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Moderator Configuration Options for ESS

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Abstract. The current, still evolving status of the design and the optimization work for the moderator configuration for the European Spallation Source is described. The moderator design has been strongly driven by the low-dimensional moderator concept recently proposed for use in spallation neutron sources or reactors. Quasi-two dimensional, disc- or tube-shaped moderators, can provide strong brightness increase (factor of 3 or more) with respect to volume para-H_2 moderators, which constitute the reference, state-of-the-art technology for high-intensity coupled moderators. In the design process other, more conventional, principles were also considered, such as the importance of moderator positioning, of the premoderator, and beam extraction considerations.

Different design and configuration options are evaluated and compared with the reference volume moderator configuration described in the ESS Technical Design Report.

1. Introduction

The European Spallation Source (ESS), which entered the construction phase in 2013 in Lund, Sweden, aims at starting operations and delivering the first neutrons in 2019 [1]. At 5 MW time-average power, and 125 MW peak power (to be achieved by 2022), ESS will be the most powerful neutron source in the world for neutron scattering studies of condensed matter. Neutrons will be produced by a 2 GeV proton beam impinging on a target made of tungsten. ESS will be the first high-power long pulse source [2], the pulse length of the beam will be of 2.86 ms, with 14 Hz repetition rate.

A key for a highly performing neutron source is the optimisation of the configuration of the target, moderator and reflector assembly [3]. The use of tungsten as spallation material will ensure a high neutron yield per incoming proton; the high density of tungsten favours the production of neutrons in a small volume, increasing the probability that neutrons will eventually be slowed down by the moderators placed next to the target. The presence of a reflector surrounding the moderators is essential to increase the slow-neutron intensity from the moderators. For a long pulse facility such as ESS, the recommended cold moderator type is a coupled, pure para-H_2 moderator [4], because it delivers the highest brightness per proton. The coupling between moderator and reflector (i.e. the absence of any neutron absorbing material to shape the pulse length) guarantees the highest peak flux from the moderator surface; pulses are shaped in time by choppers placed in the beam lines.

An extensive effort from the ESS neutronic team has been carried out to design high-brightness moderators; the current, still evolving status of the work is described in this paper.

2. The baseline of the Technical Design Report

In April 2013 the ESS Technical Design Report (TDR) was issued[1]. The TDR design was based on the best available state-of-the-art technology, which for high intensity moderators is the J-PARC coupled volume para-H_2 moderator [4]. In the TDR baseline configuration [1], there are two volume moderators filled with pure para-H_2. The MCNPX model shown in Fig. 1 reproduces the engineering design developed during the target station design update phase. The moderators have a diameter of 16 cm and a height of 13 cm, see Fig. 1. The moderators are surrounded by light water premoderators (except for the cold neutron extraction window), of which the most important part, from the neutronic point of view, is the layer between target and moderator, which is 2 cm thick. The window surface on the cold moderators for beam extraction is of 12 × 12 cm^2. On the sides of the cold moderators, thermal moderators are placed for bispectral beam extraction. The openings in the reflector for beam extraction are of 60°, with two openings per moderator, as shown in the figure. More information is available in Ref. [5].

The absolute brightness was calculated at a distance of 10 m from the moderators, using collimators to view only the moderator surfaces. The calculated peak cold brightness is a factor of 75 larger that in ILL yellow book [6] at 4 Å, a factor of 60 larger at 6 Å, and a factor of 65 larger at 10 Å.

This paper describes the work carried out after the TDR was issued, in an attempt to improve the neutronic performance of the ESS moderators beyond best established practice.

