Measurements and Simulations for the LHC BLM System at the HERA Proton Beam Dump

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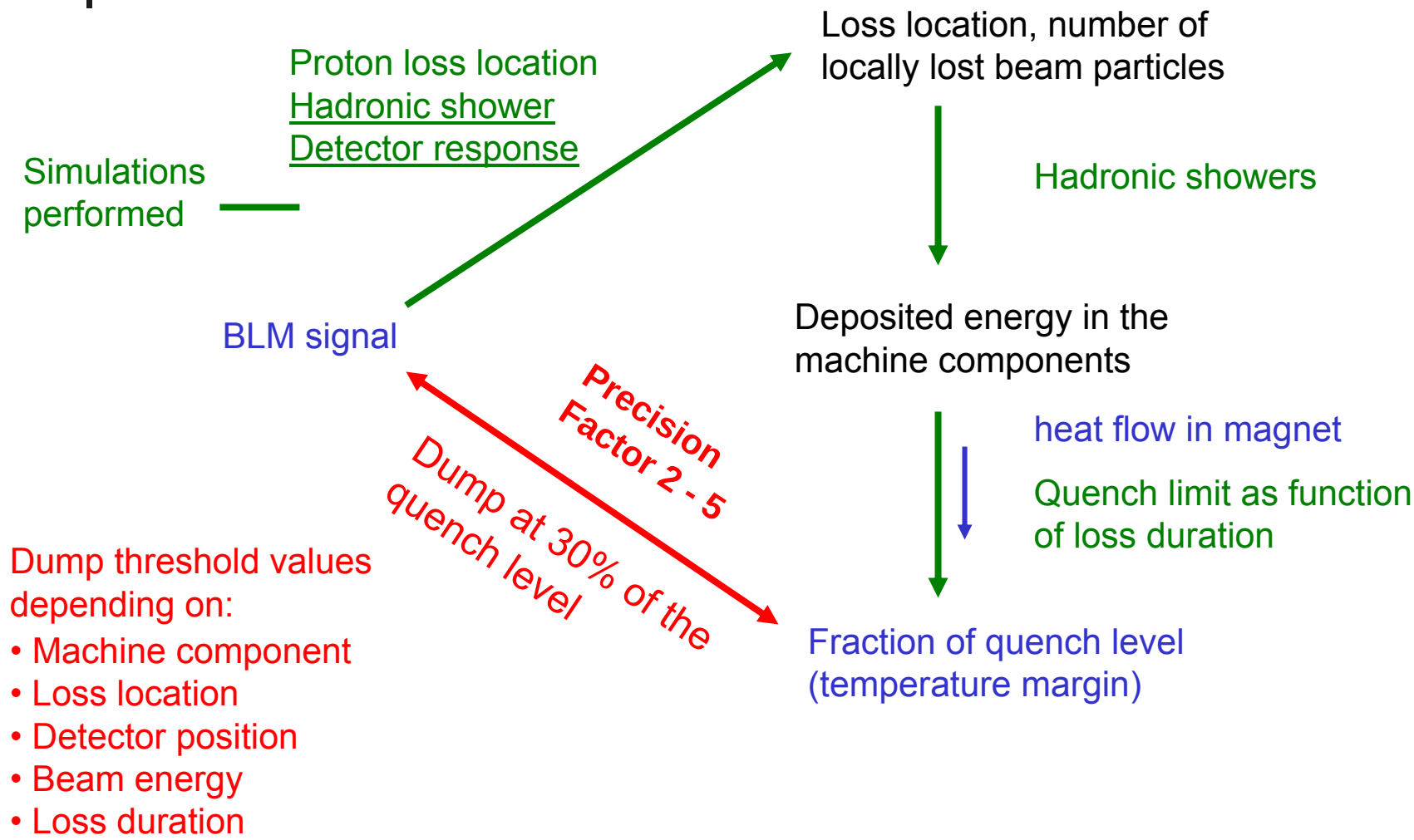
Calibration of the BLM system



Goals

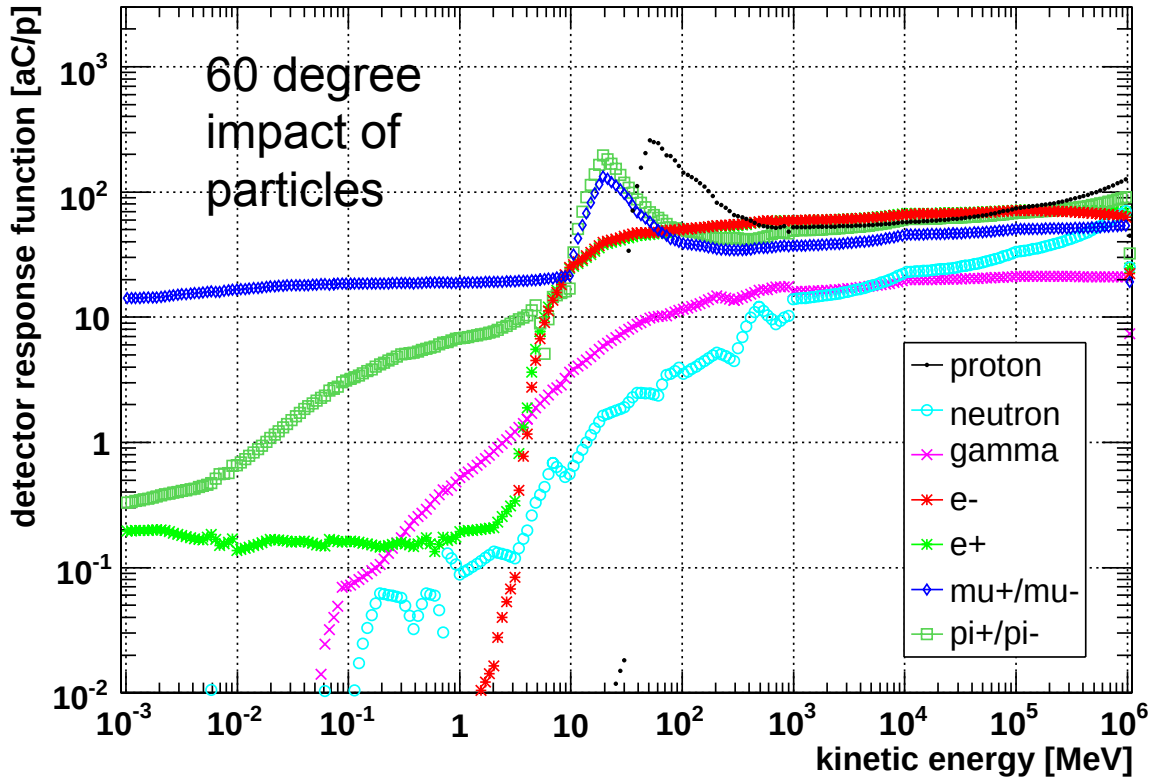
- Detector response determination
- Error on hadronic shower tail simulation (error on threshold)
- Validation of the system (long term system test in accelerator environment)

Ionization Chamber Response Simulation

Detailed detector simulation with Geant4 (8.1.p01 QGSP_BERT_HP):

- 9 different particle types
- Kinetic energy range: 1 keV – 1 TeV
- 60 deg impact angle relative to detector axis, uniform distribution

