CERN

Simulation tools for beam dump blocks and beam intercepting protection devices

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Presentation given guidelines

- Presentation not about simulation results, but about:
    - Existing simulation tools for the beam losses and tools for simulation of Beam Intercepting Devices (BIDS)
      → what is needed
    - What are the weak points of these tools and what are the envisaged R&D lines towards future development of fully satisfactory, “predictive” simulation tools
    - Selected results for illustration of both the strong and weak points of the existing tools
    - Some Material already presented in the past, but seen on another point of view

- For some aspects, considerations independent from electron or hadron machines
    - Physics interaction models are different, however problematic in design pretty close (including synchrotron radiation)
    - Energy and total power and power density very different

Workflow for BIDS design/conception

- Always starting from a functional specifications for BIDS

- First evaluation of very simplified design
  - MC simulation of particle/matter interaction via FLUKA from a first source term
    - Collision at the IP producing debris→ High energy pp or e+e- collision particle generator at √s

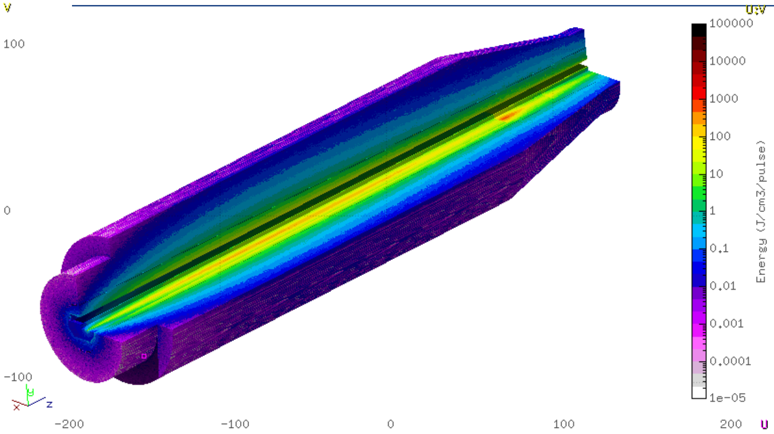
    - Direct (grazing) impact on protection (or not, like magnets) devices → "Fixed target"-like experiment (loss maps)→ needed interaction cross section at energies compatible with primary beam (50 TeV + N for hh , 200 GeV + N for ee)

- Finite element analysis for design
  - Requires material thermomechanical properties at every service temperature
  - Requires proper modelling capability of finite element codes under extreme conditions (even induced phase transition)

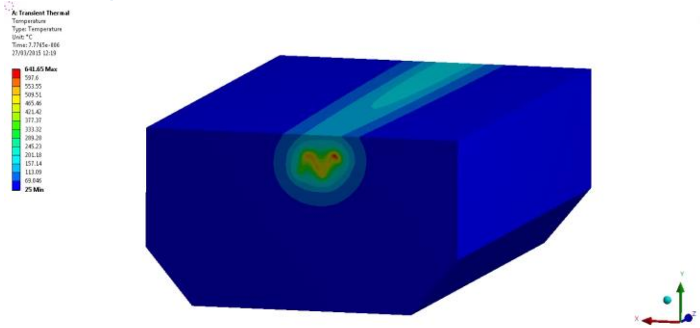
- Iterations to take into account:
  - Technique for final (and eventually) industrial production
  - Maintainability

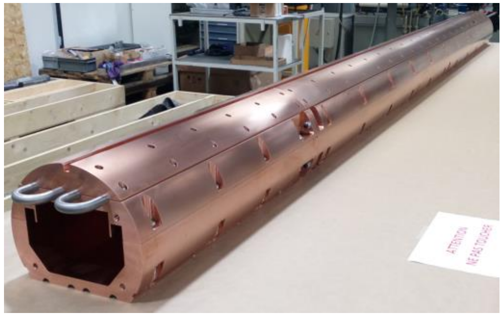
An example: SPS beam internal dump 4th generation, 5th in construction

