Machine Protection Issues and Strategies for the LHC

Rüdiger Schmidt and Jörg Wenninger for the
Working Group on Machine Protection

EPAC 2004 Luzern

- Machine Protection as for several other accelerators
- Energy in the LHC beams … and the consequences
- Beam losses and protection of the LHC
- Availability of the protection systems
- Conclusions

On behalf of the CERN staff and the outside collaborators

Machine protection: Protection of accelerator equipment

PAC 2003 invited presentation "C.Sibley: Machine Protection Strategies for High Power Accelerators"

- High power / high (stored) energy accelerators became a topic of intense research….

EPAC 2004: About 25 papers related to LHC Machine Protection and Collimation (in total ~100 papers on LHC)

- Very large stored energy in beams and magnets
- Very low quench margin for beam losses to superconducting magnets
- Unprecedented complexity of the accelerator
- In case of equipment damage long repair times (exchange of superconducting magnets about 30 days)

“Brake systems” for superconducting accelerators: discharge of the energy

Energy in the LHC beams

- Regular and irregular beam extraction discharging beam energy into a specially designed target (beam dump block)
- Beam cleaning with collimators, limiting particle losses around the accelerator
- Beam loss monitors to detect beam losses, and requesting a beam dump when beam losses too high

Energy in the magnets

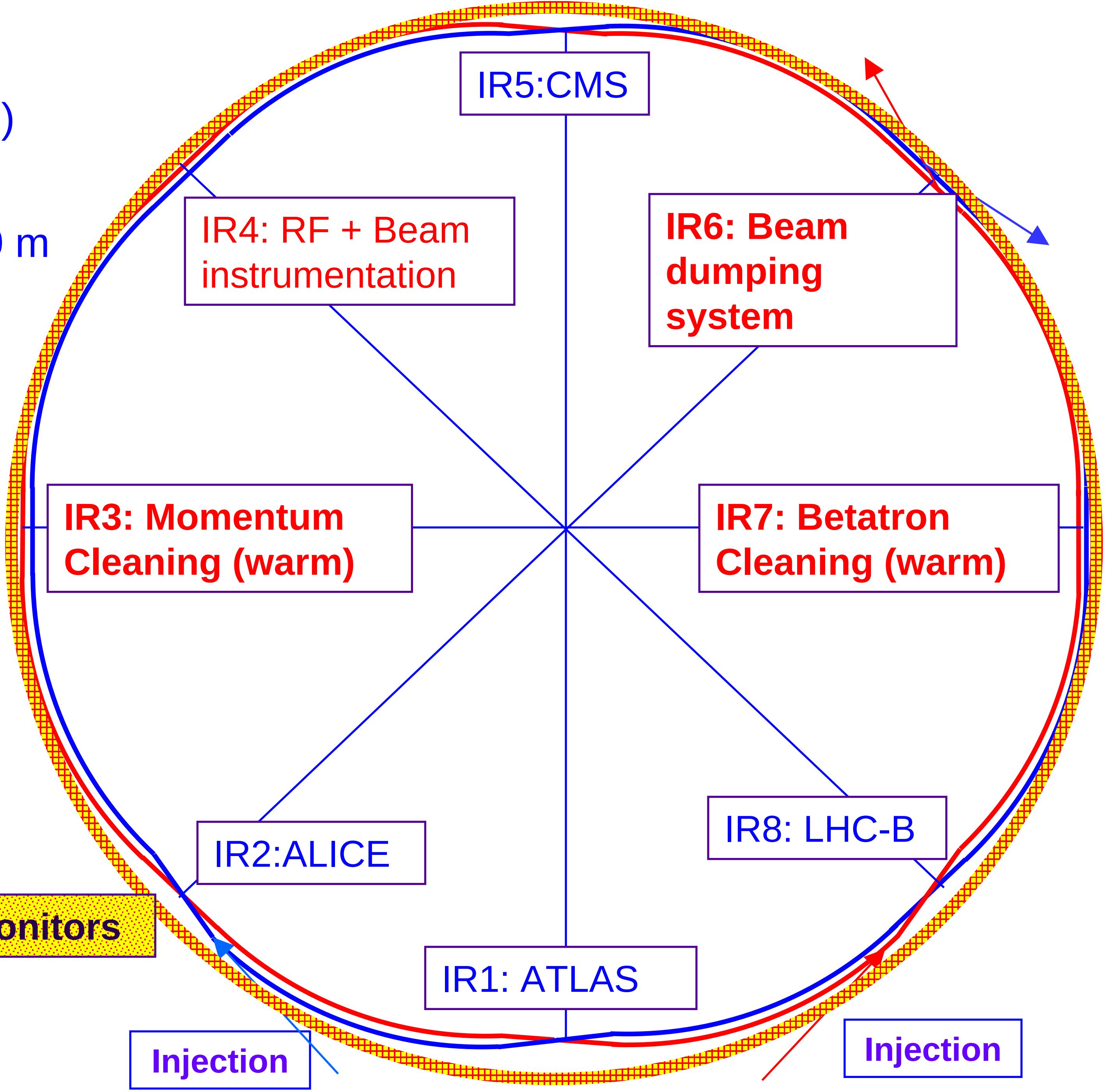
- After a quench: discharge the magnet energy into the magnet coils (quench heaters)
- Discharge the energy stored in the electrical circuit into resistors (energy extraction)
- …….dump the beam