- 2 mm thick detector wall of stainless steel leads to **energy cut-off**:
  - Protons ~30 MeV
  - Electrons, pions ~3MeV
- Deposited energy is converted with W-value (N_2: 34.8 eV per electron-ion pair, ICRU report 31)



Validation with different Particle Beams

- Proton (400 GeV, T2, SPS extraction line): 13%
- Gamma (662 keV, Cs137, SC-RP): 14%
- Neutron (174 MeV, TSL, Sweden): 13%
- Mixed radiation field (120 GeV, H6, CERF target area): 17%

Results:

- Linearity of detector at intermediate intensities (up to 100 μA)
- Systematic error of 17% on the detector response functions

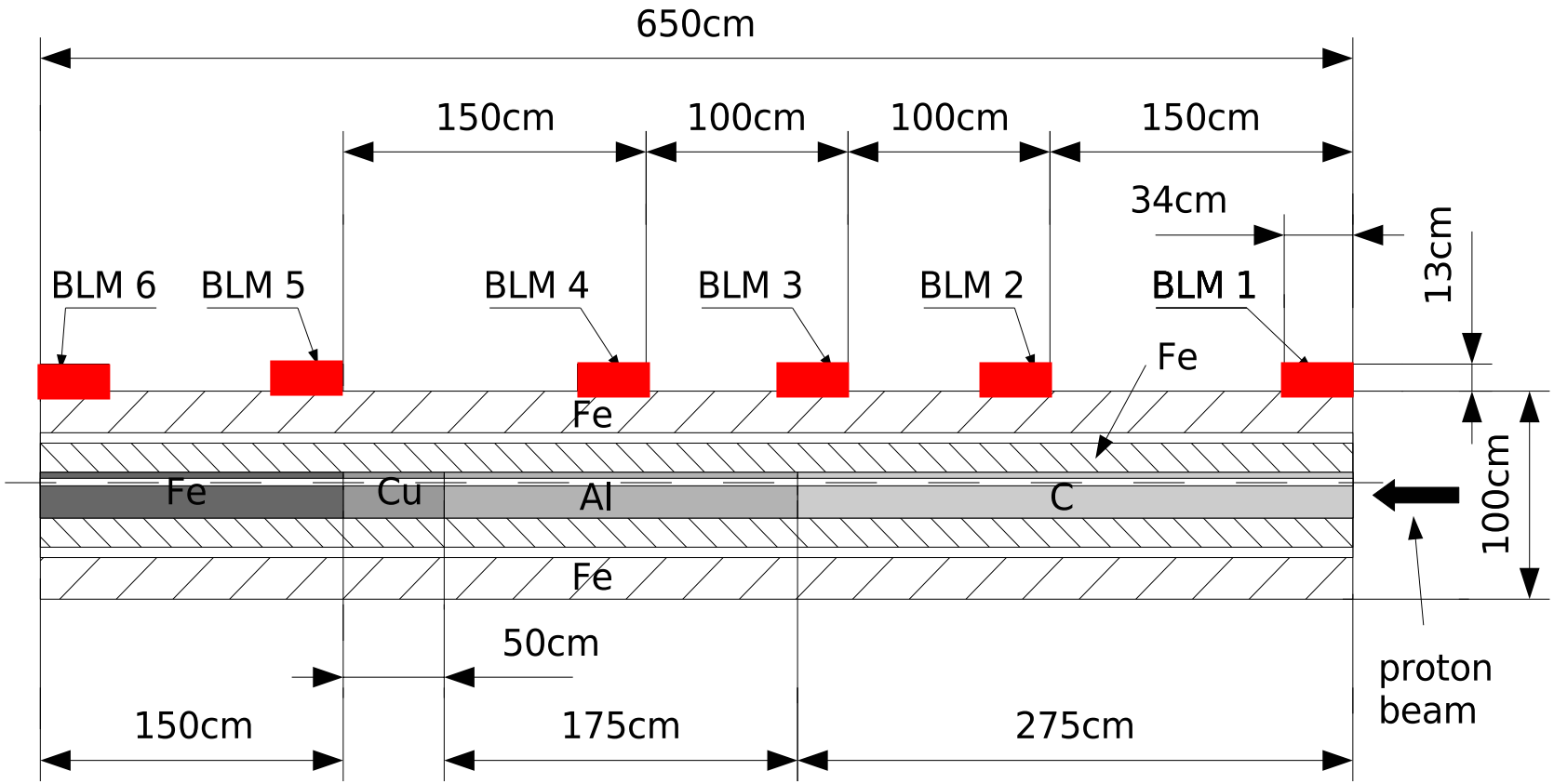
HERA Proton Beam Dump

- Proton – e^-/e^+ collider
- Circumference: 6 km
- Injection energy: 39 GeV
- Top energy: 920 GeV
- Beam current: ~100 mA
- ~ 1.3×10^{13} protons
- 96 ns bunch spacing
- Superconducting dipole magnets
- BLM System: pin diodes

- Internal dump
- Inner core filling pieces: Carbon, Aluminum, Copper, Iron
- Surrounded by a 14 cm iron tube
- Iron blocks 6.5x1x0.2 m outer shielding

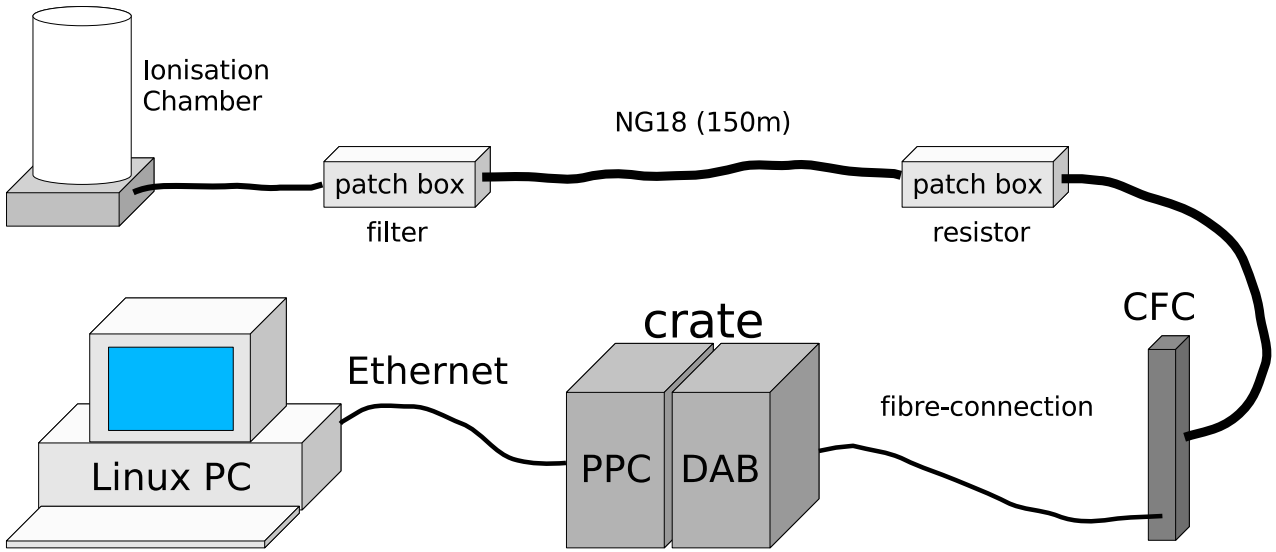
HERA Dump Installation

- 6 ionization chambers on top of the dump
- Longitudinal spacing ~ 1 m
- Beam impinging from the right side