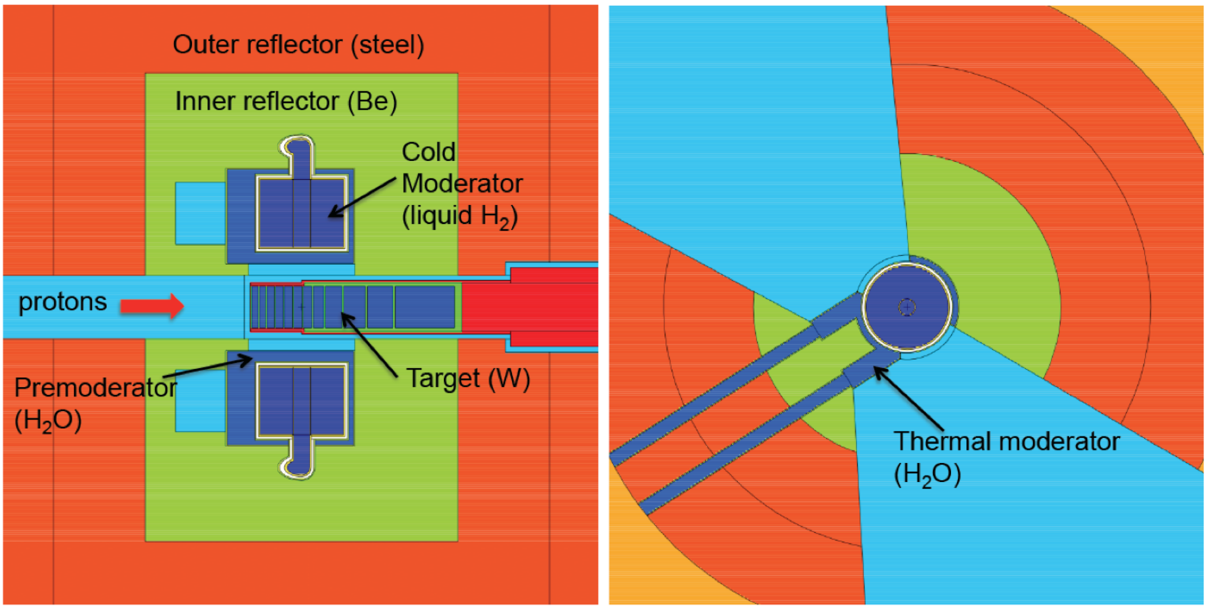

Figure 1. MCNPX[7, 8] geometry of the reference TDR moderator configuration.

3. Low-dimensional moderators

Much of the work was based on the concept of low-dimensional moderators for increased brightness, which are explained in details in Refs.[9, 10]. The basic principles of low-dimensional moderators is explained by the single-collision model [10]: the mean free path of thermal neutrons in para-H_2 is of about 1 cm, while is of about 11 cm for cold neutrons. Assuming that one collision only is needed to bring a thermal neutron to the cold regime, it is shown that the moderator brigthness is increased for quasi two dimensional (flat) or quasi one-dimensional (tube) moderators. The brightness distribution map in the moderator face is shown in Fig. 2 for a 10 cm and a 1.5 cm tall moderator, showing the presence of regions of higher brightness in the tall moderator, while a flat moderator essentially has a single hot spot of neutron emission. In order to work, it is required that the moderators are filled with close to pure para-H_2; this can be achieved in high-power facilities by use of catalyzers.

The resulting brightness as a function of moderator height is shown in Fig. 3. Note that brigthness increase corresponds to a decrease in total neutron emission (red curve) as well as of the total heat load in the moderator. Therefore a high intensity moderator is not the brightest one; however, it is worth noting that, for the cylindrical shape used for the calculations in Fig. 3, already for 3 cm thickness the total neutron emission is about 80 % of the maximum reached at 10 cm.

