MATERIAL TESTING WITH HIGH ENERGY BEAMS IN HIRADMAT

46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

R. Losito, EN/STI, CERN – HB2010, 30/9/2010

Acknowledgments

- Direct or indirect contributions from

- O. Aberle, R.W. Assmann, A. Bertarelli, R. Catherall, F. Cerutti, A. Dallocchio, I. Efthymiopoulos, S. Evrard, B. Goddard, C. Hessler, C. Maglioni, M. Meddahi, R. Schmidt, T. Stora, V. Vlachoudis

Outline

- HiRadMat
  - motivations
  - the facility
- Failure from Beam Impact
- Experiments without failure…
- Do we have a problem???
- Conclusions

HiRadMat: Motivations

- Collimation
  - 360 MJ stored in LHC, 500 kW on collimators for a 10 seconds for 1% beam loss at 7 TeV.
  - On average, 10^{16} protons lost/year on collimators.
  - Will materials in collimators survive?
- Machine protection
  - Damage with 0.0005% of loss.
  - Lots of near beam devices (roman pots, wire scanner…)

HiRadMat: Motivations

- Large amount of information available for resistance to radiation (nuclear, aerospace, accelerators…)
- Typically, exposure to Co source or neutrons in a reactor up to a given dose
  - Displacement at the base of damage.
- That covers some of our problems but not all !!!

HiRadMat: Motivations

- How do materials react to "pulsed" solicitation
  - Shock waves
  - fatigue superposed to material weakening due to radiation?
- What happens when a high (stored) energy beam hits a material?
- What parameter can we use for characterisation of material damage for practical use (i.e. to define limits for machine protection)?

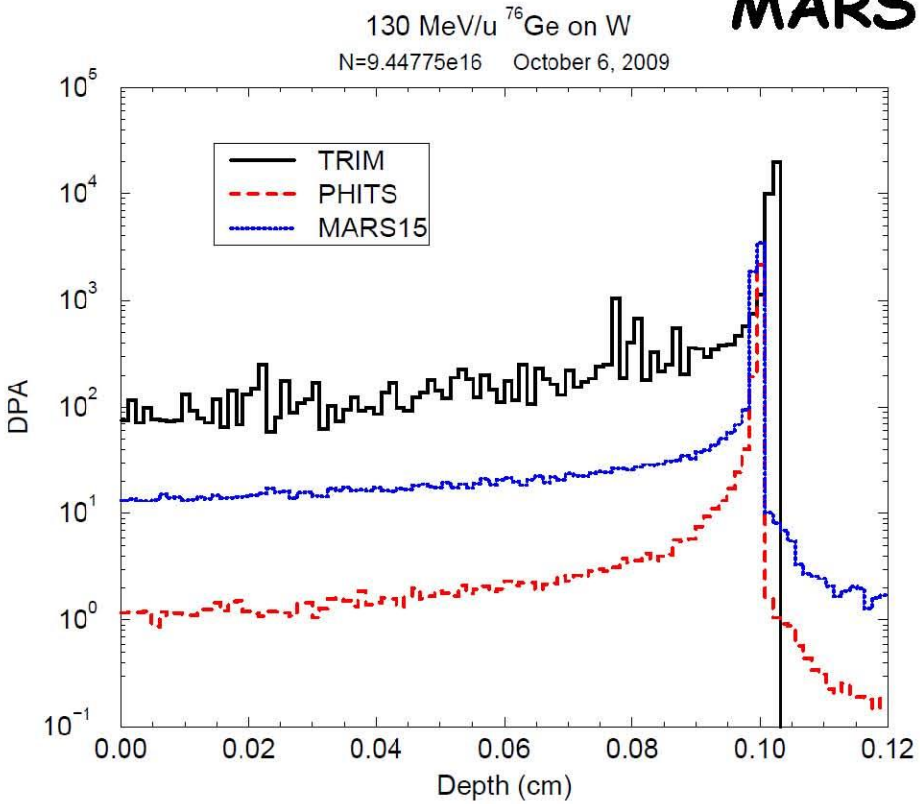
HiRadMat: Motivations

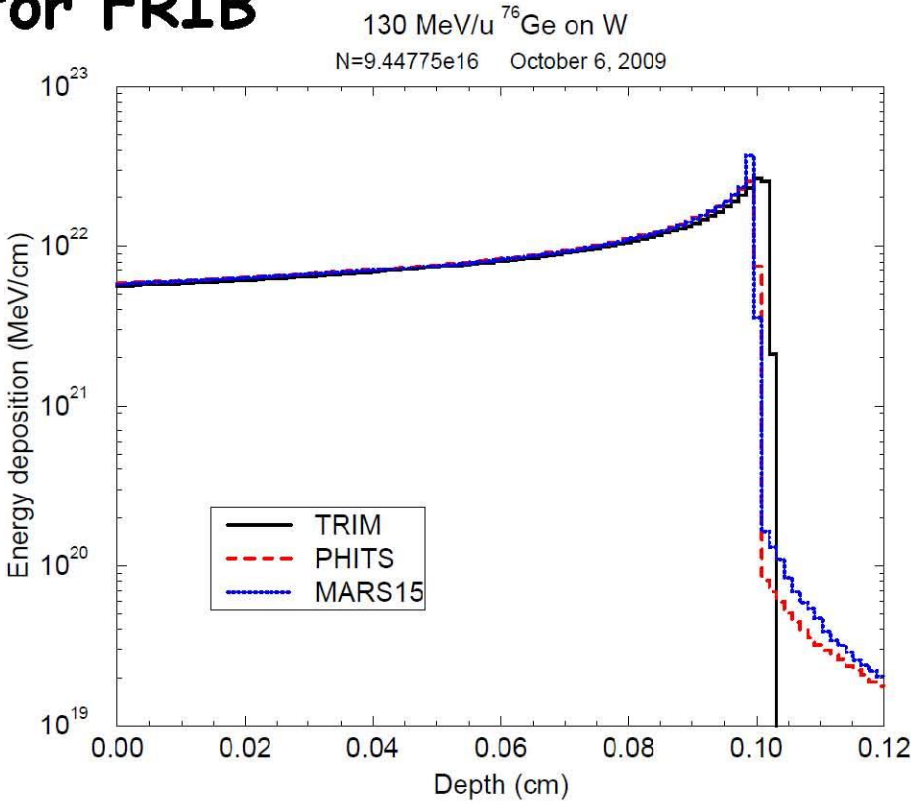
- Material characterisation by DPA?
  - See N. Mokhov, WEO1B02, WEO1B05, and whole WEDO1B.
  - No way to measure
  - Large discrepancies among different simulation programs:

  - N. Mokhov, in Proc. 10th Workshop on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-10), June 2-4, 2010, CERN, Geneva, Switzerland; also Fermilab-Conf-10-329-APC.

