Monolith Vessel, Proton Beam Window and TBD: Design progress

Consorcio ESS-BILBAO & Instituto de Fusión Nuclear & ESS-AB

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Introduction

ESS-BILBAO Consortium

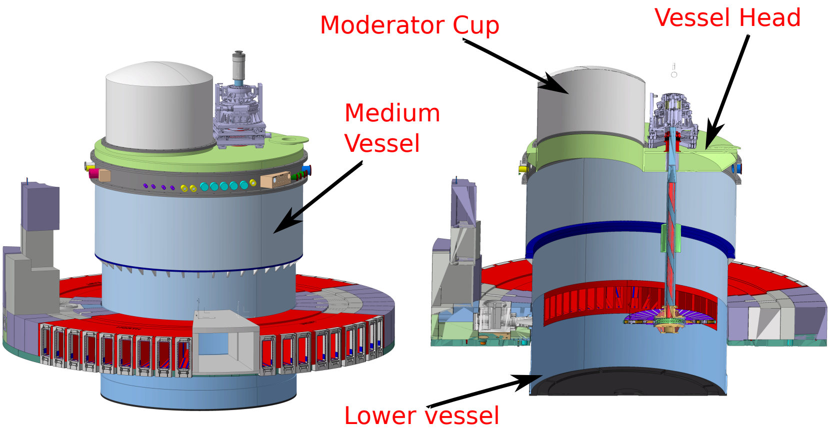
Role and functions

- The Spanish Government has taken the decision to make ESS-BILBAO the only contractor from Spain to ESS project.
- Staff of 65 scientists & engineers and the possibility to hire extra staff.
- ESS-BILBAO has been nominated as Spanish representing entity for ESS operational phase.
- ESS-BILBAO has already received the money for the following years activities ($>$ 20 M€) and additional grants will be provided in due time.
- ESS-BILBAO is a private entity, so we have a large flexibility to employ and subcontract.
- On December 2014, ESS-Bilbao was chosen as ESS partner for TBD, Proton Beam Entrance Window and Monolith Vessel.
- TBD and proton beam window KO meeting held on April 2015.
- Monolith vessel KO meeting held on October 2015.
- TBD and TBDS PDR held on July 2016.
- TBDS CDR held in July 2016.

Monolith vessel

Monolith Vessel: Introduction

Geometry



Monolith Vessel: Introduction

Requirements overview

- The Vessel has the following functions, interfaces, assembly requirements and structural requirements to handle.
- Leak tight barrier confinement
- Seismic load, Internal over Pressure
- Load and vacuum load resistant.
- Feedthroughs, covers and seals
- Manufacturing capability and tolerances achievable
- Installation and alignment
- High Vacuum compatible design, incl. vacuum testing possibility
- Handling and logistics Safety incl. radiation safety
- RCC-MRx Class 3 Component
- Life time 45 years

Monolith Vessel: Introduction

Main Loads (SF1 conditions)

- Dead Weight
- Target Weight
- Vacuum ($10^{-2} Pa$)
- Radiation damage

Accidental loads (SF3 conditions)

- Overpressure 2 bar
- Seismic loads

Design criteria

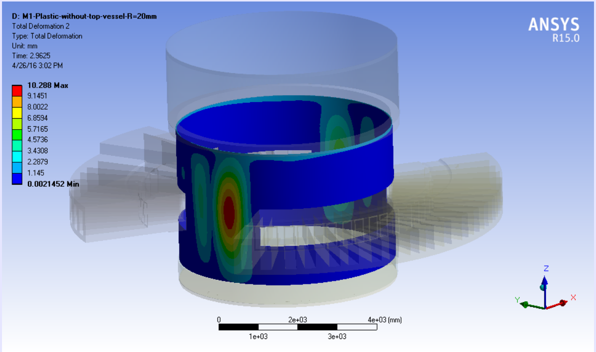
- Maximum deformation in the Target supports limit to 2 mm on nominal conditions

Optimization process: Lower vessel optimization

Buckling analysis

The RCC-MRx design criteria for buckling demands stability under a load multiply factor of 2.5 (DW+Vacuum). This criteria is fulfill by 20 mm thickness plate even considering a very conservative value for corrosion (0.2 mm for PH 4 water at 80^o C).

Optimization process: Lower vessel buckling analysis



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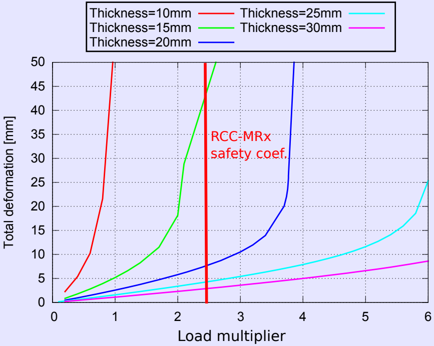

Optimization process: Medium vessel optimization

Buckling analysis

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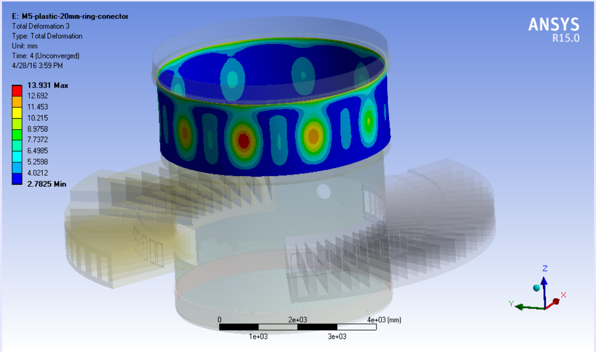
Lower vessel buckling analysis



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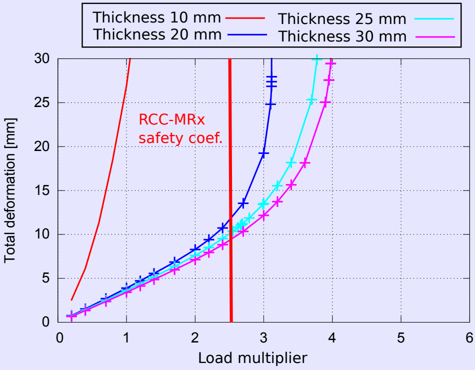
Lower vessel buckling analysis

