
LPSS: 4 MW long pulse spallation source, 60 Hz, 6.7 % duty factor

Cold neutrons

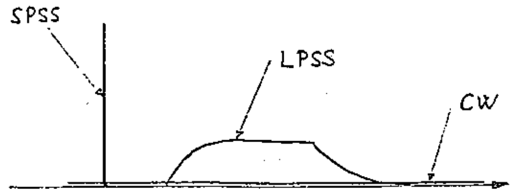


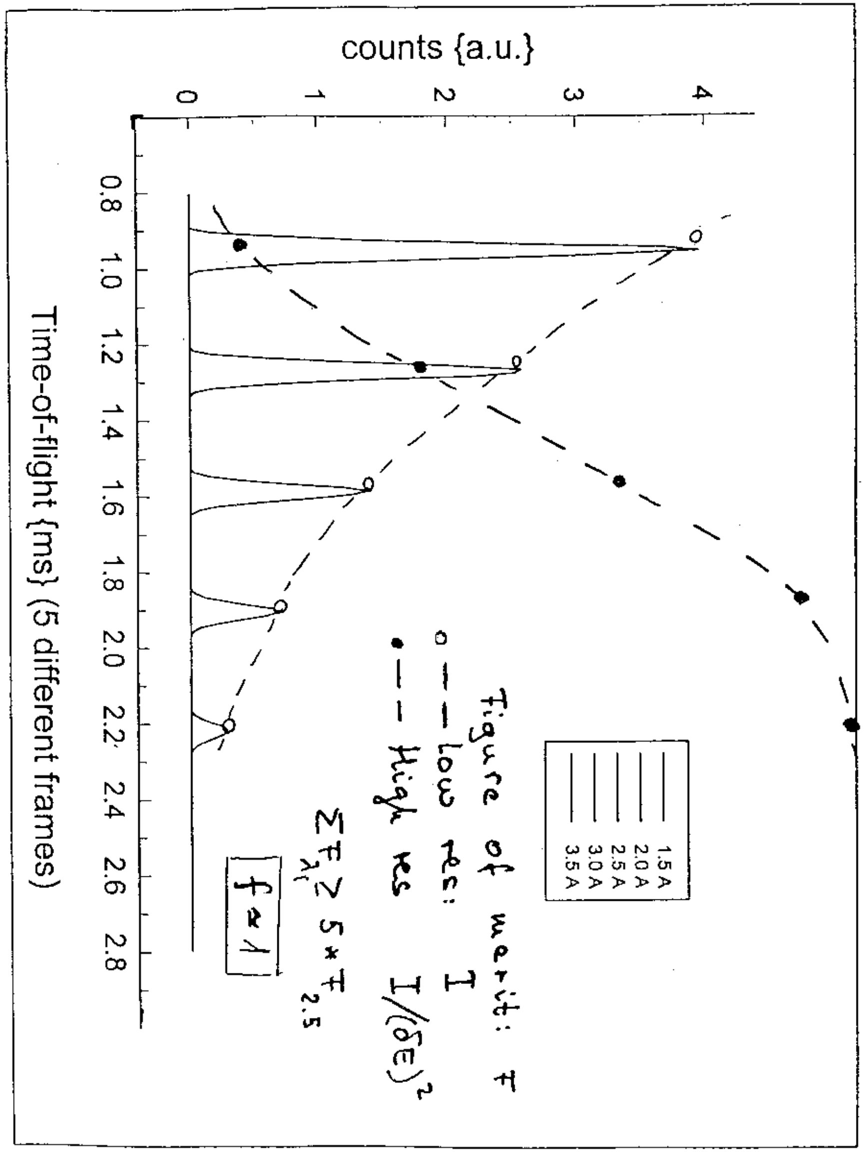
$\int \phi \, dt$ instead of ϕ_{max}

Thermal neutrons



Hot neutrons (~0.5 A) hot moderator assumed for CW and LPSS (guessed performance), without hot source: ~10 times smaller flux for CW & LPSS





LPSS optimum: 20-30 Hz rep. rate
2-3 ms pulses
Δλ band narrow:
long instruments
>50 beams/target station

LPSS superior to SPSS:

cold neutrons

thermal neutrons in thermalized regime

SPSS superior to LPSS:

hot, epithermal neutrons

thermal neutrons in slowing down regime (high res.)

LPSS performance: in neutron scattering at 5 MW

$$\bar{\Phi}_{sample} \gtrsim 10\, \Phi_{ILL}$$

Los Alamos project: 1 MW
Potencial: 10-20 MW

F. Mezei's OHP Drawings for the Lecture II

F. MEZEI

JAERI, 1996. 10. 29

PULSED SOURCE OPTIMIZATION FUNDAMENTALS

Optimize:

No. of experiments/year/M$

$$\downarrow$$

$$\phi N$$

Issues:

"Useful" flux ϕ vs. $L_{\text{Source-sample, detector}}$

No. of beams N

⟹ Rep. rates

Pulse lengths

TOF Monochromator

Narrow band approximation

Time average flux: (losses neglected e.g. absorbtion)

$$\langle \varphi_{sample} \rangle = \langle \Phi(\lambda) \rangle \frac{d\Omega}{4\pi} \delta\lambda$$

$$\downarrow$$

$$= \Phi(\lambda)_{peak} \frac{d\Omega}{4\pi} c \Delta\lambda =$$

$$\Phi_{peak} = \frac{\int \Phi \, dt}{t_p}$$

$$= \Phi(\lambda)_{peak} \frac{d\Omega}{4\pi} \delta\lambda$$

$\Rightarrow$ Mean flux theorem:

$$\langle \Phi \rangle = \Phi_{peak}$$

state-of-the-art linac:

e.g. ESS: $\langle \Phi \rangle \simeq 3 * 10^{16}\ n/cm^2/$

$\simeq 20 * \Phi_{ILL}$

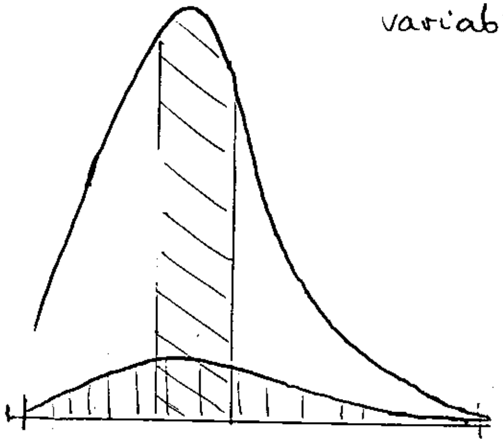
$\Rightarrow \langle \Phi \rangle$ independent of wavelength band:

$$\Delta\lambda = \frac{h}{m} \frac{T_{rep}}{L} \qquad t_p = \frac{m}{h} \delta\lambda L$$

as long as $t_p < t_s$

$$(\Delta\lambda)_{min} = \frac{T_{rep}}{(t_p)_{max}} \delta\lambda = \frac{T_{rep}}{t_s} \delta\lambda = \frac{1}{c_s} \delta\lambda$$

TOF Wavelength band monochromator:



variable $\frac{T}{L}$

"USEFUL" $\Delta\lambda$, $\delta\lambda$

TOF - Monochr. efficiency factor

$$gf = \frac{\Delta\lambda_{eff}}{\Delta\lambda}\,\frac{\delta\lambda}{\delta\lambda_{requ.}} = \frac{\Delta\lambda_{eff}}{\delta\lambda_{requ.}}\,\frac{1}{C} < 1$$

$$\Delta\lambda_{eff} = \Delta\lambda\,\frac{\sum_{i=1}^{n} t_i}{n\,t_i(max)} \qquad g = \frac{\delta\lambda}{\delta\lambda_{requ}}$$

t_i: ideal meas. time in range $\Delta\lambda_i$

General case:

$$\boxed{\langle\Phi\rangle = gf\,\Phi_{peak}}$$

A) Broad band:

$$\frac{\Delta\lambda_{eff}}{\Delta\lambda} < 1 \quad \text{if} \quad \Delta\lambda > \Delta\lambda_{max}$$

$$\Rightarrow L_{min} \propto \frac{T}{\Delta\lambda_{max}}$$

B) Too good $\delta\lambda$

$$\delta\lambda = c_{ch}\Delta\lambda \le c_s\Delta\lambda$$

$$\Delta\lambda_{min} = \delta\lambda_{req}/C_s$$

$$L_{max} = \frac{h}{m}\,\frac{T C_s}{\delta\lambda_{req}} = \frac{h}{m}\,\frac{t_p}{\delta\lambda_{req}}$$

Examples:

- SANS: $\delta\lambda_r \approx 0.5$ Å $\qquad t_p = 1$ ms

  $L_{max} \approx 8$ m !

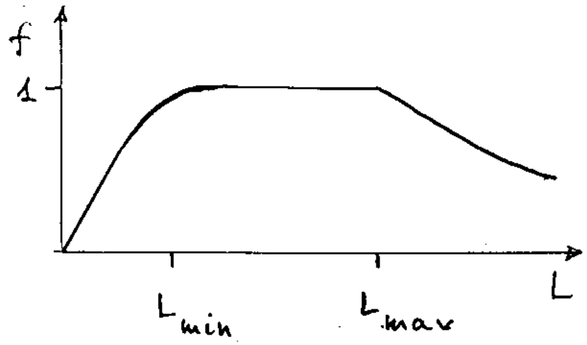
  $\Rightarrow t_p$ should be $\underline{\ge 2-3 \text{ ms}}$

- Powder diffr.:

  $\delta\lambda_r \approx 0.01$ Å ; $\Delta\lambda_{max} \sim 2$ Å $\qquad T = 16$ ms

  $L_{min} \simeq 32$ m

  $L_{max} \simeq 400$ m



(But $L_{max} < L_{min}$ possible:

e.g. SANS $T = 16$ ms

$\lambda_{min} \simeq 8$ m $(\Delta\lambda_{max} \simeq 8$ Å)

Neutron guides:

for $\lambda \gtrsim 0.5 - 1$ Å : OK for

$L \lesssim 200$ m

⇒ $\Theta_c = 3\Theta_c^{Ni}$ commercially available

⇒ Optical tricks:

eye-of-the-needle
ballistic guides etc.

Narrow $\Delta\lambda$ band advantages:

a) Can concentrate on (q, ω) range

b) Little variation of intensity and resolution across $\Delta\lambda$

c) Large source - sample/detector distances possible (50 - 200 m)

$$L_{max} = \frac{h}{m}\frac{t_s}{\delta\lambda} = 4\,\frac{t_s[\mathrm{ms}]}{\delta\lambda[\text{Å}]}\,[\mathrm{m}]$$

⇒ many beam positions on a single target station (~ 50)

Worst case for narrow band approach:

$\frac{\delta\lambda}{\lambda} \simeq 10\%$ (SANS, NSE, diffuse sct.)

$\Rightarrow L_{max}[\mathrm{m}] = 6\, t_s[\mathrm{ms}]$

$(\Delta\lambda)_{min}/\lambda \geq 0.1/c_s$

⇒ need large t_s and c_s
i.e. reduced repetition rate

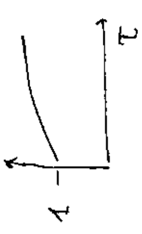
[Until now: rep. rate was irrelevant
Φ_{peak} (and c_s) mattered only]

MINIMUM DISTANCE (MD)

Theorem
(For thermalized spectra!)

