FLUKA for assessing machine protection strategies in high energy particle accelerators

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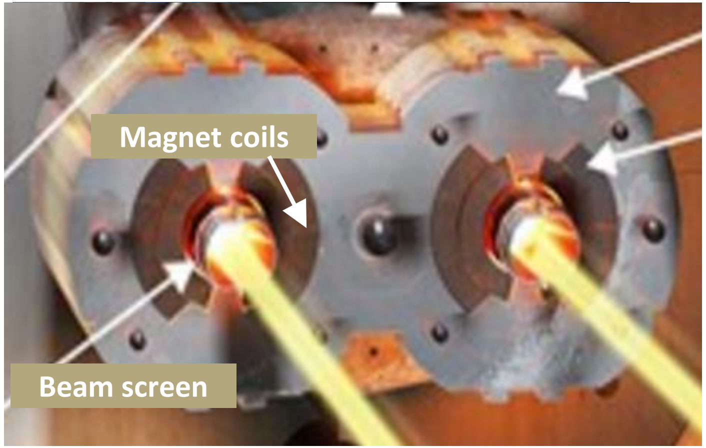
Machine protection



- Accelerator operation → beam losses → energy deposition in the accelerator components

- High energy accelerators: Super Proton Synchrotron (CERN), Tevatron (FermiLab), Relativistic Heavy Ion Collider (BNL), Large Hadron Collider (CERN)…

- Even small beam losses can imply high energy deposition
  - Affects accelerator operation (losing beam)
  - Can lead to physical damage of the equipment

  Machine protection

- Superconducting magnets: dipoles, quadrupoles... kinds of damage
  - Permanent damage (~100 J/cm^3)
  - Quench (some m J/cm^3)

  Nominal LHC proton beam at 7Z TeV: 362 x10^6 J

- Magnet quench: change of state from superconductivity to normal conductivity when temperature, magnetic field or current density rise over a critical value. Triggered by high amount of energy deposited in the coils → quench level (in mW/cm^3 for beam losses >5s, steady state)

A significant part of machine protection in high energy accelerators focuses on protecting superconducting magnets from beam losses that would deposit enough energy to trigger a quench.

Magnet protection from quenching

Magnet quench levels: power deposition in magnets cannot be measured directly!

Quench levels are estimated with model calculations and cross-checked with quench tests (controlled beam loss experiments)

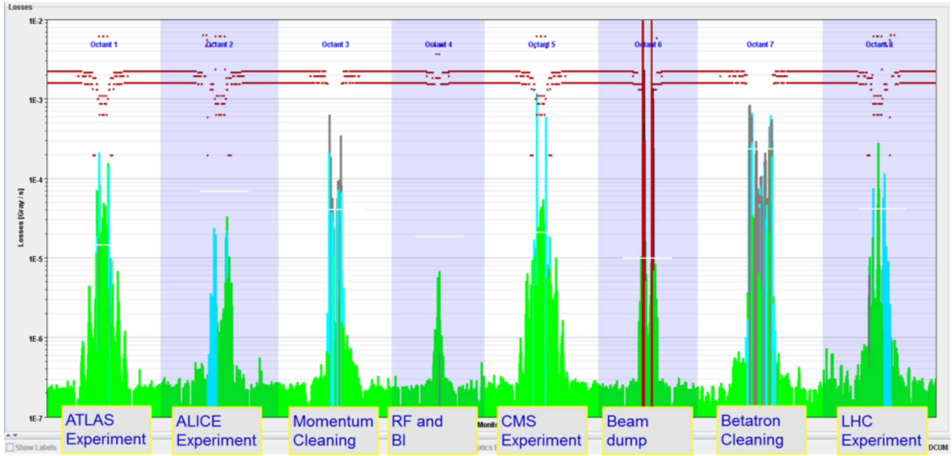
★ **Particle shower simulations → FLUKA**

Position of the beam losses: BLMs

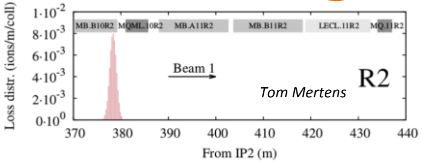
Beam Loss Monitors (BLM) signals → only experimental measure to analyze beam losses.