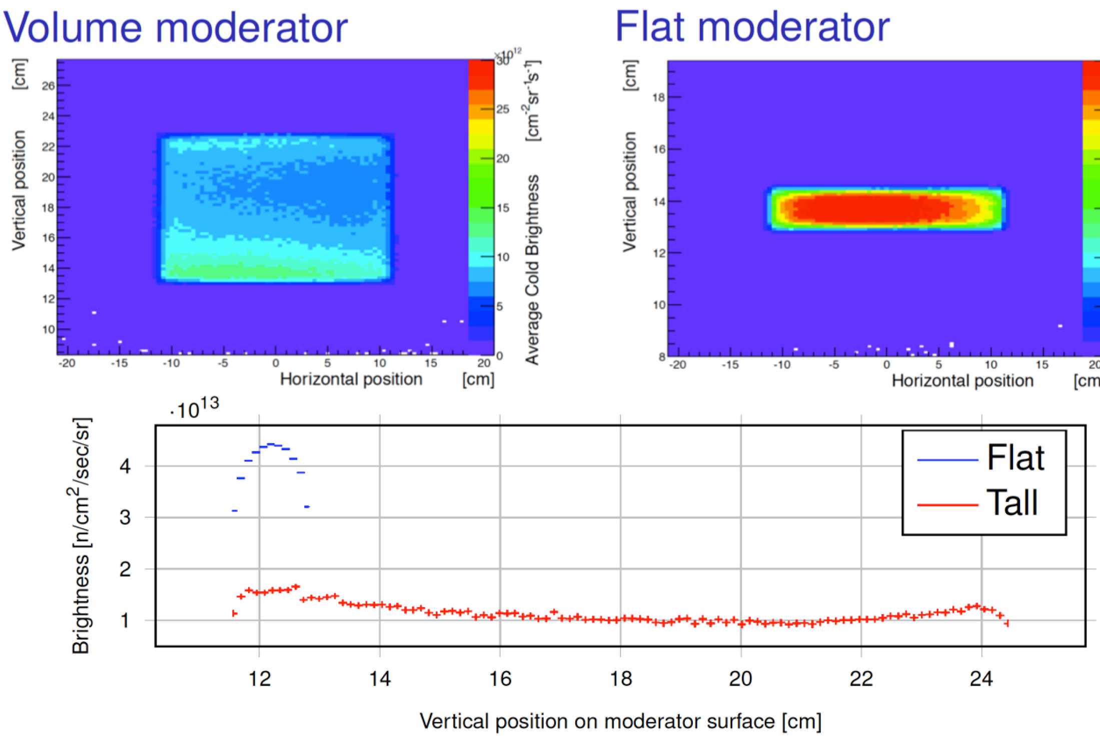

Figure 2. *Top:* Calculated brightness map from volume moderator (left) and flat moderator (right). *Bottom:* Brightness distribution along the moderator height for volume and flat moderator.

3.1. Other design principles

- Perturbation effect: in addition to the moderator shape effects, a brigthness increase is observed in low-dimensional moderators by the simple fact that being more compact, less reflector materials is removed around the moderators for beam extraction.
- Premoderator: the importance of the premoderator is well established and premoderators are widely used for cold neutron sources. The premoderator gives a spectral shaping, bringing neutron energies down from 1 MeV range to thermal. We have found that this

plays a crucial role not only for the cold moderator, but also for the thermal one (in which case the thermal moderator can be considered more as a scatterer than a moderator). As a result, we found that an extended premoderator, with dimensions practically equal to the Be reflector, and thickness of about 3 cm, gives a substantial gain in both thermal and cold moderator brightness.

- Position optimization: even though in a coupled moderator many of the neutrons reaching the moderator have been scattered by the inner reflector, we found that the positioning of the moderators close to the neutron production hotspot is quite important for brightness optimization. Additionally, it may be advantageous to place the thermal moderator above the target hotspot, rather than the cold moderator, because the thermal moderator is more compact, making it possible to place both thermal and cold moderators very close to the hotspot.
- Extraction optimization: a single moderator will not necessarily be able to serve the whole ESS instrument suite. However, we have found that in some cases this is possible; this is the case for the 3 cm pancake; if two moderators are installed, the ability to serve all the instruments by one or the other moderator is an advantage for maximum availability/flexibility.

