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The future of ESS is bright

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Abstract. The European Spallation Source ESS has still a huge upgrade potential by using an accelerator ring structure for proton pulse compression that can change the long pulse to a medium pulse structure. Therefore, we consider the performance of a medium pulse structure on the existing ESS target, moderator and neutron instrumentation. A medium proton pulse will enhance the neutron peak brightness of thermal and cold neutrons by about one order of magnitude and even up to two orders of magnitude at shortest wavelengths used at ESS, largely increasing the performance of the ESS instruments for neutron scattering. The arguments for a medium pulse length are that it is best adapted to the resolution requirements of the ESS instruments, the coupled moderator, the typical long instruments; furthermore, that it seems feasible to realise a medium pulse length by advanced, slow extraction from an accelerator ring, and feasible for the rotating tungsten target to take the high-power load. We discuss the implications of a medium proton pulse length and its specific choice for the instrument resolution, and for moderator and target. The proposed upgrade is stimulated by the new project ESSnuSB for a neutrino super beam at ESS and motivated by the synergy effect of using a common pulse compressor ring. The upgrade will be a most economical and efficient path for the ESS to a next higher level from an already world leading long-pulse source, transforming with a medium pulse structure into an even much more powerful, future next generation neutron source.

1 Introduction

The European Spallation Source ESS [1] is approaching operation with beam on target in 2025. Yet it is timely to look ahead into future perspectives of ESS. The present work is motivated further by the synergies of a major ESS upgrade and a new project, the ESS neutrino super-beam project ESSnuSB, which is detailed in a recently completed conceptual design report [2]. For any explanation of that the universe has survived from the matter-antimatter annihilation after the Big Bang, there must be enough charge-parity violation (CPV) in nature. Such a CPV has till now not been observed. However, an observation of a difference in the flavour oscillation of neutrinos and antineutrinos, respectively, would be a sign of CPV. It is therefore now a paramount interest to try to discover such a difference and in particular also to measure its value. With the world's most powerful proton LINAC at ESS, it has been concluded that a more precise value of the CPV can be measured with the ESSnuSB large neutrino detector located at a distance from the ESS neutrino source in Lund where the neutrino flavour oscillation has its second maximum, as compared to the other long baseline neutrino experiments in the world, which have their neutrino detectors located at the closer first oscillation maximum. Therefore, it is proposed to raise the power of the ESS LINAC from 5 MW to 10 MW by increasing the frequency of the 2.86 ms long proton pulses accelerated in the LINAC from 14 Hz to 28 Hz, extract the additional 14 proton pulses per second sideways from the LINAC, inject them into a 400 m circumference compressor ring during many turns, and finally extract the stored protons in one turn, thereby creating 1.3 μs short pulses. Such a ring could also be used for pulse compression for neutron spallation at ESS, offering a tremendous possible increase in neutron peak brightness. In this context, it is most important to point out the appropriate best use of compressed pulses for neutron instrumentation at ESS, and next how to meet the challenge of an unprecedented peak power of protons hitting the target. Taking the proton beam with a compressed pulse of 1.3 μs on the neutron spallation target would increase the instantaneous power load on the ESS target to a peak power of 275 GW. As proposed earlier, one mitigation to achieve an acceptable peak power, is a slow extraction of protons in multiple turns from the ring [3]. Clearly, to optimise the structures for generating spallation neutrons and neutrinos is an overarching endeavour, combining considerations of the best benefit for neutron instrumentation with possible technical realisations for target and accelerator. Hence, we will aim for a new flexible accelerator ring that can deliver short 1.3 μs proton pulses for neutrino production and medium proton pulses of about 50 μs, - as will be discussed here -, for spallation neutrons, in

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each case with 14 pulses per second and each with final 5 MW power.

