Particle shower simulations for LHC quench tests: methodology, challenges and selected results

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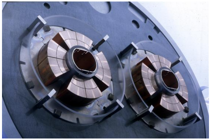
on behalf of the many people contributing to the simulation analysis of quench tests:

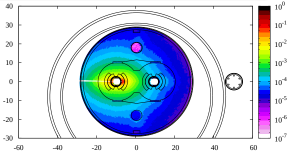
B. Auchmann, T. Baer, C. Bracco, R. Bruce, F. Cerutti, V. Chetvertkova, L.S. Esposito, A. Ferrari, P.P. Granieri, W. Höfle, A. Mereghetti, A. Priebe, S. Redaelli, B. M. Salvachua, M. Sapinski, N.V. Shetty, L. Skordis, A. Verweij, V. Vlachoudis, J. Wenninger, D. Wollmann

Workshop on Beam-Induced Quenches

Sept 15$^{\mathrm{th}}$, 2014

All quench tests were analysed by means of FLUKA, and a few also with Geant4 by colleagues from BE/BI (A. Priebe et al.)



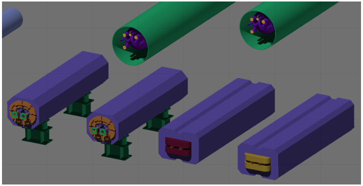


FLUKA is the tool regularly used at CERN to perform LHC beam-machine interaction simulations in the context of

- machine protection
- collimation
- high-luminosity upgrade
- design studies (dumps, absorbers, etc.)
- radiation to electronics (R2E project)
- activation
- controlled beam loss experiments (quench tests)
- ...

Types of beam losses in the LHC typically studied with FLUKA – normal, accidental and artificially induced:

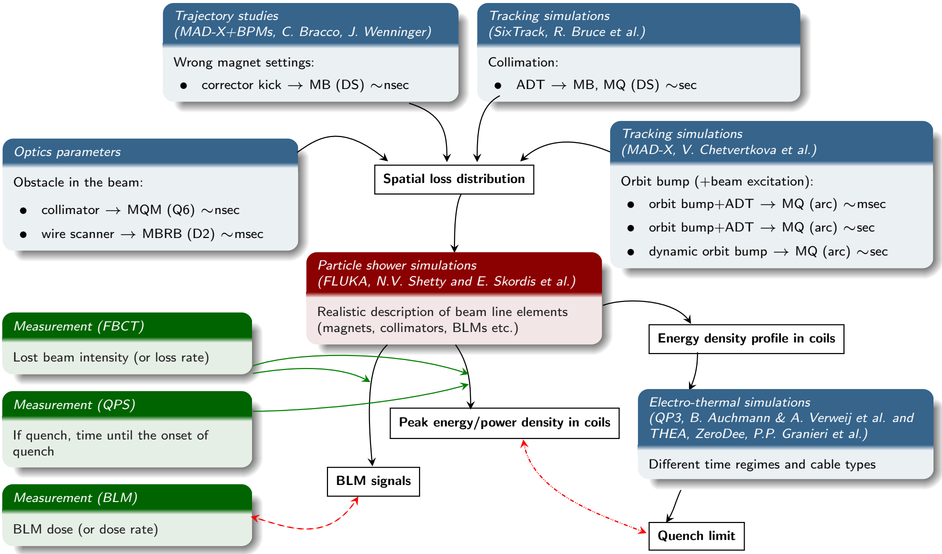
- luminosity production in experiments
- halo collimation
- residual gas in vacuum chamber
- dust particles falling into beam
- injection and dump failures
- deliberately generated losses (MDs)
- ...



modular: FLUKA element database (magnets, colls, etc.)

Contents

LHC quench tests (2008–2013): recap of the (simulation) analysis chain



Measurement input to tracking simulations (e.g. ADT gain) or to electro-thermal simulations (e.g. time profile of BLM signal) not shown in illustration.