Lightly pressurized ionization chambers.

Trigger a beam extraction system if losses go over a threshold.



Assessing machine protection strategies: FLUKA

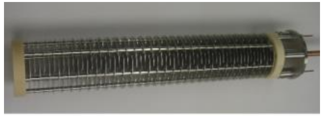


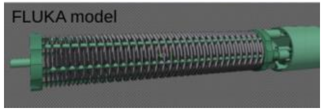
Information on beam losses
Spatial distribution of the particles, position on the accelerator and energy spread(MAD-X, SixTrack)

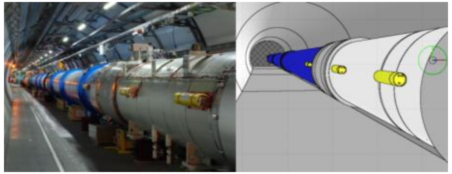
➕ **Creating a realistic geometry in FLUKA**

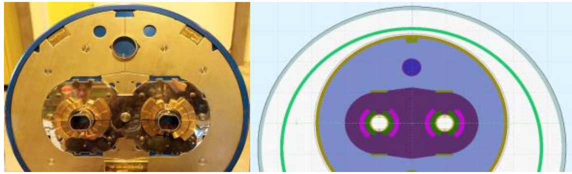
FLUKA beam: SOURCE card

A.Lechner, Workshop on Beam-Induced Quenches 2014





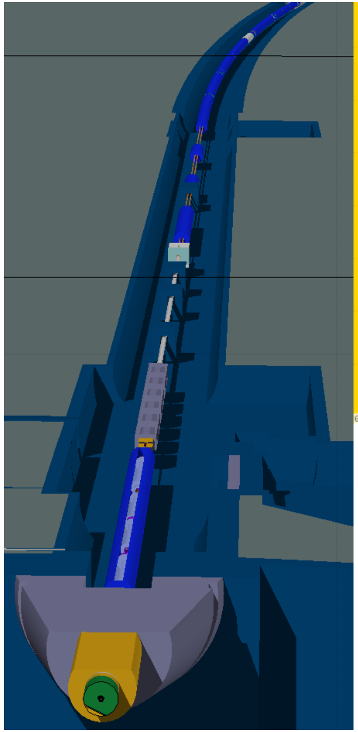


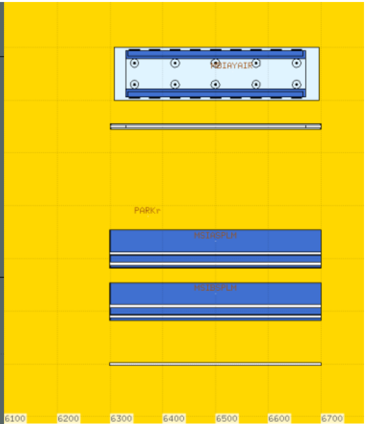


FLUKA settings: geometry

Complex geometries → Lattices

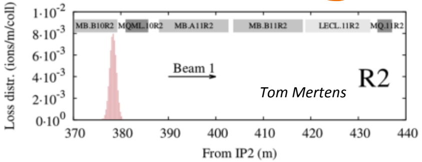
Every needed element of the accelerator beam line is defined (bodies, regions, materials) in the FLUKA geometry only once in the 'parking' region.
'Copies' of these elements (lattices) are transported using ROT-DEFI cards to the correct beam line position.
Every time particles hit a lattice region, they get transported by the ROT-DEFI card to the parking, interact with the actual element of the accelerator line and get transported back to the beam line.

