HIGH ENERGY BEAM IMPACTS ON BEAM INTERCEPTING DEVICES: ADVANCED NUMERICAL METHODS AND EXPERIMENTAL SET-UP *

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Abstract

Beam Intercepting Devices are potentially exposed to severe accidental events triggered by direct impacts of energetic particle beams. State-of-the-art numerical methods are required to simulate the behaviour of affected components. A review of the different dynamic response regimes is presented, along with an indication of the most suited tools to treat each of them. The consequences on LHC tungsten collimators of a number of beam abort scenarios were extensively studied, resorting to a novel category of numerical explicit methods, named Hydrocodes. Full shower simulations were performed providing the energy deposition distribution. Structural dynamics and shock wave propagation analyses were carried out with varying beam parameters, identifying important thresholds for collimator operation, ranging from the onset of permanent damage up to catastrophic failure. Since the main limitation of these tools lies in the limited information available on constitutive material models under extreme conditions, a dedicated experimental programme has been proposed, relying on the HiRadMat test facility at CERN. Experimental aspects such as sample-holder design and test set-up are described in this paper.

THERMALLY INDUCED DYNAMIC PHENOMENA

The rapid interaction of highly energetic particle beams with matter induces dynamic responses in the impacted structure [1]. Response types can be divided in different categories depending on several parameters, mainly deposited energy, maximum energy density, interaction duration and strength of the impacted material.

Three dynamic regimes can be identified at increasing deposited energy, namely Elastic Stress Waves, Plastic Stress Waves and Shock Waves.

Stress Waves in the Elastic Domain

This regime is encountered in cases of relatively low energetic impacts, when induced dynamic stresses do not exceed the material yield strength. Changes of density are negligible and pressure waves propagate at the elastic sound speed (C_0) without plastic deformation. These phenomena can be effectively treated with standard implicit FEM codes [2] or even with analytical tools [3].

Stress Waves in the Plastic Domain

When the dynamic stresses exceed the material yield strength, plastic stress waves appear propagating at velocities slower than elastic sound speed ($C < C_0$). Changes of density can still be considered negligible. This regime can be treated at an acceptable degree of approximation with standard implicit FEM codes [4].

Shock Waves

When the deposited energy is high enough to provoke strains and stresses exceeding a critical threshold (ε_c , σ_c), a shock wave is formed propagating at a velocity higher than C_0, potentially leading to severe damages in the affected component. A shock wave is characterized by a sharp discontinuity in pressure, density and temperature across its front.

It can be shown that for metal-based materials, shock waves do not appear unless changes of phase occur [5].

HYDROCODES

When dealing with changes of phase and significant changes of density one has to resort to a new class of wave propagation codes, called Hydrocodes. These are highly non-linear Finite Element tools, using explicit time integration schemes, developed to study very fast and intense loading on materials and structures [6].

Unlike standard, implicit FEM codes, hydrocodes usually rely on complex constitutive material models, which must be able to encompass a much larger range of densities and temperatures, including changes of phase. Strength and failure models are also more complicated as they must account for the effects of strain rate, temperature, density change etc.

The Equation of State (EOS) is integrated in Hydrocodes to model the behaviour of materials under any state and condition. It provides the evolution of pressure as a function of density, temperature and energy. Analytical EOS can only describe a single-phase region of the material. Tabular EOS can be used to appreciate material behaviour over different phases without any loss in precision. Additionally, polynomial EOS can be interpolated from tabular ones. In this work a tabular EOS has been used for tungsten, while a polynomial EOS has been assigned to copper.

To model the behaviour of materials in the extreme conditions leading to shock waves, an advanced yielding criterion is needed. The model must take into account the effects of strain rate and temperature. The most used models are Johnson-Cook, Steinberg-Guinan and Johnson-Holmquist. In the present work the Johnson-Cook model has been chosen for both tungsten and copper.

*Work partly carried out through the European Coordination for Accelerator Research and Development (EuCARD)

On the same basis, dynamic failure models must consider many factors such as strain, strain rate, temperature, maximum and minimum pressure and fracture toughness. The maximum plastic strain failure criterion and minimum hydrostatic pressure failure criterion (P_{min}) were used to model the behaviour of tungsten, while the maximum plastic strain failure criterion was used for copper.