Overview of simulations and their complexity

Category	Loss generation (energy, duration)	Source term for shower simulations	From source location to magnet(s) of interest
Kick	Inject and kick (450 GeV, ∼nsec)	Impacts on MB beam screen	Within same magnet
Obstacle	Inject and dump (450 GeV, ∼nsec)	Impacts on collimator	Dozens of meters of beam line
	Wire scanner (3.5 TeV, ∼msec)	Inelastic collisions in fibre	Dozens of meters of beam line
Orbit bump	Orbit bump+ADT (4 TeV, ∼msec)	Impacts on MQ beam screen	Within same magnet
	Orbit bump+ADT (4 TeV, ∼sec)	Impacts on MQ beam screen	Within same magnet
	Dynamic orbit bump (3.5 TeV, ∼sec)	Impacts on MQ beam screen	Within same magnet
Collimation	Collimators+ADT (4 TeV, ∼sec)	Inelastic collisions in IR7 collimators	Hundreds of meters of beam line

Color coding = complexity of deriving impact/loss distribution

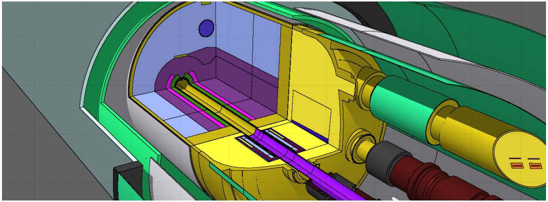
Color coding = complexity of geometry model

Green = simple; Orange = intermediate; Red = complex

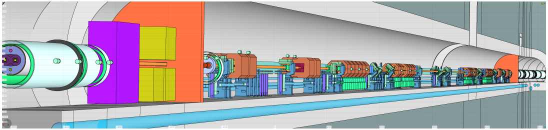
Contents

FLUKA geometry models for shower simulations

Realistic 3D geometry models of accelerator components:

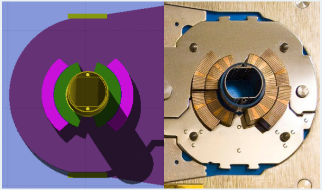


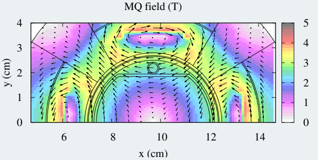
From single magnets to hundreds of meters of beamline:



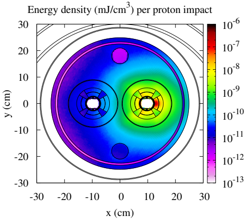
Magnet models

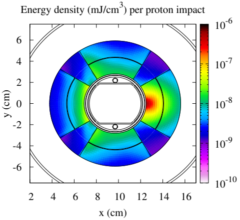
- Include beam screen, cold bore, coils, collars, insulators, yoke, cold mass shell, thermal shields and cryostat
- The coils are modelled as a homogeneous material mixture of superconductor, copper stabilizer, insulator (Kapton), and liquid helium
  - Examples of effective coil densities: ρ(MB)=7.2 g/cm^3, ρ(MQ)=6.9 g/cm^3
- Realistic description of magnetic field





Calculation of energy/power density in superconducting coils





Peak energy density (fast regime):

$$\varepsilon_p = \varepsilon_{i,j,k}\Big|_{max} \times N$$

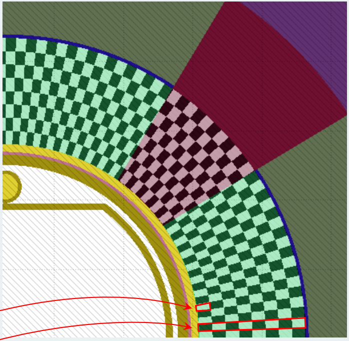
Peak power density (steady-state regime):

$$\omega_p = \varepsilon^{\bar{r}}_{j,k}\Big|_{max} \times \frac{\mathrm{d}N}{\mathrm{d}t}$$

- $\varepsilon_{i,j,k}$: simulated energy density in bin i,j,k of cylindric mesh (r, ϕ, z)
- $\varepsilon^{\bar{r}}_{j,k}$: radial average over coil width, i.e. $\sum_i \varepsilon_{i,j,k} \cdot V_{i,j,k} / \sum_i V_{i,j,k}$, where $V_{i,j,k}$ is the volume of bin i,j,k
- $\mathrm{d}N/\mathrm{d}t$ and N: measured proton loss rate or total number of protons lost†

Mesh

- Energy density distribution in coils is calculated by superimposing a cylindric mesh on geometry model
- Typical bin sizes:
  - Δr=∼2–3 mm, $\Delta\phi$=2° and Δz=∼10 cm

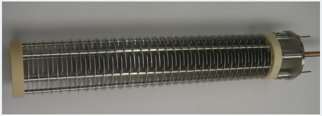


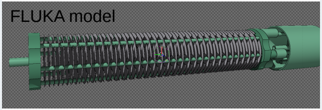
† *Except for quench test with wire scanner, where the number of interactions is calculated analytically.*