Similar to HERA, TEVATRON, RHIC … already proposed in first LHC design study 1991

LHC

eight arcs (sectors)

eight long straight section (about 700 m long)



Beam Loss Monitors

Recalling LHC Parameters

Momentum at collision	**7 TeV/c**
Momentum at injection	450 GeV/c
Dipole field at 7 TeV	8.33 Tesla
Number of magnets	~10000
Number of electrical circuits	~1700

High beam energy in LHC tunnel
Superconducting magnets at 1.9 K
Stored energy in magnets very large
Unprecedented complexity

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

Normalised emittance	**3.75 µm**
Typical beam size	200-300 µm

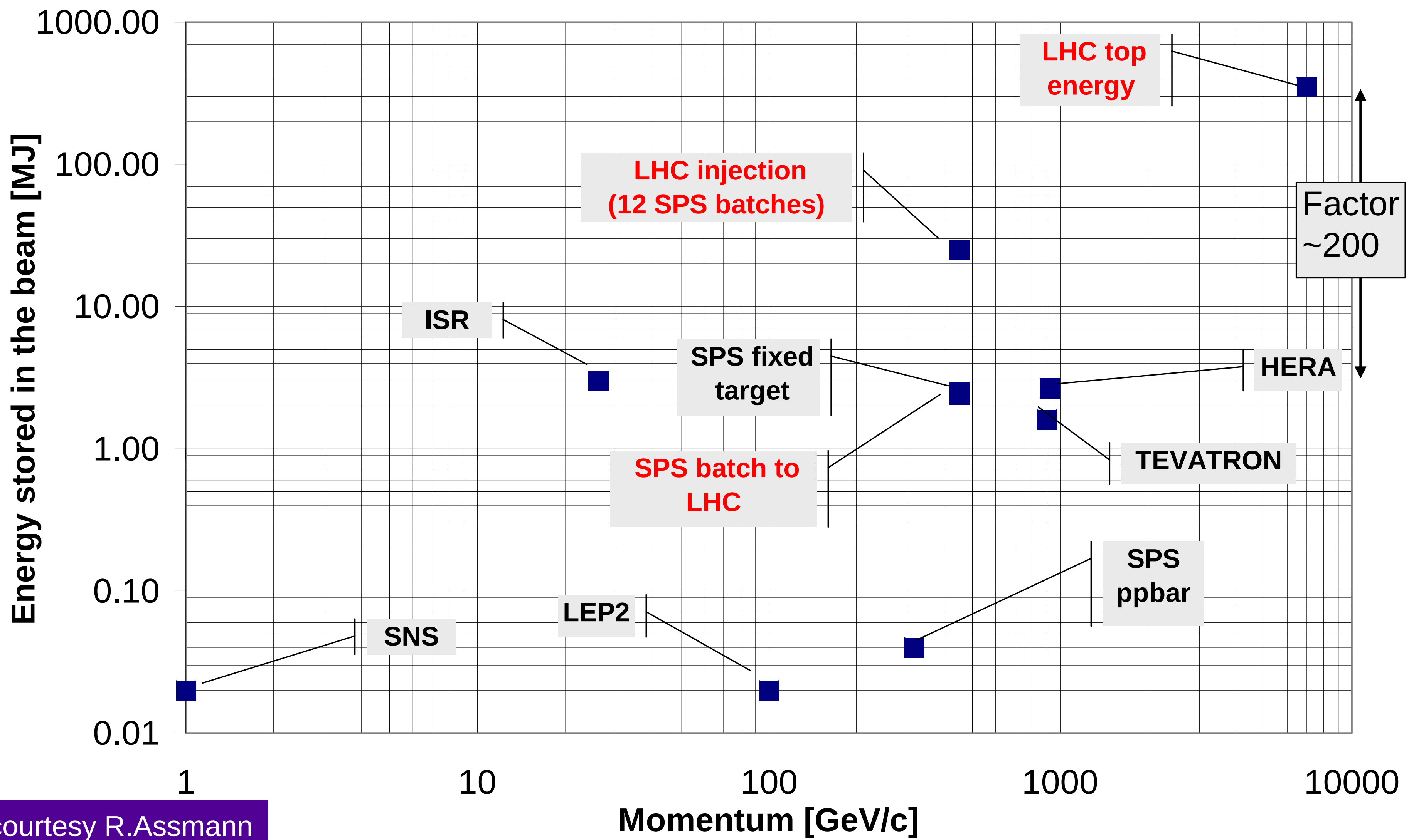
High luminosity at 7 TeV
very high energy stored in the beam