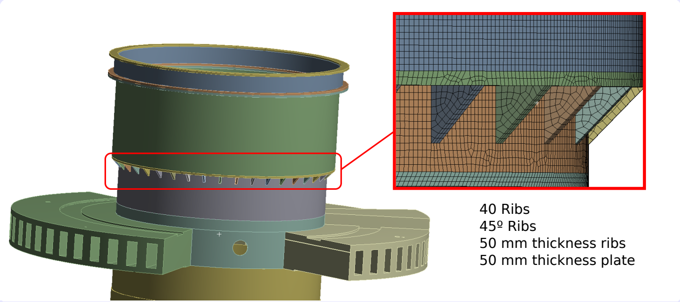


Optimization process: Forge Ring

Ribs proposal

The forge ring was proposed in order to introduce a step in the vessel geometry that avoids neutron streaming. However, the manufacturing process for this large forge elements demands a significant production (∼ 120 days), over cost and delay risk. ESS-Bilbao proposes to decouple shielding from vessel and introduce extra stiffness elements.

Ribs analysis

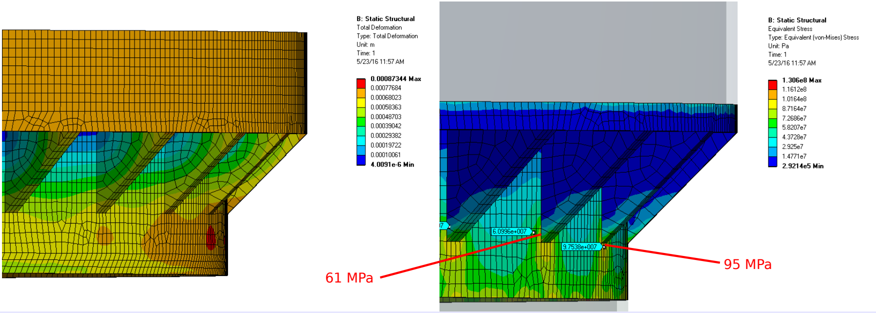


Optimization process: Forge Ring

Ribs proposal

To compensate the stability provided by the ring 40 ribs with 50 mm thickness are needed. These ribs are working in compression conditions hence, no full penetration weldings are needed. The shielding ring, is still needed but it can be manufactured in four pieces starting from two 10 mm thickness plates.

Ribs analysis

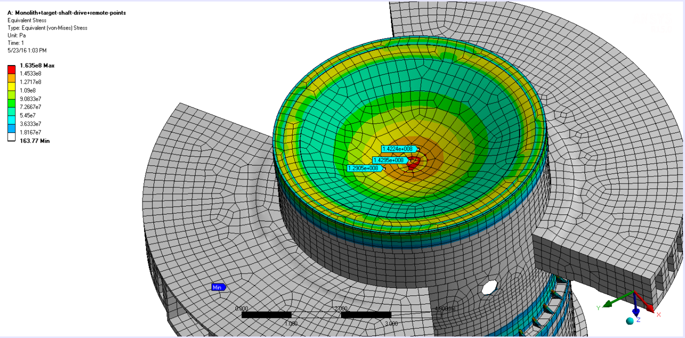


Optimization process: Bottom plate

Bottom plate optimization proposal

The bottom plate has only compression loads on nominal conditions due to the weight of the Target Monolith shielding, so its thickness is defined by vacuum tested. However, in this test the deformation of the plate is not critical hence, the thickness is limited by stress criteria. Based on that 50 mm is enough to fulfill RCC-MRx design rules ($P_m + P_b < 1.5S_m$).

Von Misses equivalent stress (50 mm)



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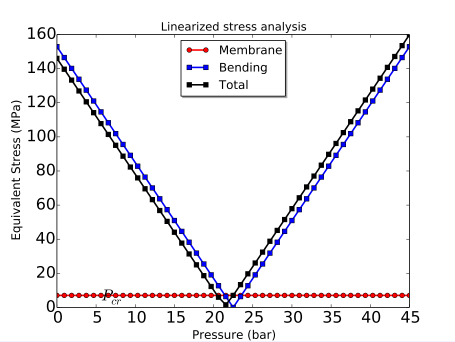
Linearized analysis at maximum stress element (50 mm)



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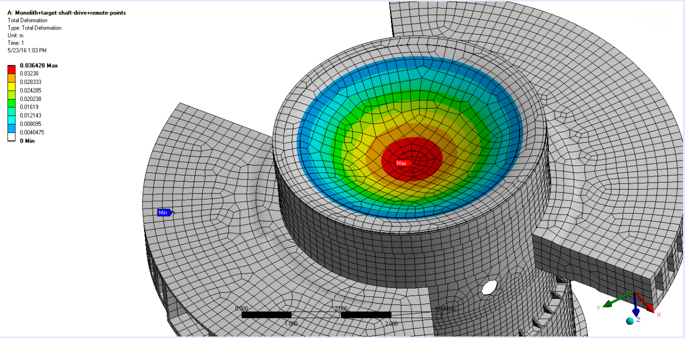
Total Deformation (50 mm)



Optimization process: Lower & Medium Vessel

Remarks for the process

The proposed modifications reduces significantly the total weight of the monolith vessel with no significant effect on safety margins. Hence, we consider the optimization process is completed for the lower and medium vessel.