ESS is based on the long-pulse spallation source concept [4,5]. The ESS long pulse structure is directly generated by a powerful 5 MW LINAC without the typical use of a compressor ring at short-pulse spallation sources. This choice has been taken as a best cost-benefit compromise [5]. There are certainly benefits of the long pulse structure as discussed in [6]. Perhaps most importantly, it can make consequently use of fully coupled moderators providing highest average flux. Only one moderator system is required to serve all instruments. Any instrument specific resolution can be generated by pulse shaping choppers, which can favourably tailor sharper pulses with even symmetric pulse shape. With such flexibility in setting resolution requirements, typically an ESS instrument can cover more experimental needs than single instruments at other facilities. The ESS average flux is comparable to the existing most intense reactor sources ILL at Grenoble, FRM-2 at Munich and HFIR at Oak Ridge, albeit with a peak brightness that at least for cold neutrons is superior to the best current short pulse spallation sources, JPARC and SNS. The first construction goal at ESS will be to achieve 2 MW at 0.8 GeV. With further optimization of the moderator [7], it will already yield about the same neutron flux that has been predicted by the originally design for 5 MW [1].

A compressor ring at ESS producing short pulses, which is required by ESSnuB to achieve a sufficient suppression of the background from cosmic radiation in the large underground neutrino detector, also creates new opportunities for neutron production and its time structure. The conventional approach for an upgrade by using short pulses would be to build a new target station and new instrumentation. Such an approach however would take neutrons from the existing neutron target and diminish its value. In this paper, we want to explore an exiting alternative, the potential of using compressed pulses for the existing target and the coupled moderator, and the existing neutron instrumentation [6]. Most characteristic features of the ESS are the long proton pulse of 2.86 ms generated with 14 Hz repetition rate by a most powerful 5 MW superconducting LINAC, a He-cooled rotating tungsten target, and a new developed coupled moderator of high brightness, which offers cold and thermal neutrons for each neutron beam port [7]. To achieve adequate time-wavelength resolution, beamlines and instruments at ESS, shown in Figure 1, tend to be comparatively long, up to 160 m, nonetheless, pulse-shaping choppers are required for most of the instruments, essentially cutting intensity for resolution. Now a first simple goal is to preserve the full flux by generating a sufficiently short pulse for all instruments.

The potential of a medium pulse source to reach higher neutron peak brightness has been recognised earlier [3,8]. In Ref [8] the authors envisaged to build a new target station with dedicated neutron instruments, which would require a much longer lead time for realisation. In contrast, the upgrade concept presented here can take a short-cut with realisation within the next decade.

In the following, we first briefly discuss the aspects for accelerator and target, and next the time-wavelength dependent response of the coupled ESS moderator. The consequences for the various neutron instruments will be discussed within a preliminary analysis to guide a realistic and most promising upgrade path of ESS.

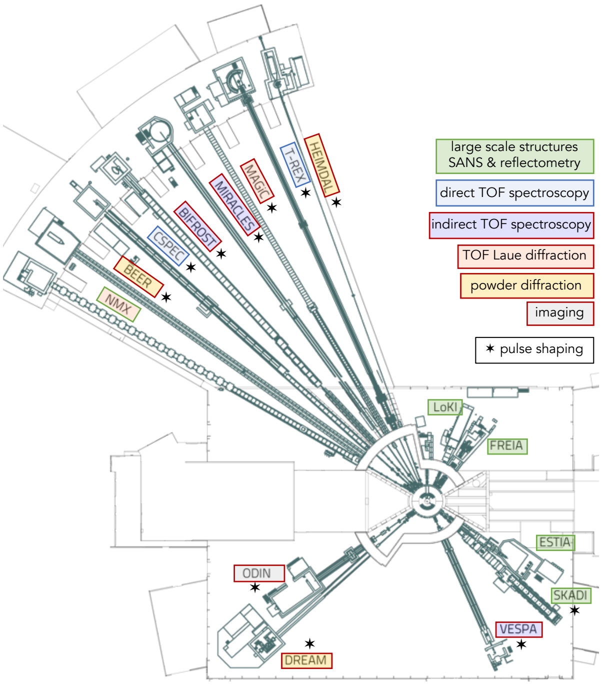

Fig. 1. Layout of the ESS neutron scattering instruments. A major fraction of the instruments, marked with an asterisk, uses pulse shaping choppers.

