The Spallation Material, ESS TAC 14

Consorcio ESS-BILBAO & European Spallation Source ERIC

F. Sordo on behalf of the ESS-Bilbao Team

October 6, 2016

Table of contents

Introduction

ESS-BILBAO Consortium

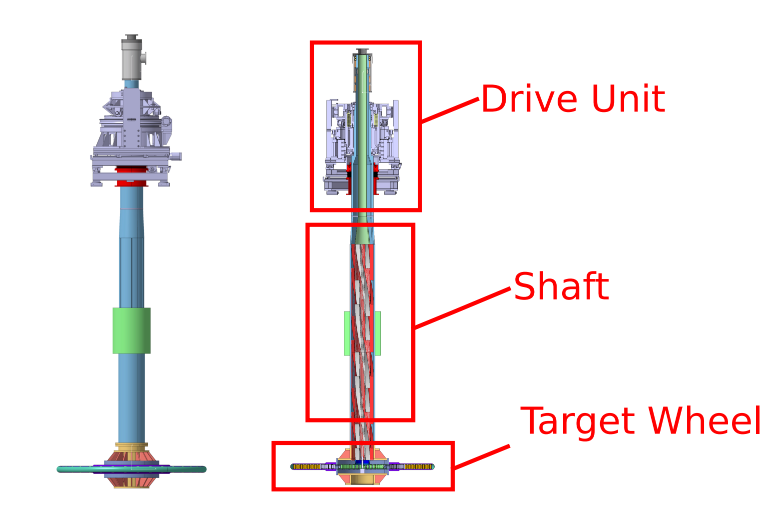
Role and functions

- The Spanish Government has taken the decision to make ESS-BILBAO the only contractor from Spain to ESS project.
- ESS-BILBAO has been nominated as Spanish representing entity for ESS operational phase.
- ESS-BILBAO is a public entity. However, we have a large flexibility to employ and subcontract.
- On November 2014, ESS-Bilbao was chosen as ESS partner for Target Wheel, shaft and drive unit.
- On October 2015, and International Panel Chair by Matt Fletcher evaluate the Target Base Line with positive feedback.
- On September 2016, Critical design review for the Spallation Material and the Cassettes.
- Critical design review for the Spallation Material was approved with “B comments”.
- Critical design review for the Cassettes has two “A comments”. We considered it will be fix in a couple of weeks.

The Spallation material and the cassettes

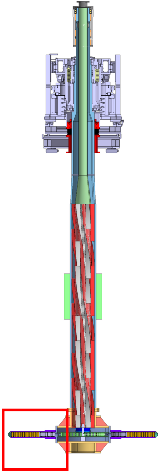
The ESS Target

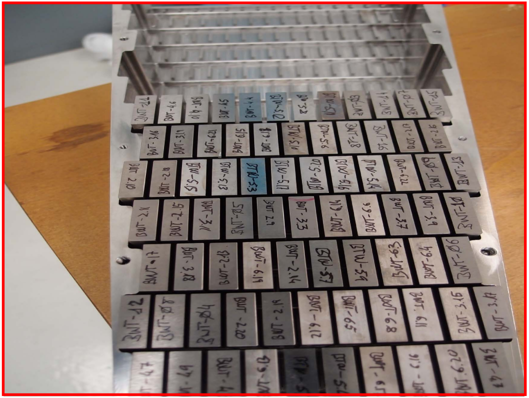
Main components: Target wheel, shaft and Drive Unit



The ESS Target

September 27th, Critical design review for Target Spallation Material

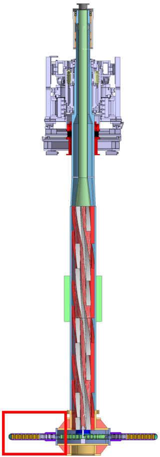


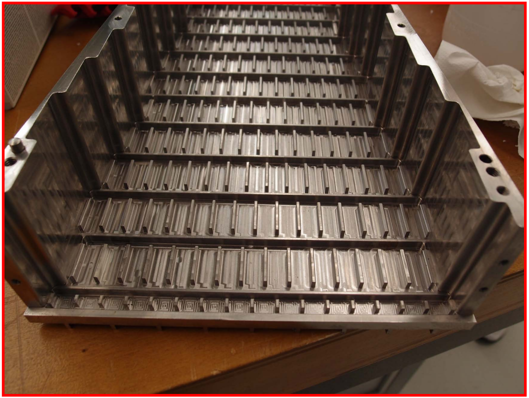


Spallation Material

The ESS Target

September 28^{th}, Critical design review for Target Internal structures





Internal structures (SS-316L)

