Corrigendum: The European Spallation Source Design (2018 Phys. Scr. 93 014001)

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There are a number of corrections that should be noted. Nevertheless, the scientific content discussed in the paper is not affected by these corrections.

Page 1: Revised author list. A number of authors who contributed to the paper were missing in the author list. Antonio Vergara has been added as the article editor. Finally, one author’s name was also misspelled in the author list and is corrected. The list of missing authors and the corrected author’s name are detailed in the relevant sections of this article.

Page 4: Modification of texts. The second sentence in the first paragraph of section 3 Timeline should be modified. The modified text is written in italic font below.

Page 6: Revised author list for the Accelerator Design. There is a misspelled name in the author list. Specifically, I Levinsen should be corrected to Y Levinsen. The revised author list for the part The ESS Design: Accelerator Design is given below:

H Danared, I Alonso, E Bargallo, B Cheymol, C Darve, M Esbraqi, H Hassanzadegan, A Jansson, I Kittelmann, Y Levinsen, M Lindroos, C Martins, Ø Midttun, R Miyamoto, S Molloy, D Phan, A Ponton, E Sargysan, T Shea, A Sunesson, L Tchelidze, C Thomas, M Jensen, W Hees, P Arnold, M Juni-Ferreira, F Jensen, A Lundmark, D McGinnis, N Gazis, J Weisend II

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Page 36: Missing source in the caption for figure 42. The source of the figure should be specified in the caption for figure 42.
Figure 42. Perspective view of quadrupole magnets type Q5 (left), Q6 (middle) and Q7 (right) for spoke LWU, elliptical LWU and dogleg LWU respectively. Pictures by courtesy of A Fabris et al, Accelerators Group, Elettra—Sincrotrone Trieste S.C.p.A, Trieste, Italy.

Page 36: Missing source in the caption for table 28. The source of the data should be specified in the caption for table 28.

Table 28. Magnet parameters and performance for quadrupoles type Q5, Q6 and Q7. Data by courtesy of A Fabris et al, Accelerators Group, Elettra—Sincrotrone Trieste S.C.p.A, Trieste, Italy.

Page 37: Missing source in the caption for table 29. The source of the data should be specified in the caption for table 29.

Table 29. Coil parameters for quadrupole types Q5, Q6 and Q7 (in parenthesis the values at the minimum required coolant flow). Data by courtesy of A Fabris et al, Accelerators Group, Elettra—Sincrotrone Trieste S.C.p.A, Trieste, Italy.

Page 37: Missing source in the caption for figure 43. The source of the figure should be specified in the caption for figure 43.

Figure 43. Perspective view of corrector magnets type C5 (left) and C6 (right) for spoke LWU and elliptical/dogleg LWU respectively. Pictures by courtesy of A Fabris et al, Accelerators Group, Elettra—Sincrotrone Trieste S.C.p.A, Trieste, Italy.

Page 37: Missing source in the caption for table 30. The source of the data should be specified in the caption for table 30.

Table 30. Magnet parameters and performance for correctors type C5 and C6. Data by courtesy of A Fabris et al, Accelerators Group, Elettra—Sincrotrone Trieste S.C.p.A, Trieste, Italy.

Page 66: Revised author list for the Target Design. A number of authors who contributed to the paper were missing in the author list The ESS Design: Target. The revised author list for the part The ESS Design: Target is given below:

M Anthony\(^1\), E Pitcher\(^1\), L Coney\(^3\), M Göhran\(^1\), J Haines\(^4\), R Linander\(^1\), D Lyngh\(^1\), U Oden\(^1\), K Bakov\(^1\), Y Lee\(^1\), L Zanini\(^1\), M Kickules\(^1\), Y Bessler\(^2\), J Ringnér\(^1\), J Jurns\(^1\), A Sadeghzadeh\(^1\), P Nilsson\(^1\), M Olsson\(^3\), J-E Presteng\(^1\), H Carlsson\(^1\), A Polato\(^1\), J Harborn\(^1\), K Sjögren\(^1\), G Muhrer\(^1\), F Sordo\(^4\)

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Page 70: New section 1.9 Add a new section 1.9 with table C1 as below.

