Particle tracking for collimation studies

R. Bruce, on behalf of the LHC collimation team

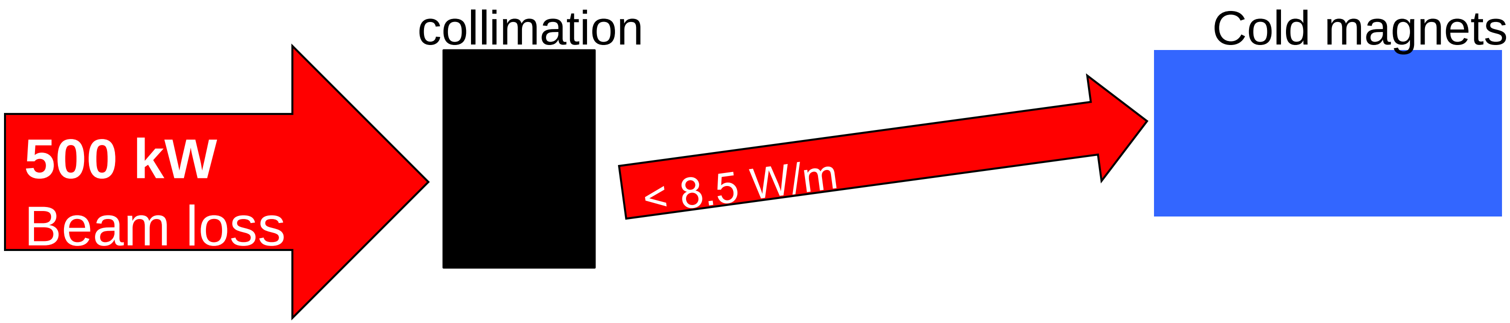
Contributions from numerous colleagues:
FLUKA team, BLM, OP

Outline

- Introduction: LHC collimation
- Brief recap of collimation quench test
- Simulation tools for tracking: SixTrack
  - Capabilities of the code
  - Assumptions and inputs
  - Simulation flow
- Simulations of the 2013 collimation quench test
- Outlook: Improvements to SixTrack