The ESS Target

Main Target parameters

- Spallation Material: Hot Rolled W
- Internal Structures and shielding: SS-316L
- Target Vessel and shaft: SS-316L
- Beam Power: 5 MW
- Max Proton Energy: 2 GeV
- Life Time: 5 years
- Coolant: helium
- Helium Pressure: 10 bar
- Helium flow mas: 3 kgs^{-1}
- RCC-MRx Class 2 Component
- Life time 5 years

Load Scenarios

Loads scenarios

SF levels

- SF 1 and 2 are operating conditions associated with Normal operation, start and stop, and normal operational incidents.
- SF 3 Conditions are Operating Conditions which are rare and leads to shutdown and inspection, limit to 10 times in the lifetime.
- SF 4 Conditions are highly improbable but relevant for safety.

Load cases not considered for design proposes

- **Failure of rastering magnets:** " The impact of the beam produces an increase of temperature in the range of thousand degrees in any tungsten target"
- **Stationary wheel:** If the wheel stops without shutdown the beam, the temperature of the spallation material will increase $\sim 100^o C$ per pulse.

Geometry Proposal

Load scenarios considered for design

Requirement	**Loads**	**Level**
Operating Conditions	Design Beam Operating pressure (10 bar) Operational cooling conditions (3 kg s^{-1}) Wheel rotation	SF1
Vertically displaced beam	Vertically displaced beam Operating pressure (10 bar) Operational cooling conditions (3 kg s^{-1}) Wheel rotation	SF2
Unsynchronized wheel	Horizontally displaced beam Operating pressure (10 bar) Operational cooling conditions (3 kg s^{-1}) Wheel rotation	SF2
Loss of coolant flow and pressure	Design beam, Wheel rotation Operating pressure ($<$ 10 bar) Operational cooling conditions ($<$ 3 kg s^{-1})	SF3
Shut-down	No beam, Wheel stopped Operating pressure (10 bar) No coolant flow	SF3

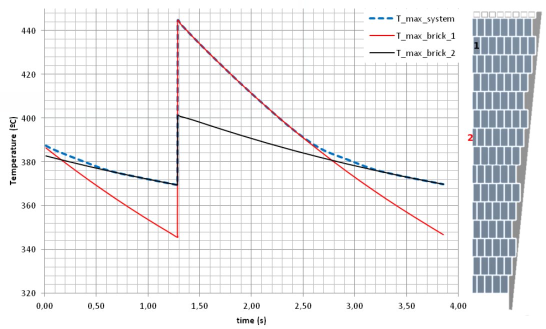
SF1: Normal operation conditions

SF1: Normal operation conditions

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^{o}C}$, which occurs **in the brick 1**. The front rows bricks have higher heat deposition by protons but they are better cooled, for this reason at the end of the cooling the temperature of these bricks is lower than others. The brick 2 has the maximum temperature at the end of the cooling cycle.

Temperature evolution

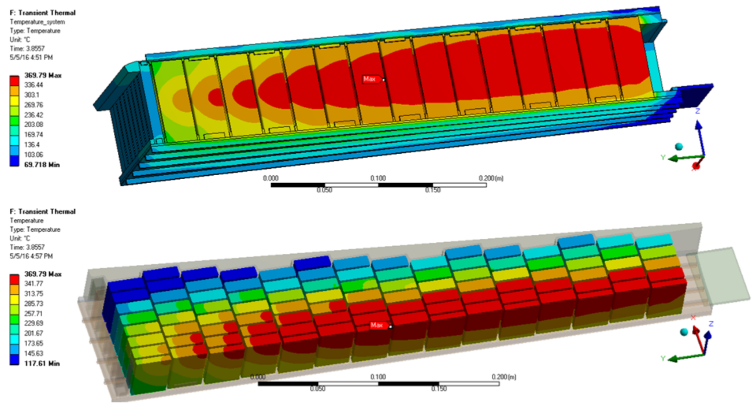


SF1: Normal operation conditions

Temperature profiles

The **maximum temperature at the end of the cooling is 370°C** and **after the pulse is 445°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of cooling