Optimization process Summary

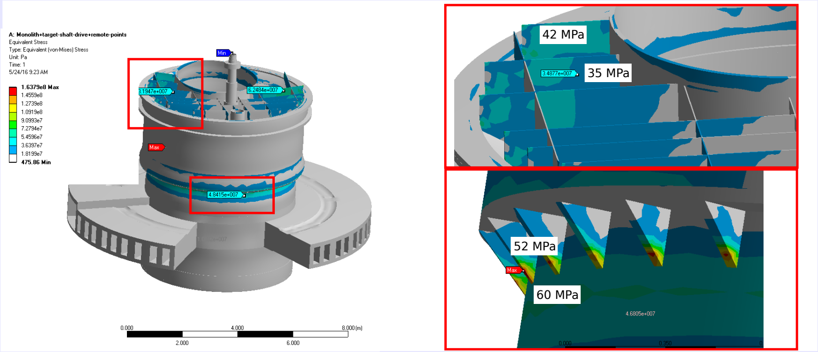
	Units	**PDR**	**ESS-Bilbao**	**Weight fract**
Bottom-vessel	[kg]	15610	9960	63.81%
Lower Vessel 1	[kg]	3394	3394	100.00%
Lower Vessel 2	[kg]	10600	7327	69.12%
Shielding Ring	[kg]	7700	1576	20.47%
Extra shielding	[kg]	-	0	
Medium vessel	[kg]	8200	6100	74.39%
Connection Ring	[kg]	8218	8218	100.00%
Vessel head	[kg]	26185	26185	100.00%
				W. Reduction
TOTAL	[kg]	79908	62760	17147

Nominal conditions [SF1]

Load scenario

Under nominal operational conditions, the monolith vessel have to withstand the dead weight of the structure and the differential pressure produced by vacuum. The protection level on this scenario is LEVEL A. Nominal stresses are far below S_m limit so no additional consideration is needed. Regarding buckling, λ is above 2.5 hence, there is still large safety margin.

Stress and displacement



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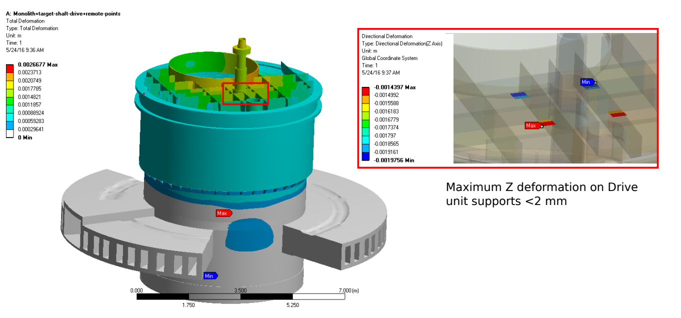

Maximum Z deformation on Drive unit supports <2 mm

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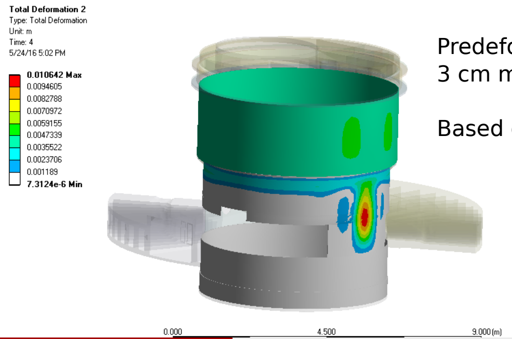

Predeformed shape considering 3 cm manufacturing error.

Based on linear backling mode 3

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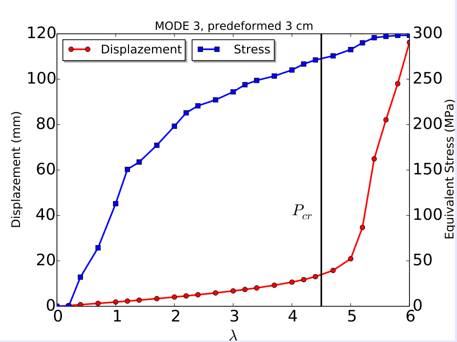
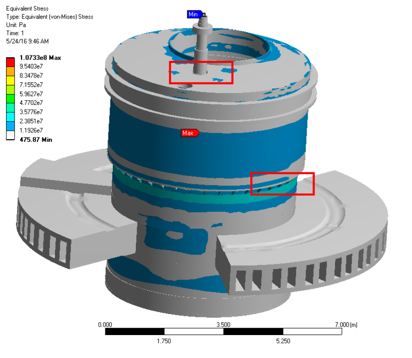


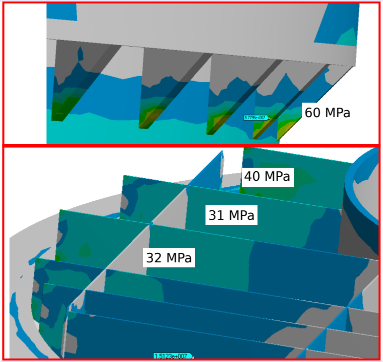
Overpressure [SF2]

Load scenario

An accidental condition could produce an overpressure in the monolith vessel. The release valves will be set at 2 bars, so the monolith have to withstand 1 bar difference pressure. The protection level on this scenario is LEVEL A. Nominal stresses are far below S_m limit so no additional consideration is needed.

Stress and displacement





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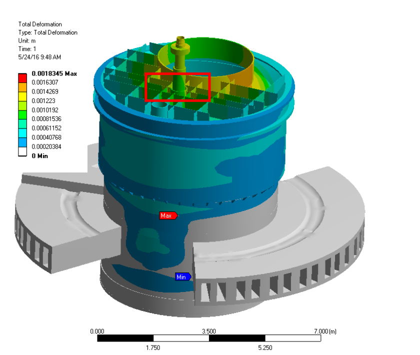
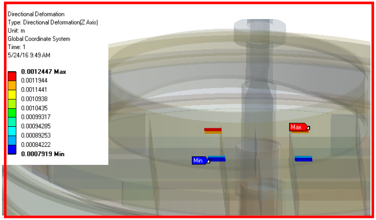




Vertical displacement of Drive unit supports below 2 mm

Seismic events [SF4]

