Beam Loss Scenarios and Strategies for Machine Protection at the LHC

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presenting material that has been worked out / discussed in the Machine Protection WGand Beam Cleaning WG

LHC parameters and challenges

LHC stored energy and associated risks

Beam lifetime and particle losses

Protection and collimation for beam operation

HALO 2003 Monthauk

Outline

- LHC parameters
  - LHC stored energy and associated risks
- Machine protection and LHC layout
- Beam lifetime and particle losses
- Failures and Protection strategies
  - Single turn failures - injection and dump
  - Multiple turn failures
- Beam losses and machine aperture
- Beam monitoring and collimators
- Conclusions

Recalling LHC Parameters and Challenges for Protection

Momentum at collision	**7 TeV/c**	
Momentum at injection	450 GeV/c	
Dipole field at 7 TeV	8.33 Tesla	
Circumference	26658	m
Number of electrical circuits	~1700	
Number of magnets	~8000	

High beam energy in LHC tunnel

Superconducting NbTi magnets at 1.9 K

Stored energy in magnets very large

Luminosity	**10^{34} cm^{-2}s^{-1}**	
Number of bunches	2808	
Particles per bunch	$1.1 \cdot 10^{11}$	
DC beam current	0.56	A
Stored energy per beam	**350**	**MJ**

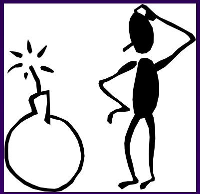
Normalised emittance	**3.75**	**μm**
Beam size at IP / 7 TeV	15.9	μm
Beam size in arcs	200-300	μm

High luminosity at 7 TeV

very high energy stored in the beam

beam power concentrated in small area

Energy in Magnets and Beams



Energy in the magnet system: 11 GJ

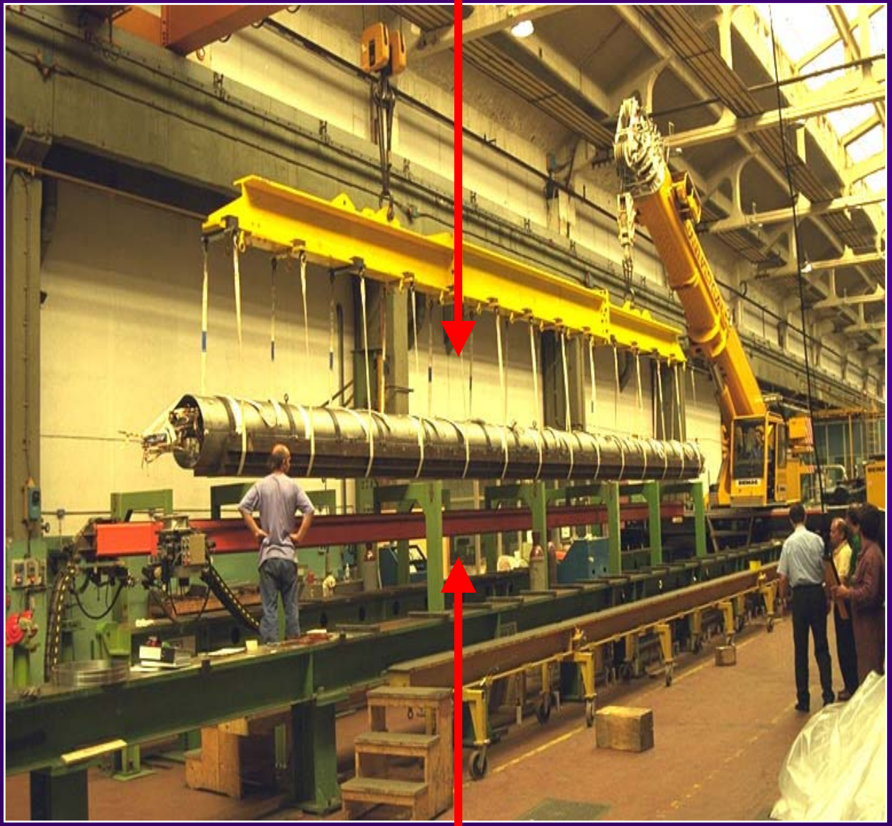
- In case of failure, extract energy with a time constant of up to about 100 s

Energy in two LHC Beams: 700 MJ

- Dump the beams in case of failure within 89 μs after dump kicker fires

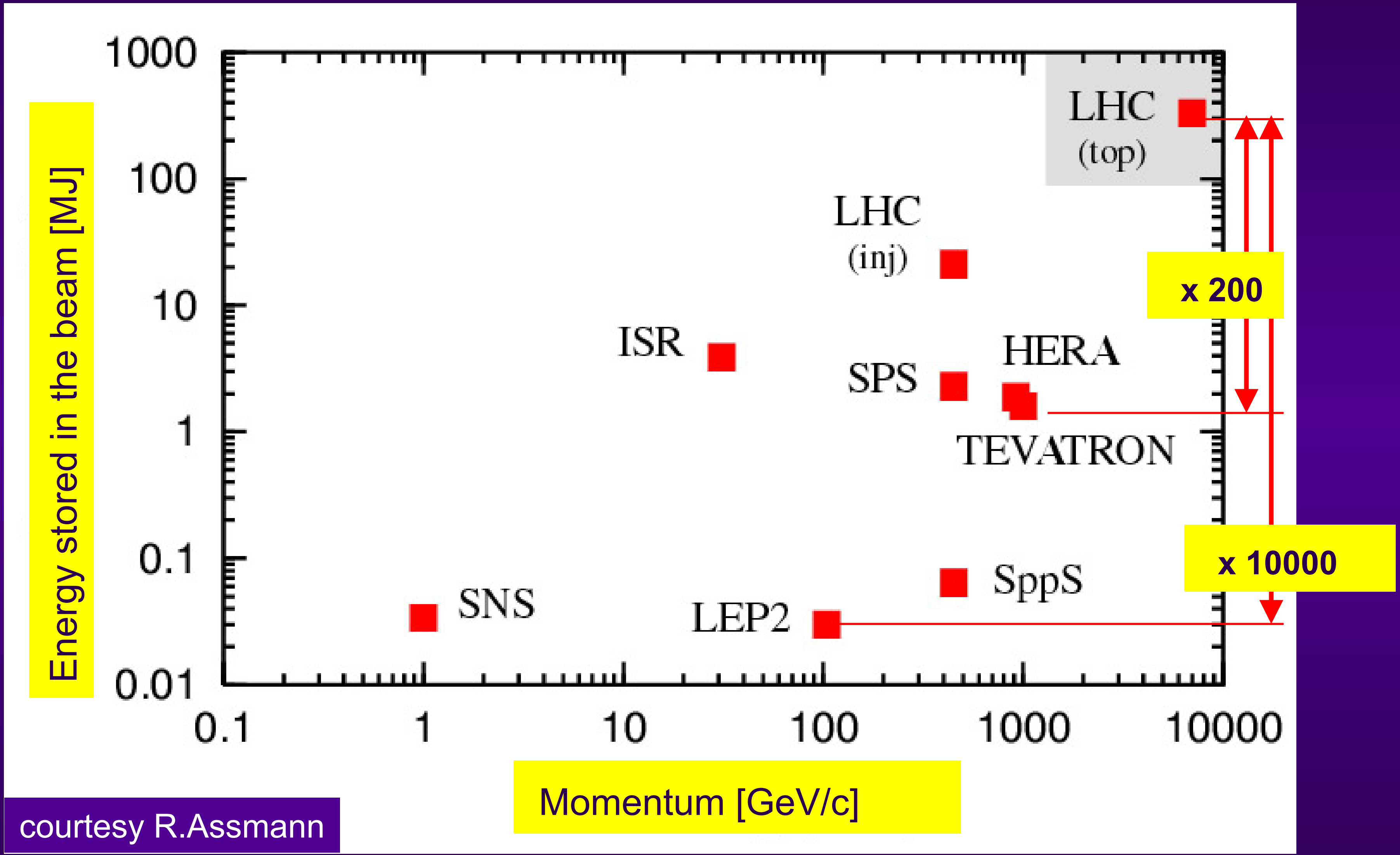
One beam, nominal intensity corresponds to an energy that melts 500 kg of copper

Drop 35 tons from 28 km



Drop it from 2 km

Challenges: Energy stored in the beam



Transverse energy density: even a factor of 1000 larger

LHC and other accelerators

- Particle momentum = 7 • Tevatron / HERA
- Luminosity = 1.1 • B-Factories, 200 • Tevatron
- Complexity = 3-6 • LEP / HERA
- **Energy stored in beams = 100 • SPS / Tevatron / HERA**
- **Energy density in beams = 1000 • SPS / Tevatron / HERA**

In **other accelerators** there is already **concern** due to large stored beam energy and accidents happened :

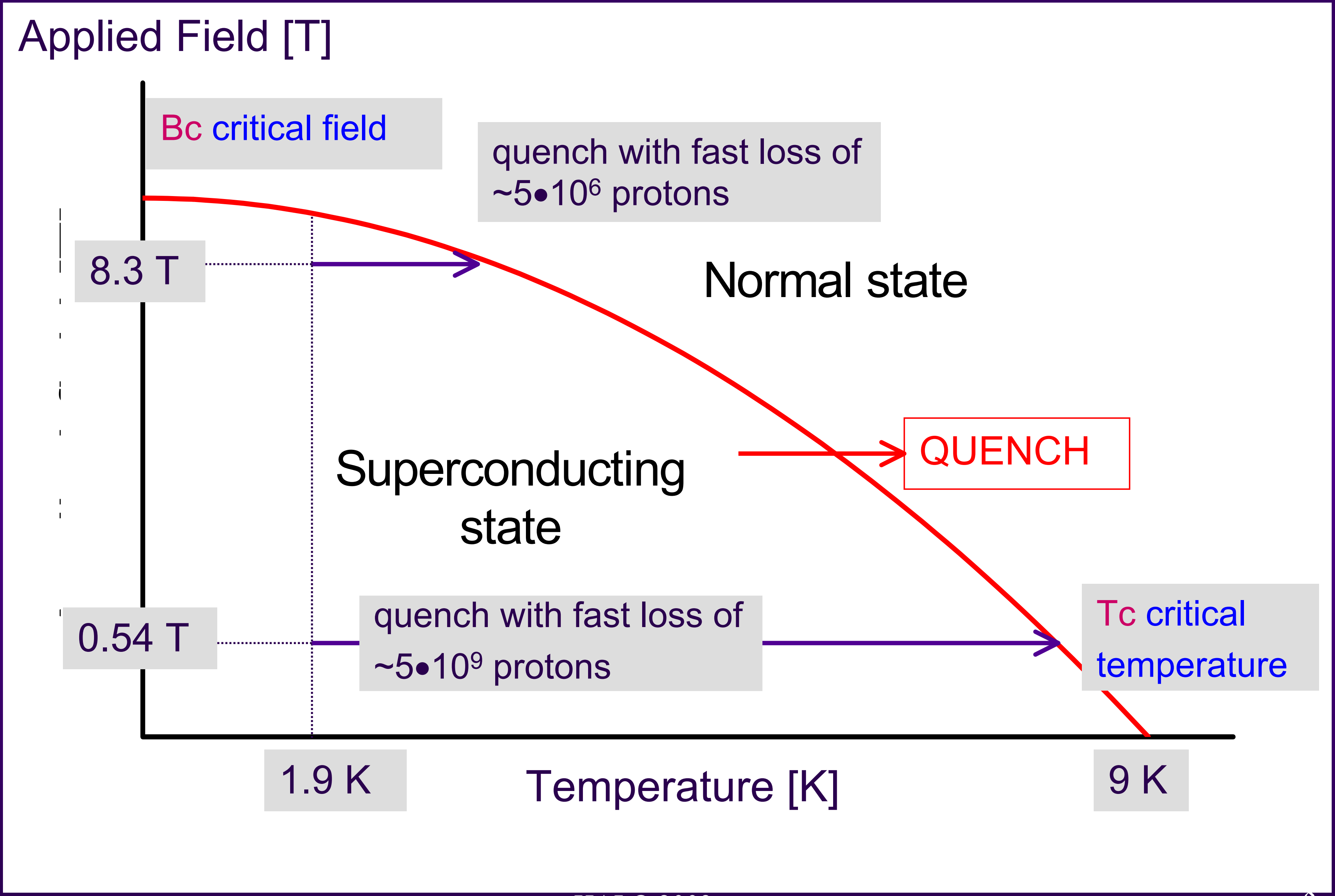
- **SPS: holes drilled through vacuum chamber, UA2 detector damaged**
- **Tevatron: several accidents last year, part of central detector CDF damaged**

Energy conservation: Where do the particles finally go?