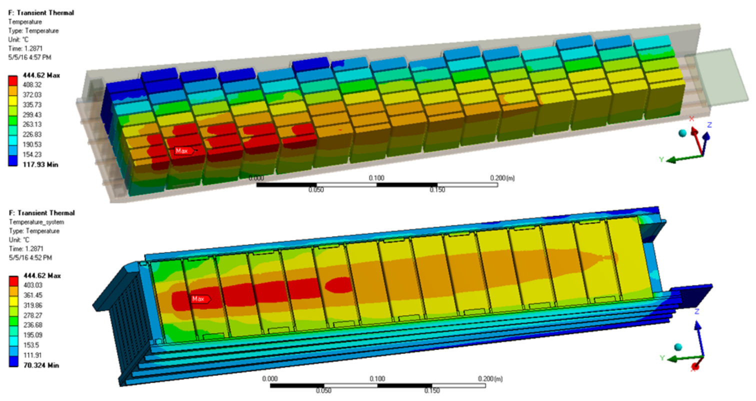


SF1: Normal operation conditions

Temperature profiles

The **maximum temperature at the end of the cooling is 370°C** and **after the pulse is 445°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of pulse

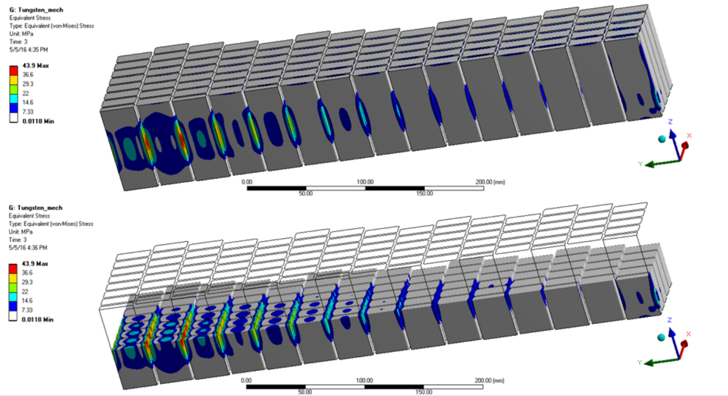


SF1: Normal operation conditions

Equivalent von-Mises stress profiles

The maximum equivalent stress at the **end of the cooling is 44 MPa** and **after the pulse is 110 MPa**.

End of cooling

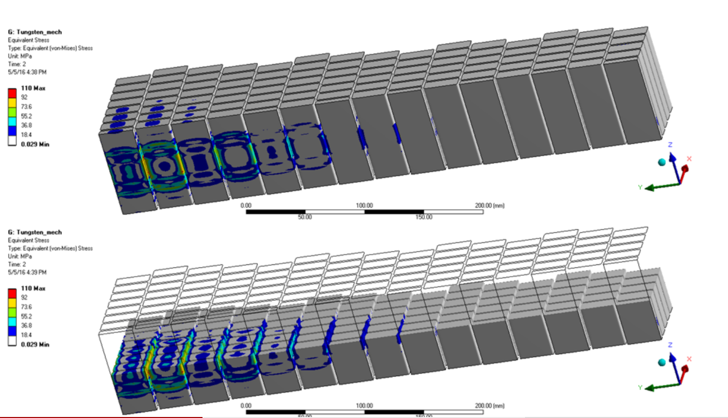


SF1: Normal operation conditions

Equivalent von-Mises stress profiles

The maximum equivalent stress at the **end of the cooling is 44 MPa** and **after the pulse is 110 MPa.**

End of pulse



Summary of the load cases

Load cases

	Clas	Max Tem [°C]	MT limit [°C]	Average Stress [MPa]	AS limit [MPa]	Stress Amplitude [MPa]	SA limit [MPa]
Normal Operation	SF1	445	500	77	100	40	50
Vertical displacement	SF2	457	700	77	-	42	-
Unsynchronized wheel	SF2	448	700	69	-	34	-
Channel blockage	SF2	518	700	91	-	44	-
Tungsten brick break	SF2	545	700	86	-	36	-
Shut-down	SF3	647	700	-	-	-	-

