University of Malta

- Introduction

- Overview of WP8 work

- Possible Contributions to WP11

Presenter: Marija Cauchi

on behalf of University of Malta
and CERN partners

INTRODUCTION

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- University of Malta: one of 38 partners in the EuCARD project
- 8 EuCARD Work Packages (WP) divided into 4 main activities:
  - Project Management, Networking, Transnational Access, Joint Research
- University of Malta involved in **Joint Research** activity
  - In particular: **WP8 – Collimators and Materials**
- Work of 2 PhD students
  - **G. Valentino**: Fast Automatic Beam-Based Alignment
  - **M. Cauchi**: Thermo-mechanical study of LHC collimators in case of Accident Scenarios

WP8 WORK - OVERVIEW

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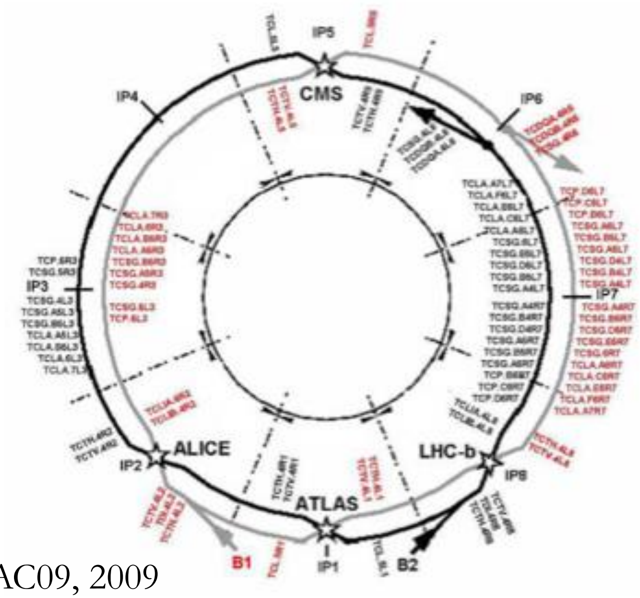
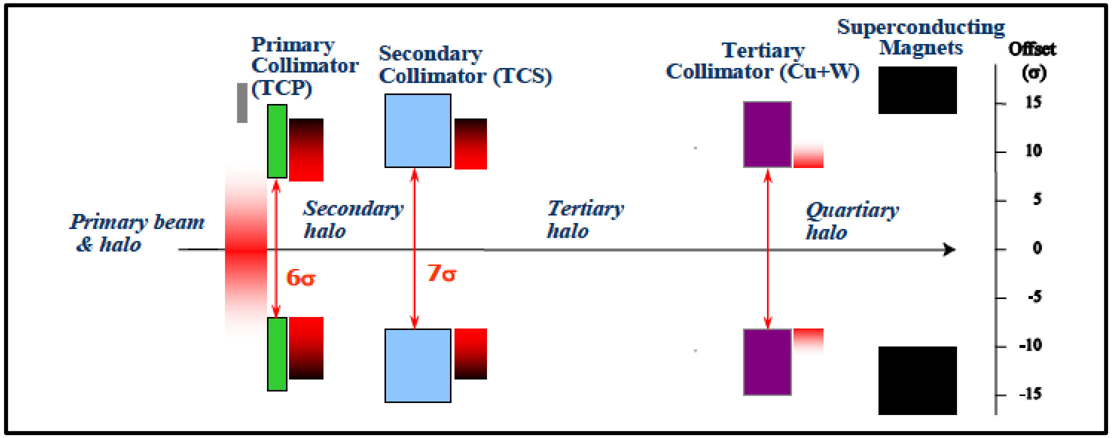
LHC Collimation System

- Several collimators around the LHC rings
- Beam cleaning & machine protection
- Multi-stage cleaning process
- Enabling the LHC to reach its luminosity performance



R. Assmann et al., Operational Experience with LHC Collimation, PAC09, 2009



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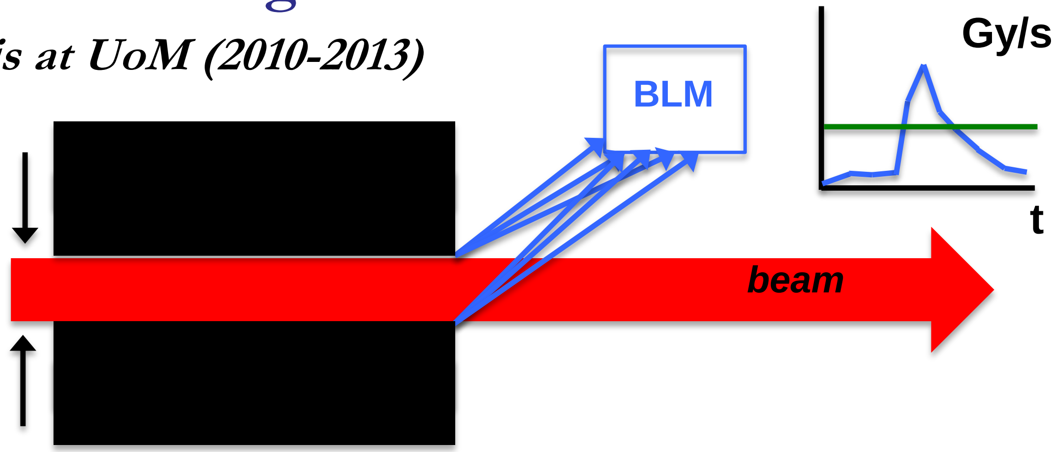
Fast Automatic Beam-Based Alignment

(G. Valentino) *PhD thesis at UoM (2010-2013)*

Alignment procedure:



Algorithms developed to speed up and automate the alignment:

1. **Initial coarse alignment around BPM-interpolated orbit** - jaws moved from initial to tighter settings around estimate of beam orbit
2. **Automatic threshold selection** - a threshold for the BLM signal is selected based on previous values
3. **BLM-based feedback loop** - jaws moved in 5 μm steps until they touch the beam & the losses exceed the threshold
4. **Pattern recognition of loss spikes** - the ensuing spike pattern is classified using a Support Vector Machine (SVM) model

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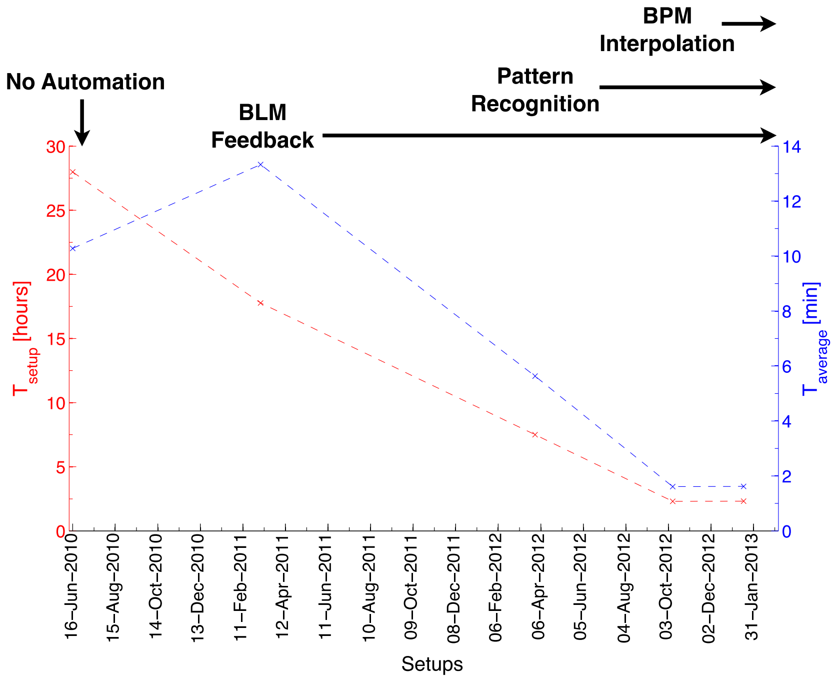
Fast Automatic Beam-Based Alignment