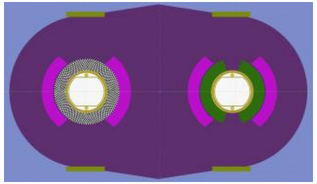




A. Mereghetti

Assessing machine protection strategies: FLUKA





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Spatial distribution of the particles, position on the accelerator and energy spread(MAD-X, SixTrack)

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Creating a realistic geometry in FLUKA

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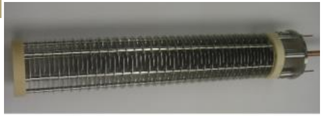
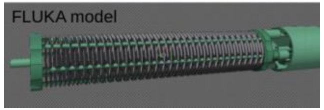
Choosing detectors and FLUKA settings
Scoring dose in BLMs, energy deposition in the coils and energy in each component

FLUKA beam: SOURCE card





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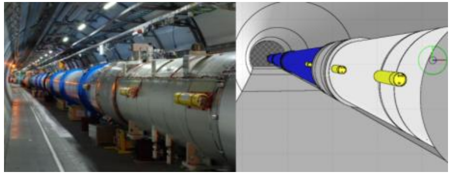
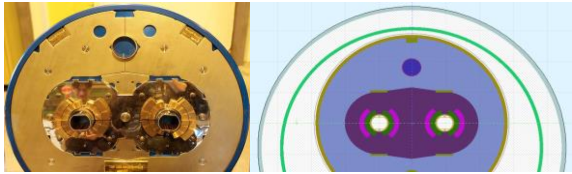




FLUKA settings: scoring

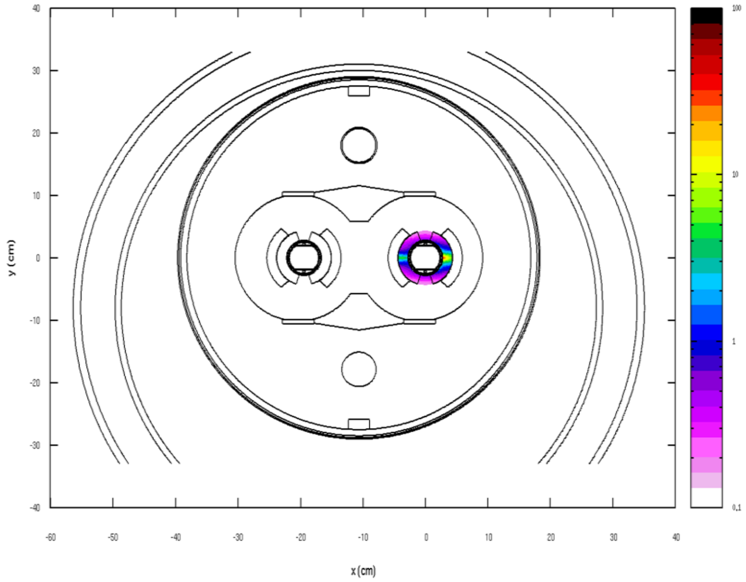
SCORING: USRBINs

★ Energy deposition in magnet coils (divided in longitudinal segments for long magnets)

Cylindrical mesh → ΔR: 0.2 cm, Δϕ: 2º, Δz: 10 cm

★ Energy deposition in all magnet body

Cylindrical mesh → ΔR: 1 cm, Δϕ: 2º, Δz: 10 cm



★ Total energy deposited per region in all regions

```
USRBIN        8.0   ENERGY    -21.0  @LASTREG    400.0   10000.0           EDpRL
USRBIN        1.0      0.0  -10000.0      1.0      1.0      1.0&
```

FLUKA settings: physics and biasing

```
DEFAULTS                                        PRECISIO
PHYSICS      12001.0     1.0     1.0            COALESCE
PHYSICS        3.0                              EVAPORAT
```

In case of a heavy ion beam

```
PHYSICS     1.0    0.1    0.15    2.0    2.0    1.0   IONSPLIT
PHYSICS     2.0                                       EM-DISSO
```