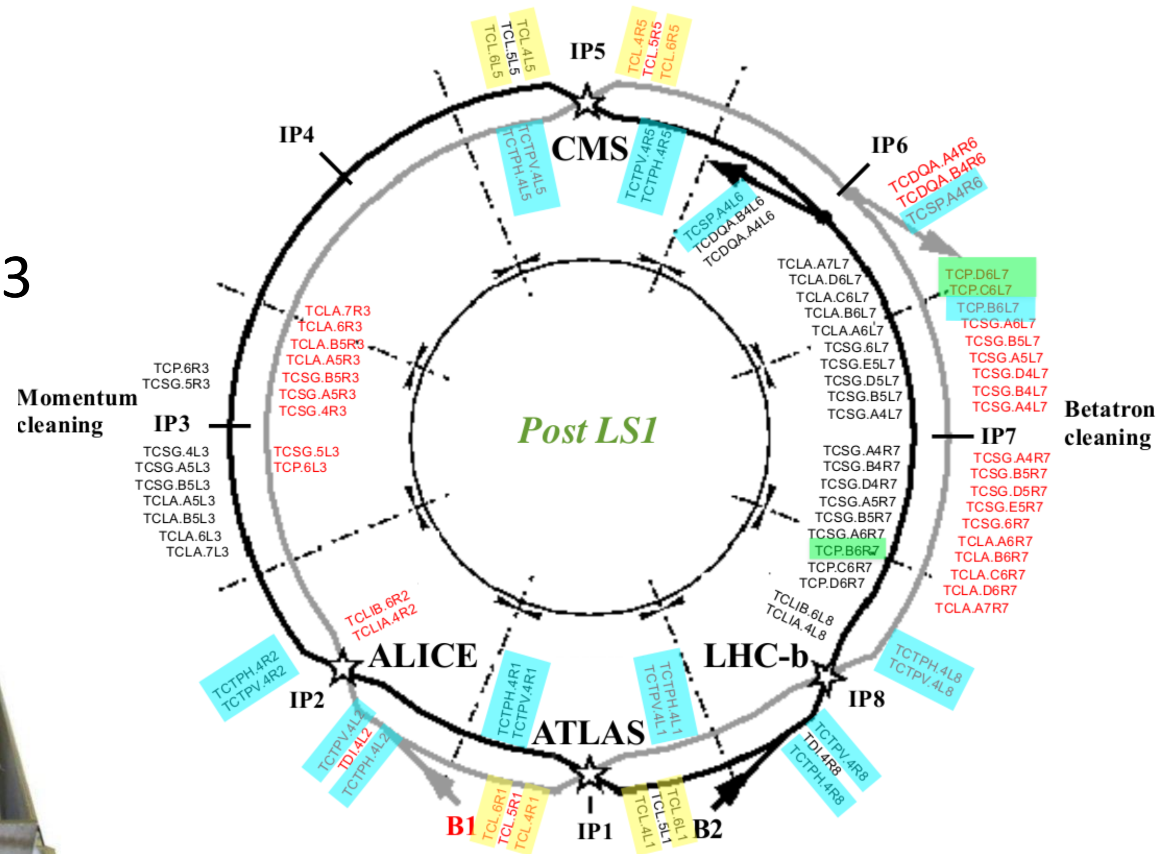
Introduction

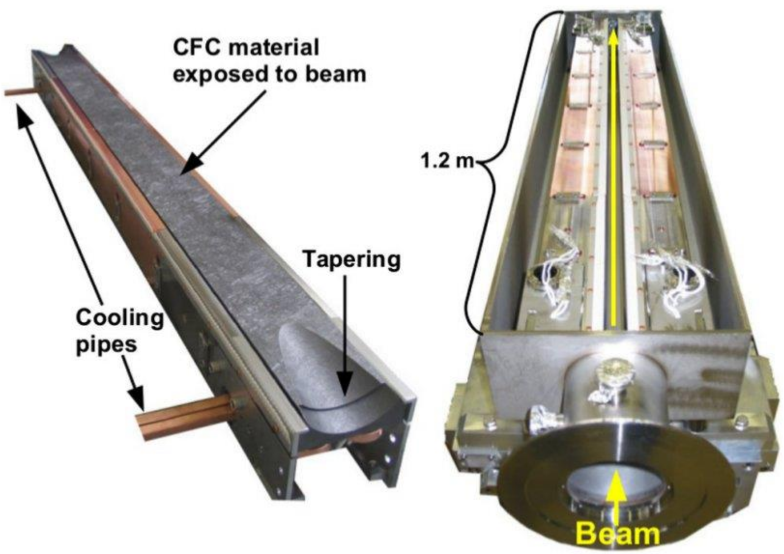
- Very high stored energy in LHC (nominal 362 MJ). Maximum specified loss rate from beam is 500 kW, while design quench limit is 8.5 W/m.
- Need a very efficient collimation system to intercept unavoidable beam losses that otherwise might quench superconducting magnets!



LHC collimation system

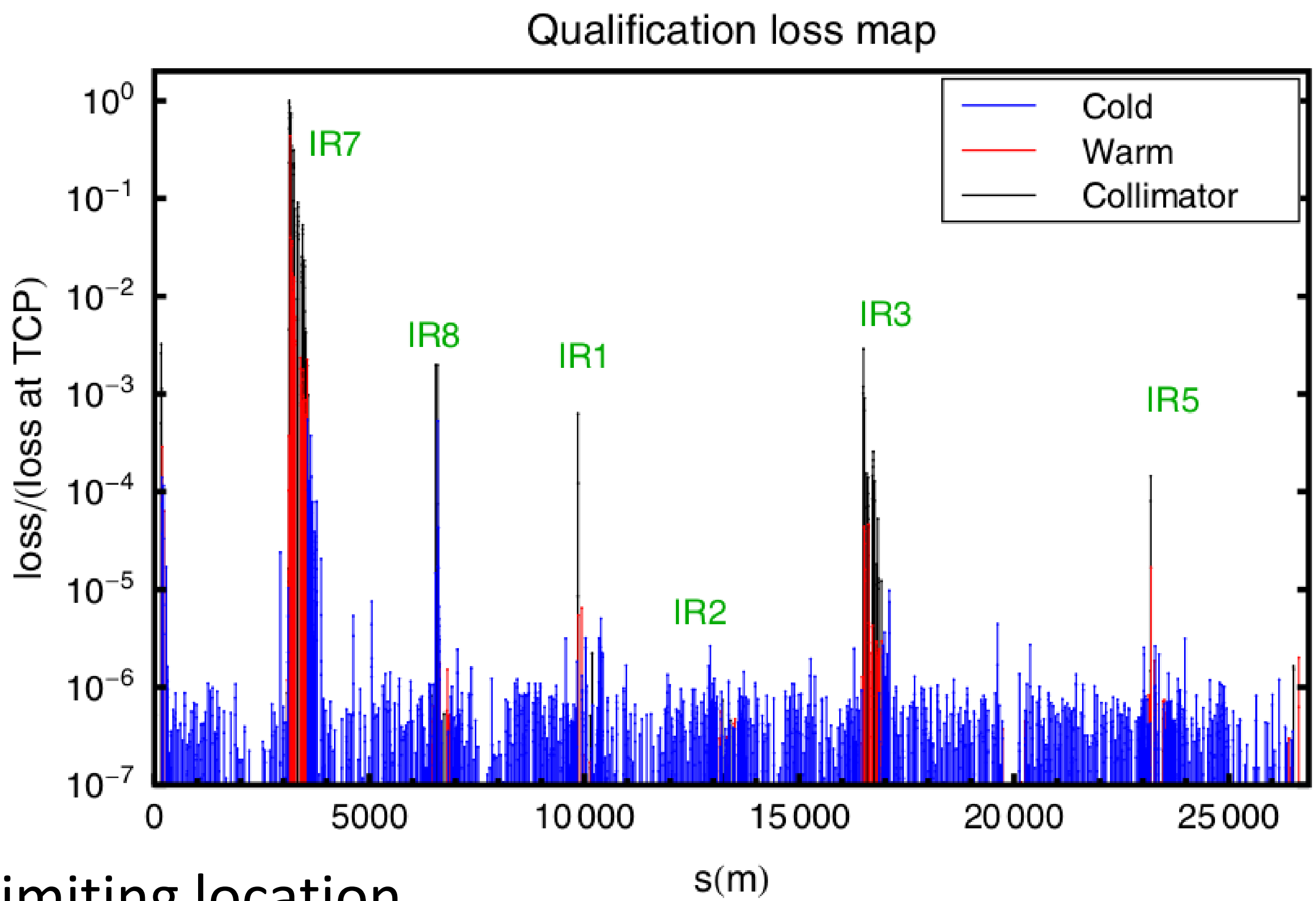
- LHC collimation system:
  - > 100 movable devices
- Betatron cleaning: IR7, momentum cleaning: IR3





Loss maps

- To qualify performance of collimators: provoked beam losses with safe low-intensity beam before high intensities allowed
- Losses measured with beam loss monitors (BLMs) around the ring
- Some leakage to cold magnets unavoidable
- IR7 dispersion suppressor (DS) limiting location