- Particles could ....
  - **collide with a proton in the counter - rotating beam**
  - **be extracted into the beam dump blocks**
  - **collide with a gas molecule**
  - **collide with the aperture of the machine - hopefully with a collimator and not with the aperture of a sc magnet**

- The only component that can stand a fast loss of the full beam at top energy is the beam dump block - all other components would be damaged
- At 7 TeV, fast beam losses with an intensity of about **5% of a “nominal bunch”** could damage superconducting coils

Operational margin of a NbTi superconducting magnet



The risks of uncontrolled beam losses

Damaging equipment in case of uncontrolled release of part of the beam into the magnets

- Dipole magnet replacement would take about 30 days

Damaging equipment in case of full beam loss into magnets

- No realistic estimation of possible damage

Magnets could quench due to beam losses, or due to other failures

- Quench recovery at 7 TeV could take several hours

Beam losses without quench due to a large variety of failures (sc magnets, resistive magnets, other elements…)

- Recovery from 7 TeV could take hours

Collimators and beam abosorbers

Collimators for cleaning the beam halo (see presentation of J.B.Jeanneret)

- close to the beam 5-10 σ
- must be movable
- must be accuratly adjusted (within a fraction of one σ)
- position depends on optics and possibly energy

Collimators for protection of equipment

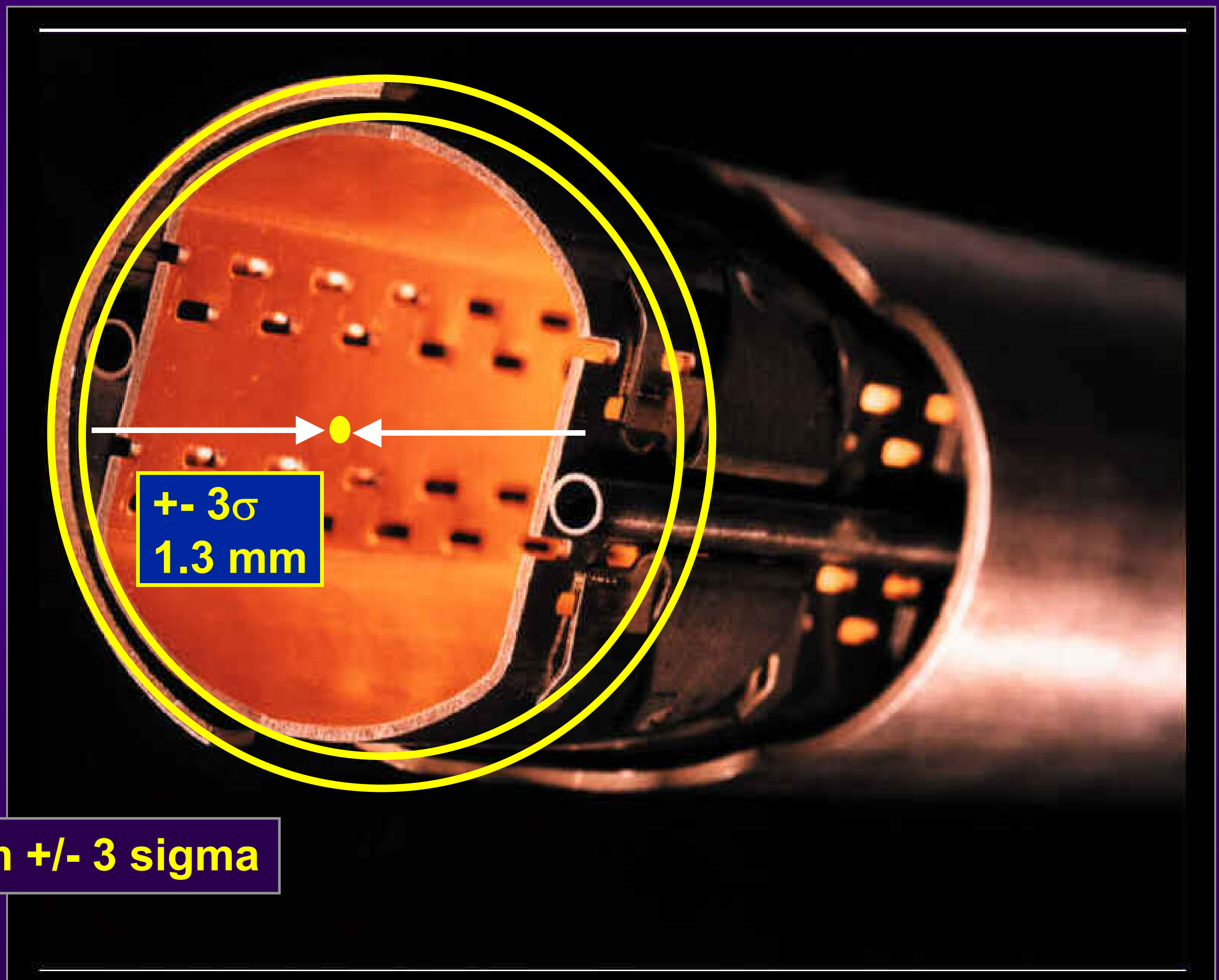
- shadow the equipment 10-40 σ
- should be movable
- some adjustment might be required
- position might depend on optics and possibly energy

Absorbers for protection of equipment

- shadow the equipment at some 10 σ
- fixed position
- no adjustment

Energy density: Beam in vacuum chamber at 7 TeV ….

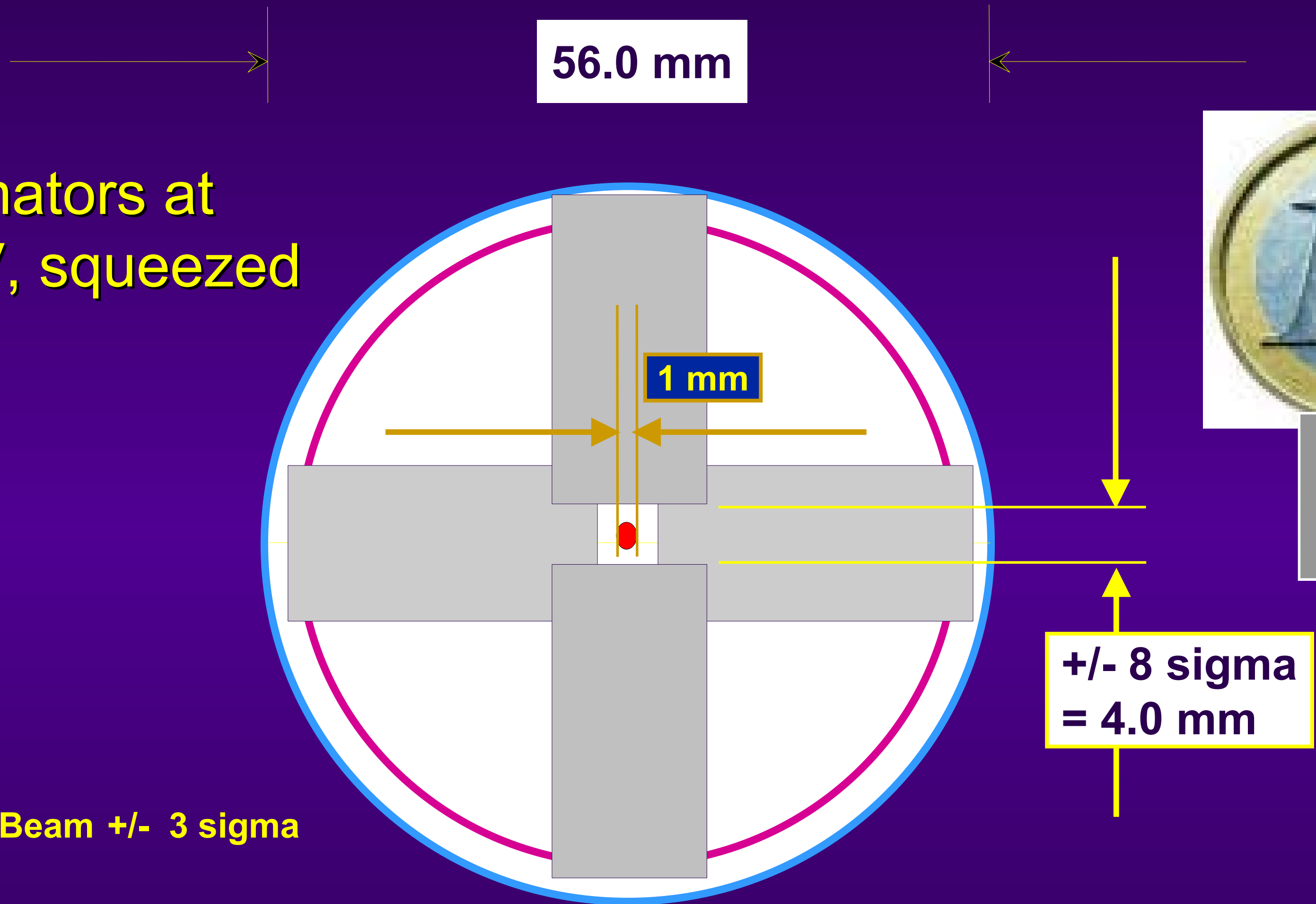
56.0 mm



Beam +/- 3 sigma

…and the requirements for collimator opening

Collimators at
7 TeV, squeezed



Ralph Assmanns EURO

Beam +/- 3 sigma

Example: Setting of collimators at 7 TeV - with luminosity optics

Beam must always touch collimators first !

