Failures in magnet and powering systems

- circulating beams

Rüdiger Schmidt

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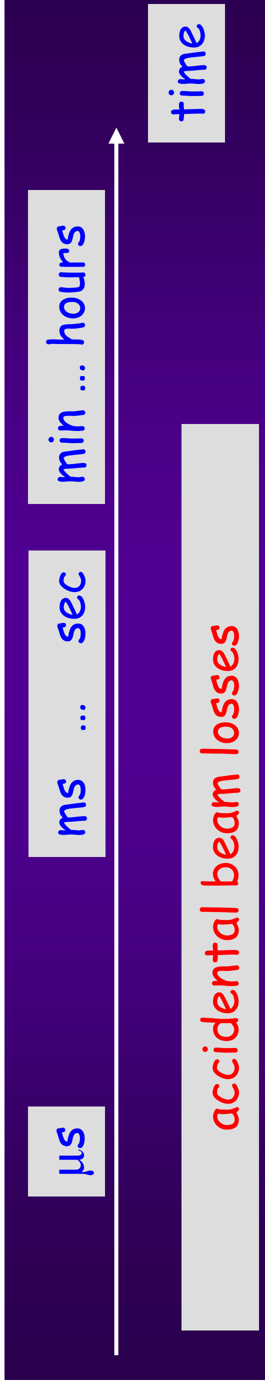
Time constant for beam losses
Quenches in superconducting magnets
Other failures during powering
Most critical failures
Conclusions

Beam losses and time constant



Very slow beam losses (lifetime 0.2 hours or more)

Cleaning system to limit beam losses around the ring: see presentations on cleaning system and collimators

Very fast beam losses (some turns to some milliseconds)

Fast beam losses (5 ms – several seconds)

Slow beam losses (several seconds – 0.2 hours)

At all times collimators limit the aperture – particles lost on collimators

Hardware surveillance and beam monitoring, detecting failure and extracting the beams into beam dump block

Ultra fast beam losses, mainly kicker magnets (single turn or less)

- **Single turn failures at injection**
- **Single turn failures at extraction**
- **Single turn failures with stored beams**

Passive protection with beam absorbers

Wrong functioning of the magnet and DC powering system and beam losses

- Failures in the hardware for magnet powering
- Quenches of superconducing magnets
- Wrong current in magnet
  - operational failures
  - problems in the software
  - wrong data in the database
  - failures in the timing system
  - ………

Failures in the magnet and DC powering system

Superconducing magnets

- Quench of superconducting magnets
- Discharge of superconducting magnets with a resistance in the circuit (after a quench, or by failure)
- Trip of a power converter for superconducing magnets (in general, long time constant for the decay of the current)
- Other failures (quench of a sc bus-bar, HTS current lead, …)

Normalconducting magnets

- Overheating of a magnet -> switch off power converter
- Trip of a power converter for normal conducing magnets (short time constant for the decay of the current – very fast orbit movement or other effects on the beams)

Quenches are much more likely at 7 TeV due to the reduced margin of the superconductor and due to the increased beam energy

Why quenches of superconducting magnets ? - with (more or less) stable beams

"Stable beams": lifetime of beam many seconds to hours

Quench not related to beam loss

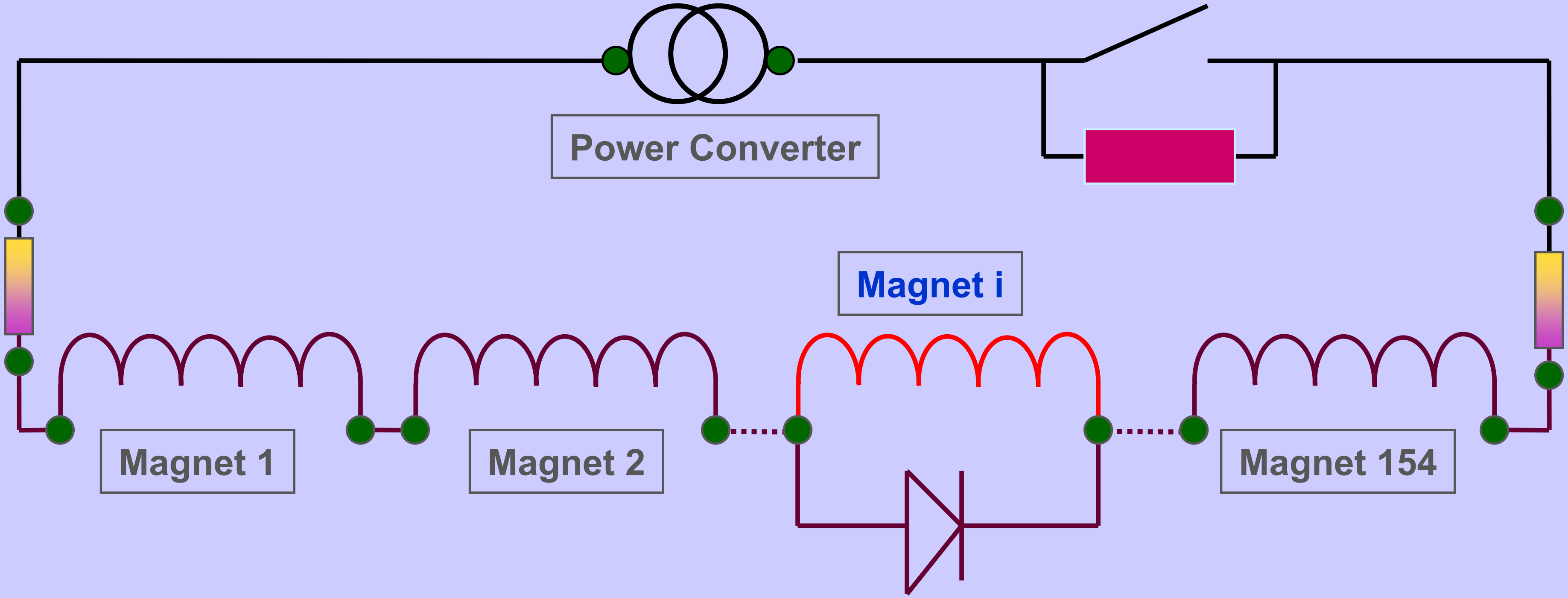
- **spontaneous quench**, for example due to re-training
- **temperature** in (part of) the magnet is too high
- **failure** in the **quench protection system** (heater firing)

Quench due to beam loss - the beam is stable

- typically protons in the **beam halo** could quench a magnet
- for example due to **decrease of beam lifetime**, or **cleaning that is not optimum**. Beam lifetime could still be many seconds to hours

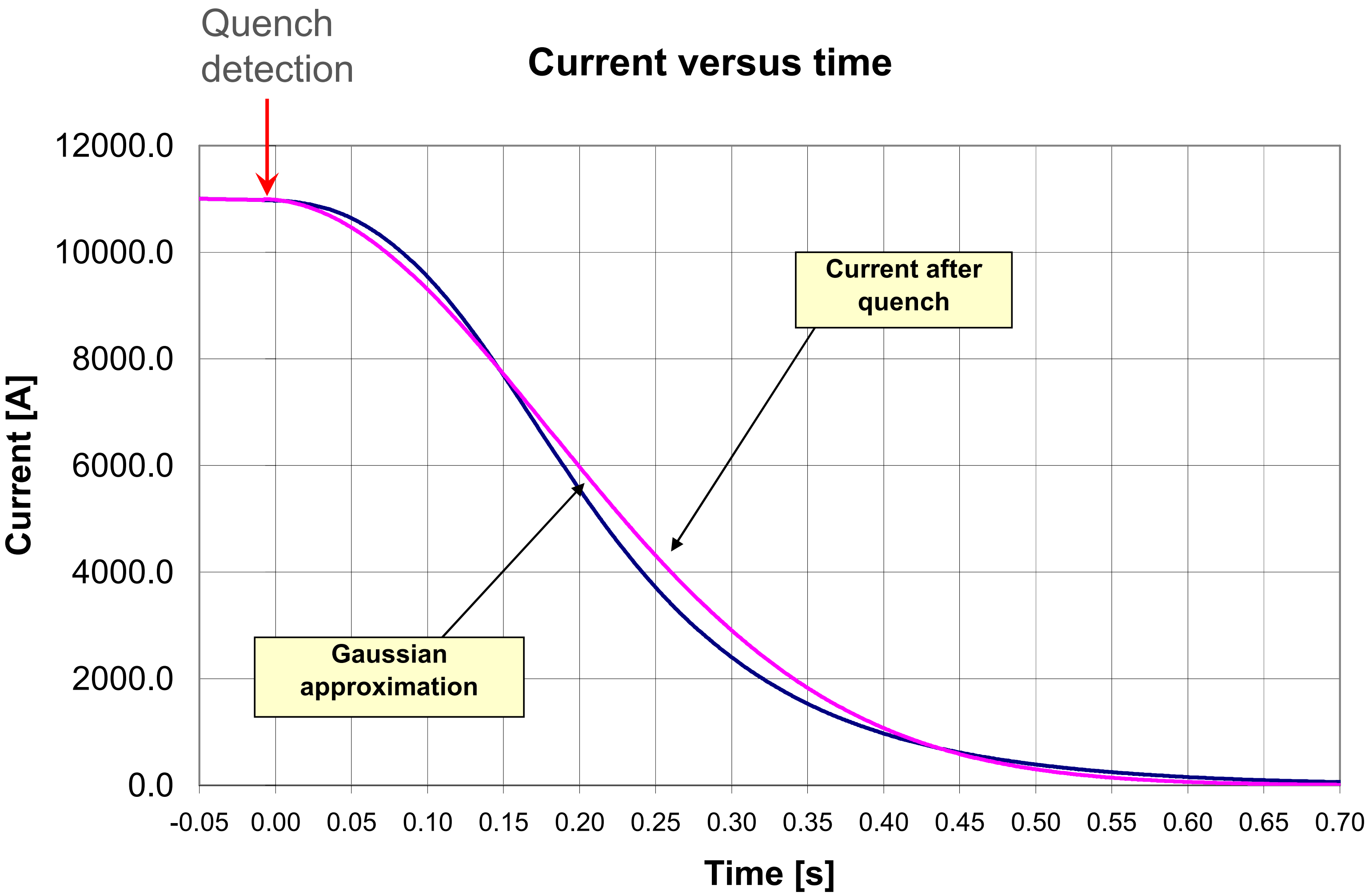
The quench protection system would detect the quench, and trigger a beam dump before the magnetic field starts to decay (M.Zerlauth)