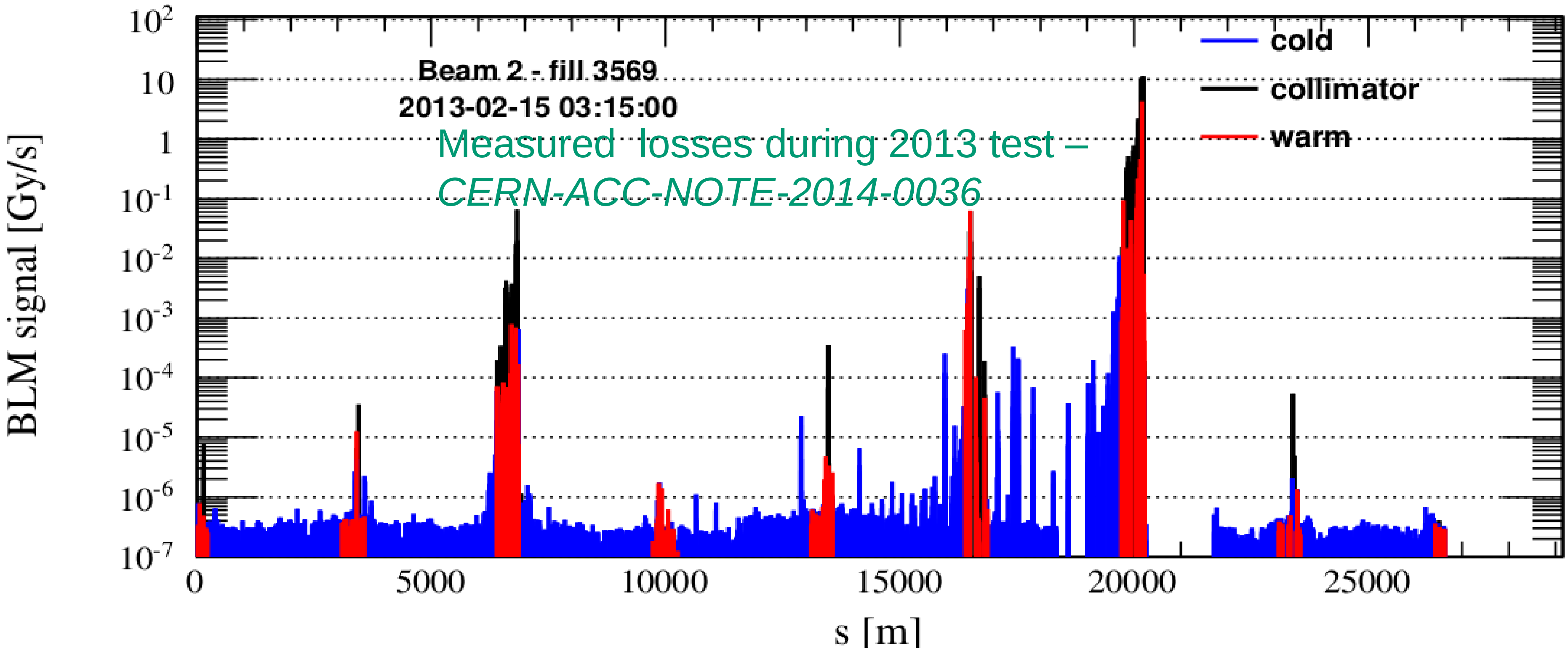


Collimation quench test

- Experimental validation of the allowed leakage to cold magnets
- Idea: with collimators in place, provoke very high beam losses with ADT (white noise) and see at what loss rate leaking protons quench downstream magnets in the DS
  - As a loss map, but with much higher intensity and loss rate
- Similar loss scenario to can be expected during operation
  - Quench test that is directly useful for understanding operational limitations
  - Can introduce operation-optimized BLM thresholds
  - Results give directly allowed loss rate and consequently (together with beam lifetime) gives the maximum allowed LHC intensity
- Simulations: extrapolate to higher energy

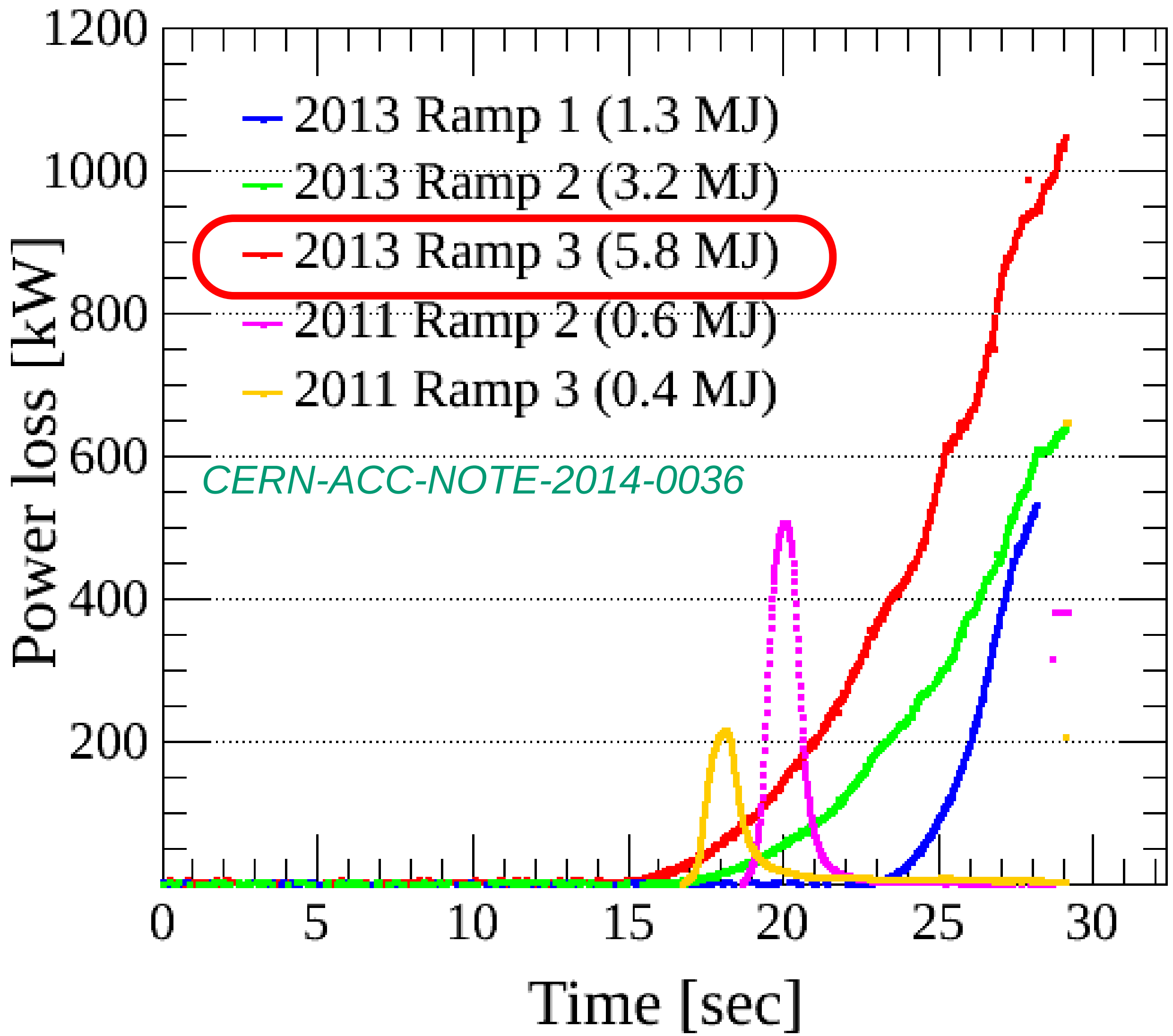
Collimation quench test (2)