Collimators might remain at injection position during the energy ramp

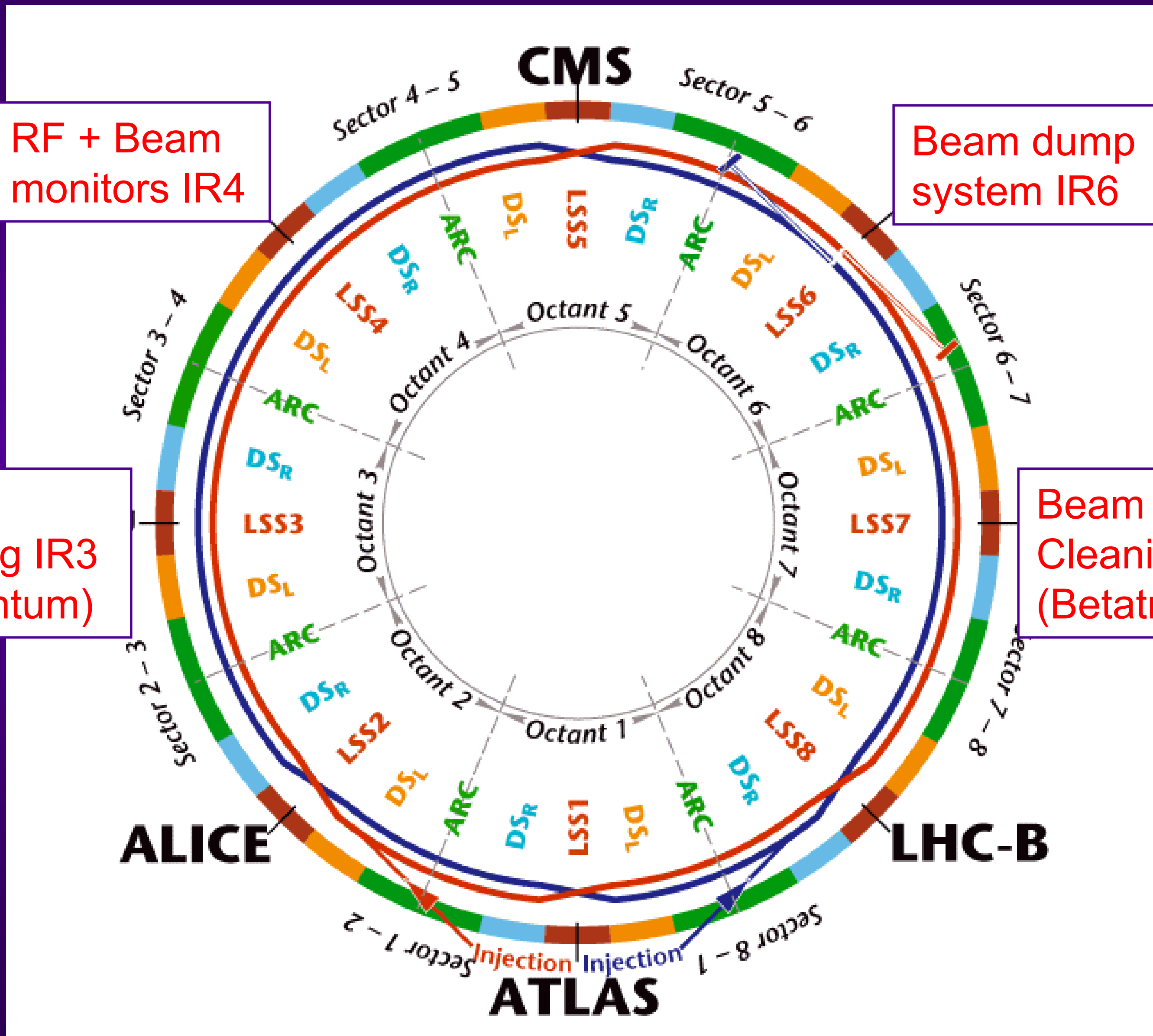
LHC ring: 3 insertions for machine protection systems

RF + Beam monitors IR4

Beam dump system IR6

Beam Cleaning IR3 (Momentum)

Beam Cleaning IR7 (Betatron)



Lifetime of the beam with nominal intensity at 7 TeV

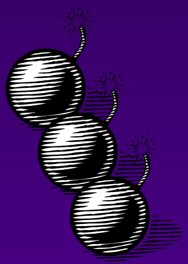
Beam lifetime	Beam power into equipment (1 beam)	Comments
100 h	1 kW	Healthy operation
10 h	10 kW	Operation acceptable, **collimation must absorb large fraction of beam energy**
12 min	500 kW	**Operation only** possibly for **short time**, collimators must be very efficient
1 s	330 MW	**Failure of equipment - beam must be dumped fast**
15 turns	order of TW	**Failure of D1 normal conducting dipole magnet - monitor beam losses, beam to be dumped as fast as possible**
1 turn	order of TW	**Failure at injection or during beam dump, potential damage of equipment, protection relies on collimators**

Beam loss time constants

Single turn failures

Ultra-fast beam loss

- Injection kickers
- Beam dump kickers
- Aperture kickers



Passive protection

- Avoid such failures (high reliability systems)
- **Rely on collimators and beam absorbers**

Multiple turn failures

Very fast beam loss (several turns)

- D1 normal conducting magnet

Fast beam loss (> 5 ms)

- Magnets, other systems

Slow Beam loss (several seconds)

- Magnets, other systems

Active Protection

- Failure detection (from beam monitors and / or equipment monitoring)
- Issue beam abort signal
- **Fire Beam Dump**

Single turn failures

- Failures during injection
  - Beam from SPS + transfer line has unacceptable parameters
  - Failure of the injection kicker
  - One element in the LHC is faulty (for example, one of the 900 orbit corrector magnets at maximum current)

- Unclean beam dump
  - Pre-firing of one kicker module - other kickers fire delayed
  - Kickers fire non-synchronised to the beam abort gap
  - Particles in Beam Abort Gap during beam dump

Multiple turn failures: "Magnet" failures

- Quench of superconducting magnets
  - Quench of a single magnet
  - Quench of more than one magnet
- Discharge of magnets with a resistance in the circuit (after quench, or by failure)
- Failure of magnet powering
  - 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 current
- Electric short in the coil of a normal conducting magnet

Multiple turn failures: Other failures

- Aperture limitation in beam pipe (circulating beam)
  - Vacuum valve moves into beam
  - Collimator moves into beam
  - Other element moves into beam
  - Loss of beam vacuum
- Failure in the RF system
  - Debunching of beam and number of protons in the abort gap… leads to single turn failure when beam is dumped
- Operational failures
- Combined failures, for example after Main Disturbances

Protection strategies: Single turn failures

Beam from injector (SPS) at 450 GeV through 2.8 km long transfer lines

- collimation in transfer lines protect injection elements against failures upstream: SPS, extraction kicker from SPS, transfer line elements, …)
- collimator after injection kicker in LHC (TDI) protects LHC elements

Injected beam: injection of high intensity beam only allowed when beam is already circulating

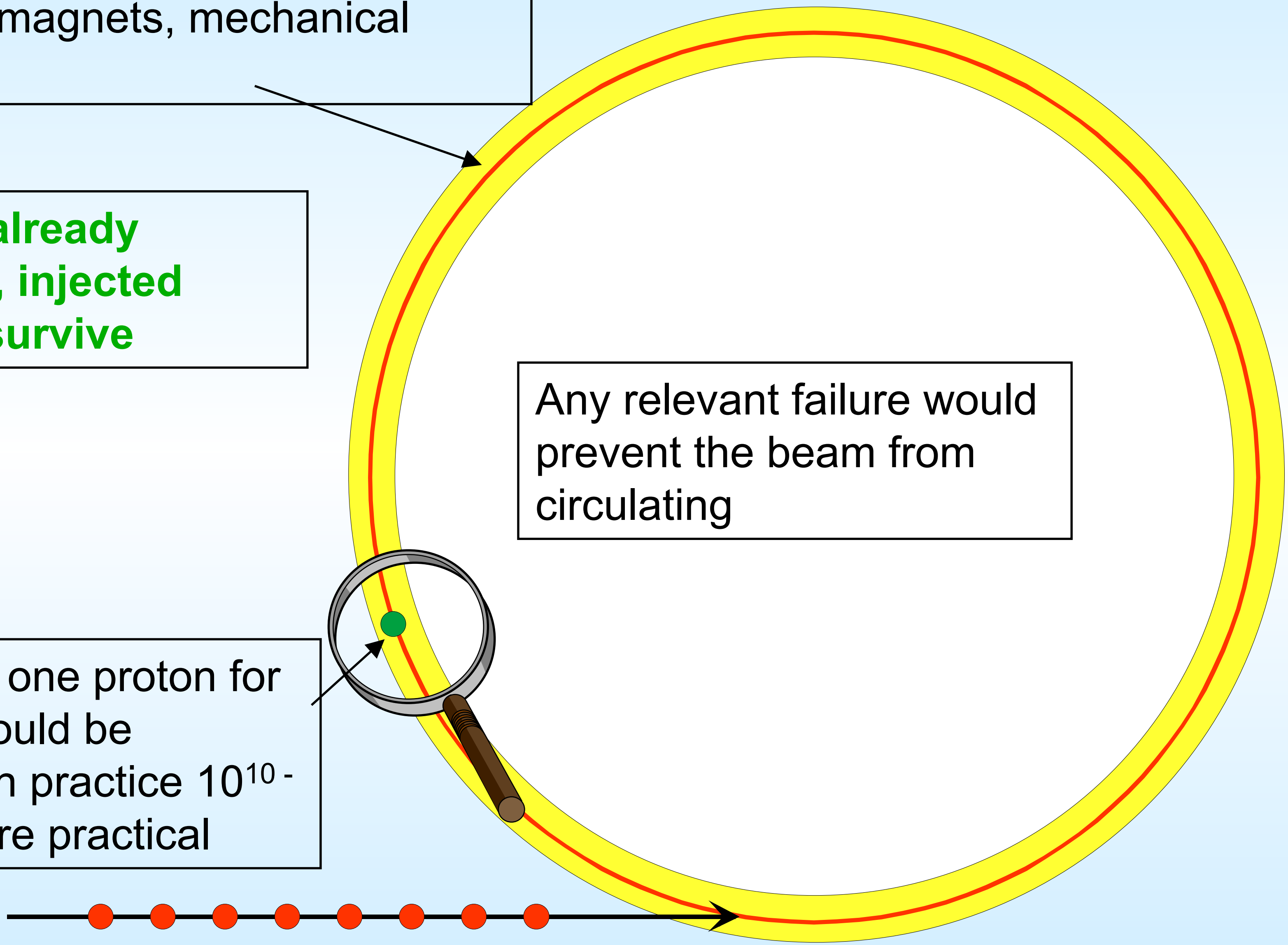
- when there is no beam in the LHC, only injection of beam with limited intensity is allowed (intensity non destructive)
- when beam already circulates - inject high intensity beam

Beam dump failure

- collimators are required to protect machine (TCDQ and others)
- enough aperture that damage of valuable equipment is avoided - impact on optics, layout, operational parameters (orbit, tune, etc.)