SPSS: (exception: TOF inelastic spectr.,

$\phi_{peak} = A\,p(\tau)$ $p(\tau) \simeq const = 1$



$I_S = A\tau$ $\delta\lambda = \frac{h}{m}\frac{\tau}{L_S}$

LPSS: $m = E_L V_L / E_S V_S$

$I_L = m A \tau_{eff} \frac{\delta t}{t_{S(ource)}}\, i(t)$ $\hat{\phi}_\infty = m A \frac{\tau_{eff}}{t_S}$

$i(t) \simeq const = 1$

$\delta\lambda = \frac{h}{m}\frac{\delta t}{L_L}$

Equal resolution:

$\delta t = \frac{L_L}{L_S}\tau$

$\frac{I_L}{I_S} \simeq m\tau_{eff}\frac{1}{t_S}\frac{L_L}{L_S} \geq 1$ if

$L_S < m L_L \frac{\tau_{eff}}{t_S}$

E.g.: $m = 3.3$ $L_L = 120$ m $\tau_{eff}/t_S \simeq 1/3.3$

$\boxed{L_S(min) = 120 \text{ m}}$

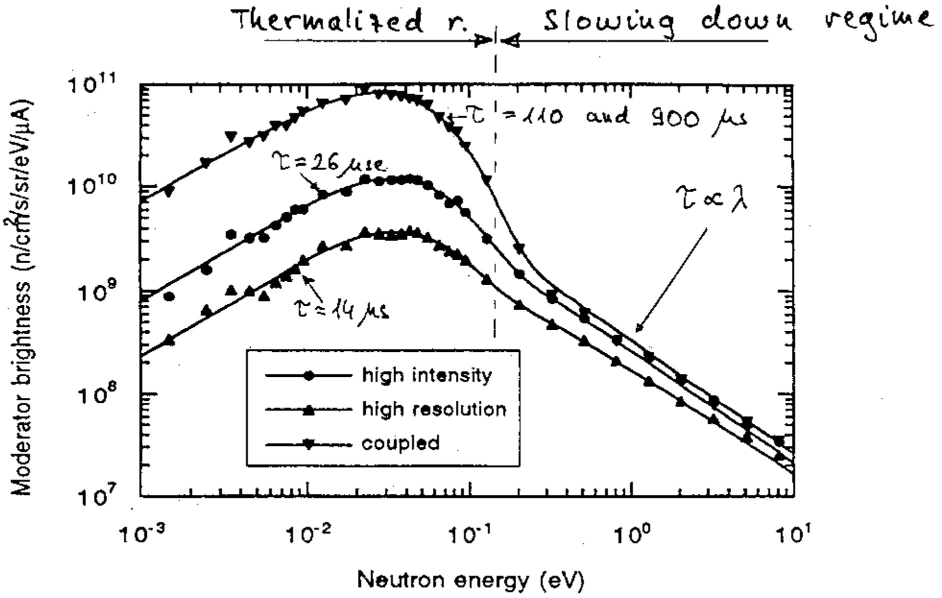
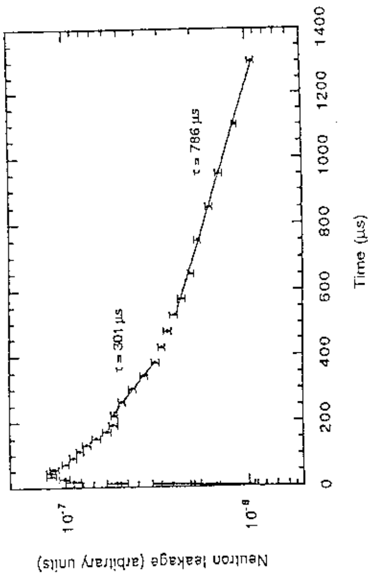
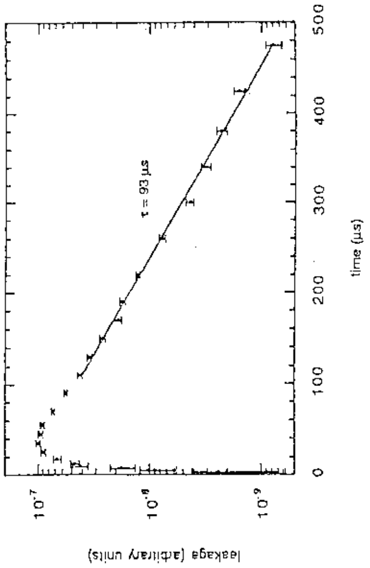
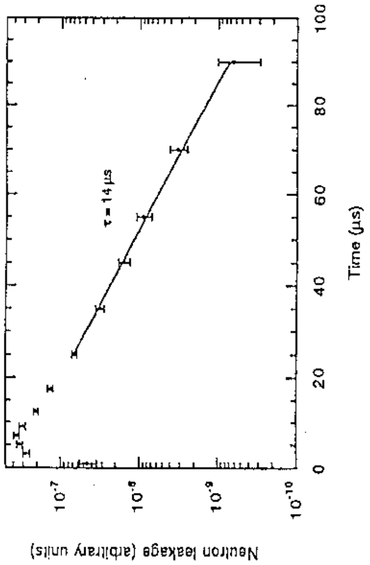


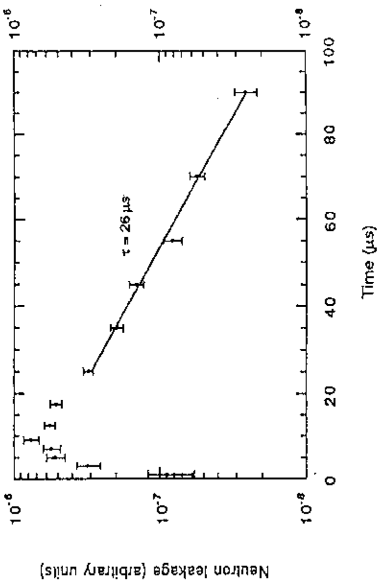
Fig. 2. Average moderator brightness as a function of neutron energy for three water moderators.

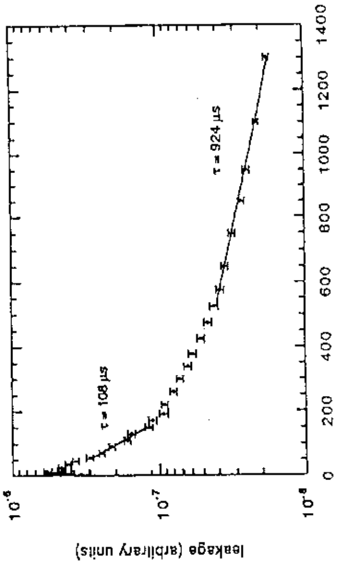
Ferguson et al, ICANS XIII.


Neutron leakage (arbitrary units)
10^{-7}
10^{-8}
Time (μs)
0
200
400
600
800
1000
1200
1400
τ = 301 μs
τ = 786 μs

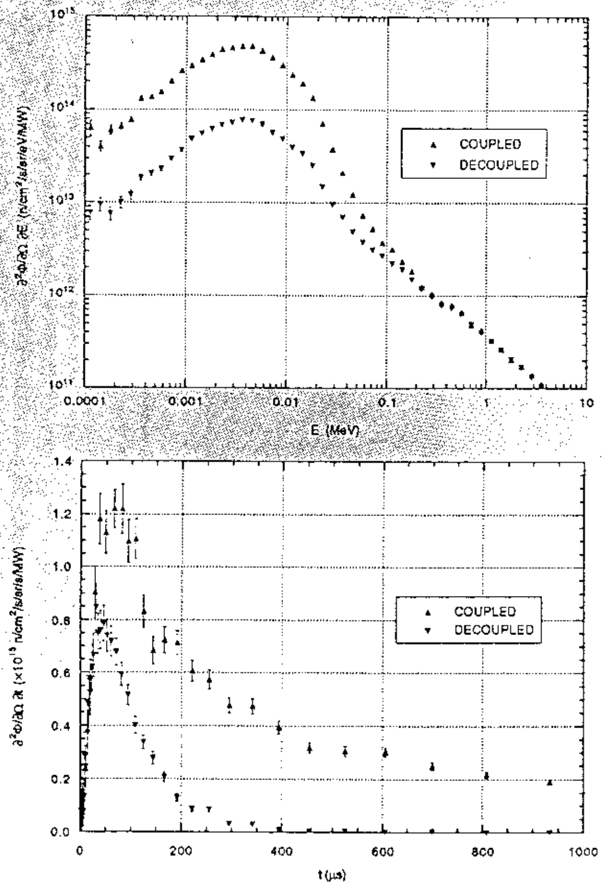

leakage (arbitrary units)
10^{-7}
10^{-8}
10^{-9}
time (μs)
0
100
200
300
400
500
τ = 93 μs


Neutron leakage (arbitrary units)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Time (μs)
0
20
40
60
80
100
τ = 14 μs


Neutron leakage (arbitrary units)
10^{-6}
10^{-7}
10^{-8}
Time (μs)
0
20
40
60
80
100
τ = 26 μs

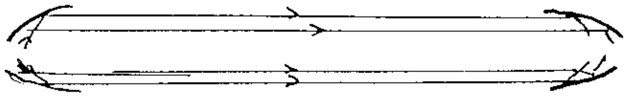

leakage (arbitrary units)
10^{-6}
10^{-7}
10^{-8}
0
200
400
600
800
1000
1200
1400
τ = 108 μs
τ = 924 μs

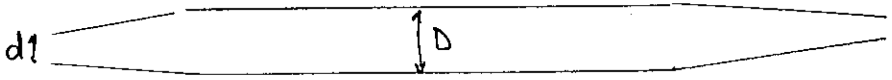
Coupled and Decoupled LH$_2$ Moderator Energy Spectra & Time Distributions



Los Alamos

Ballistic neutron guides:

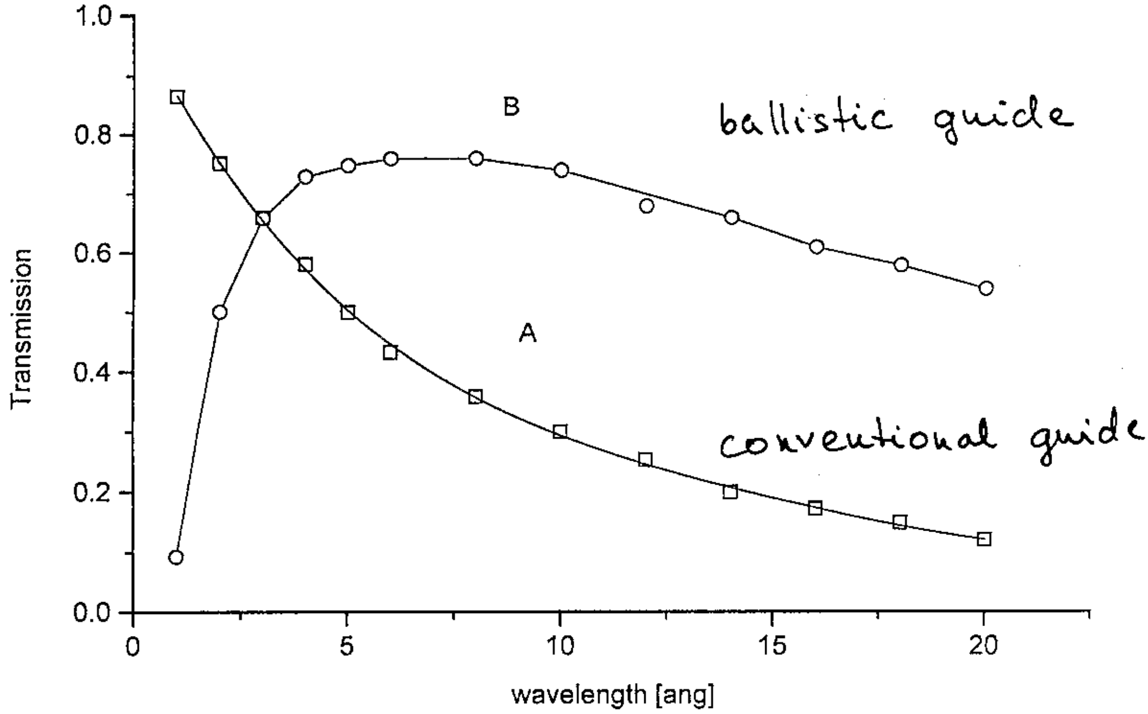




$n = \frac{D}{d} \simeq 3 - 6$

No. of reflections: $\propto \frac{1}{n^2}$

200 m long guides:



Fast choppers: counter-rotating: $\delta t \doteq 10\,\mu s$
parallel rotating: $\delta t > 20\,\mu s$
tunable for choise of
resolution.

