

Is nuclear fusion a sustainable energy form?

A. M. Bradshaw

Max Planck Institute for Plasma Physics, Association IPP-Euratom, Boltzmannstr. 2, 85741 Garching, Germany and Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany

T. Hamacher

Institute for Energy Economy and Application Technology, Technical University of Munich, Arcisstrasse 21, 80333 München, Germany

U. Fischer

Association FZK-Euratom, Karlsruhe Institute of Technology, Postfach 3640, 76021 Karlsruhe, Germany

Abstract

An acceptable criterion for strong sustainability in the consumption of natural resources is an effective, or virtual, limitlessness of supply, which can be defined, albeit arbitrarily, as corresponding to a few million years. The fuels for nuclear fusion – lithium and deuterium – satisfy this condition because of the abundance of lithium in seawater and of deuterium in all forms of water. The possible use of lithium-ion batteries on a large scale, particularly in the automobile industry, could, however, use up all the known terrestrial reserves and resources of lithium in the next few decades. Little attention has been paid so far to the financial, energetic, and above all, environmental aspects of lithium extraction from seawater. The neutron multipliers foreseen for fusion power plants, in particular beryllium, represent a major supply problem and require that other, sustainable solutions be urgently sought.

Published in Fusion Engineering and Design 86 (2010) 2770

doi: 10.1016/j.fusengdes.2010.11.040

This is the “revised personal version” of the final journal article.

1. Introduction

The description of fusion as “sustainable”, or, alternatively, of it satisfying the requirements of “sustainability”, has become common, particularly in the fusion community itself. Thus, we read in a recent newsletter of the European Fusion Development Agreement (EFDA): “The path that leads toward using fusion as a sustainable source of energy for the future goes via the exploitation of the next generation of fusion devices, and in particular ITER, which is designed to demonstrate the scientific and technical feasibility of fusion” [1]. What does “sustainable” actually mean? In terms of its ecological, socio-economic meaning, it refers to a state of society in which human well-being is maintained, but in a way such that the needs of future generations are not compromised. This definition is based on that of sustainable development given in 1987 in the Brundtland Report [2], and derives from the concept of intergenerational equity [3]. An alternative definition is to say that we should maintain – or in some parts of the world – improve the quality of human life, while living within the capacity of the planet to maintain a particular size of population [4]. Surprising as it may seem, the first use of “sustainable” in this sense - in the English language at least - only goes back to the 1980’s [5]. The word has, however, already acquired several shades of meaning. In particular, it has been noted that strict definitions cannot be upheld in practice: even in primitive societies man’s interaction with his environment left visible, indelible marks. This has led to the concept of “weak” sustainability, which merely requires that the sum of “natural” and “manufactured” capital (natural capital = natural resources!) remains constant from one generation to the next. This economist’s definition allows an almost unlimited substitution of natural resources by man-made capital and is seen by many as a recipe for a continuing exploitation of natural resources without considering or consulting (how could it take place?) future generations [6]. Understandably, it has not found sympathy with ecologists and environmentalists, who equate “sustainability” with “strong sustainability”.

If we look at current world energy supply, the application of the stricter definition of sustainability gives a very negative result. At present, global energy supply relies to the extent of 81% on fossil fuels [7], which are – quite apart from being the main cause of anthropogenic CO₂ emissions – valuable natural resources of the planet and threatened by exhaustion in the next 1-2 centuries. The so-called renewable energy forms – mainly biomass and combustible waste as well as hydroelectricity – only account for 13% [7]. Although the terms “renewable” and “regenerative” are not good physical descriptions, the latter are of course almost by definition sustainable, because their origin is in most cases the sun, which is “limitless” as a source of energy, at least for the next 4 billion years! Research on renewable energies is now attracting considerable funding. The development of nuclear fusion by the middle of this century is also one of main components of energy R&D policy in many countries. Fusion is seen by some as an alternative to nuclear fission, which at present accounts for 5.9 % of world energy supply (13.8 % of world electricity production) [7], in particular for base-load electricity supply. The application of strict sustainability criteria to fusion focuses the discussion onto two issues: the serious problem of nuclear waste and the availability of the fusion fuels – deuterium and lithium – as well as of other materials in a future power plant, in particular the necessary neutron multiplier(s). If we can assume that recent favourable prognoses concerning the waste in future fusion power plants [8] hold true, then the discussion centres on the extent of natural resources, in particular of lithium. Although this issue has been treated by several authors, notably by Eckhartt [9] and by Fasel and Tran [10] there are three reasons for looking at the problem again: Firstly, the recent predictions of future demand for lithium-ion batteries are alarming: it is conceivable that the automobile industry may acquire, and according to some estimates even use up, at least the terrestrial lithium reserves in the next few decades. Secondly, although this could be regarded as a