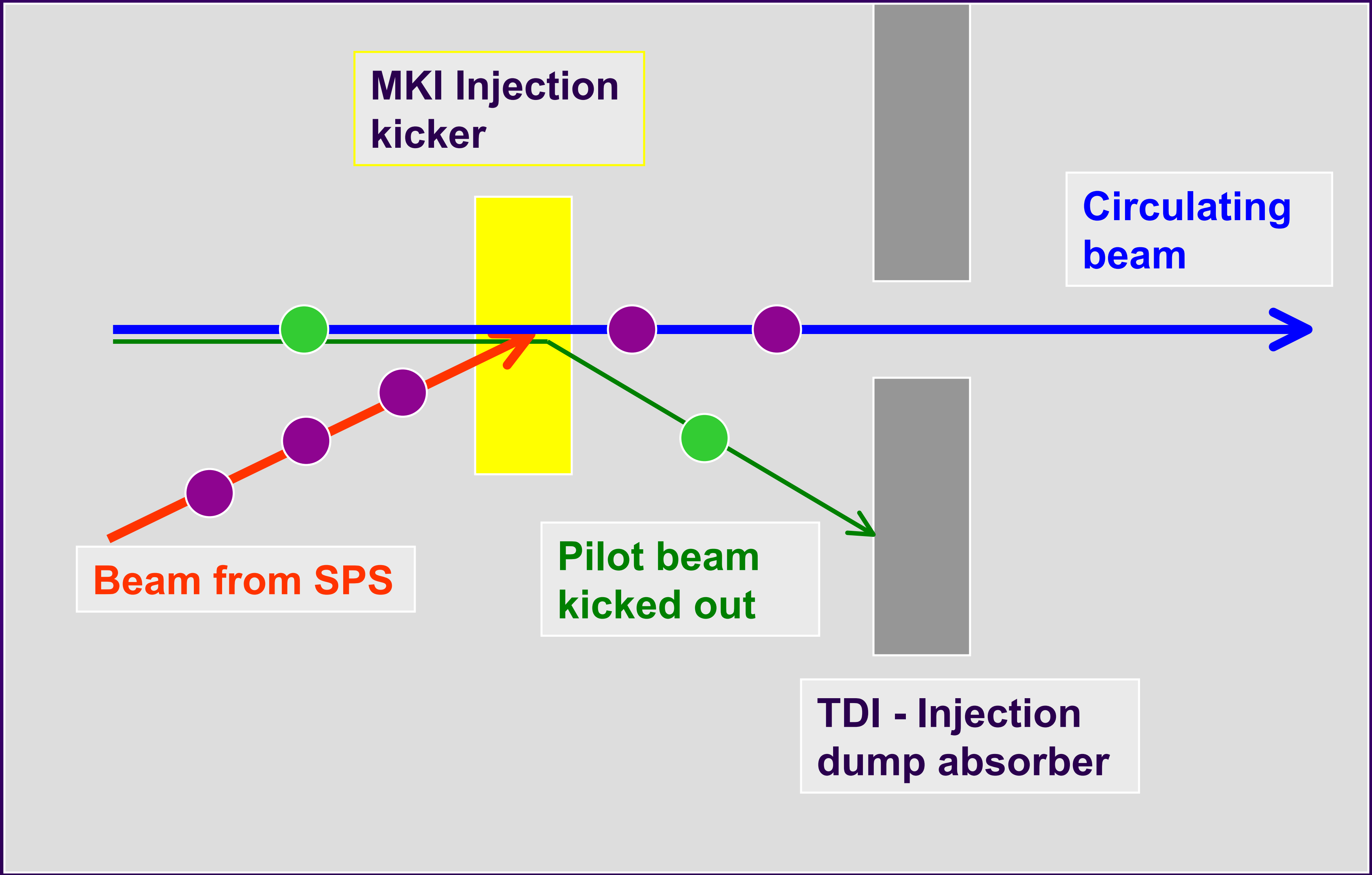
LHC ring with several 1000 objects that could prevent the beam from circulating (magnets, mechanical objects, …)

If beam is already circulating, injected beam will survive

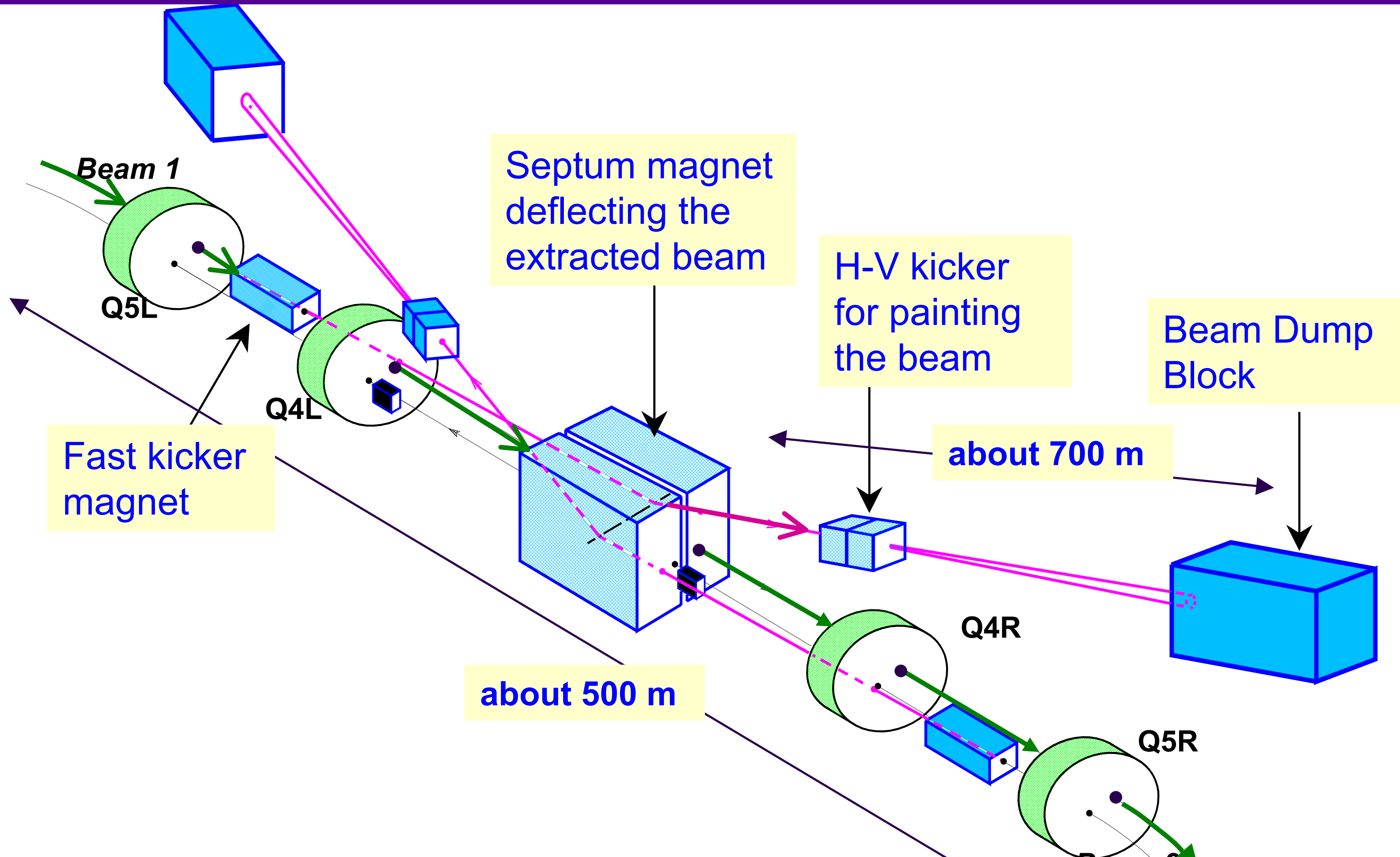


In principle, one proton for checking would be sufficient - in practice 10^{10} - 10^{11} are more practical

Injection: Replacing pilot beam by batch from SPS



Dump the beam with the system in IR6 in case of unacceptable losses



Slide from AB - Beam Transfer Group

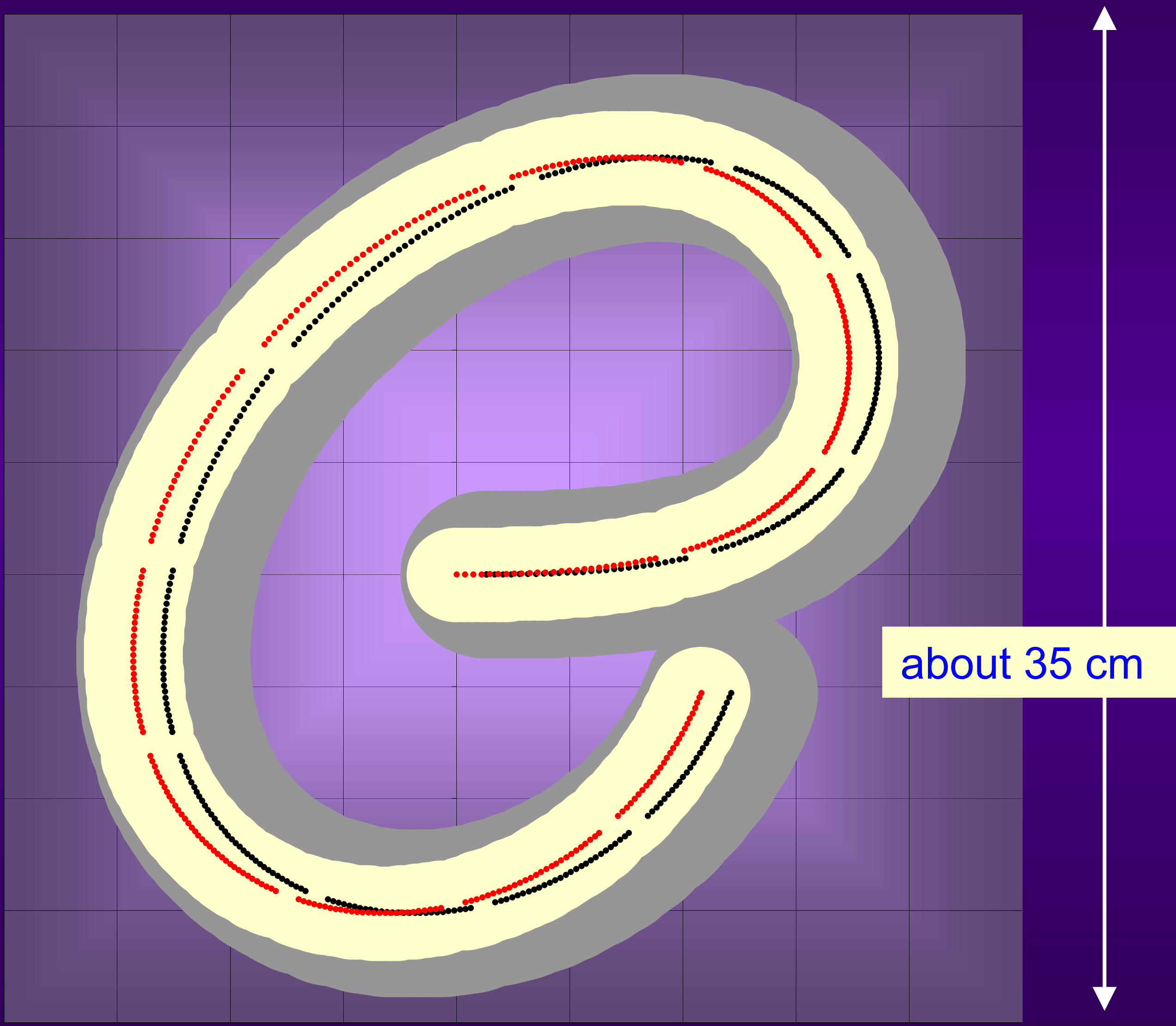
Painting the Beam on Beam Dump Block

initial transverse beam dimension in the LHC about 1 mm

beam is blown up due to long distance to beam dump block

additional blow up due to fast dilution kickers: painting of beam on beam dump block