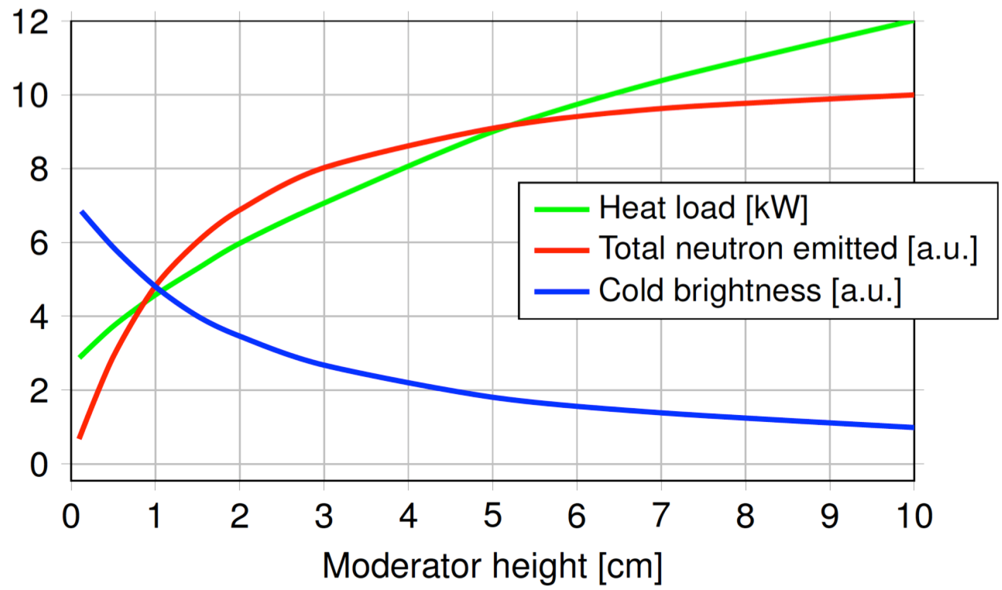

Figure 3. The integral cold brightness ($0 < E < 20$ meV) increases with decreasing height of the flat moderator (blue curve). On the contrary, the total number of emitted neutrons (brightness multiplied by the viewed area of the emitting surface) increases (red curve) with increasing moderator height, as well as the heat load (green curve).

4. The pancake moderator

The pancake design makes use of most of the concepts and findings described above. The resulting model is shown in Figure 4. The important features of this design are the following:

- 3 cm tall, 20 cm diameter cylindrical vessel containing pure para-H_2; the viewed surface can be up to 3 cm (Height) × 20 cm (Width), even though usually neutrons are extracted from a window 3 cm (H) × 6 cm (W). The choice of the diameter is considered a good balance between cold and thermal brightness, in the sense that it gives near maximum cold performance, while allowing a higher thermal brightness since the water wings are moved a bit closer to the neutron hotspot (Fig. 5).
- Neutron extraction for 2 × 120° angular openings.
- Water wings on the side of the cold moderator, for thermal neutron extraction. The viewed surface can be up to 3 cm (H) × 12 cm (W), or even more, even though usually neutrons are extracted from a window 3 cm (H) × 6 cm (W) or smaller.
- Extended premoderator between target and cold and thermal moderators, making use of findings described in section 5, for increased thermal brightness, with the additional advantage of reduction of the amount of Be close to the target.

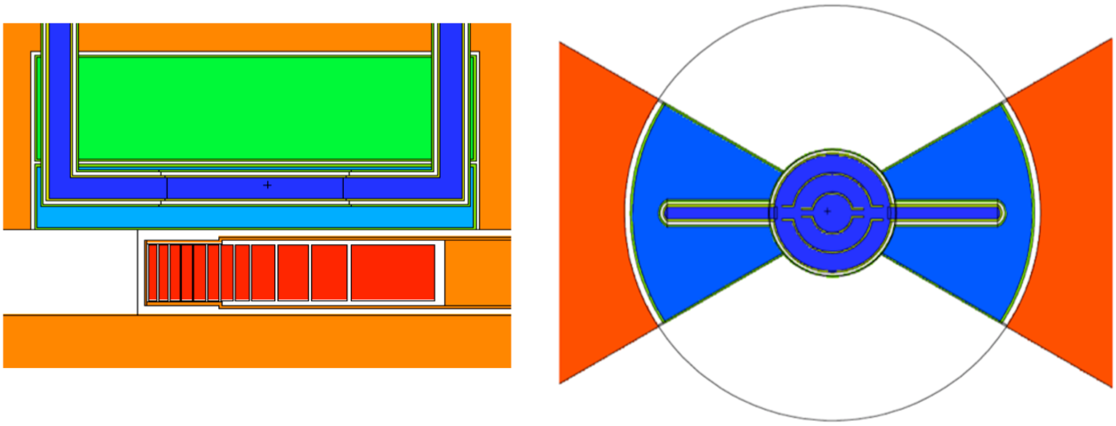

Figure 4. Reference geometry for the pancake configuration. See explanation in the text.