Acquisition System

- 8 ionization chambers around dump
- In tunnel patch box:
  - Filter: 1 µF +10 kOhm
- Surface patch box:
  - 21.5 kOhm
- t = 40 ms

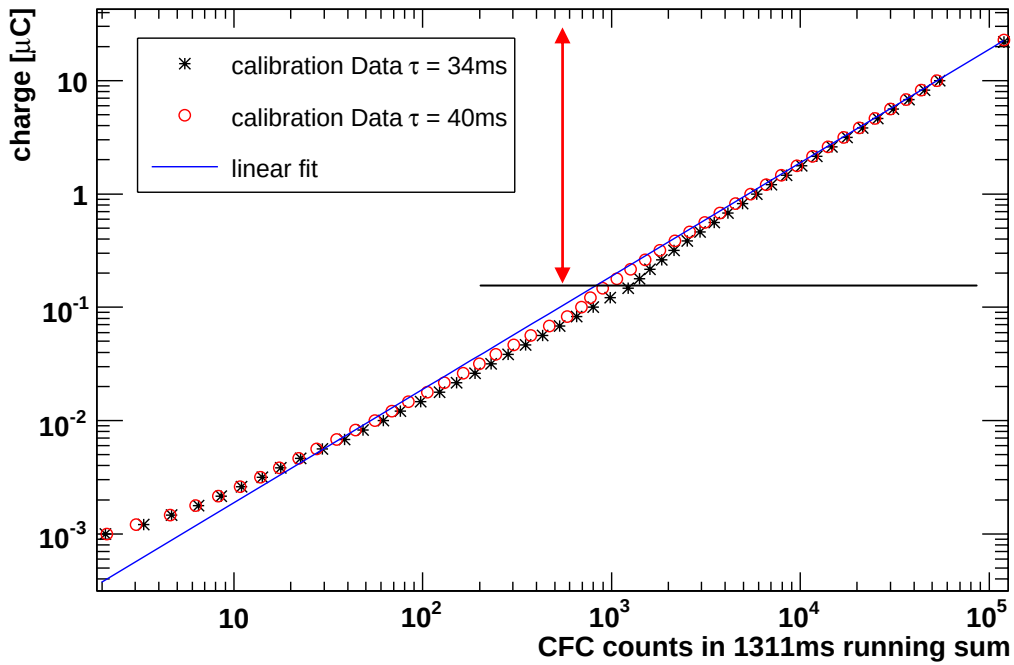


- CFC
- DAB card
- Power PC
- Data stored on Linux machine
- Continuous acquisition every second
- Post mortem since Jan. 2007 (40 µs, 1.7 s)

Electronics Calibration

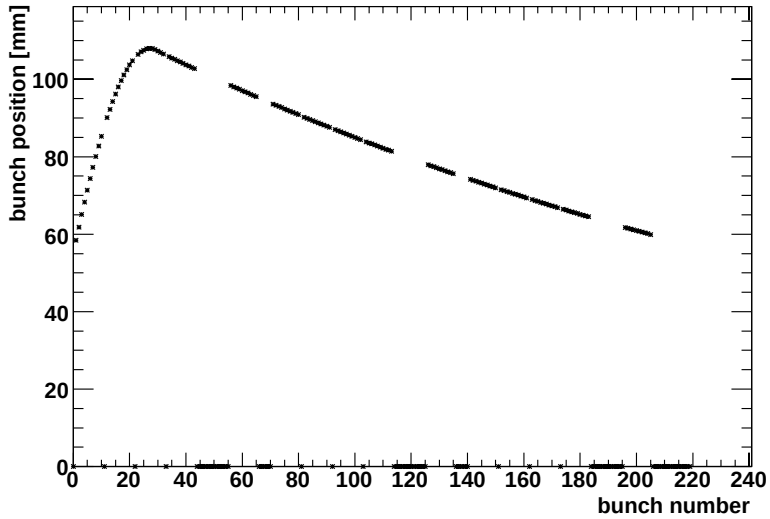
- Lab-calibration with an equivalent network:
  - Ionization chamber replaced with a capacitor
  - Implementation of all filters and resistors
- Measurement data was cut below 0.15 µC ~ 900 CFC counts (kink, relative error 20%)
- Maximum relative error 10% in used range

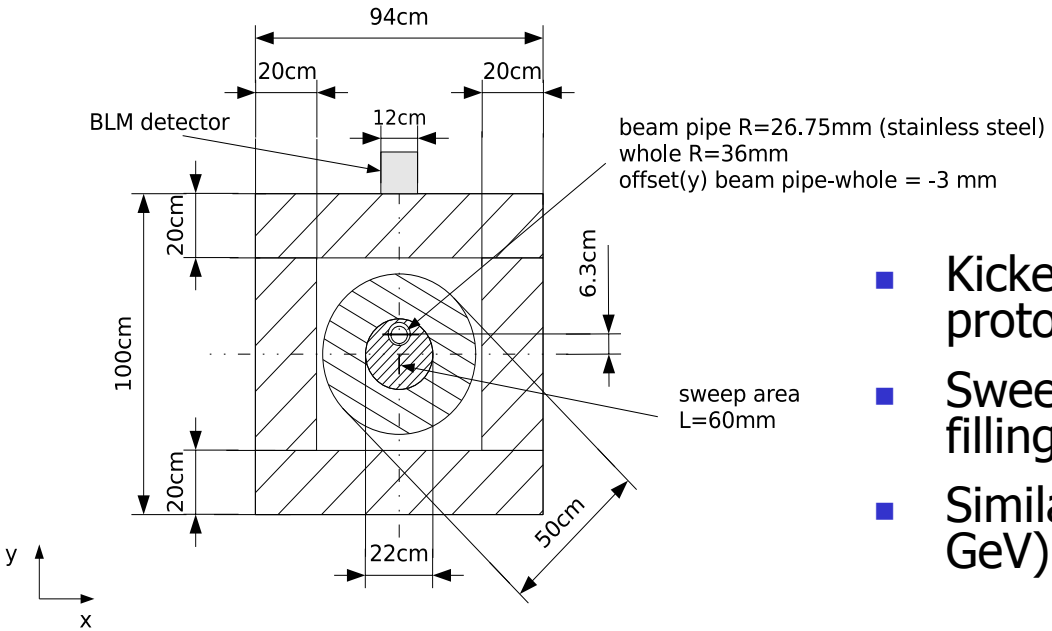
Induced charge versus measured CFC counts



Beam Sweep during Extraction

- Beam is sweep over front face of dump
- Sweep area L ~ 60 mm
- Beam is diverted downwards in respect to the beam orbit
- Diversion of 60 – 120 mm