- Several collimation quench tests performed:
  - 2011 protons at 3.5 TeV (*CERN-ATS-Note-2011-042-MD*)
  - 2011 Pb ions at 3.5 TeV Z (*CERN-ATS-Note-2012-081 MD*)
  - 2013 protons at 4 TeV (CERN-ATS-Note-2014-0036 MD). Main focus today



2013 collimation quench test result

- 1 MW losses achieved without quench
- Factor 2-5 higher than expected quench limit (but now we have better estimates!)
- unprecedented losses: ~3 times the Tevatron beam on the TCP's in ~10 s

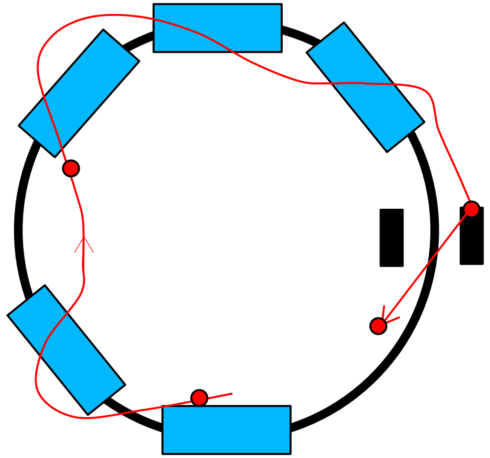


Simulation tools

- Crucial to relate experimental data to theoretical studies / simulations to better understand on quench limit
- Need a very good understanding of the beam cleaning and to quantitatively predict losses around ring in future configurations
  - Loss maps used to determine BLM thresholds
- SixTrack with collimation routine used for simulating cleaning of LHC collimation system.
  - Output: distribution of primary proton losses
- Additional shower simulations needed to relate the losses to BLM signal (see talk A. Lechner)
- Additional electro-thermal simulations needed to assess quench (see talk A. Verweij)