- Total setup time depends on: the beam time consumed, the number of beam dumps *d*, and the turnaround time
- No costly beam dumps due to high losses from 2011 onwards
- > 100 hours saved for LHC operation in 2011-2013 vs 'manual' 2010 alignment

$$T_{setup} = T_{beam} + d \times T_{turnaround}$$

$$T_{average} = \frac{T_{beam}}{C}$$

Limitation (loss spikes) + **jaw movements**
(86 x 2 x 2 x 15s) + **(8 mm / 5 µm / 8 Hz)**
≈ 1.5 hours



Algorithms + Results published in *PRST-AB, IPAC, ICAP, IEEE, ICALEPCS*

Only flat top alignments shown here

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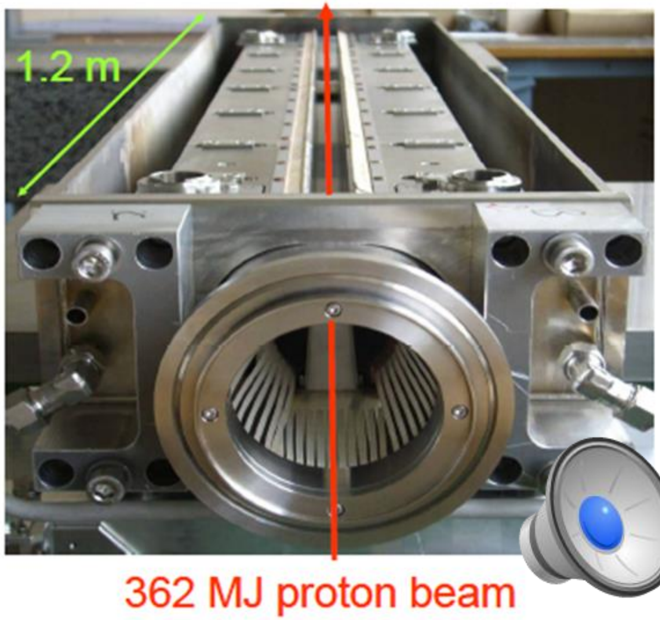
Accidental impacts on TCTs (M. Cauchi) *PhD thesis at UoM (2010-Present)*

- Highly energetic LHC beams
- Need to investigate the robustness and effects of beam accidents on a fully assembled collimator, based on LHC accident scenarios
- Dedicated beam experiment (**HRMT-09**) set-up at the HiRadMat (High-Radiation to Materials) facility
  - Overview of Tests – Test 1, Test 2, Test 3
  - Beam Test Results
  - Conclusions & Further Actions (to be followed in EuCARD 2)



R. Assmann, A. Bertarelli, A. Rossi, "Requirements for 2012 Tests on Fully Assembled Collimators and on Collimator Material Samples in the HiRadMat Facility", EDMS No. 1178003, LHC-TC-ES-0004.

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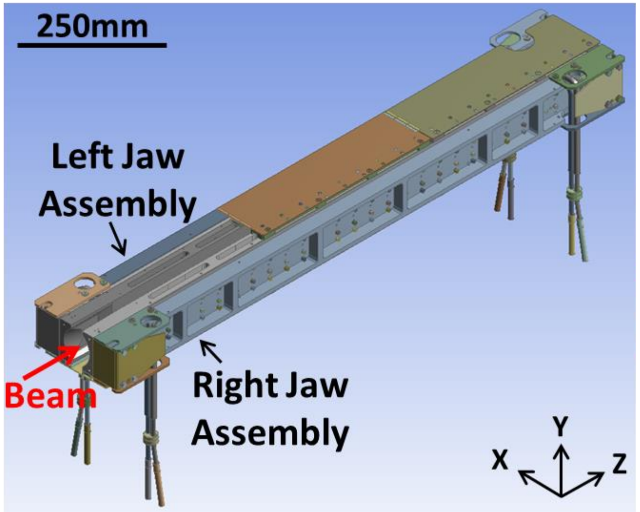
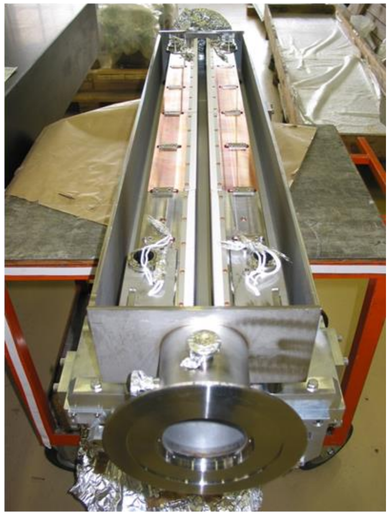
HiRadMat Beam Impact Tests on TCT

Results published in *IPAC13* and submitted to *PRST-AB*

- HRMT-09: involving a Phase I Tertiary Collimator
- Tests performed in August 2012
- Main aim: to address effects of asynchronous beam dump (relevant nominal 7TeV case) and to benchmark simulations for the LHC cases at 5TeV

  A. Bertarelli et al., "Limits for Beam Induced Damage: Reckless or Too Cautious?", Proceedings of Chamonix 2011 Workshop on LHC Performance.