1.9 Target Subproject Setup The development and build of the ESS Target Station largely relies on contributions from institutes and competences centred within Europe in order to benefit from the existing experience and knowledge base. The in-kind partners involved in the Target subproject are listed in table C1.

Page 70: Missing references in section 2.2—Fourth sentence in the first paragraph. The reference [ULLMAIER95] should be added.

Compared to other tungsten alloys such as densimet® and tungsten with 10% rhenium impurity, the pure tungsten has better residual ductilities under neutron irradiations showing the lowest degree of irradiation induced microstructural disintegration [ULLMAIER95].

[ULLMAIER95] Ullmaier H and Carsughfi F 1995 Radiation damage problems in high power spallation neutron sources Nucl. Instrum. Methods Phys. Res. B 101 406–21

Page 70: Missing reference in section 2.2—Fifth sentence in the first paragraph. The reference [RIETH] should be added.

The higher thermal conductivity of the pure tungsten than those of the compared tungsten and tantalum based alloys results in smaller temperature gradients within the spallation volume [RIETH].

[RIETH] Rieth M, Hoffmann A, Materna-Morris E and Rohde M Tungsten materials for structural divertor applications Technical Report, KIT (http://bibliothek.fzk.de/zb/veroeff/80215.pdf)

Page 70: Missing reference in section 2.2—Seventh sentence in the first paragraph. The references [HABAINY15, TSERPELIS15, SHEN15] should be added.

It shows a high mass density and superior mechanical strength compared to sintered and HIPed and forged tungsten [HABAINY15, TSERPELIS15, SHEN15].

[HABAINY15] Habainy J, Iyengar S, Lee Y and Dai Y 2015 Fatigue behaviour of rolled and forged tungsten at 25°, 280° and 480° C J. Nucl. Mater. 465 438–47

[TSERPELIS15] Lövberg-Tserpelis A 2015 A comparative study of the fatigue properties of tungsten from different processing routes Master’s Thesis Department of Mechanical Engineering, Division of Materials Engineering, Faculty of Engineering, Lund University

[SHEN15] Shen T, Dai Y and Lee Y 2015 Microstructure and tensile properties of tungsten at elevated temperatures J. Nucl. Mater. 468 348–54

Page 70: Missing reference in section 2.2—Fifth sentence in the second paragraph. The reference [HABAINY15] should be added.

The unpolished specimens showed a fatigue limit of 150 MPa, whereas the polished one showed 237.5 MPa at 25°C [HABAINY15].

Page 70: Missing reference in section 2.2—Second sentence in the third paragraph. The reference [GORYNIN92] should be added.

For the test carried out at temperatures up to 500°C, the irradiated tungsten specimens fail in a brittle regime even at low radiation damage of 0.1 dpa [GORYNIN92].
Page 70: Missing reference in section 2.2—First sentence in the fourth paragraph. The reference [HABAINY16] should be added.

In order to understand the mechanical behaviour of tungsten under proton irradiation, a post-irradiation examination (PIE) was performed on the tensile and bending test specimens [HABAINY16].

[HABAINY16] Habainy J, Dai Y, Lee Y and Iyengar S 2016 PIE program of STIP-V tungsten specimens for ESS target engineering (The 6th High Power Targetry Workshop, 11–15 April Oxford, UK)

Page 71: Missing reference in section 2.2—Second sentence in the fifth paragraph. The reference [ROEDIG04] should be added.

It has been estimated about 20% loss of thermal conductivity in tungsten after 0.1 dpa of radiation damage [ROEDIG04].

[ROEDIG04] Roedig M, Kuehnlein W, Linke J, Pitzer D, Merola M, Rigal E, Schedler B and Visca E 2004 Post-irradiation testing of samples from the irradiation experiments PARIDE 3 and PARIDE 4 J. Nucl. Mater. 329–333 766–70

Page 71: Missing reference in section 2.2—Second sentence in the sixth paragraph. The reference [HABAINY14] should be added.