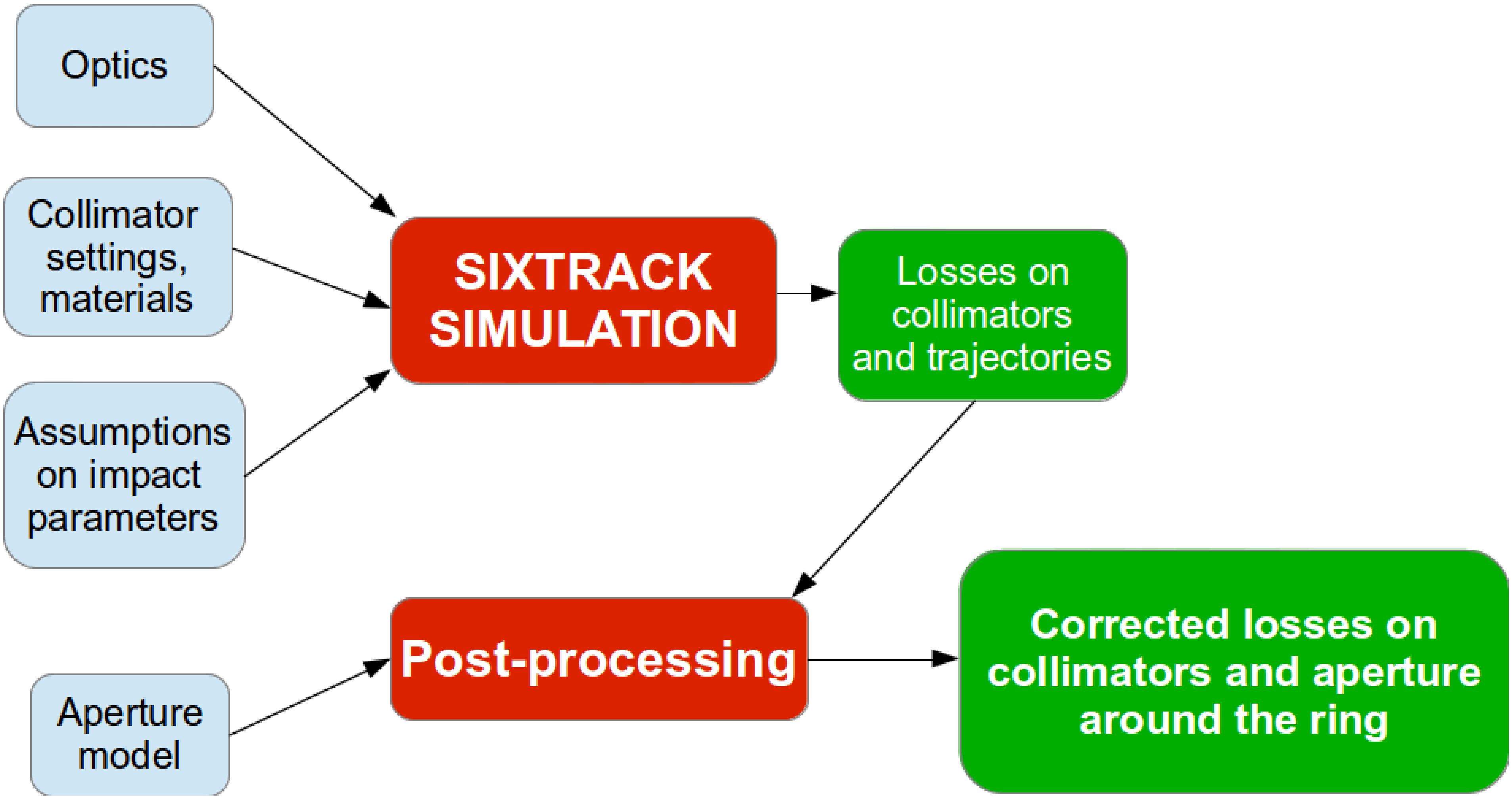
Tracking: SixTrack with collimation

- SixTrack: 6D thin-lens symplectic element-by-element multi-turn tracking
  - Used initially for dynamic aperture studies
  - Includes non-linearities up to order 20



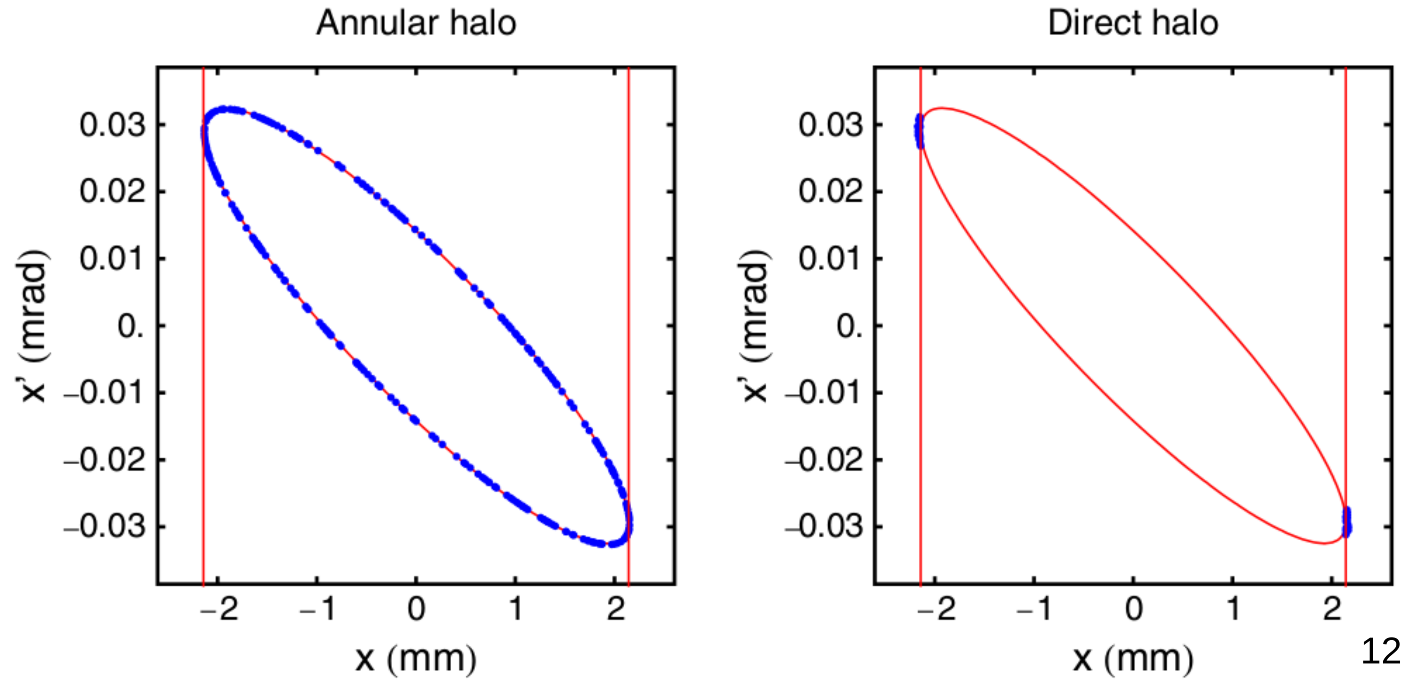
- SixTrack extended for collimation studies (thesis G. Robert-Demolaize 2003)
  - Including K2 scattering routine (Jeanneret and Trenkler) to treat particle-matter interaction in collimators
  - Advantage over e.g. MAD-X or other “pure” tracking tools that do not include particle-matter interaction
- This setup used to design the present LHC collimation system, which has worked extremely well during Run 1

SixTrack simulation flow



SixTrack inputs

- Optics: thin-lens model generated using MAD-X
- Statistics: Usually track about 6e6 macro particles to have sufficient resolution of peaks close to presumed quench limit
- Usually ~200 turns are sufficient
- Starting conditions: annular halo from the start of the ring, or direct halo generated directly at collimators