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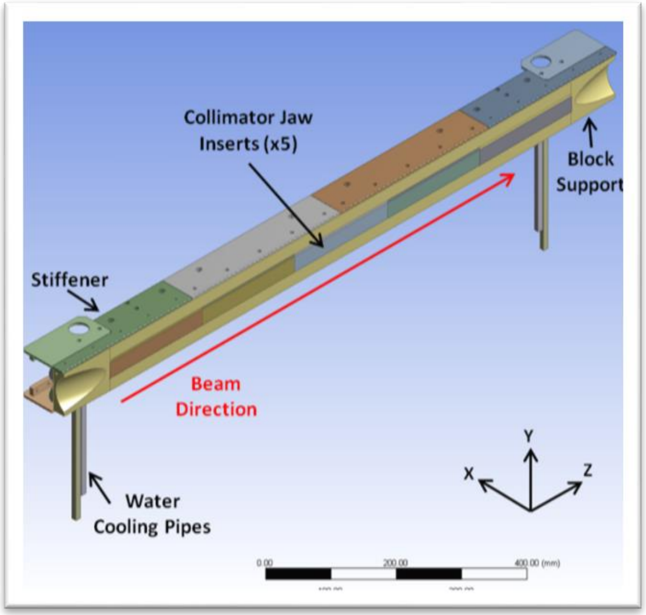
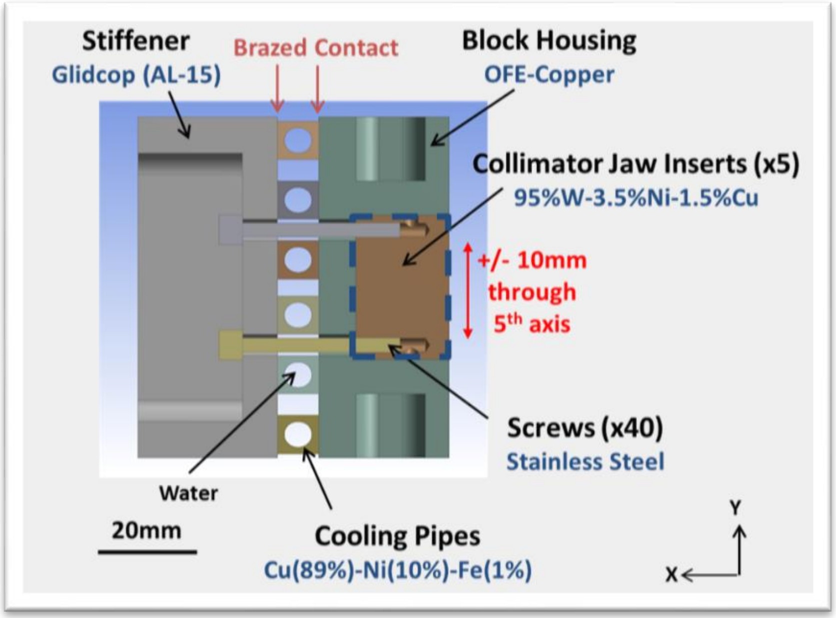
Tertiary collimator design





- Two Jaws enclosed in vacuum tank
- Total Length: 1 m + 0.2 m
- Jaw Material: INERMET 180
- 2 motors per Jaw for position + tilt
- 5th axis for vertical position (max: +/- 10 mm)

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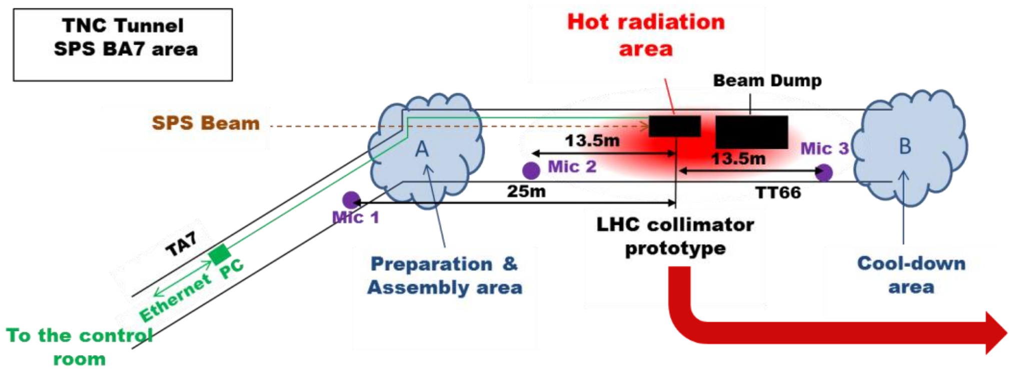
Experimental Setup

- HiRadMat installation layout



- Measurement sensors (standard + special equipment) - position (LVDTs), jaw temperature, collimator tank temperature, water temperature, water pressure, vacuum pressure
- Microphones, BLMs, BPMs, BCTs

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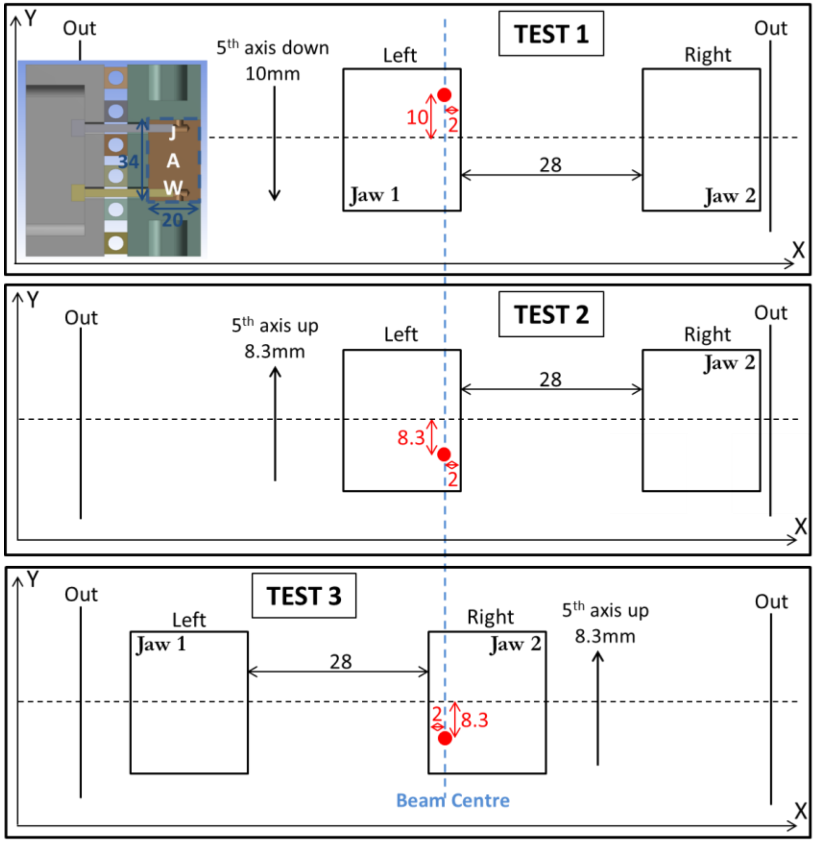
Overview of Tests

- 3 High-Intensity Shots

Test 1 – Design Error Case: Asynchronous Beam Dump in operation of during collimator setup

Test 2 – Shot just below damage limit to collect reference data to assess damage

Test 3 – Disruptive scenario for Asynchronous Beam Dump



- Equivalent beam intensity at 440GeV calculated to obtain equivalent damage levels (Ref: Collimation Working Group Meeting, 30th July 2012)