The oxidation characteristics of hot rolled tungsten for the temperature range from 400 °C up to 900 °C have been investigated [HABAINY14].

[HABAINY14] Habainy J, Nilsson C, Wendel J, Iyengar S, Lee Y and Dai Y 2014 Oxidation behaviour of pure tungsten in mildly oxidising atmospheres (12th Int. Workshop on Spallation Materials Technology, 19–23 October, Bregenz, Austria)

Page 71: Missing reference in section 2.2—Second sentence in the eighth paragraph. The reference [128] should be added.

Above 700 °C, tungsten oxide may become volatile in the presence of water vapour [128].

[128] Greene G A and Finfrock C C 2001 Vaporisation of tungsten in flowing steam at high temperatures Exp. Therm. Fluid Sci. 25 87–99

Page 71: Missing reference in section 2.2—Third sentence in the eighth paragraph. The reference [LEE15] should be added.

Furthermore, tungsten oxidation can generate exothermic heat, which is enough to heat up the tungsten blocks beyond the point of volatilisation [LEE15].

[LEE15] Lee Y and Hartl M 2015 ESS materials handbook Technical Report no. ESS-0028465

Page 71: Missing reference in section 2.4—Second sentence in the second paragraph. The reference [FARRELL01, MALOY01] should be added.

Indeed, the ferritic/martensitic steels irradiated at LANSCE with the irradiation temperature below 164 °C showed prompt necking at less than 2% plastic strain at the dpa value of as low as 0.5 [FARRELL01, MALOY01].

[FARRELL01] Farrell K and Byun T S 2001 Tensile properties of candidate SNS target container materials after proton and neutron irradiation in the LANSCE accelerator J. Nucl. Mater. 296 129–38

[MALOY01] Maloy S A, James M R, Willcutt G, Sommer W F, Sokolov M, Snead L L, Hamilton M L and Garner F 2001 The mechanical properties of 316L/304L stainless steels, alloy 718 and mod 9Cr ± 1Mo after irradiation in a spallation environment J. Nucl. Mater. 296 119–28

Page 71: Missing reference in section 2.4—First sentence in the third paragraph. The reference [SAITO05, DAI08] should be added.

Several kinds of austenitic steels from Europe, Japan and the USA have been irradiated to a maximum dose of 17.3 dpa and a sample of the specimens have been tested [SAITO05, DAI08].

[SAITO05] Saito S, Kikuchi K, Usami K, Ishikawa A, Nishino Y, Kawai M and Dai Y 2005 Tensile properties of austenitic stainless steels irradiated at simq target 3 J. Nucl. Mater. 343 253–61
Page 71: Missing reference in section 2.4—First sentence in the fourth paragraph. The reference [MCCLINTOCK14] should be added.

The tensile samples taken from the beam entrance region of the target vessel at SNS have been tested after the service lifetime of the first and second target [MCCLINTOCK14].

[MCCLINTOCK14] McClintock D A, Vevea B J, Riemer B W, Gallmeier F X, Hyres J W and Ferguson P D 2014 Post-irradiation tensile properties of the first and second operational target modules at the Spallation Neutron Source J. Nucl. Mater. 450 130–40

Page 71: Missing reference in section 2.4—Fourth sentence in the fourth paragraph. The reference [130] should be added.

At 5 MW operation, the radiation damage in the target wheel BEW is 1.2 dpa yr⁻¹ [130].

[130] Sordo F et al 2015 Radiation damage analysis for the ESS target Technical Report no. ESS-0037287

Page 73: Correction of numbers in section 2.10.1. The second paragraph should be corrected as follows.

The helium operation pressure is set to 1.1 MPa with corresponding volume flow of up to 2 m³ s⁻¹, and available blowers or compressors on the market is limited.

Page 79: Correction of figure reference in section 3.2.1. The figure referencing figure 81 in the second to the last sentence should be changed to figure 77.