NUMERICAL ANALYSIS OF TUNGSTEN COLLIMATORS

The analysis was carried out on a complete jaw assembly of an LHC Phase I Tertiary Collimator (TCT). The part of the jaw directly interacting with the beam is essentially composed of five Inermet® 180 (95% W, 3.5% Ni, 1.5% Cu) blocks, each 200 mm long. These are fixed with stainless steel screws to a support made of OFE-Cu. This is in turn brazed to cooling pipes made of Cu-Ni alloy (90% Cu, 10% Ni), while these are brazed to a back-stiffener (made of Glidcop®, a dispersion strengthened copper).

Two complementary 3D models were implemented in Autodyn® [7] based respectively on a) Lagrangian (full jaw assembly) and b) Smoothed Particle Hydrodynamics (SPH) algorithms (for the most loaded W block).

Accident Scenarios

Seven accident cases, with different degrees of severity and probability, were identified. All of the cases are based on an asynchronous beam abort event [8], assuming all of the bunches have the same impact parameter (2 mm). The relevant parameters for each case are provided in Table 1.

Table 1: List of Accident Cases

Case	Beam Energy [TeV]	Norm. Emittance [μm rad]	N. of Impacting Bunches	Energy on Jaw [kJ]	TNT Eqv. [g]
1	3.5	3.50	1	38.6	9.2
2	5	7	1	56.2	13.4
3	5	3.5	1	56.5	13.5
4	5	1.75	1	56.6	13.5
5	5	1.75	2	111.3	26.6
6	5	1.75	4	216.1	51.6
7	5	1.75	8	429.8	**102.7**

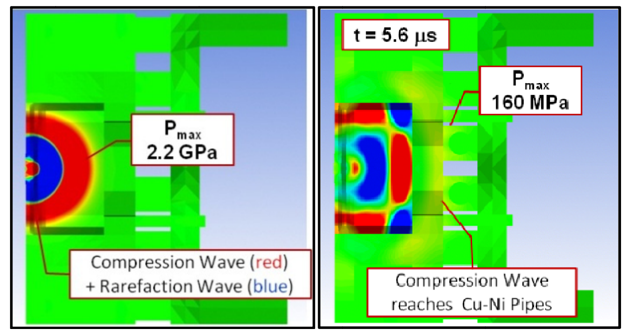
A complete FLUKA [9], [10] model of the TCT collimator was set up and full shower simulations were carried out providing the energy deposition distribution for each case.

Results

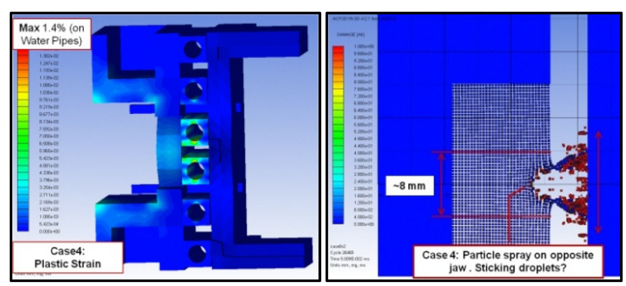
All the single-bunch cases, both at 3.5 and 5 TeV, at all emittances, lead to damage levels which can be compensated by shifting the jaw 8-10 mm (so-called "5th axis"), thus exposing fresh, intact surface to the beam. A groove is created on the two first W blocks with an extension roughly proportional to the bunch energy. The size of the damaged region is already much larger than the beam size so no sensible difference is found when varying the beam emittance.

It is important to note that the so-called shock impedance between W and Cu, defined as $Z = \rho_0 U_s$ (with ρ_0 initial density and U_s shock velocity) plays a key role in limiting the damage as it confines most of the wave energy inside the tungsten block (Figs. 1-2).

The appearance of limited plastic deformations on cooling pipes and screws can be observed (Fig. 3). W particles are sprayed on a larger area of the opposite jaw (Fig. 4): this jaw is not directly damaged, however possible re-solidified droplets stuck on its surface may affect its final flatness.



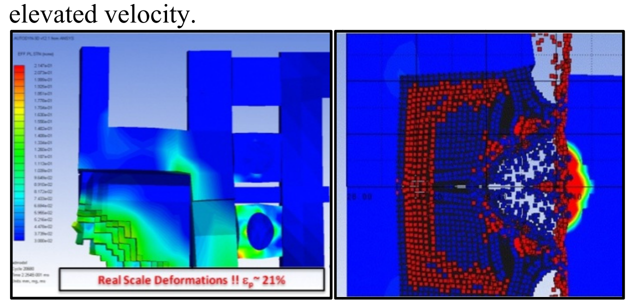
Figures 1 and 2: Case 4. Propagation of the shock wave in the jaw assembly. Note the wave is mostly reflected at the W-Cu interface, only partially transmitted to Cu support.