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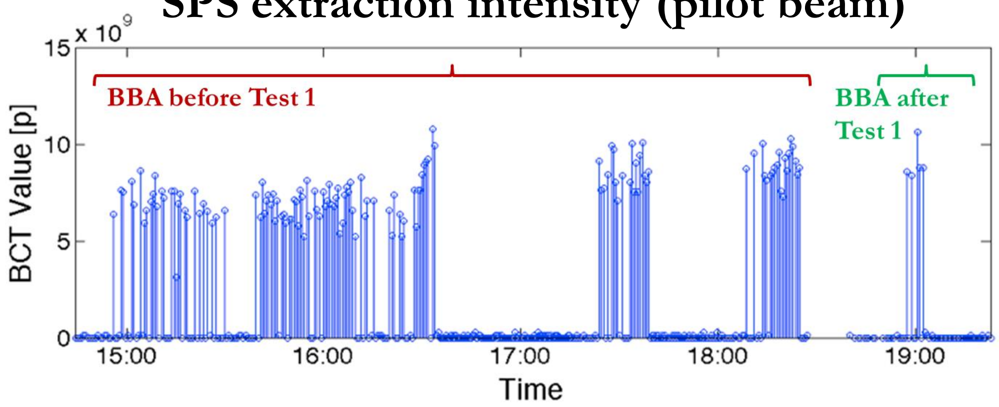
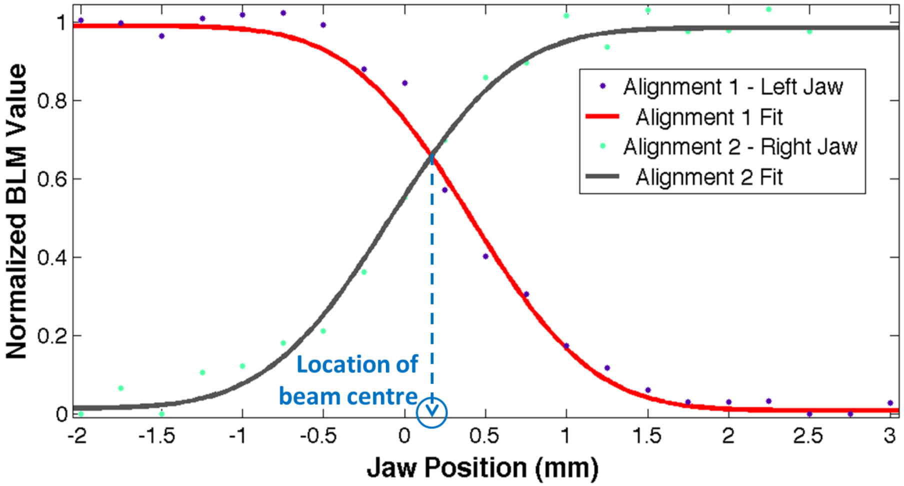
Beam Test Results: Beam-based alignment

- Beam-based collimator setup using low-intensity bunches (pilot bunches with ~ 5 – 10 x 10^9 ppb)
- Scans with left and right jaws through the beam before and after each test
- High-intensity beams scraped down in the SPS to “pilot” intensity (thanks to K. Cornelis from BE-OP-SPS)

SPS extraction intensity (pilot beam)



Alignment of left and right jaws before Test 1



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Beam Test Results: Experimental Measurements

- Beam parameters of high-intensity tests

Test	1	2	3
SPS extraction intensity [x 10^{12}p]	3.36	1.04	9.34
Number of bunches	24	6	72
Average bunch intensity[x 10^{11}p]	1.40	1.73	1.30
Bunch spacing [ns]	50	50	50
Beam energy [GeV]	440	440	440
Beam size at impact ($\sigma_x x \sigma_y$) [mm^2]	0.375 x 0.375	0.5 x 0.5	0.49 x 0.49
Energy on jaw [kJ]	87.89	27.72	249.87
TNT equivalent [g]	21.01	6.62	59.72

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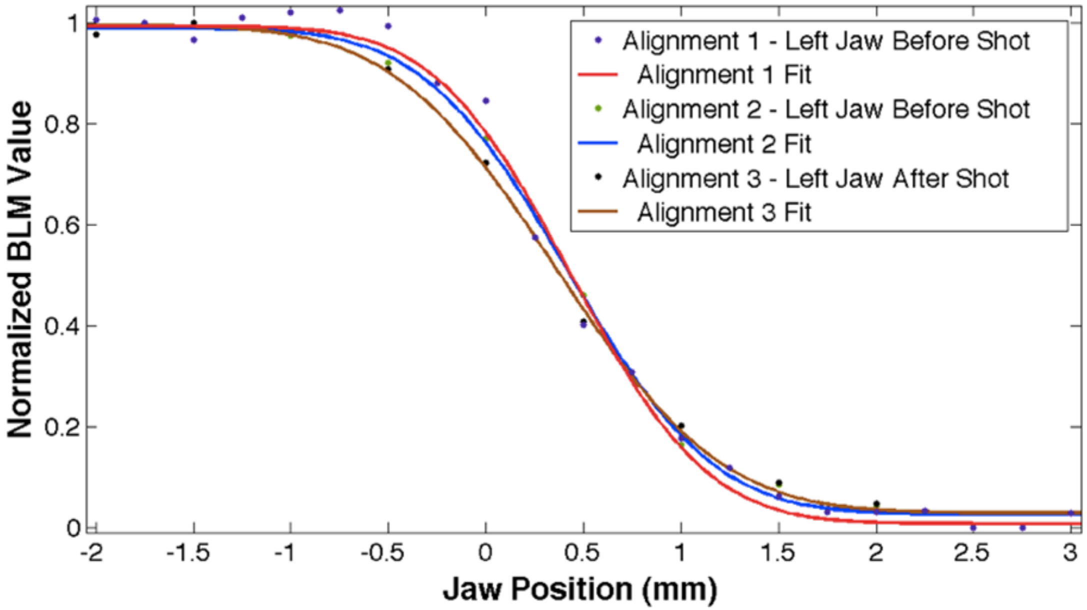
Beam Test Results: Experimental Measurements

- Beam-based setup performed after Test 1 and Test 2 as an attempt to check the **surface integrity** of jaws and collimator mechanics after beam impact
- Major damage of the jaw might result in different values in the results of the BBA procedure (difficult to conclude on errors in the range of 100μm)



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Summary: Sequence of Tests

Test	Intensity [x 10^{11}p]	Number of bunches
BBA before Test 1	5.674	79 pilot
Test 1	33.6	24 high-intensity
BBA after Test 1	1.5065	18 pilot
BBA before Test 2	4.049	35 pilot
Test 2	10.36	6 high-intensity
BBA after Test 2/before Test 3	2.32	22 pilot
Test3	93.4	72 high-intensity
TOTAL	**147.9**	

TNT Equivalent = 87.35g

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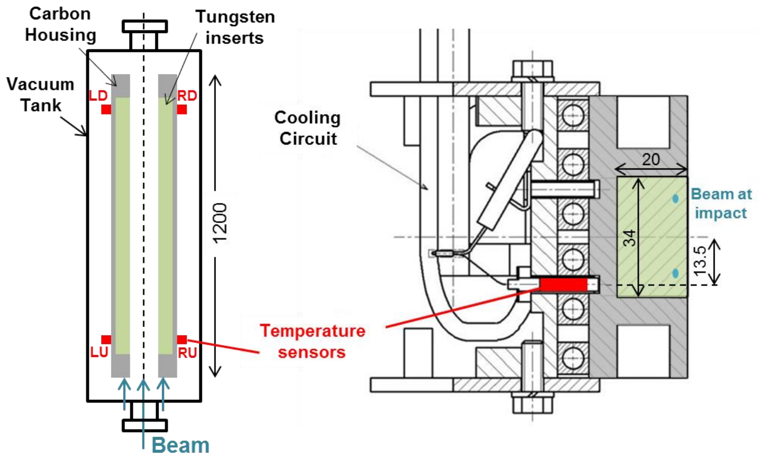
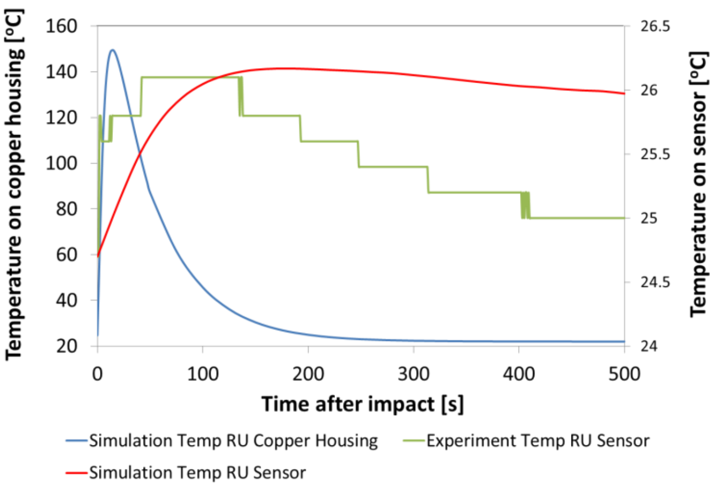
Beam Test Results: Experimental Measurements