beam impact within less than 0.1 ms



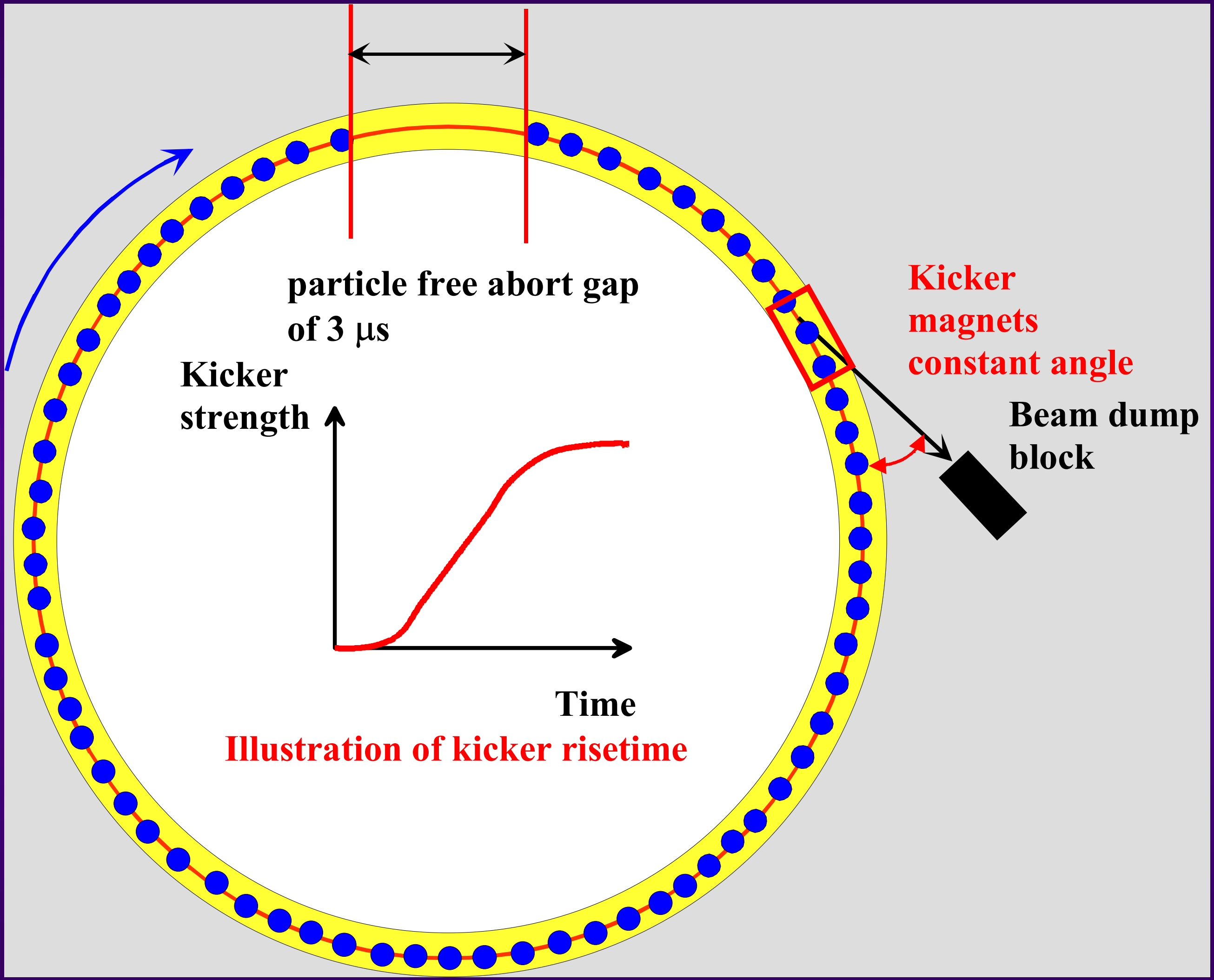
M.Gyr

Requirement for clean beam dump

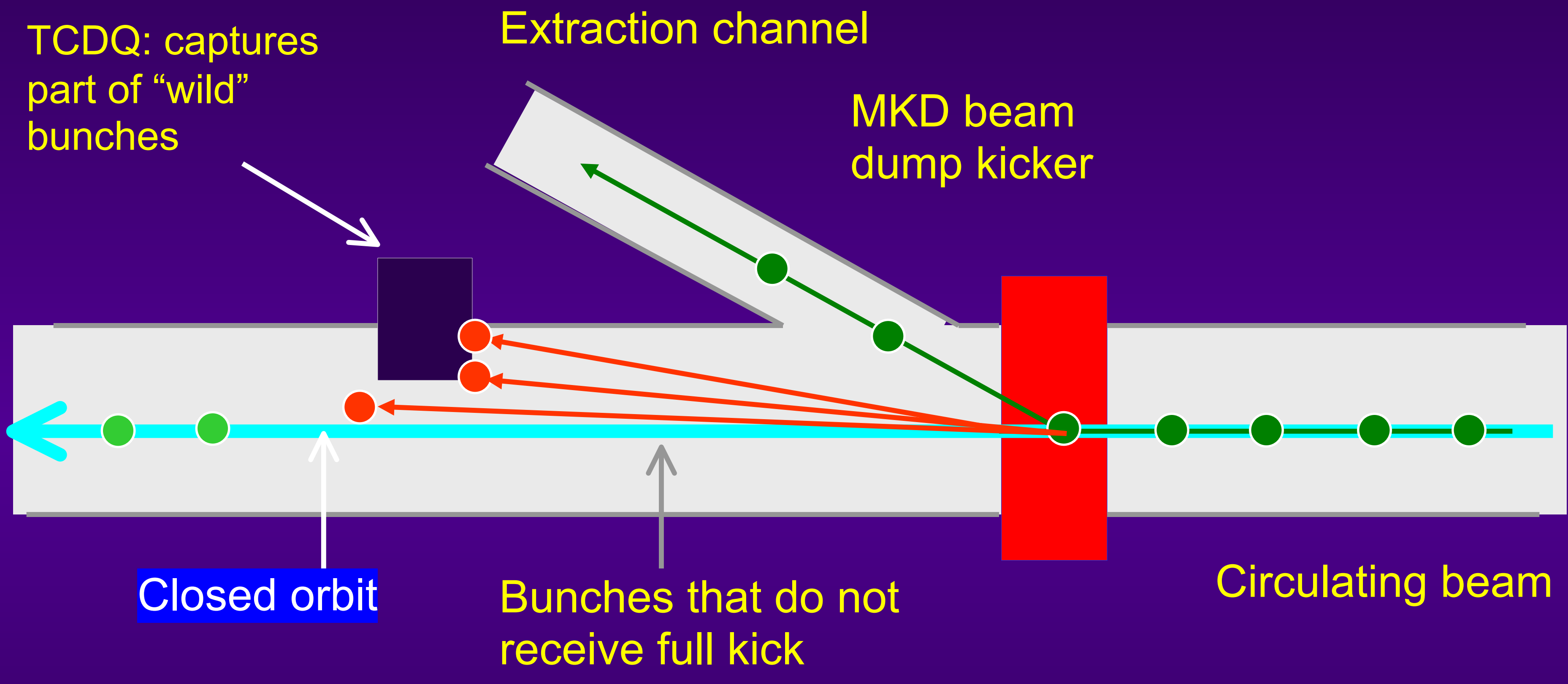
Beam dump must be **synchronised** with particle free gap

Strength of kicker and septum magnets must **match energy** of the beam

« Particle free gap » must be **free of particles**



Beam dump kicker failure (schematic)



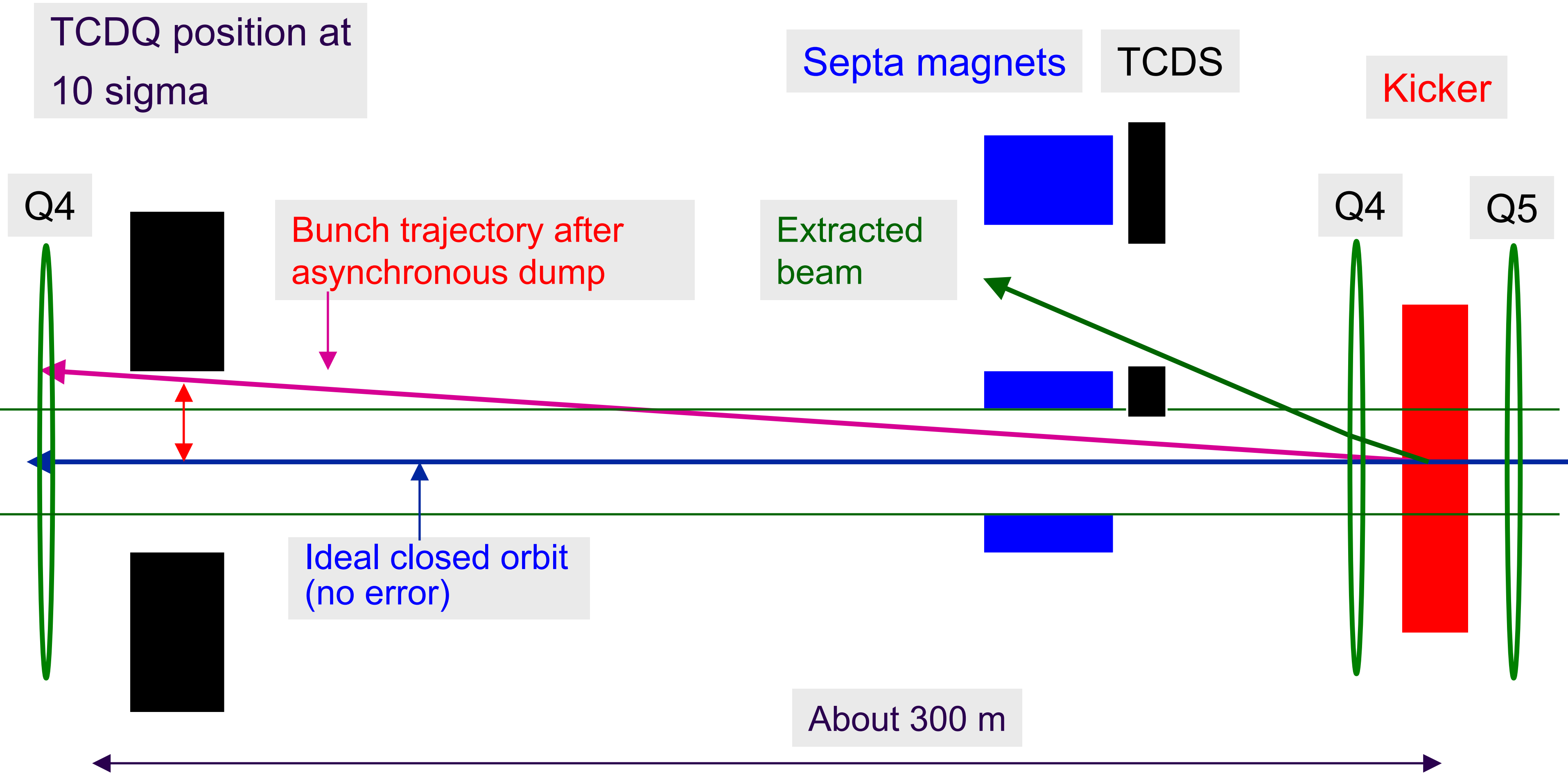
Bunch can oscillate around closed orbit with:

amplitude = nominal position of TCDQ (10 σ) + closed orbit at TCDQ

Minimise distance between closed orbit and TCDQ

… but respect that TCDQ must be in the shadow of collimators in IR7

Schematic drawing of extraction trajectory in case of failure - closed orbit errors to be limited to 4 mm



