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MUON COLLIDER GRAPHITE TARGET STUDIES AND DEMONSTRATOR LAYOUT POSSIBILITIES AT CERN

F. J. Saura*, R. Franqueira†, D. Calzolari, M. Calviani, A. Lechner,
R. Losito, D. Schulte, A. M. Krainer, CERN, Geneva, Switzerland
C. Rogers, STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, OX11 0QX, UK

Abstract

Muon colliders offer enormous potential for research of the particle physics frontier. Leptons can be accelerated without suffering large synchrotron radiation losses. The International Muon Collider Collaboration is considering 3 and 10 TeV (CM) machines for a conceptual stage. In the core of the Muon Collider facility lays a MW class production target, which will absorb a high power (1 and 3 MW) proton beam to produce muons via pion decay. The target must withstand high dynamic thermal loads induced by 2 ns pulses at 5-50 Hz. Also, operational reliability must be guaranteed to reduce target exchanges to a minimum. Several technologies for these systems are being studied in different laboratories. We present in this paper the results of a preliminary feasibility study of a graphite-based target, and the different layouts under study for a demonstrator target complex at CERN. Synergies with advanced nuclear systems are being explored for the development of a liquid metal target.

BEAM PARAMETERS

In the framework of the Muon Collider project, the Muon Accelerator Program (MAP) [1] studies previewed the target working parameters. According to these studies, a 5 GeV/c proton round beam will impact the target with an intensity of $3.76 \cdot 10^{14}$ protons per bunch with a repetition rate of 5 Hz. The bunch length considered is 2 ns and, therefore, the total average beam power reaches 1.5 MW.

TARGET CONCEPT

The initial concept for the present study has been the CERN Neutrinos to Gran Sasso (CNGS) target [2]. This target operated at max. power of 520 kW, but it was capable of accepting up to 750 kW. It is thought that, with a careful design optimisation and R&D, this concept could potentially withstand 1.5-1.7 MW. The target is placed after the proton driver, and has the function of producing pions, which subsequently will decay in muons. Past studies optimized the pion production on a graphite target [3].

The Muon Collider target is currently conceived as an 80 cm long isostatic graphite rod inserted in an aluminum internal vessel which provides an isolated confinement of the target. It is filled with static helium gas (at 1 bar) which prevents graphite from sublimating [4] due to high temperatures (≈ 1800 °C), and promotes heat dissipation via natural convection. The inner vessel is finned to enhance the heat exchange between helium and water which will flow (3 m/s) between the internal vessel and an aluminum external vessel.

The whole assembly will be surrounded by a tungsten shielding to shield the pion capture solenoid from the high radiation [5]. This shielding is also water cooled to evacuate the heat from the energy deposited in it, which accounts for 34 % of the total beam power. The full concept is shown in Figure 1.

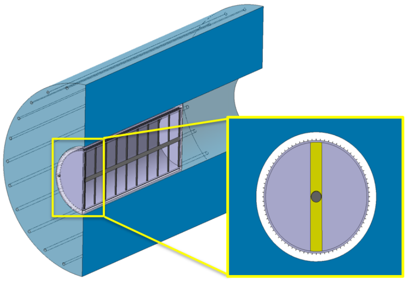

Figure 1: Current Muon Collider target 3D concept.

Figure 2 schematically details the bodies, dimensions and materials of the current proposal.

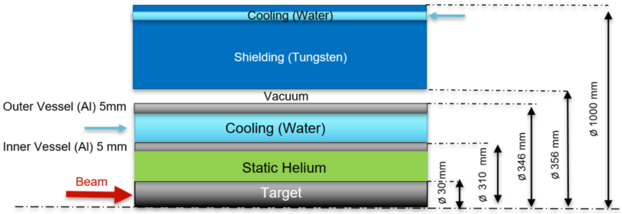

Figure 2: Muon Collider target schematic concept (not to scale).

PARAMETRIC ANALYSIS

Energy Deposition

The conceptual design strategy consisted in studying the thermal behaviour of the target rod under different load cases. A parametric study along five different beam sigma and four working frequencies has been developed. Rod radius has been kept proportional to three times the beam sigma size. The length has been kept fixed to 80 cm equal to 1.79 nuclear lengths. FLUKA [6] studies have been conducted to produce the energy deposition map in the target.

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[*] f.saura@cern.ch
[†] rui.franqueira.ximenes@cern.ch

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Table 1: Maximum Temperature and Power Deposition for 1.5 MW as a Function of the Beam Sigma

T peak (°C)	Transient				Steady state	Power Deposited
Sigma (mm)	5 Hz	10 Hz	20Hz	50Hz	Average	(W)
1	4301	3908	3735	3641	3583	44832
2	3318	3221	3177	3152	3135	59000
5	2740	2721	2713	2708	2704	90632
10	2305	2297	2293	2290	2288	129207
15	1947	1943	1940	1938	1938	163214

Thermal Analysis

Radiation cooling has been applied as the only heat extraction mechanism, this being considered the main worst case scenario. Thermal simulations have been run in ANSYS Mechanical® [7] for every case.