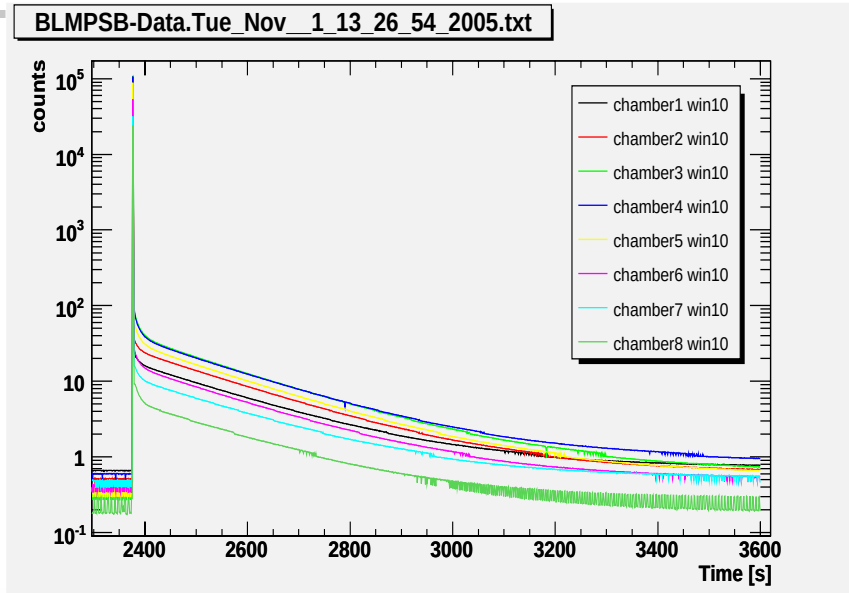




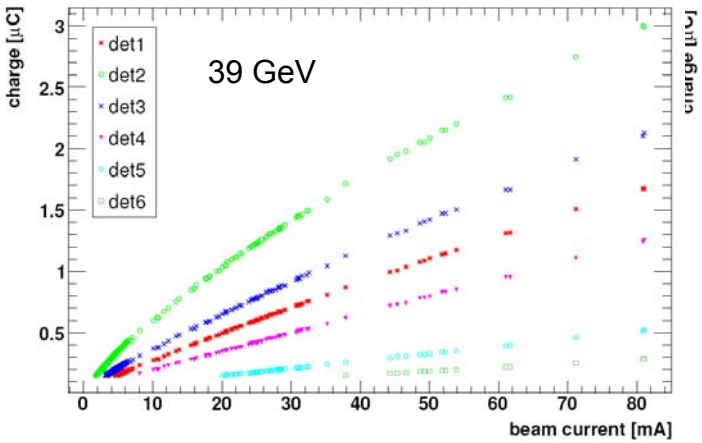
- Kicker magnets ~ 80 m upstream of proton dump
- Sweep area relative to centre of Carbon filling piece -6 to -61 mm
- Similar for both energies (39 GeV and 920 GeV)