mitigating factor, the latest conceptual designs for the tritium breeding blankets in the DEMO fusion reactor have much smaller initial lithium loadings than those expected from the European Power Plant Conceptual Study (PPCS) [8]. Thirdly, the debate as to the practical limits of sustainability and of sustainable development has recently moved from the more academic fields of environmental ethics and ecological economics into the more journalistic domain [11, 12], so that the political implications of the claims of the fusion community in this respect should be carefully examined.

In the next section we look at the lithium reserves and resources worldwide and examine prognoses of future lithium demand for energy storage, in particular in the automobile industry. We also review the corresponding situation for beryllium and lead, two proposed neutron multipliers in fusion reactors. In section 3 we examine the loading and burn-up of lithium, beryllium and lead in the two reactors described in the European DEMO Conceptual Study. Finally, we return in Section 4 to our main theme, namely, the “limitlessness” of fusion power and sustainability.

2. Availability of fusion raw materials

The deuterium-tritium reaction



is the only one at present conceivable for the first generation of fusion power plants. As is well known, it is the intention to breed the tritium primarily via the reaction between lithium-6 and the fusion neutrons:



Neutrons will also be lost, however, through parasitic absorption in non-breeding materials, such as the structural materials of the reactor itself. To achieve tritium self-sufficiency, it will be necessary to employ a neutron multiplier, such as beryllium or lead, producing further neutrons via (n, 2n) reactions in the so-called blanket of the reactor. The European fusion programme, for example, considers two blanket development lines: The Helium-Cooled Pebble Bed (HCPB) blanket with lithium ceramics pebbles (Li_4SiO_4 or Li_2TiO_3) as breeder material and beryllium pebbles as neutron multiplier [13], as well as the Helium-Cooled Lithium-Lead (HCLL) blanket with the Pb-Li eutectic alloy [14] acting both as breeder and neutron multiplier. The blanket design and the related R&D efforts are based on the use of the same coolant (helium) and the same modular blanket structure to minimise the development costs as much as possible. The strategy aims at providing validated engineering designs of breeder blankets for a fusion power demonstration reactor (DEMO). Following this guideline, a European DEMO reactor study [15] has been recently conducted to demonstrate, among other things, the technological potential and viability of a fusion power plant based on helium coolant technology, in particular the utilisation of HCLL and HCPB breeder blankets. The main DEMO reactor parameters are displayed in Table 1. Fig. 1a shows a CAD model of the DEMO torus sector with blanket modules of the HCLL type. Fig. 1b shows a single HCLL blanket module in an exploded view.

The one primary fuel component - deuterium - is present to the extent of 1 part in 6 400 (156 ppm) in naturally occurring hydrogen and for fusion purposes would probably be extracted by electrolysis of heavy water obtained from freshwater via the GS isotopic exchange process

[16]. Since the potential deuterium reserves are vast (the concentration of lithium-6 in seawater is a factor of 10^4 less), it is sensible to concentrate, as have previous authors [9, 10], on the availability of lithium.

World lithium production was estimated to be 22 800 t in 2008, having increased at the rate of 7.2 % p. a. in the last decade [17, 18]. The reason for this growth has been the rise in the use of lithium for both primary and secondary batteries, which currently accounts for 23 % of total lithium use. Mobile phones and laptops now use almost exclusively lithium-ion secondary batteries because of their high energy density and low weight compared to nickel-cadmium and nickel-metal hydride cells. The lithium-ion battery appears to be the device of choice in future automotive applications. The glass and ceramic industry continues, however, to be the major consumer (31 %). Other uses include aluminium production, lithium greases, continuous casting in the steel industry and pharmaceuticals. There are two primary sources: lithium minerals, mainly spodumene, but also petalite and lepidolite, and lithium-containing brines. Like petalite, spodumene is a lithium aluminium silicate. The minerals are used directly in the ceramics and glass industries, as well as for making certain Li compounds. High concentrations of lithium up to 1500 ppm are found in the salt brines under salars in North and South America and in China. Salars in Chile and Argentina have become particularly important in recent years and are the most important source of lithium carbonate, which is the main starting point for lithium compounds and for the metal itself [17]. Seawater has not been seriously considered as a commercial source of lithium, although the extraction possibilities have been discussed in general [19] and experiments employing ion exchange with magnesium oxide substrates have been performed [20].