Table 1 shows the maximum peak temperatures resulting from this analysis, both in transient as well as in steady state. It also shows the respective thermal power deposited in the rod. Having a fixed ratio with respect to the beam size, the target is impacted by the same number of protons in each configuration. However, only larger targets contain the secondary particles and therefore they receive the largest overall energy deposition. With smaller radius, a fraction of the beam energy leaves the lateral side of the target as secondaries. It can be seen how temperature decreases as energy is spread in time (frequency) and space (beam sigma).

DYNAMIC STRUCTURAL

To explore the thermo-mechanical response of the target, the sigma 5 mm / 5 Hz case has been chosen as an intermediate and representative design point. The maximum energy density in this case is 173 J/cm^3/pulse. The thermal case has been solved considering both natural and radiation cooling. Helium natural convection around the rod has been modelled using the Raithby and Hollands [8] approximation for annular cylinders.

Dynamic stress waves, which result from the beam impact, have been assessed through the explicit thermo-mechanical solver LS-Dyna® [9]. Appropriate mesh refinement (0.5 mm) and time stepping ($5 \cdot 10^{-11}$ s) have been taken into consideration to capture the stress waves propagating inside the material while respecting the Courant number condition.

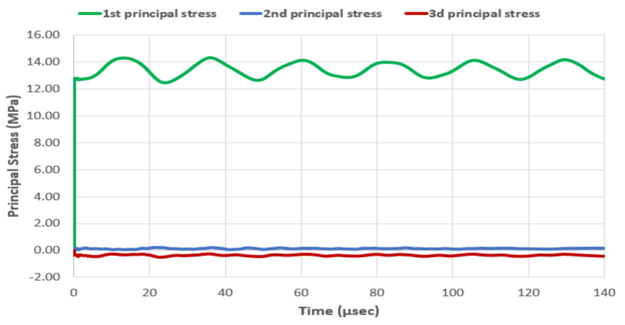

Figure 3: Principal stresses over time, which result following a single beam impact from a steady state initial condition.

Figure 3 represents the principal stresses in the most stressed point of the solid. It can be appreciated that most of the stress is due to the quasi-static load as result of the high steady state temperature. The maximum principal stress is +14 MPa, and the minimum principal stress is -0.48 MPa. Stress waves have an amplitude of 2 MPa. The maximum Christensen factor is 0.27, which guarantees the survival of the graphite rod from a single beam impact.

It is foreseen to perform a detailed fatigue [10] analysis. Fatigue results are very sensitive and highly dependent on the material properties. A characterisation campaign of graphite in high temperature and radiation levels should be carried out to achieve confident results in this aspect. Similar facilities like CNGS or T2K have already successfully survived high-cycle fatigue under high power beams [11, 12].

CFD COOLING

FLUKA studies executed on the full assembly showed that most of the thermal energy is deposited in the tungsten shielding (Fig. 4), heating this up to hundreds of degrees Celsius. 3D computational fluid dynamics (CFD) steady state studies have been performed in ANSYS Fluent® [13], aiming at both assessing the temperatures reached in the assembly and properly designing the cooling system. Water cooling pipes have been added close to the shielding surface to minimise its temperature and the radiative heat to the external superconductive solenoid.

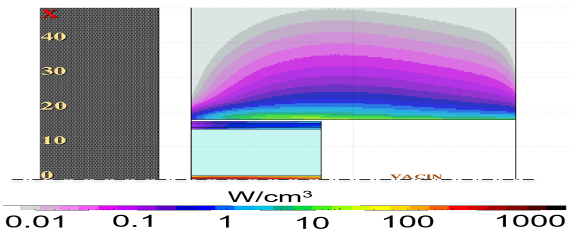

Figure 4: FLUKA energy deposition.

Results foresee a maximum steady state temperature in the graphite rod about 2530°C (1.5 MW) and show that the outer surface of the shielding is kept under 80°C (Fig. 5). Further shielding cooling optimisation is foreseen to be executed in the course of the studies.

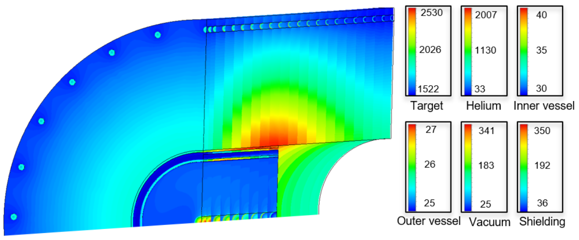

Figure 5: CFD results. Local temperature field shown per body [°C].