DPA & ED Comparison: 130 MeV/u ^{76}Ge on W

MARS for FRIB





Pencil beam, uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with R=0.03568 cm, L=0.12 cm

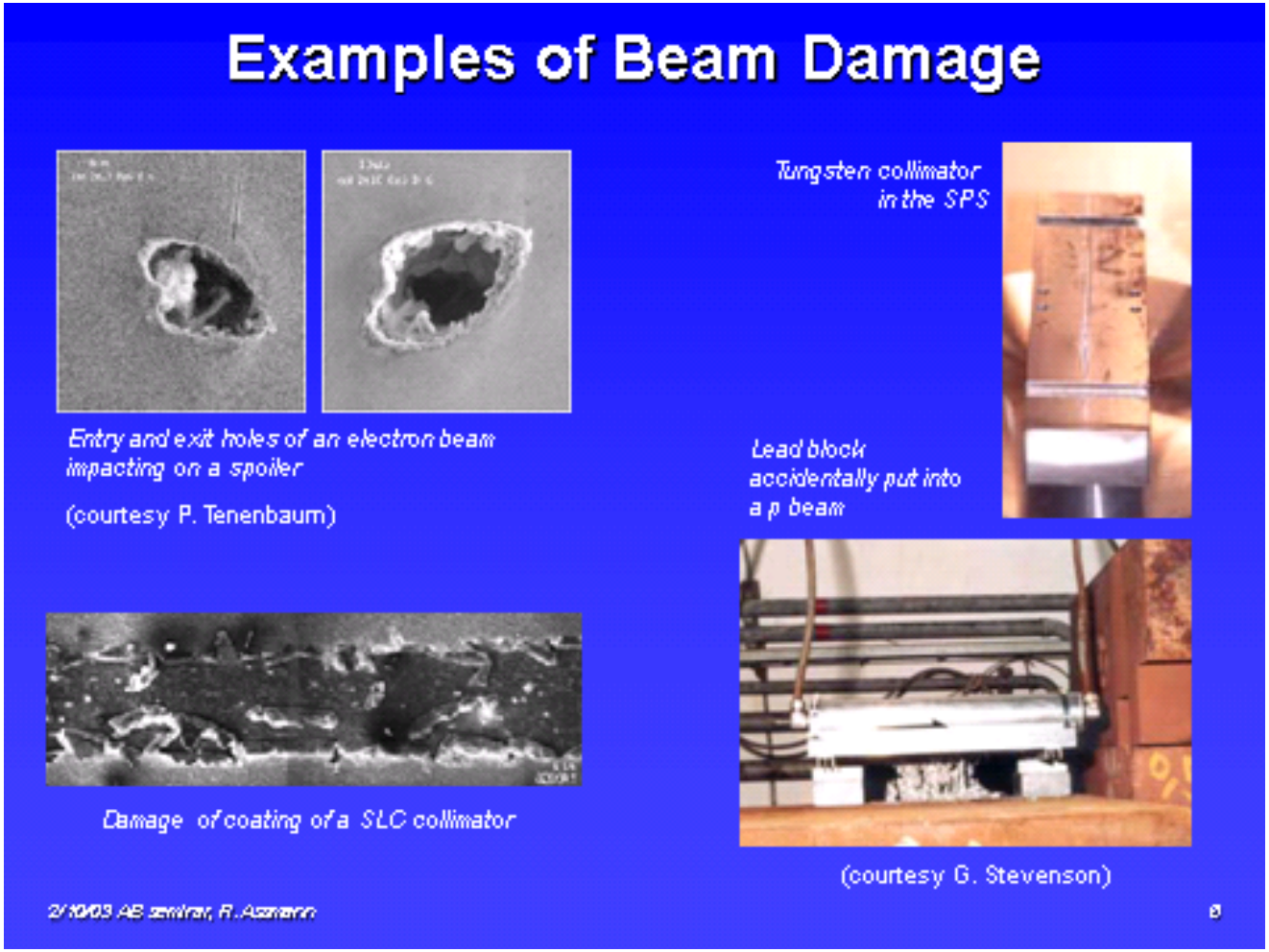
TRIM and PHITS results: Courtesy Yosuke Iwamoto

HiRadMat: Motivations

- Material characterisation by DPA?
  - DPA effects disappear with annealing??
    - See MOPD065
  - Does DPA mean anything for the following cases??