A quench in 154 superconducting dipole magnets in series

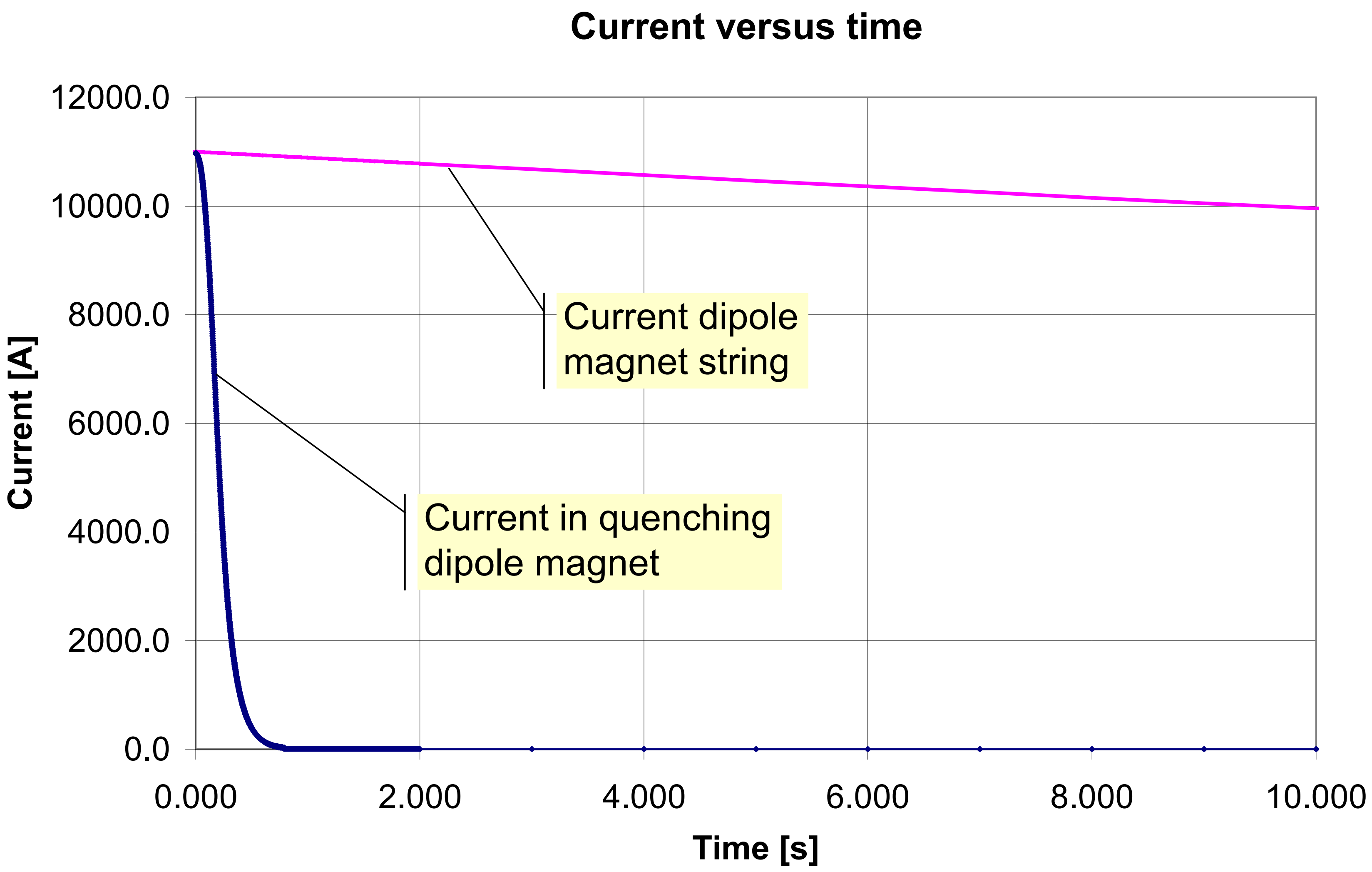


- when one magnet quenches, **quench heaters** are **fired** for **this magnet**
- the **current** in the quenched magnet **decays** in about **200 ms** (at 7 TeV)
- a resistor is switched into the electrical circuit, τ typically 100 s
- the current in all other magnets flows through the bypass diode that can stand the current for this time

Current decay for a quench of a superconducting (dipole) magnet



Current decay in string of magnets



During a quench: effect on closed orbit

Orbit movement due to the current decay in the **quenched magnet**

- Gaussian decay of magnetic field => orbit movement accelerates
- for 7 TeV current decay time constant about 200 ms
- Main dipole decaying field moves orbit by **1σ in 4.6 ms, 2σ in 6.5 ms, 3σ in 7.9 ms**
- Orbit can move from **2σ to 3σ within ~1.9 ms**
- Orbit can move from **25σ to 26σ within 0.3 ms**

Orbit movement due to the current decay in the **magnet string**

- slow current decay, but magnetic field changes in many magnets
- for 154 dipole magnets, the effect compensates in first order

Why quenches of superconducting magnets ? - with unstable beams

"Unstable beams" due to equipment failure or operational failure (not a quench)

- if the failure is detected, the beam would be dumped
- if beam losses are detected with BLMs, the beam would be dumped

Assuming that the beam **is not dumped**: magnets will quench due to beam loss

- **the quench** in a magnet **can accelerate** the beam loss
- for beam losses with a time constant above, say, some 10 ms, the **final time constant for beam loss** is **determined by the quench**

Case A: An initial failure would lead to the beam to be lost in more than, say, 100 ms. The beam halo would quench the magnet, the quench protection systems would detect the quench and trigger the beam dump in time.

Case B: An initial failure would lead to the beam to be lost in much less than 100 ms. The quench protection systems would trigger a beam dump too late (relying on other monitors).

Other failures during magnet powering

Power converter failures

- Power converter off (exponential current decay, for example in case of water failure, etc.)
- Power converter control failure - for example power converter ramps current with maximum voltage
- Wrong reference value for the magnet current

Magnet failures

- Magnet overheating, for example due to cooling problem (power converter to be switched off only after beam is dumped)