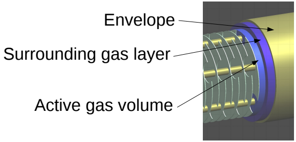
Modelling BLMs

LHC Beam Loss Monitors

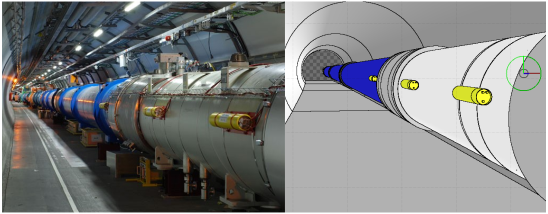
- Ionization chambers filled with $\sim$1500 cm^3 nitrogen gas at 1.1 bar
- FLUKA geometry model accurately reproduces circular electrodes, alumina spacers and stainless steel housing



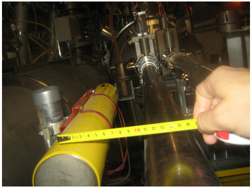


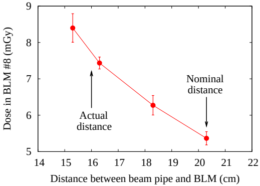


Placement in accelerator model:

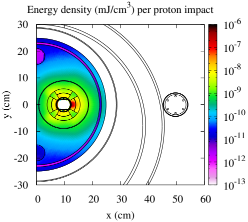


Accurate positioning can matter:





Calculation of BLM signals



BLMs typically measure the peripheral part of the shower:

→ dose generally orders of magnitude smaller than in coils

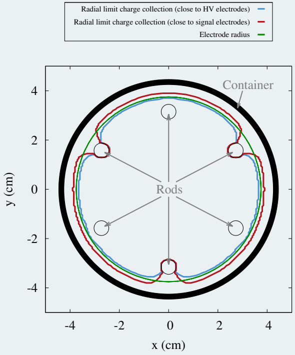
BLM dose or dose rate:

$$D = \frac{E_p}{m_{gas}} \times N \quad \text{or} \quad \frac{dD}{dt} = \frac{E_p}{m_{gas}} \times \frac{dN}{dt}$$

- E_p: simulated energy deposition in the (cylindric) gas volume between the 61 electrodes per impacting proton (or per inelastic collision)
- m_{gas}: nominal mass of the BLM gas between electrodes (ρ=1.2·10^{-3} g/cm^3, V=1524 cm^3)
- dN/dt and N: measured proton loss rate or total number of protons lost

Charge collection efficiency

- In reality, charges can also be collected from radii larger than the electrode radius, while not all charges in the gas volume between electrodes are collected
- Detailed simulation studies for different LHC beam loss scenarios indicated that these two contributions more or less compensate



Collection efficiency map by courtesy of F. Pietropaolo.

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Example I

Quench of MB.B10R2 after pilot bunch (Beam 1) was kicked vertically with 750 μrad in MCBCV.9R2 due to wrong corrector setting during aperture scan in IR2 (MCBCV.9R2 $\leftrightarrow$ MB.B10R2: $\sim$25 m).

Category	Loss generation (energy, duration)	Source term for shower simulations	From source location to magnet(s) of interest
Kick	Inject and kick (450 GeV, $\sim$nsec)	Impacts on MB beam screen (C. Bracco&J. Wenninger)	Within same magnet

Color coding = complexity of deriving impact/loss distribution

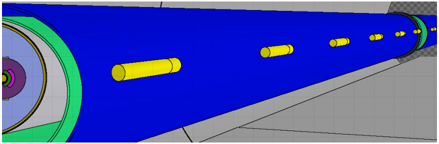
Color coding = complexity of geometry model

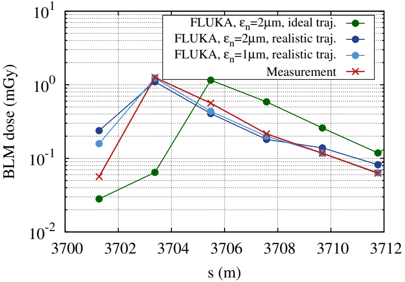
Inject and kick (2008) → quench of MB (450 GeV, ∼nsec)

Normalization

From BCT, integrated over entire loss event:

$$N = 2 \times 10^9 \text{ protons}$$





Beam trajectory:

- Reconstructed with MAD-X by matching against BPM readings (deviation from ideal orbit at injection)
- Some uncertainty remains