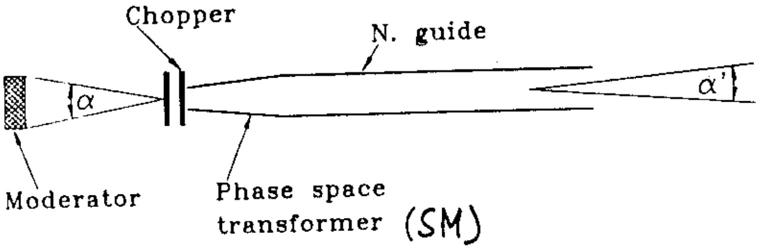
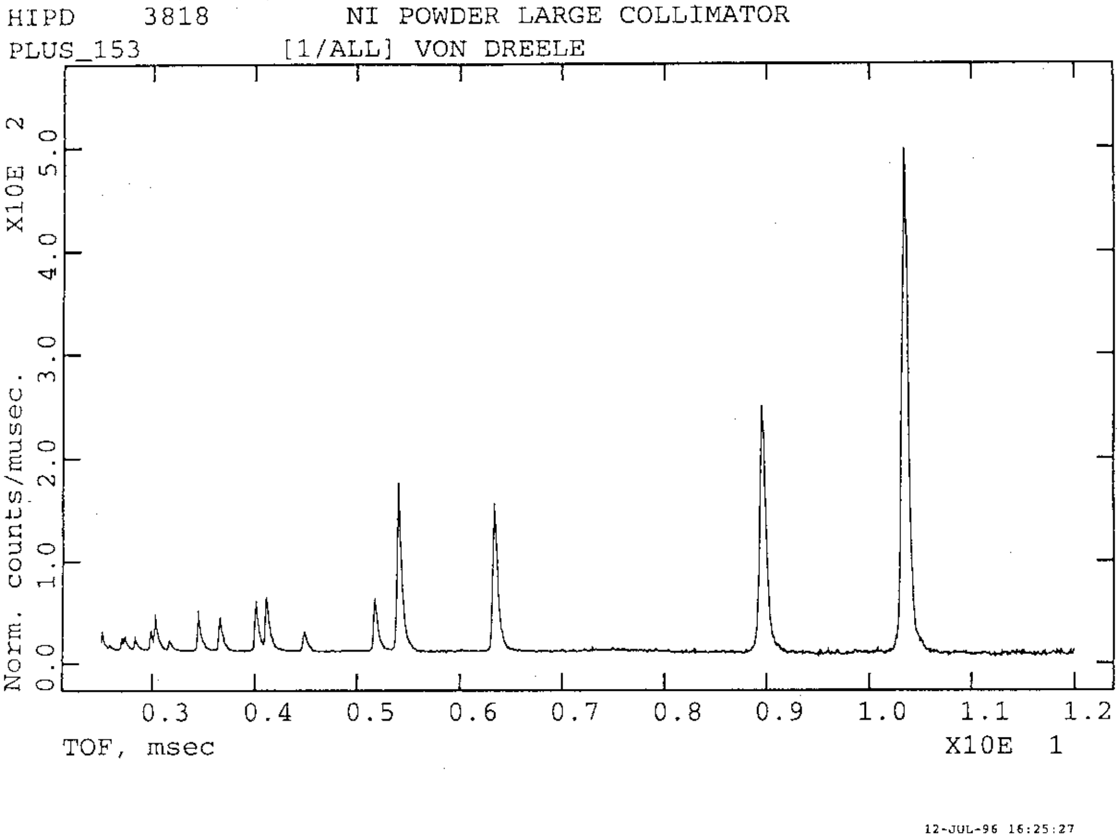
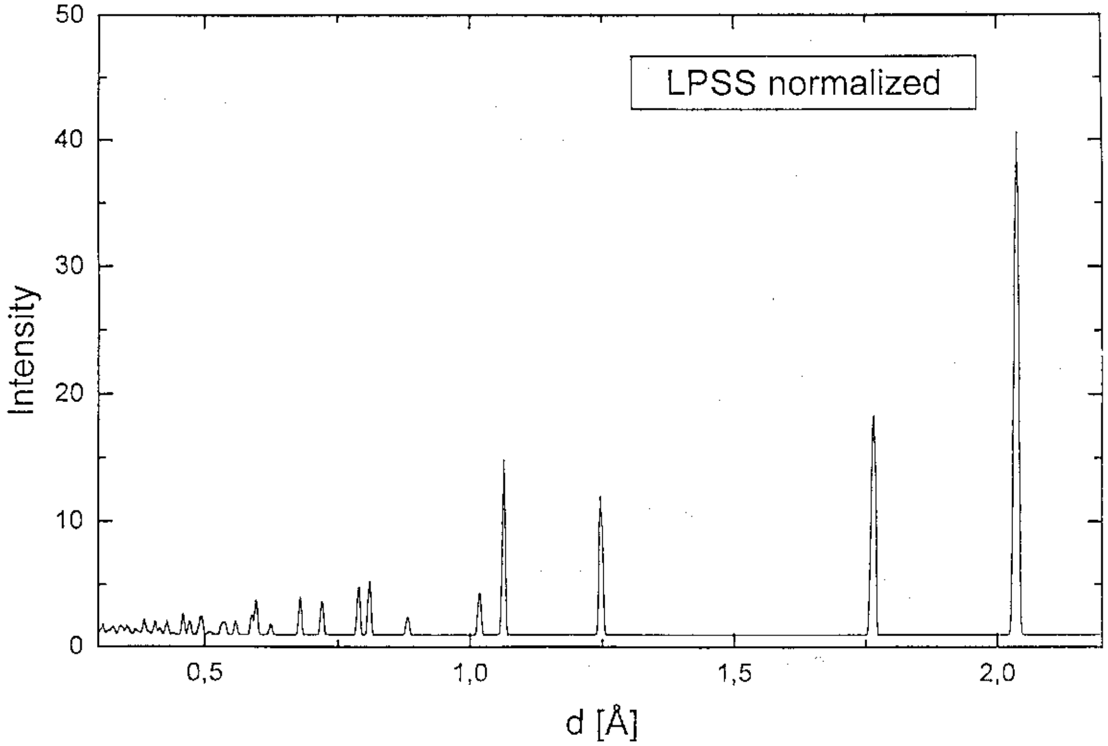
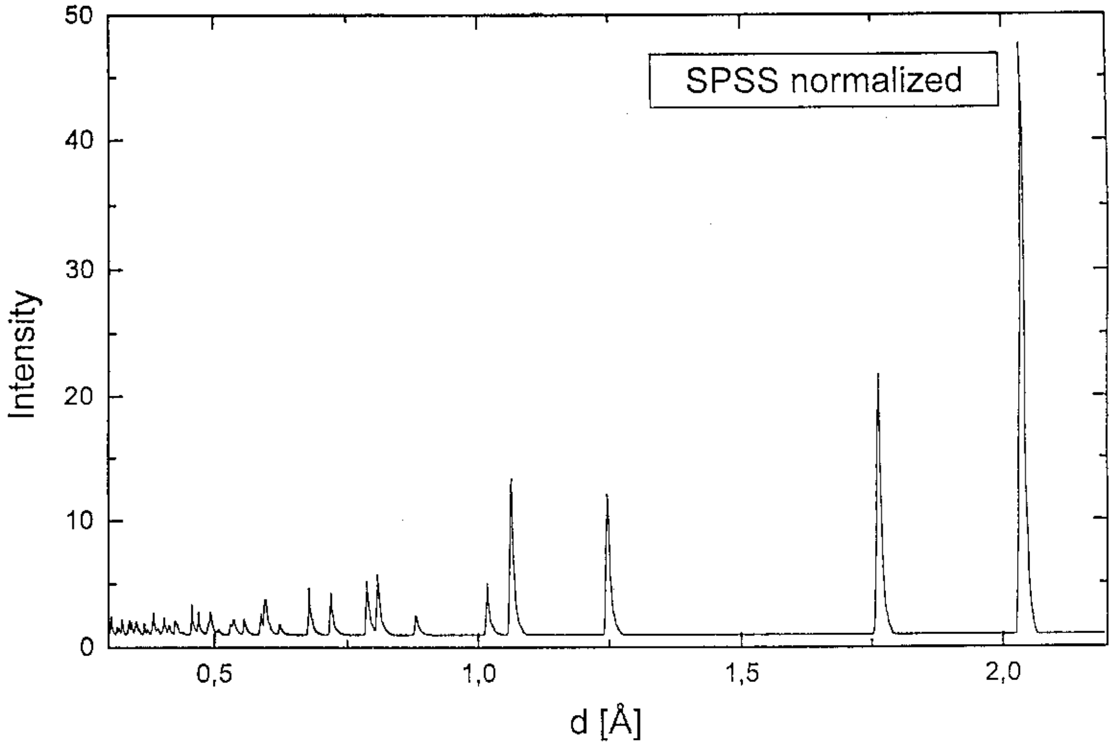


Fig. 4. The principle of the "eye-of-the needle" neutron beam line design, utilizing the large divergence of the beam across the narrow chopper slit.

use: Supermirrors


HIPD 3818 NI POWDER LARGE COLLIMATOR
PLUS_153 [1/ALL] VON DREELE
Norm. counts/musec. X10E 2
0.0
1.0
2.0
3.0
4.0
5.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
TOF, msec
X10E 1
12-JUL-96 16:25:27


LPSS normalized
Intensity
0
10
20
30
40
50
0,5
1,0
1,5
2,0
d [Å]



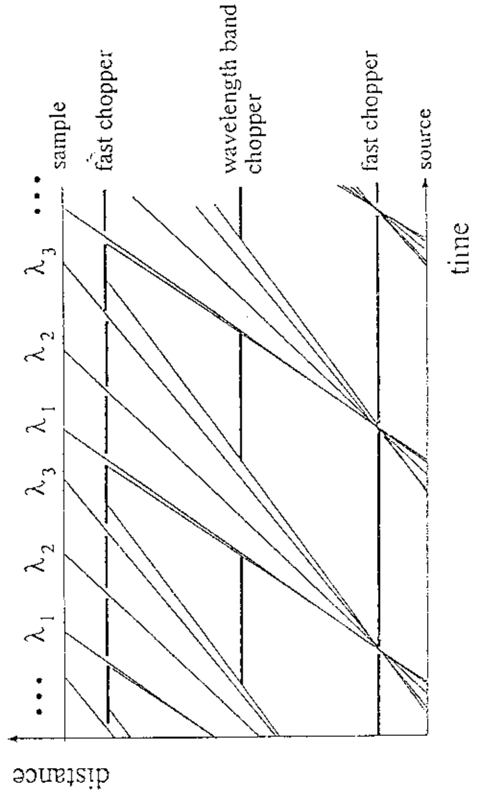


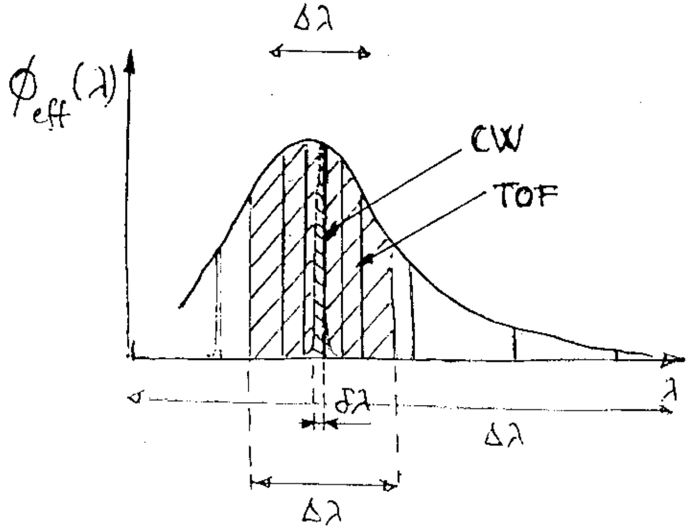
Fig. 6. Principle of TOF monochromator - TOF analyser inelastic spectroscopy with repetition rate multiplication [12].

Repetition Rate Multiplication
(FM 1995)

= generalized TOF - monochromator

TOF inelastic spectroscopy

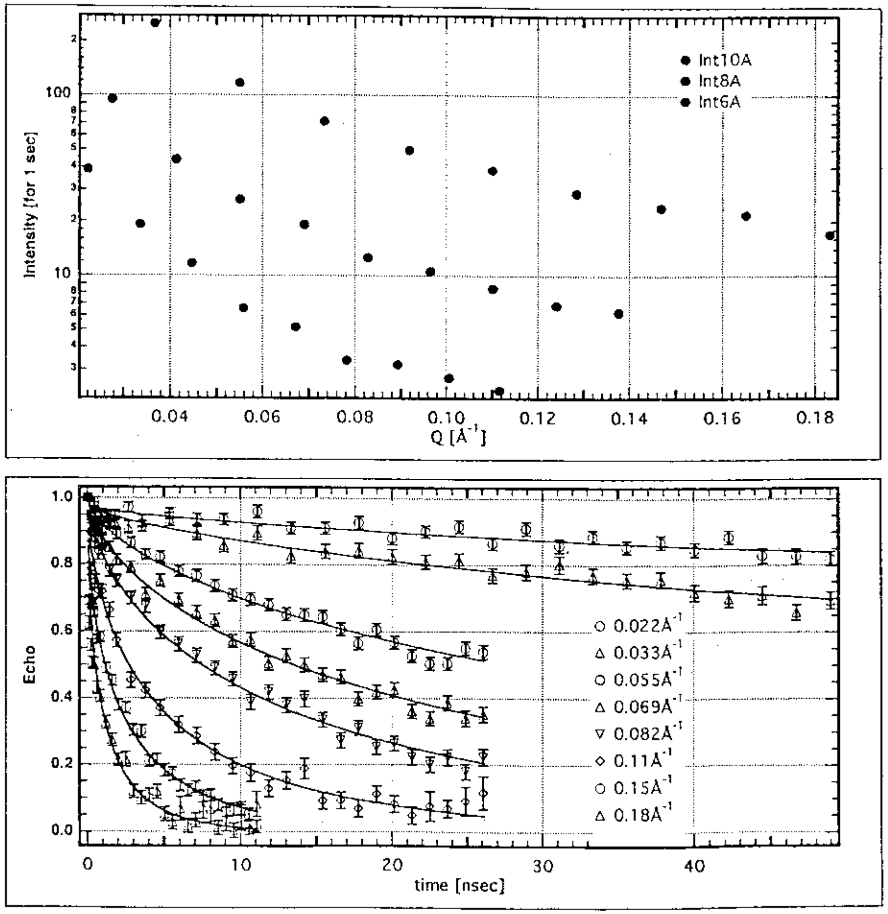
Repetition Rate Multiplication
(RRM)