beam power concentrated in small area

Some numbers for 7 TeV

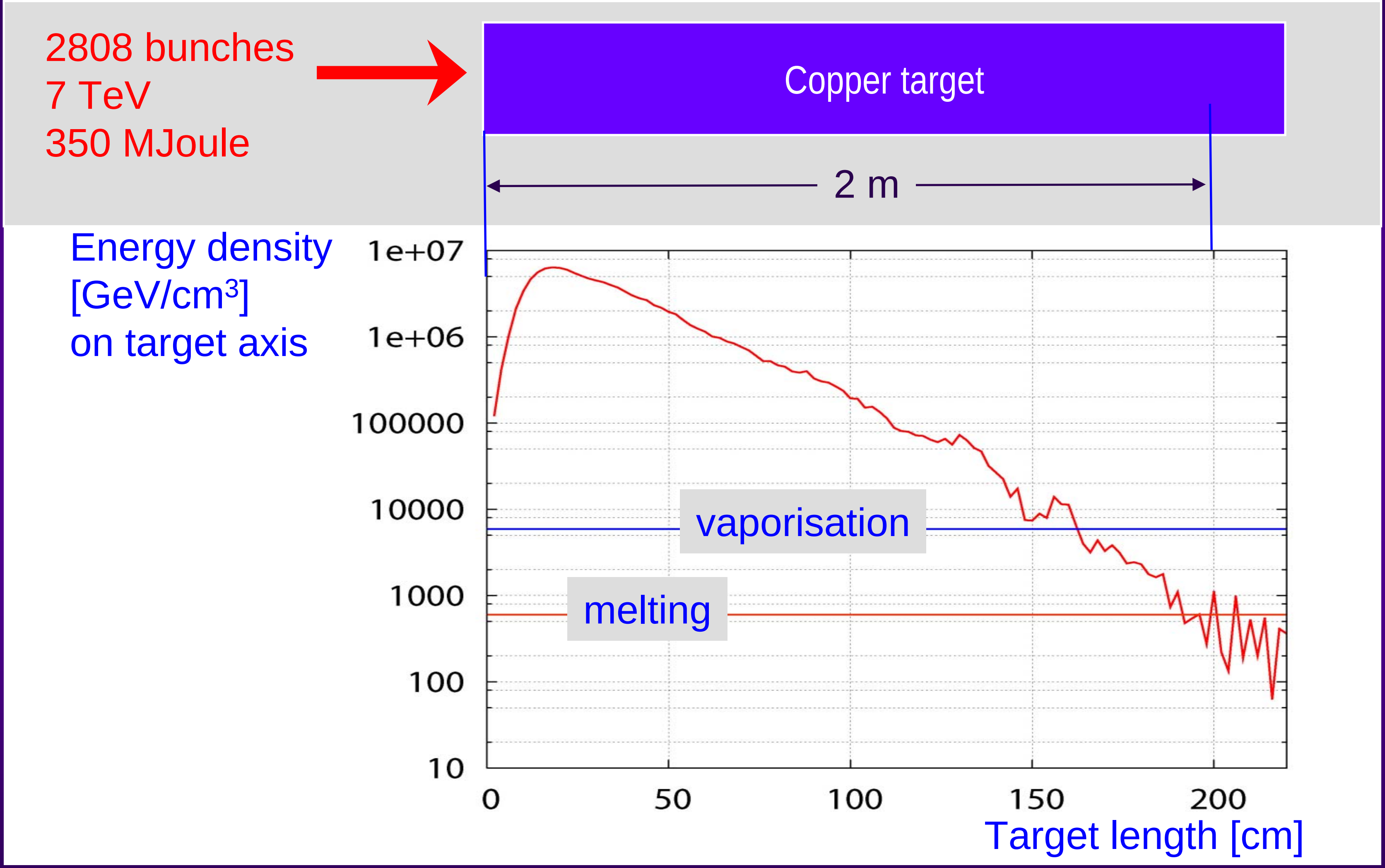
Energy stored in the magnet system:	10 GJoule
Energy stored in one (of 8) dipole circuit:	1.1 GJoule
Energy stored in one beam:	350 MJoule
Average beam power, both beams: some	10 kWatt
Instantaneous beam power for one beams:	3.9 TWatt
…..during 89 μs	
World Total Net Electricity Generation 2002:	1.7 TWatt
Energy to heat and melt one kg of copper:	700 kJ