How much lithium is available on or in our planet? The yearly statistics of the US Geological Survey (USGS) are a good starting point; these together with other, essentially similar estimates in millions of tons (Mt) are shown in Table 2. Reserves are defined as proven deposits that can be extracted economically at the present time. Resources are concentrations of the material in such a form and quantity that its extraction is potentially feasible. We note from Table 1 that in 2010 the USGS drastically increased its estimate largely as a result of a re-assessment of the potential of the salars in South America and China. Lithium reserves are divided up approximately 2:1 between brines and minerals [18]. Without discussing any further details we also note that the sum of lithium reserves and resources is probably over 30 Mt. In seawater the lithium concentration is on average 0.17 ppm, or 0.17 g per ton. Multiplying by the total volume of seawater ($1.3324 \times 10^9 \text{ km}^3$ [23]) gives a lithium content of 226 000 Mt.

How much lithium will be needed for non-fusion purposes in coming years? It is currently accepted that batteries, in particular for hybrid electric vehicles, will lead to a massive increase in demand, and this will dominate the market in the next few decades. (The possibility that lithium batteries might be also be used for large-scale storage of electricity for industrial and domestic use is normally not considered.) The extent of this demand and how long existing reserves will last is a matter of some controversy [21, 22, 24, 25]; the discussion has recently been summarised by Angerer et al [25]. For present purposes a “worst case” scenario is appropriate. If we assume that (i) the whole global automobile fleet of approx. 10^9 units is “electrified” over the next 40 years linearly in time, (ii) plug-in hybrids with 16 kWh batteries as in the GM Volt are the system of choice (completely electric vehicles, e.g. Renault Fluence, will require larger batteries), (iii) 400 g Li are required per kWh [24] and recycling takes place every ten years with 80% efficiency [25], then approximately 10 Mt lithium will be required by 2050. This figure is greater than the present known reserves, but smaller than the sum of reserves and resources (Table 1). If lithium-ion batteries find large-

scale application in non-automotive energy storage, as now seems increasingly likely [26], then there is even more cause for concern.

The situation with regard to beryllium and lead should also be discussed. Beryllium is regarded as a very rare metal. Despite its presence in over 90 known minerals, only bertrandite and beryl occur in minable concentrations. Annual production was 140 t in 2009; figures for the total reserves are not available, but the resources amount to only 80 000 t [18]! Lead production (from mines) in 2009 was 3.9 Mt, with at least as much again from recycling. Lead reserves amount to 79 Mt and resources 1.5 Gt [18]. Since concern has been expressed as to the future availability of helium [27], we will – for reasons of space – look at this potential problem in a further paper.

3. Consumption of fusion raw materials in future power plants

In this chapter we first consider the initial loadings and burn up of lithium-6, as well as of beryllium and lead, in the two types of power plant. With a nominal fusion power of 2.385 GW and assuming tritium self-sufficiency (Tritium Breeding Ratio, TBR = 1.0), the DEMO power plant will have a Li-6 burn-up of 266 kg p. a. The actual burn-up might be higher by about 10 % assuming a TBR \approx 1.10, thus giving 292 kg p. a. of Li-6. Such a TBR value will be required to ensure tritium self-sufficiency while accounting for tritium losses in the fuel cycle and uncertainties in the predicted TBR. For the HCPB and HCLL DEMO reactors, TBR values from 1.08 to 1.11 have been obtained [28]. The related Li mass inventory required at the start-up of the DEMO reactor amounts to 10 t (3.6 t Li-6) and 28 t (25 t Li-6) for the HCPB and the HCLL types, respectively. (This corresponds to enrichments of 36 and 90 %, respectively. A new chemical exchange technique for enrichment will be necessary, since the now disused COLEX process used massive quantities of mercury [29]). The initial beryllium mass loading for the HCPB DEMO is 120 t and the annual burn-up of Be amounts to 190 kg. The HCLL DEMO needs to be loaded with about 5 120 tons PbLi, of which 4 092 t are lead. The annual burn-up of lead is 3.1 t.