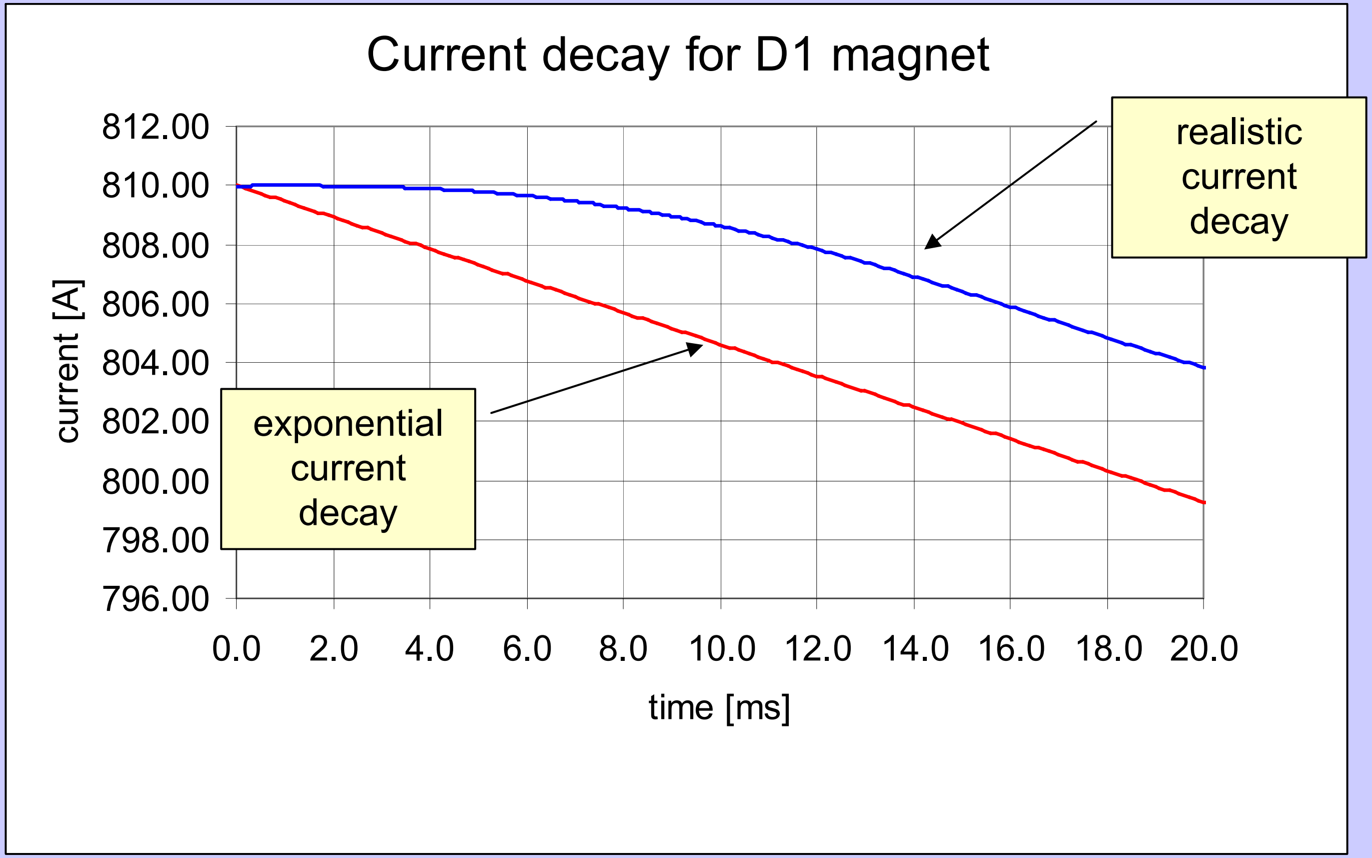
At 450 GeV, power converter failures might be more frequent causes for beam loss than quenches

Normal conducting magnets: orbit movement in case of powering failures

Name of the Magnet (Dipoles)		Max dx/dt at 450 GeV				Max dx/dt at 7 TeV	
	Number of circuits	nominal ramp	PC off	PC ramp max U	Time for 1σ	PC off	Time for 1 σ
		mm/ms	mm/ms	mm/ms	ms	mm/ms	ms
D1 normalconducting separation IR1 IR5	2	0.0100	0.0900	2.3000	0.6	0.4600	0.7
D3 D4 normalconducting magnets in IR3	2	0.0250	0.1100	3.2000	0.4	0.1100	3.0
D3 D4 normalconducting magnets in IR7	2	0.0100	0.0600	2.7500	0.5	0.0600	5.3
MCBWH	8	0.0006	0.0222	0.7330	1.7	0.0599	5.3
MCBWV	8	0.0017	0.0210	0.6890	1.8	0.0564	5.6

- For PC failures (D1, D3, D4), short time too pessimistic, does not take into account power converter response (1-3 ms to be added)
- At 450 GeV, power converter applying maximum voltage creates fastest orbit changes, 20-30 times faster than a power converter trip (such failure is not very likely)
- **At 7 TeV, power converter trip for D1 is the fastest mechanism for orbit changes**

D1 magnet – realistic current decay at 7 TeV



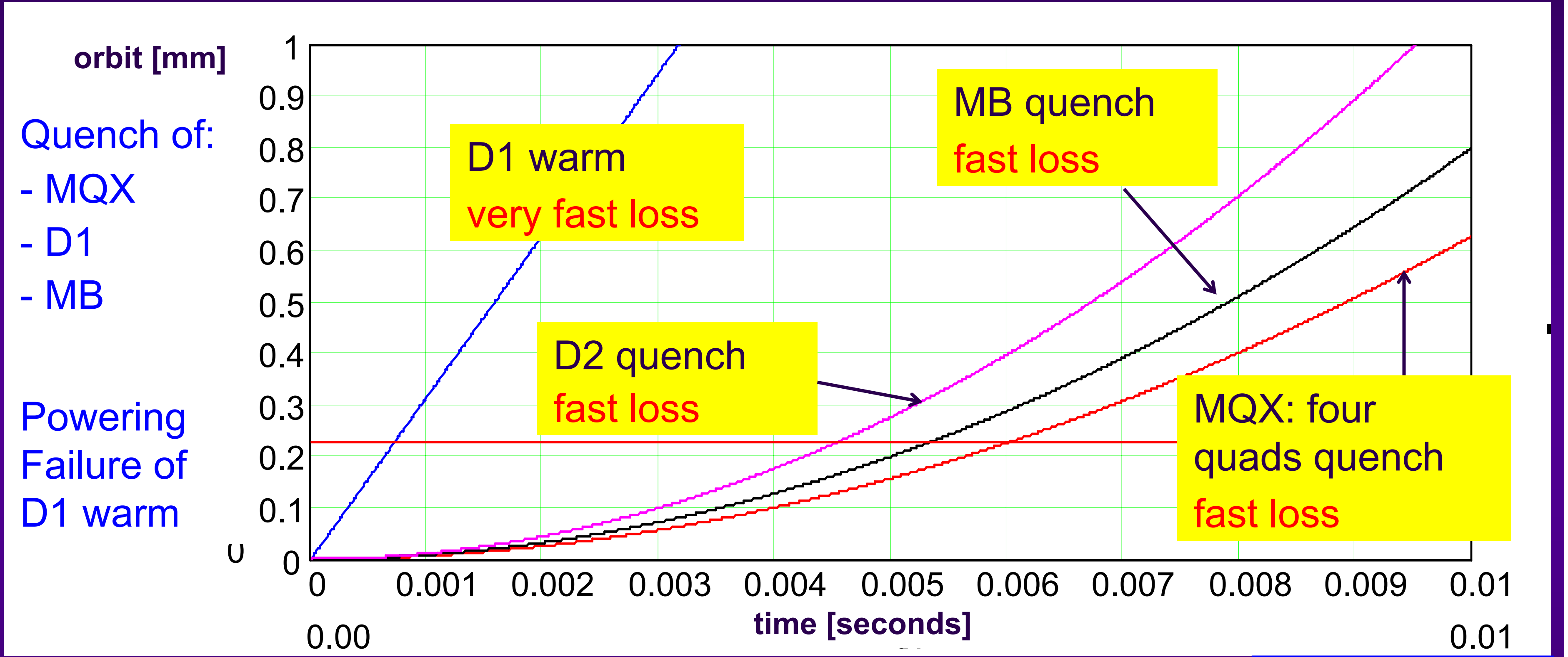
- Simulation using SABER that includes power converter electronics (A.Beuret)
- Current decay slower than for exponential decay
- Protection systems designed to cope with exponential decay – the delay is used as safety margin

Superconducting magnets: orbit movement in case of powering failures and quench

Name of the Magnet (Dipoles)		Max dx/dt at 450 GeV			Max dx/dt at 7 TeV	
	Number of circuits (magnets)	nominal ramp	PC ramp max U	Time for 1σ	PC ramp max U	Quench: Time for 2 to 3 σ
		mm/ms	mm/ms	ms	mm/ms	ms
MB main bends	**8 (154)**		**0.0096**	**130.0**		**1.5**
D1 superconducting separation magnets IR2 IR8	**4**		**0.1460**	**8.6**		**1.2**
D4 superconducting separation magnets IR4	**2**		**0.1140**	**11.0**	**0.0070**	**2.2**
MCBH/V	**752 (752)**	**0.0019**	**0.0037**	**341.2**	**0.0003**	**5.9**
MCBXV	**24 (24)**	**0.0004**	**0.0092**	**136.4**	**0.0029**	**3.0**
MCBXH	**24 (24)**	**0.0013**	**0.0156**	**80.2**	**0.0049**	**3.0**

- At 450 GeV, powering failures of sc magnets in IR2, 4 and 8 are most critical
- At 7 TeV, quenches of the sc D1 magnets and the main dipole magnets are most critical
- Orbit corrector quenches are less critical, most critical are few orbit correctors in the insertions (values for maximum current)