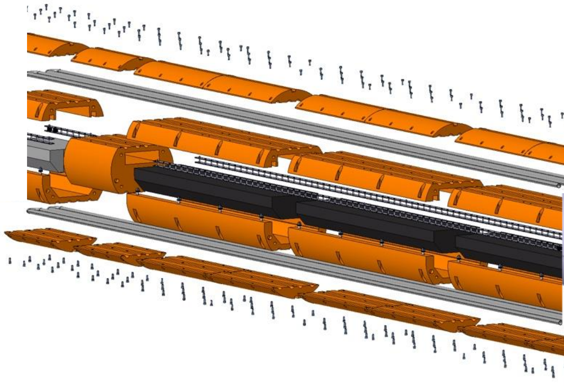
Fluka studies of energy deposition

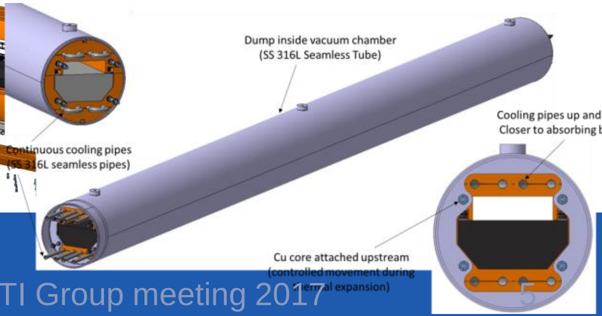


Ansys studies of transient stresses







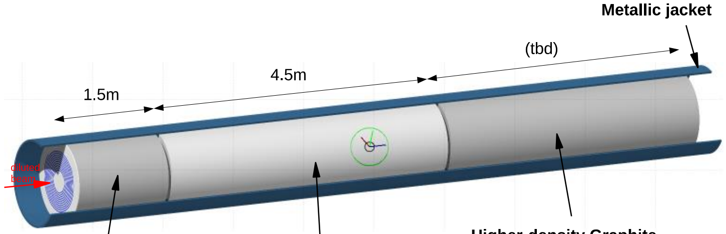


Example for BIDS design

FCC-hh dump concept (LHC-like Graphite dump)

- **Beam sweeping à-la LHC to reduce energy density.**
- Failure scenarios consideration
  like sweep change due to dilution
  kicker failure or asynchronous beam dump

a) Initial proposal/geometry



Higher-density Graphite segment (1.8 g/cm³)

Higher material density at upstream end gives rise to a steeper shower build-up and hence reduces the overall dump length
Note: the presence of the higher-density graphite has only a small effect on the maximum energy density in the low-density segment if the beam is diluted across the dump face

Low-density Graphite segment (1.0 g/cm³)

Lower material density in the region of the shower maximum reduces the max. energy density and temperature

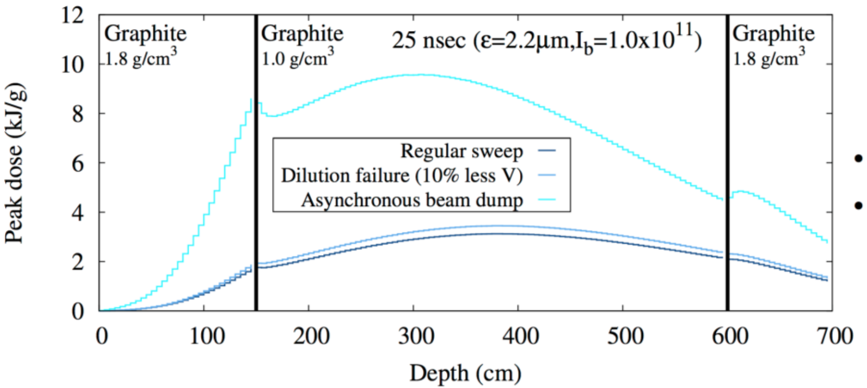
Higher-density Graphite segment (1.8 g/cm³)
+ possibly other materials (tbd)

Higher material density gives rise to better attenuation of the longitudinal shower tails and hence reduces the dump length

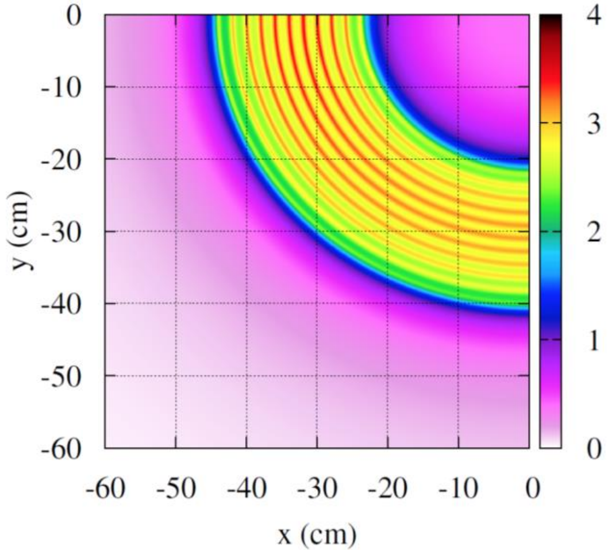
Total core length expected < 10-12m

Core radius depends on sweep pattern (+ a certain margin to jacket)

b) Fluka based energy deposition along long. axis



- Latent heat Graphite: ~8.7 kJ/g [1]
- Melting: ~17 kJ/g [1]