2 Accelerator, target and moderator

2.1 Accelerator

The plan for the ESS neutrino Super Beam project ESSnuSB is to operate the ESS LINAC at 28 Hz, where the additional pulses are used for neutrino production. As already described, this implies a doubling of the power from 5 to 10 MW and an accumulator ring, which requires the addition of an H^- source, with pulse compression from 2.86 ms to 1.3 μs. Within this upgrade, the energy of the ESS LINAC will increase from 2 GeV to the originally designed 2.5 GeV. The short pulses are required for detecting neutrino oscillations with a sufficient signal-to-background ratio. In fact, these pulses have a sub-structure of four separated pulses, and to decrease the instantaneous power load for the target, the beam will be split and delivered to four separate targets.

With advances of accelerator technology, it appears feasible to extract alternatively longer pulses to adjust to the acceptable peak power for the neutron spallation target and to better match to the moderation times of thermal and cold neutrons. A proposal in this direction has been made already in 2013 [3]. This scheme is proposing to use a large stacked (4 rings) storage ring with a circumference of 1100 m and fast strip line kickers to enable low loss bunch-by-bunch extraction generating a bunch-train of a total length of 50-100 microseconds. Another very interesting proposal has been made by S. Machida [9,10] to use a cyclotron like extraction scheme from an accumulation ring. Back-of-the-envelope calculations indicate that the scheme would have low losses in the extraction region and that the proposed extraction mechanism is feasible. Finally, slow extraction from the ESSnuSB accumulation ring using a fast integer resonance scheme has also been proposed by M. Olvegaard [9,10]. The challenges to operate a high-power H^- ion LINAC are substantial, which can be met with recent technical advances by direct H^+ injection to a ring as presented by C. Prior [9,10].

2.2 Target

The ESS target [11] is a rotating tungsten wheel, which is cooled by He-gas flow, and seems to be a most favourable choice in view of high-power load. The original design stems from the SNQ design study by G. Bauer *et al.* in 1981 [12], which already included a compressor ring as an upgrade option. With the choice of tungsten, the SNQ target should have been capable to take the compressed pulses from the 5 MW source operating at 100 Hz, corresponding to a peak power of 71 GW, for compressed pulses of 0.7 μs [12]. The rotating tungsten target has been taken also as the preferred choice for the SNS second target station STS [13]. At final average power at SNS of 2.8 MW at 60 Hz repetition rate and 0.85 μs proton pulse duration, the peak power will reach 55 GW. One may further compare to the peak power of targets at other short pulse spallation sources, 40 GW at JPARC using a liquid mercury target like the current SNS target, and 50 GW on a stationary tungsten target for the ISIS-II upgrade project [14]. This comparison suggests that without severe modifications, the ESS target should be capable for taking similarly a peak power near to 50 GW, which would correspond to an acceptable minimal pulse length of about 7 μs.

Note that the pulse compression has no impact on slow processes like target cooling, although radiation embrittlement may have an impact for the required elastic properties. The relevant fast process is due to thermo-mechanical shock waves. The dynamical stress limit of the tungsten material is 90 N/mm^2. The dynamical stress/strain due to shock waves can be estimated by $\sigma = E\,\alpha\,\Delta T$, where $E\,\alpha$ is the product of the elasticity module and thermal expansion coefficient, and ΔT is the temperature gradient emerging in a tungsten block upon the proton pulse impact. A rough, conservative estimate yields $\Delta T \sim 150$ K, with 357 kJ/pulse, the specific heat of tungsten, and heat distribution profile [10], indicating that the stress/strain can be unacceptably high, $\sigma \sim 270$ N/mm^2.

There are two mitigations. One is stress release for $t_p > t_0$, *i.e.* if the proton pulse duration t_p is larger than the time t_0 of sound waves passing through the heated region. Estimating $t_0 \sim 20\ \mu$s for a characteristic length of $\Delta l \sim 10$ cm yields that a pulse of $t_p > \sim 60\ \mu$s is acceptable. The second, and relative straightforward option seems to be a modification of the currently large tungsten block structure towards a more granular target. Filling the rotating target wheel with smaller blocks or grains of a few cm size will reduce temperature gradients to less than 50 K to stay below the dynamical stress/strain limit.