SixTrack inputs (2)

- No diffusion included – implicit assumptions on the depth *b* of impacts on the collimators
  - Measurements: from diffusion during steady physics conditions with stored beams, expect 0.02µm<*b*<0.3µm (PRSTAB 16, 021003)
  - Simulation studies: during provoked losses (3^{rd} order resonance or transverse damper excitation) expect order of 10µm as in quench test
  - No dramatic differences expected in loss pattern between these scenarios (PRSTAB 17, 081004)

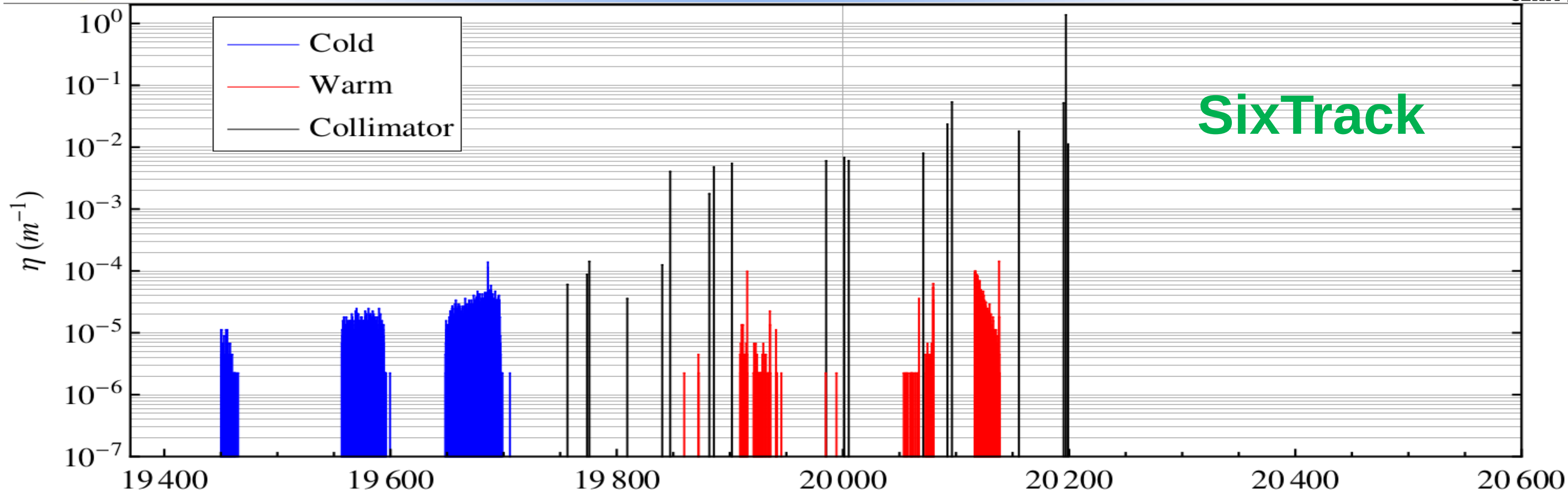
- Output: distribution of losses around the ring and on collimators

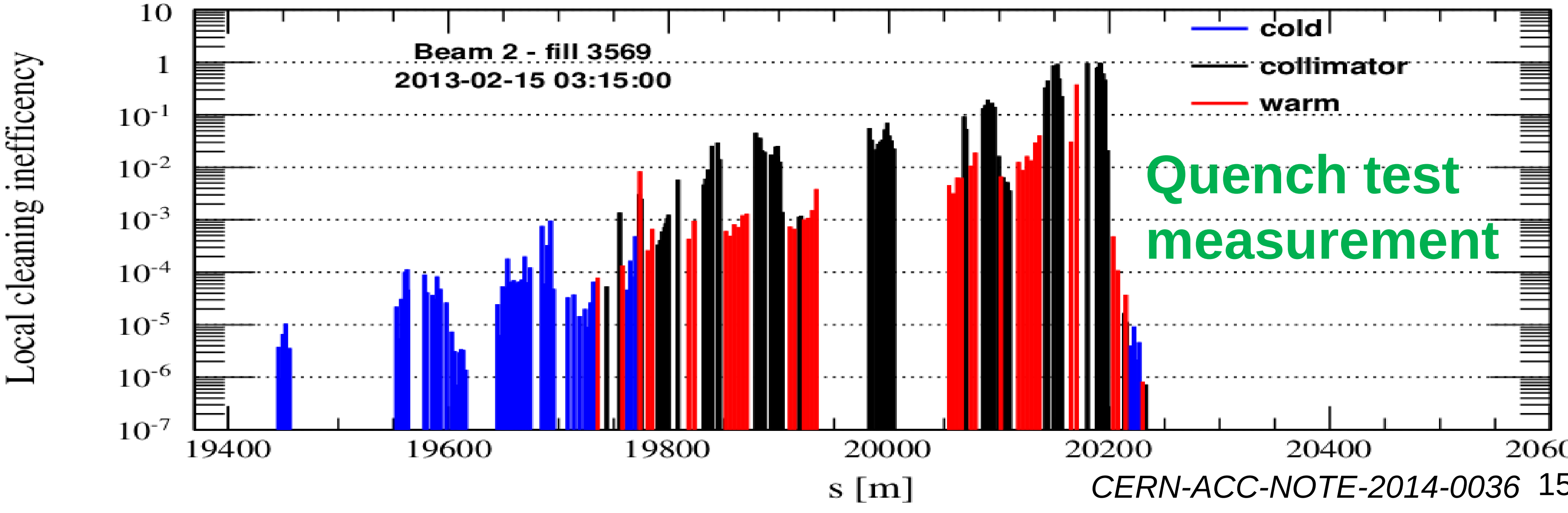
Quench test studies with SixTrack

- For quench test: Pre-study with SixTrack with different collimator settings performed to estimate leakage to DS
  - Compare with estimated quench level, choose settings where leakage is so high that quench is a priori possible
  - Different settings tried in measurements with low-intensity loss maps
- Chose very relaxed settings, significantly more open than used during standard operation
  - relaxed settings used in 2011 (in mm) with an additional 1 sigma retraction of the secondary collimators in IR7 and IR6
  - Collimators very efficient – need to make cleaning worse for quench test so that a quench is a priori possible!