Page 80: Correction of wording in section 3.3.3. The ‘collimator’ in the first paragraph should be corrected to ‘moderator’.

Page 80: Redundant reference in section 3.3.3. The [137, 141] in the first paragraph should be corrected to [137], removing [137, 141].

Figure 83 shows the fluid dynamic behaviour of the cold collimator system, over five beam pulses [137].

Page 81: Missing reference in the captions for figures 82. Reference [137] must be added to the captions for figure 82.

Page 82: Analysis of neutron heat. LEFT: Visualisation of the input data. RIGHT: 3D fit for CFD simulation [137].

Page 81: Missing reference in the captions for figures 83. Reference [137] must be added to the captions for figure 83.

Page 83: Computational fluid dynamics simulation results, showing temperature and pressure fluctuations during five beam pulses [137].

Page 81: Insertion of a new sentence in section 3.4. With an insertion of a new sentence, the first paragraph of section 3.4 should begin as follows.

3.4 Manufacturing moderator vessels Extensive investigations were performed early in the project at Forschungszentrum Jülich, department ZEA, as preparation for the manufacturing of the ESS cold and thermal moderator vessels. Machining, welding and quality assurance tests have been performed on the AL6061-T6 alloy that is used for the volume cold moderators. Nine vessels ...

Page 82: Missing source in the caption for figure 85. The source of the figure should be specified in the caption for figure 85.

Page 82: Missing reference in section 3.5.1—Third sentence in the first paragraph. The reference [WEEKS88, KAPUSTA03] should be added.

Its total elongation is more than 4% at a thermal neutron dose of 10²³ neutrons cm⁻² that corresponds to about 1.5% of silicon yield in aluminium [WEEKS88, KAPUSTA03].

Page 82: Missing reference in section 3.5.2—First sentence in the second paragraph. The reference [DAI16] should be added.

The SINQ Target-9 has been irradiated with a total proton charge of 13.2 A h⁻¹ during 2011 and 2012, without any structural failure in its safety-hulls [DAI16].

Page 83: Missing reference in section 3.5.3—Second sentence in the first paragraph. The reference [WEEKS88] should be added.

... so there is room for further relaxation of the dpa-based lifetime limit.

Page 83: Missing reference in section 3.5.3—Third sentence in the first paragraph. The reference [FARRELL99] should be added.

Displacements and point defects in aluminium self-anneal [FARRELL99] at a moderately elevated temperature, so there is room for further relaxation of the dpa-based lifetime limit.
[FARRELL99] Farrell K 1999 Materials selection for the hfr cold neutron source Technical Report no. ORNL/TM-99-208 ORNL

Page 83: Missing reference in section 3.5.4—Second sentence in the first paragraph. The reference [ITER98] should be added.

Swelling increases monotonically with dose, bounded above by an estimate of 1% for beryllium containing 5000 appm of helium, after irradiation at temperature between room temperature and 350 °C [ITER98].

[ITER98] ITER-EDA 1998 ITER material properties handbook Technical Report ITER Document G74 MA 4 98-06-28 R 0.1, pub. pkg. #6, ITER

Page 83: Missing reference in section 3.5.4—First sentence in the second paragraph. The reference [CHAKIN12] should be added.

Neutron irradiation may lead to a decrease in thermal conductivity of beryllium [CHAKIN12].

[CHAKIN12] Chakin V, Reimann J, Moeslang A, Latypov R and Obukhov A 2012 Thermal conductivity of highly neutron-irradiated beryllium in nuclear fusion reactors J. Nucl. Mater. 57 2–7

Page 83: Missing reference in section 3.5.4—Third sentence in the third paragraph. The reference [ANDERL98] should be added.

Studies of the chemical reactivity of irradiated beryllium and steam indicate that hydrogen generation is enhanced at a temperature of 700 °C, in a test in which the specimen experienced a temperature excursion above 1000 °C [ANDERL98].