Spectral analysis conditions

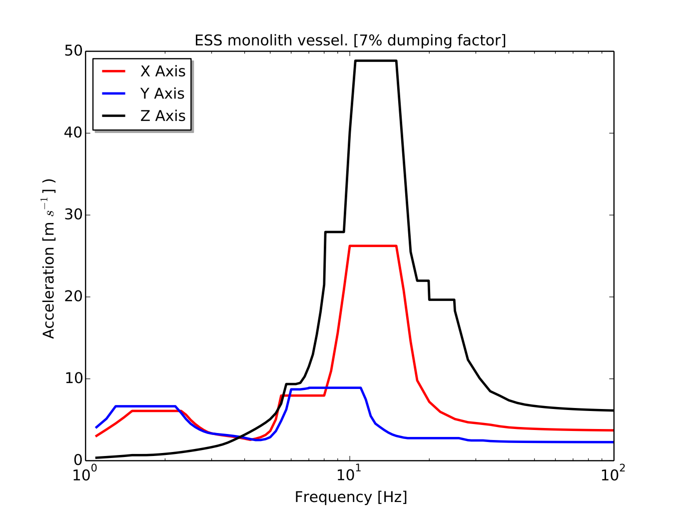
The RCC-MRx code allows evaluation of the seismic response by means of spectral analysis. To perform this evaluation we have considered the first 100 modes (maximum frecquency above 200 Hz). The remaining mass is included as rigid response (Gupta Method).

Combination of responses

Taking into account that the accelerograms consider an attenuation factor of 7%, the eigenfrequences of the systems are not coupled ($f_i/f_{i+1} > 10\%$). Hence, the SRSS combination mode has been selected.

Seismic events [SF4]

Reference accelerograms for monolith Vessel. [7% Dumping factor]

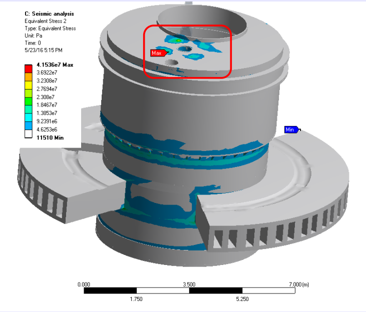


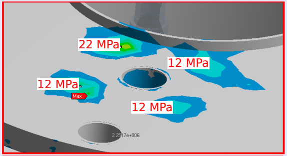
Seismic events [SF4]

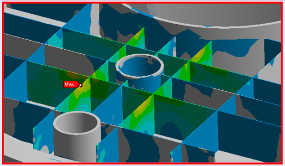
Stress in the Head Vessel

The main loads in the Vessel are produced by the movement of the Target in the first 1-5 modes on frequencies between 1-10 Hz. This loads are transmitted to the target supports, however the ribs structure inside the head of the vessel mitigates the deformation. Maximum stresses are far below the RCC-MRx (Level A).

Von Misses equivalent stress





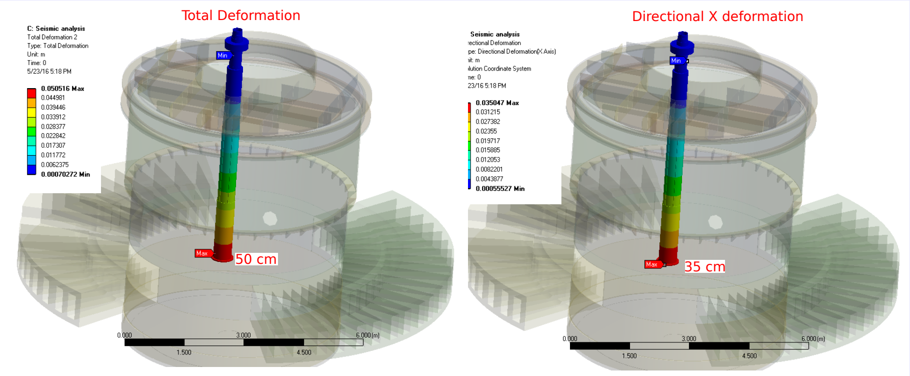


Seismic events [SF4]

Target shaft deformation

The displacement of the target shaft could produces impacts on surrounding elements (pedestal, moderator-reflector ...) that should be considered. However, this is not in the scope of Monolith Vessel analysis.

Maximum deformation



Conclusions

Main remarks for lower and medium vessel

- Optimization process is completes for lower and medium vessel. A 30% weight reduction has been achieve.
- RCC-MRx analysis for nominal conditions is completed (Steady State and buckling).
- RCC-MRx analysis for seismic events is completed.

Main remarks for conection ring and head of the vessel

- Optimization is on going.
- We already have a solution already fulfill the requirements (Lower and medium vessel analysis). However, there is room for upgrades.

Proton beam window

Proton Beam Entrance window: Introduction

Introduction

- The plug is situated in its own separate shaft attached to the monolith vessel
- Shielding blocks and plug structure is extracted vertically
- Alignment is a very important issue to ensure a reproducible and correct positioning of the window
- The shaft is filled with shielding to avoid streaming
- All connections to the PBW instrumentation, cooling and cabling is made from above

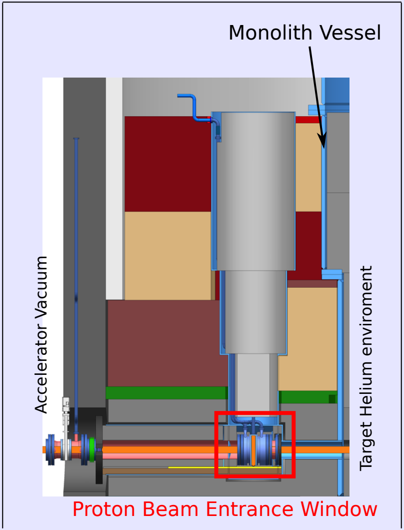
Proton Beam Entrance window: Requirements

Requirements

- Material: Al-6061-T6
- Boundary temperature : 50^o C
- Maximum operational temperature: 60^o C
- Minimum Al-6061-T6 thickness: 1.0 mm
- Coating for beam instrumentation : $\sim$ 0.100 mm
- Pressure difference: 1 bar
- Maximum leak rate: $2 \cdot 10^{-5}$ $mbar \cdot l \cdot s^{-1}$ $[3 \cdot 10^{-6} Pa \cdot m^3 \cdot s^{-1}]$
- Vertical insertion