* Thresholds for secondary particle production applied to all materials: electron, positron: 1.0 MeV, photons: 0.1 MeV

```
EMFCUT     -0.001   0.0001    0.0     1.0  @LASTMAT     1.0PROD-CUT
EMFCUT     -0.001   0.0001    0.0   PARKr  @LASTREG     1.0
```

** Transport thresholds for all other particles: set to default values for PRECISIO

***Reducing the average number of secondaries produced in a collision by a factor of 0.2 in all regions

```
BIASING             0.2           1.0  @LASTREG
```

FLUKA settings: user routine customization

All user routines are compiled in the executable, some also need cards to be activated

Magfld.f→ Bmagfld.f, which includes

MAGFLD→ customized to handle MB magnetic field

MAGUSRINI→ USRINI for setting up magnetic fields just before the first source particle of an event is unloaded from stack and begins to be transported

MAGCNST→ create a constant magnetic field

MAGLOAD→ check if the magnetic field is there and if it is correctly positioned, else load it

MAGPRINT → print magnetic field values

FLUKA settings: user routine customization

Usrglo.f → called using USRGCALL card in input, used to start up the magnetic field before any other initialization is done

Comscw.f → For USRBIN over the whole MB do not score in the beam pipe and beam screen in order to evaluate the peak in the coils

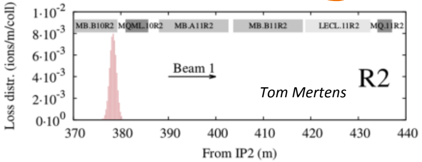
Source.f → called using SOURCE card in input, adequated to read particle distribution provided by tracking simulations and correctly place it in the geometry. The 'loaded' particle distribution is also printed in a .84 file.

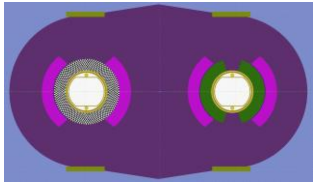
FLUKA settings: user routine customization (crosscheck impact position of the distribution)

Mgdraw.f → to generate a file where the exact impact location of each of the particles transported from the original particle distribution is printed (boundary crossing from Vacuum to material with subroutine BXDRAW)

Usrmed.f → to flag materials for generating the impact location file (only activates mgdraw when the particles cross from regions with a region number immediately higher than vacuum, exactly at boundary)

Assessing machine protection strategies: FLUKA





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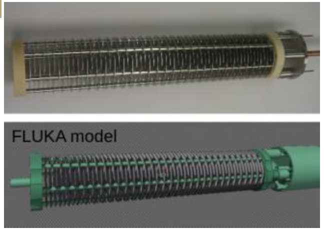

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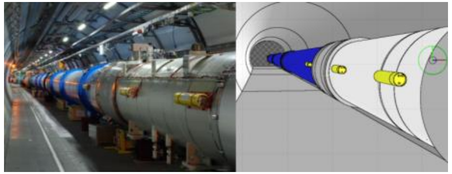
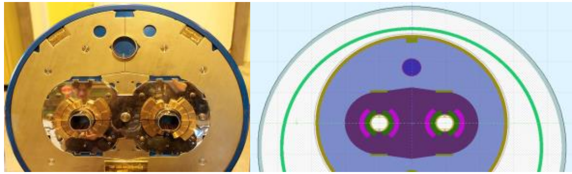
Choosing detectors and FLUKA settings
Scoring dose in BLMs, energy deposition in the coils and energy in each component

Simulations

FLUKA results: what can we learn

Scoring dose in BLMs	Scoring energy deposition in magnet coils	Scoring energy deposition in all components
Validate the loss location estimated by tracking simulations	**Estimate of quench levels**	**Evaluate if the heat load can be evacuated by the cryogenics**





Some machine protection strategies evaluated in FLUKA: ion runs in LHC (Pb-Pb)

$$\text{BFPP1: } {}^{208}Pb^{82+} + {}^{208}Pb^{82+} \longrightarrow {}^{208}Pb^{82+} + {}^{208}Pb^{81+} + e^{+}$$
$$\sigma = 281 \text{ b}, \quad \delta = 0.01235$$