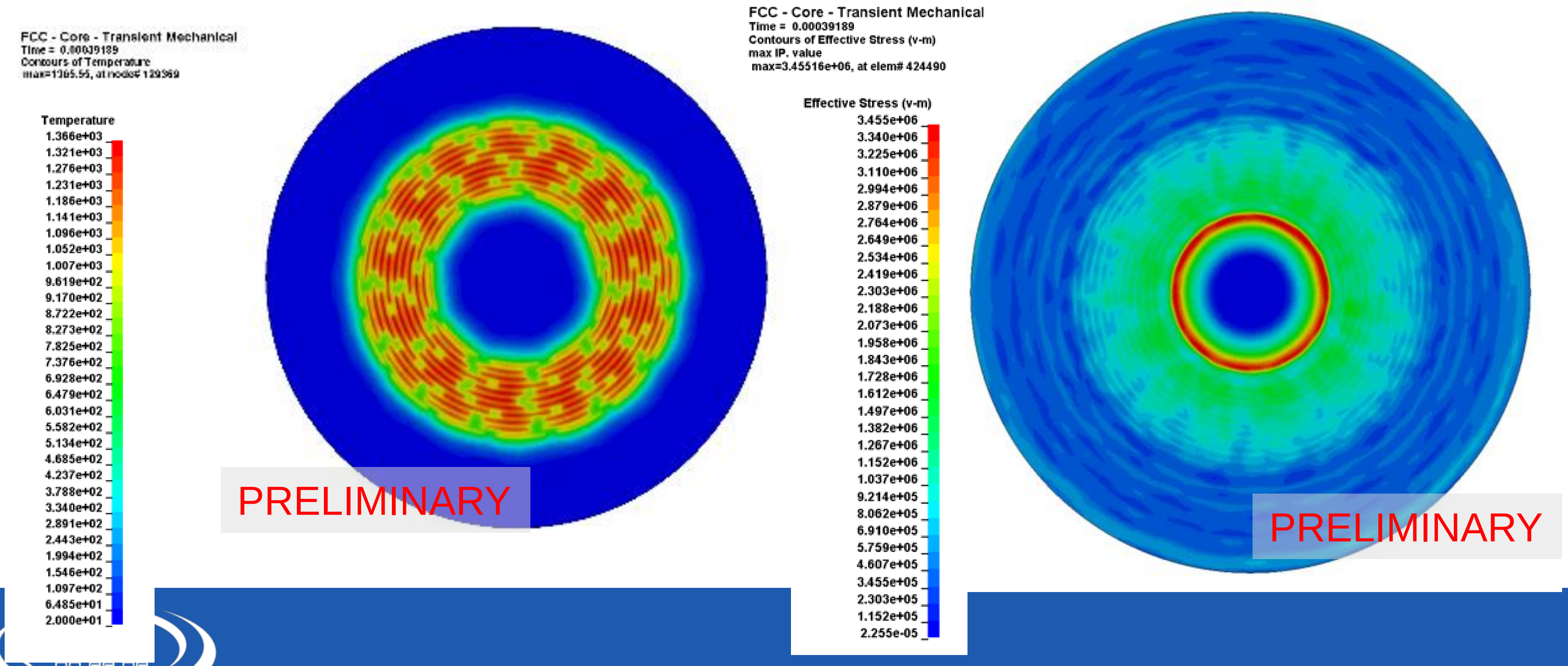


Material development:

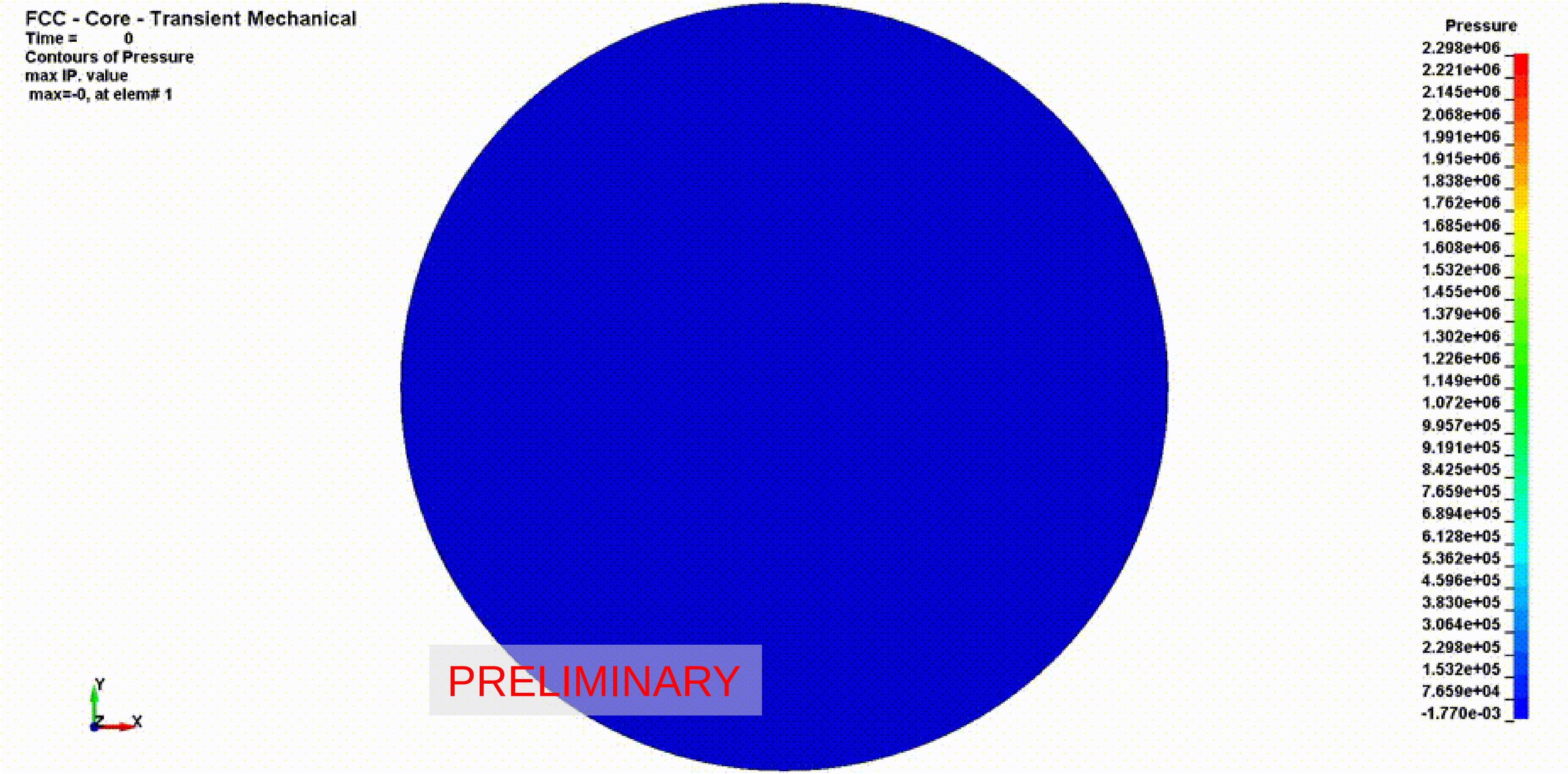
- Working together with companies and other research institutes to investigate low density graphite thermomechanical properties
- Still exploring alternatives for less traditional material

c) Preliminary thermo-mechanical assessments

- Analysis of low density graphite core (ρ=1.0 g/cm^3)
- **Challenging calculations, at the limit of today's software and material properties**
- LS-DYNA employed for explicit dynamical calc.