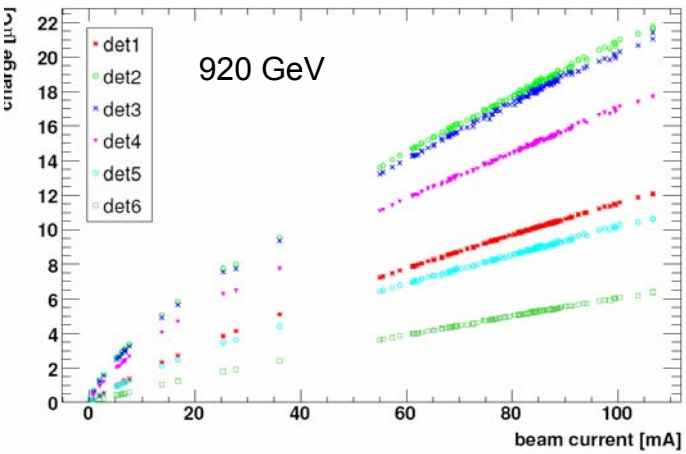
Measurement Results

- Data include electronic calibration



Detector signal versus beam intensity





Space Charge Effect Correction

Above critical ionization rate density a dead zone forms due to slow moving ions

Simplified space charge effect correction from literature, thesis of R.M. Zwaska

X_0: effective length of detector

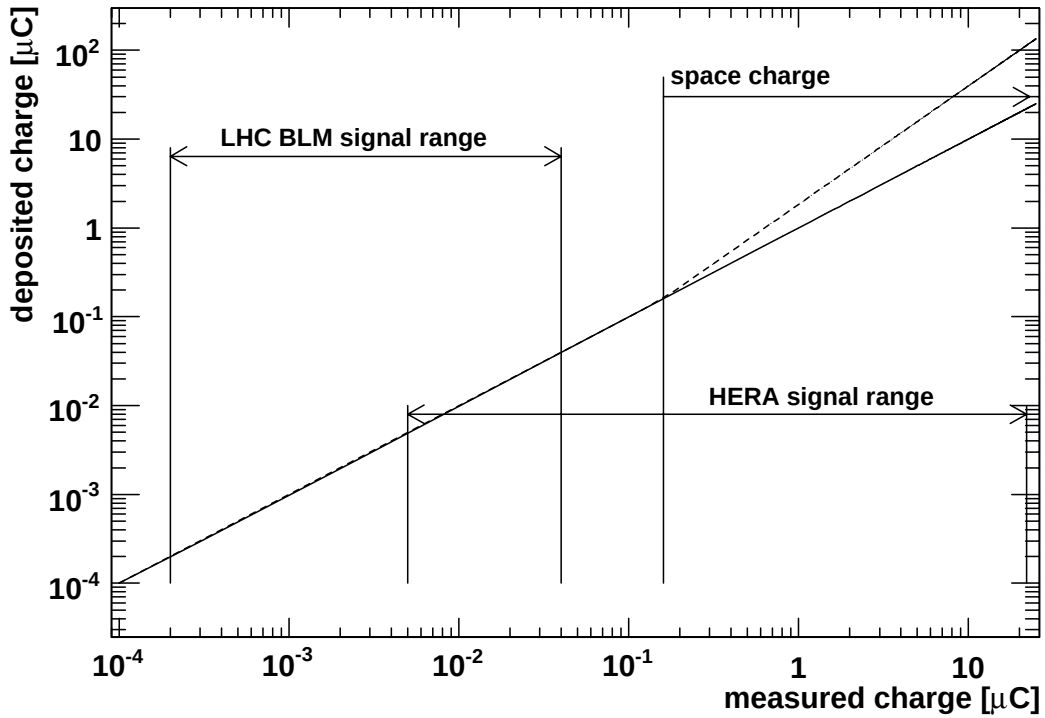
Φ : ionization rate

d: electrode spacing

ε_{sc}: collection efficiency

μ: ion mobility

U: applied bias voltage



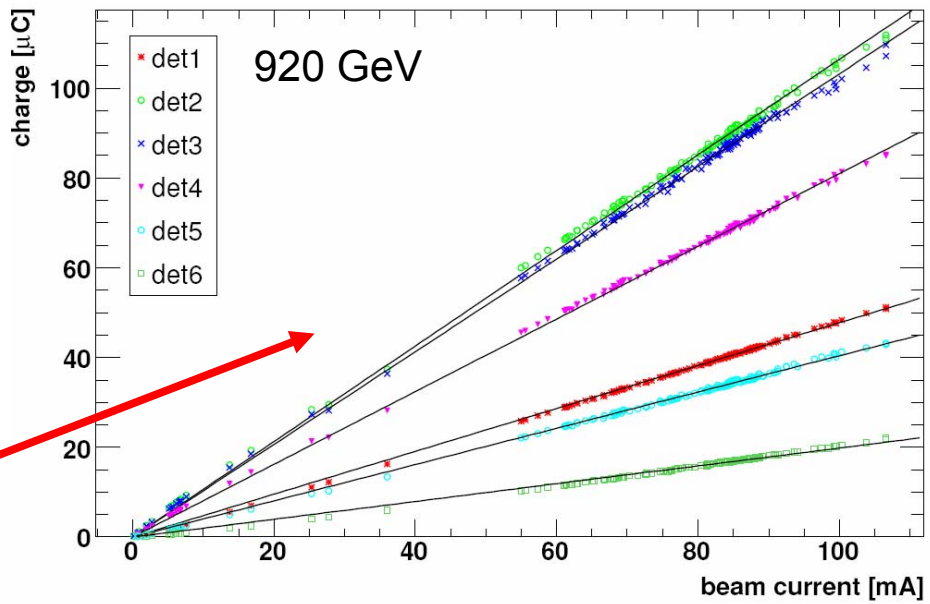
$$x_0 = \left[\frac{\varepsilon_0}{q} \frac{4\mu U^2}{\phi} \right]^{1/4}$$

$$\varepsilon_{sc} = x_0 / d$$

Correction Factors

- At injection energy and low beam intensity was no correction applied
- At 90 mA beam current up to factor ~ 3
- At top energy and low beam intensity ~ 1.6
- Top energy and beam current of ~ 100 mA a factor of ~ 5

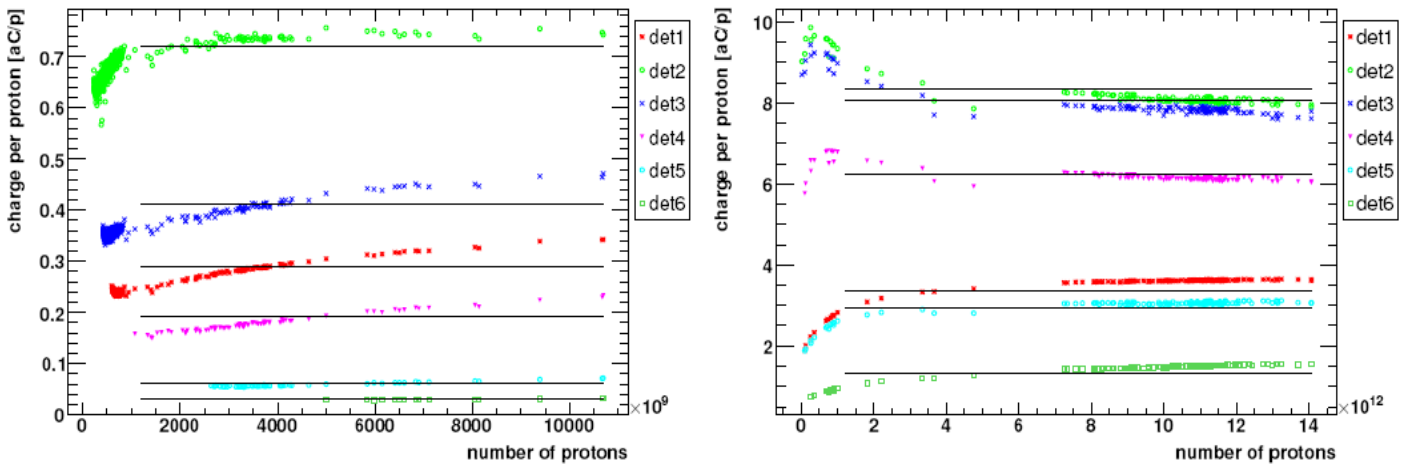
detector	39 GeV		920 GeV	
	I_{min}=1 mA	I_{max}=90 mA	I_{min}=1 mA	I_{max}=100 mA
1	1	2.25	1.09	4.2
2	1	2.72	1.59	5.12
3	1	2.43	1.57	5.08
4	1	2.05	1.43	4.78
5	1	1.53	1.08	4.03
6	1	1.26	1	3.38



Space charge effect corrected measurements

Systematic Uncertainties

- Systematic error taken into account in the final results
  - Background (remanent radiation) ~ 0.1%
  - Beam intensity ~ 2%
  - Electronics ~10 %
  - Misalignment of the detectors investigated in the simulation (1 – 10%)
  - Estimated error from plots (4 sigma) below is about 15% including beam sweep (bunch pattern) effects, the space charge effect corrections and statistical error



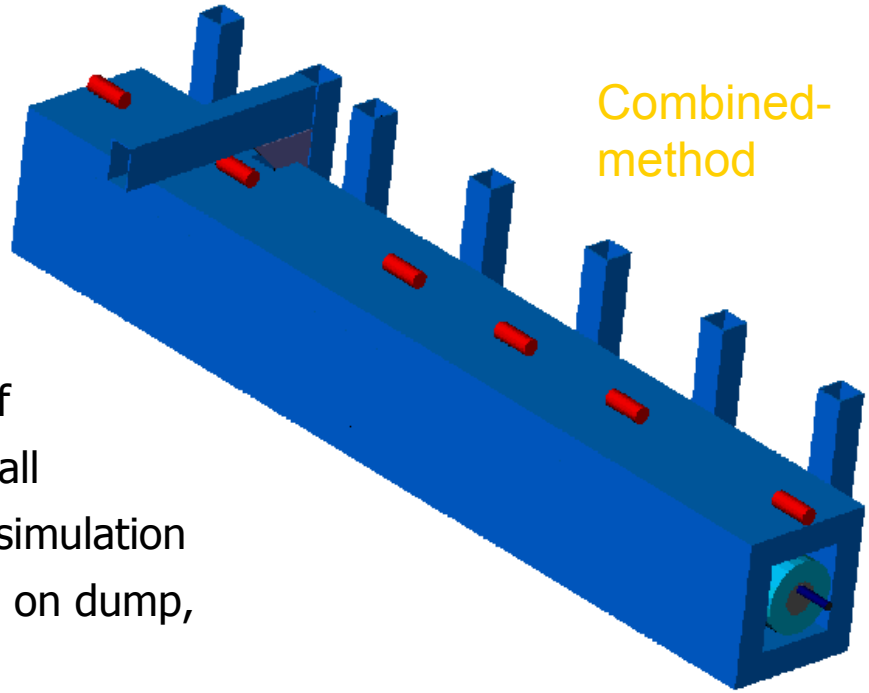
Final Measurement Results

- Relative detector signal for each detector placed on the HERA proton beam dump at injection and high energy.
- total statistical and systematical uncertainty, (range 16% to 21%)

		4 sigma	total			
detector	39 GeV [aC/p]	$^{a)}$ error	$^{b)}$ error	920 GeV [aC/p]	$^{a)}$ error	$^{b)}$ error
1	0.291	0.026	0.066	3.37	0.14	0.71
2	0.720	0.018	0.132	8.35	0.25	1.54
3	0.413	0.029	0.081	8.06	0.23	1.48
4	0.191	0.021	0.041	6.26	0.16	1.15
5	0.063	0.004	0.013	2.95	0.09	0.57
6	0.031	0.001	0.006	1.32	0.12	0.28