- **Temperature measurements** were made during the three tests

- Temperature increases recorded found to be lower than expected and are not really compatible with the post-mortem observations presented later

- One of the reasons for these discrepancies might be the high thermal resistance (due to the low contact pressure) between the temperature probe and the support to which it is attached, leading to an incorrect temperature recording





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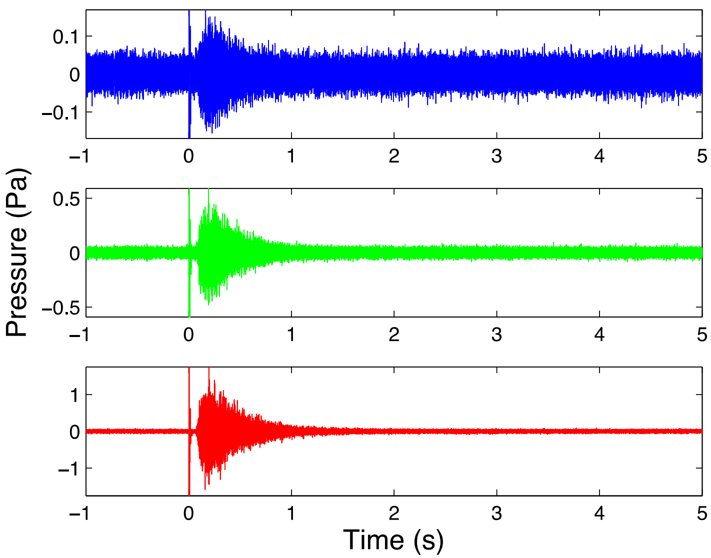
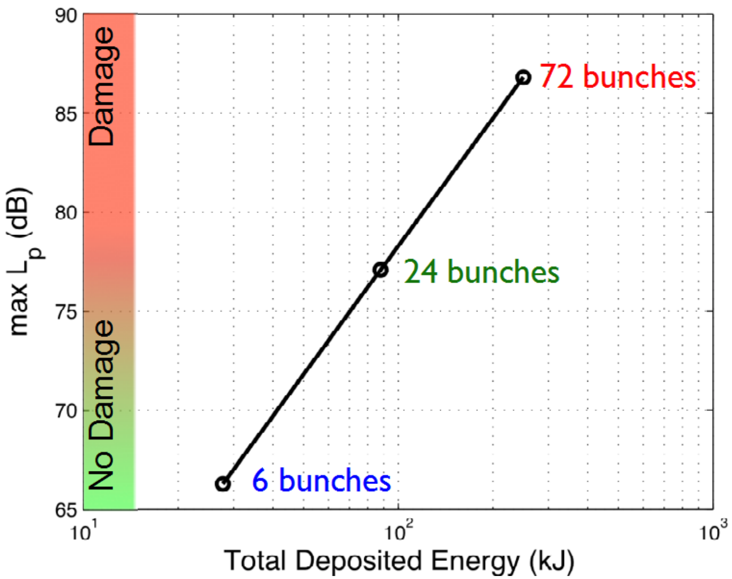
Beam Test Results: Experimental Measurements

- **Sound measurements** – D. Deboy's presentation (KUG)
- Microphones capture the response of the whole collimator structure to the impulsive excitation caused by the beam impact



Filtered sound pressure signals for three tests at Microphone 1



Sound pressure level for Microphone 1 for the three tests

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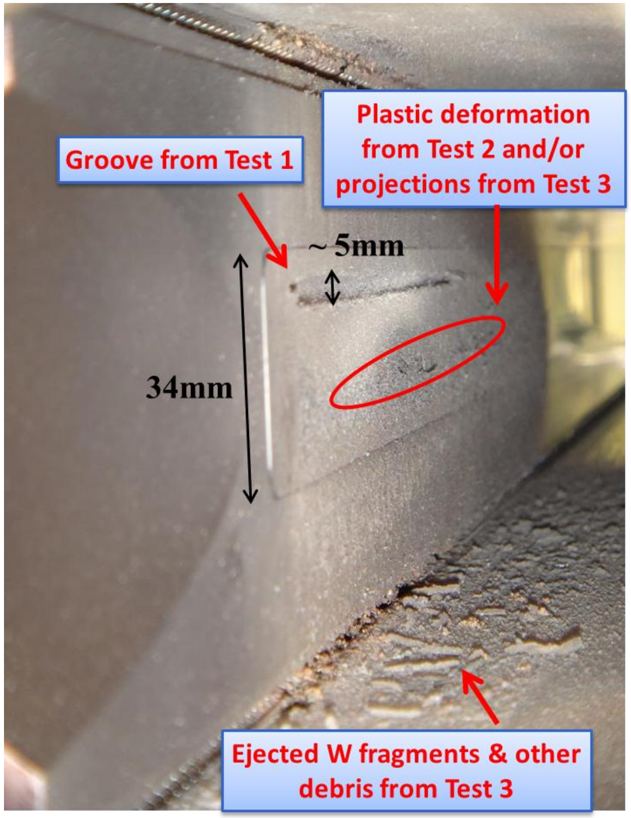
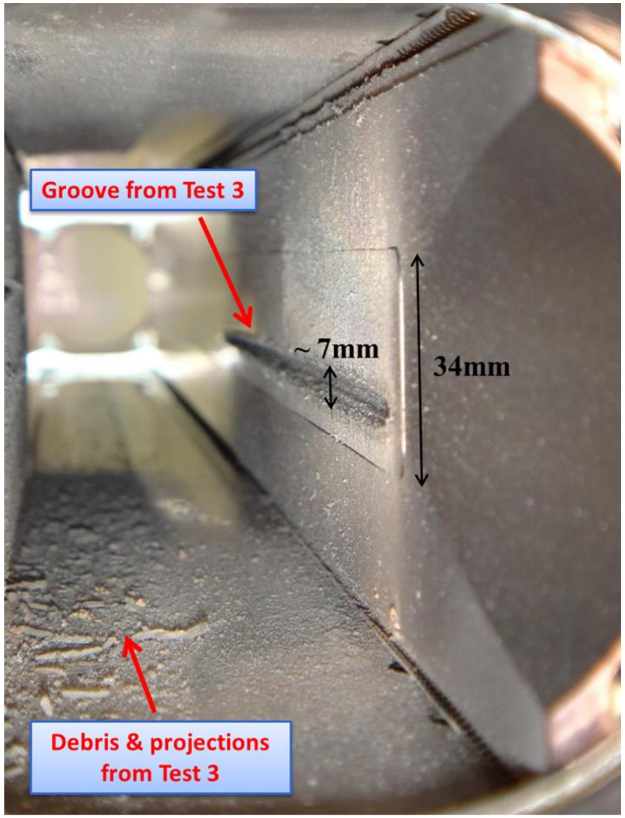
Beam Test Results: Preliminary Post-Mortem Analysis