The pancake moderator is designed for increased cold brightness. The cold brightness is on average a factor of 2.4 the brightness delivered by the TDR moderators. For extraction of thermal neutrons, the thermal brightness is a factor of 1.5 the TDR. Thermal neutrons are extracted from the sides of the cold moderator. The thermal brightness can be increased by bringing the water closer to the neutron hotspot, but this can be obtained only at the expense of reduced cold brightness.

5. The second moderator

The pancake moderator brings not only an increased performance with respect to the TDR design, mainly in the cold brightness, and partially also in the thermal brightness, but also the fact that a flat moderator can serve the whole ESS instrument suite covering 2 × 120° beam extraction sector. This gives the opportunity to use the slot for the second moderator (the bottom moderator) to add flexibility to the facility. In other words, a second moderator can be used to supplement top pancake with either: *i*) a larger emission surface, resulting in a high intensity moderator, or *ii*) a moderator with a different overall wavelength spectrum, i.e.

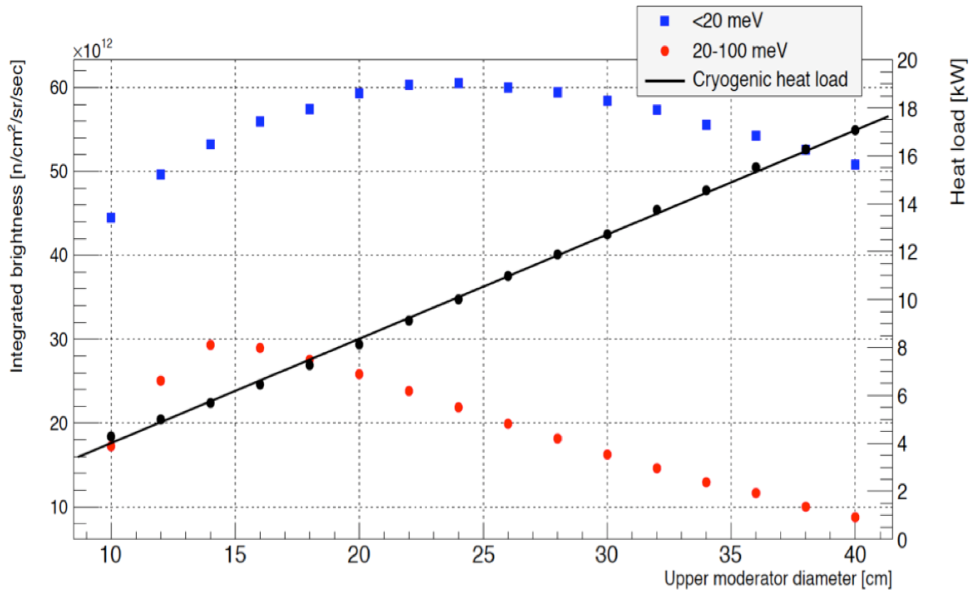

Figure 5. Integrated cold and thermal brightness for a pancake moderator, and heat load on the cryogenic parts (structure and hydrogen), as a function of the moderator diameter. The model (see Fig. (4)) includes some structure and pipes.

with increased thermal brightness with respect to the cold brightness, or *iii*) a combination of both things. The increased emission surface was discussed thoroughly. Essentially the gain in intensity with the moderator height is a balance between reduced brightness and increased area, and is seen in Figure 3; calculations for a 6 cm tall cold moderator were performed; its brightness is reduced with respect to the 3 cm pancake by about a factor of 1.5. Effort was particularly focussed on designing a moderator that would improve the thermal component of the spectrum.