Bound- Free Pair Production is the main contribution to fast Pb-Pb beam burn-off

BFPP losses deposit energy in several LHC superconducting dipoles risking to quench them

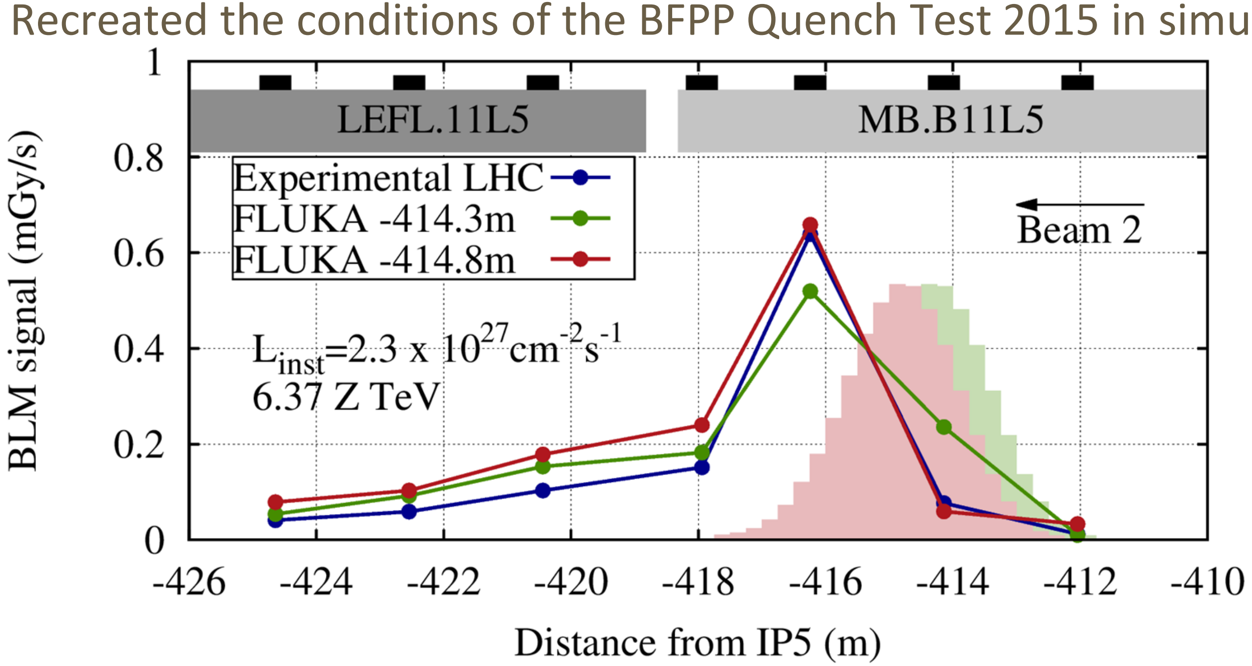
1. BFPP quench test 2015: validating loss location and estimating quench levels. Left of IP5 (CMS).