How much lithium would be required annually if fusion were to provide the base-load electricity supply in the second half of this century? For this estimation we will assume that (i) global demand for energy doubles by 2050 (compared to 2007 [7]), (ii) the percentage provided by electricity doubles (mainly due to electromobility), and (iii) the base-load provided by fusion power is 30 %. Approximately 24 000 TWh would then be required from fusion power stations. On the basis of year-round operation and 1 GWe per unit (corresponding to DEMO HCPB or HCLL), 2 760 fusion power stations would be required. These would consume 806 t lithium-6, for which 10 050 t of natural, non-enriched lithium would be required annually. Thus, the present lithium reserves of 9.9 Mt (see above) – if used *only* for fusion – would last for only 990 years. If both reserves and resources are taken into account, then there is sufficient lithium for 3 540 years. Somewhat problematical are the initial lithium loadings. The sum of the lithium inventories for all power plants would be 9 940 t lithium-6 (corresponding to 124 000 t natural lithium) and 69 000 t lithium-6 (corresponding to 860 900 t natural lithium) for HCPB and HCLL, respectively. The latter represents almost one tenth of the reserves. Once again, we emphasise that these figures make no allowance for the consumption of lithium in other areas, particularly energy storage. On the other hand, if we consider the potential of seawater, then there is enough lithium, at least theoretically, for the operation of 2 760 power plants for 23 million years!

The beryllium burn-up in 2 760 HCPB power plants would be 524 t annually and the initial loading 331 000 t, vastly exceeding the present estimation of resources (see above)! The

situation for lead in HCLL power plants is somewhat better: the annual burn-up would be 8 560 t and the initial loading 11.3 Mt. With 1.5 Gt resources (see above) the burn up is such that there would be sufficient lead for about 175 000 years, assuming it were available only for fusion. This situation is far from optimal, but better than for beryllium.

4. Discussion and conclusions

In books, learned journals and even newspaper articles the fusion fuels are often described as “limitless” or “virtually limitless”. In a recent recommendation on energy research policy, for example, the German National Academies of Science put fusion and so-called renewable energy forms on the same footing because of the “practically unlimited availability” of deuterium and lithium [30]. Defining sustainability and establishing appropriate metrics means making a compromise. In the case of natural resources, such as minerals, strong sustainability may be equated with “effective limitlessness”, if the substance concerned is available for millions of years on the basis of a given rate of consumption. The age of the genus *homo* (2 – 2.5 million years) is not an unreasonable time scale on which to base a definition of “effectively limitless”. The availability of lithium (and deuterium) in seawater – enough Li for 14 million years – would be sufficient to meet such a criterion. The extraction process could, however, prove to be a daunting task: costs, energy requirements and above all environmental aspects, must be considered. To extract about 10 000 tons of lithium, which we have seen could be the possible annual consumption in the “age of fusion”, at least $\approx 5 \times 10^{10}$ tons of sea water are required! (The total could be much higher depending on the efficiency of the extraction process.) It is often forgotten that the oceans of the world constitute a huge, complex ecosystem.

All the other uses of lithium are not dependent on nuclear properties, so that the isotopic composition is to a first approximation unimportant. The chemistry of Li-6 and Li-7 in a battery is expected to be identical, apart from a possible small difference in diffusion rates. It is thus necessary, as soon as the decision is made to build a DEMO power plant, to start the large-scale isotopic enrichment of lithium-6. “Depleted Li” can then be used for all other applications. In the meantime it is essential that lithium be re-cycled, particularly in the case of batteries where this is relatively straightforward. At a time when lithium carbonate is readily prepared from South American brines and costs only a few Euros per kg, this is probably a pious hope! Alternative types of battery, such as the zinc-air device, are being developed, but rechargeable versions are not yet available. Zinc-air batteries could be safer than lithium-ion batteries; moreover, there are 200 Mt Zn reserves and 1.9 Gt resources [18].

The neutron multiplier is an absolutely essential feature of the breeding blanket, and will assume critical importance when the first power stations are built. The tritium breeding ratio has to be greater than 1 not only to compensate for tritium losses by radioactive decay and retention in various components of the tritium cycle, but also in the introductory phase of fusion in order to supply the tritium inventory for the start up of further reactors. Beryllium is clearly not a sustainable solution. As we have seen in the previous section, there is probably only sufficient minable beryllium available to provide the initial loading for about 150 HCBP-type power plants, as opposed to the necessary figure of over 2 760! The situation with lead is somewhat better, but even the HCLL power plant could not be described as “sustainable”, at least not on the basis of a definition in terms of “virtually limitless”. It may be possible, however, to build power reactors without neutron multipliers such as beryllium and lead; several options have been discussed. The availability of helium, which is important not only for the blanket, but also for the cryogenic system, will be discussed in a forthcoming paper. The present discussion shows that it is important that all such aspects – not just the primary

fuels – are studied in applying (“strong”) sustainability criteria.