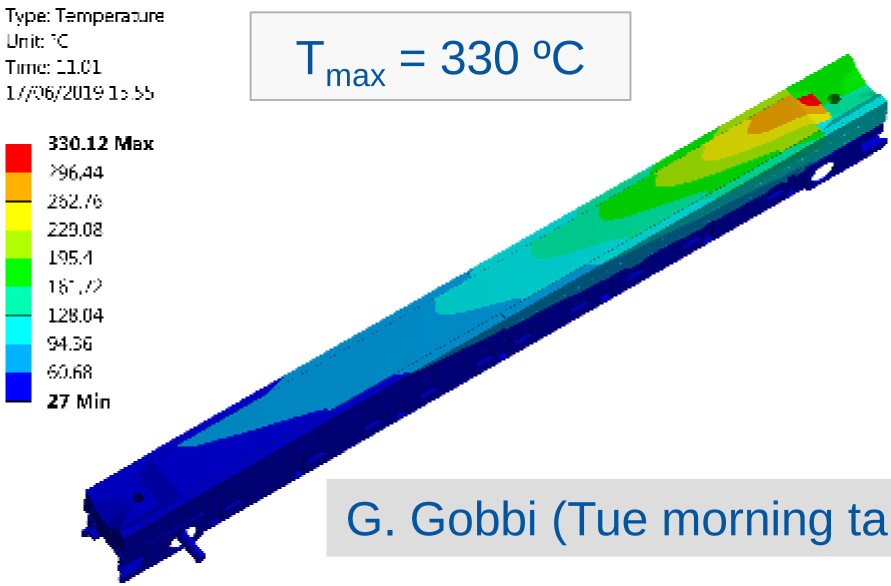


Negative hydrostatic component of the stress tensor → i.e. **pressure in the material**



T. Polzin

Deformation for most loaded TCS jaw



T_{max} = 330 ºC

G. Gobbi (Tue morning talk)

Deflection = 375 µm

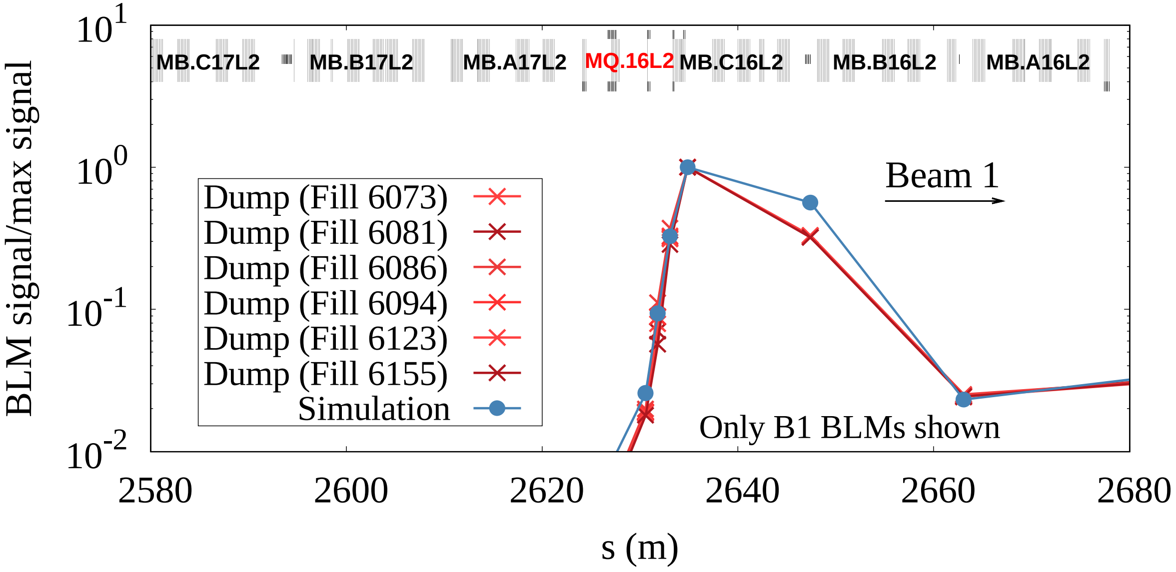
Temperature profile on the jaw after 10 s assuming a beam lifetime of 12 minutes

Power deposited: 92 kW

- Jaw assembly survives without plasticity (except pipes)
- Onset of plasticity on cooling pipes could be addressed by using different material

Loss location prediction

- Exiting tools, together with tracking tools and BLMs data, evolved thanks to the LHC experience
- Identification of 16L2 within 1 m and first hypothesis considering nature of trapped elements at cryogenic temperature