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TARGET FUTURE PROSPECTS

Future tasks will involve:

- Continuation of CFD studies of a single pulse transient analysis, and further assessment, via fluid-structure interaction (FSI), of vessels.
- Shielding cooling optimisation.
- Evaluation of the damage caused by radiation levels of the Muon Collider target, coupled with post irradiation examination of the CNGS target.
- Characterisation campaign of graphite in high temperature and radiation levels under torsional loads, and investigation into 3D Carbon/Carbon [14] thermo-mechanical behavior.
- Development the full assembly mechanical design details.
- Technical feasibility studies of a heavy liquid metal target. Liquid metal targets do not suffer fatigue, are easy to cool and less affected by shock waves, but it is a targetry technology that is yet to be mastered.

DEMONSTRATOR FACILITY

A demonstrator facility could be fundamental in the future to assess the feasibility of the different systems and critical technologies of the Muon Collider. Particularly, the production target and the muon cooling section. Assuming a first siting at CERN, two locations for its implementation have been explored: the ISR option and the TT10 option.

ISR

The first proposal considers a small scale demonstrator inside the Intersection Storage Rings (ISR) complex on the CERN Meyrin site. The facility would be located at the surface level, leading to reduced civil engineering works. Moreover, the existing infrastructure could be used for the demonstrator, such as the TT7 extraction line which could be extended for the extraction of the proton beam from the Proton Synchrotron (PS) to the proposed test facility. The negative aspect of this configuration is the impossibility to be expanded into a final facility at a later stage. The radio protection limitations due its location and the existence of the surrounding buildings would limit this proposal to an ultimate 10 kW beam power demonstrator.

TT10

The second proposal brings the demonstrator underground, at the same depth as CERN's Super Proton Synchrotron (SPS). A dedicated extraction line from the TT10 injection to SPS would deliver the 26 GeV/c proton beam from the Proton Synchrotron (PS) to the demonstrator facility. Together with the strategic location in the molasse, 40 meters underground, the 7 ns bunches of $1.0 \cdot 10^{13}$ protons would allow the exploitation of the test facility up to approximately 80 kW, corresponding to roughly the maximum beam power the PS could offer in dedicated mode. As opposed to the first option, the TT10 layout would be compatible with a second stage upgrade to the final Megawatt-range Muon Collider Facility. Naturally, this layout would require a higher initial investment, despite presenting a long term cost benefit.

In this proposal, a conceptual 3D layout has been made (Fig. 6). The target complex and the cooling section are physically separated and accessible via different shafts (Fig. 7) to allow interventions in the cooling part without being limited by the cool-down time of the target area. The target lies in a trench and is handled remotely, an approach employed in other facilities [11, 12, 15] and studies [16–18]. A dedicated tunnel for the target systems' services and a zone for radioactive storage are also present.

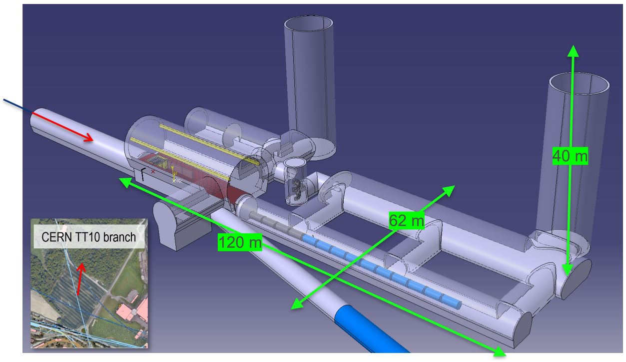

Figure 6: TT10 Muon Collider demonstrator concept at CERN.

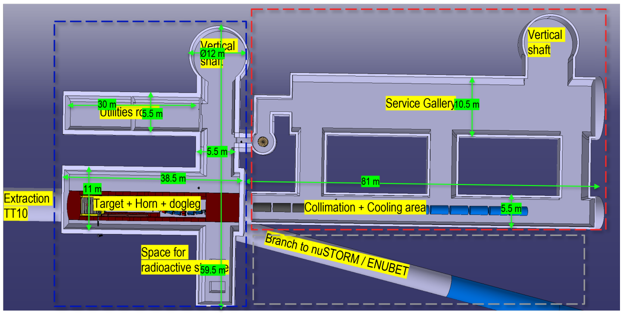

Figure 7: Target complex (blue dashed area) and cooling area (red dashed area) of the TT10 layout.

CONCLUSIONS

Summarising the main aspects shown in the present paper: peak temperatures, and therefore, peak stresses, decrease with wider beam sigma and faster frequencies. This is due to the energy density dispersion in space and time. The present target withstands a 1.5 MW/ 5Hz/ sigma 5mm single pulse with a Christensen factor of 0.27. It is possible to use static helium to cool the isostatic graphite target; and to use a forced flow of water to cool the vessels and shielding.

CERN presents the conditions to host a Muon Collider demonstrator as a conceptual proposal for a major complex.

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