Clearly, a thorough analysis and simulation of the ESS target and possible modifications are of very high interest, since the above considerations suggest a possible stable solution avoiding destructive shock waves even for short proton pulses. There are more material aspects to consider in detail, like the internal steel structure in the wheel, its enclosure material with the proton beam window. With respect to the proton beam spread, the current rastering scheme could be replaced by an appropriate defocusing of the proton beam, however, in comparison to the LINAC, the ring will generate already much a larger beam size.

2.3 Moderator

Optimising for high neutron flux and long pulses the ESS has chosen a coupled, 3 cm flat moderator with a “butterfly” shape, where a thermal water moderator is placed next to a para-hydrogen cold source, with open view to all instrument beamlines [7]. It is straightforward to evaluate the performance of the ESS moderator for shorter pulses, since the response of reflector and moderator to generated spallation neutrons is unchanged and the neutron pulse is determined by a convolution of the proton pulse with this response function. The corresponding wavelength-time dependent neutron flux distribution for a 50 μs short pulse as calculated by Vitess [15] is shown in Fig. 2.

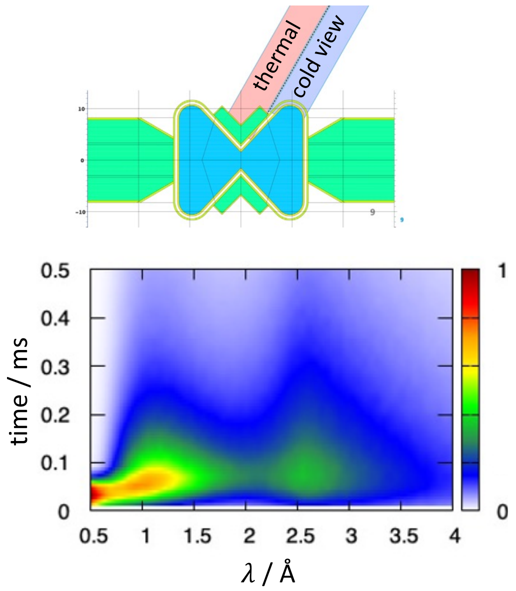

Fig. 2. (top) The ESS butterfly moderator and (bottom) the wavelength-time dependent brightness for 50 μs proton pulses in an approximate Vitess model.

There are two peaks related to the spectra from the thermal and cold moderators. The time dependence displays a characteristic asymmetry, whose asymptotic behaviour is independent of the proton pulse duration. Upon entering the epithermal region near 0.5 Å, one may note relatively sharp neutron pulses, since the neutron energies essentially decouple from the moderator.

The effect of varying proton pulse duration is shown in Fig. 3. While the integrated flux remains unchanged, a large increase in peak brightness is found for a compressed shorter pulse length: for a 50 μs pulse, the gain is approximately an order of magnitude at 4 Å, a factor 18 at 1Å, and a factor 57 at 0.5 Å. For cold neutrons, as shown in Fig. 3 (*top*), the neutron pulse width is essentially the same for proton pulses shorter than ~100 μs. In the MCNPX [16] simulations, the cold moderator is viewed under an angle of 30 degrees, and thus viewing the full depth of the cold para-hydrogen moderator resulting in a pulse width of ~300 μs. For larger viewing angles, the width is expected to be shorter down to ~200 μs.