Fluka development for FCC BIDS

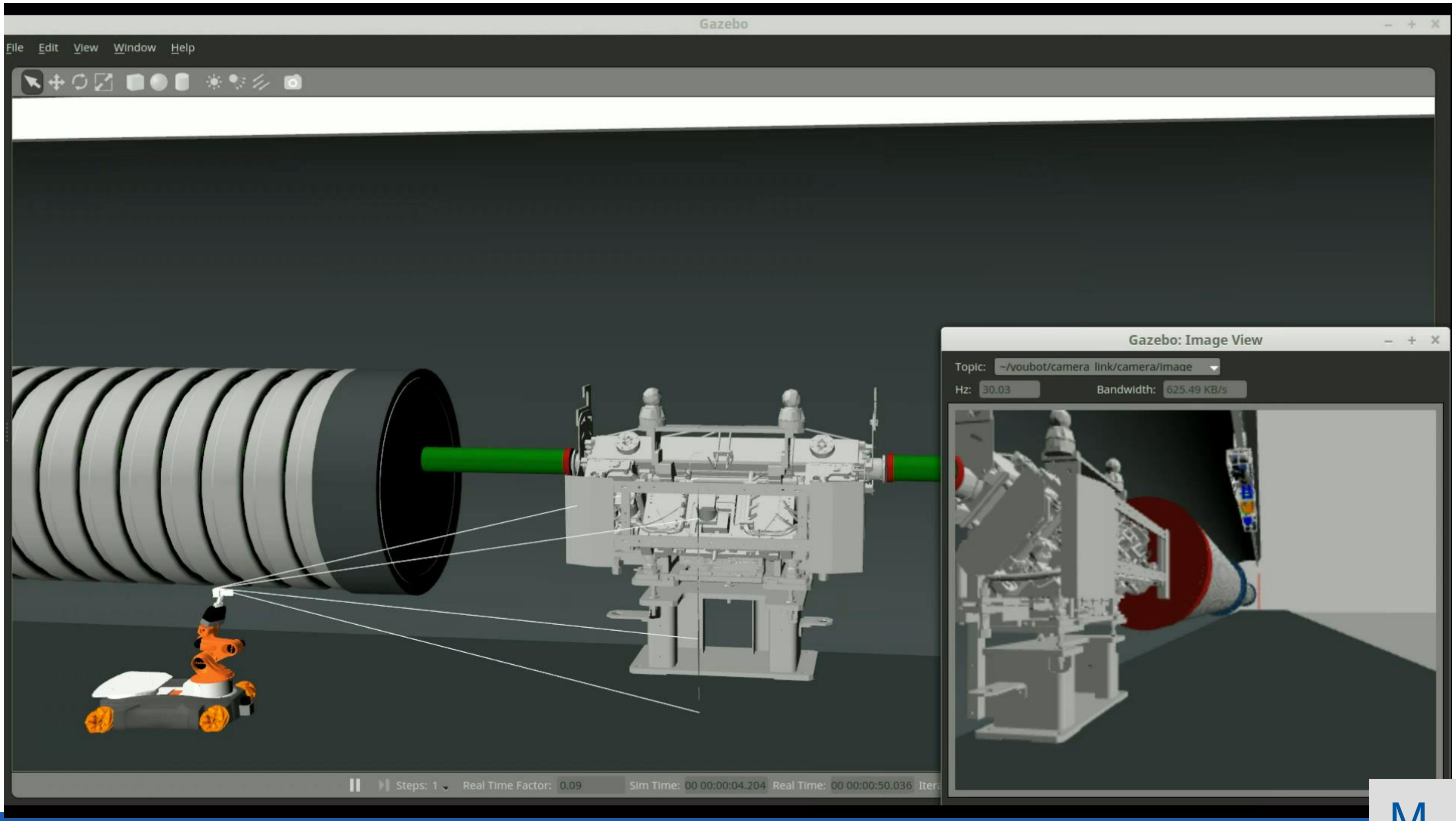
- Fluka works well at very high energies for example for cosmic rays (astrophysics) applications
- LHC collisions CM corresponds to about 1e5 TeV beam equivalent energy fixed target experiment
  (10000 TeV → √s~ 20 TeV)
  - Double differential cross sections
  - Check with available LHC to be pursued
    (DPMJET already improved, used regularly)
- Data not available for pN single diffractive cross section in interval 7-50 TeV
  - Indirect validation LHC primary beam loss data (BLMs)
  - Precise data validation is relevant for collimation efficiency evaluation
  - Interaction model transition from 7 to 50 TeV to be explored in more depth

FCC BIDS design considerations

- Beam intercepting devices based on cumulated experience from LHC/Injectors operation
  - Initial technical design very often inspired by that, including for the lepton collider.
  - Operational experience helping to take decisions and proposition for FCC (internal/external dumps for example)
- High Reliability, maintainability
  - The numbers of equipment scales with machine dimension, (even if only always two beam dumps and not more…)
- Minimize irradiated volume wrt absorbing requirements
  - Less active material quantity in particular for hh machine
- Design and material choice considered also to:
  - Reduce dose during interventions (with or w/o telemanipulation)
  - Final disposal

Collimators remote handling

- Inspection and telemanipulation from **a Train Inspection Monorail a la LHC**
- Here a collimator used as example: remote handling should be considered at design stage