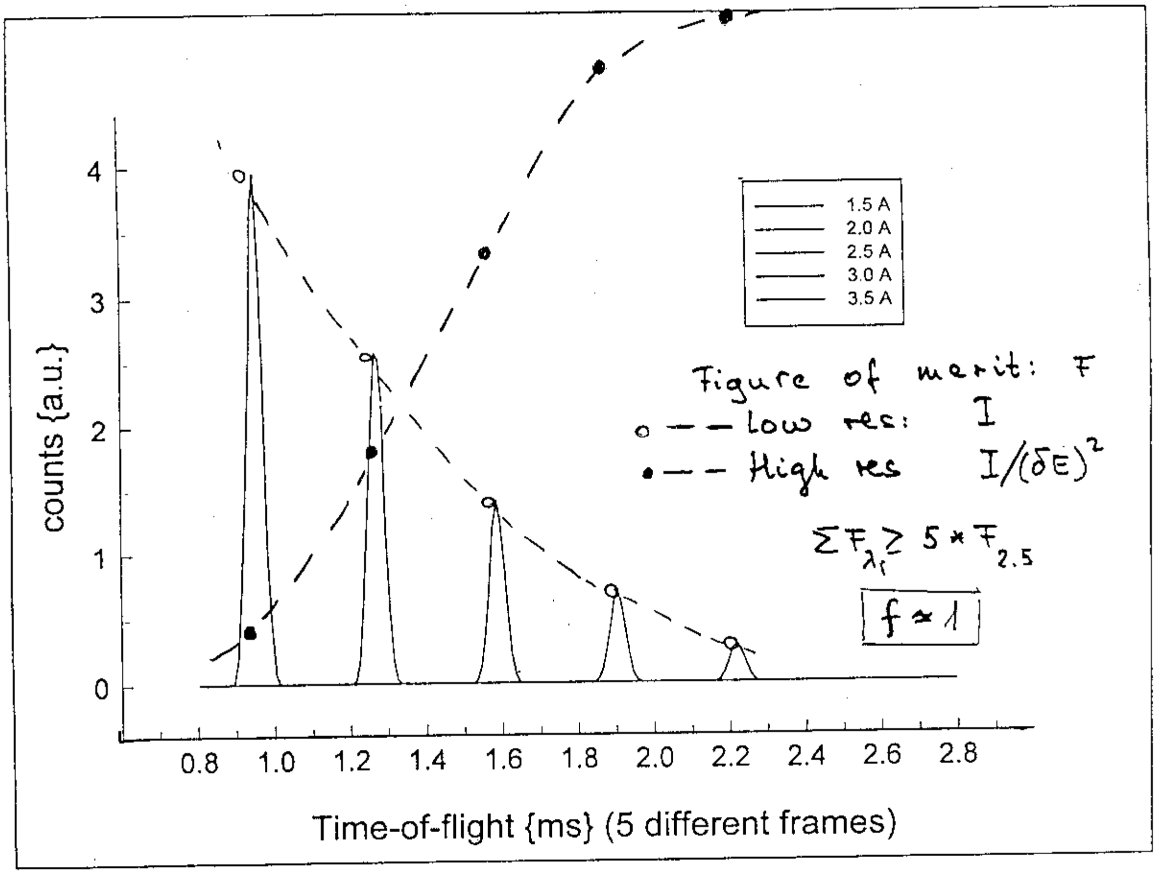


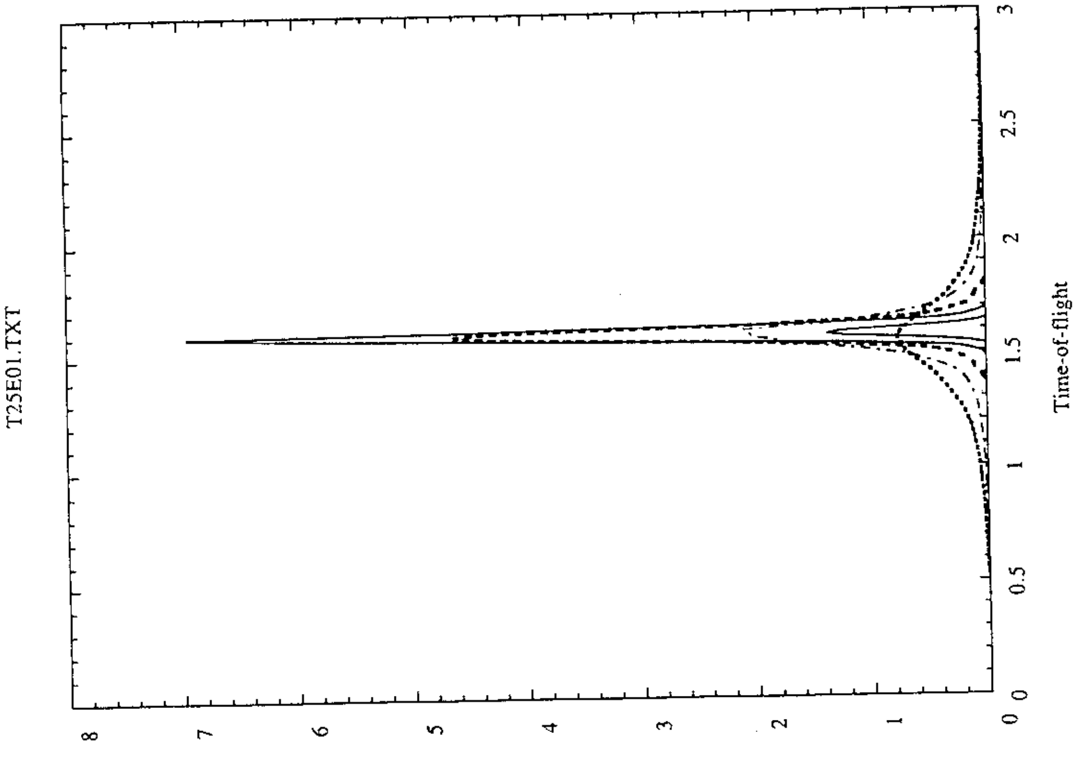
– $\Delta\lambda$ can be relatively small ($\ll \lambda$)

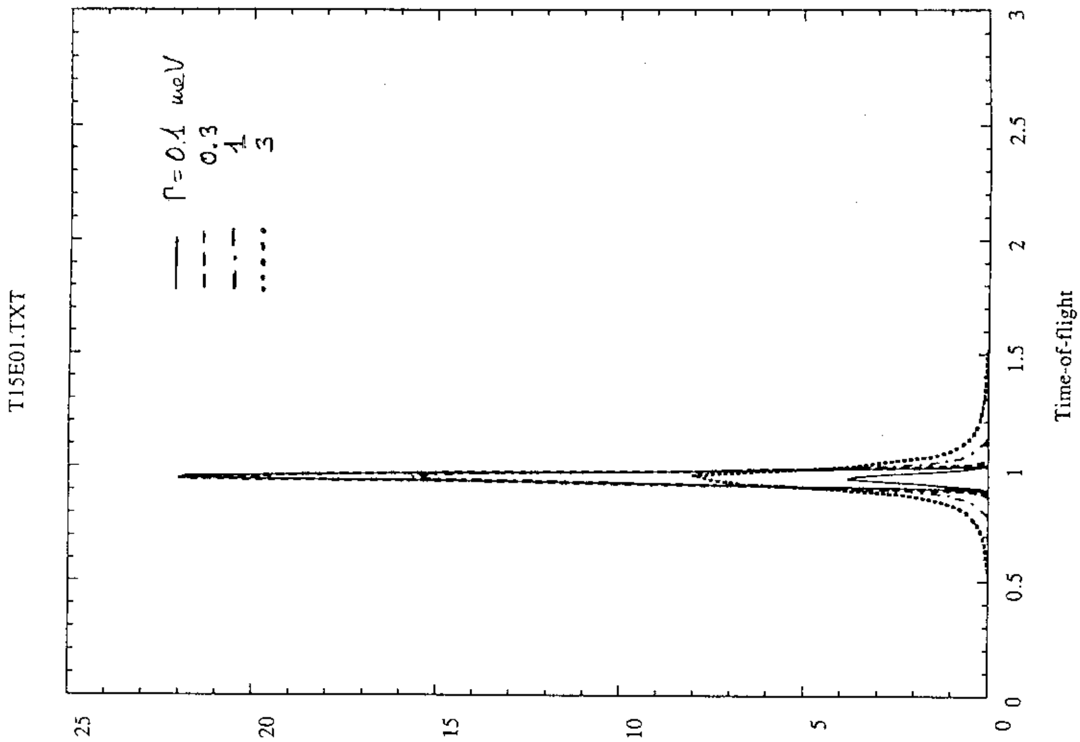
$\lambda_1, \lambda_2, \lambda_3 \ldots \lambda_n$: Information processing

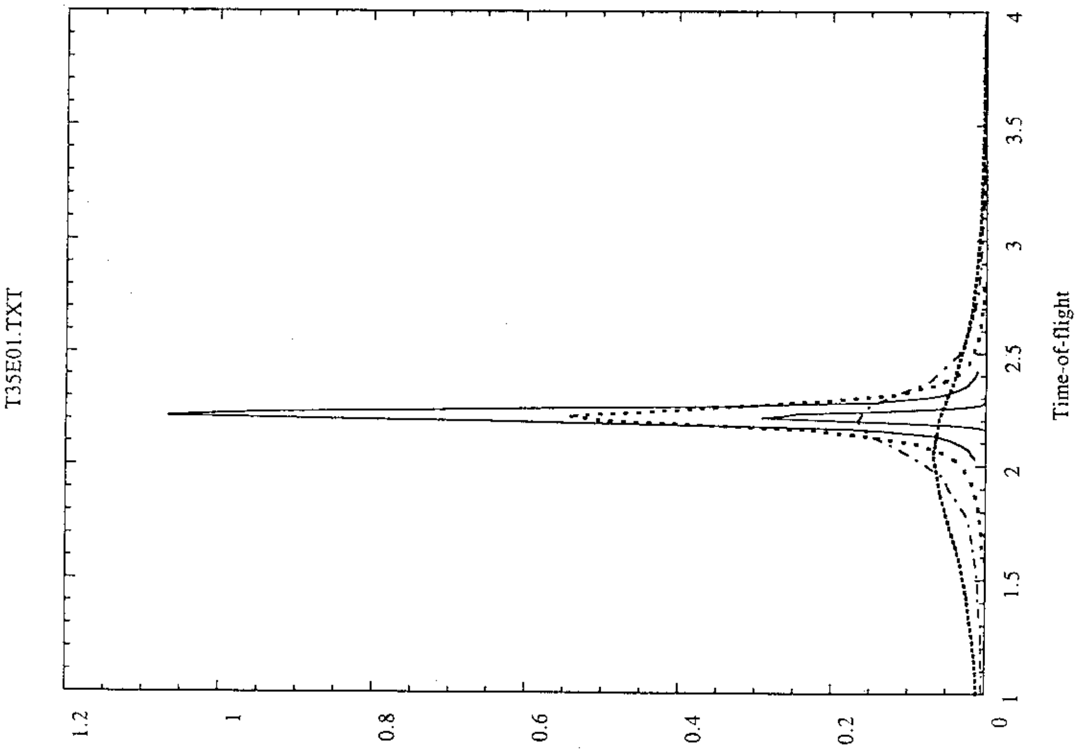
Polystyrene in deuterated cyclohexene c=0.022g/cm^3