Lost of coolant and pressure cases [SF2]

	Time average. [^oC]	Pulse peack Temp. [^oC]	Limit [^oC]
Design	393	454	700
Low pressure [6.2 bar]	393	454	700
Low massflow [2 kg s^{-1}]	524	585	700
High inlet temp. [240^oC]	586	647	700
Low helium pressure and massflow [6.2 bar and 2.4 kg/s]	467	528	700

Spallation material: Quality evaluation

Spallation material: Quality evaluation

Evaluation of different suppliers

Taking into account the large differences on W grades, ESS-Bilbao is developing its own QA process to accept "W Suppliers" in the official "Call for tender process". Samples from 6 suppliers are under analysis at CEIT. This task will be completed in the next month and the data included in the CDR for Spallation material .

QA analysis on going at CEIT

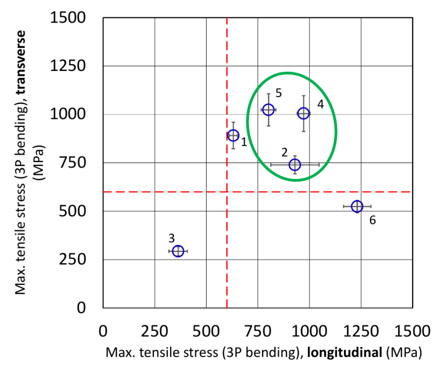
1	2	3
 Grey spots (oxide) on surface	 Thin continuous (oxide) layer on surface	   Damaged edges. Scratches on surface, slightly oxidized (finger prints).
4	**5**	**6**
 Bright smooth surface, free from oxides	 Brightest, smoothest surface, probably polished. Free from oxides	 Rough surface, free from oxides. Bricks slightly shorter??

Spallation material: Quality evaluation stage 1

General properties

The stage 1 evaluates general properties of the material like density, young modulus,tensile stress, chemical composition, residual stresses and fractography.

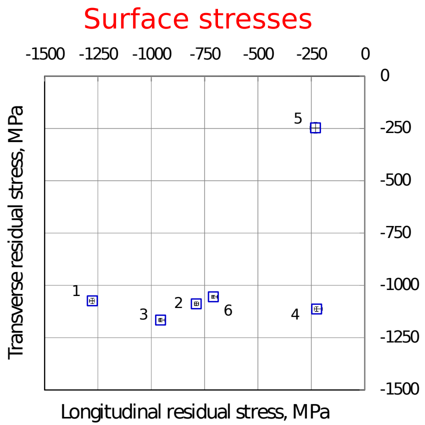
Tensile stresses, density, chemical composition and young modulus



W supplier	Visual inspection	Density, ρ ($g\ cm^{-3}$) Geom. ± assoc. error	Density, ρ ($g\ cm^{-3}$) Water displ. ± sd	E, Young modulus sRPN (GPa) ± assoc. error	HV (1 kg) RP ($kg\ mm^{-2}$) ± 95% cl	Res. stresses, surface (MPa) ± sd σ_{11} (LD)	Res. stresses, surface (MPa) ± sd σ_{22} (TD)	Fractography	Chemical composition Impurities above threshold
1	Grey spots (oxide) on	19.22 ±0.03	18.95 ±0.22	403.9 ±0.7	423.7 ±25.7	-1276 ±9	-1074 ±13	Brittle, transgranular, distorted cleavage ,	-
2	Thin continuous (oxide)	19.16 ±0.03	19.21 ±0.03	405.9 ±0.8	496.5 ±9.5	-789 ± 11	-1088 ± 9	Brittle, transgranular, distorted cleavage , oriented facets Minor	-
3	Damaged edges.	18.27 ±0.03	17.69 ±0.03	364.9 ±0.7	355 ±6	-956 ± 20	-1166 ± 8	Brittle, intergranular fracture, equiaxed grains, high porosity	-
4	Bright smooth surface,	19.24 ±0.03	19.20 ±0.03	408.1 ±0.8	496 ±6.0	-225 ± 27	-1113 ± 11	Brittle, transgranular, distorted cleavage , oriented facets	-
5	Brightest, smoothest surface.	19.22 ±0.03	19.23 ±0.01	406.4 ±0.8	412 ±16	-230 ±24	-247 ±26	Brittle, transgranular, distorted cleavage , oriented facets	>30 ppm O (44 ppm)
6	Rough surface, free from oxides.	19.26 ±0.03	19.15 ±0.05	391.4 ±0.7	470 ±5.0	-709 ± 18	-1055 ± 7	Brittle, transgranular, distorted cleavage , oriented facets	-