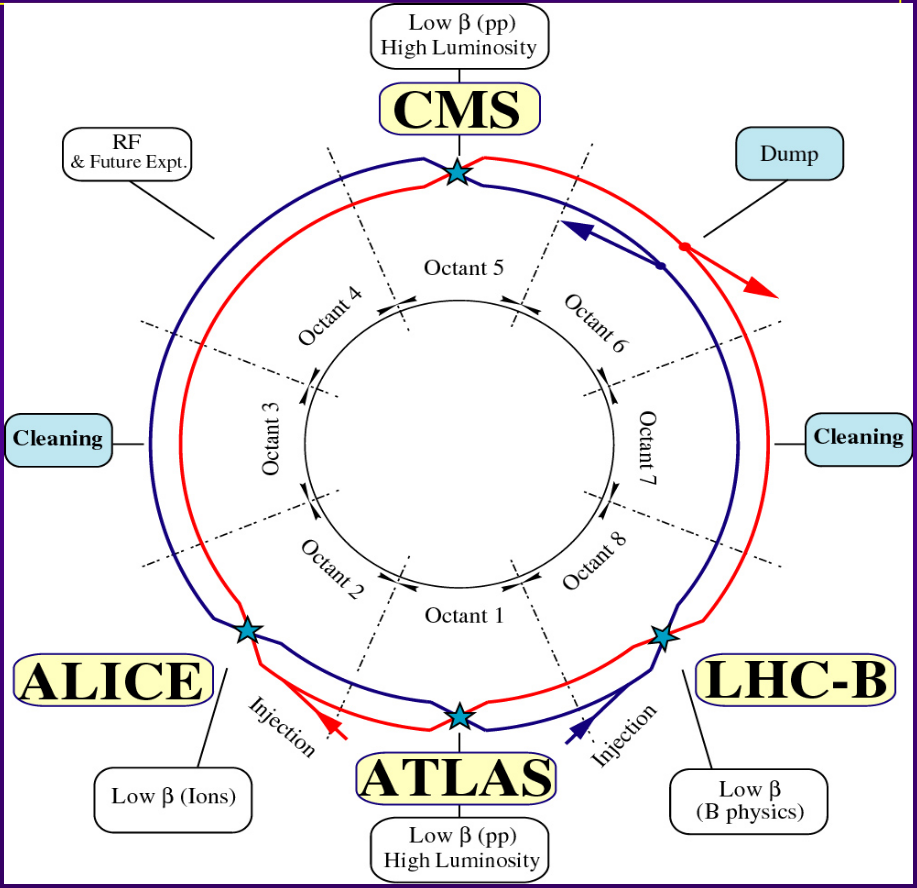
Slow beam losses: a very complex beam cleaning system including many collimators should catch the particles

Collimators close to the beam are required during all phases of operation

Two warm LHC insertions dedicated to cleaning:

IR3	**Momentum cleaning** **1 primary** **6 secondary**
IR7	**Betatron cleaning** **4 primary** **16 secondary**

Two-stage collimation system.



54 movable collimators for high efficiency cleaning, two jaws each +
other absorbers for high amplitude protection

Beam losses and aperture

Most critical is the operation at 7 TeV with squeezed optics:

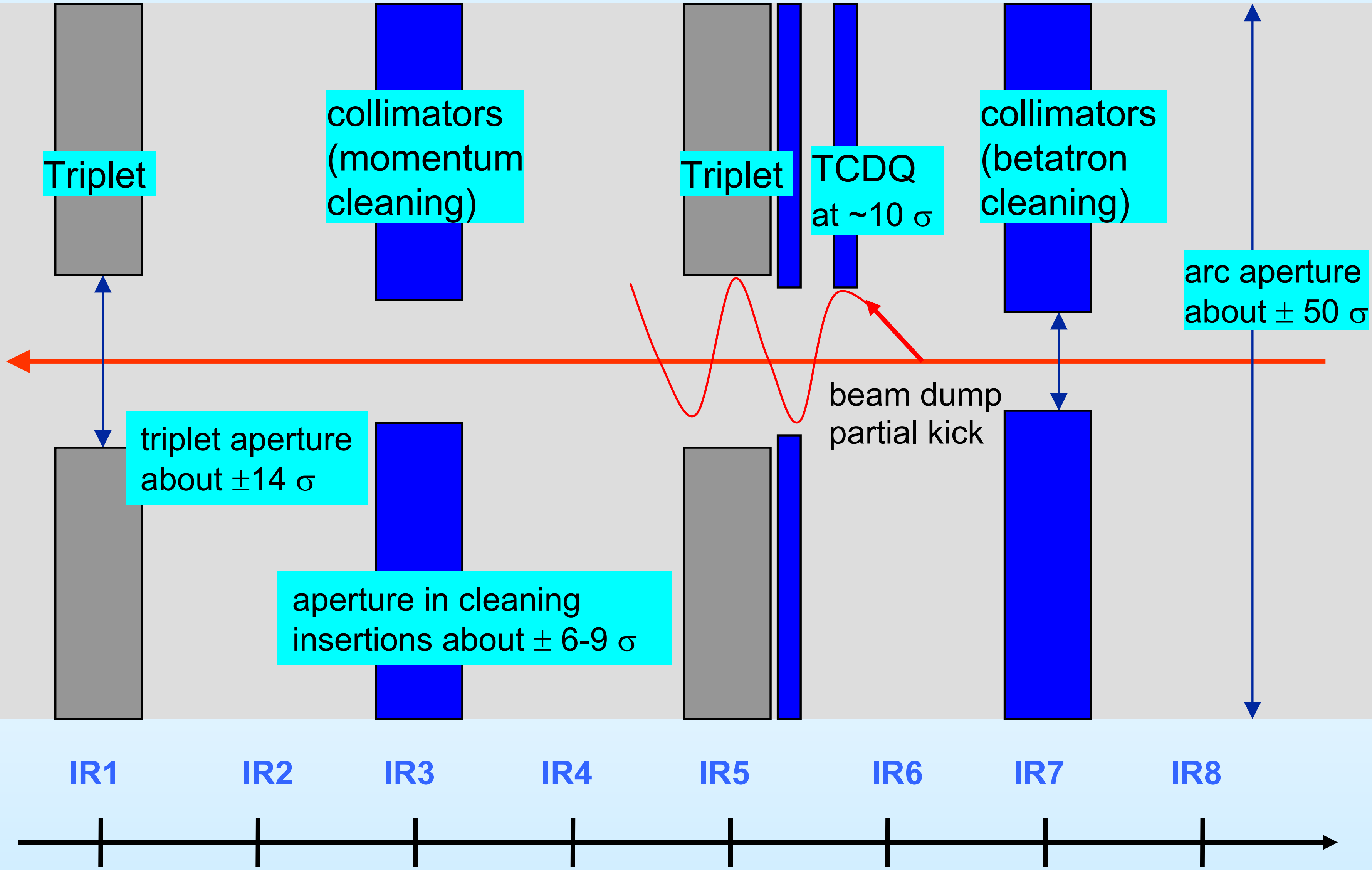
- β-function up to 4850 m in insertions IR1 and IR5 => limited aperture
- very strong low- β quadrupole magnets with orbit offset due to beam crossing angle at β = 4000 m (fast orbit change for quench)
- normal conducting dipole magnets at β = 4000 m (powering failure leads to very fast beam losses)
- superconducting dipole magnets at β = 2000 m (quench)
- strong superconducting dipole magnets around the accelerator

- Fast orbit changes are the most critical failures
  - collimators at a position of about 6-9 σ from the beam
  - 1% of the beam would damage the collimators

- Good control of the closed orbit is one of the keys to safe operation

Critical apertures around the LHC (in units of beam size σ)

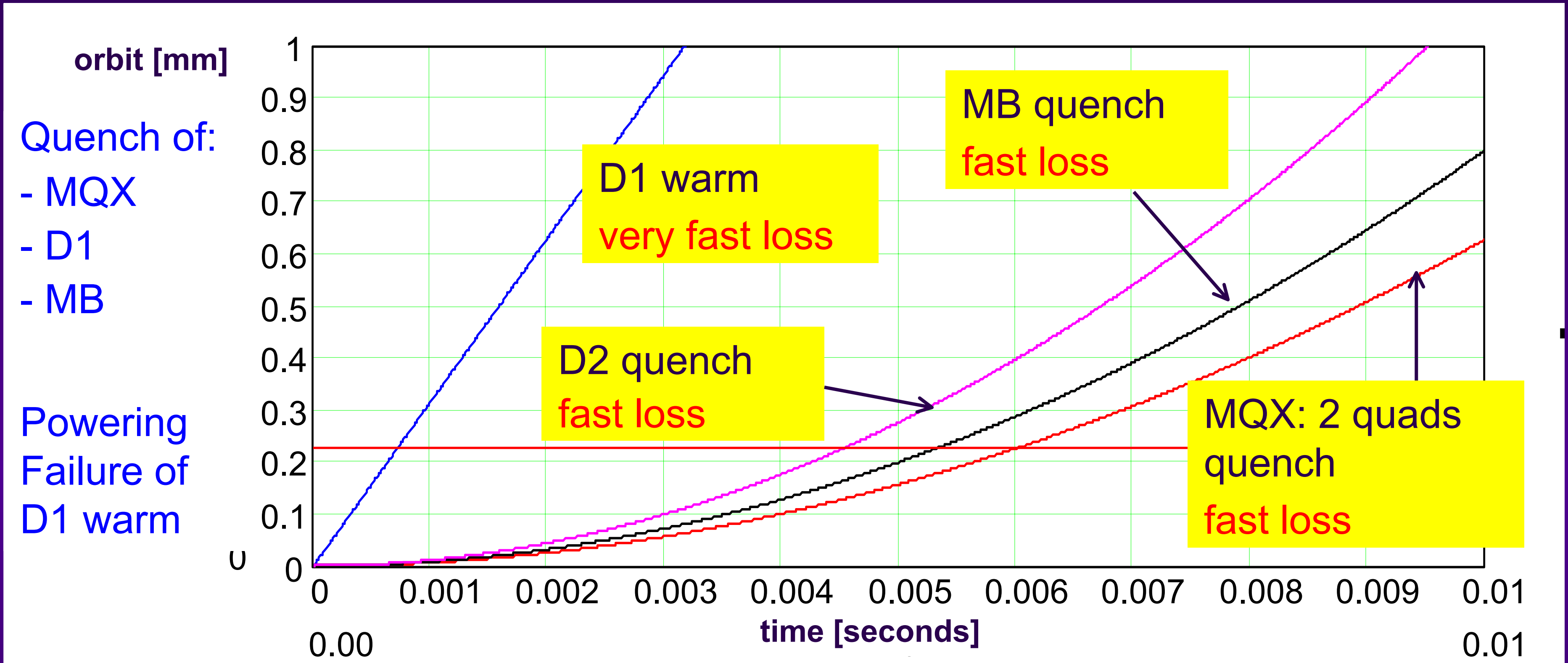
7 TeV and β^* = 0.5 m in IR1 and IR5



Local absorbers to protect of the triplets - IR1 and IR5 (possibly behind D1 towards the arc)