Acknowledgements

The authors acknowledge useful discussions with R. A. Bradshaw, I. Milch, N. Modl, Y. Poitevin, J. Raeder, R. Schlögl, M. Q. Tran, Y. Tytgat and M. Zmitko.

References

1. G. Falchetto, R. Coehlo and C. Konz, Fusion News No. 4, EFDA, Garching (2010)
2. Report of the World Commission on Environment and Development (Brundlandt Commission): *Our common future* UN (1987).
3. R. M. Solow, *Intergenerational equity and exhaustible resources*, Rev. Econ. Studies **41** (1974) 29.
4. R. U. Ayres, J. C. J. M. van den Bergh and J. M. Gowdy, *Strong vs. weak sustainability: Economics, natural sciences and consilience*, Environm. Ethics, **23** (2001) 155.
5. OED Online, Oxford University Press (2010).
6. R. U. Ayres, *On the practical limits to substitution*, Ecol. Econ. **61** (2007) 115.
7. *Key World Energy Statistics 2009*, International Energy Agency (IEA), Paris (2009)
8. D. Maisonnier et al, *A Conceptual Study of Commercial Fusion Power Plants*, EFDA report, Garching (2005).
9. D. Eckhartt, *Nuclear fuels for low-beta fusion reactors: Lithium resources re-visited*, J. Fusion Energy, **14** (1995) 329.
10. D. Fasel and M.Q. Tran, *Availability of lithium in the context of future D-T fusion reactors*, Fusion Eng. Des. **75-79** (2005) 1163.
11. Economist online debate on “sustainable development”, The Economist, London (July 2009).
12. U. Grober, *Die Entdeckung der Nachhaltigkeit*, Kunstmann, Munich (2010).
13. U. Fischer, P. Batistoni, et al, *EU blanket design activities and neutronics support efforts*, Fusion Sci. Techn. **47** (2005), 1052 -1059
14. A. Li Puma et al, *Breeding blanket design and systems integration for a helium-cooled lithium–lead fusion power plant*, Fusion Eng. Des. **81** (2006), 469-476
15. D. Maisonnier, *European DEMO design and maintenance strategy*, Fusion Eng. Des. **83** (2008), 858-864
16. e. g. B. M. Andreev, *Separation of hydrogen isotopes in the H₂O/H₂S system*, Sep. Sci. Tech. **36** (2001) 1949.
17. Roskill Information Services, London: *The Economics of Lithium, 11th Edition*, 2009.
18. US Geological Survey (minerals.usgs.gov/minerals/pub/mcs/): *Mineral Commodity Summaries* (2010).
19. K. Schwochau, *Extraction of metals from seawater*, Topics Current Chem. **124** (1984) 91.
20. R. Chitrakar, H. Kanoh, Y. Miyai and K. Ooi, *Recovery of lithium from seawater using manganese oxide absorbent (H_{1.6}Mn_{1.6}O₄) derived from Li_{1.6}Mn_{1.6}O₄*, Ind. Eng. Chem. Res. **20** (2001) 2054.
21. W. Tahil, *The trouble with lithium, Reports 1 and 2*, Meridian International Research, Martainville, www.meridian-int-res.com, (2007, 2008).
22. R. K. Evans, *Know Limits*, Industrial Minerals, **7** 48 (2008) and *An abundance of lithium, Report 2*, (unpublished).
23. M. A. Charette and W. H. F. Smith, *The volume of earth’s ocean*, Oceanography, **23** (2010) 112.
24. W. Tahill, *How much lithium does a LiIon battery really need?* Meridian International Research, Martainville, www.meridian-int-res.com, (2010).
25. G. Angerer, F. Marscheider-Weidemann, M. Wendl and M. Wietschel, *Lithium für Zukunftstechnologie*, Report Fraunhofer Institut für System- und Innovationsforschung, Karlsruhe (2009).
26. Corvus Energy, Vancouver: www.corvus-energy.com/press_release2010.html.
27. K. H. Kaplan, *Helium shortage hampers research and industry*, Physics Today, June 2007, p. 31.