Livingston type plot: Energy stored in the beam



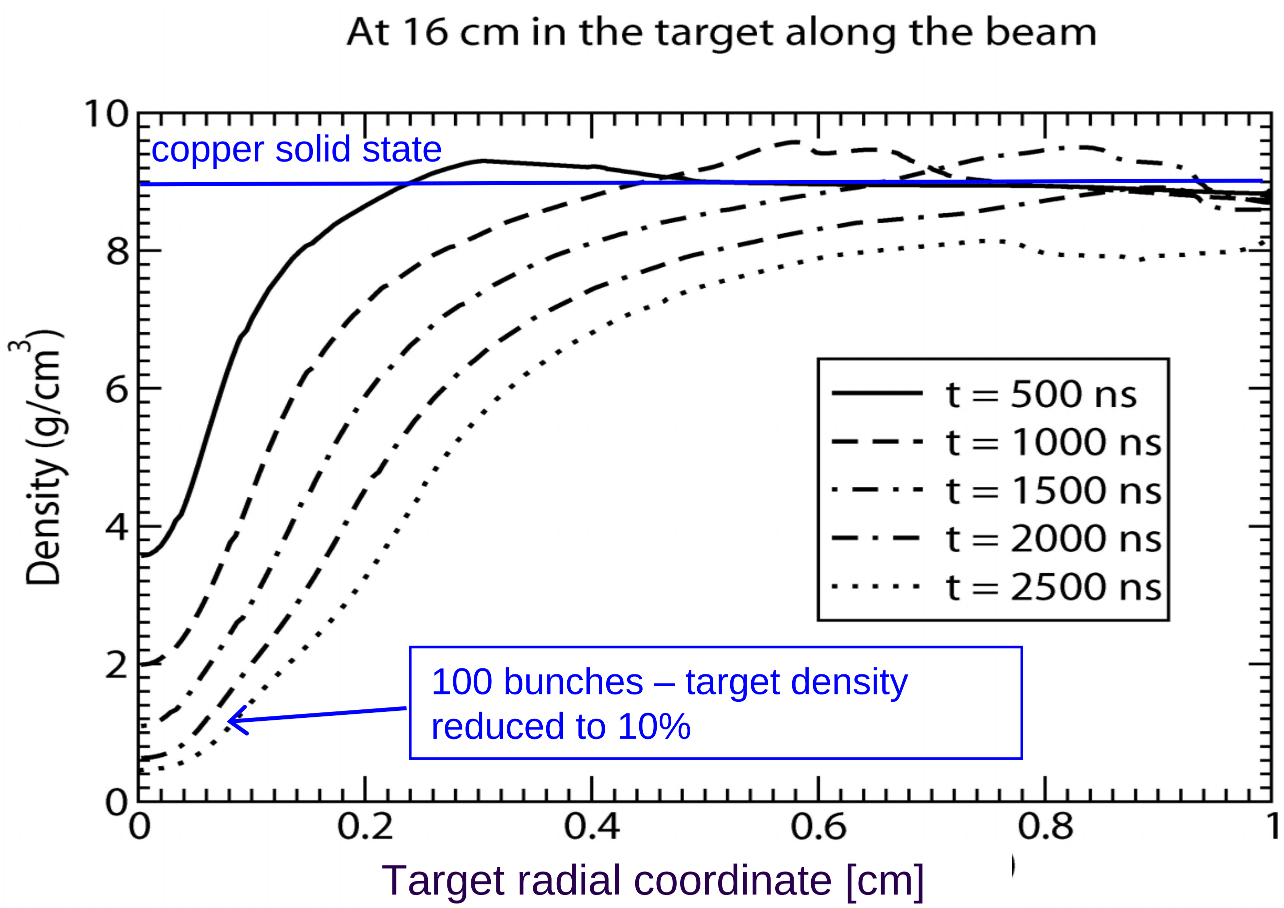
courtesy R.Assmann

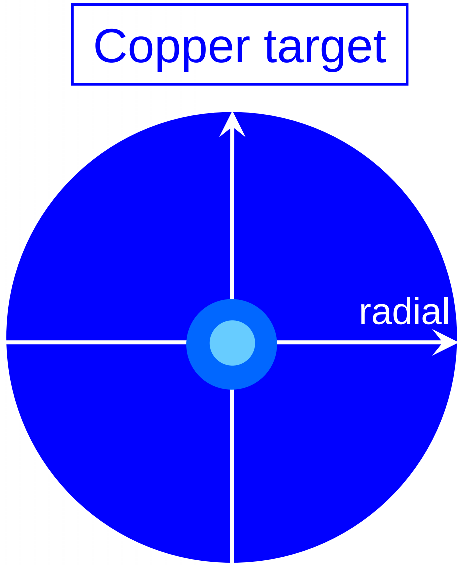
Full LHC beam deflected into copper target



N.Tahir (GSI) et al.

Density change in target after impact of 100 bunches





- Energy deposition calculations using FLUKA
- Numerical simulations of the hydrodynamic and thermodynamic response of the target with two-dimensional hydrodynamic computer code

MOPLT042, N.Tahir (GSI) et al.

Bunch intensities, quench and damage level

- Intensity one “pilot” bunch — $5 \cdot 10^{9}$
- Nominal bunch intensity — $1.1 \cdot 10^{11}$
- Batch from SPS (216/288 bunches at 450 GeV) — $3 \cdot 10^{13}$
- Nominal beam intensity with 2808 bunches — $3 \cdot 10^{14}$

- Damage level for fast losses at 450 GeV — $\sim 1\text{-}2 \cdot 10^{12}$
- Damage level for fast losses at 7 TeV — $\sim 1\text{-}2 \cdot 10^{10}$

- Quench level for fast losses at 450 GeV — $\sim 2\text{-}3 \cdot 10^{9}$
- Quench level for fast losses at 7 TeV — $\sim 1\text{-}2 \cdot 10^{6}$

Damage assessment approximate, supported by experience in SPS, future tests at SPS planned

Protection and Beam Energy

A small fraction of beam sufficient for damage

Very efficient protection systems throughout the cycle are required

A tiny fraction of the beam is sufficient to quench a magnet

Very efficient beam cleaning is required

- Sophisticated beam cleaning with about 50 collimators, each with two jaws, in total about 90 collimators and beam absorbers
- Collimators are as close as 2.2 mm (full gap, for 7 TeV with fully sqeezed beams), particles will always touch collimators first!