Measurement and simulation of quench test, zoom IR7

LHC Collimation Project
CERN



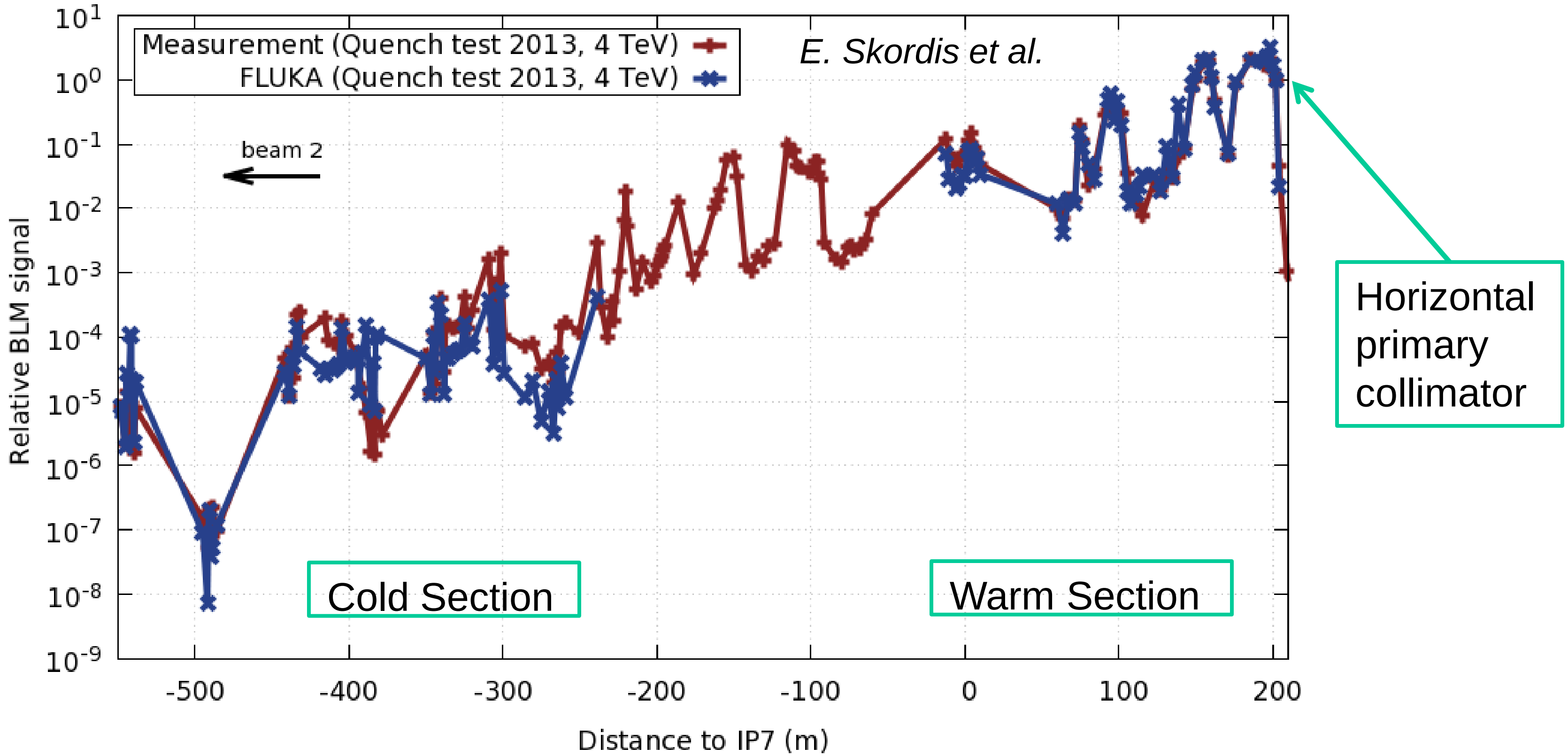


Remarks on results

- Qualitatively good agreement – loss locations reproduced
- Quantitative differences can be observed: warm losses, height of DS losses. But:
  - SixTrack counts primary proton losses
  - BLMs are sensitive to secondary shower particles. Depends on impact distribution, BLM placement, materials between impact and BLMs.
    - Significantly different transfer function (proton loss) -> (BLM signal) can be expected at different locations
- To compare more quantitatively with BLM measurements, need shower calculation

Example result with FLUKA shower calculation

- Using SixTrack output as starting conditions for FLUKA – *E. Skordis et al., collimation review 2013*.
- More details and updated results in next talk (A. Lechner)



Further reading

- Benchmark of combined simulation chain (SixTrack tracking + FLUKA shower) with 2011 LHC data recently published, including machine imperfections.
- Typically agreement within a factor 2 with measurements, although losses span 7 orders of magnitude

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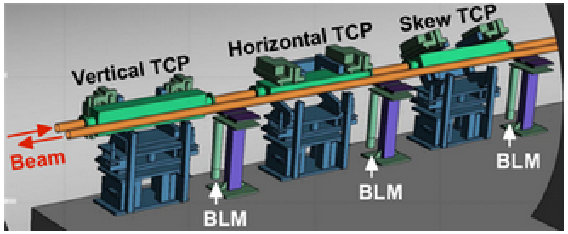


EDITORS' SUGGESTION

Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider

This paper documents the enormous effort expended by the LHC collimation working group to understand, simulate, and measure beam losses around the LHC.