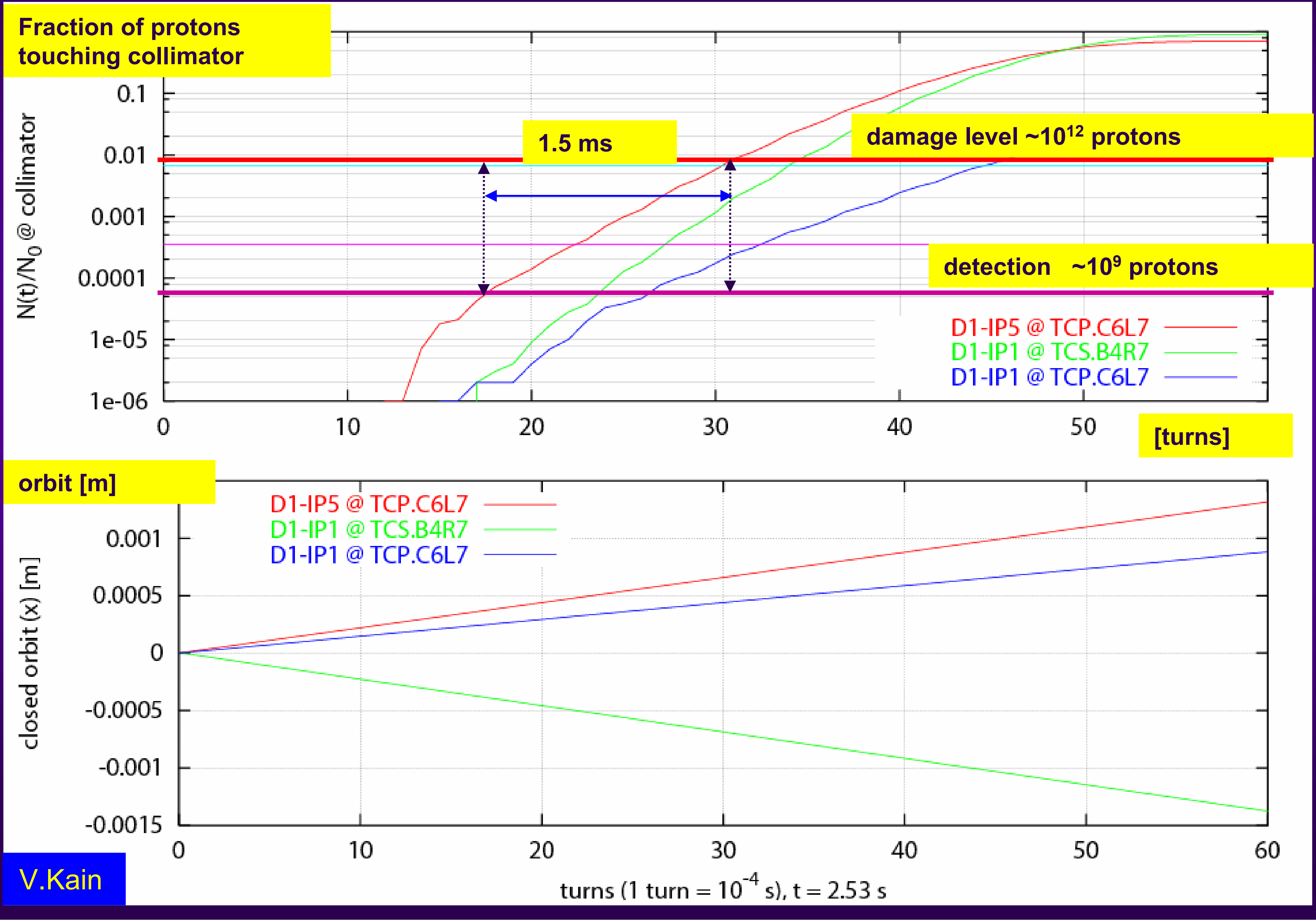
Orbit movement for dipole magnet failures



V.Kain / O.Brüning

- Squeezed optics with max beta of 4.8 km
- All four quadrupole magnets quench, approx. Gaussian current decay time constant 0.2 s (orbit offset due to crossing angle)
- Powering failure for D1, exponential current decay, time constant 2.5 s
- Quench of one MB, approx. Gaussian current decay time constant 0.2 s

Fastest mechanism for multiturn proton losses: failure of D1 in IR1 and IR5 (pessimistic time constants, 7 TeV)



Fraction of protons touching collimator

1.5 ms

damage level ~10^{12} protons

detection ~10^{9} protons

[turns]

orbit [m]

V.Kain

Future Work: Multi-layer Simulation for failure analysis for LHC

Starting with a failure, and then:

=> Effect on beam including beam losses at aperture limitations
=> Detection with Monitoring Systems (HW, beam)
=> Reaction of Protection Systems (Interlocking, beam dump, beam absorbers)
=> Partial damage

Effect on beam: particle tracking

- realistic particle distributions
- realistic machine
  - full aperture model + alignment errors
  - field errors
  - realistic orbit correction
  - collimation, incl. setting errors

Detection & Reaction:

- full description of protection system hierarchy
- failures of protection system equipment (BLMs, beam dump, etc)

Overall Protection Level – Full Analysis of LHC Failures

Potential outcome

- detailed realistic distribution of beam losses around LHC after a failure
- can we operate LHC with part of the BLM system not working ?
- what interlocks are most efficient ?
- optimisation of interlock strategy: what needs to be included ?
- better ideas of possible damage

Simulation methodology developed for Failure Analysis during Injection Process – V.Kain

Conclusions

- Failures in the magnet and powering system are the most likely cause of beam losses at the LHC
- The number of mechanisms for beam losses due to wrong functioning of the magnet and powering system is practically unlimited
- The most likely failures should be detected early by HW surveillance and the beams should be dumped before the magnetic field changes
- However, it is not conceivable to detect all such failures before the beams are affected

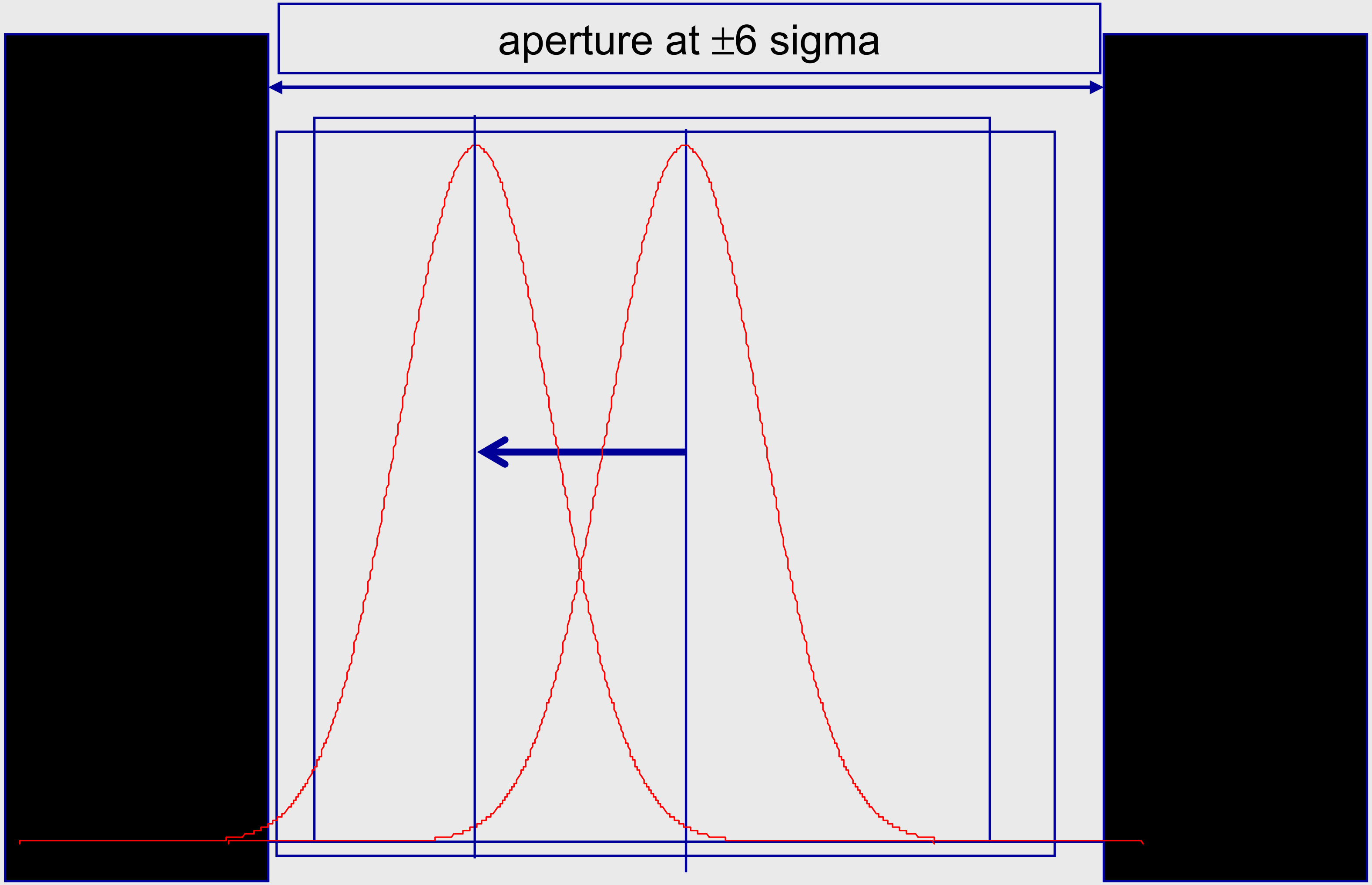
………..therefore beam monitors are required

- Operational failures (driving a power converter with the wrong value for the current) are expected to have longer time constants as the most critical failures
- Due to the most critical failures, the protection systems are designed to detect beam losses and dump the beams within a few turns
- For all failures, redundancy in the detection is envisaged