Estimated orbit parameters at corrector:

x (mm)	x' (µrad)	y (mm)	y' (µrad)
-1.3	-71	3	-40

BLM dose *D*:

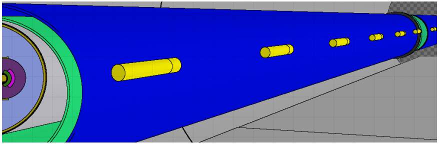
- Pattern very sensitive to y,y' at corrector
- Not much sensitive to x,x' at corrector
- After trajectory reconstruction:
  - **all measured signals (except for most upstream BLM) reproduced within 20%**
  - signal in most upstream BLM determined by backscattered particles: very sensitive to exact impact location

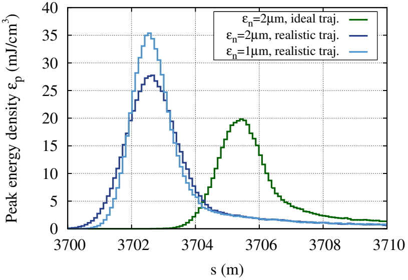
Inject and kick (2008) → quench of MB (450 GeV, ∼nsec)

Normalization

From BCT, integrated over entire loss event:

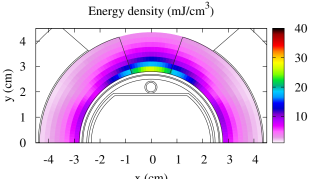
$$N = 2 \times 10^9 \text{ protons}$$



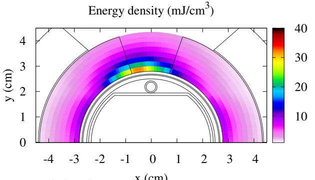


Peak energy density ε_p:

- Very sensitive to emittance ε_n: realistically it was $<1\mu$m, but exact value not known
- Very sensitive to x,x' at corrector: horiz. offset moves peak further into coils
- Moderately sensitive to y,y' at corrector: determines longitudinal position of peak, but less its absolute value



ε_n=2µm, ideal traj.



ε_n=2µm, realistic traj.

Example II

Quench of MBRB.5L4 due to losses induced by wire scanner after several attempts with different wire speeds (MBRB.5L4 $\leftrightarrow$ wire scanner: $\sim$33 m).

Test designed and carried out by M. Sapinski et al.

Category	**Loss generation (energy, duration)**	**Source term for shower simulations**	**From source location to magnet(s) of interest**
Obstacle	Wire scanner (3.5 TeV, $\sim$msec)	Inelastic collisions in fibre	Dozens of meters of beam line

Color coding = complexity of deriving impact/loss distribution

Color coding = complexity of geometry model

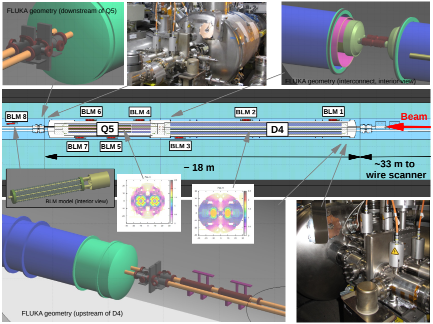
Wire scans (2010) → quench of MBRB (3.5 TeV, ∼msec)

Normalization

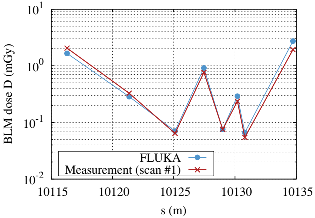
If wire speed (v_w) is constant, then one gets for the total number of protons lost (per scan):

$$N = I\frac{f_r d_w}{v_w}\left(1 - exp\left(-\frac{l_{av}}{\lambda}\right)\right) \qquad (1)$$

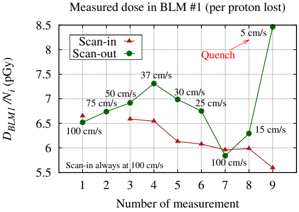
I = stored intensity, f_r = LHC revolution frequency, d_w = wire diameter, l_{av} = average path length of protons in the wire ($\sim d_w \pi/4$), and λ = inelastic interaction length.