Proton Beam Entrance window: "Pan Pipe"

Position in the monolith vessel

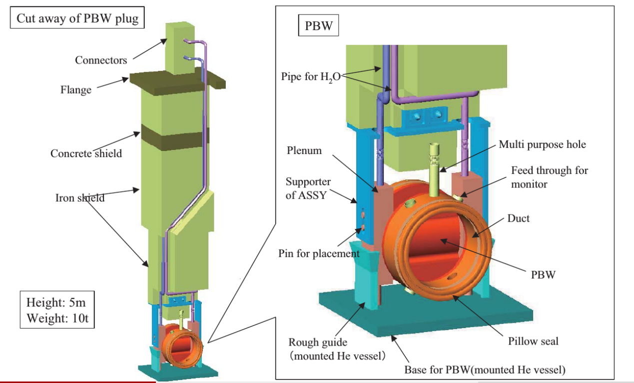


Proton Beam Entrance window: Pillow seal

The Pillow seal J-PAC solution

The Pillow seal already used by J-PAC is a commercial product with 0.6 m diameter that fulfill our vacuum requirements (Tested leaks in the level $\sim 7 \cdot 10^{-7}\ Pa \cdot m^3 \cdot s^{-1}$). The seal is also prepared for remote handling operation.

Proton Beam entrance window at J-PAC



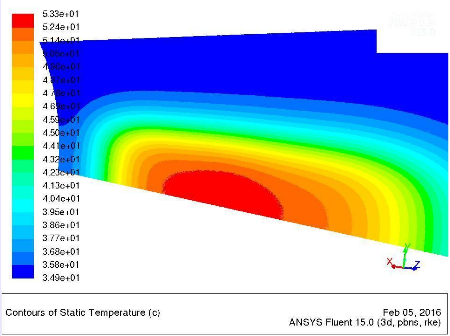
Proton beam window: Beer can model

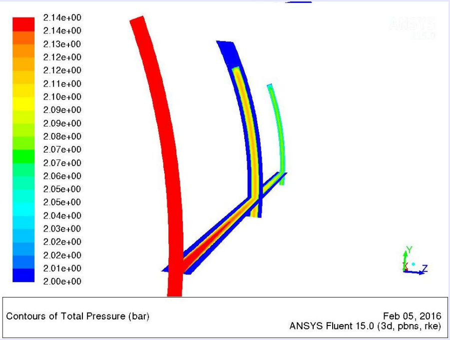
Basis

- Water at $35^o C$, $3.5 m/s$.
- Ambient temperature $= 50^o C$
- Thickness 1.0 mm.
- $60^o C$ temperature limit respected.

Proton beam window: Beer Can

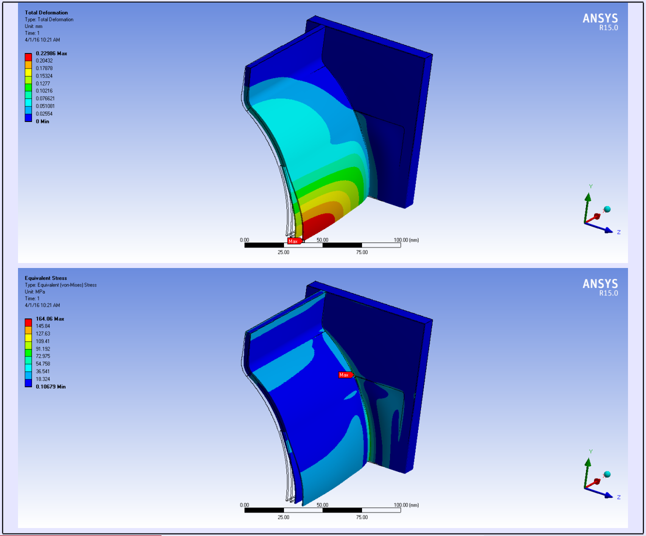
Temperatures





Beer Can

Deformations < 0.3 mm and low Stresses



Proton Beam Entrance window: Conclusions

Main remarks

- New material criteria introduce close to 3 times more power in the system due to the increase in the thickness.
- The pan pipe proposal cooled with helium seams not to be feasible in the actual conditions
- The "Beer Can" concept cooled by water is feasible. Formal change will be proposed if "Pan Pipe" limitations are confirmed.
- PDR schedule for September 12, 2016

Tunning TBD

Introduction

TBD Technical solution

The analysis of the requirements and beam conditions concludes with a proposal for the TBD: a graphite cylinder enclosure on a copper body and also a set of boundary conditions for the design process. The following are the more significant ones:

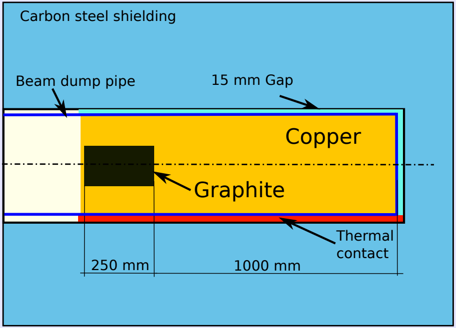
- Residual dose rate shows problems in case of accidental failure.
- Metallic materials will not have significant radiation damage along the life of the TBD
- TBD can not have an active cooling system so, only conduction and radiation are available to remove the heat.
- The TBDS Carbon Steel will act as "heat sink", so thermal contact with the TBD is critical for the operation.
- QA level: $RCC - MR_X - 2012\ NR_3$

Tuning Beam Dump concept

Conceptual design

The analysis performed in the "Requirements evaluation" is based on the maximum "instantaneous" thermal gradient that the material can withstand. However, a proper thermal design is needed to avoid large steady state temperatures and gradients that could produce the mechanical failure of the material.

