Radiation load studies for SC solenoids near the production target

International MUON Collider Collaboration

General remarks on:
- Quench, rad damage
- Predictive ability of codes

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with input from several CERN colleagues
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- Disclaimer:
  - These slides were compiled on short notice. They are certainly not complete and don’t give a comprehensive summary.
  - I am aware that others worked on this subject in the past – apologies if no due credit is given to all the previous work.

Superconducting (SC) solenoids near target

- In order to capture pions and decay muons, SC solenoids are needed around/downstream the target
  - +/-20T, with tapering down to few T
- Vicinity of the target intrinsically implies a high radiation load which needs to be carefully studied

Superconducting (SC) solenoid - effects of radiation load

- Instantaneous effect due to heating: magnet becomes resistive (quench)
  - Total power deposition in magnet cold mass ⟺ Cryo capacity
  - Local power density (&gradient) in coils
- Cumulative radiation damage affecting magnet lifetime
  - Dose (organic materials like insulators)
  - DPA (superconductor)

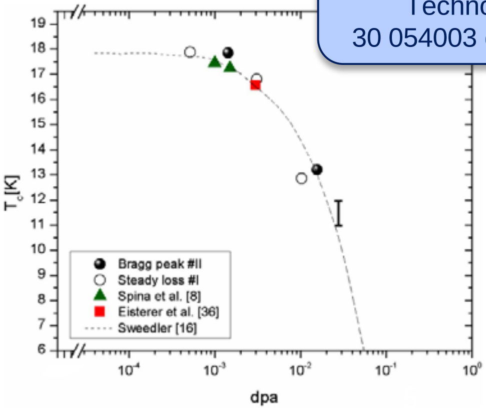
Acceptable limits can depend on magnet technology (NbTi, Nb3Sn, HTS)

Shielding design needs to account for all aspects

Superconducting (SC) solenoid
- acceptable limits for radiation-induced effects

- It is key to establish the acceptable limits for radiation-induced effects since this impacts the shielding design
- For illustration – limits (order of magnitude) assumed for shielding design of Nb3Sn magnets in HL-LHC:
  - Local power density O(few 10 mW/cm³)
  - Dose (insulator) O(few 10 MGy)
  - DPA (superconductor) O(few 10^{-3} DPA)

R. Flükiger et al. Supercond. Sci. Technol. 30 054003 (2017)



Radiation load to solenoid - some bold scaling: is quenching a driving design factor?

- Let's naively take the Nb3Sn limits* for HL-LHC magnets
- Hypothetical scenarios:
  - Magnet shall survive 10 years (200 days of operation per year)
    - In order to stay below O(10 MGy) the power density needs to stay below O(0.5 mW/cm^3) ⇒ well below quench level
  - Magnet is exchanged every year (less shielding, smaller aperture)
    - In order to stay below O(10 MGy) the power density needs to stay below O(5 mW/cm^3) ⇒ probably still below quench level

In such cases, total power evacuation & cumulative rad effects drive shielding design

*For max allowed dose this seems reasonable, but the minimum quench power density depends on coil specifics and operating conditions (e.g. current) – would need more detailed studies.

Radiation load to solenoid - some bold scaling: is quenching a driving design factor?

- The limits for quench/rad damage have to be scrutinized
  - Quench due to local power deposition density must still be considered in the global picture
- It is crucial to closely collaborate with magnet experts
  - Electro-thermal simulations needed to quantify quench margin for such high-field solenoids
  - Can we possibly expect higher margins with respect to radiation damage in future magnet developments?

Shielding design is part of a multi-disciplinary and multi-parameter optimization problem

Drive beam parameters

Target technology
Solid, powder, liquid

Radiation leakage

Engineering design and integration
Target, shielding, cooling, cryostat, supports, …

Coil technology
NbTi, Nb3Sn, HTS

Quench margin, damage level

Peak field, aperture

Shielding
Material, thickness

Evidently this is a very simplified view…

Production yield, capture

Previous Monte Carlo studies for heat load and radiation damage on solenoid

- Mainly based on MARS (+MCNP) and FLUKA
- Studies for muon collider and neutrino factory target stations:
  - N. Mokhov et al. “Target and Collection Optimization for Muon Colliders” AIP Conference Proceedings 372, 61 (1996).
  - X. Ding et al. “A pion production and capture system for a 4 MW target”, IPAC’10, Kyoto, Japan, 2010.
  - N. Souchlas et al., “Energy Deposition within Superconducting Coils of a 4-MW Target Station”, TUP179, PAC11.
  - J.J. Back et al. “Particle production and energy deposition studies for the neutrino factory target station” Phys. Rev. STAB 16, 021001 (2013).
  - J.J. Back “Energy deposition studies for the Neutrino Factory target station” JINST 6 P06002, 2011.
  - K.T. McDonald et al. “Energy deposition in the target system of a muon collider/neutrino factory” IPAC14, Dresden, Germany, 2014.
  - N. Souchlas et al.,“Energy Flow and Deposition in a 4-MW Muon-Collider Target System”, IPAC12 New Orleans, 2012.