6. The Optimized Thermal (OT) moderator

For maximum performance, the moderator should be placed near the hot spot of neutron production in the spallation target. In tungsten, because of its high-density, this is an area extended only a few cm starting about 10 cm from the target edge. The effect is mitigated by the presence of the Be reflector, however it is significant: the effect on vertical placement was calculated to be of about 3%/cm, while for horizontal placement is of about 1-2%/cm.

The thermal brightness can be improved if a moderator is specifically designed to improve this part of the spectrum. It was found that brightness of the thermal moderator increases if a water layer, approximately 3 cm thick, is placed between target and moderator, in a similar way to what happens to the top pancake (Fig. 6). The combination of optimal placement of the moderator with respect to the neutron production hot spot, and of the presence of this water layer, is found to give an increase up to a factor of 1.7 with respect to the brightness of the top pancake, for the same moderator height. The cold moderator next to the water moderator, shown in Fig. 6 is similar to a tube moderator and will provide high cold brightness; however it is highly directional and its brightness will decrease with the angle of beam extraction with respect to the tube axis.

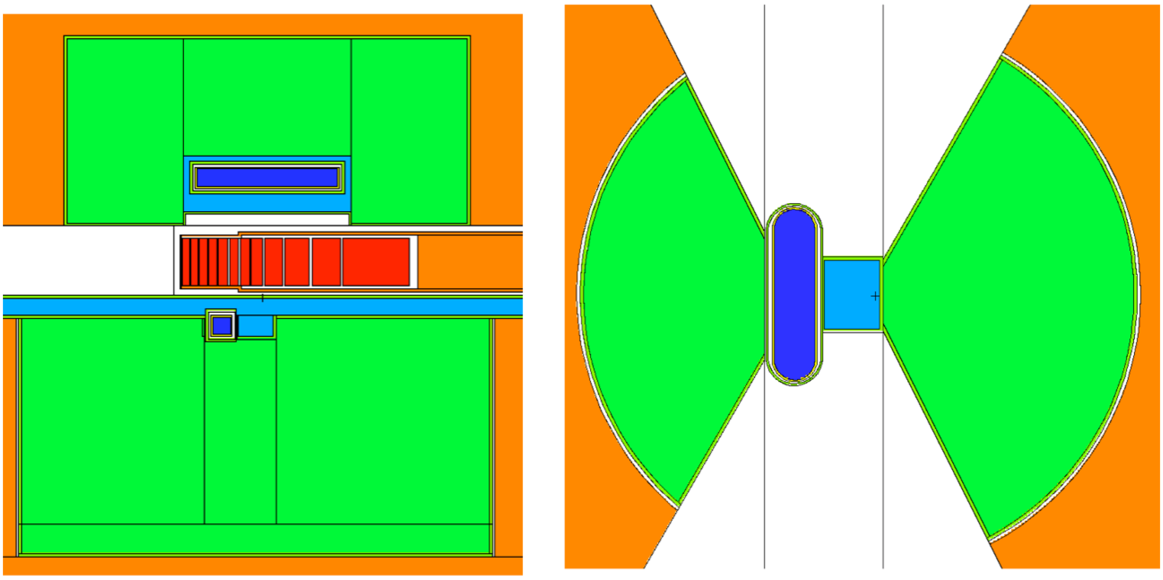

Figure 6. Geometry with a pancake 3 cm top moderator, and an optimized thermal moderator (3 cm tall) on bottom. *Left*: side view showing the 3 cm water layer between target and moderators. *Right*: top view showing the thermal moderator (light blue) and the cold moderator (dark blue), surrounded by the beryllium reflector (green).

7. Results and next steps

In Fig. 7 calculated wavelength spectra for the TDR, pancake and OT moderators are shown. Flat moderators offer a clear brightness increase with respect to the original TDR design based on volume moderators. Cylindrical pancake moderators are excellent cold moderators with a brightness about 2.5 times higher than the TDR moderators. The increase in thermal brightness is however limited, only a factor of 1.5: the thermal brightness remains the weak part of this moderator configuration. It is important to note that the TDR design suffers also from this drawback, as the peak thermal brightness is only a factor of 7 higher than the ILL yellow book, as opposed to the cold brightness which is 60 to 75 times higher than the yellow book. In an attempt to increase the thermal brightness we have developed the Optimized Thermal design. The OT is capable of delivering a thermal brightness higher than the pancake for a bigger emission surface. This increase is due to both optimal positioning of the water moderator (close to the neutron production hotspot) and to the optimal use of the extended premoderator (3 cm water layer between target and moderator). In order to deliver a good cold brightness, the OT has a cold tube moderator of its side. The resulting thermal-cold performance is enhanced (there is also come increase in cold brightness compared to the pancake). However, it is limited to a sector of about 60°, because of the strong directionality of the cold moderator, which means that this optimized thermal moderator must be used in conjunction with a top moderator.