FEM model

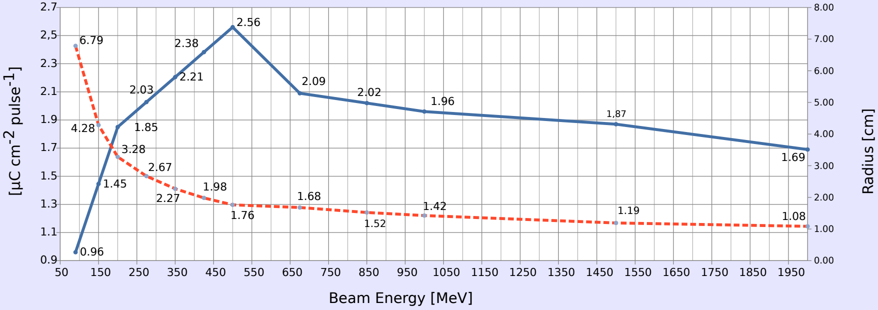


Beam Conditions

Extreme beam conditions

The most demanding beam conditions are produced when all the footprint of the beam has the maximum current. The repetition rate is reduced to the minimum frequency in order to have the maximum energy per pulse. Based on this, a "Radius" can be associated to each energy level.

Beam Radius for extreme beam



Tuning Beam Dump: Geometry for thermal analysis

Beam conditions

The radius that generated the maximum power for low energy mode (90 MeV) exceeds the maximum beam radius criteria, so low energy mode maximum power is limited to 8 kW.

	90 MeV	200 MeV	500 MeV	2000 MeV
Current density [$\mu C \cdot cm^2$ - pulse]	0.96	1.85	2.56	1.69
Frequency [Hz]	1	1	1	1
Max Energy [kJ/pulse]	8.0	12.5	12.5	12.5
Radius* [cm]	5.4*	3.3	1.76	1.08
Power [kW]	8.0	12.5	12.5	12.5

Tunning Beam Dump: Geometry for thermal analysis

FEM-thermal

- The FEM-thermal model includes TBDS-Carbon Steel, Stainless steel pipe, copper body, carbon cylinder and copper window.
- 15 mm air gab has been considered in the contact between the pipe and carbon steel in half of the surface.
- Transient thermal solution starts from a thermal steady state considering half of the time in between pulses as "cooling period" previous to the pulse.
- Radiation is not considered.
- 10^5 hexahedral elements.

FEM-mechanical model

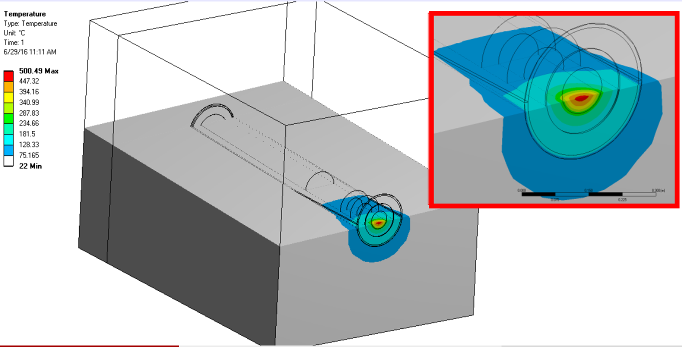
- FEM-mechanical model, only metallic components inside the pipe are considered.
- Elastic analysis based on RCC-MRx procedures
- Mechanical limits for free oxygen copper has to be develop following RCC-MRx rules.

Tuning Beam Dump: FEM-thermal analysis

Steady state temperature

The thermal gradient generated by steady state conditions is much more severe than the "rise" due to the pulse. In low energy modes maximum of temperature is produced in the graphite body and in the copper window. For high energy modes the maximum is moved in the beam direction to the copper body.

Steady State temperature for a low energy beam (90 MeV, 8.0 kW, 1 Hz)



Tuning Beam Dump: FEM-thermal analysis

Steady State maximum temperature for different beam conditions

	90 MeV*	200 MeV	500 MeV	2000 MeV
Graphite max temp. [^oC]	361	350	164	92
Copper window max temp. [^oC]	361	288	151	88
Copper body max temp [^oC]	174	197	127	87
Steel pipe max temp [^oC]	164	192	126	82
TBDS max. temp [^oC]	113	35	96	69

Note

* Total power in 90 MeV case is limited to 8 kW.

Tuning Beam Dump: FEM-thermal analysis

Maximum Transient temperature for different beam conditions

	90 MeV*	200 MeV	500 MeV	2000 MeV
Graphite max temp. [^oC]	367	354	166	95
Copper window max temp. [^oC]	370	295	157	93
Copper body max temp [^oC]	174	197	127	89
Steel pipe max temp [^oC]	164	192	126	83
TBDS max. temp [^oC]	113	135	96	69

Note

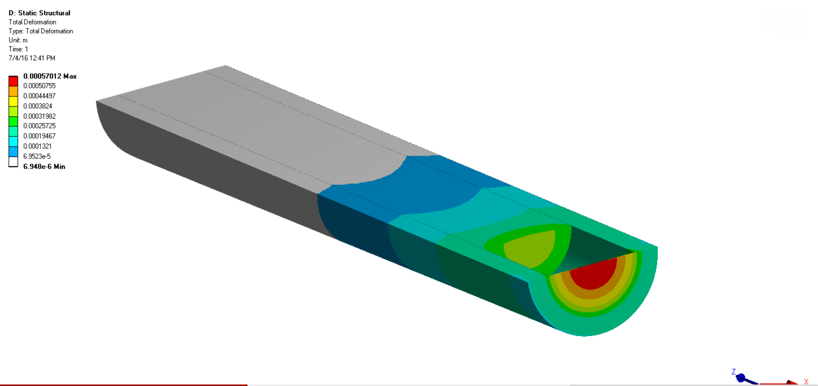
The cooling concept based on conduction generates a temperature profile much more severe than the pulse itself.

Tuning Beam Dump: FEM-mechanical analysis

Deformation & Equivalent Stress

The total deformation is below 1 mm no significant changes in the thermal contacts are expected. Regarding the Equivalent Stress the linear analysis shows peak stress values in the range of 500 MPa.