References

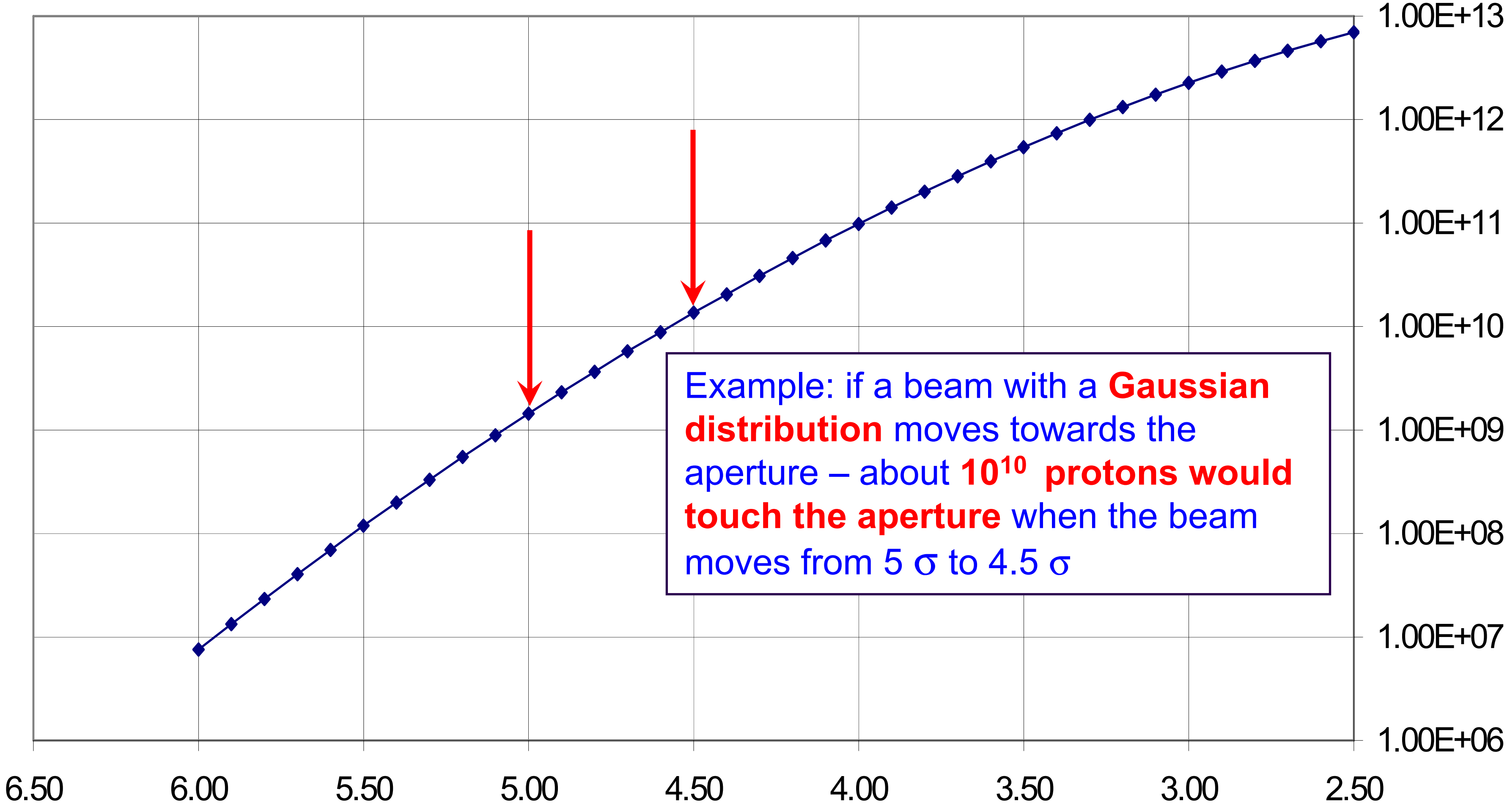
- O.Brüning, Mechanisms for Beam Losses and their Time Constants, LHC Workshop Chamonix 11, 2001
- .V.Kain, Studies of equipment failures and beam losses in the LHC, Diploma thesis, Wien, October 2002.
- V.Kain, Power converter failure of the normal conducting D1 magnet at experiment insertions IR1 and IR5, CERN-LHC Project Note 322, CERN, October 2003
- V.Kain et al., Equipment Failure and Beam Losses in the LHC, 8th European Particle Accelerator Conference, Paris, France, 3 - 7 June 2002

Reserve Slides



movement of the closed orbit assuming Gaussian particle distribution

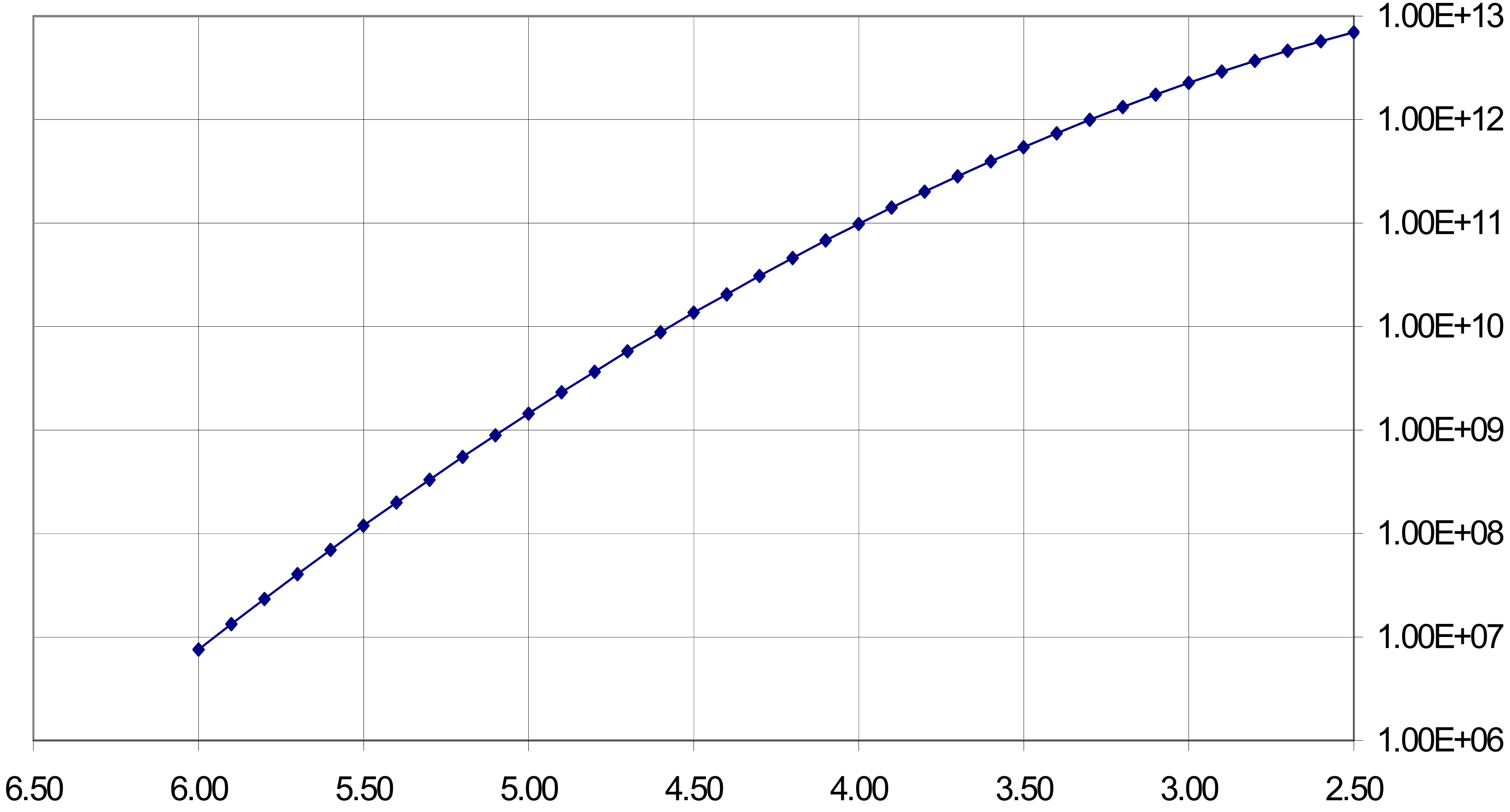
Number of particles touching the aperture when the beam moves



Example: if a beam with a **Gaussian distribution** moves towards the aperture – about **10^{10} protons would touch the aperture** when the beam moves from 5 σ to 4.5 σ