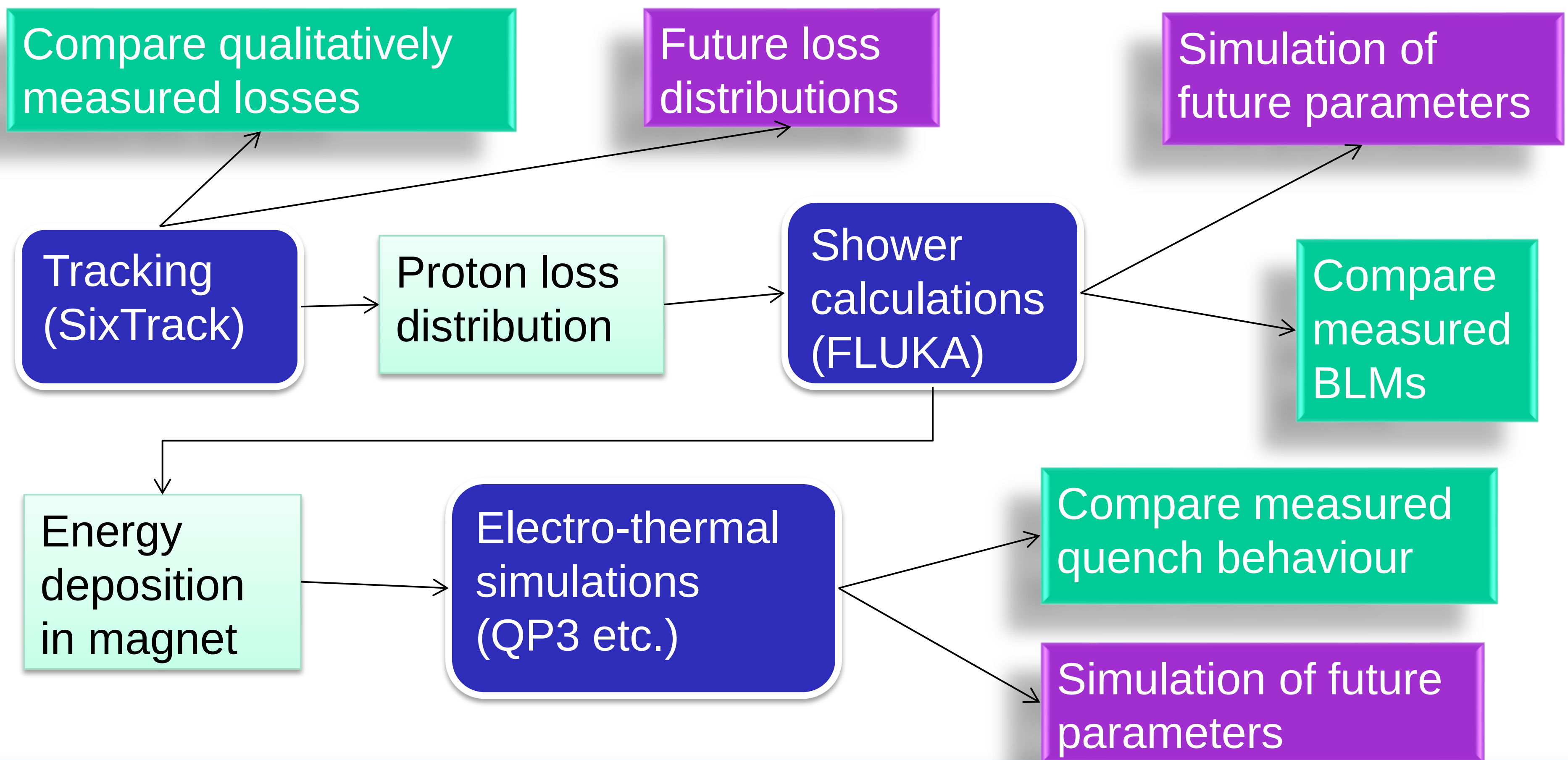
R. Bruce *et al.*

Phys. Rev. ST Accel. Beams **17**, 081004 (2014)

More Highlights

Simulation work-flow used in 2013 collimation review

- The very good agreement between simulations / measurements at 4 TeV can be used to predict behaviour at higher energy



SixTrack improvements

- Improved halo modelling recently implemented for better control of the impact parameter (R. Bruce CWG 2013.10.14)
  - Some improvements can still be envisaged, e.g. for off-momentum halos. On-going studies
- Improved scattering routine (C. Tambasco CWG 2014.03.31)
- SixTrack-FLUKA coupling
  - on-going work (FLUKA team, collimation team)
  - Idea: use FLUKA, running in parallel, to directly simulate the scattering, instead of the internal SixTrack scattering routine

SixTrack alternatives

- Codes with similar functionality are developed within the HiLumi project by collaborating institutes
  - **MERLIN** : University of Manchester and Cockcroft Institute, University of Huddersfield
  - **BDSIM** : Royal Holloway, University of London

Summary

- SixTrack used to simulate the cleaning of LHC collimators
  - Multi-turn tracking, including particle-matter interaction in collimators
    - Necessary features for simulating collimation quench test!
- SixTrack used to simulate cleaning with several collimator configurations as preparation for quench test.
  - Selected configuration with more open collimators than in physics
- SixTrack output: primary proton losses around the ring
  - For quantitative BLM comparison, need second step of shower calculation. More details in next talk (A. Lechner)
- Extensive benchmarks performed. Agreement with BLM measurements of combined simulation SixTrack+FLUKA for collimation losses typically within a factor 2
- 3-step simulation can be used to predict quench behaviour at higher energy