Deformation at the end of the pulse for a low energy beam (90 MeV, 8.0 kW, 1 Hz)



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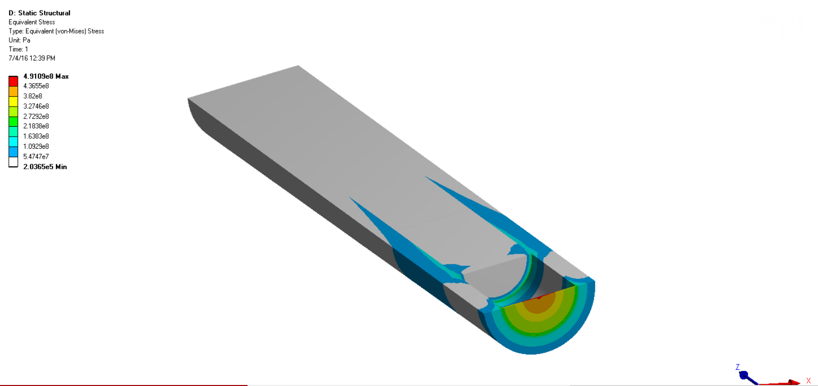

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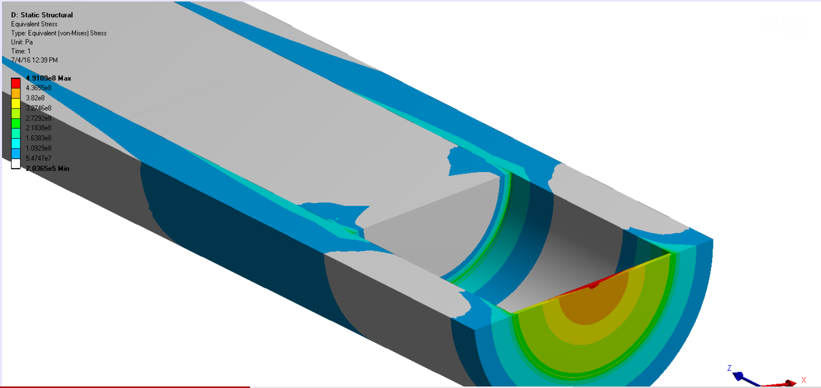
The total deformation is below 1 mm no significant changes in the thermal contacts are expected. Regarding the Equivalent Stress the linear analysis shows peak stress values in the range of 500 MPa.

Deformation at the end of the pulse for a low energy beam (90 MeV, 8.0 kW, 1 Hz)



Tuning Beam Dump: FEM-mechanical analysis

RCC-MRx considerations

The stress produced in the beam dump material is mainly produced by the thermal gradient (Secondary loads "Q"). Following the $RCC - MR_x$ procedures:

- P_m (~ 0 MPa) $< S_m$ (70 MPa, 2/3 Yield Stress limit)
- $P_m + P_b$ (~ 0 MPa) $< 1.5\ S_m$
- $P_m + Q_m$ (<500 MPa) $< S^A_{em}(\theta, G)$
- $P_m + Q_m + P_b + F$ (500 MPa) $< S^A_{et}(\theta, G)$

Tuning Beam Dump: FEM-mechanical analysis

RCC-MRx considerations: Preliminary approximation for S_{em}^{A}

A detail analysis of free oxygen copper for mechanical properties will be done in the design process (and approved by ESS materials group). However, the initial evaluations shows that 500 MPa on linear model is a relative low value:

$$S_{em}^{A}(\theta, G) = [\tfrac{r}{r+1} \cdot R_m(\theta, G) + \tfrac{E}{r+1} \cdot \tfrac{1}{100}[A_{gt}(\theta, G)]/2.5 \sim 2010 \text{ MPa}$$

Copper Values

- $R_m(\theta, G)$: $\sim 2/3$ Yield Stress limit ($\sim$ 70 MPa)
- $A_{gt}(\theta, G)$: Elongation at maximum stress ($\sim$ 17 %)
- E: Young modulus ($\sim$ 117 GPa)
- r: Efficient related with shape of the stress curve ($\sim$ 3)

Tunning TBDS: Shielding

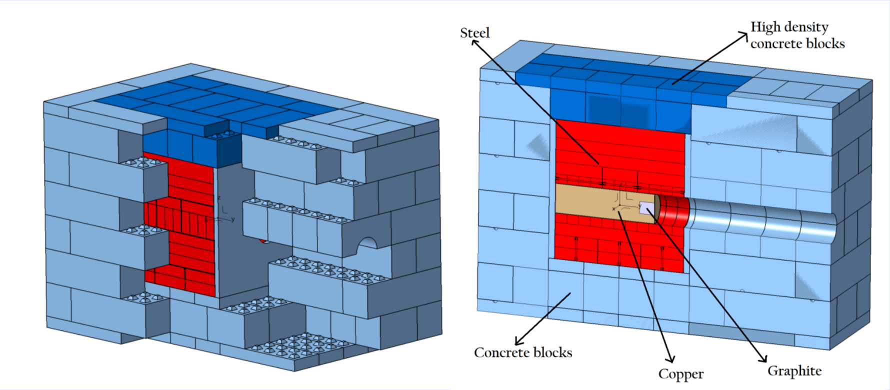
Optimization process

After the shielding optimization process, the beam dump shielding has been reduced from 600 t (Steel) to 60 t Steel + 200 t concrete. The criteria considered for the optimization are the following:

- Tritium production on the ground: ($<$ 25 Sv year^{-1} considering 552 h year^{-1})
- Activation in the accelerator components: (100 mSv h^{-1})