HERA Dump Simulation

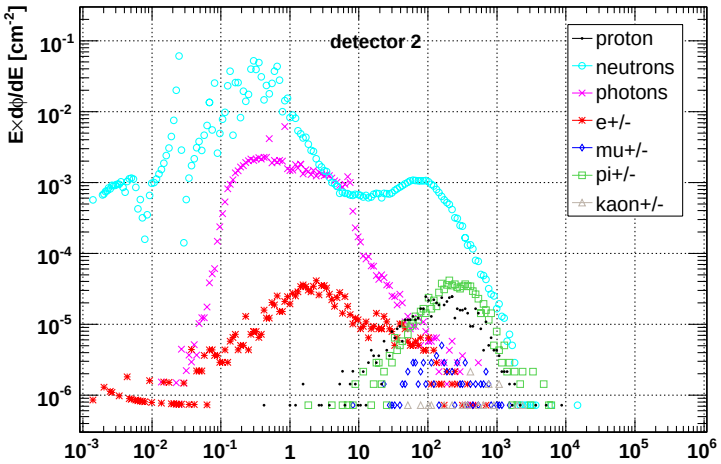
- Geant4 (8.1.p01), Physics lists:
  - LHEP
  - FTFP
  - QGSP-BERT-HP



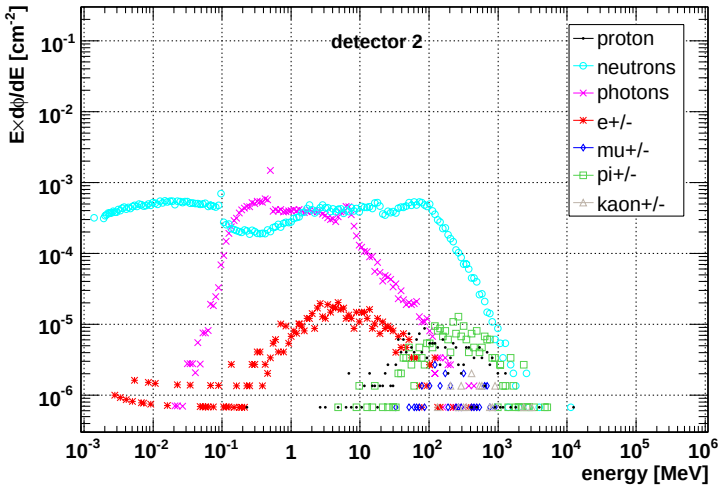
- Black-hole method: first step: recording of particle fluence spectra in a box covering all 6 detectors; second step: detector signal simulation
- Combined-method: detector implemented on dump, energy deposition in sensitive gas
- Folding-Method: used particle fluence spectra from black-hole and folds it with pre-simulated detector response functions
- FLUKA (courtesy of Roderik Bruce) black-hole method with Geant4 detector signal simulation

Comparison of Particle Spectra

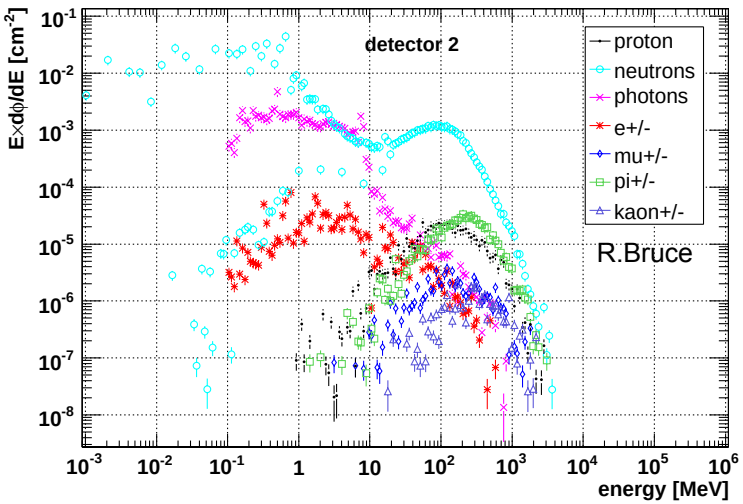
QGSP_BERT_HP (920GeV)



FTFP (920GeV)



FLUKA (920GeV)



- QGSP-BERT-HP and FLUKA show similar spectra
- FTFP far off, less low energy neutrons and less total number of particles
- Spectra similar at different detector positions (differ only in height)

Verification of the equivalent Methods

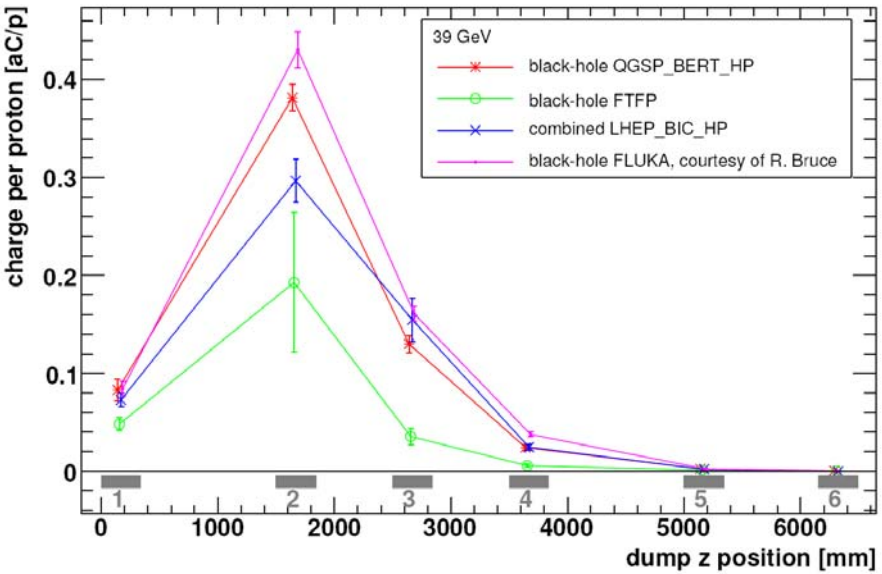
- The combined-method results are equivalent to black-hole method results
- Folding-method shows largest deviation of 18% for the first four detector compared to the black-hole method

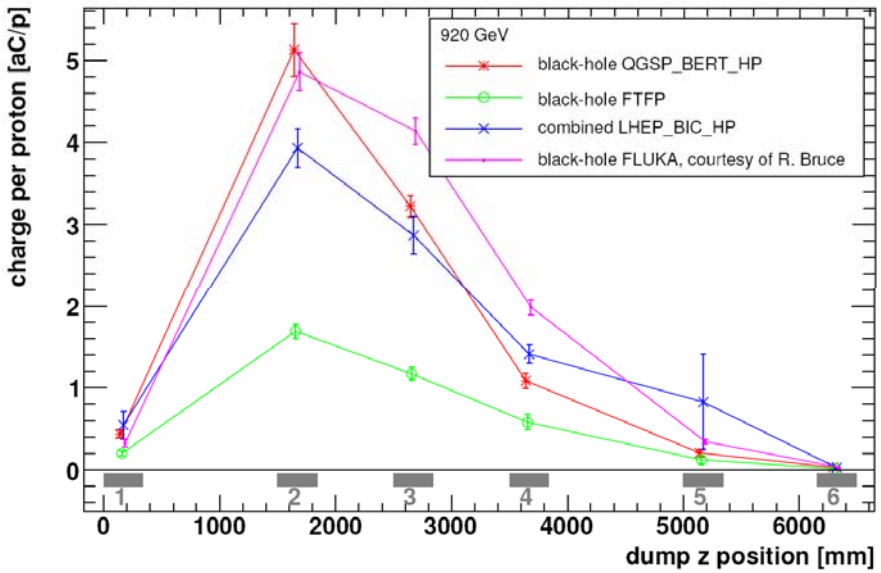
Systematic uncertainties in the simulations:

- Backscattered or created particles from tunnel wall ~ 5%
- Detector signal simulations (response function error) ~ 17%
- Simplification of beam parameters (sweep, …) ~ 10%
- Differences in the simulation models (QGSP-BERT-HP to FLUKA) ~ 20%

Simulation results

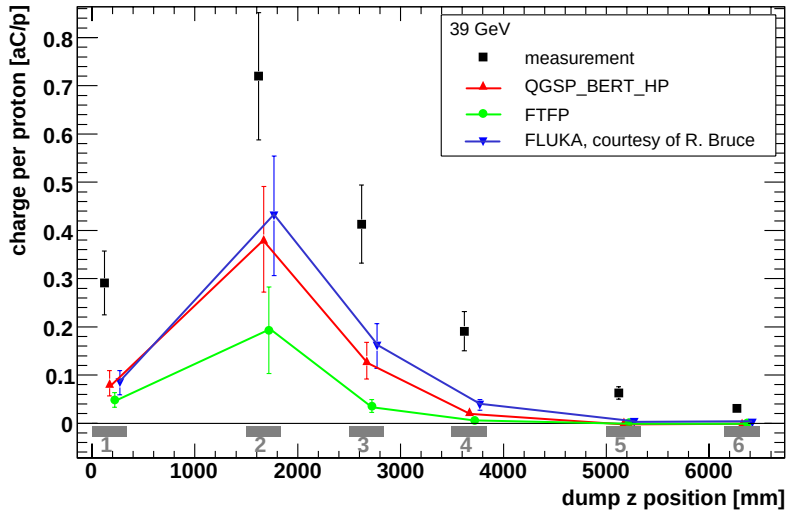
- Simulated detector signals from Geant4 QGSP-BERT-HP and FLUKA agree best at both energies with a maximum deviation of 40%
- LHEP (Geant4) is similar
- FTFP show much lower signal (spectra)
- FLUKA shows a slightly wider shower at 920 GeV
- Strong dependence on simulation code and physics models

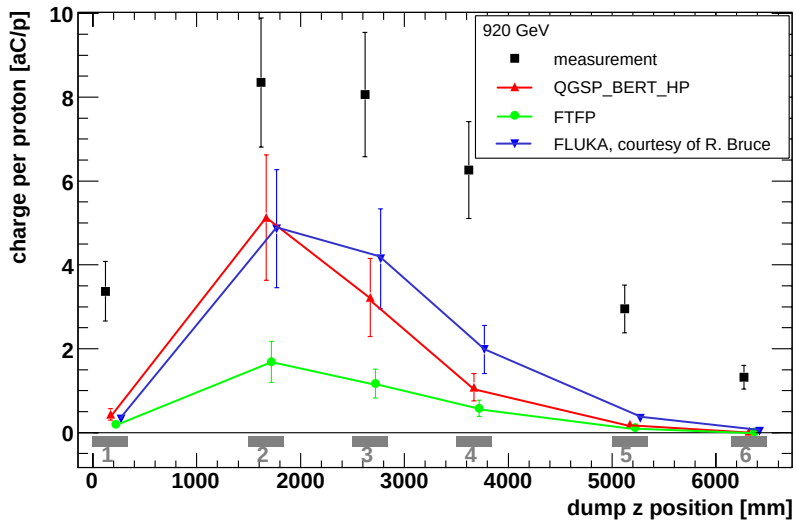




Comparison of Measurements and Simulations

- Significant difference in absolute height and longitudinal shape between measurement and simulation.
- QGSP-BERT-HP and FLUKA closest to data
  - Detector 2: Geant4 and FLUKA within 40% to the measurements at both energies
  - Between 1.5 and 3.5 m difference of about 70%
- Consequences for LHC:
  - Geant4 (QGSP-BERT-HP) and FLUKA for the threshold simulation





Estimation of an LHC BLM detector threshold

Ingredients:

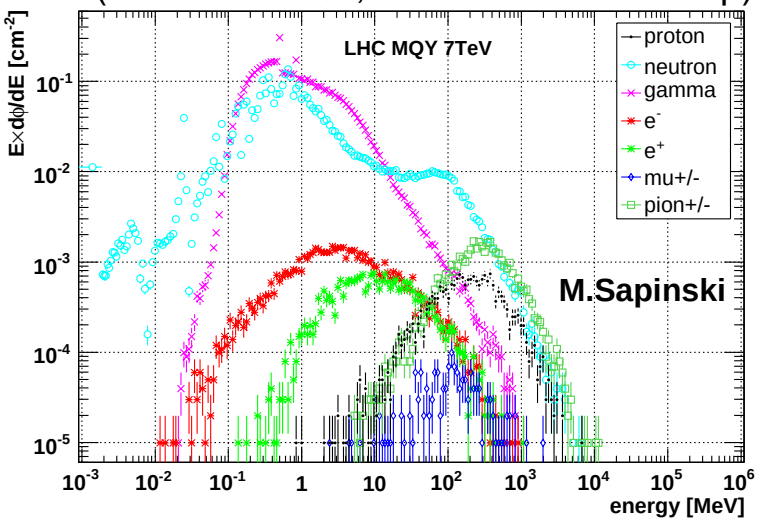
- Detector response functions
- MQY magnet simulation (Mariusz Sapinski)
- Quench levels (Dariusz Bocian, LHC project note 44)
- Folding-method:
  - Folding pre-simulated detector response functions with simulated particle fluence spectra
  - Simplified and faster approach to generate detector signal

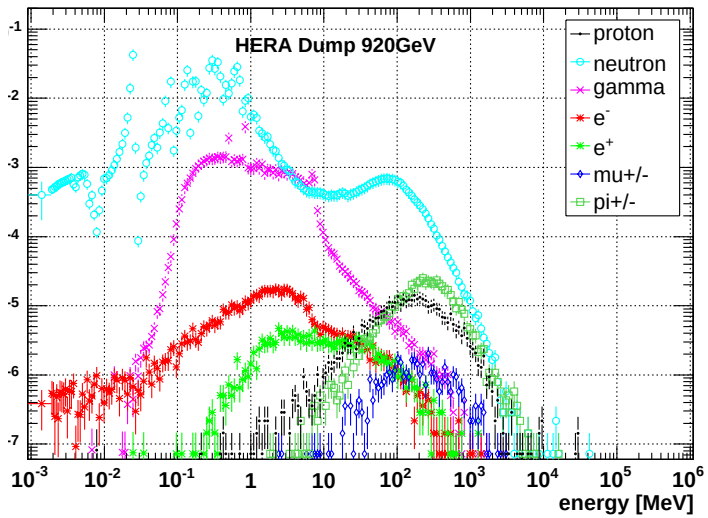
Comparison to in the past calculated detector thresholds