2. Displacing BFPP losses to less sensitive locations: IR1 (ATLAS), IR5 (CMS)

3. Intercepting BFPP losses with strategically installed collimators: IR2 (ALICE)

BFPP Quench Test: understanding loss locations

Recreated the conditions of the BFPP Quench Test 2015 in simulations



FLUKA successfully recreates experimental BLM signal patterns

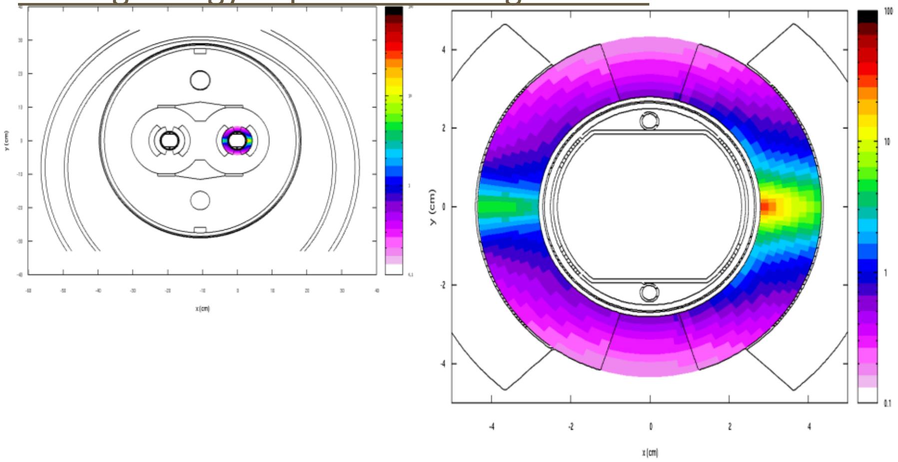
BLM signal patterns are highly sensitive to loss location

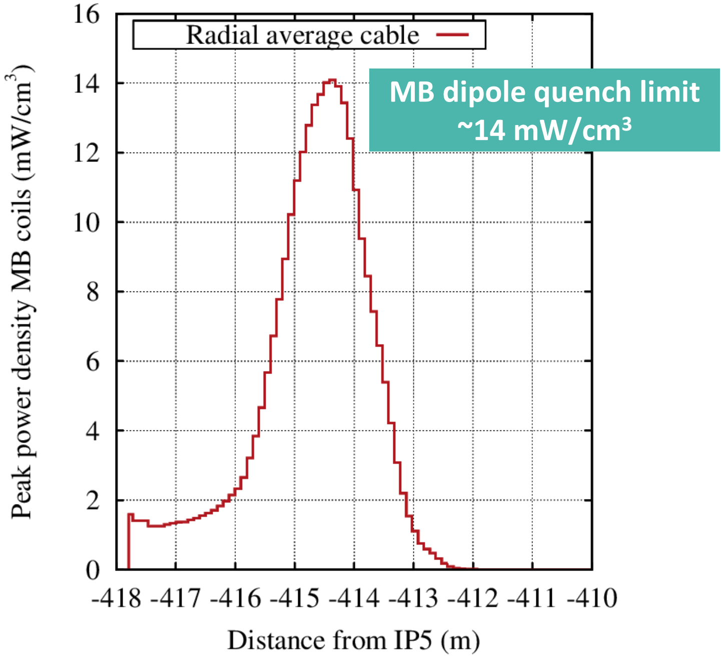
Validation of the estimated loss location