[ANDERL98] Anderl R A, McCarthy K A, Oates M A, Petti D A, Pawelko R J and Smolik G R 1998 Steam-chemical reactivity for irradiated beryllium J. Nucl. Mater. 258–263 750–6

Page 93: New paragraph at the end of section 1 Introduction. Add a new paragraph with table C2 at the end of section 1 Introduction as follows.

The development of the ESS Integrated Control System relies on contributions from institutes and competences centred within Europe in order to benefit from the existing experience and knowledge base. The in-kind partners involved in the ICS subproject are listed in table C2.

Table C2. ICS Subproject In-Kind Partners.

| Institution          | Main deliverables                                                                 |
|----------------------|-----------------------------------------------------------------------------------|
| CEA (FR)             | Controls for ESS warm linac, proton source and LEBT, controls for RFQ            |
| ESS-Bilbao (ES)      | MEBT controls integration                                                         |
| IFE (NO)             | Main control room implementation, client software development for the Integrated Control System, data centre contributions |
| PSI (CH)             | IOC architecture and platforms, I/O card definition and selection                 |
| TUT (EE)             | EPICS EtherCAT driver/slave development, cyber-security assessment and methodology for controls, FPGA based IOC |
| Univ. of Łódź (PL)   | IPMI-EPICS-BLM-RTM                                                                |
| ZHAW (CH)            | MPS Services, BIS design and procurement                                          |
| STFC (UK)            | Detector controls development                                                     |

Page 118: Addition to acknowledgement. Additional colleagues should be acknowledged. Below is the list of additional colleagues to be acknowledged:

J Klingmann, Lund University. A Takibayev, ESS. E Klinkby, T Schoenfeldt, DTU.

Page 118: Addition of missing references into the list. The references below should be added to the list.

[ULLMAIER95] Ullmaier H and Carsughi F 1995 Radiation damage problems in high power spallation neutron sources Nucl. Instrum. Methods Phys. Res. B 101 406–21

[RIETH] Rieth M, Hoffmann A, Materna-Morris E and Rohde M Tungsten materials for structural divertor applications Technical Report KIT (http://bibliothek.fzk.de/zb/veroeff/80215.pdf)

[HABAINY15] Habainy J, Iyengar S, Lee Y and Dai Y 2015 Fatigue behaviour of rolled and forged tungsten at 25°, 280° and 480 °C J. Nucl. Mater. 465 438–47

[TSERPHELIS15] Lövberg-Tserpelis A 2015 A comparative study of the fatigue properties of tungsten from different processing routes Master’s Thesis Department of Mechanical Engineering, Division of Materials Engineering, Faculty of Engineering, Lund University

[SHEN15] Shen T, Dai Y and Lee Y 2015 Microstructure and tensile properties of tungsten at elevated temperatures J. Nucl. Mater. 468 348–54

[GORYNIN92] Gorynin I V, Ignatov V A, Rybin V V, Fabritsiev S A, Kazakov V A, Chakin V P, Tsykanov V A, Barabash V R and Prokofyev Y G 1992 Effects of neutron irradiation on properties of refractory metals J. Nucl. Mater. 191–194 421–5

[HABAINY16] Habainy J, Dai Y, Lee Y and Iyengar S 2016 PIE program of STIP-V tungsten specimens for ESS target engineering (The 6th High Power Targetry Workshop, 11–15 April, Oxford, UK)