HiRadMat: Motivations

Courtesy
R. Assmann
CERN



HiRadMat: Motivations

Courtesy
R. Schmidt,
V. Kain

CERN

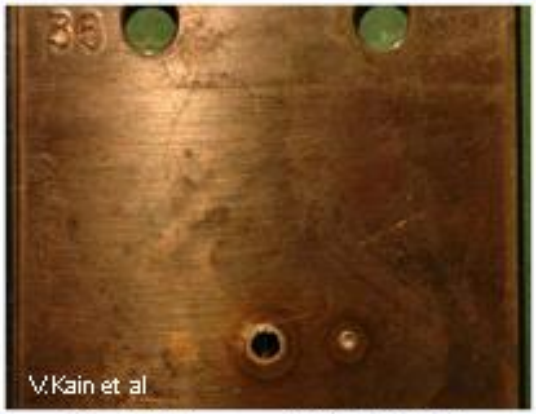
Beam damage with SPS proton beam

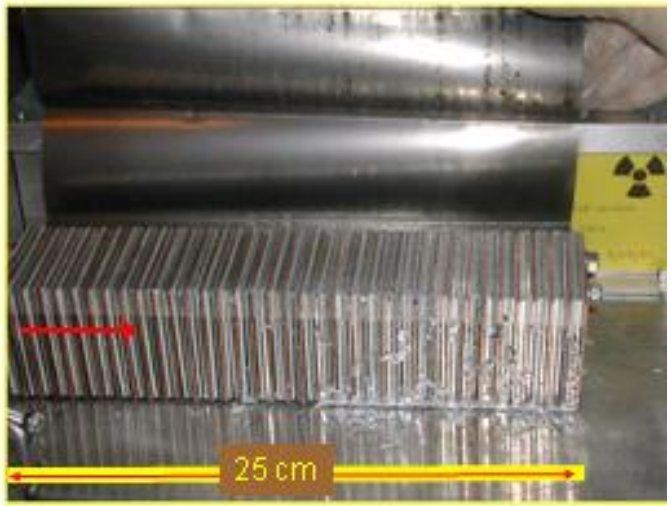
- Controlled experiment, 450 GeV
- $8 \cdot 10^{12}$ protons clear damage
- beam size about 1 mm

above damage limit for copper

- stainless steel no damage
- $2 \cdot 10^{12}$ protons

below damage limit for copper





0.1 % of the energy of the LHC beams with final parameters

Rüdiger Schmidt CERN Case Study: Risk management and innovation in complex environments page 77

HiRadMat: Motivations

- Therefore, primary goal is to understand which is the intensity limit to have visible (measurable?) damage!
  - melting, grain growth, modification of yield…
- Second (long term) is to develop a better understanding of the influence of beam impact on materials.
  - Need to have *measurable* parameters to set limits
  - Any idea? (for discussion!!!)

HiRadMat: The facility

- Proposed by R. Assmann and finally approved in 2009.
- Presently under construction. Due to start sometimes in 2011 (depending on access conditions)
- Designed for test of materials hit by high energy proton or ion pulses
- Proposed in EUCARD as transnational access facility: experiment may apply for funding (see EUCARD website).

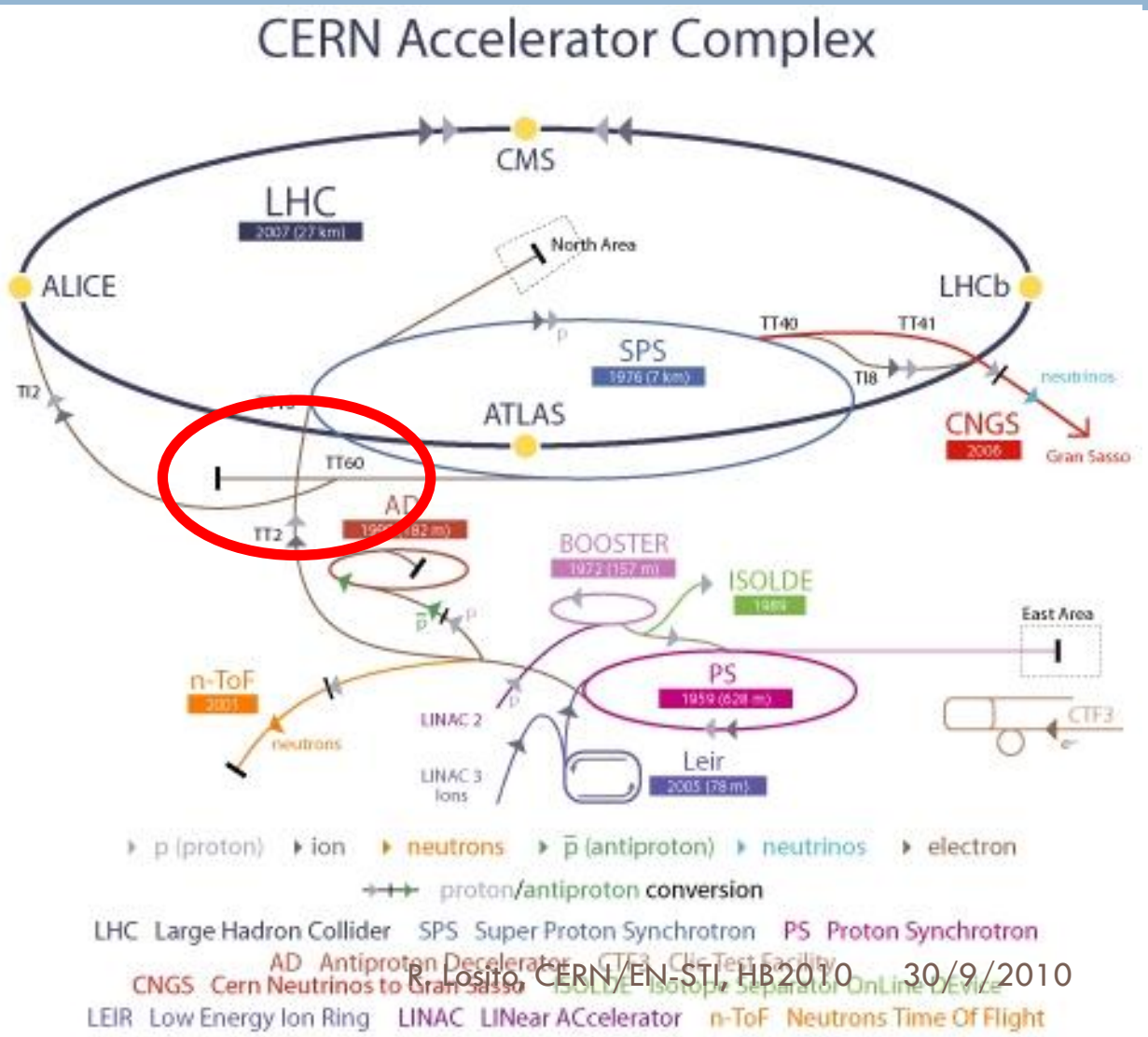
Specification for a Test Facility with High Power LHC Type Beam