- Preliminary visual inspection by means of a camera (no detailed metrology)





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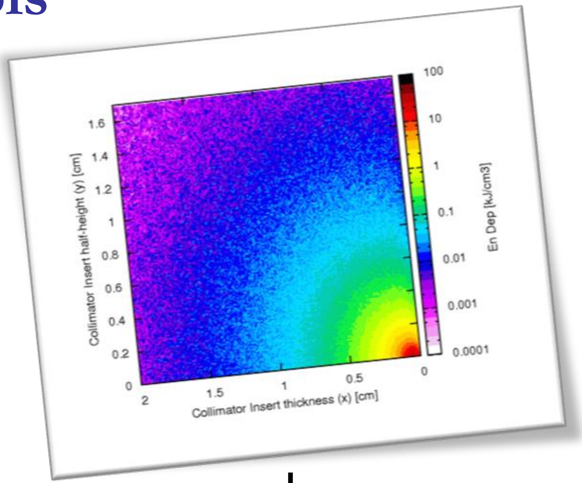
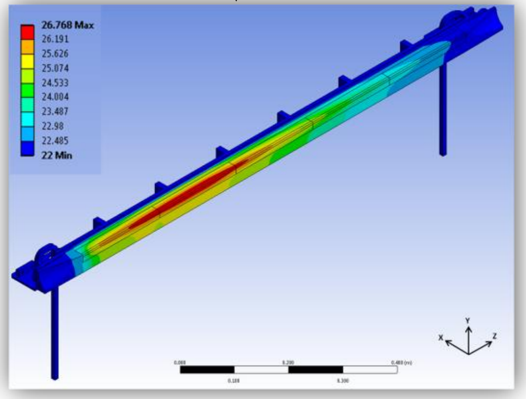
Numerical Benchmarking: Simulation Tools

- Implementation of a numerical approach through finite element analysis highly necessary
- FLUKA models set up and full shower simulations provide energy deposition distributions (L. Lari)
- 3D maps loaded in the ANSYS and AUTODYN 3D models through dedicated subroutines in order to provide the input thermal load in terms of power density distribution
- An uncoupled FLUKA-ANSYS/AUTODYN approach



Finite Element Method



Work with FLUKA performed by L. Lari

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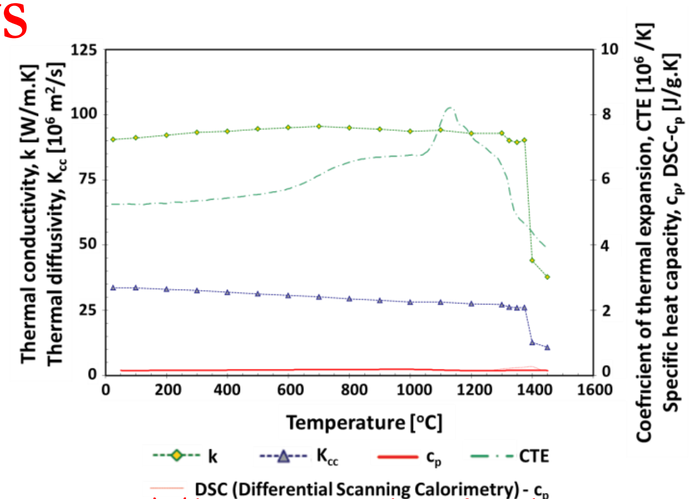
Numerical Benchmarking: Implicit code analysis (ANSYS)

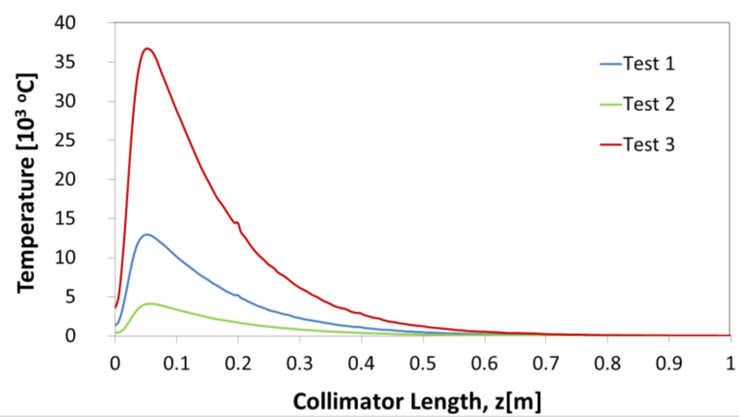
Summary of test parameters as simulated by ANSYS

Test	1	2	3
SPS extraction intensity [x 10^{12}p]	3.36	1.04	9.34
Number of bunches	1	1	1
Simulated bunch intensity[x 10^{11}p]	3.36	1.04	9.34
Thermal shock duration [μs]	1.174	0.256	3.622
Beam energy [GeV]	440	440	440
Beam size at impact ($\sigma_x x \sigma_y$) [mm^2]	0.53 x 0.36	0.53 x 0.36	0.53 x 0.36



Thermo-physical properties of Inermet 180

- First preliminary assessment of the extent of beam-induced damage (T_{melt} of CuNi phase ~ 1343°C)
- $\tau_{shock} << \tau_{diffusion}$: justifies assumption to consider deposited energy as linearly growing during thermal shock