[ROEDIG04] Roedig M, Kuehnlein W, Linke J, Pitzer D, Merola M, Rigel E, Schedler B and Visca E 2004 Post irradiation testing of samples from the irradiation experiments PARIDE 3 and PARIDE 4 J. Nucl. Mater. 329–333 766–70
tungsten in mildly oxidising atmospheres (12th Int. Workshop on Spallation Materials Technology, 19–23 October, Bregenz, Austria)  
[LEE15] Lee Y and Hartl M 2015 ESS materials handbook Technical Report no. (ESS-0028465)  
[FARRELL01] Farrell K and Byun T S 2001 Tensile properties of candidate SNS target container materials after proton and neutron irradiation in the LANSCE accelerator J. Nucl. Mater. 296 129–38  
[MALOY01] Maloy S A, James M R, Willcutt G, Sommer W F, Sokolov M, Sned L L, Hamilton M L and Garner F 2001 The mechanical properties of 316l/304l stainless steels, alloy 718 and mod 9cr ± 1mo after irradiation in a spallation environment J. Nucl. Mater. 296 119–28  
[SAITOO05] Saito S, Kikuchi K, Usami K, Ishikawa A, Nishino Y, Kawai M and Dai Y 2005 Tensile properties of austenitic stainless steels irradiated at sinq target 3 J. Nucl. Mater. 343 253–61  
[DAI08] Dai Y, Egeland G W and Long B 2008 Tensile properties of EC316LN irradiated in SINQ to 20 dpa J. Nucl. Mater. 377 109–14  
[MCCINTOCK14] McClintock D A, Vevea B J, Riemer B W, Gallmeier F X, Hyres J W and Ferguson P D 2014 Post-irradiation tensile properties of the first and second operational target modules at the Spallation Neutron Source J. Nucl. Mater. 450 130–40  
[WEEKS88] Weeks J R, Czajkowski C J and Tichler P R 1990 Effects of high thermal and high fast fluences on the mechanical properties of type 6061 aluminium in the hfbr Effects of Radiation on Materials: 14th Int. Symp. vol 2 (American Society for Testing and Materials)  
[KAPUSTA03] Kapusta B, Sainte-Catherine C, Averty X, Scibetta M, Decroix G M and Rommens M 2003 Present status on the mechanical characterisation of aluminium alloys 5754-NET-0 and 6061-T6 irradiated at high fluxes Technical Report INIS-FR-1862 CEA Saclay  
[DAI16] Dai Y, Blau B, Geissmann K, Schweikert H and Wohlmuther M 2016 The behaviour of AlMg3 after irradiation at high proton and neutron fluences (13th Int. Workshop on Spallation Materials Technology 30 October–4 November 2016 Chattanooga, USA)  
[LU08] Lu W, Ferguson P D, Iverson E B, Gallmeier F X and Popova I 2008 Moderator poison design and burn-up calculations at the sns J. Nucl. Mater. 377 268–74  
[FARRELL99] Farrell K 1999 Materials selection for the hfn cold neutron source Technical Report no. ORNL/TM-99-208 ORNL  
[ITER98] ITER-EDA 1998 ITER material properties handbook Technical Report ITER Document G74 MA 4 98-06-28 R 0.1, pub. pkg. #6, ITER  
[CHAKIN12] Chakin V, Reimann J, Moeslang A, Latypov R and Obukhov A 2012 Thermal conductivity of highly neutron-irradiated beryllium in nuclear fusion reactors J. Nucl. Mater. 57 2–7  
[ANDERL98] Anderl R A, McCarthy K A, Oates M A, Petti D A, Pawelko R J and Smolik G R 1998 Steam-chemical reactivity for irradiated beryllium J. Nucl. Mater. 258–263 750–6

Page 120: Correction of typos in [137]. The typos in reference [137] should be corrected as follows.  
[137] Bessler Y, Schumacher P, Hanusch F, Henkes C, Natour G, Butzek M, Klaus M, Lyngh D and Kickules M. 2016 Final design, fluid dynamic analysis and testing of a supercritical hydrogen moderator for the ESS Proc. ICEC2016, 7–11 March 2016 New Delhi, India, ICEC2016-ID-10-P3-266.  

Page 120: Removal of [141]. The [141] should be removed from the reference list.  
[141] Nilsson P et al. 2016 Cryogenic hydrogen cooling of a heated moderator vessel pp 60722 (Proc. ICEC2016, 26–30 June 2016 Charlotte, NC, USA)  

Note: It should be noted that D McGinnis has not consented to the addition of the new authors mentioned here, and has subsequently requested for his name not to appear on the author list of this Corrigendum.

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