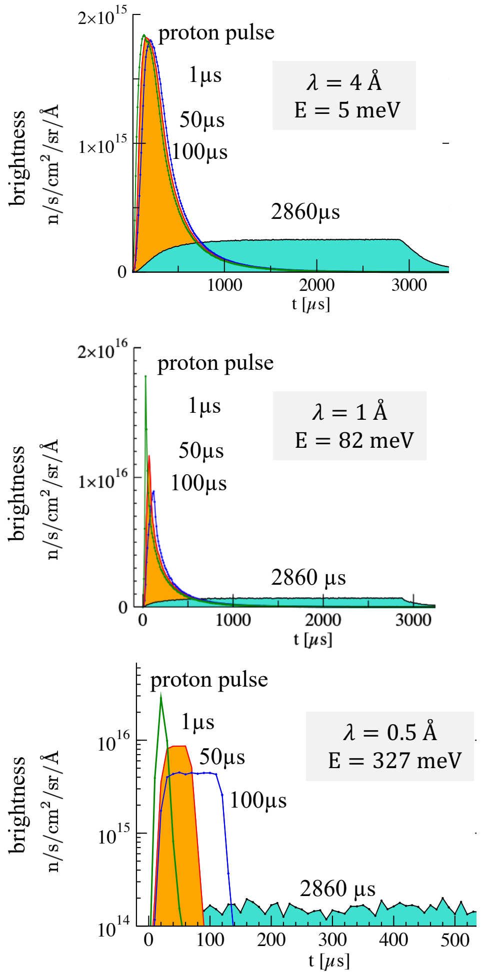

Fig. 3. Neutron brightness of the ESS moderator obtained by MCNPX simulations for various proton pulse lengths, from short pulse 1μs to medium pulse lengths of 50 and 100 μs, and the long pulse of 2860 μs, for neutrons at 4 Å (*top*), 1Å (*middle*) and 0.5Å (*bottom*, *note log-scale*).

For thermal neutrons, as shown in Fig.3 (*middle*) for 1 Å, the neutron pulse width varies significantly with the proton pulse length, which leads to significant further gain. For a 50μs proton pulse the gain factor is 18. Particularly, upon entering the epithermal region, the widths of neutron pulses are essentially determined by only by the proton pulse width for proton pulses, if longer than ~20 μs. For 50 μs proton pulse duration, we observe a gain factor in peak brightness of 57 at 0.5Å, see also Fig. 3 (*bottom*) on log-scale.

3 Neutron instruments

A first evaluation of the possible performance gain for the neutron scattering instruments at ESS [6] can be obtained by comparing the gain in Fig. 4 for the wavelength band used by each instrument, resulting in a gain varying from almost one order of magnitude at long wavelengths up to two orders of magnitude at short wavelength below 1 Å. However, the latter fact also reflects that the peak brightness of the long pulse is comparatively low to short pulse sources. The shortest wavelengths used at ESS instruments are about 0.5 Å for competitiveness, increasing difficulties to use choppers and efficient transport by neutron guides. A more accurate estimate of the actual gain for the instruments needs to consider the instrument specific requirements for time-wavelength resolution and the wavelength band of operation.

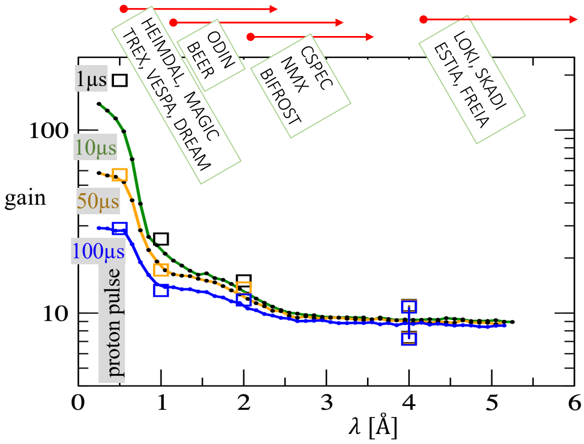

Fig. 4. The relative gain in peak brightness for ESS instruments as a function of wavelength for medium proton pulse lengths with respect to the case of the long 2860 μs proton pulse. Lines show results of gains from Vitess simulations for 10 μs (*green*), 50 μs (*orange*), and 100 μs (*blue*), while squares represent estimates from MCNPX for 1 μs (*black*), 50 μs (*orange*), and 100 μs (*blue*).
Red arrows indicate the approximate the wavelength band of operation for four groups of instruments, see text for more details.

The class of instruments for **large scale structures** appears to be best suited for the long pulse. Nonetheless, in all cases, for the SANS instruments LOKI and SKADI, for reflectometers ESTIA and FREIA, as well as for NMX the time-of-flight Laue diffractometer for macromolecular crystallography, improved resolution is generally desirable, certainly not a disadvantage.