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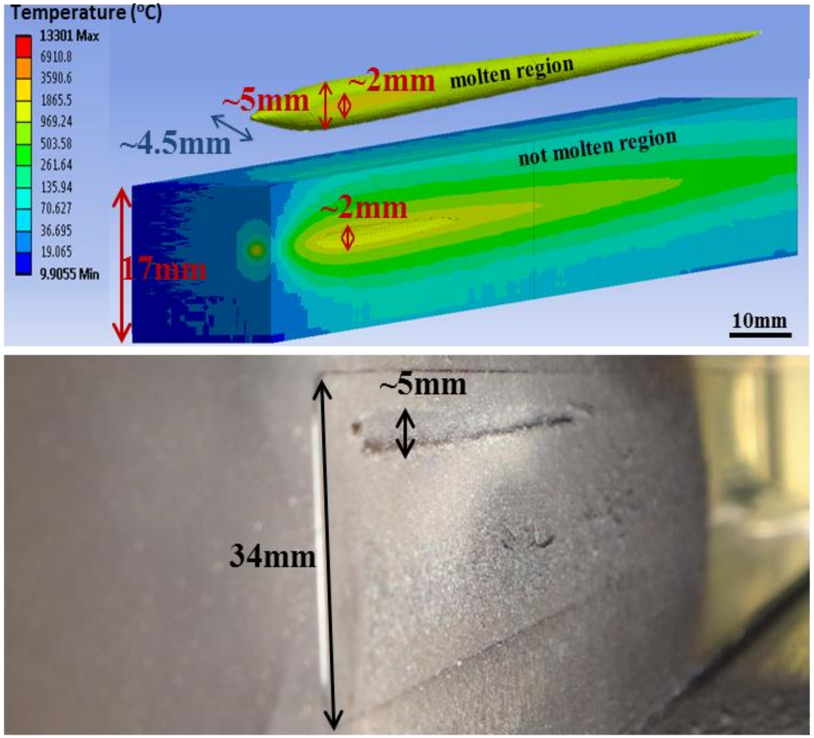
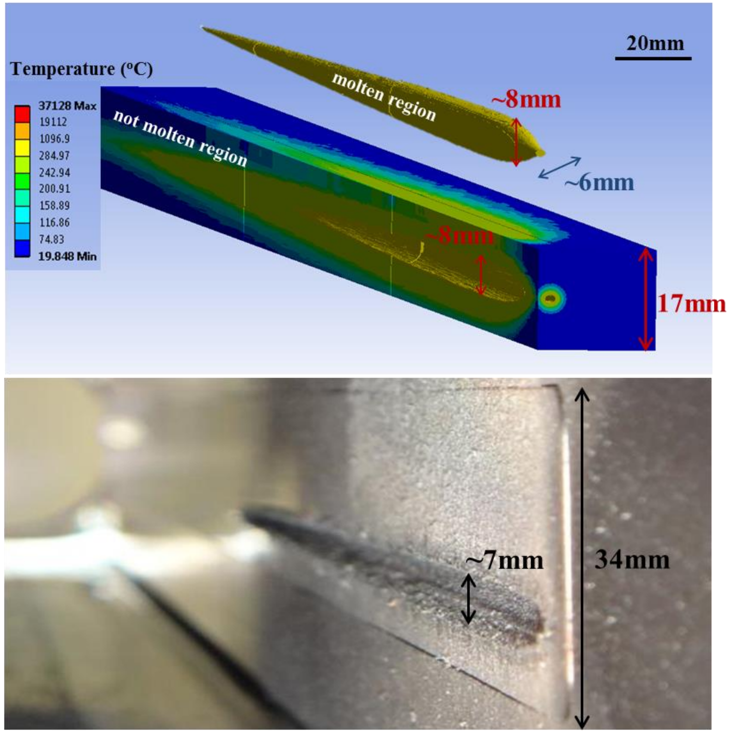
Numerical Benchmarking: Implicit code analysis (ANSYS)

- Structural comparison between experiment and simulations currently limited to the dimension and shape of groove generated by beam impact on jaw inserts

Test 1



Test 3



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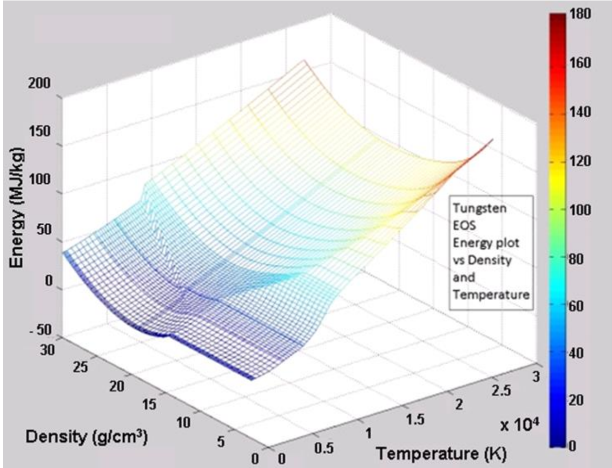
Numerical Benchmarking: Explicit code analysis (AUTODYN)

Summary of test parameters as simulated by AUTODYN

Test	1	2	3
SPS extraction intensity [x 10^{12}p]	3.36	1.04	9.34
Number of bunches	24	6	72
Simulated bunch intensity[x 10^{11}p]	1.40	1.73	1.30
Bunch spacing [ns]	50	50	50
Beam energy [GeV]	440	440	440
Beam size at impact ($\sigma_x x \sigma_y$) [mm^2]	0.53 x 0.36	0.53 x 0.36	0.53 x 0.36



3D plot of the SESAME used as the EOS for tungsten

- Accuracy of results depends on the reliability of the implemented material models:
  - ➢ Equation of state (EOS): SESAME table
  - ➢ Strength model: Johnson-Cook,
  - ➢ Failure model: Hydro (Pmin)

Work with AUTODYN performed by F. Carra

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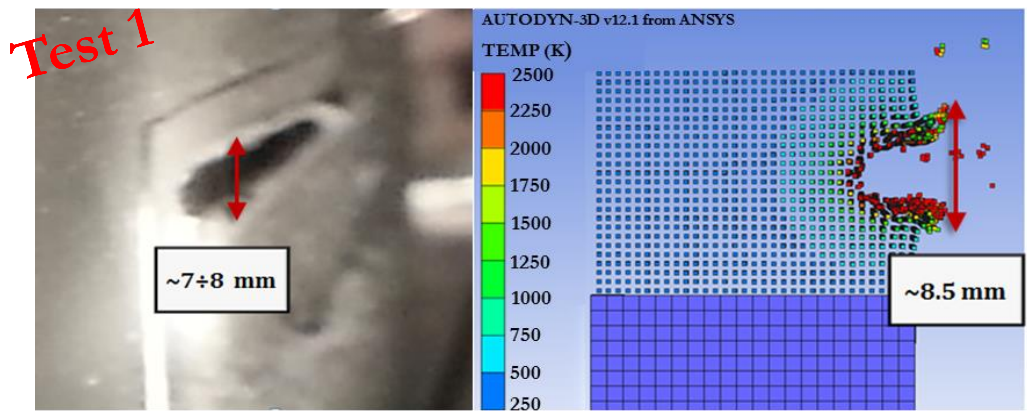
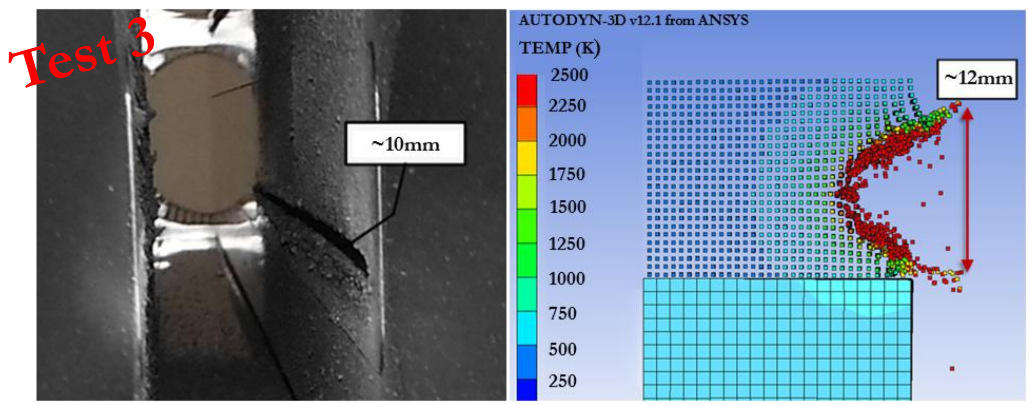
Numerical Benchmarking: Explicit code analysis (AUTODYN)