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Bandwidth: 625.49 KB/s

Steps: 1

Real Time Factor: 0.09

Sim Time: 00 00:00:04.204

Real Time: 00 00:00:50.036

M. Di Castro

Attempt to integrate virtual reality/robotics and FLUKA residual dose rate estimates

- Simulated dose field with FLUKA and VR intervention to evaluate dose during leak detection intervention on LHC external dump or collimator dismantling
- Help in deciding best intervention technique (robotic or not)
- Just a first attempt for a very specific case:
  - Tools: VR and FLUKA simulations → Important for FCC maintenance

What we are missing, main aspects

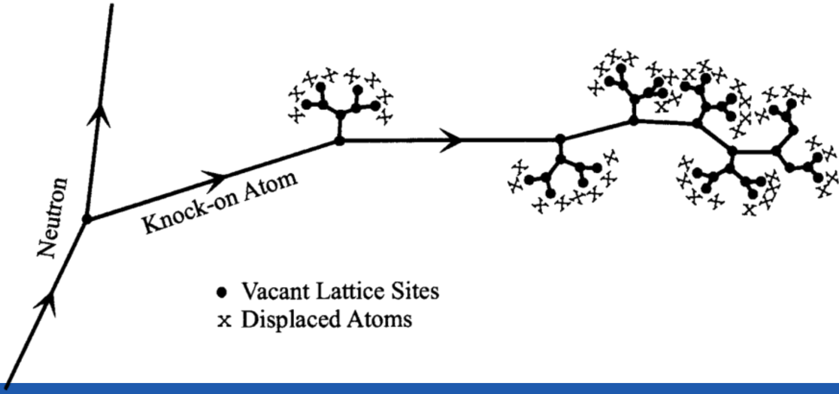
- Material properties characterization beyond more common use (high temperature/high strain)
  - Graphite based material in particular, but all material in general
  - Material properties also in phase transition
  - Material properties evolving due to irradiation (dpa and swelling due to gas production-important for material coatings)
  - Need for dynamic calculations (LS-DYNA, Autodyn and similar)
- Advanced collimation techniques simulation tools
  - Crystal collimation full model to be implemented in FLUKA
- Specific source term for FCC-ee collisions
  - Existing but not included yet

DPA

- **The unit that is commonly used to link the "*radiation damage effects*" with "*macroscopic structural damage*" is the displacement per atoms**
- It is a "measure" of the amount of radiation damage in irradiated materials

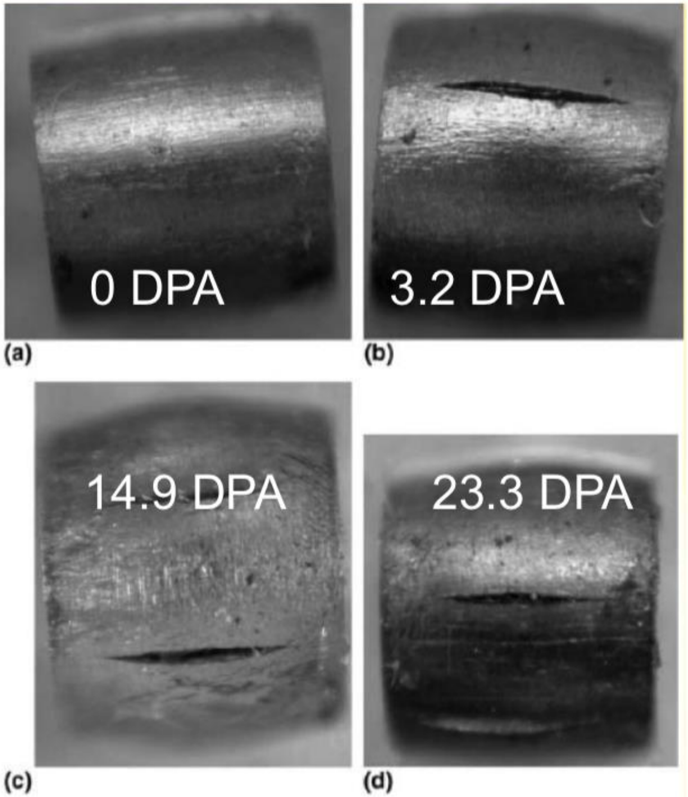
  3 dpa means each atom in the material has been displaced from its site within the structural lattice an average of 3 times