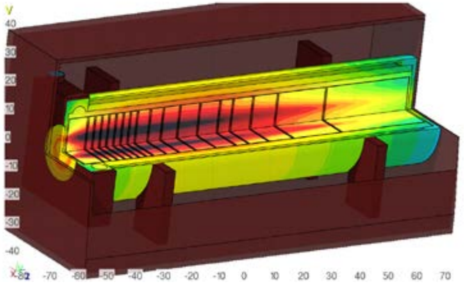
List of references is certainly far from complete

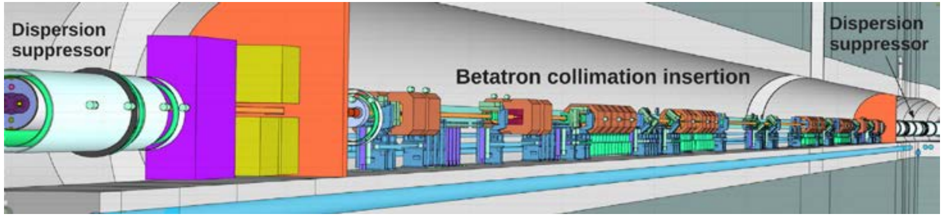
Provide already some useful insight

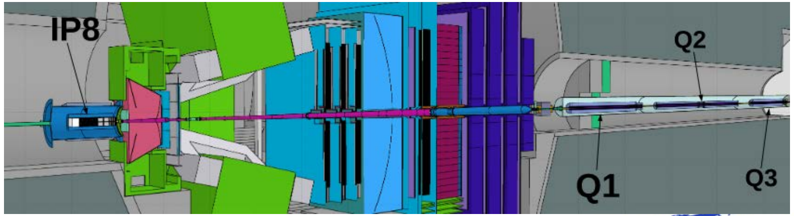
Radiation load calculations
- use of FLUKA at CERN

https://fluka.cern

- FLUKA is used for a large variety of CERN machines and facilities (from targetry studies to beam losses in present and future colliders)
  - Energy deposition on target and magnets
  - Radiation damage (DPA and gas production)
  - Particle yield optimization
  - Radiation field and background characterization
  - Radiation to electronics
  - [Radiation Protection aspects by HSE-RP with the same tools and models]





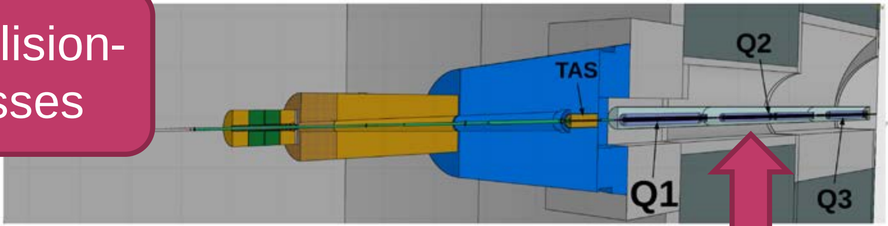


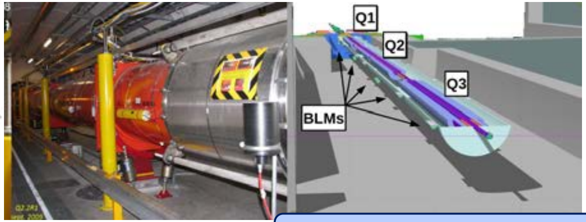
How much can we trust radiation load calculations for SC magnets?

- Had the opportunity to extensively validate FLUKA energy deposition simulation in the last two LHC runs
  - Dose measured in vicinity of SC magnets (beam loss monitors)
  - Energy deposition in NbTi coils for quench experiments and operational beam losses – comparison with electro-thermal models
- Evidently, the scenario (and energy) is different for a muon collider target, but the results still give us confidence about the achievable accuracy