Spallation material: Quality evaluation stage 1

Surface stresses and diffraction peaks



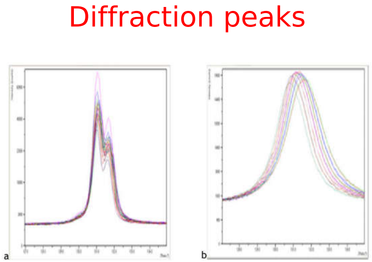


Figure 3. X-rays (321) diffraction peaks, samples 5 (a) and 2 (b).

Spallation material: Quality evaluation stage 1

FRACTOGRAPHY (fracture under tension stress in longitudinal direction)

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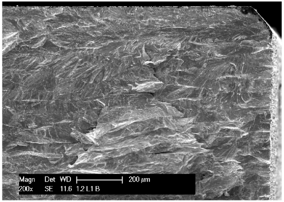


Figure 20. 1, L, x200. Horizontal direction is the presumed transverse-to-the rollin direction.

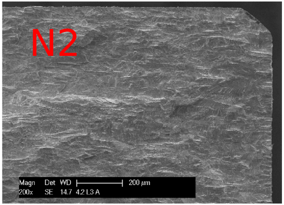


Figure 22. 4, L, X200

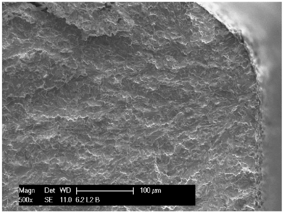


Figure 24. 6, L, x500

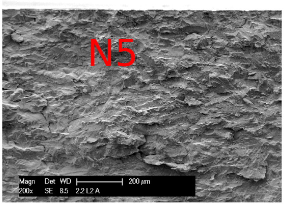


Figure 21. 2, L, x200

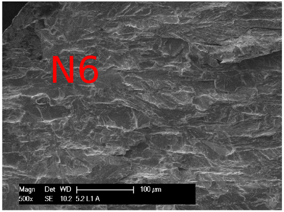
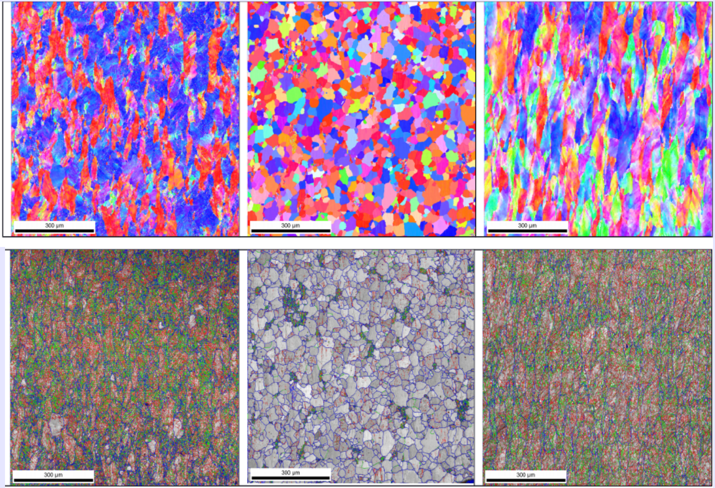


Figure 23. 5, L, x500

Fractographic patterns coherent with the other observations of mechanical or physical properties

Spallation material: Quality evaluation stage 2

Grain structure and morphology

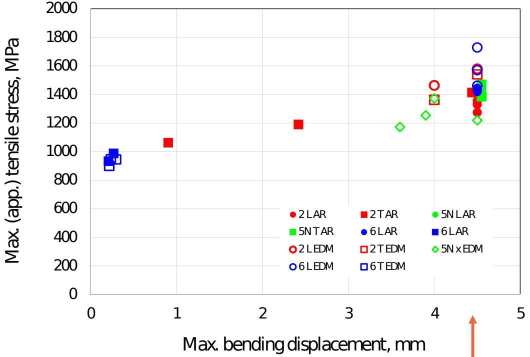


Supplierts 2, 5 and 6. Gran structure in the middle plane.