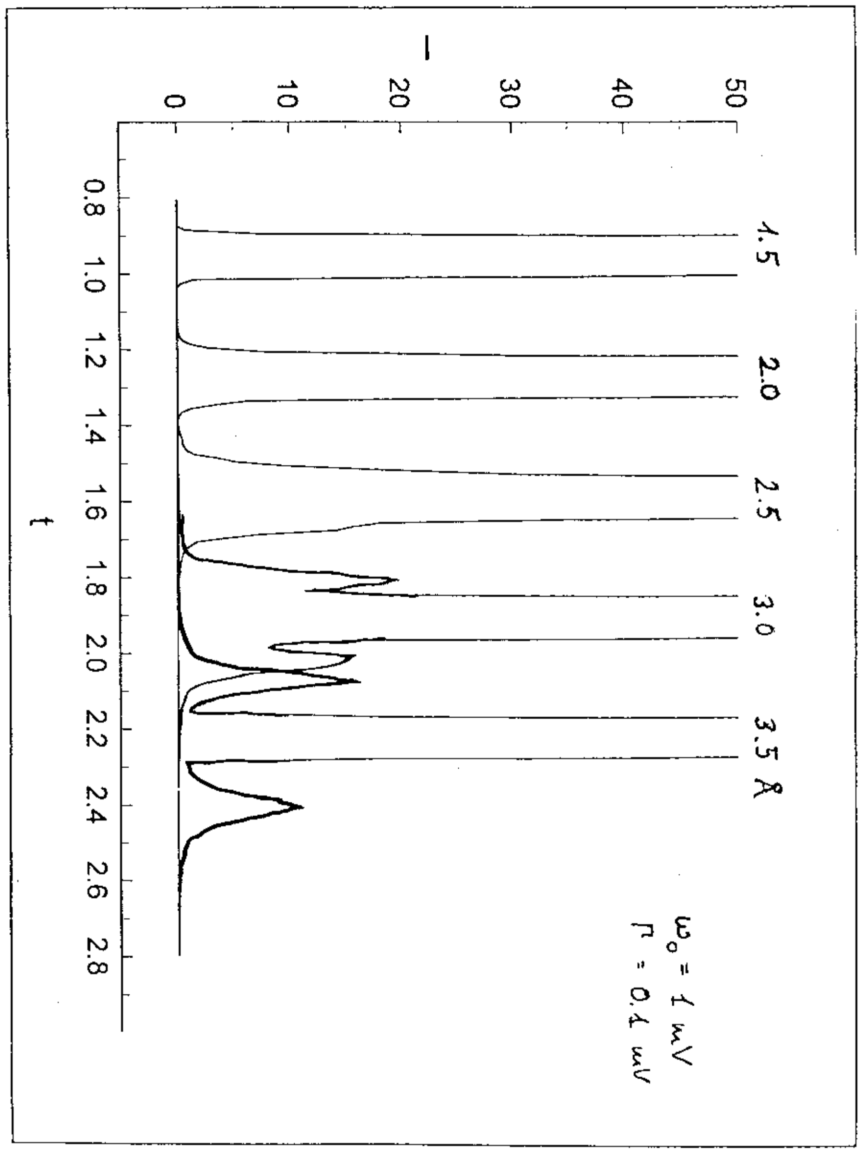



counts {a.u.}
0
1
2
3
4
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Time-of-flight {ms} (5 different frames)
1.5 A
2.0 A
2.5 A
3.0 A
3.5 A
Figure of merit: F
○ — — Low res: I
● — — High res I/(δE)²
ΣF_λᵢ ≥ 5 * F_2.5
f ≈ 1


T25E01.TXT
Time-of-flight
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6
7
8


T15E01.TXT
Γ = 0.1 meV
0.3
1
3
Time-of-flight
0
5
10
15
20
25
0
0.5
1
1.5
2
2.5
3


T35E01.TXT
Time-of-flight
0
0.2
0.4
0.6
0.8
1
1.2
1
1.5
2
2.5
3
3.5
4



CONCLUSIONS:

Conditions for $\langle\Phi\rangle_{eff} = \Phi_{peak}$

⇒ SANS, NSE, etc. $(\delta\lambda/\lambda \sim 5-10\%)$

$t_{sp} \sim 2-3$ ms

⇒ Anything else:

T_{rep}, t_{sp}: rather free
(Rep. Rate. Multipl. !

⇒ With $c \simeq 6-10\%$

$\nu_{rep} \sim 30$ Hz

⇒ L : 20 – 150 m, many guides

$N_{beam} \sim 50$ / target station

⇒ $\Delta\lambda$ small: OK
large: careful!

⇒ $\frac{L_{ch}}{L} = C_S$ e.g. $L_{ch} \simeq 4$ m $C_S \simeq 6\%$

$L \gtrsim 60$ m

F. Mezei's OHP Drawings for the Lecture III

F. MEZEI JAERI. 1996. 10. 30

NEXT GENERATION NEUTRON SOURCES

Today:

ILL (57 MW) ISIS (0.2 MW)

complementary
e.g.
10 x SANS 5 X
HiRes PD
(~ 1 Å)

Next generation: e.g. Kohn panel (US)

ANS (300 MW) Short Pulse Sp. S. (1 MW)

not feasible as **reactor**
(too expensive!)

Can it be achieved
by spallation?
(= much cheaper!)

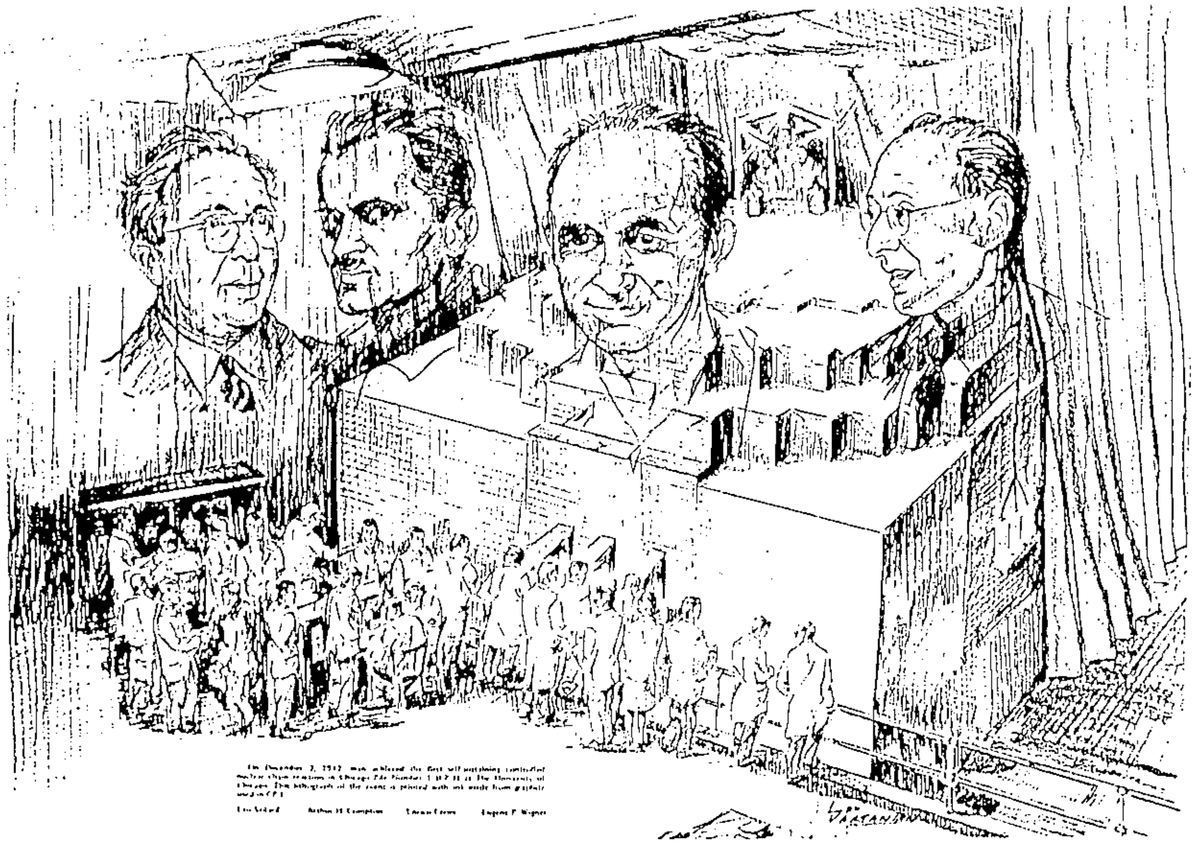
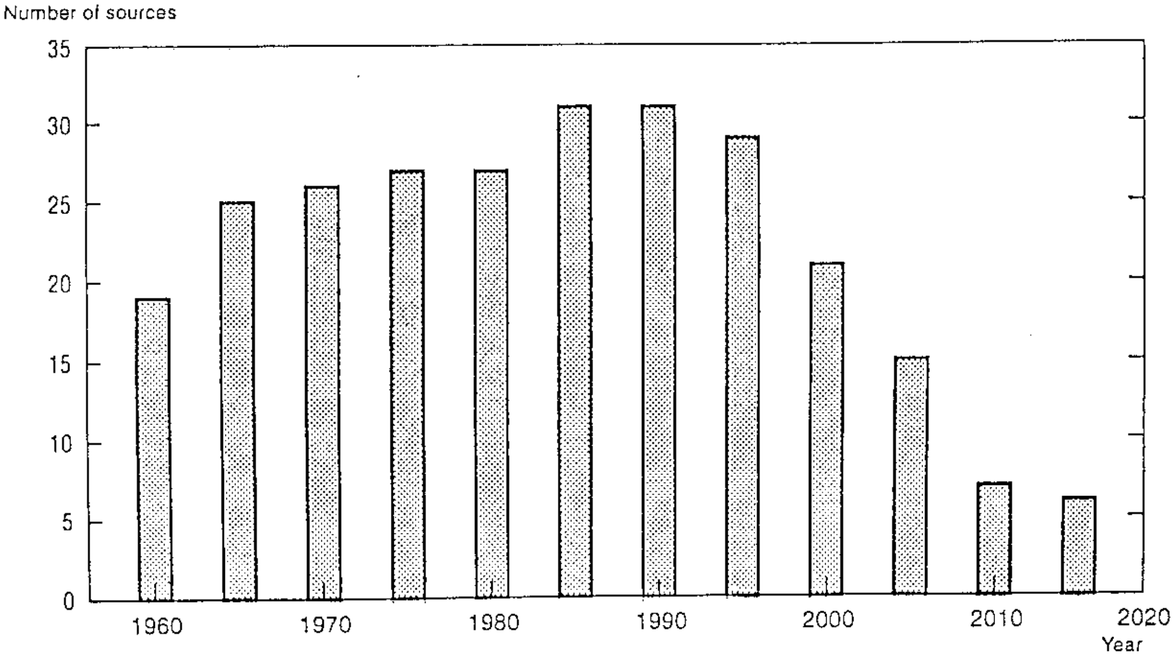


Figure 29. Number of neutron sources in OECD countries



Source: Table 1.

ICANS XII. 1993

COMPARISON OF NEUTRON EFFICIENCY OF REACTOR AND PULSED SOURCE INSTRUMENTS

F. Mezei, Hahn-Meitner-Institut/BENSC, Pf. 390128, D-14091 Berlin

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.)

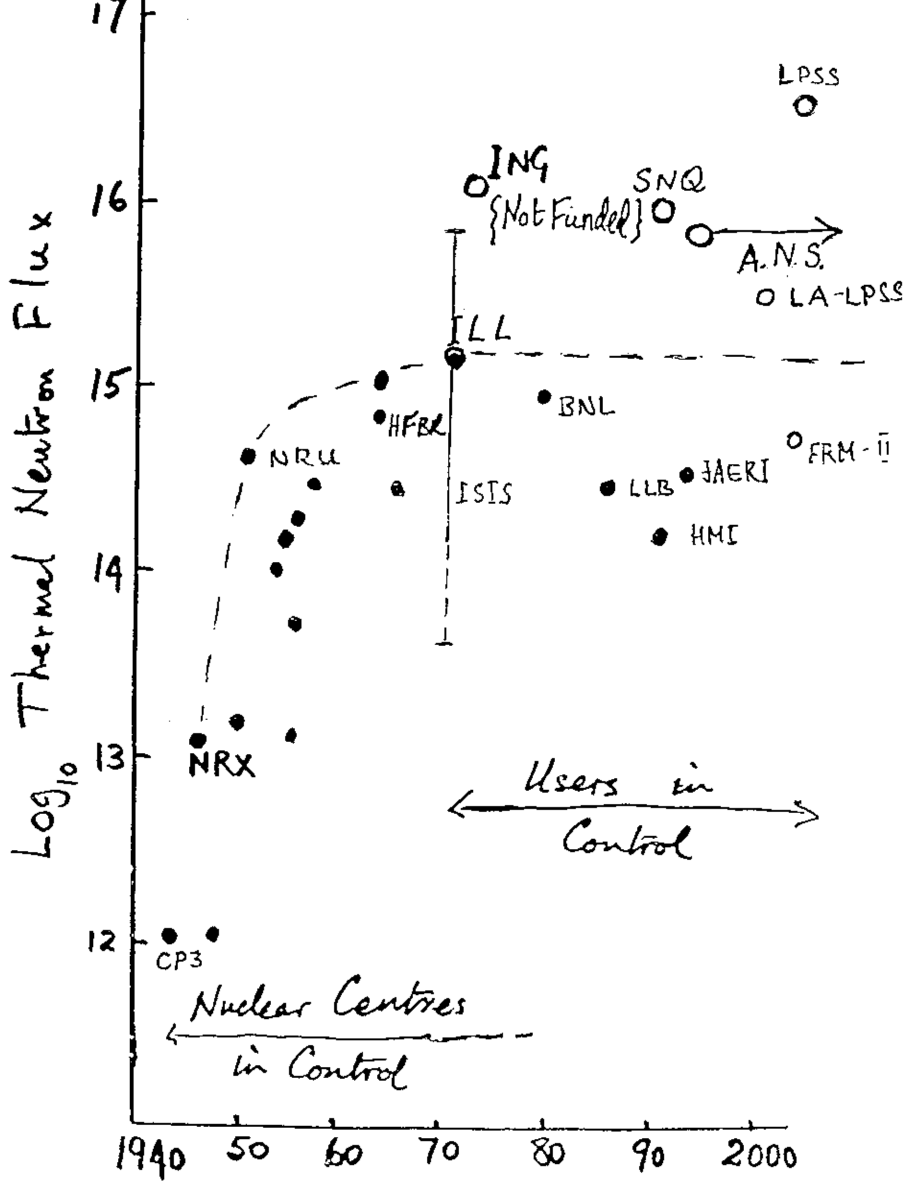
On the surface, this suggests that in order to cover all scientific opportunities offered by neutron scattering, both types of sources are needed. However, the argument of "complementarity" is incomplete: It does not include the costs aspect. What should really be compared is the "value for the money",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

Egelstaff (1991)

FIG.1.