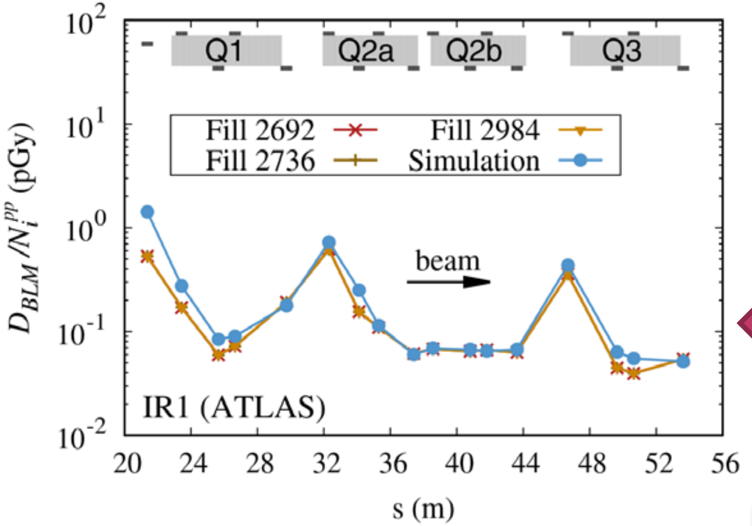
Experience with FLUKA heat load calculations for SC magnets (NbTi) in the LHC

Example: collision-induced losses





F. Cerutti, M. Sabate



Total power deposition in cold mass of final focus quadrupoles (13 TeV, 10^{34} $cm^{-2}s^{-1}$):

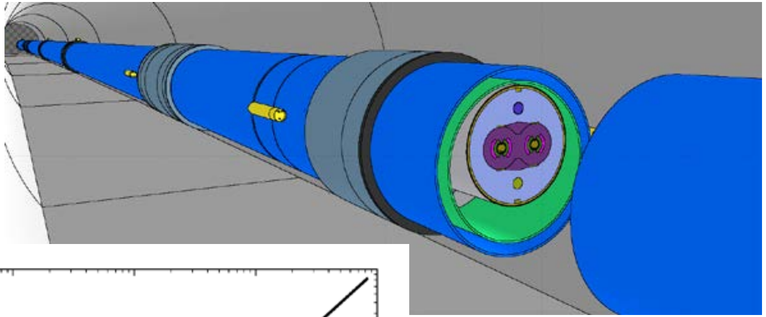
- Simulation (FLUKA): 125 W
- Measurement (by cryo group): 115-135 W

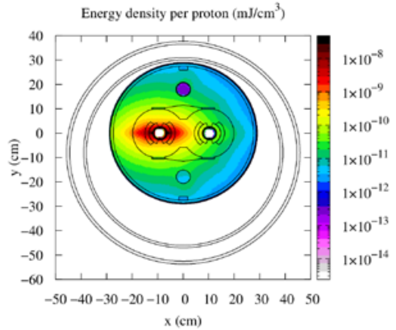
Dose in beam loss monitors outside of magnets: agreement generally within a few 10%

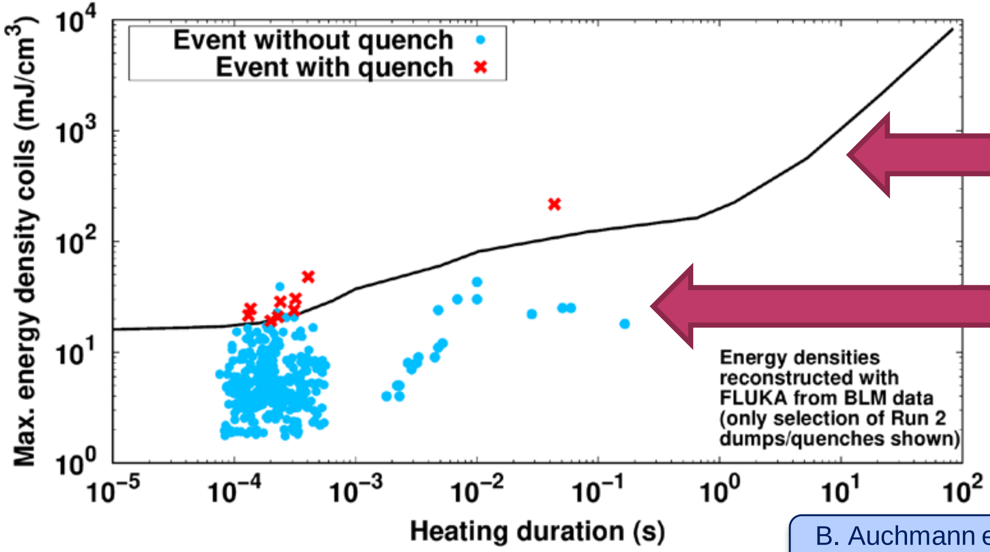
A. Lechner et al., Phys. Rev. Accel. Beam (22), 071003, 2019.