R. Assmann, A. Bertarelli, I. Efthymiopoulos, B. Goddard, C. Hessler, T. Markiewicz[1], M. Meddahi, R. Schmidt, J. Sheppard[1], H. Vincke

Abstract

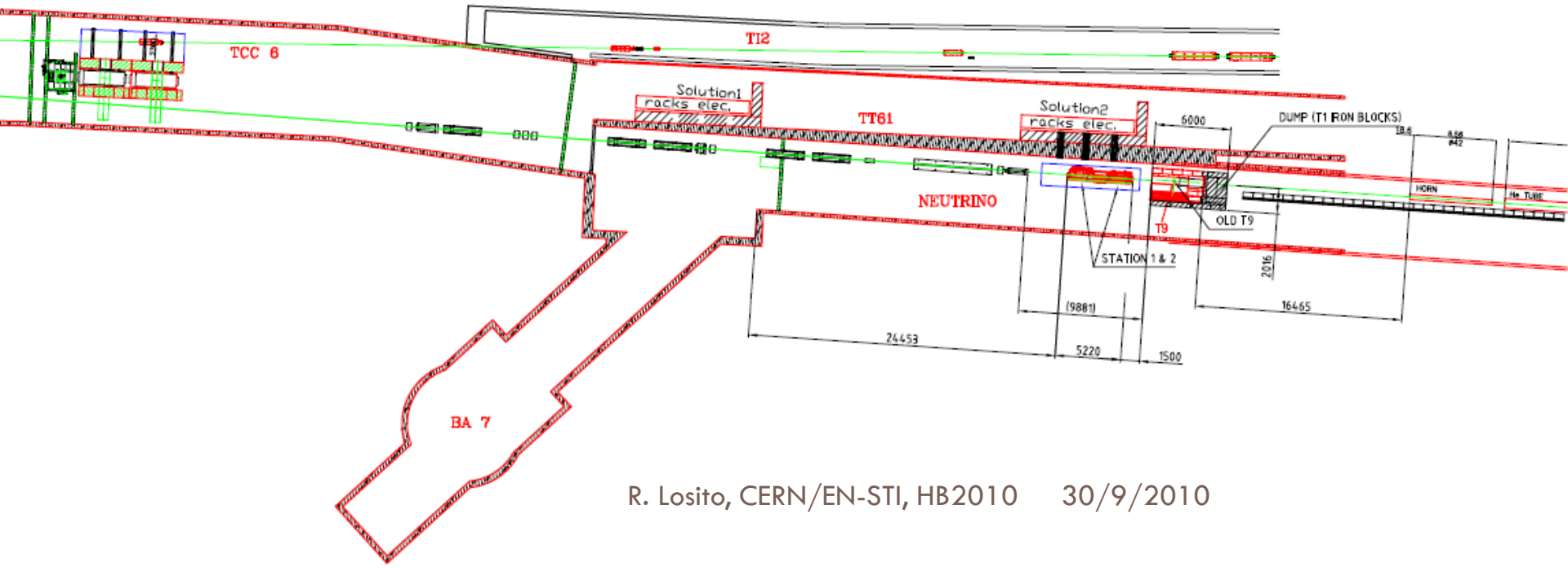
The characteristics of the LHC beam mean that the energy deposited in the event of interaction with accelerator components can be much above the damage thresholds of materials. This report specifies a test facility with high intensity LHC-type beam, as included in the framework of the "phase 2 LHC collimation project" and the "EUCARD proposal to FP7". The specified facility is required to test accelerator components and materials for sufficient robustness with beam shock impact, prior to installation into the LHC or its injectors. A 7 μs long pulse can be extracted about every 30 seconds and delivered into a small transverse area (controllable around 1 mm^2), carrying an energy of up to 2 MJ. The corresponding pulsed peak power is 340 GW for protons and 2.3 GW for lead ions. The facility will also provide opportunity for reproducing and analyzing any possible primary and secondary effects from beam-induced damage encountered during LHC operation.

HiRadMat: The facility



HiRadMat: The facility

- Built in the old gallery of the WANF experiment, in a derivation from the TI2 line from SPS to LHC.
- Access possible when LHC runs.



HiRadMat: The facility

- Protons :

Beam Energy	440 GeV
Pulse Energy	up to 3.4 MJ
Bunch intensity	$3.0 \cdot 10^{9}$ to $1.7 \cdot 10^{11}$ protons
Number of bunches	1 to 288
Bunch length	11.24 cm
Bunch spacing	25, 50, 75 or 150 ns
Pulse length	7.2 μs
Beam size at target	variable around 1 mm^2

HiRadMat: The facility

- Heavy Ions :

Beam Energy	173.5 GeV/nucleon (36.1 TeV per ion)
Pulse Energy	up to 21 kJ
Bunch intensity	$3 \cdot 10^7$ to $7 \cdot 10^7$ ions
Number of bunches	52
Bunch length	11.24 cm
Bunch spacing	100 ns
Pulse length	5.2 μs
Beam size at target	variable around 1 mm^2

HiRadMat: The facility

- 10^{16} protons/year available
  - Divided in 10 slots to allow availability of beam for several experiments
    - Not sufficient for fatigue studies…
    - Pre-irradiation…

HiRadMat: The facility

- Safety aspects have been considered for the design of the facility:
  - Access to experimental zone under strict controlled procedures: access in the area modified to allow access control dedicated to the facility
  - Necessity to implement ALARA principle in the design of experiment
  - Overhead crane and some remote handling available
  - Experiments shall have to provide a risk analysis together with the scientific proposal.