Neutron Sources:

Flux limitation: heat production MW/l

Fission: 180 MeV/n

How to overcome the heat production limit?

Spallation: 25 MeV/n

Long Pulse Spallation Source (LPSS) + TOF Wavelength Band Monochromator Concept:

<u>use more of the produced neutrons</u>

- several wavelength instead of one: information processing
- source only needed for 10 % of the time

Flux on the sample: at same heat production - density

Φ(LPSS) ~ 70 *Φ(Reactor)

Feasible today: 10-20 MW LPSS

F. Mezei, Proc. ICANS XIII. (PSI, 1955)

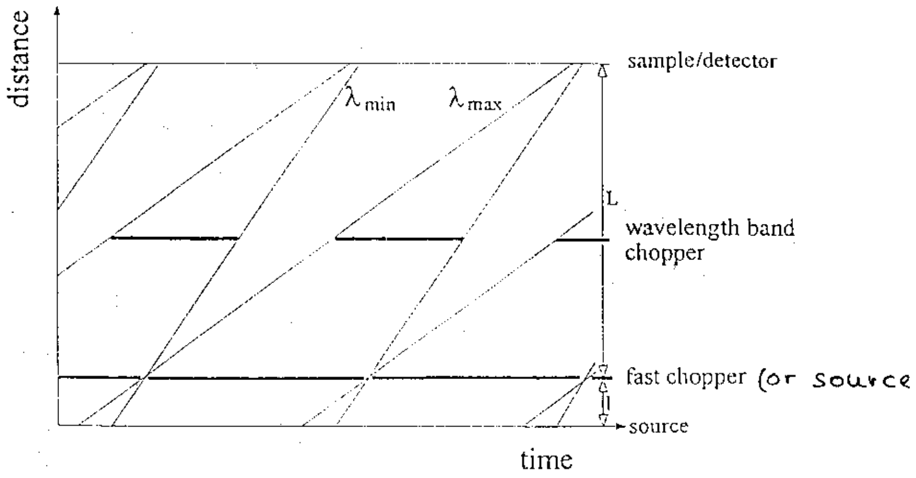


Fig. 1. The principle of TOF monochromators, after Ref. [1].

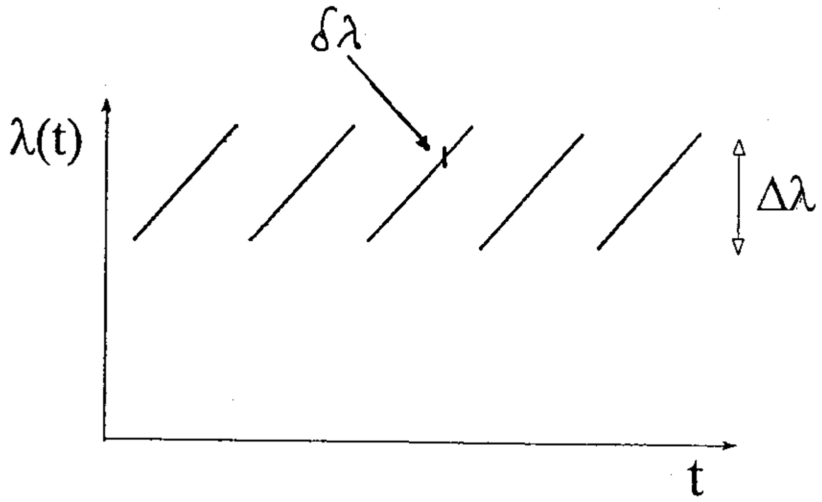


Fig. 2. Time dependence of the wavelength of the monochromatic beam in a TOF monochromator.

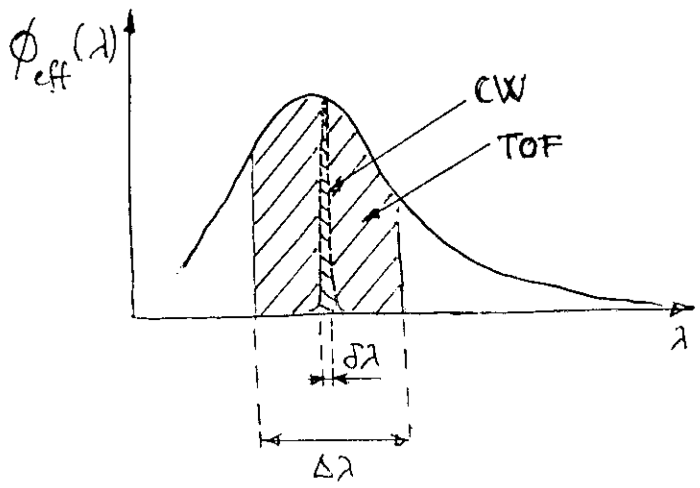
$$\delta\lambda = \delta t_{ch} / L$$

$$\Delta\lambda = T_{rep} / L$$

Duty factor:

f. chopper: $c \simeq \frac{\delta\lambda}{\Delta\lambda}$

source $c_s \simeq \frac{\ell}{L}$



- $\Delta\lambda$ can be relatively small ($\ll \lambda$)

$\lambda_1, \lambda_2, \lambda_3 \dots \lambda_n$: Information processing

TOF Monochromator

Narrow band approximation

Time average flux: (losses neglected e.g. absorbtion)

$$\langle \varphi_{sample} \rangle = \langle \Phi(\lambda) \rangle \frac{d\Omega}{4\pi} \delta\lambda$$

$$\downarrow$$

$$= \Phi_{peak}(\lambda) \frac{d\Omega}{4\pi} c \Delta\lambda = \qquad \Phi_{peak} = \frac{\int \Phi \, dt}{t_p}$$

$$= \Phi_{peak}(\lambda) \frac{d\Omega}{4\pi} \delta\lambda$$

⇒ Mean flux theorem:

$$\langle \Phi \rangle = \Phi_{peak}$$

state-of-the-art linac:

e.g. ESS: $\langle \Phi \rangle \simeq 3 \times 10^{16}$ n/cm²/

$\simeq 20 \times \Phi_{ILL}$

⇒ $\langle \Phi \rangle$ independent of wavelength band:

$$\Delta\lambda = \frac{h}{m} \frac{T_{rep}}{L} \qquad t_p = \frac{m}{h} \delta\lambda L$$

as long as $t_p < t_s$

$$(\Delta\lambda)_{min} = \frac{T_{rep}}{(t_p)_{\dots}} \delta\lambda = \frac{T_{rep}}{t_s} \delta\lambda = \frac{1}{C_s} \delta\lambda$$

Mean flux theorem:

$$\bar{\Phi}_{sample} = g\, f\, \hat{\Phi}_{peak}$$

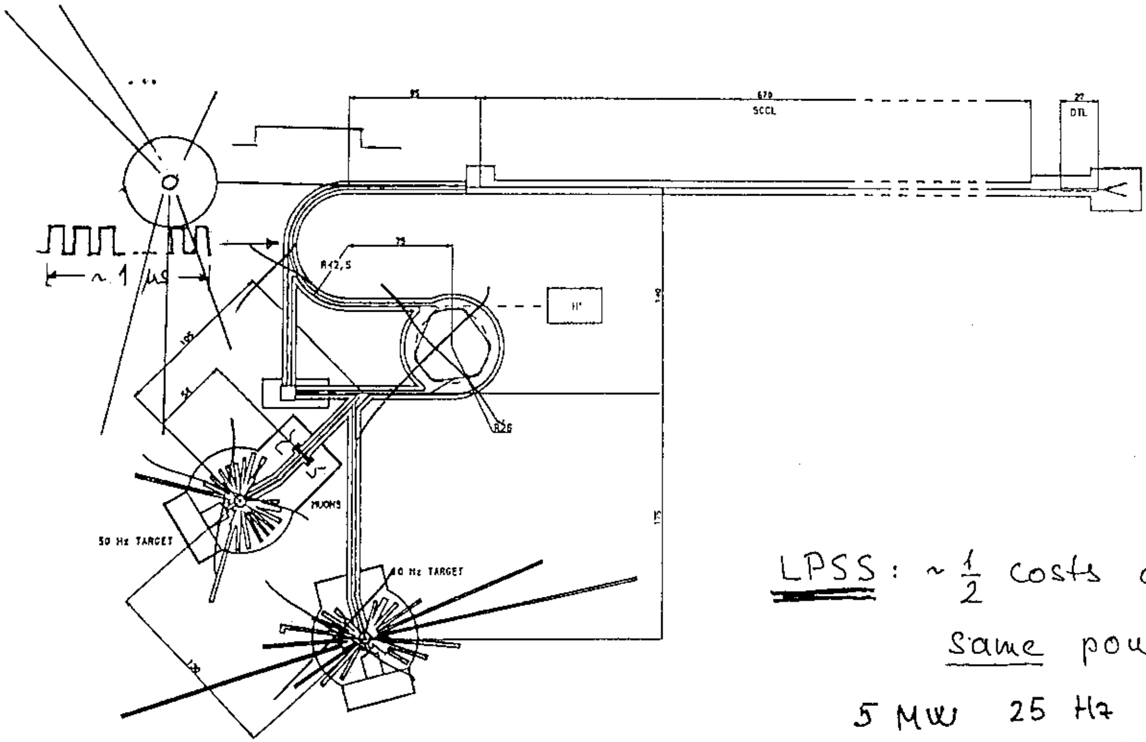
$$g = \begin{cases} 1 & \text{if } \delta\lambda = \delta\lambda_{desired} \\ \delta\lambda / \delta\lambda_{desired} & \end{cases}$$

"usefulness" of the bandwidth $\Delta\lambda$

$$f^{-1} = \frac{n t_i^{max}}{\sum_{i=1}^{n} t_i}$$

t_i = ideal measuring time with wavelength λ_i

$t_i^{max} = max(t_i)$



LPSS : ~ $\frac{1}{2}$ costs at
same power
5 MW 25 Hz 2 ms
600 Mio $
(basis: ESS study)

Figure 1.1 ESS Layout

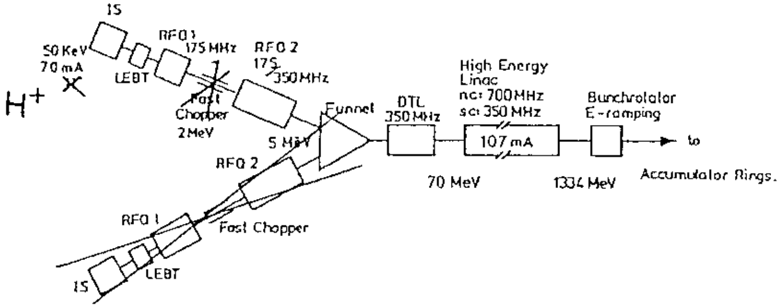


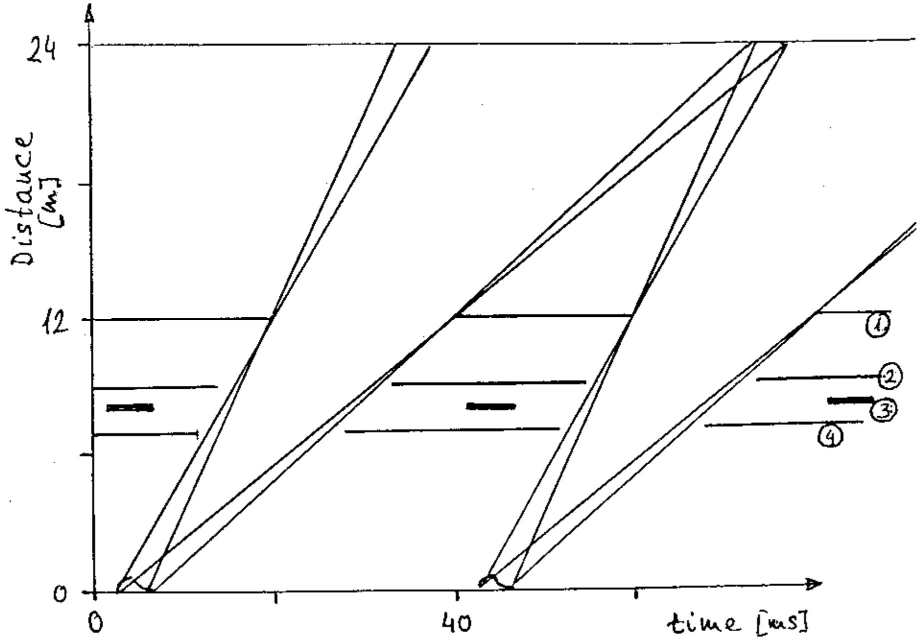
Fig 2.1: Proposed ESS linac scheme.