BFPP Quench Test: estimating quench levels

Recreated the conditions of the BFPP Quench Test 2015 in simulations

Scoring energy deposition in magnet coils





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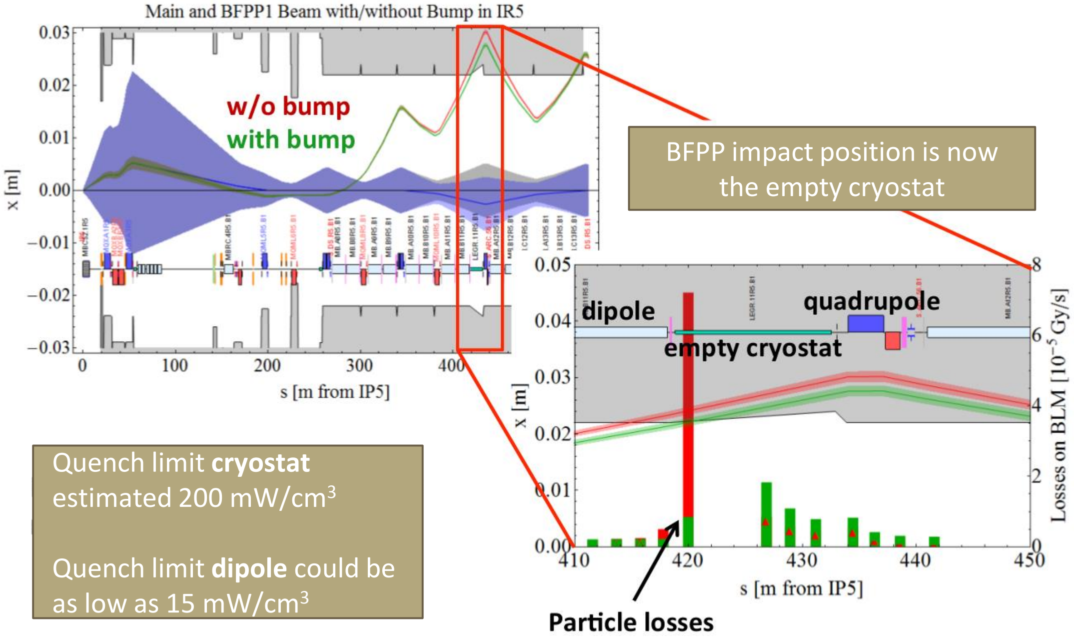
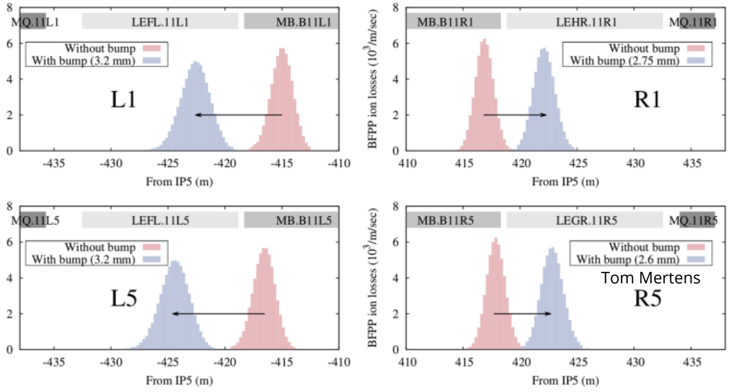
Displacing BFPP losses to less sensitive locations



BFPP impact position is now the empty cryostat



Quench limit **cryostat** estimated 200 mW/cm^3

Quench limit **dipole** could be as low as 15 mW/cm^3

M. Schaumann, ColUSM #66, 2015

Displacing BFPP losses to less sensitive locations

Scoring energy/power deposition in magnet coils: quench estimation

Cryostat (most exposed unit)
Peak power density: few mW/cm^3

Dipole
Peak power density reduced from 44 mW/cm^3 to almost negligible using bump

Quadrupole
Peak power density <2mW/cm^3.
Quench limit estimated 53mW/cm^3.

No quench risk.

Scoring energy deposition in all components: cryogenics evaluation

LHC cryogenics can evacuate ~150W (120W dynamic plus static loads) from magnet cold mass elements at 1.9K.

Total power to the cold mass significantly lower than cryogenics limit

No challenge for cryogenics.

Feasible machine protection strategy

Some machine protection strategies evaluated in FLUKA: ion runs in LHC (Pb-Pb)