HiRadMat: The facility

- The facility has been proposed within Eucard as a Transnational access facility. Experiments may apply for funding (see EUCARD website).
- CERN will provide some instrumentation (especially for measuring the quality of the beam), but every experiment shall have to provide the instrumentation necessary to its execution.
- We hope to build up a stock of useful instrumentation with time

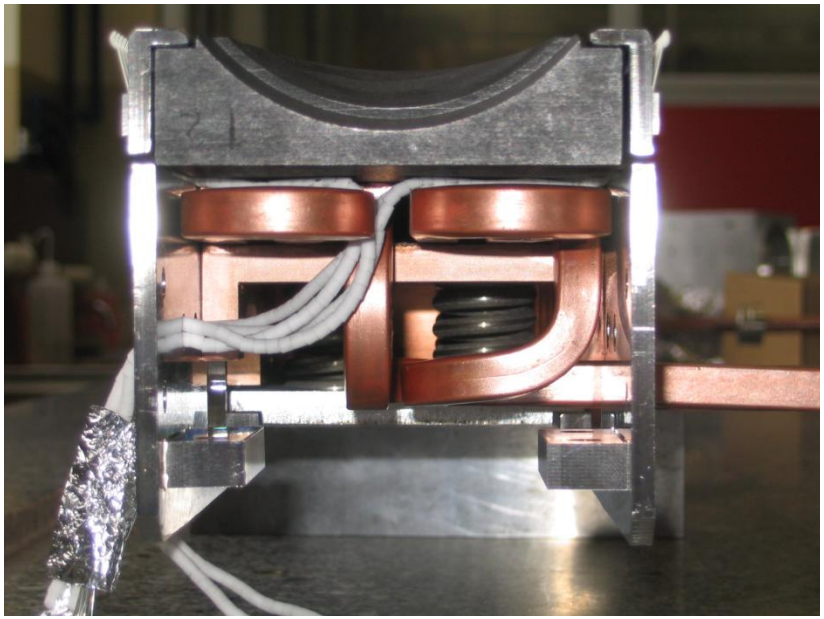
Failure from beam impact

- Impact with energy deposition keeping the material below elastic (rupture) limit
  - Not really the goal of the facility
  - However useful information can be extracted
    - Calibration of radiation detectors in different radiation fields.
    - Possibility of long term irradiation on small samples not excluded and can be proposed
    - Single Event Upset test station?
  - Sometimes we believe we are below the elastic limit, but….