Spallation material: Quality evaluation stage 2

Tensile stress at 400$^o C$

Tensile strength, 400ºC in air (3P bending)
L and T orientations, fracture nucleated either from as-received on from EDM surface



Surface in tension:

AR: as-received surface, filled symbols
EDM: electro-discharge machined

Circles, L direction (long.)
Squares: T direction (transv.)

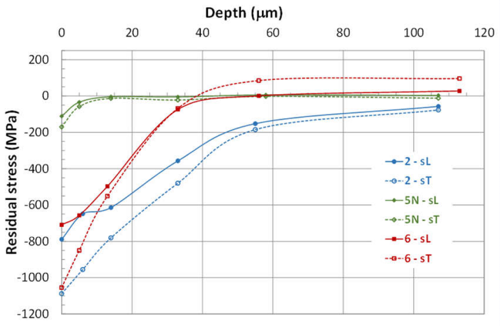
The maximum displacement allowed by the bending rig was 4.5 mm

Spallation material: Quality evaluation stage 2

In the second stage 2 suppliers shows optimal properties for our application

- Bricks 2 & 6: strong level of sub-surface biaxial compressive stresses up to resp. 30 and 50 mm
- Brick 5N: weak compressive surface stress up to less than 10 mm

Surface residual stresses



Spallation material: Quality evaluation stage 2

CDR review panel: L. Yongjoong, Y. Dai (PSI), D. Arghya (RAL), I. Srinivasan

The committee thanks the project team for the high quality of the work presented. The committee appreciates the evaluation method for the selection of the spallation material, and thus agrees with the rankings proposed.

Acquisition strategy

Acquisition strategy

Procurement process following the Spanish lays for Publish institutions

ESS-Bilbao is a public body thus we need to follow the procedures for public procurement. Based on the singularity of the product and the QA analysis process develop by CEIT, ESS-B will justify that there is a limit number of suppliers that can fulfill the technical requirements. This supplier will be "invite" to the Call for Tenders.

Spallation material Quality control

ESS-Bilbao has established the criteria that has to be fulfill by the supplier and the tests that have to be completed in the acceptance process.

- Material requirements: Factory test under Supplier responsibility. Documentation will be review by ESS-Bilbao before shipping to Spain.
- Acceptance test: Testing process to validate the "Supplier factory test" under ESS-Bilbao responsibility.

Acquisition strategy

Material requirements:

- Trazability: The bricks will be identify individually along all the production process.
- Material produced by hot rolling: The material will have directional structure associated with the hot rolling process with clear grain elongation along the rolling direction. Annealing processes after the rolling should be avoided.
- Compressive residual stresses: The material will have compressive residual surface stresses in the longitudinal and transverse direction above 500 MPa. The residual stresses will be measured by X-ray diffraction or equivalent technique (ASTM E2860-12)
- Chemical composition: O and N concentration below 15 ppm. (ASTM E1569-09)
- Chemical composition: C and S concentration below 30 and 10 ppm (ASTM E 1941-10)
- Density: The minimum admissible density should be $19.0\ g \cdot cm^3$. (ASTM B311-12)
- Surface roughtness: Ra $= 1.6\ \mu m$.
- Dimensional control: Bricks dimensions will be control according to the drawings.

Acquisition strategy

Material requirements:

- Tensile fracture stress in longitudinal direction: The mean RT fracture stress on longitudinal direction will be above 600 MPa at room temperature (ATSM E8/E8M-15a)
- The supplier will provide the statistical probability distribution and its standard deviation. This information will be consider for the final definition of the number of pieces to be tested in the acceptance process.