Experience with FLUKA heat load calculations for SC magnets (NbTi) in the LHC

Example: beam loss by µm-sized obstacles (e.g. dust)







Black line = quench level predicted by electro-thermal calculations

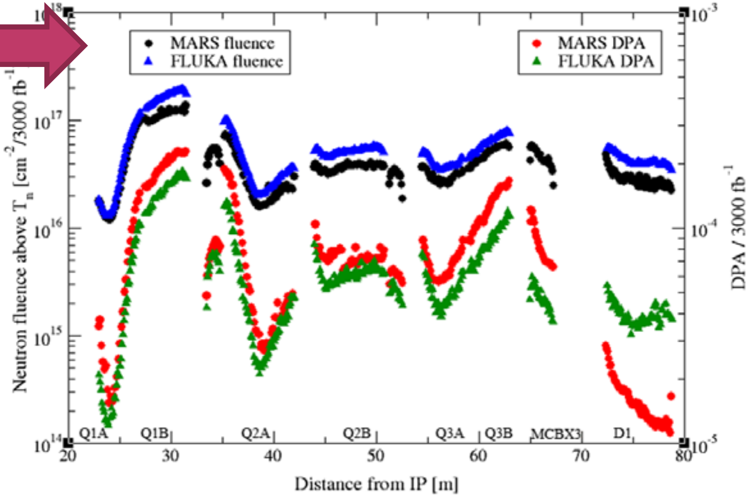
Points= energy density in SC coils reconstructed with FLUKA (each point is one loss event)

B. Auchmann et al., Phys. Rev. Accel. Beam (18), 061002, 2015.
L. Bottura et al., Phys. Rev. Accel. Beam (22), 041002, 2019.

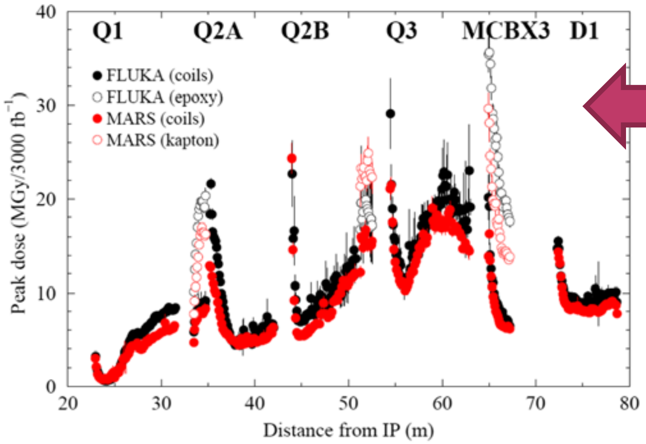
Comparison of FLUKA and MARS for SC magnet coils (Nb3SN) in HL-LHC

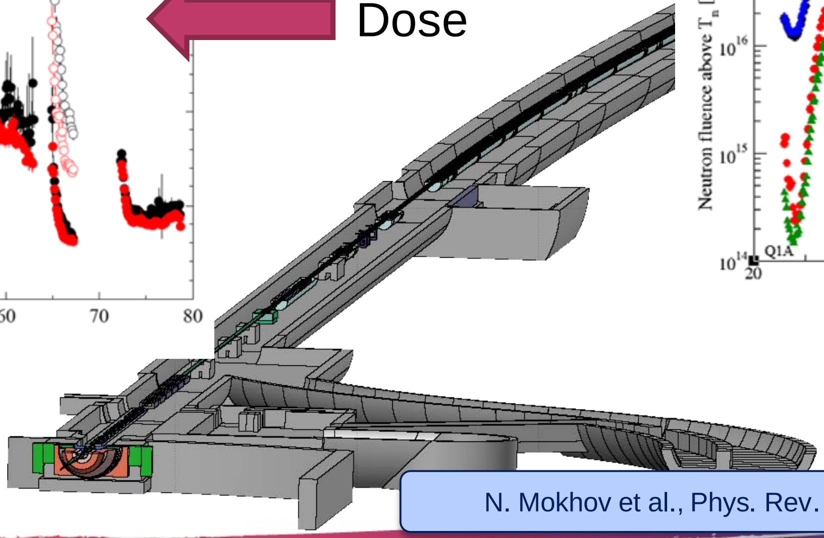
Example: collision-induced losses

DPA



Dose





N. Mokhov et al., Phys. Rev. STAB (18),051001 (2015)

Conclusions

- Any new target/shielding design studies depend on a close collaboration with magnet experts
  - Magnet technology? Review limits for quench and long-term radiation damage
  - Design needs to be an iterative process (field quality, aperture vs shielding thickness)
- Predictive ability of shower simulation codes
  - Experience with FLUKA at CERN (for other scenarios) gives a good confidence in radiation load predictions to magnets
  - Still, suitable engineering margin to be accounted, in particular for point-like quantities (e.g. power density in coils)

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Thank you
For your attention