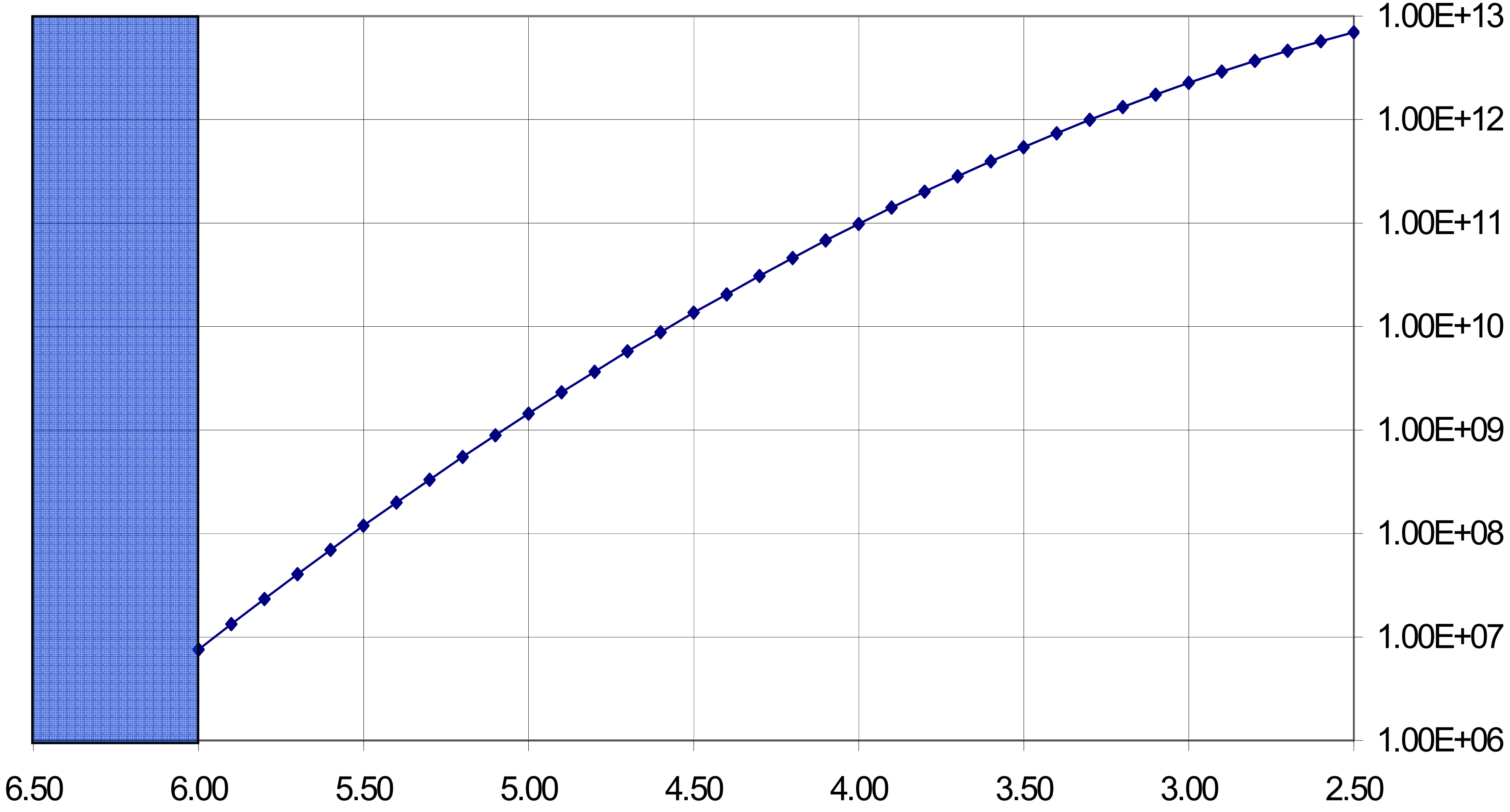
movement of the beam with respect the aperture in units of beam size σ (0 corresponds to the centre of the beam at the aperture)

Before the failure

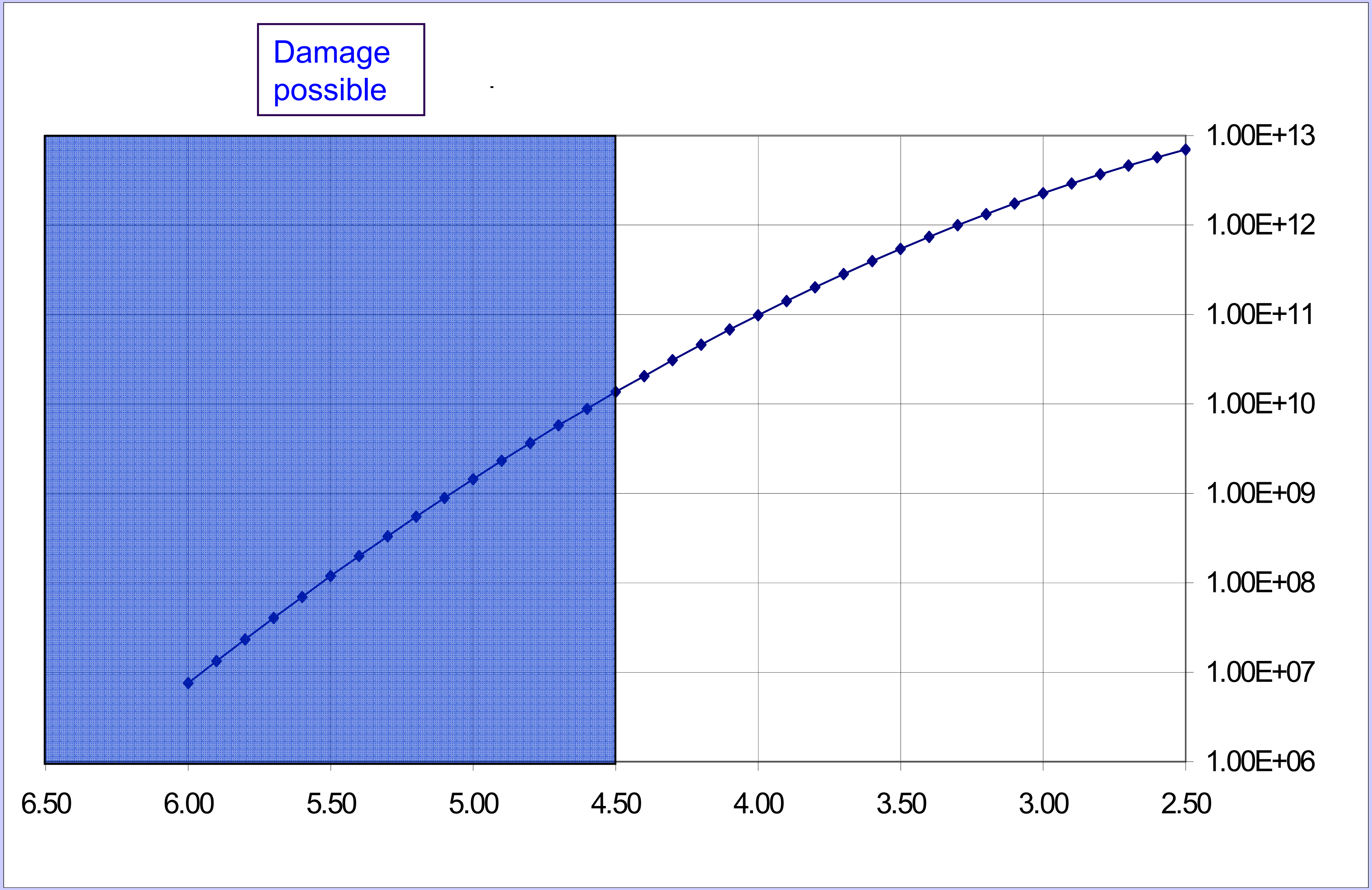


Assuming that the beam moves toward the aperture, and touches the cold aperture first