The combination of a top pancake and an OT at the bottom, is a valid possibility for ESS. However, other possibilities are currently under consideration, and different designs are on the table exploting the design approach developed in the last two years and discussed in this paper.

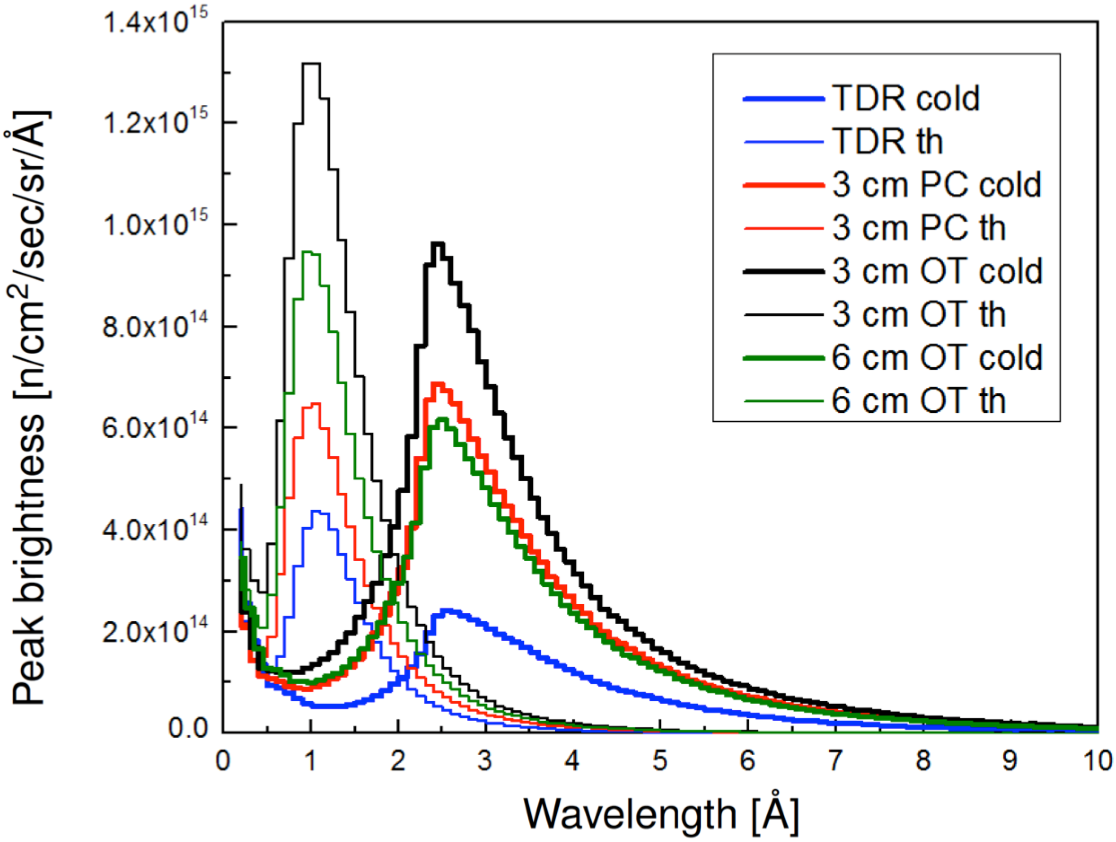

Figure 7. Calculated wavelength spectra from TDR, pancake (PC) and Optimized Thermal (OT) configurations. See explanation in the text.

Acknowledgments

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