- An absorber in in the **non-crossing plane** can be installed without any loss of aperture - such mask **could be fixed**
- An absorber in the **crossing plane** would possibly **slightly reduce the** aperture
  - it would be preferable to have a movable device
- With such absorbers **the operational flexibility** would **increase in a significant way**
  - larger orbit excursions in IR5, IR1 and IR6 (TCDQ) would be acceptable without dumping the beam - crossing angle can be better optimised
  - relaxing parameters for the cleaning insertion
  - relaxing parameters of the exact positioning of the collimators in IR3 and IR7

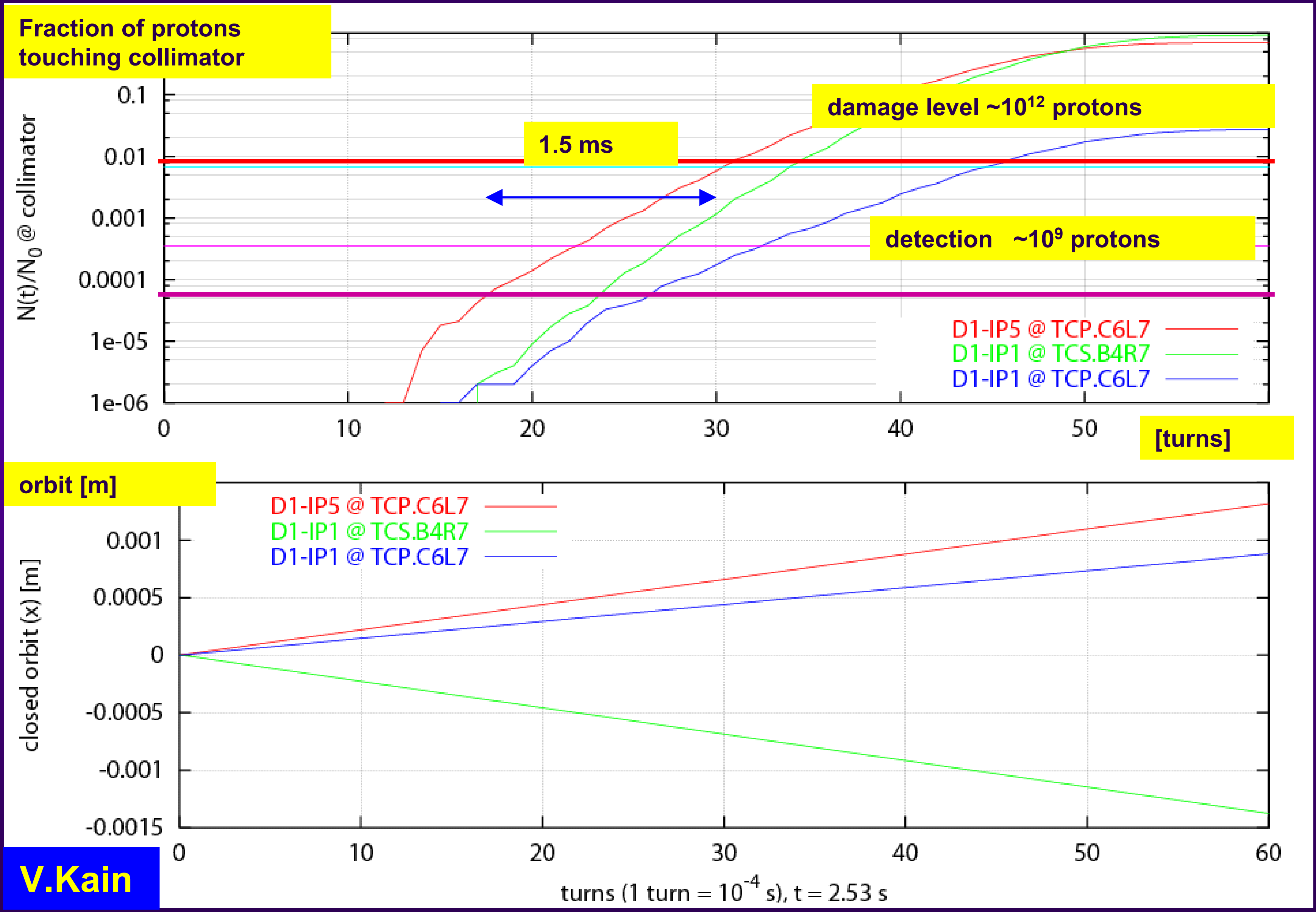
Examples: Orbit change at collimator after failure



Assumptions:

- Squeezed optics with max beta of 4.8 km
- All 4 quadrupole magnets quench, approx. gaussian current decay time constant 0.2 s
- 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

Proton losses for failure of D1 in IR1 and IR5



Beam Loss Monitors

Primary strategy for protection in case of fast beam losses: Beam loss monitors at collimators continuously measure beam losses

- Beam loss monitors indicate increased losses => **MUST BE FAST**

After a failure, detected by loss monitors (…..or by hardware signals):

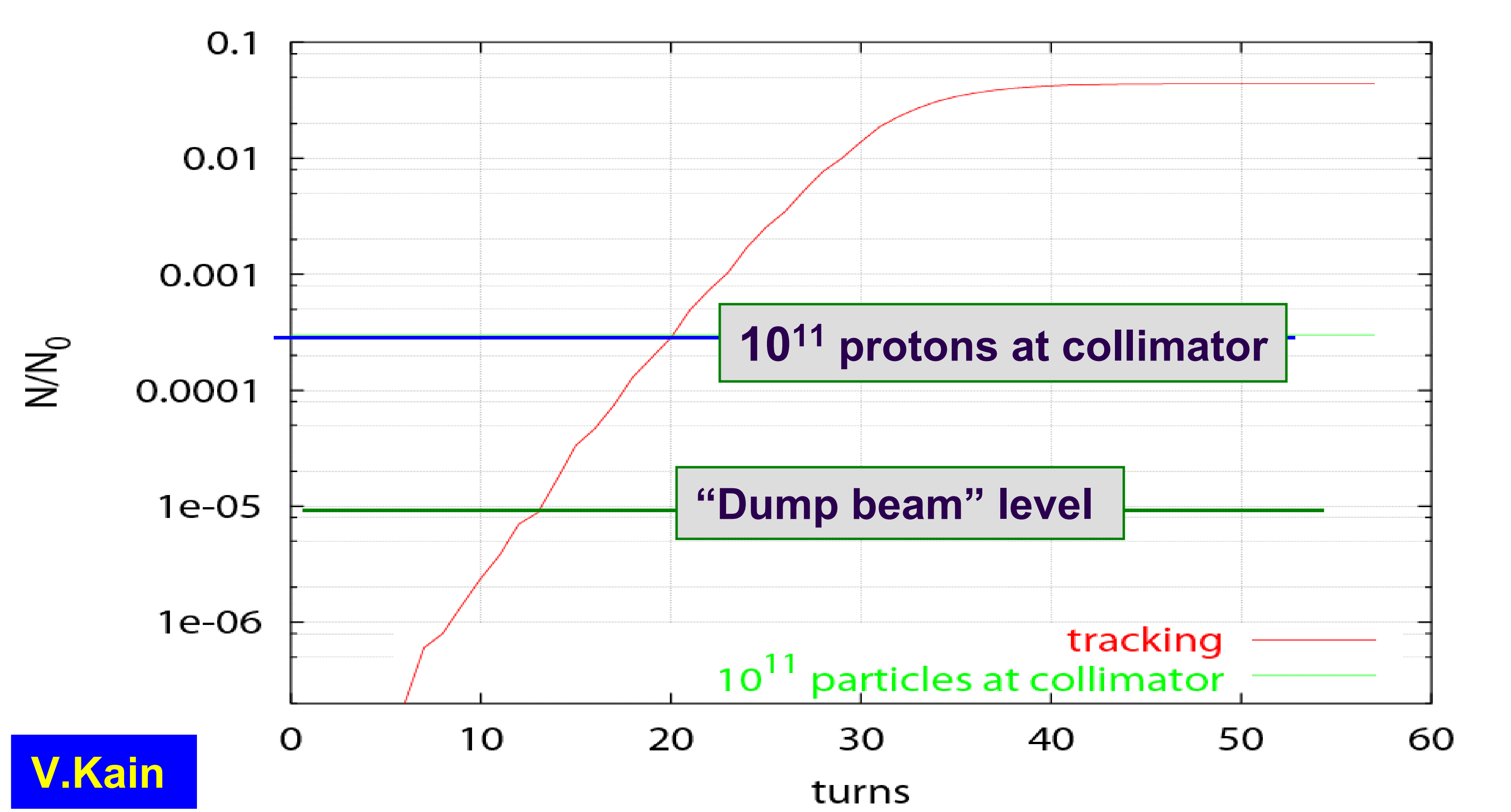
- Beam loss monitors break Beam Permit Loop
- Beam dump sees “No Beam Permit” => dump beams

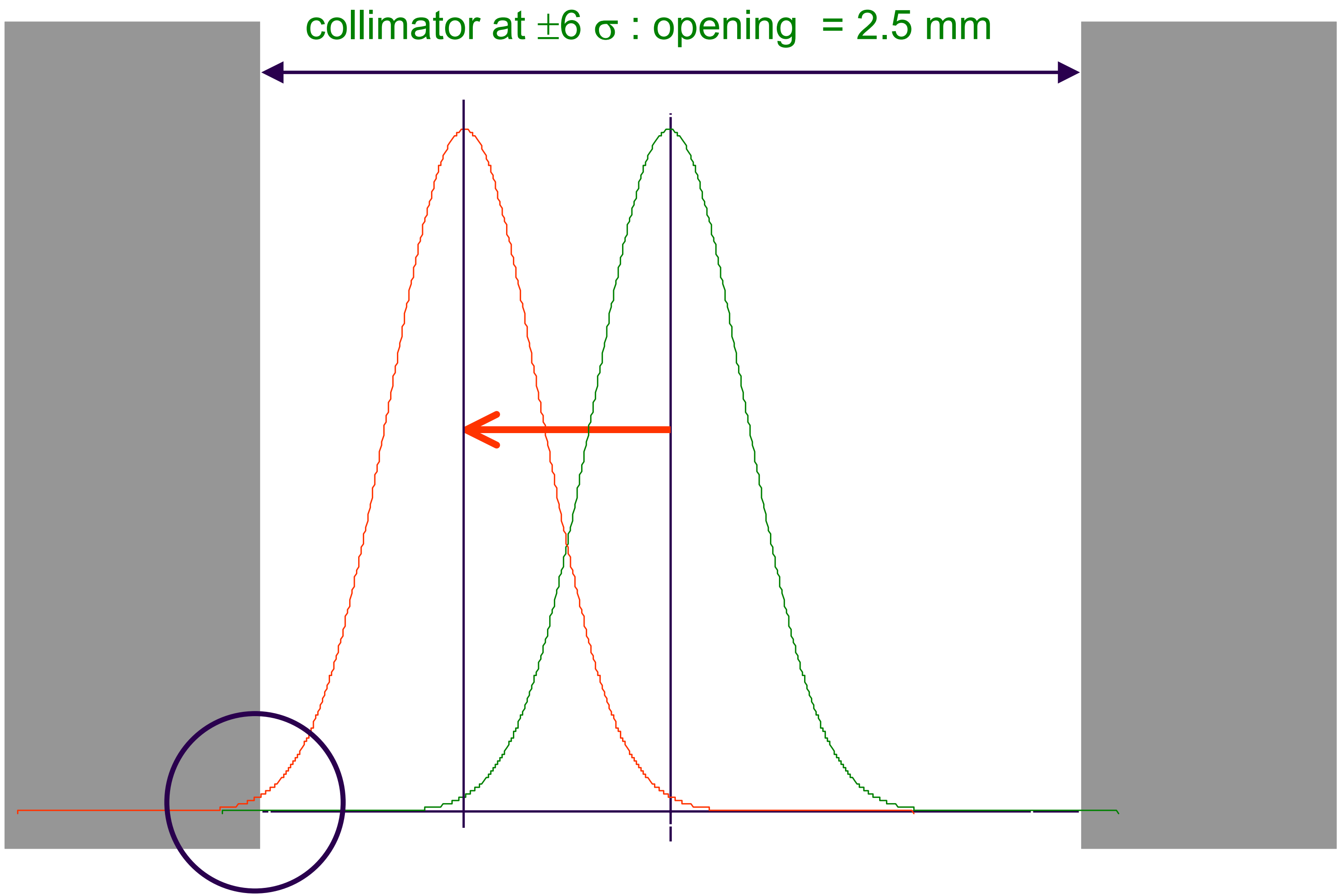
In case of equipment failure, enough time is available to dump the beam before damage of equipment - including all magnets and power converters - but issues such a General Power Cut etc. are still being addressed