Figures 3 and 4: Case 4. Residual Plastic strain on Cu and damage extension on W. Note how the SPH model allows particles sprayed on the opposite jaw to be visualized.

For cases 5 and 6 the jaw damage extension is higher so it cannot be compensated by 5th axis travel. Severe plastic deformations can be observed on cooling pipes and screws, although visible failures are not detected.

The SPH simulations anticipate permanent damage on the opposite jaw, provoked by W particles impacting at elevated velocity.



Figures 5 and 6: Case 7. Plastic strain in Cu and Cu-Ni (left) and damage extension on the two jaws (right).

The only case studied leading to catastrophic damage is case 7. In this scenario one may expect: a) water leakage due to very severe plastic deformation on the pipes (Fig. 5); b) extended eroded and deformed zone on the W jaw; c) projections of hot and fast solid W bullets (T~2000 K, V_{max}~1 km/s) onto the opposite jaw and slower particles hit tank covers (at velocities just below the ballistic limit); d) risk of permanent bonding between the two jaws due to the projected re-solidified material (Fig. 6).

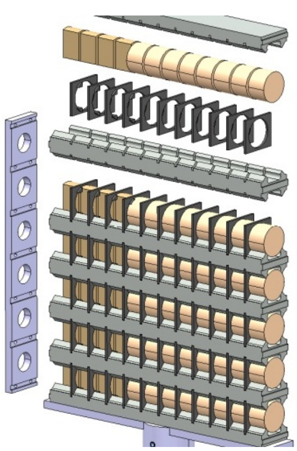
EXPERIMENTAL VALIDATION

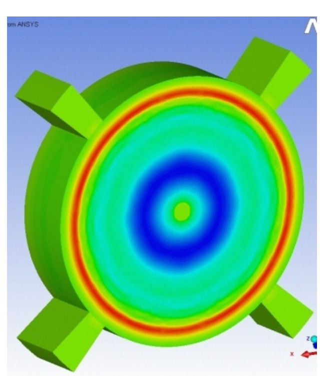
Hydrocodes are extremely powerful tools with steadily growing capabilities; however results must be carefully treated. As shown, a large set of parameters is required to correctly model material behaviour.

Unfortunately, scientific literature providing properties for materials of interest under extreme conditions is very scarce; besides, most of the existing information is often classified as it is drawn from military research. Finally, very few data is available for alloys and compounds.

Consequently, the results presented here are affected by uncertainties which will only be fully mastered once data obtained through direct material characterization becomes available.

With this in mind, specific experimental testing has been proposed based on CERN's HiRadMat facility [11]. Fig. 7 shows a preliminary layout of a multi-material test bench, which would enable testing up to six different materials. The test bench would be integrated by a series of fast acquisition devices to acquire real-time displacements, velocities, strains of a given sample. Two different specimen shapes have been embarked upon: a cylindrical one (upstream) to measure simple-shaped shock waves, easily benchmarking numerical simulations (Fig. 8), and a flat one (downstream) allowing extreme phenomena generated on the surface of a jaw (melting, material splashes, debris projections etc.) to be visualized and optically acquired.





Figures 7 and 8: HiRadMat test bench showing material samples and graphite holders (left). Propagation of a shock wave in a cylindrical material sample (right): note how the graphite holders, thanks to their low shock impedance, do not affect the shock wave pattern.

CONCLUSIONS

While thermally-induced dynamic phenomena up to the melting point of metals can be reasonably well treated with standard FEM codes, advanced wave propagation codes (Hydrocodes) become necessary when changes of phase and density occur.

Thorough numerical analysis of an LHC TCT (tungsten collimator) was carried out, relying on advanced simulation techniques applied to a complex 3D model. Several asynchronous beam abort cases were studied with different values of beam emittance, energy and intensity. Type and extent of expected damage are illustrated.

The most important issue for these types of simulations concerns the reliability of constitutive material models, as they are beyond commonly available data. Only specific tests in dedicated facilities can provide this information. The concept and preliminary design of a multi-material test bench to be tested at CERN's HiRadMat facility have been presented.

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