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
**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

**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 \((\rho=1.0 \text{ g/cm}^3)\)
- 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 \(\rightarrow\) i.e. **pressure in the material**
Deformation for most loaded TCS jaw

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

- \( T_{\text{max}} = 330 \, ^\circ\text{C} \)
- Deflection = 375 \( \mu\text{m} \)

G. Gobbi (Tue morning talk)

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

Power deposited: 92 kW
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

![Graph showing BLM signal/max signal against s (m) with markers for different dump fills and a simulation line.]

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
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
The unit that is commonly used to link the “radiation damage effects” with “macroscopic structural damage” is the displacement per atom.

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

DPAs: open challenges

- What is known:
  - Simulating particles-matter interaction to predict/estimate DPAs

- What the community is exploring:
  - Method to \textit{experimentally determine} the DPA for metallic materials in collaboration with Japan within the RADIATE collaboration

- What the community would like to develop
  - \textit{Simulate/evaluate macroscopic material properties change (curve stress-strain, material density, gas cumulation, etc…)} given a certain amount of DPA
  - \textit{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
    • Unknown 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** $E_n \leq 20$ MeV (group-wise) → Calculate the NIEL from NJOY
  - **Low energy** $E_n \leq 20$ MeV (point-wise) → Calculate the recoil if possible. Treat recoil as a “normal” charged particle/ion