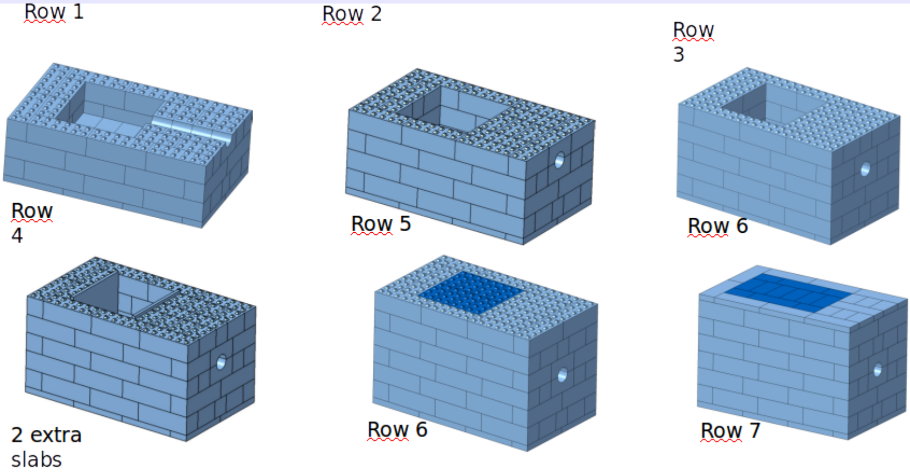
Tunning TBDS: Shielding Geometry

Geometry based on commercial elements (concrete blocks and carbon steel plates)



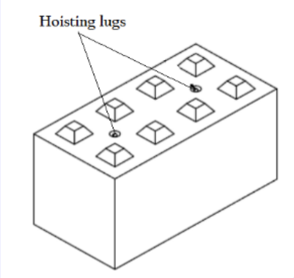
Tunning TBDS: Shielding Geometry

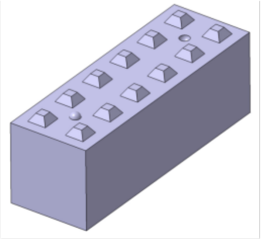
Geometry based on commercial elements (concrete blocks and carbon steel plates)



Tunning TBDS: Shielding Geometry

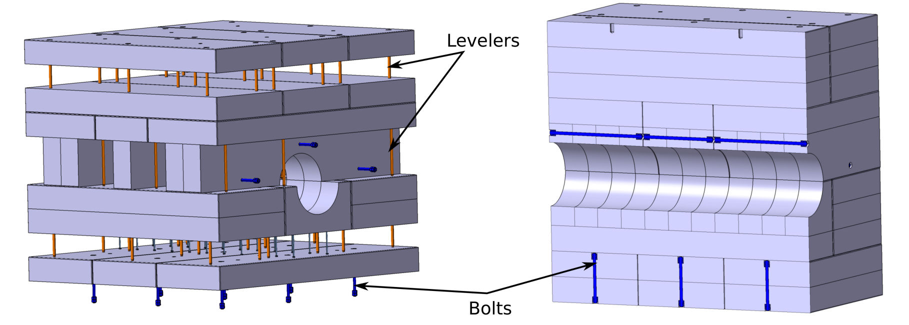
Geometry based on commercial elements (concrete blocks and carbon steel plates)





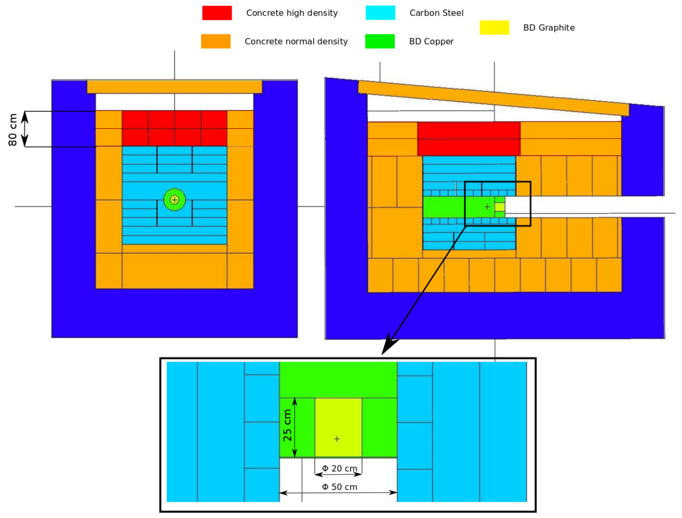
Tunning TBDS: Shielding Geometry

Geometry based on commercial elements (concrete blocks and carbon steel plates)



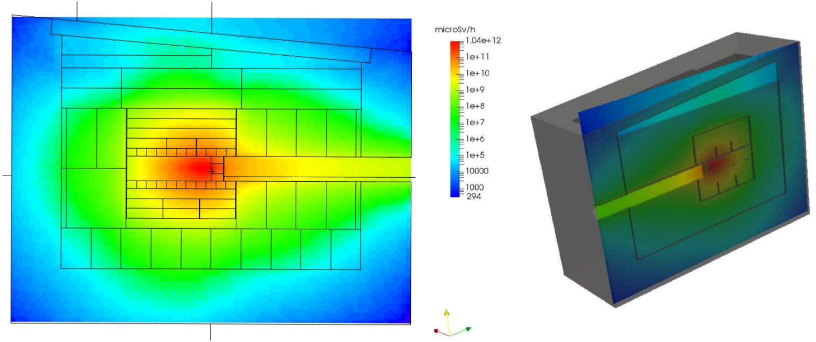
Tunning TBDS

MCNP model including 6 mm gaps in between elements



Shielding Results

Dose Map and areas of interest



Shielding Results

Results conclusions

The dose values obtained in the areas of interest are lower than the dose limits established (25 Sv/year and 100 mSv/h for different zones).

	Below	Behind	Side Wall	Above
Limits	**25 Sv/year**	**25 Sv/year**	**25 Sv/year**	**100 mSv/h**
Final design	21.4 $Sv/year$	13.9 $Sv/year$	24.3 $Sv/year$	64.8 mSv/h

Conclusions

TBD

- Operational conditions and design criteria has been clarified in close collaboration with ESS accelerator division
- The proposed concept can fulfill the criteria of no active cooling.
- PDR has been completed

TBDS

- Shielding optimization has been completed with a significant reduction in the steel needed.
- Commercial concrete blocks has been identity for light and heavy concrete.
- On going discussions with manufactures for carbon steel procurement process.