Depending on the resolution required for the science application, one may expect modest gains by factors varying from one to four.

There are two **direct time of flight spectrometers**, the cold and thermal instruments CSPEC and TREX, respectively. The possible gains are an order of magnitude in the cold range, and even higher for thermal neutrons at wavelengths below 1Å, see Fig. 4, achieving a resolution, which otherwise requires pulse shaping. The pulse-shaping for multiple discrete wavelengths focuses on the central part of the neutron pulse. Hence, the existing choppers can still be used to improve the resolution further at a much higher peak brightness or can be applied to cut-off the asymptotic tail of the pulse without loss in signal or band width.

All other instruments at ESS use pulse shaping choppers near to the monolith at ~6.2 m distance from the source to generate, -depending on the instrument length-, one or more continuous wavelength spectra with flexible resolution. Reducing the neutron pulse width at the moderator, will shrink each wavelength band. While this will be useful and possible to work with, the preference should be a pulse that is short enough that instruments normally can operate without pulse-shaping.

There are three **indirect time of flight spectrometers**, the backscattering spectrometer MIRACLES, the extreme environment spectrometer BIFROST, and the vibrational spectrometer VESPA, which use a wavelength band near ~6.3 Å for backscattering, and larger than approximately 1.5 Å and 0.5 Å, for BIFROST and VESPA respectively. At large wavelength, see Fig.2, the impact of the proton pulse duration on the neutron pulse width is negligible for $t_p <$ 100 μs. For the backscattering instrument, viewing the source at an angle of 54°, the expected neutron pulse width is ~200 μs, which results in a total resolution of 3.5 μeV. Pulse shaping can still yield an ultimate ~2 μeV resolution within 260 μeV energy transfer near the elastic line. A time resolution of ~200 μs at 20 meV incoming energy is a typical goal for the BIFROST instrument as specified in the instrument proposal. It is also achievable for medium proton pulses of less than ~100 μs. A better time resolution would be preferred for the instrument VESPA, covering energy transfers from ~250 meV down to 4 meV. A pulse width of 70 μs results in 1% resolution for 250 meV, suggesting to preferably aim for a proton pulse of ~50 μs. The performance gain for these instruments is up to one order of magnitude, with even possibly higher gain at short wavelengths depending on the achievable proton pulse, see Figure 4. Essentially there are no needs anymore to employ pulse shaping choppers.

In the diffraction class of instruments, the **powder diffractometers** DREAM and HEIMDAL use rather flexible pulse shaping to adapt resolution. Choosing a typical good time-wavelength resolution of ~0.3% can be achieved with a 50 μs proton pulse. The existing pulse shaping chopper systems can still be used for much finer resolution, to detect subtle symmetry breaking and peak splitting, albeit using the much higher peak brightness on a smaller wavelength band. Modifying the slit pattern of the chopper disks can generate multiple wavelength frames to recover the full wavelength band. These instruments using wavelengths $\lambda > 0.5$ Å strongly benefit from shorter pulses and higher peak brightness. Similar estimates can be made for the **engineering diffractometer** BEER and the polarised **single crystal diffractometer** MAGIC, starting with $\lambda > 1$ Å and $\lambda > 0.6$ Å, respectively. For the specific engineering case of strain analysis, a symmetric peak shape would be preferable. Again, this can be done with the existing pulse-shaping choppers for a smaller wavelength band, or with many wavelength frames for the full wavelength band using a modified slit pattern.

While in many cases for **imaging** the time structure is not used, - so called ‘white beam’ imaging -, there is an enormous information potential in the wavelength dependent transmission signal that can be measured at pulsed sources with sufficient time resolution. Examples include diffraction contrast at Bragg edges and inelastic scattering contrast, whereas epithermal short pulses also allow for resonance absorption contrast [17]. The resolution requirements given for the imaging instrument ODIN vary from 0.3% to 10% and these are realized by pulse shaping choppers.

In summary, we note that a ~50 μs proton pulse will cover the most demanding cases. It is further worthwhile to note that shorter pulses will improve the signal-to-background ratio for all instruments.