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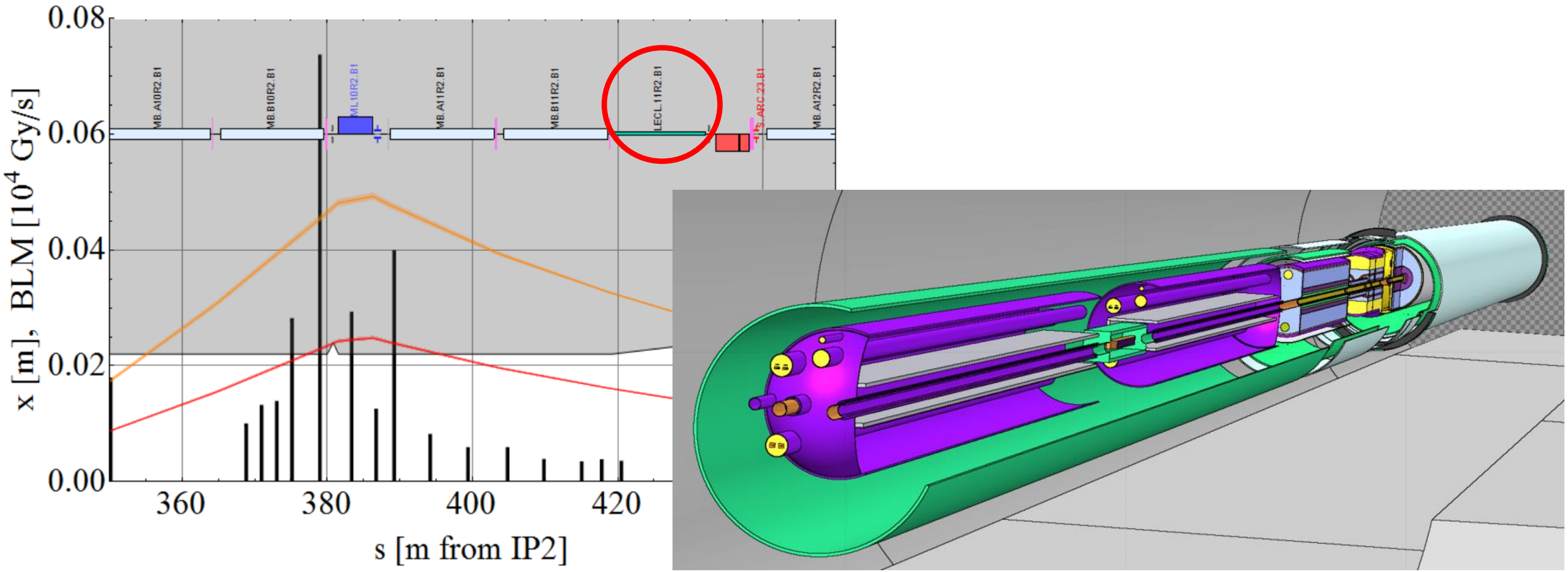
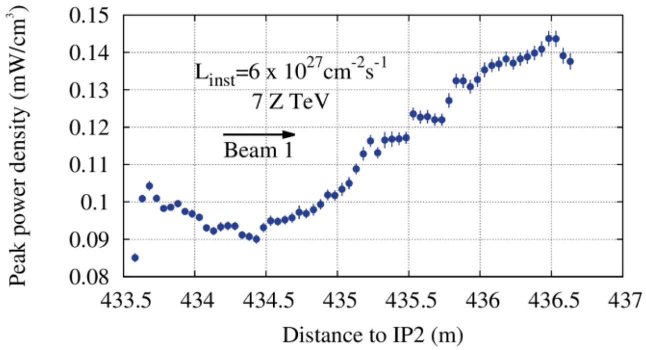
Intercepting BFPP losses with collimator



Intercepting BFPP losses with collimator



Scoring energy/power deposition in magnet coils: quench estimation

Quadrupole (most exposed unit)
Peak power density <0.15mW/cm^3.
Quench limit estimated 53mW/cm^3.

Other components
Peak power density even lower.

No quench risk.

	Total power
Quadrupole	2 W
Dipole	2 W
Collimator impacted jaw	71 W
Collimator non-impacted jaw	11 W
Collimator tank	10 W
Cryostat	16 W

No challenge for cryogenics.

Feasible machine protection strategy

Conclusions and outlooks

- A lot of the machine protection in high energy particle accelerators is for protecting superconducting magnets from beam losses that would deposit enough energy to trigger a quench.

- Power deposition in those magnet coils cannot be measured, only BLM signals are available → Particle shower simulations in FLUKA are essential

- FLUKA simulations have been proved successful in validating the loss location estimated by tracking simulations, estimating quench levels and evaluating if the heat load resulting from different machine protection strategies can be evacuated by the cryogenics, therefore serving as a very valuable tool for assessing and evaluating different machine protection strategies

Thanks for your attention!