BLM dose D: **very good absolute agreement for first scans (better than 30%).**



However, Eq. (1) no longer valid for later scans (wire oscillation, sublimation, ...):



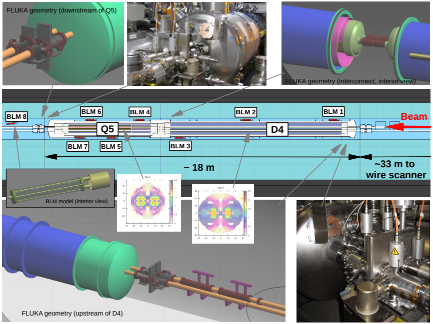
Wire scans (2010) → quench of MBRB (3.5 TeV, ∼msec)

Normalization (cont.)

To account for wire oscillations, sublimation etc. during last scan, an empirical factor f_e is introduced (derived from BLM comparison):

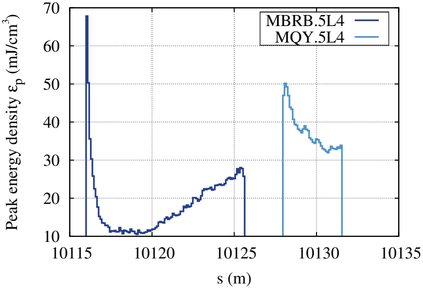
$$N = I \frac{f_r d_w}{v_w} \left(1 - exp\left(-\frac{l_{av}}{\lambda}\right)\right) f_e \qquad (2)$$

I = stored intensity, f_r = LHC revolution frequency, d_w = wire diameter, l_{av} = average path length of protons in the wire ($\sim d_w \pi/4$), and λ = inelastic interaction length.



Peak energy density ε_p:

- Includes empirical normalization factor
- Time at onset of quench not exactly known → integrating over entire loss event gives upper limit
- Maximum occurs in magnet front → some uncertainty since coil return region is very complex and not entirely modelled



Examples III and IV

Two quenches of MQ.12L6 by means of orbit bump and beam excitation with the ADT, in one case provoking millisecond losses and in the other case steady-state losses (over 20 s).

Test designed and carried out by A. Priebe and M. Sapinski et al.

Category	Loss generation (energy, duration)	Source term for shower simulations	From source location to magnet(s) of interest
Orbit bump	Orbit bump+ADT (4 TeV, ∼msec)	Impacts on MQ beam screen (from V. Chetvertkova et al.)	Within same magnet
	Orbit bump+ADT (4 TeV, ∼sec)	Impacts on MQ beam screen (from V. Chetvertkova et al.)	Within same magnet

Color coding = complexity of deriving impact/loss distribution

Color coding = complexity of geometry model

Orbit bump+ADT (2013) → 2× quench of MQ (4 TeV, ∼msec and ∼sec)

Normalization

First test (∼msec loss duration):

From BCT, integrated over entire loss event:

$$N = 8.2 \times 10^8 \text{ protons}$$

Second test (∼sec loss duration):

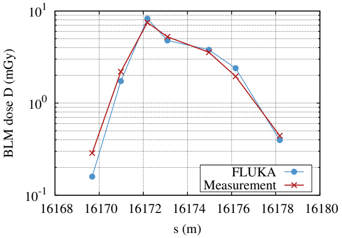
From BCT, maximum loss rate:

$$\frac{dN}{dt} =\sim 3.6 \times 10^8 \text{ protons/sec}$$

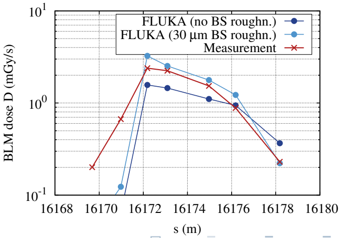
BLM dose *D*:

- Very good agreement with measurement for first test (**better than 20%** for BLMs at or downstream of loss location predicted by MAD-X)
- Some larger discrepancies remain for second test
  - even small surface roughness can significantly affect results → see Vera's talk
  - difficult to determine proton loss rate which matches BLM integration window

First test (∼msec loss duration):



Second test (∼sec loss duration):



Example V

No quench of MBs/MQs in the DS next to IR7, after ~1 MW proton impact on primary collimator (TCPs ↔ DS cell 9/11 ~500–650 m).