Failure from beam impact

Collimator jaw with copper support

Collimator assembly

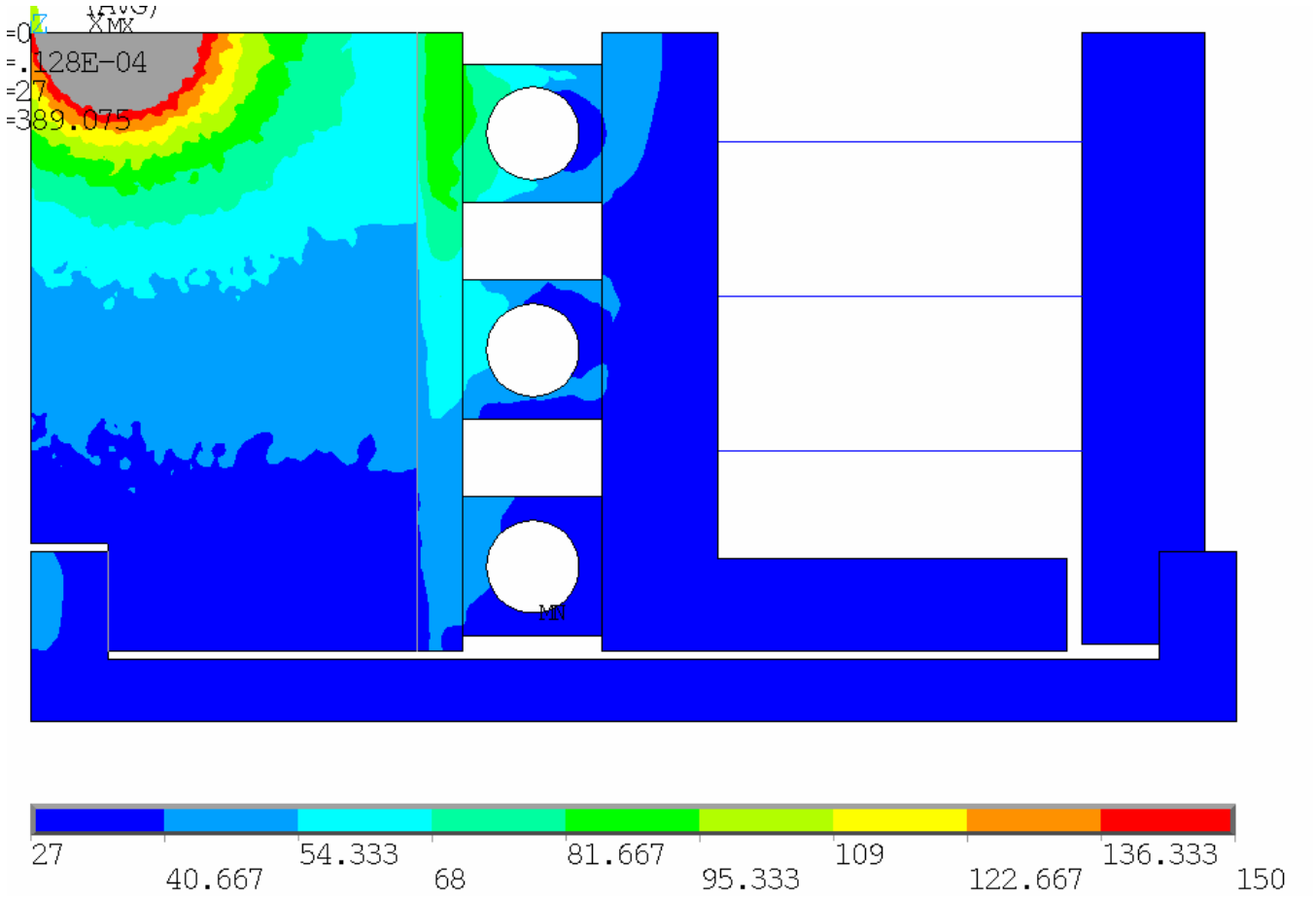


Failure from beam impact

Courtesy

A. Bertarelli
A. Dallocchio

CERN



Failure from beam impact

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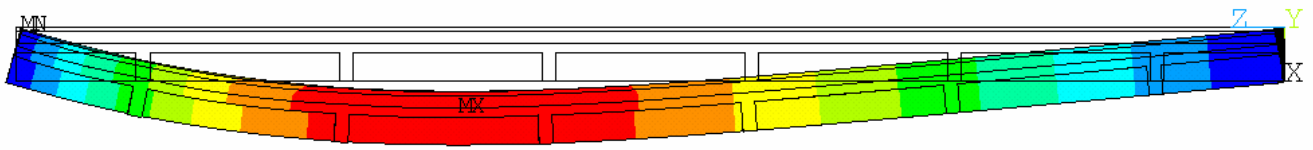
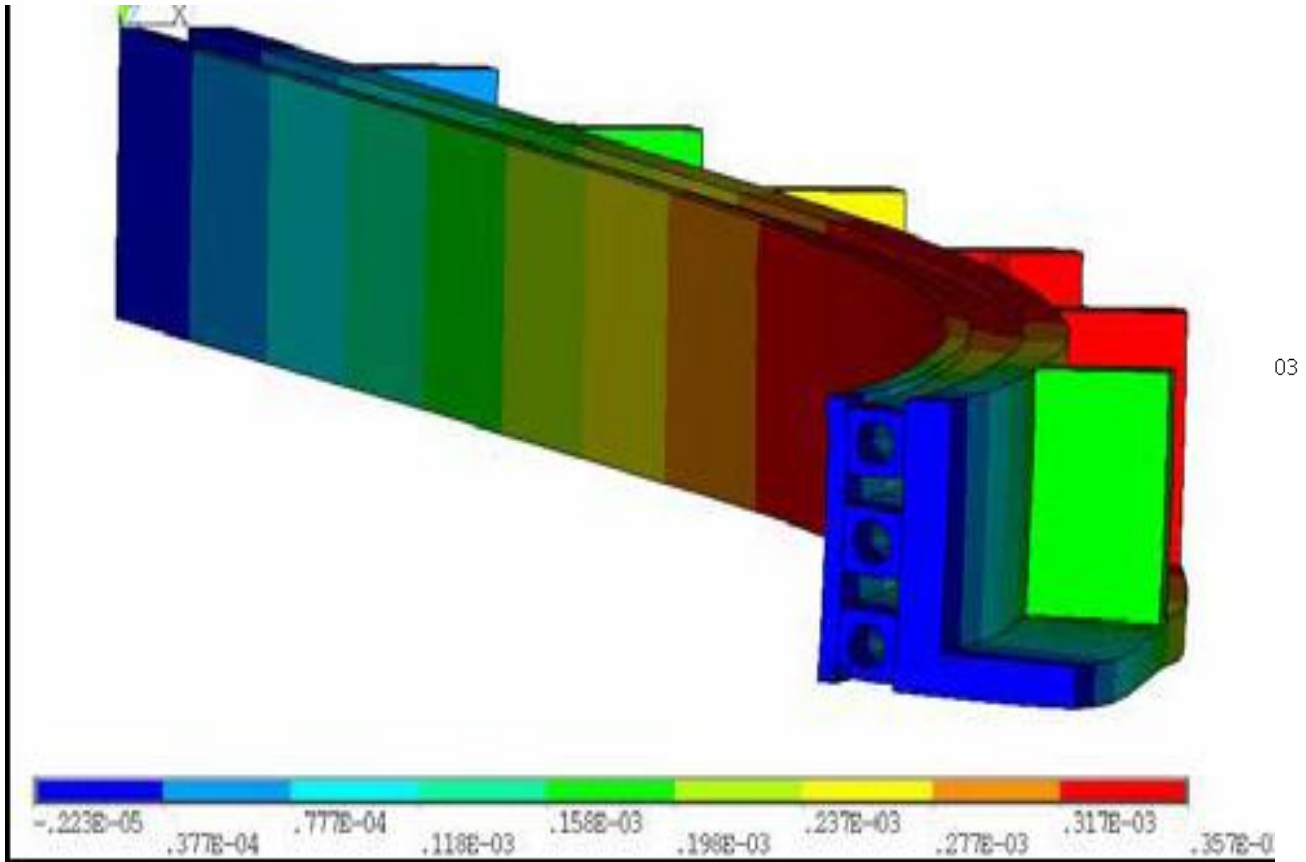




Failure from beam impact

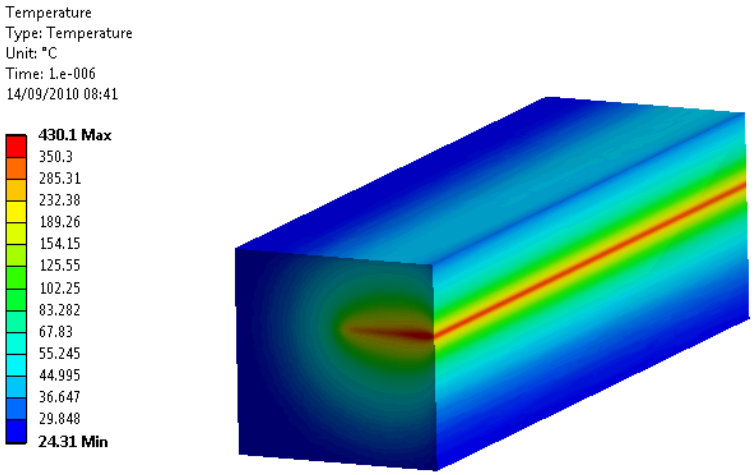
- Impact with energy deposition driving materials beyond the elastic (or rupture) limit:
  - Not easy to simulate for complex systems (like an LHC collimator)
  - Modeling of dynamic stresses is necessary to understand the behavior of the material