Shower Simulation

- Impact point of the protons at the beam screen, beginning of the coil
- Impact angle of 0.24 mrad
- Quench level calculation:
  - Scoring of energy deposition in the coil of the magnet in cells (volume: 0.08 to 0.16 cm3)
- MQY spectra dominated by neutrons and gammas
- HERA dump spectrum dominated by neutrons, fewer charged particles
- The relative number of particles is about a factor of 10 different

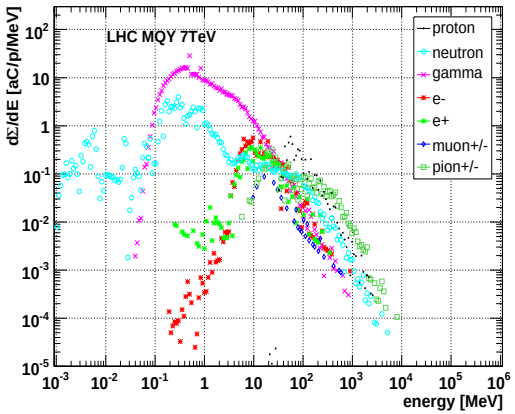
Recording of particle fluence spectra outside of cryostat in a 3.4 m long detector strip (7 TeV for MQY, 920 GeV HERA dump)

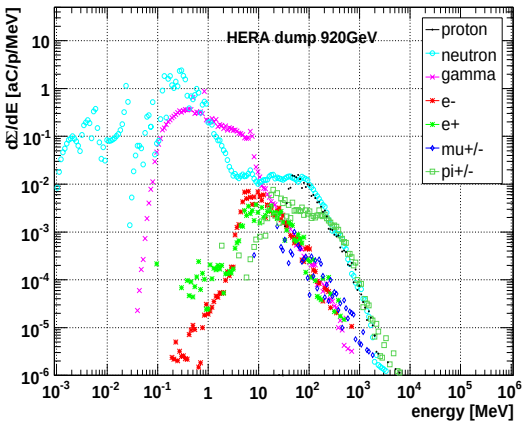




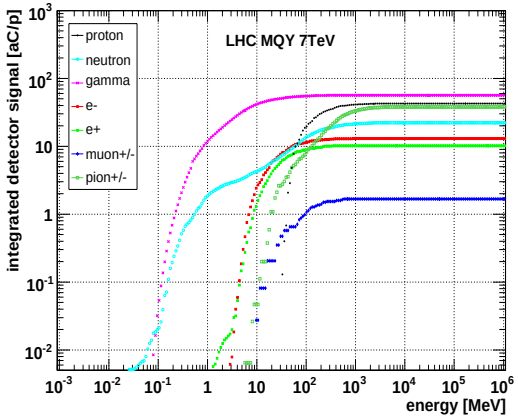
Generation of Detector Signal

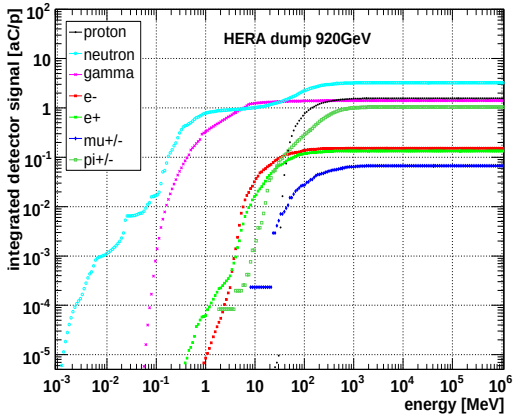
Detector signal Σ (folding of detector response function with spectra





Integrated detector signal





- Both detectors at 1.5 m after proton impact corresponds to detector 2 at HERA dump

Contribution of the different particle types to the signal

	LHC MQY	HERA dump
e+/-	12.6%	3.8%
gamma	30.7%	18.5%
mu+/-	0.9%	0.9%
neutron	12.1%	42.6%
pi+/-	20.6%	13.6%
proton	23.1%	20.6%
total signal [aC/p]	184.14	7.61

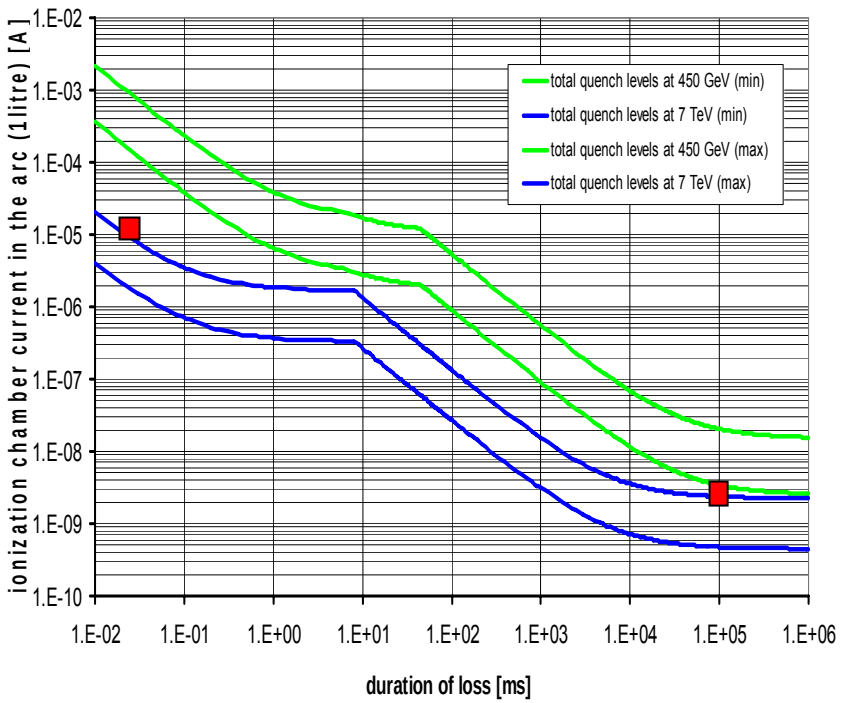
Comparison to previously calculated Thresholds

- Loss duration dependent quench limits for the MQY magnet.
- Previously calculated minimum and maximum BLM signals for LHC arc magnets
- Interpolation between the HERA beam dump measurement (70% uncertainty at 16 λ_0) and the mixed radiation field measurement (17% uncertainty at 3 λ_0) yields an
- estimated uncertainty on the LHC threshold simulations of 50%
- For a detector placed between 0.5 to 3.5 m after impact.

loss duration	quench limit
	MQY
$<100\,\mu s$	$5\ \mathrm{mJ/cm^3}$
$100\,s<$	$5.29\ \mathrm{mW/cm^3}$

LHC project note 44: 0.9 mJ/cm3 for LHC arc dipoles

LHC project note 44



- Transient losses: 1.4×10^{-5} A (at 40 µs)
- Steady state losses: 3×10^{-9} A (at 100 s)

Conclusions

- Detector response functions simulated
- Validated for different irradiation scenarios within 17%
- Hadronic shower measurements and simulations performed
- Geant4 (QGSP-BERT-HP) and FLUKA most accurate
- Simplified BLM detector signal generation with Folding-Method validated
- Estimated uncertainty on LHC BLM detector threshold simulation: 50%
- Calculated detector thresholds within BLM system specifications

Acknowledgements

http://cern.ch/blm

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