Test designed and carried out by LHC Collimation Team

Category	Loss generation (energy, duration)	Source term for shower simulations	From source location to magnet(s) of interest
Collimation	Collimators+ADT (4 TeV, ~sec)	Inelastic collisions in IR7 collimators (by R. Bruce et al.)	Hundreds of meters of beam line

Color coding = complexity of deriving impact/loss distribution

Color coding = complexity of geometry model

Collimators+ADT (2013) → no quench (4 TeV, ∼sec)

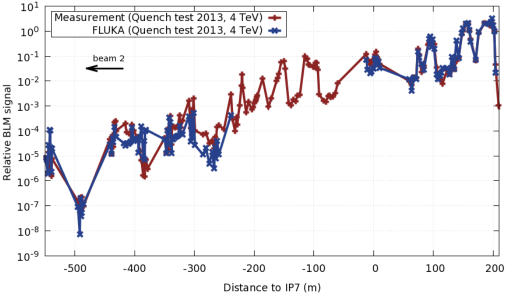
BLM dose D:

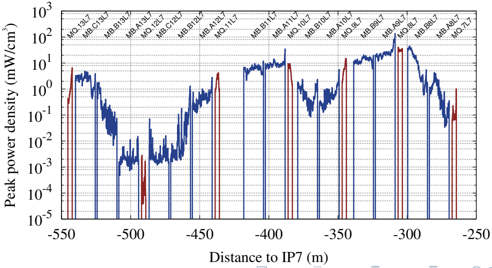
- An overall good agreement is achieved over hundreds of meters of beamline
- However measured BLM signals are locally underestimated by a factor 3–4 at the most exposed magnet

Peak power density ω_p:

- Maximum occurs at magnet front (like for other tests with distant loss location) → some uncertainty since coil return region is very complex
- Efforts to refine geometry models are presently ongoing, i.e. to improve relevant details of the IR7 FLUKA geometry, to increase the accuracy of scoring techniques for the bent MB coils, etc.

Note: exceptionally the rightern plot shows the power deposition in coils at the inner coil edge and not the radial average over the coil width.





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Summary and conclusions

Agreement with BLM signals (not all results were shown):

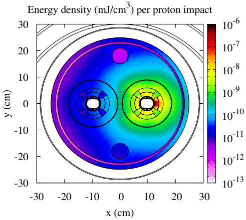
- the controlled beam loss conditions of the quench tests provided us an excellent opportunity to validate our energy deposition calculations in the TeV regime
- for four of the seven considered tests, we were able to achieve an absolute agreement better than 20–30% in BLMs downstream of loss location
- in one case, no comparison was possible since BLMs saturated
- for the remaining tests, BLMs generally agree within a few factors at the most exposed magnet (challenging simulations!)

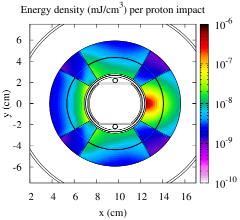
Energy/power density in superconducting coils:

- Particle shower simulations are an essential part of the analysis chain as the energy deposition in magnet coils cannot be measured directly
- Most tests $\rightarrow$ several attempts under different conditions (intensity, loss rate, magnet current)
  - Depending if magnet quenched or not, shower simulation provide a lower or upper bound to the quench level

BACKUP

Lower and upper limit of energy/power density in superconducting coils





Peak energy density (fast regime):

$$\varepsilon_p = \varepsilon_{i,j,k}\Big|_{max} \times \int_{t_0}^{t_1} \frac{\mathrm{d}N(t')}{\mathrm{d}t}\mathrm{d}t'$$

Peak power density (steady-state regime):

$$\omega_p = \varepsilon^{\bar{r}}_{j,k}\Big|_{max} \times \frac{\mathrm{d}N(t_1)}{\mathrm{d}t}$$

- $\varepsilon_{i,j,k}$: simulated energy density in bin i,j,k of cylindric mesh (r, ϕ, z)
- $\varepsilon^{\bar{r}}_{j,k}$: radial average over coil width, i.e. $\sum_i \varepsilon_{i,j,k} \cdot V_{i,j,k} / \sum_i V_{i,j,k}$, where $V_{i,j,k}$ is the volume of bin i,j,k
- $\mathrm{d}N/\mathrm{d}t$: measured proton loss rate†

Most tests → several attempts under different conditions (intensity, loss rate, magnet current) until magnet quenched

Attempts resulting in no quench:

- t_1: time stamp at the end of losses (or at the maximum loss rate in case of steady-state losses)
- Predicted ε_p/ω_p yields a lower limit for quench level

Attempts resulting in quench:

- t_1: time stamp at the onset of quench
- In principle, predicted ε_p/ω_p yields an estimate of the quench level,
  - → however time stamp at the onset of quench not always sufficiently well known (±5 ms)
  - → by integrating over entire event, one can get an upper limit

† *Except for quench test with wire scanner, where the number of interactions is calculated analytically.*