Magnet quenches

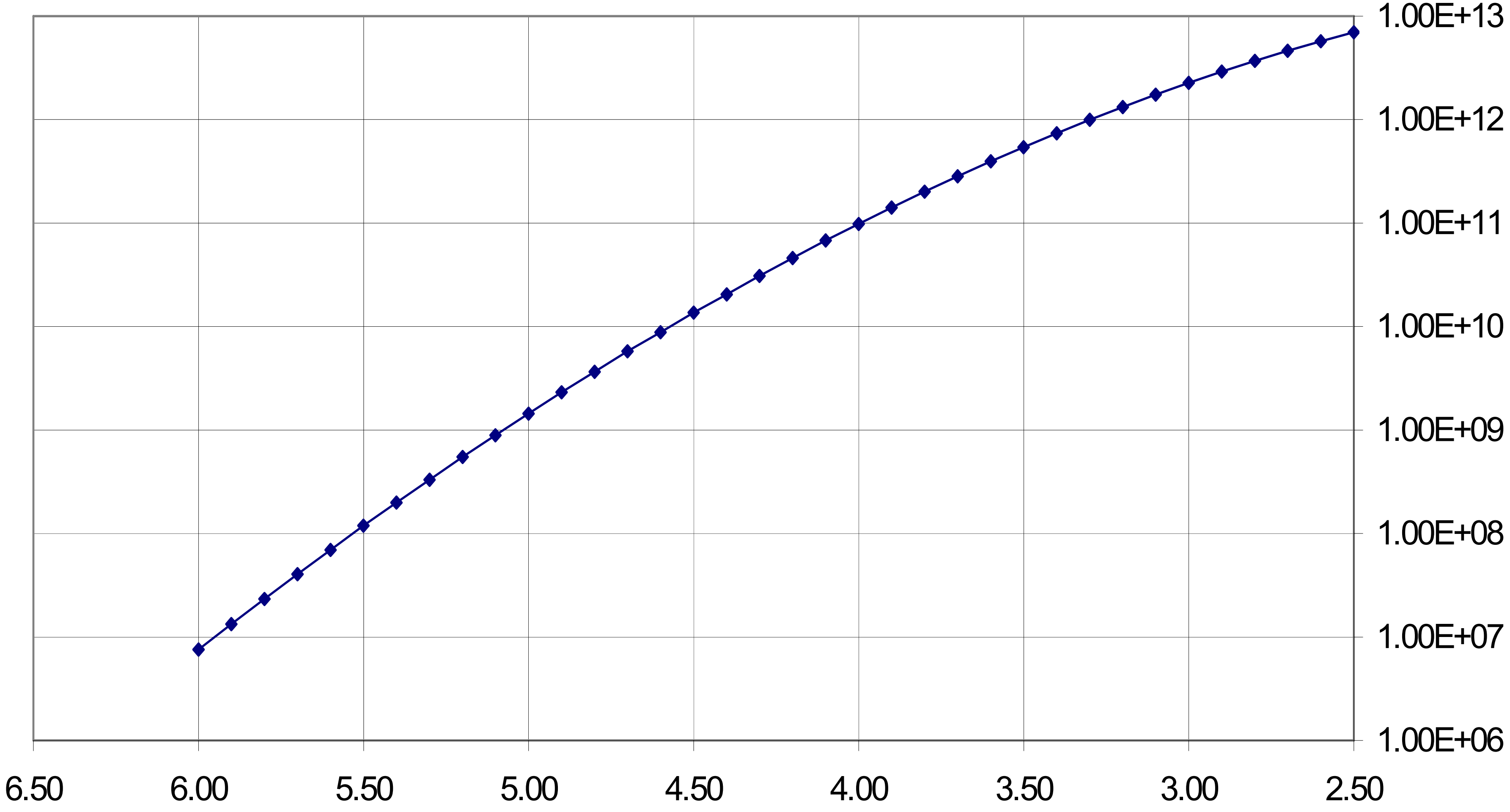


Assuming that the beam moves toward the aperture, and touches the cold aperture first



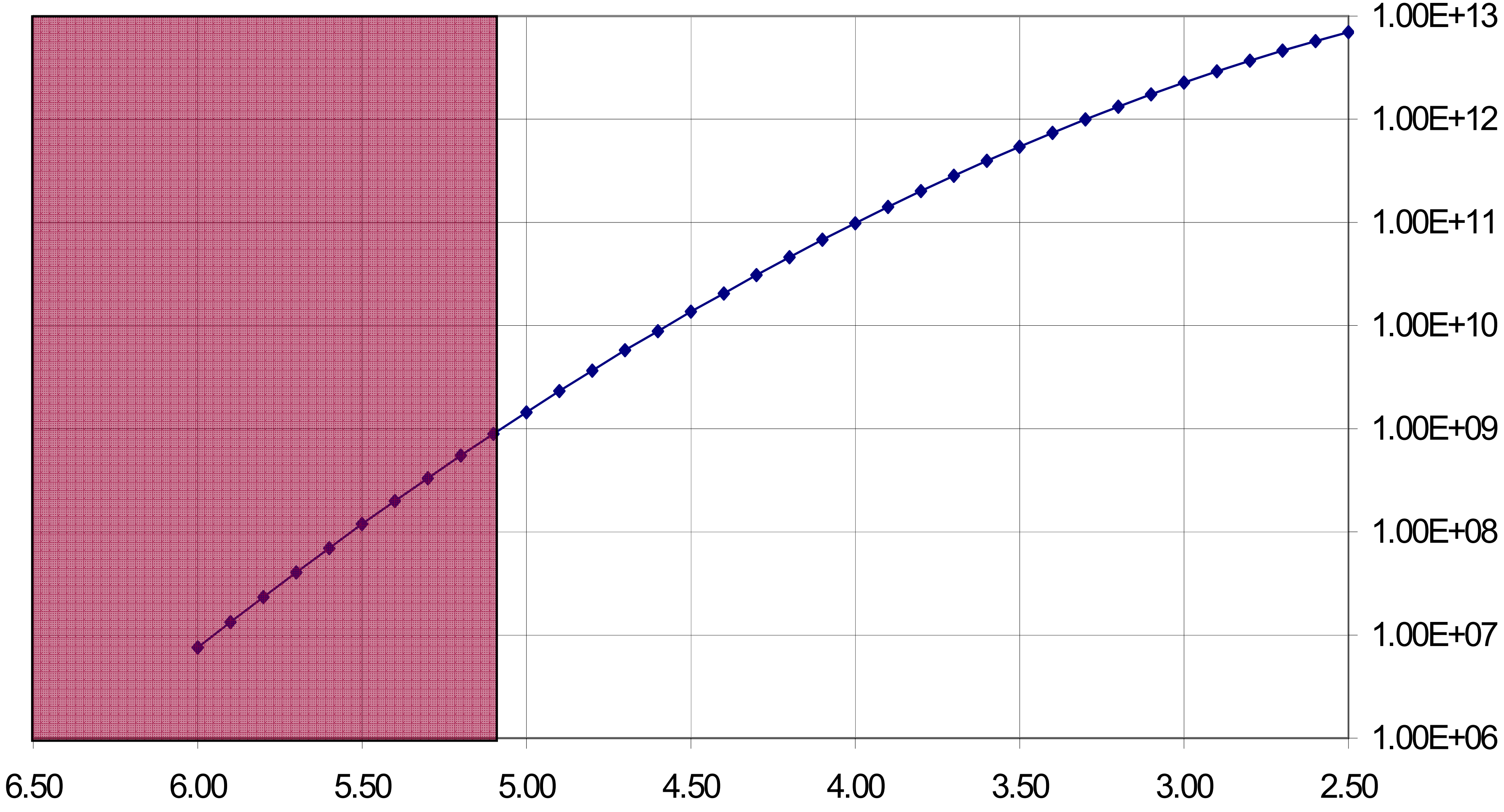
If the beam moves faster than 1.5 σ in 15-20 ms, damage after a quench is detected not excluded

Before the failure

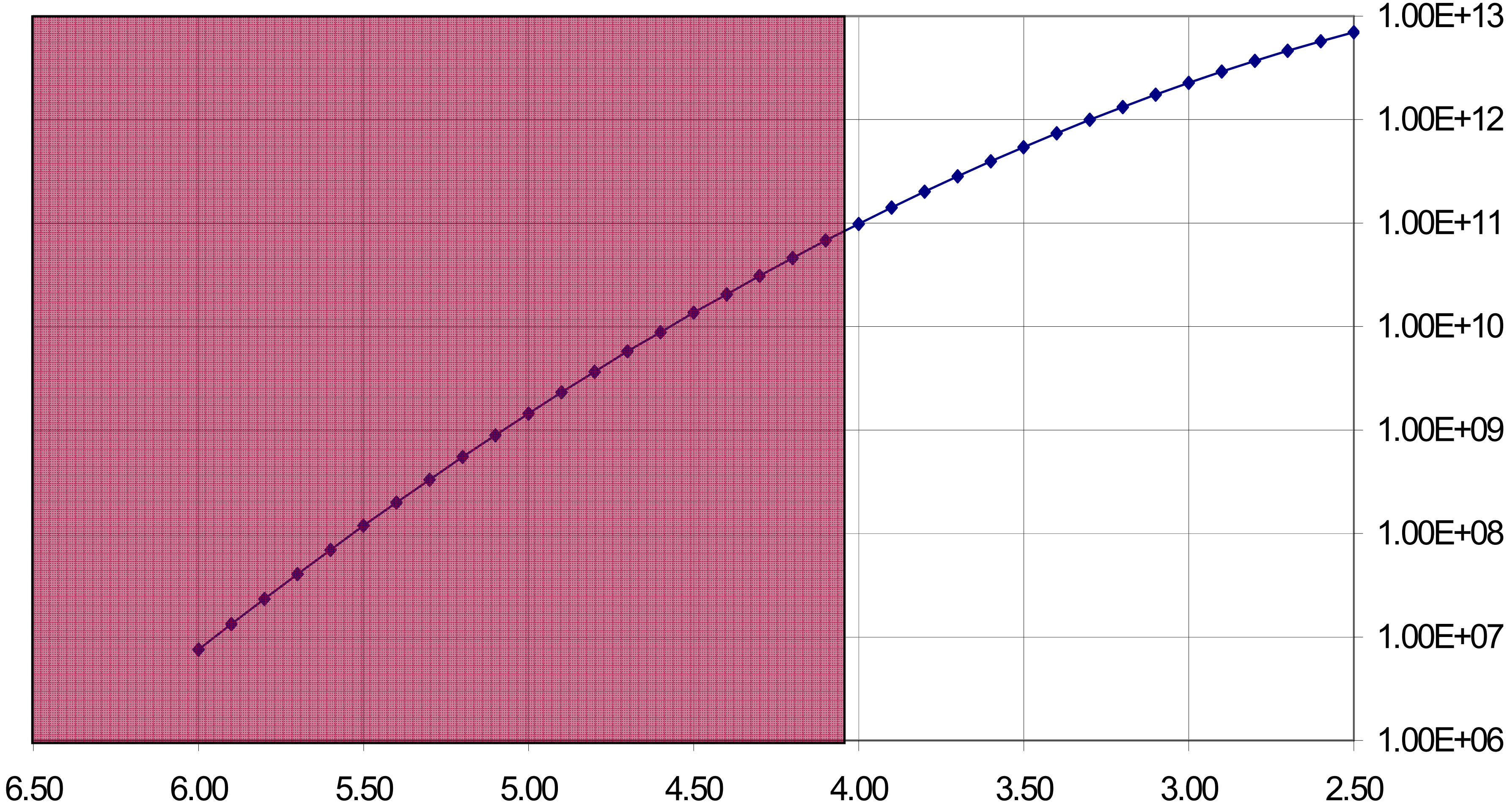


Assuming that the beam moves toward the aperture, and touches a carbon collimator first