- Simulations performed with the smoothed-particle hydrodynamics (SPH) technique in AUTODYN to numerically visualize the grooves

- AUTODYN simulations show that in addition to the groove, there is a region around the groove where the material undergoes plastic deformation





Work with AUTODYN performed by F. Carra

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Conclusions

- Predicting the consequences of highly energetic particle beams impacting protection devices such as collimators is a fundamental issue in the design of state-of-the- art accelerator facilities for high-energy particle physics
- Experiment recently designed and carried out at the CERN HiRadMat facility
- Performed tests entailed the controlled impact of intense and energetic proton pulses on both jaws of a tertiary collimator
- Preliminary results and visual inspection of the outcome of these tests have been presented and discussed
- The extent of the damage caused on the jaws of the collimator can already be observed and good agreement with the results of advanced simulations has been achieved

CONTRIBUTIONS TO WP11

University of Malta

Future Work

- One immediate follow-up of these tests is to move the jaws to a controlled area in order to be analyzed in more detail (e.g. to cut and inspect sections, etc.) after the necessary activation cool-down of the collimator
- Analysis of TCT test results being reviewed also in light of observations in the advanced material tests (HRMT-14)
- Goal: to reach a conclusion as to what is the total intensity that the TCT collimator can survive
- Future detailed discussions on possible contributions from the University of Malta side

ACKNOWLEDGMENTS

University of Malta

CERN

- Collimation team (BE-ABP and EN-MME)
- FLUKA team (F. Cerutti & team)
- EN-STI (A. Masi, J. Lendaro, R. Bebb & team)
- HiRadMat team (I. Efthymiopoulos & team)
- BE-OP-SPS team (especially K. Cornelis & team)
- RP team (C. Theis, K. Weiss & team)

University of Malta

- PhD Supervisors: Pierluigi Mollicone, Nicholas Sammut

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Any Questions?

Back-up Slides

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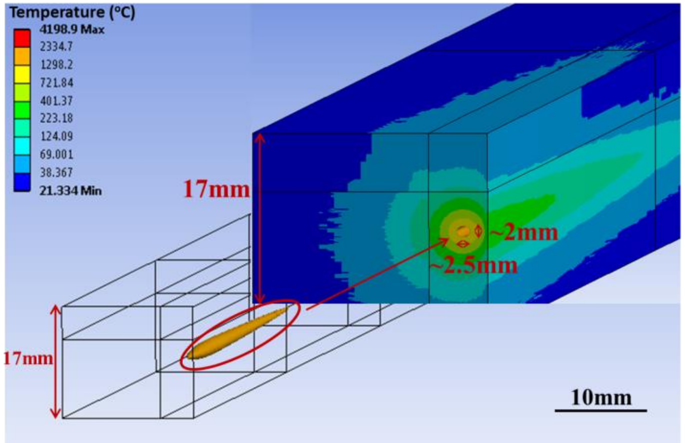
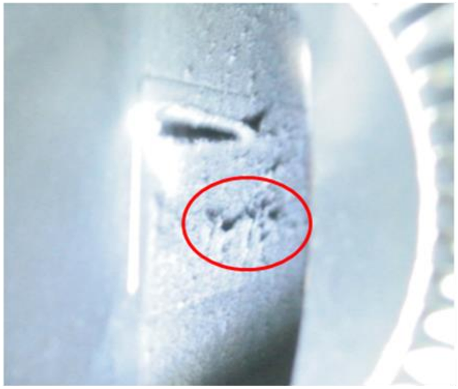
Numerical Benchmarking: Test 2

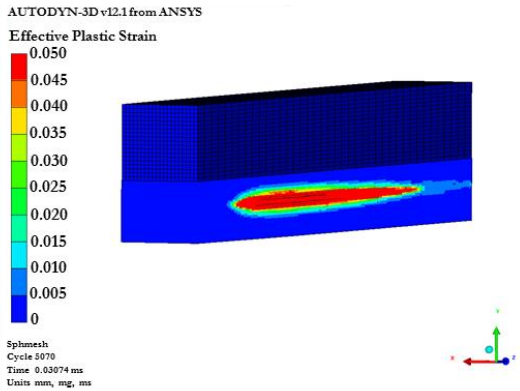
- Structural comparison between experiment and simulations currently limited to the dimension and shape of groove generated by beam impact on jaw inserts

ANSYS



AUTODYN





Back-up Slides

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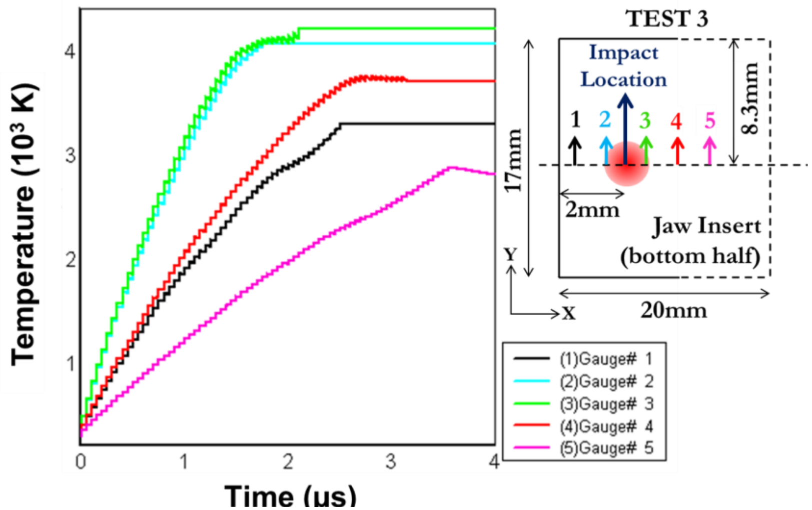
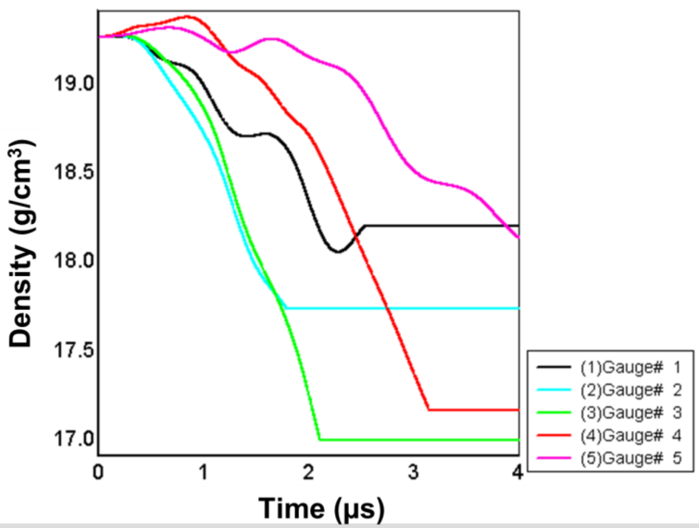
Constant density assumption





- 5 gauges at the most loaded longitudinal section at the vertical position of the impact for Test 3
- Plots show that the most loaded element (given by Gauge 3) has a 12% density reduction which is within the acceptable target density reduction range quoted in []
- Justified to assume that the density remains constant for the duration of the impact -> an uncoupled FLUKA- ANSYS/AUTODYN approach