Failure from beam impact

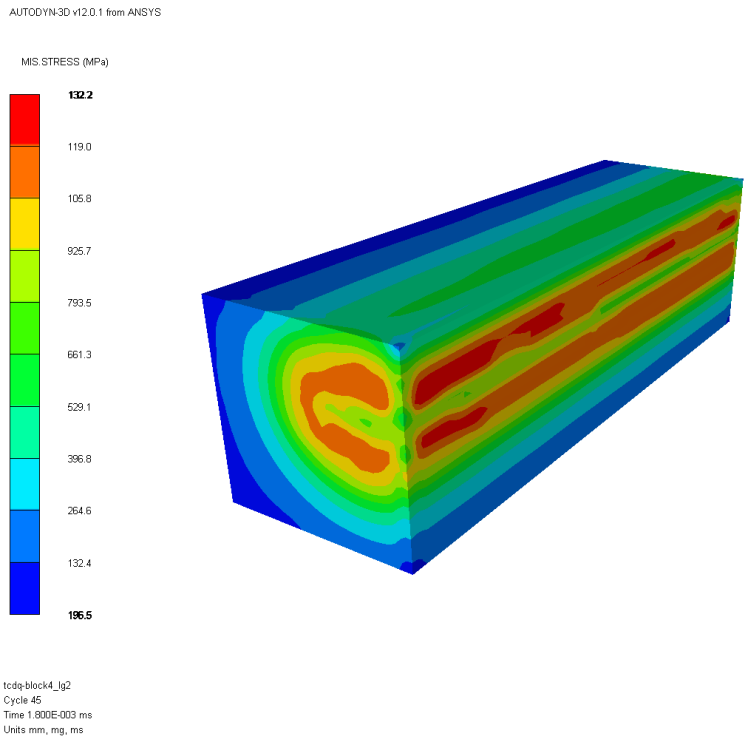
- TCDQ is a 6 m long collimator that protects the elements downstream the extraction kickers from asynchronous beam dumps.
- It has to withstand about 30 nominal LHC bunches
- Made of 12 graphite blocks, maximum of energy deposition (at 7 TeV) is between 6th and 9th block

Failure from beam impact

Steady state

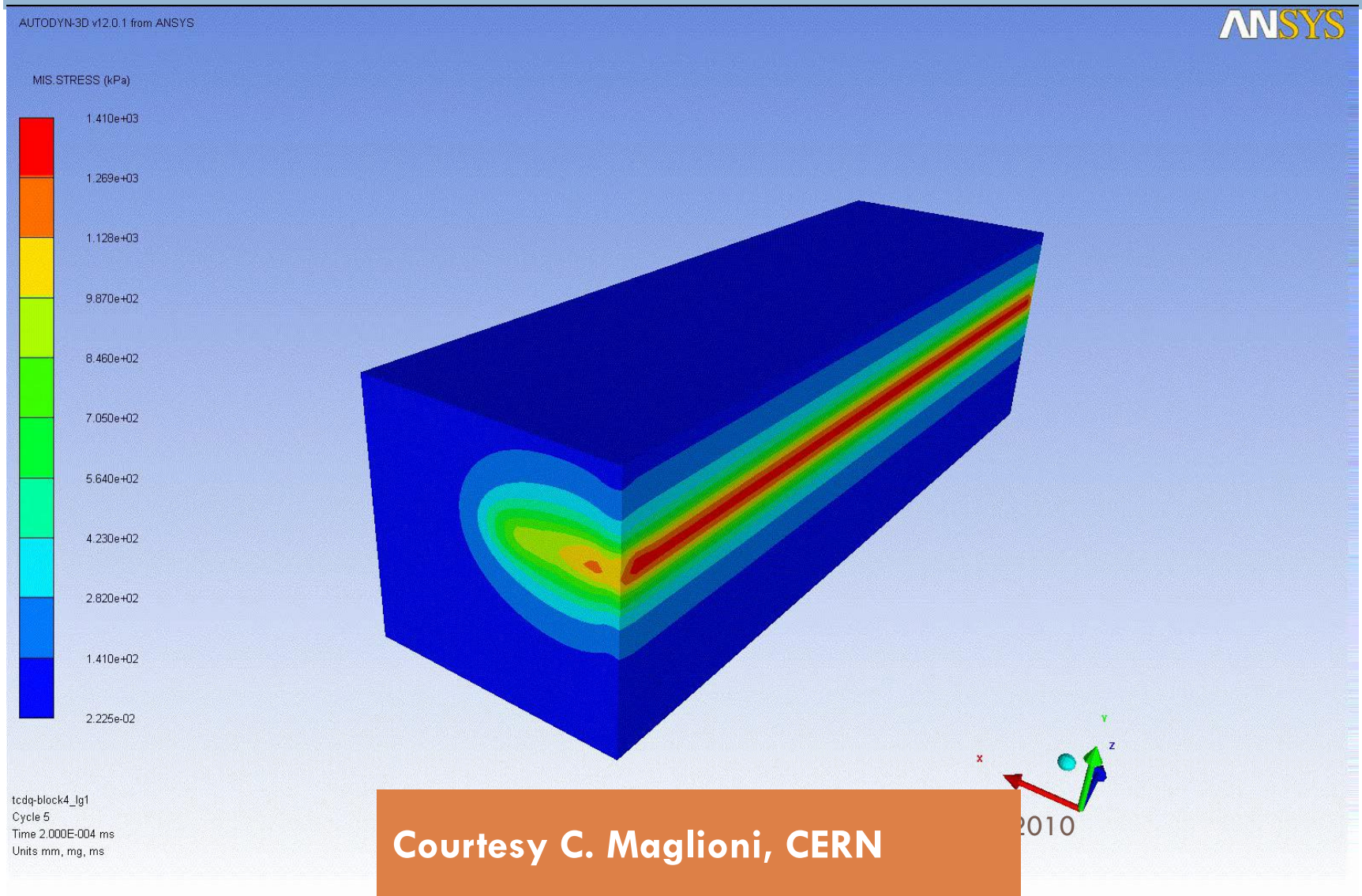


Shock wave



Courtesy C. Maglioni, CERN

Failure from beam impact



Courtesy C. Maglioni, CERN

Failure from beam impact

- An important goal is to validate our capacity to simulate dynamic behaviour of the systems.
- It is an ideal facility to study shock waves
- Can fatigue studies be carried out with 10^{15} protons?
- Vacuum windows?