Acquisition strategy

Acceptance test: (subcontracted to a qualify third party)

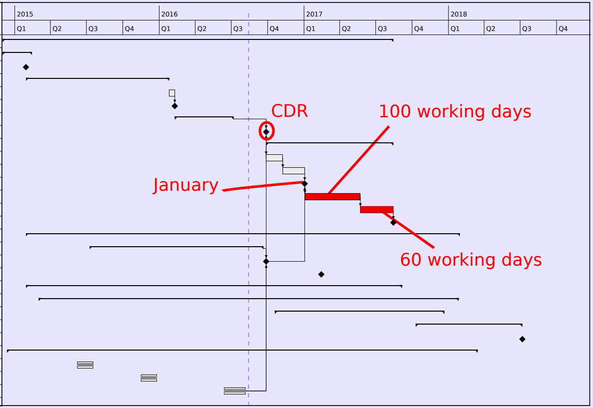
- Metrology: A significant number of samples (100) will be individually measured to check the external dimensions of the brick (including density).
- Tensile test: Statistical sampling plan will be defined according to the data provided by the supplier (40-100 bricks).T he tensile stresses will be evaluated by means of bending test at room temperature in longitudinal direction.
- Structural inspection: Three samples from the tensile test population (those having the lower, mid and highest fracture stress) will be analyzed by SEM-EBSD metallography in longitudinal direction. The analysis will consider large enough areas containing a number of grains larger that 400.
- Surface residual stress: Three samples will be analyzed by means of X-ray diffraction [ASTM E2860-12].

Schedule

Schedule

Planning based on suppliers production time. (Quotation example by AT&M)

Nombre	Trab...
Spallation Material	**866d**
Preparatory works	**67d**
KO meeting	
Design phase	**330d**
MP: Preparation of Spallation material final proposal	10d
MS: spallation Material Design Review	
Final CAD modeling	**229d**
CDR:Critical desing review for Spallation Material & Vessel	
Manufacturing Phase	**230d**
Preparation of public call for tenders	30d
Public advertising	40d
MS: Spallation Material Contract Awarded	
Spallation Material Supply	100d
SAT & QA control of the Spallation material	60d
MS: Spallation material deliver for cassette assembling	
Vessel & internal structures	**2145d**
Accidental analysis	**470d**
CDR:Crititcal desing review for Spallation Material & Internal structures	
CDR: Critical desing review of the Vessel	
Shaft including internal Shielding	**1180d**
Drive Unit and Positioning system	**690d**
Feedthrough	**397d**
Assembling & testing Phase	**154d**
MS SAT	
EDD for Target wheel	**1425d**
Delayed: Review Based on the new beam parameters	30d
Delayed: Review Based on Neutronic and moderator requirements	30d
Delayed: Accidental analisis for licencing	40d



Schedule

Planning based on suppliers production time. (Quotation example by AT&M)

AT&M 安泰科技 ....Quotation

Refractory Metal & Ceramics Branch, Advanced Technology & Materials Co., Ltd. (AT&M)
Zone C, 10 Yongcheng North Rd, Haidian, 100094, Beijing, China.

To:	Dr. Fernando ESS Bilbao	From:	Mary
Mobile:	+34 688 818 972	Fax:	+86 10 58717300
Tel:	+46 46 888 31 05	Tel:	+86 10 58717301
E-Mail:	Fernando Sordo <fernando.sordo@essbilbao.org>	E-Mail:	zhangxi aoj i e@at mcn. com
CC:		Pages:	1
Subject	Project Quotation	Date:	2016/9/14

S/N	Part No.	Description	Material	Qty /pcs	Unit Price/pc	Lead Time
1	80*30*10	Tunsten Bar	W	1	[redacted]	45DAYS for 7000 pcs

The Quotation is cover all of QA Requirement.

Currency	VAT	Period of Validity
USD	VAT Excluded	180Days

Terms and Conditions:

1)This quotation is based on the drawing, specification and requirement provided. Should there be any variation, the quotation is permitted to be negotiated further.

2)This quotation is based on the material cost at the moment when the quotation is issued. Should there be any fluctuation of more than 5%, the quotation is permitted to be negotiated further.

3)This quotation is based on the currency exchange rate at the moment when the quotation is issued. Should there be any fluctuation of more than 3%, the quotation is permitted to be negotiated further.

Approval: ____________________

Conclusions

Conclusions

Summary

- The CDR of the spallation material has been completed successfully and on schedule.
- The Base line design withstands the load conditions identified for design proposed with significant safety factors.
- The evaluation process for tungsten suppliers has been completed. Based on this process a detail acquisition strategy is in place.
- The Call for Tender is on preparation. However, the acquisition time is shorter compared with our previous expectations so, probably we will delay the award a until the beginning of the new year.