- **dpa** directly linked to the Non Ionizing Energy Losses (**NIEL**) but restricted in energy
- **dpa** is a strong function of **projectile type, energy and charge** as well as material properties and can be induced by all particles in the cascade
- However **dpa** for the moment is a "**mathematical**" quantity that cannot be directly measured experimentally **but can be simulated**
- **Open question: how to predict a change in macroscopic material properties given a certain number of DPAs**



Radiation Damage Effects

- **Displacements in crystal lattice, expressed as Displacements Per Atom (DPA)**
  - Embrittlement / Creep / Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Change of thermal expansion coefficient / modulus of elasticity
  - Fatigue response
  - Accelerated corrosion
  - Void formation/ embrittlement caused by Hydrogen/Helium gas production (expressed as atomic parts per million per DPA, appm/DPA)
- **Recent high-intensity proton target facilities meet irradiation with a few to several DPA**
  - Effects from low energy neutron irradiations (as fusion/fission reactor materials) do not equal effects from high energy proton irradiations



Tungsten, 800MeV proton irradiation at LANSE

after compression to ~20% strain at room temperature

S. A. Maloy, et al., Journal of Nuclear Materials 343 (2005) 219-226.

DPAs : open challenges

- What is known:
  - Simulating particles-matter interaction to predict/estimate DPAs
- What the community is exploring:
  - Method to **experimentally determine** the DPA for metallic materials in collaboration with Japan within the RADIATE collaboration
- What the community would like to develop
  - **Simulate/evaluate macroscopic material properties change (curve stress-strain, material density, gas cumulation, etc…) given a certain amount of DPA**
  - **Direct measure of DPAs effect is extremely expensive**
    - Specifically for fibrous material (carbon fiber composite) evaluate/understand how DPA and other type of instead local damage might affect macroscopic material properties.
- What we need on top of this:
  - Prediction of gas production and consequent swelling. Consequences also on material coatings

Long term future vision

- Simulation tools
  - Simulation tools available are adequate for current studies
  - Need detailed evaluation of precision of current estimates, difficult to achieve today
    - Unknow precision translated into margin in final design
  - Needed data input not always available
    - Material (irradiated or not) thermomechanical properties for finite element analysis
    - Particle source terms
- Technical tool possible limitations and possible future works
  - Managing big geometries
    - Today we have a good fraction of the LHC model in FLUKA, what about the scaling to the FCC (ee or hh) if needed
  - Scaling LHC@home (distributed computing) for other FCC applications
  - Same objects very often simulated/studied by very different tools for different purposes
    - Example: collimators:
      - Electromagnetic simulation → Impedance
      - Finite element design
      - FLUKA calculation
      - Installation/integration/telemanipulation
    - Three different studies on the same object with different geometry description
    - Goals are different, so also properties in the geometry might be different: should one think how to generate a common initial geometry for data exchange between different applications?
  - Integration between different simulation tools to plan maintenance/interventions on BIDS

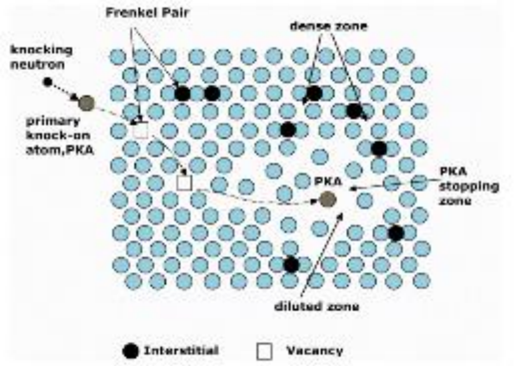
Few last considerations

- Simulation tools to determine quality of industrial processes for material treatment/manipulation
  - Hipping, brazing process

- Simulation tools also to
  - Estimate the BIDs lifetime or tentatively MTF

FLUKA Monte-Carlo DPA Implementation

- **Charged particles and heavy ions**
  - **During transport** → Calculate the **restricted non ionizing energy loss**
  - **Below threshold** → Calculate the **integrated nuclear stopping power** with the **Lindhard** partition function
  - **At (elastic and inelastic) interaction** → Calculate **the recoil**, to be transported or treated as below threshold



- **Neutrons:**
  - **High energy E_n>20 MeV** → **Calculate the recoils** after interaction. Treat recoil as a “normal” charged particle/ion
  - **Low energy E_n≤20 MeV (group-wise)** → Calculate the NIEL from NJOY
  - **Low energy E_n≤20 MeV (point-wise)** → Calculate the recoil if possible. Treat recoil as a “normal” charged particle/ion