Experiment without failures…

- One could be interested into the dynamic effects of beam impacts.
  - Hydraulic behavior of molten metal loops under beam impact
  - "Explosion" of powders (or microspheres)
  - Gas jets….
  - Localized melting of thick targets: how does it influence the production yield…

Experiment without failures…

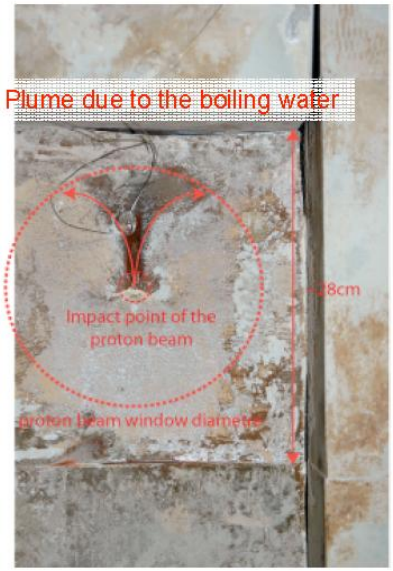
nTOF target: a problem of water chemistry, radiolysis, cooling flow….

Experiment without failures…

Courtesy D. Cano Ott

(CIEMAT)

3. Water chemistry



There are very clear signs of a strong **pitting corrosion** at the entrance of the proton beam. Such effects are very well known in nuclear power plants (cracks in the fuel cladding): the very hot (boiling) water carries more oxygen, thus allowing the Pb to change its oxidation state to higher values:

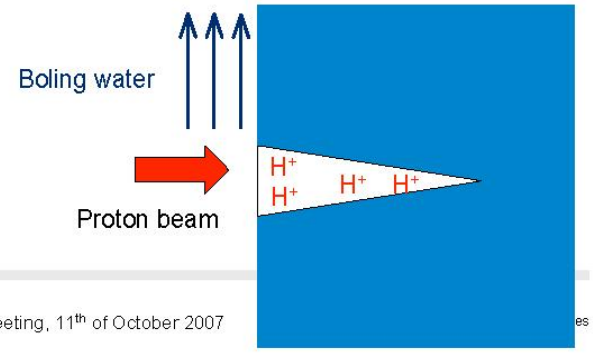
$Pb \rightarrow Pb^{2+} + 2e^-$

$Pb \rightarrow Pb^{4+} + 2e^-$

Hydroxides are formed and a very acid local medium which attacks the metal is produced:

$Pb^{2+} + 2H_2O \rightarrow Pb(OH)_2 + 2H^+$

$Pb^{4+} + 4H_2O \rightarrow Pb(OH)_4 + 4H^+$



MINISTERIO DE EDUCACION Y CIENCIA

Daniel Cano Ott, Pb target status meeting, 11th of October 2007

Experiment without failures…

Wouldn't it be better with beam???

Courtesy

S. Sgobba
CERN

Experiment without failures…

- MERIT:
  - *A **proof-of-principle test of a target station** suitable for a Neutrino Factory or Muon Collider source using a 24-GeV proton beam incident on a target consisting of a **free mercury jet** that is inside a **15-T capture solenoid magnet**.*
- BNL, MIT, ORNL, Princeton University
- CERN, RAL

Experiments without failures…

Courtesy

I. Efthymiopoulos

CERN

The MERIT experiment

*A **proof-of-principle test of a target station** suitable for a Neutrino Factory or Muon Collider source using a 24-GeV proton beam incident on a target consisting of a **free mercury jet** that is inside a **15-T capture solenoid magnet**.*

Proposal submitted to CERN – May 2004

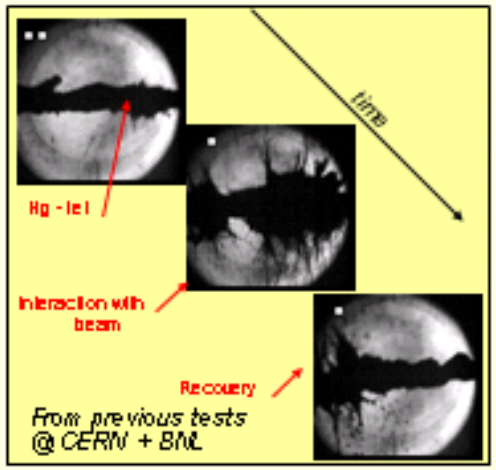
Experiment approved as **nTOF11**

Participating Institutes

- BNL, MIT, ORNL, Princeton University
- CERN, RAL

Spokespersons

- H. Kirk (BNL), K. McDonald (Princeton Univ.)



April 2008 I.Efthymiopoulos, CERN 3

Do we have a problem???

- CERN has very limited capacity to do post irradiation analysis.
- An hot cell will be available in 2013/2014 for dismantling of ISOLDE targets, no analysis tool for material testing (for the moment)
- What equipment do we really need in house and what facilities can we use outside CERN?
- Where can we find what we miss?

Conclusions

- HiRadMat is aimed at testing the behaviour of mechanical systems with high energy proton or ion beams (pulsed)
- CERN will provide some on line test infrastructure, but every "experiment" shall have to provide its own instrumentation for testing.
- CERN today has no dedicated facilities for post irradiation test and analysis.
- HiRadMat will be open to external users, and supported by the European commission as a trasnational facility (users may apply for funds to EUCARD).
- Main question to be answered: how to quantify damage in a measurable way?