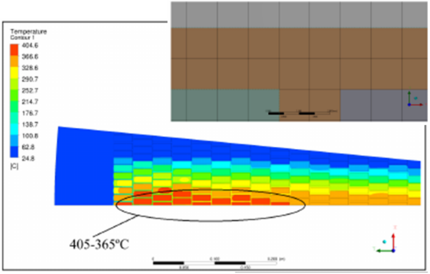
Apedinx A: Analysis model

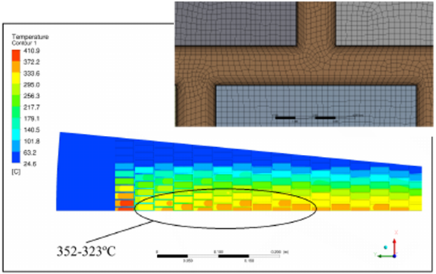
Thermomechanical simulation methodology

Turbulence role and CFD accuracy

- Turbulence play an important role ⇒ CFD solved with accuracy ($\mathbf{y^+ \approx 1 - 5}$)
- Complex fluid-tungsten boundary
- 3D-CFD transient simulation ⇒ prohibitive computing time and resources

For these reasons **solid-fluid uncoupling methodology** was chosen to solve the SF1 and SF2 main load cases.

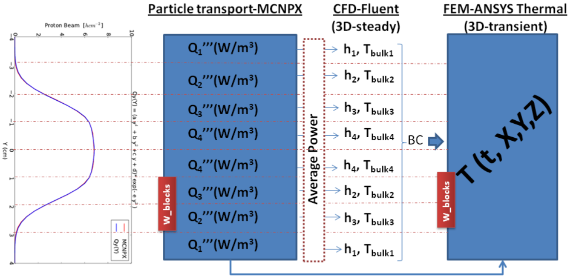


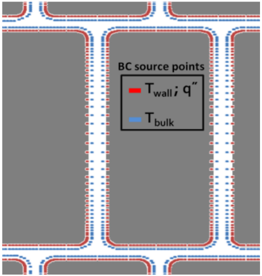


Thermomechanical simulation methodology

Steps

1. Generate the Thermal Source using MCNP.
2. Solve the CFD steady state model at average power.
3. Generate the convection BC ($\mathbf{T_{bulk}}; \mathbf{h}$) from the CFD solution (BC ESS-Bilbao Tool).
4. Solve the FEM-Thermal Transient model.
5. Solve the FEM Mechanical steady state model for the end of cooling and end of pulse.





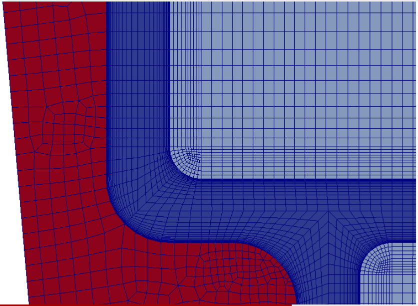
CFD-Tungsten convection BC generation

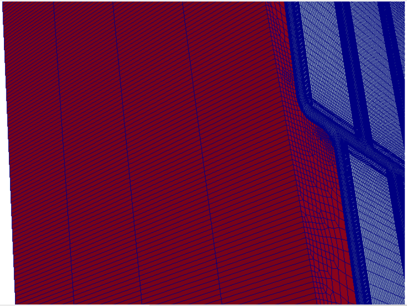
Turbulence model and mesh

- Turbulence model: $\kappa - \omega$ **SST**
- Conformal hexahedral mesh (3 zones)
- Fine boundary layer:
  - 15 elements
  - 1.24 growth rate
  - $y^+ \approx 1$

- High mesh resolution in flow directions
- Height mesh resolution: 1 element/cm*
- Mesh parameters:

Parameter	Aver. Value	Worst value
N^o Elements	2,205,420	-
Orthogonal Quality	0.992	0.29
Skewness	0.05	0.67
Aspect ratio	203.9*	244.93*





FEM-Thermal model

Mesh

Unlike the CFD problem the required mesh to accurately solve the thermo-mechanical problem is coarser. A non conformal mesh composed by 466,000 elements was employed, most are hexahedrons but some complex bodies were meshed with tetrahedrons.

Parameter	Aver. Value	Worst value
N^o Elements	465,974	-
Element Quality	0.89	0.23
Skewness	0.19	0.9
Aspect ratio	1.47	6.7