28. U. Fischer, D. Grosse, P. Pereslavytsev, S. Stickel, H. Tsige-Tamirat and V. Weber, *Neutronics design analysis of fusion power reactors based on a novel integral approach*, Fusion Eng. Des. **84** (2009) 323.
29. E. A. Symons, *Lithium isotope separation: A review of possible techniques*, Sep. Sci. Tech. **20** (1985) 633.
30. F. Behrendt, O. Renn, F. Schüth and E. Umbach, *Konzept für ein integriertes Energieforschungsprogramm für Deutschland*, Berlin and Halle (2009)

Table 1: Main parameters of the DEMO power reactor [15]

Parameter	
Major radius [m]	7.5
Minor radius [m]	2.5
B (T)	6.2
I (MA)	17.0
Plasma elongation	1.9
Plasma triangularity	0.47
Fusion power [MW]	2 358
Net electric power [MW]	1 000

Table 2: Recent estimates of lithium reserves and resources

	Reserves (Mt)	Resources (Mt)
USGS [18] (2010)	9.9	25.5
USGS [18] (2009)	4.1	13.8
Roskill [17] (2008)		27.8*
Tahill [21] (2007, 2008)	6.8	15**
Evans [22] (2008)		29.8*

* Total reserves: reserves + resources

** So-called reserve base (an earlier concept used by the USGS)

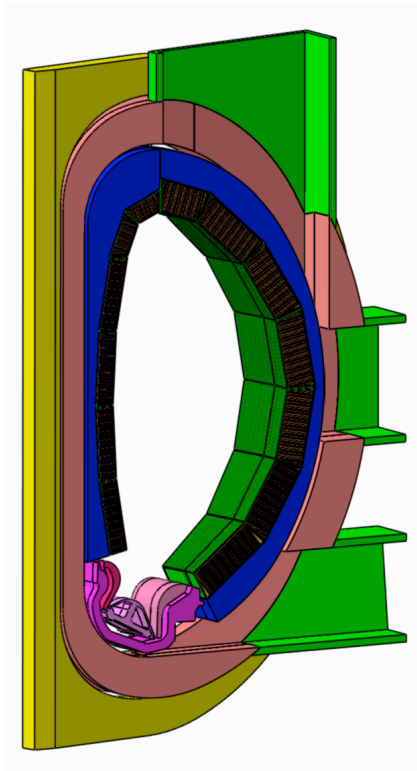


Fig. 1a: DEMO torus sector (11.25°) with integrated HCLL blanket modules.

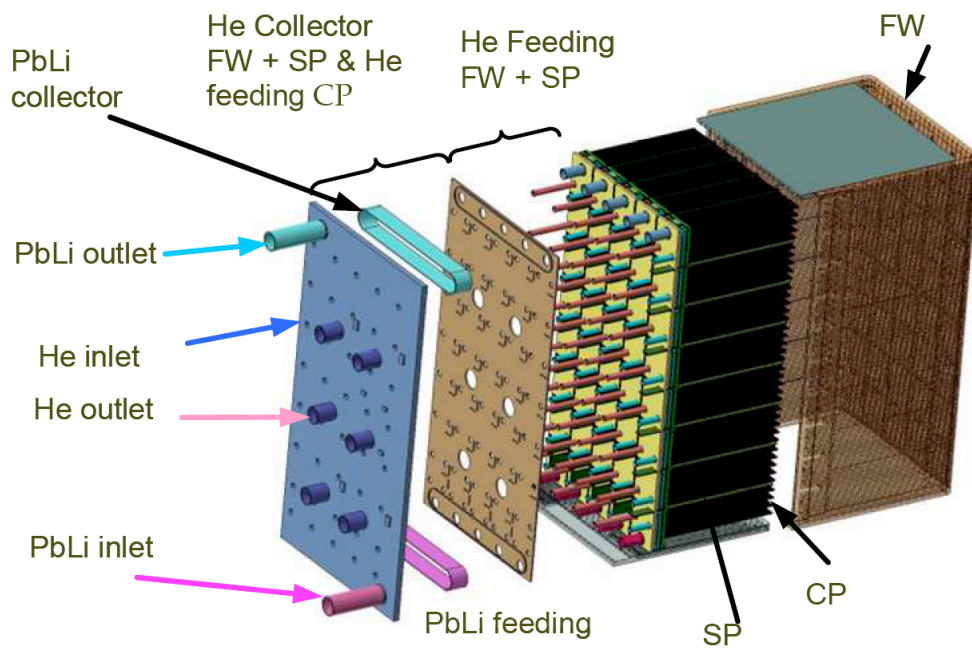


Fig. 1b: HCLL Demo blanket module box (exploded view).