It seems fortunate that many of the ESS instruments will strongly benefit from a proton pulse compression. In view of future instruments at ESS, this opens new opportunities for further optimisation particularly for less costly shorter instruments using a larger bandwidth. Hence, a shorter pulse raises the value of many still unused beamlines for shorter instruments.

4 Conclusion

With respect to the upgrade potential of the ESS, there is an obvious large possible gain in neutron peak brightness with proton pulse compression using a storage ring structure, which has been proposed as part of the ESSnuSB project. Most importantly, such an upgrade is of interest for the existing target, moderator, and neutron scattering instrumentation at the ESS. Therefore, the specific choice of optimal proton pulse duration should be that the resulting neutron pulse fits to the requirements for resolution for all instruments, at least for their standard modes of operation. In this respect, the resolution requirements for powder diffraction as well as for spectroscopy near 200 meV define the most demanding cases that could be fulfilled with a proton pulse length near 50 μs or of shorter times.

As a side remark, would it be even better to aim for a typical 1 μs short pulse? For the instruments using a flux optimised coupled moderator, there is practically no further gain compared to 10 or 50 μs. Furthermore, it does not seem to be attractive for future instrumentation to transform the ESS into a short pulse spallation source, since these usually operate more efficiently at higher frequency.

The current review of instrument performance aims to guide the common optimization for accelerator and target to realize a medium pulse at ESS. A more detailed consideration should be based on simulations of virtual experiments for all instruments. With beam on target and the following ramp-up of power, there will be a great opportunity to test a new time structure with shorter pulses at the instruments. While the average peak brightness of ESS will be already superior for a long pulse, a medium pulse length will considerably boost its peak brightness, which will preserve a world leading role of ESS in future among other existing neutron sources and upgrade projects [13-14] as shown in Fig. 5.

It is good to open this perspective now, as it assures the sustainable value of the current project and investment by a continuous upgrade path for the ESS, and it is timely to explore the detailed technical design that benefits to science with neutrons and neutrinos at ESS.

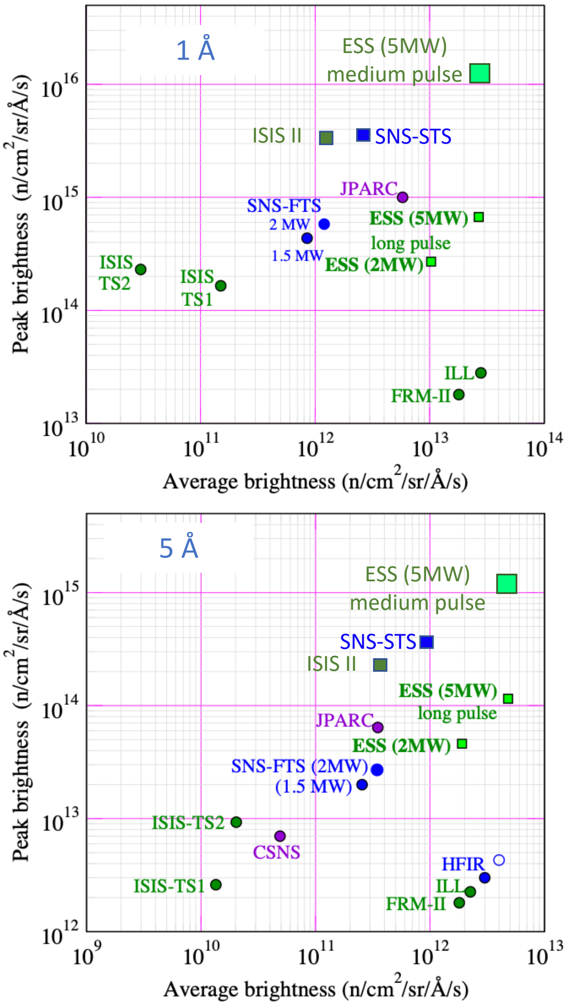

Fig. 5. Average brightness and peak brightness for the ESS with long and medium pulses in comparison to other neutron sources and upgrade projects. Top: thermal (1Å) and bottom: cold (5Å) neutrons.

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