Injection pulse: ESS 1.2 ms
NSNS 0.5 ms

LPSS : 75 mA H⁺
1.35 GeV

Costs: Linac ≃ injection + ring

$\frac{\delta\lambda}{\lambda} \sim 10\%$: outside narrow band approximation



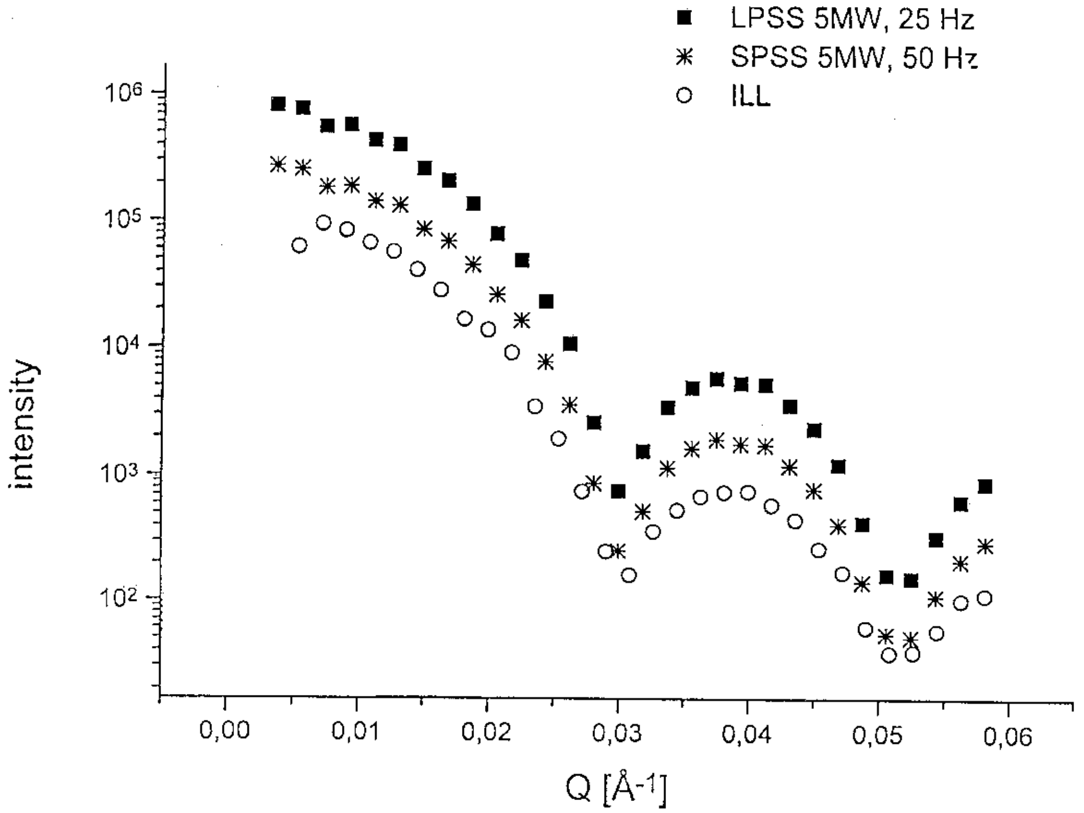
SANS example:
25 Hz
2 ms pulse length
24 m source — detector

③ t_0 chopper (fast neutrons)

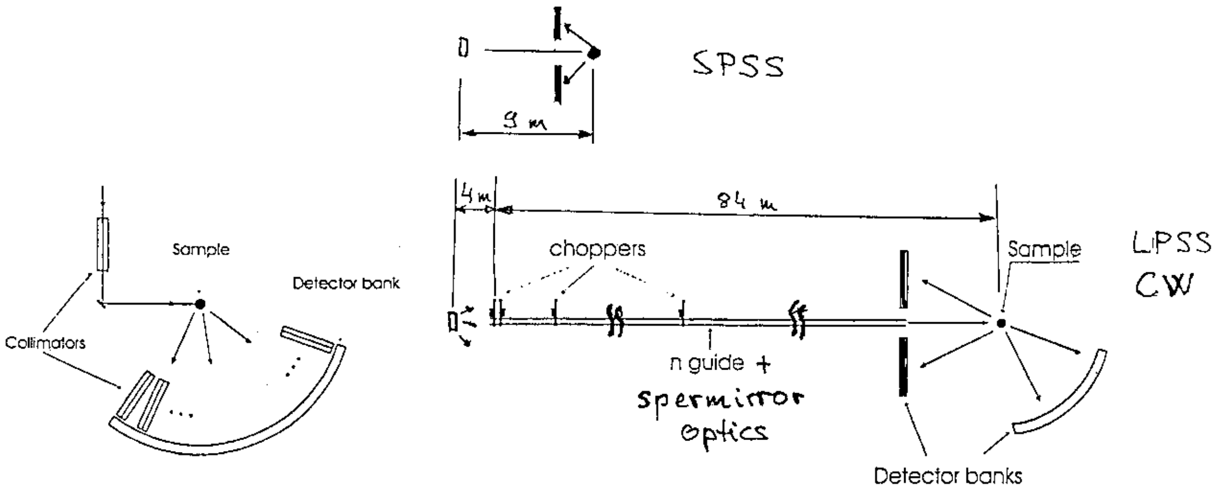
① + ④ wavelength band choppers :
filters for $\lambda < \lambda_{used} + 27$ Å

① + ② + ④ same but $\lambda < \lambda$ + 40 Å

SANS: hard spheres



Medium resolution powder diffr.

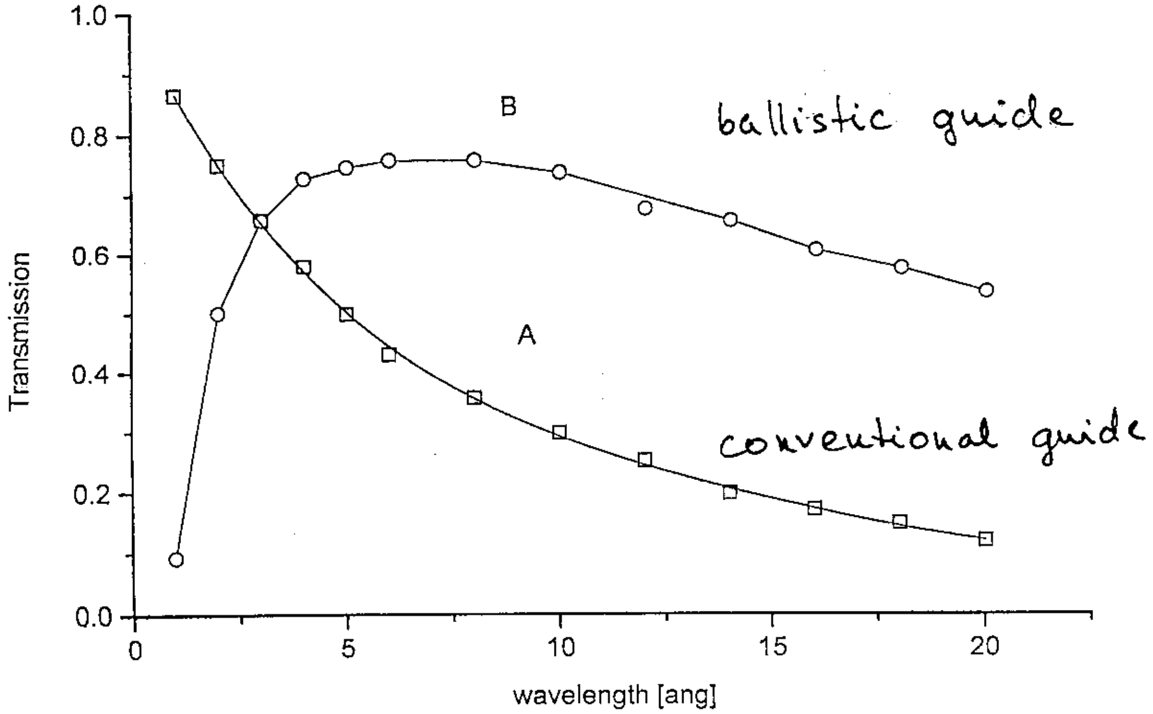


Xtal monochromator instrument

TOF monochromator instrument

Fig. 3: Layout of a crystal (left) and a TOF monochromator high resolution powder diffractometer.

200 m long guides:



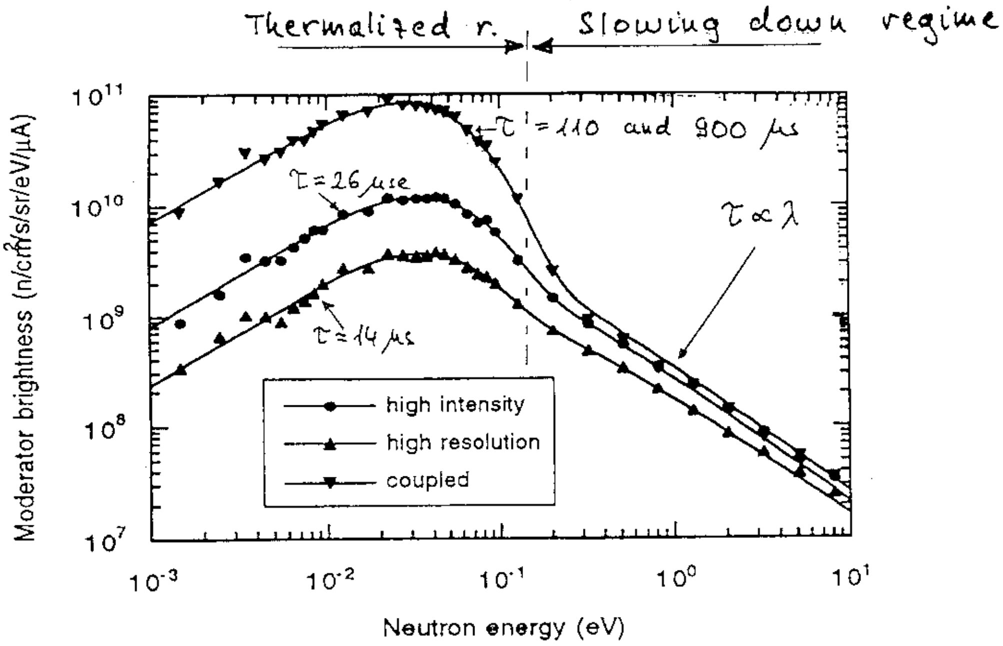
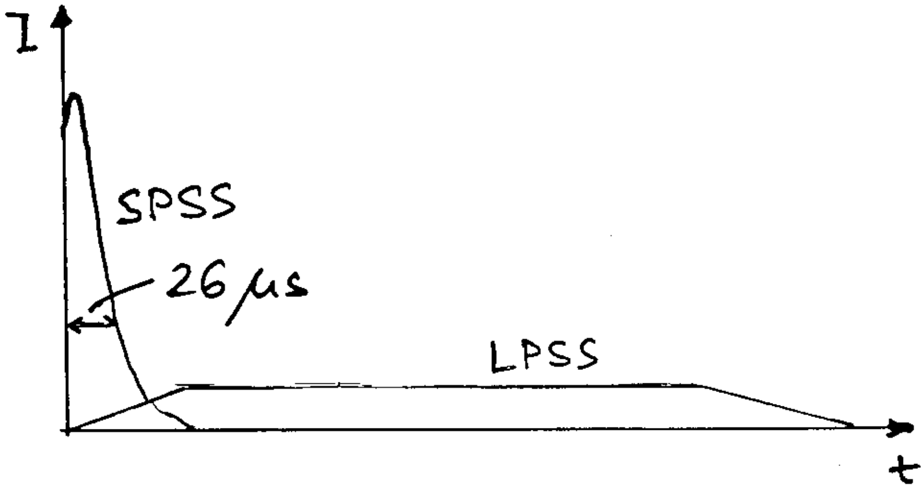
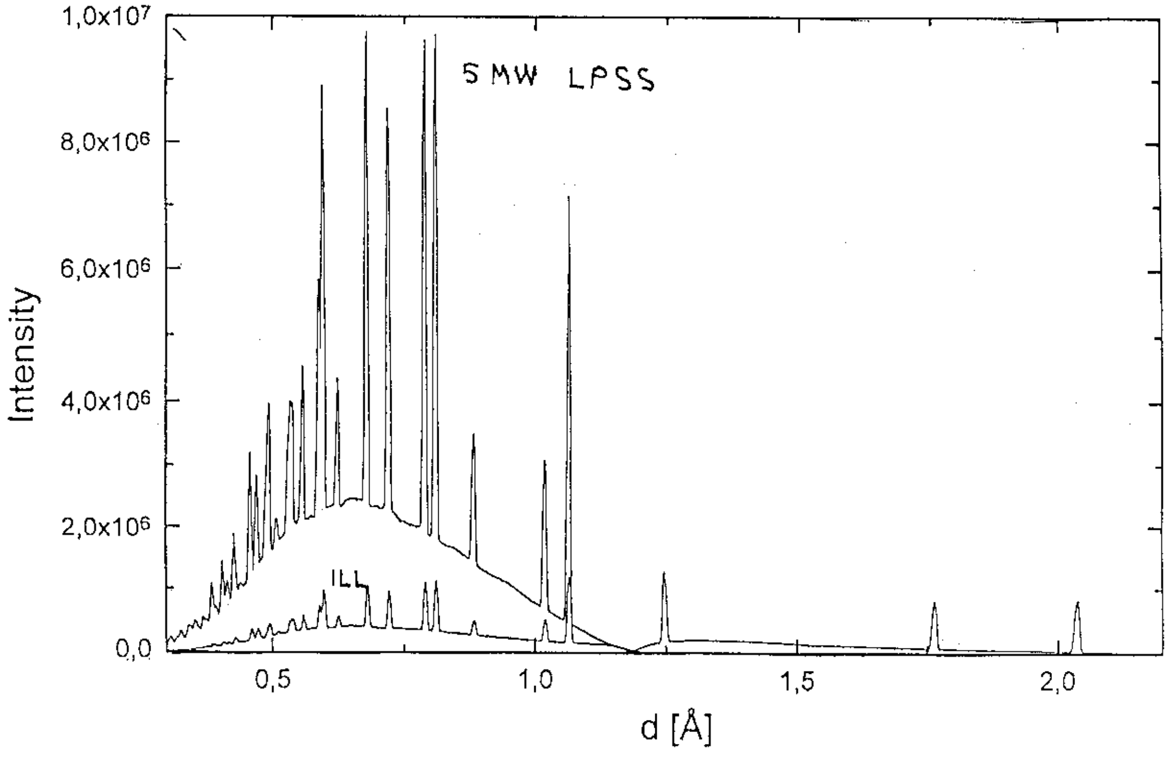
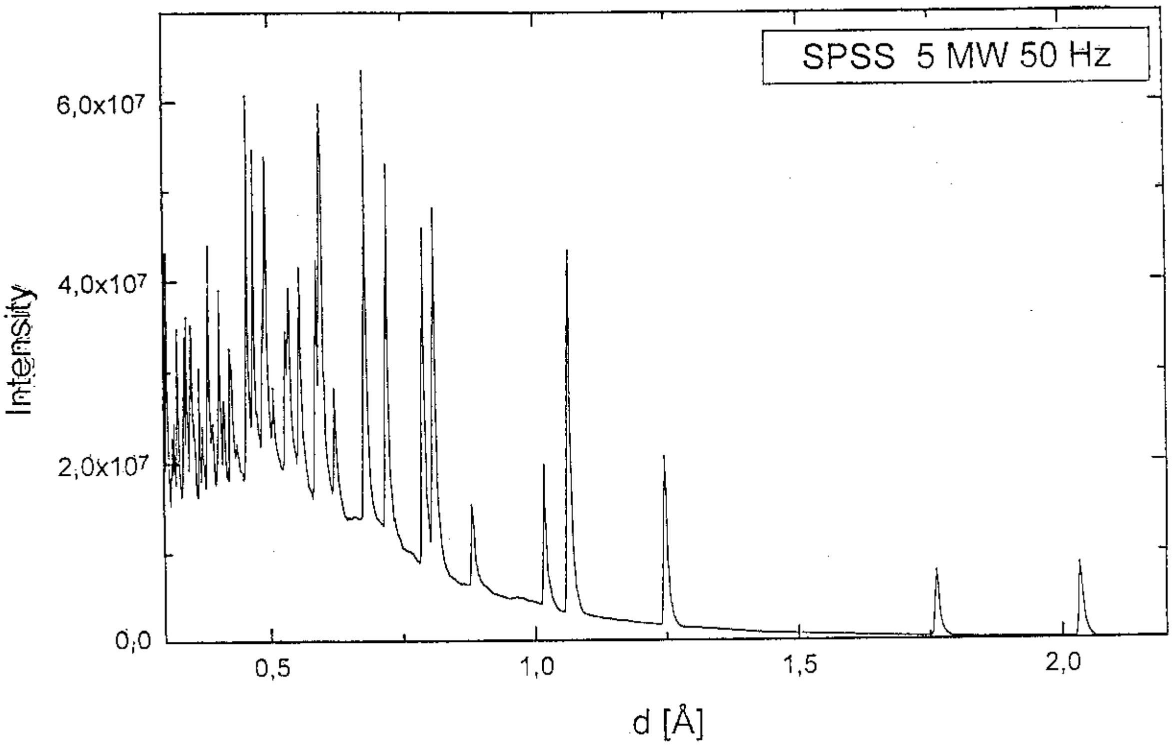