Is this sufficient ?

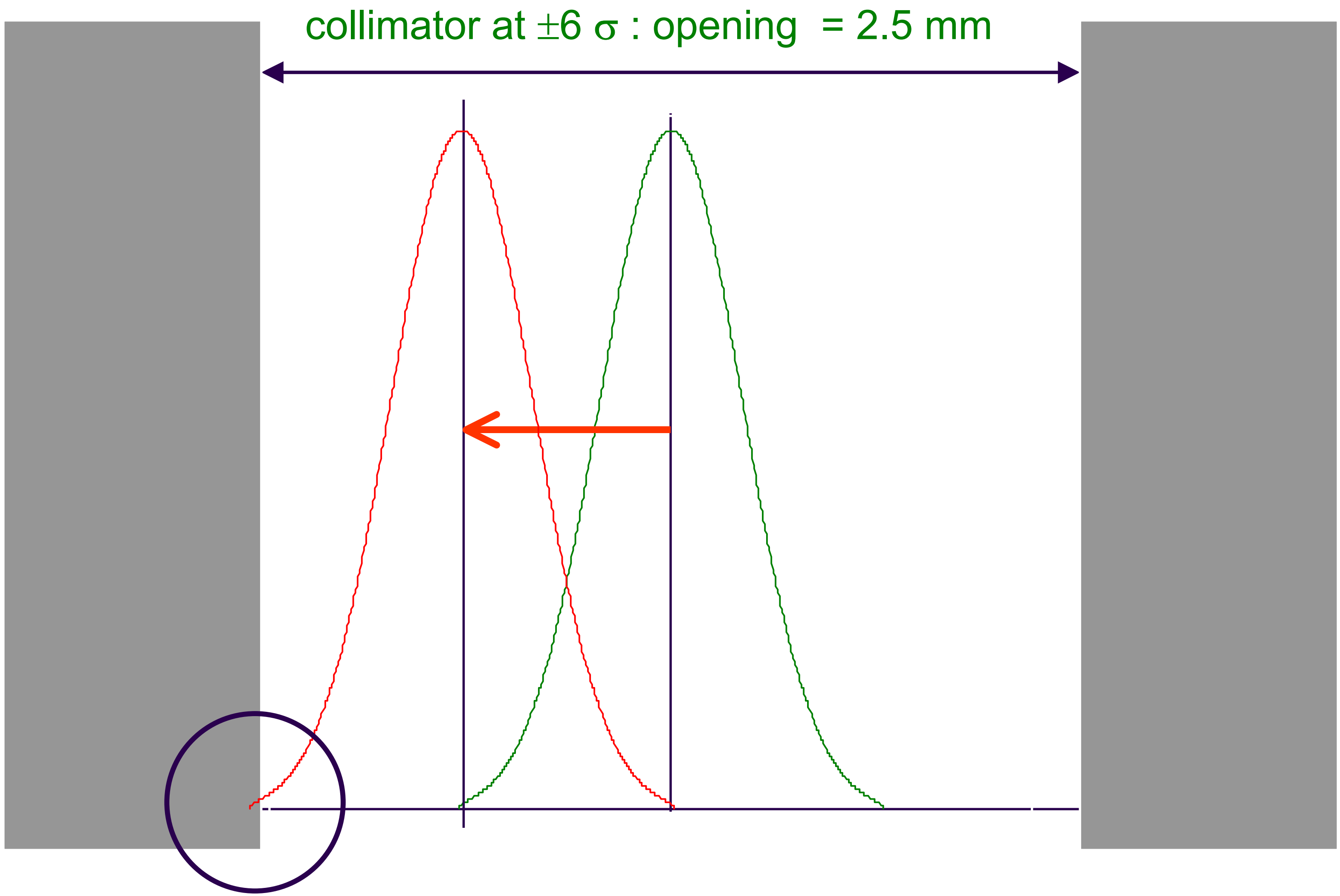
Particles that touch collimator after failure of normal conducting D1 magnets

After about 13 turns $3 \cdot 10^9$ protons touch collimator, about 6 turns later 10^{11} protons touch collimator



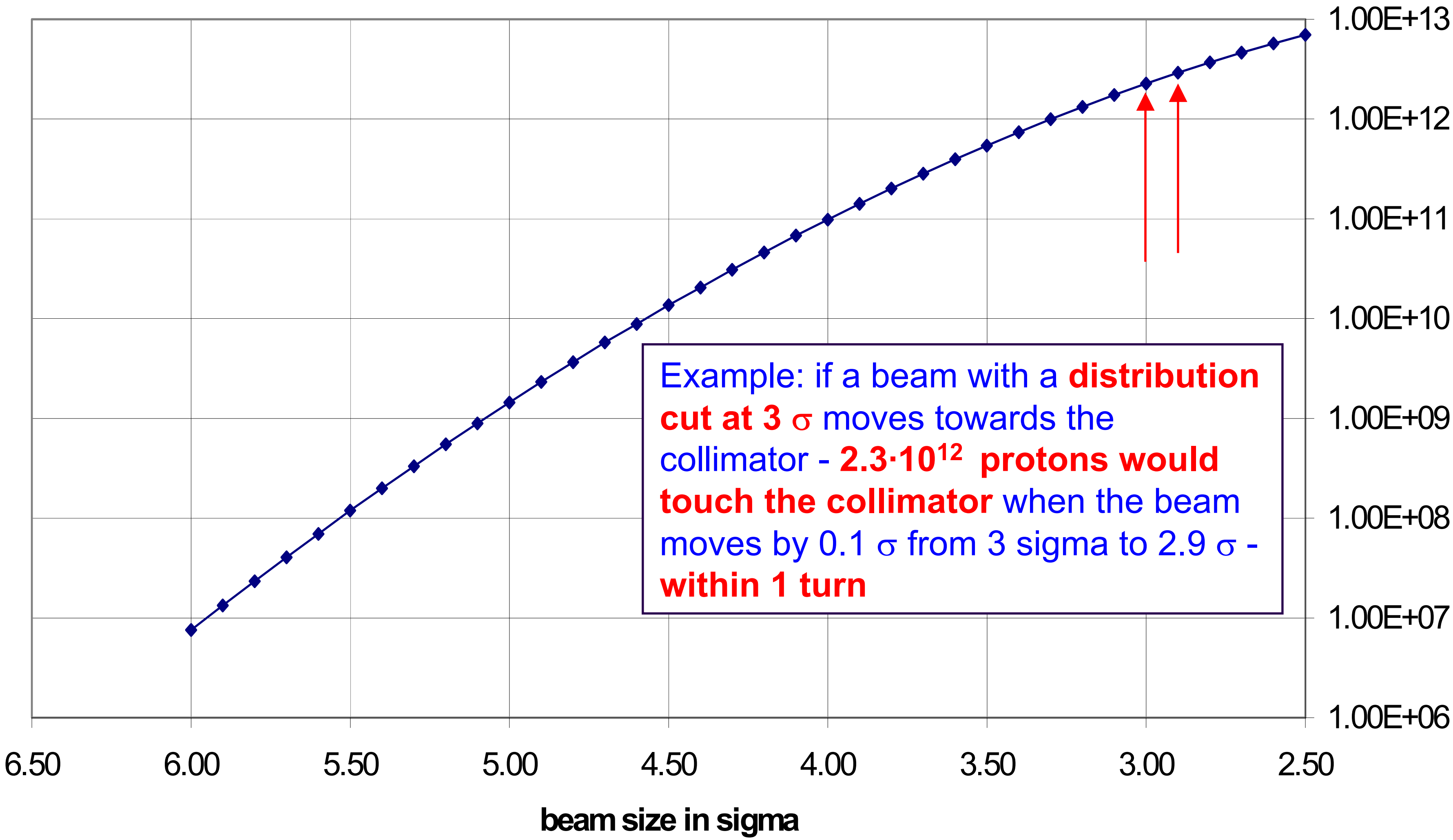


movement of the closed orbit assuming gaussian distribution in case of magnet failure (D1) this would take 20-30 turns (2-3 ms) - and the collimator jaw would be damaged => beam dump after about 10-15 turns required



movement of the closed orbit assuming gaussian distribution cut at 3 σ
signal from Beam Loss Monitor comes (too) late - Beam Position Monitors could detect such failure earlier

Number of particles touching collimator jaws when it moves into beam tail



movement of collimator with respect to the beam in units of beam size σ (0 corresponds to collimator at closed orbit - no beam)

Single turn beam loss during injection and beam dump	**Passive protection** • Avoid such failures (high reliability systems - work is ongoing to better estimate reliability) • **Rely on collimators and beam absorbers**
Multiple turn beam loss due to many types of failures	**Active Protection** • Failure detection (from beam monitors and / or equipment monitoring) • Issue beam abort signal • **Fire Beam Dump**

In case of **any failure** or **unacceptable beam lifetime**, the **beam** must be **dumped immediately,** safely into the **beam dump block**

The end of the talk ….

………not the end of intense work on machine protection and beam cleaning

For the LHC, operation, machine protection and performance must be considered together

The final layout of the collimator and beam absorber system still to be defined for the 2007 LHC start-up

A recent presentation (R.Assmann) in the LHC Chamonix workshop had the title:

Collimators and Cleaning,

could this limit the LHC performance ?

his answer was **"YES"** - and I would agree with him

Ackowledgements

The presentation is based on the work that was performed in many groups in the AB and AT Divisions

Contributions of **many colleagues** are acknowledged, in particular for the discussions in the MPWG and BCWG

Thanks for the material from:

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