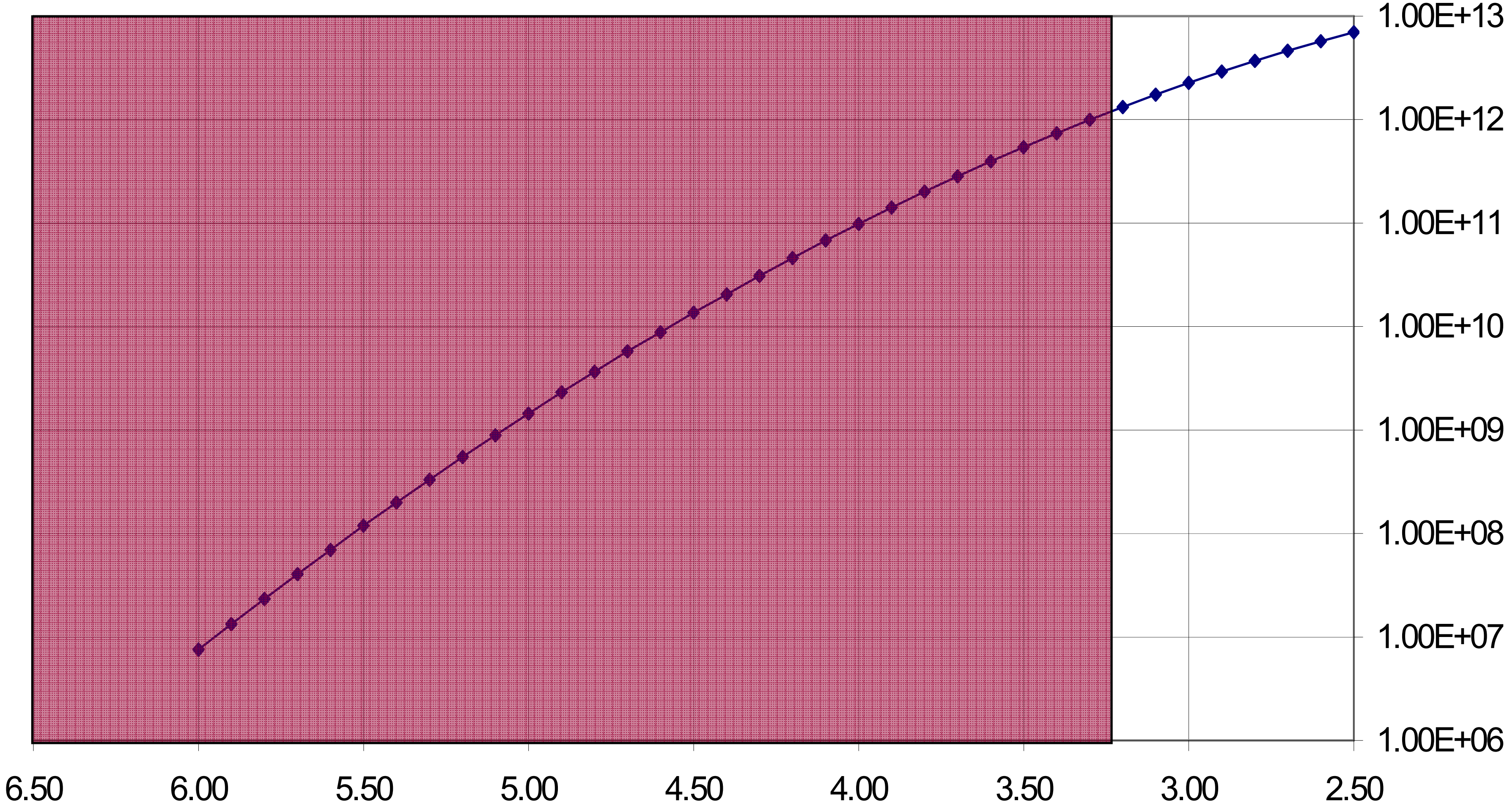
BLM detects beam loss



Magnet quenches assuming cleaning efficiency of 99.99%

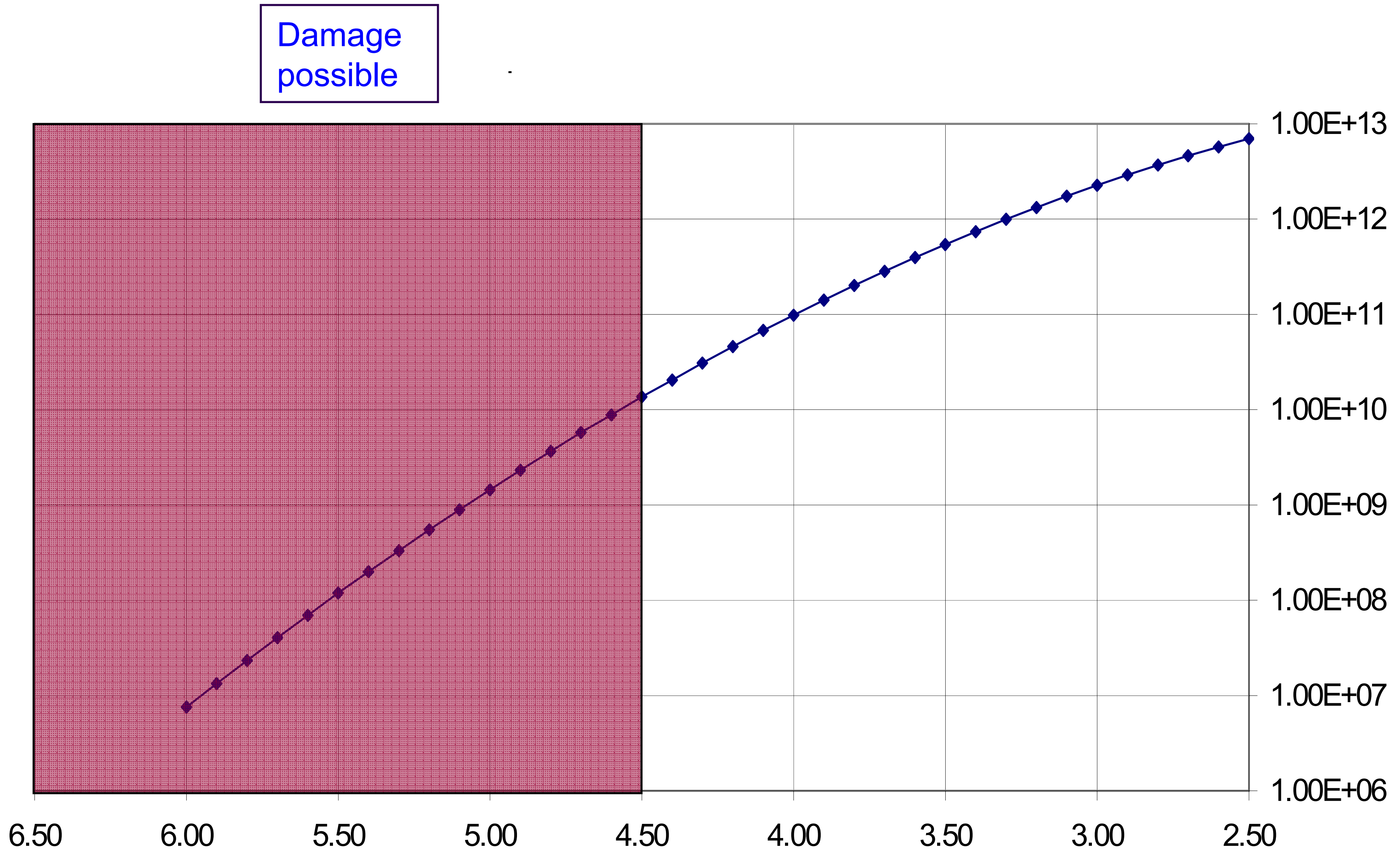


Collimator damage



BLM: If the beam moves faster than 1.5 σ / 0.3 ms, damage of the collimator not excluded

QPS: If the beam moves faster than 0.8 σ / 15-20 ms, damage of the collimator not excluded


Damage possible
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
6.50
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50