Fig. 2. Average moderator brightness as a function of neutron energy for three water moderators.

Ferguson et al, ICANS XIII.


I
SPSS
26 μs
LPSS
t


1,0x10⁷
8,0x10⁶
6,0x10⁶
4,0x10⁶
2,0x10⁶
0,0
Intensity
5 MW LPSS
ILL
0,5
1,0
1,5
2,0
d [Å]



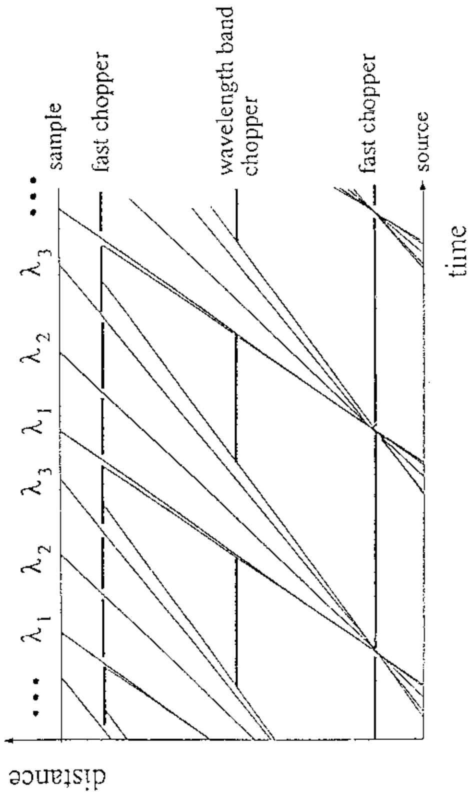


Fig. 6 Principle of TOF monochromator - TOF analyser inelastic spectroscopy with repetition rate multiplication [12].

Repetition Rate Multiplication
(FM 1995)

= generalized TOF - monochromator

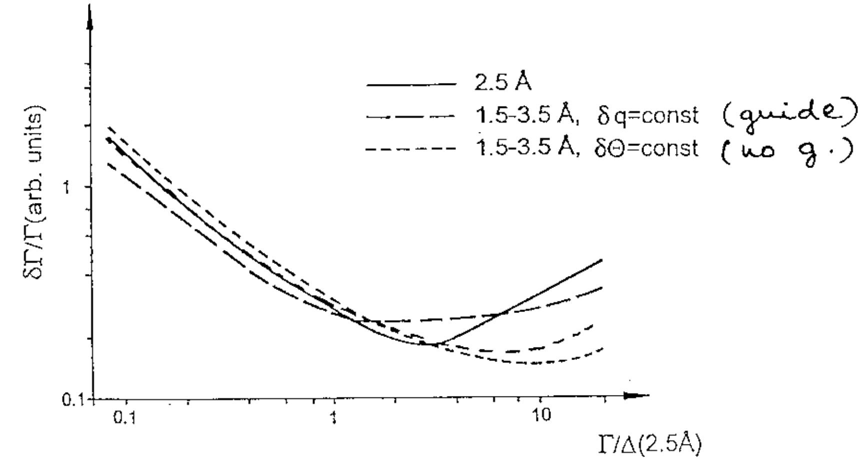
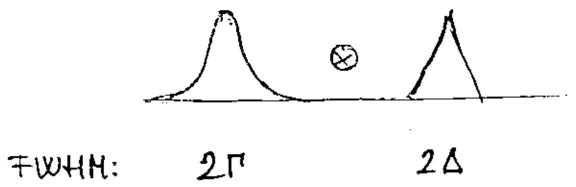


Fig. 8. Comparison of the data collection rates - as characterised by the error of the determination of quasielastic linewidths within equal measuring times - by the use of a single wavelength (continuous line) and five different wavelengths within the limits shown (see text).



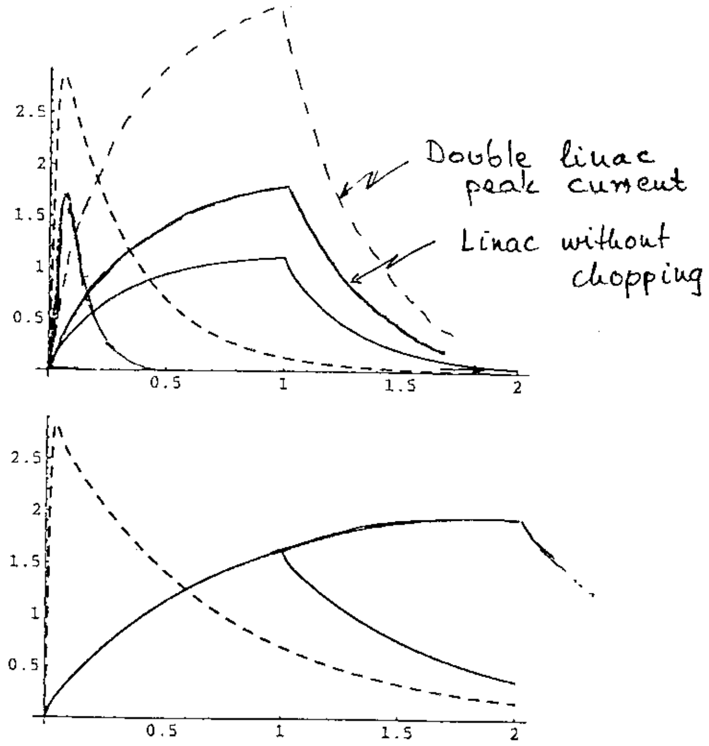


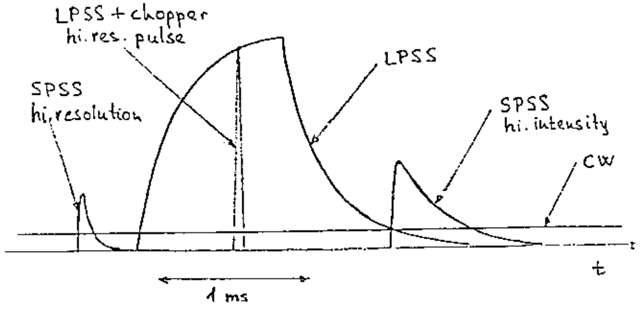
Figure 3: Pulse shapes for SPSS (dotted curve) and LPSS (solid curve) with different time constants. In the upper panel the decay constant is 300 μsec corresponding to a coupled, weakly-reflected target/moderator system (CWR) while in the lower panel the decay constant is 700 μsec, a value more typical of a strongly reflected system (CSR). The integrated intensity of the pulses in the lower panel is twice that of those in the upper panel.

Pyun x Daemen, ICANS XIII.

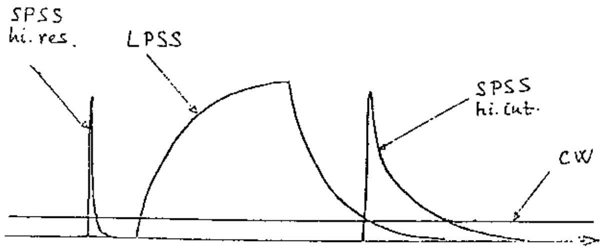
Comparison of neutron fluxes of cost-equivalent sources

CW: reactor source 60 MW (ILL)
SPSS: 0.67 MW short pulse spallation source: one of the two target stations of a 1 MW, 60 Hz source
LPSS: 4 MW long pulse spallation source, 60 Hz, 6.7 % duty factor

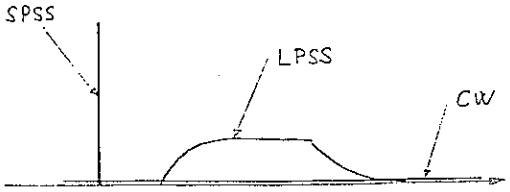
Cold neutrons



Thermal neutrons



Hot neutrons (~0.5 A) hot moderator assumed for CW and LPSS (guessed performance), without hot source: ~10 times smaller flux for CW & LPSS



LPSS optimum: 20-30 Hz rep. rate
2-3 ms pulses
Δλ band narrow
long instruments
>50 beams/target station

Reactor & LPSS superior to SPSS:

cold neutrons

thermal neutrons in thermalized regime

SPSS superior to LPSS:

hot, epithermal neutrons

thermal neutrons in slowing down regime (high res.)

LPSS performance: in neutron scattering at 5 MW

$\bar{\Phi}_{\text{sample}} \gtrsim 10\,\Phi_{\text{ILL}}$ ($5\Phi_{\text{ILL}}$ @30

Los Alamos project: 1 MW
Potencial: 10-20 MW