MOPLT005, MOPLT006, WEPLT006, R.Assmann et al.

Protection systems

First priority

- Protect (sensitive) LHC equipment from damage

Second priority

- Prevent superconducting magnets from quenching. Downtime after a quench is in the range of 1 hour – 8 hours

Not to be forgotten

- **Protect the beam:** The protection systems should only dump the beam when necessary. False beam dumps to be avoided…
- **Provide the evidence:** In case of failure, complete and correct diagnostic data should be provided (post mortem recording)

Lifetime of the beam

nominal intensity at 7 TeV

Beam lifetime	Beam power into equipment (1 beam)	Comments
100 h	1 kW	Healthy operation, **beam cleaning should capture > 99% of the protons**
10 h	10 kW	Operation acceptable, **beam cleaning should capture 99.9% of the protons** (approximately beam losses = cryogenic cooling power at 1.9 K)
0.2 h	500 kW	**Operation only** possibly for **10 s**, **beam cleaning must be VERY efficient**
1 min	6 MW	Equipment or operation **failure** - operation not possible - **beam must be dumped**
<< 1 min	> 6 MW	**Beam** must be **dumped VERY FAST**

Failure scenarios for beam losses

A large number of different mechanisms can cause particle losses into equipment

Classification of particle loss mechanisms according to time constant for the loss

Single turn beam losses: ultra fast (within a single turn or less)

passive protection with collimators and beam absorber

Multiturn beam losses

- Very fast (some turns to some milliseconds)
- Fast (10 ms – several seconds)
- Slow (several seconds – 0.2 hours)

mainly active protection by extracting the beams into beam dump block

Single turn beam losses

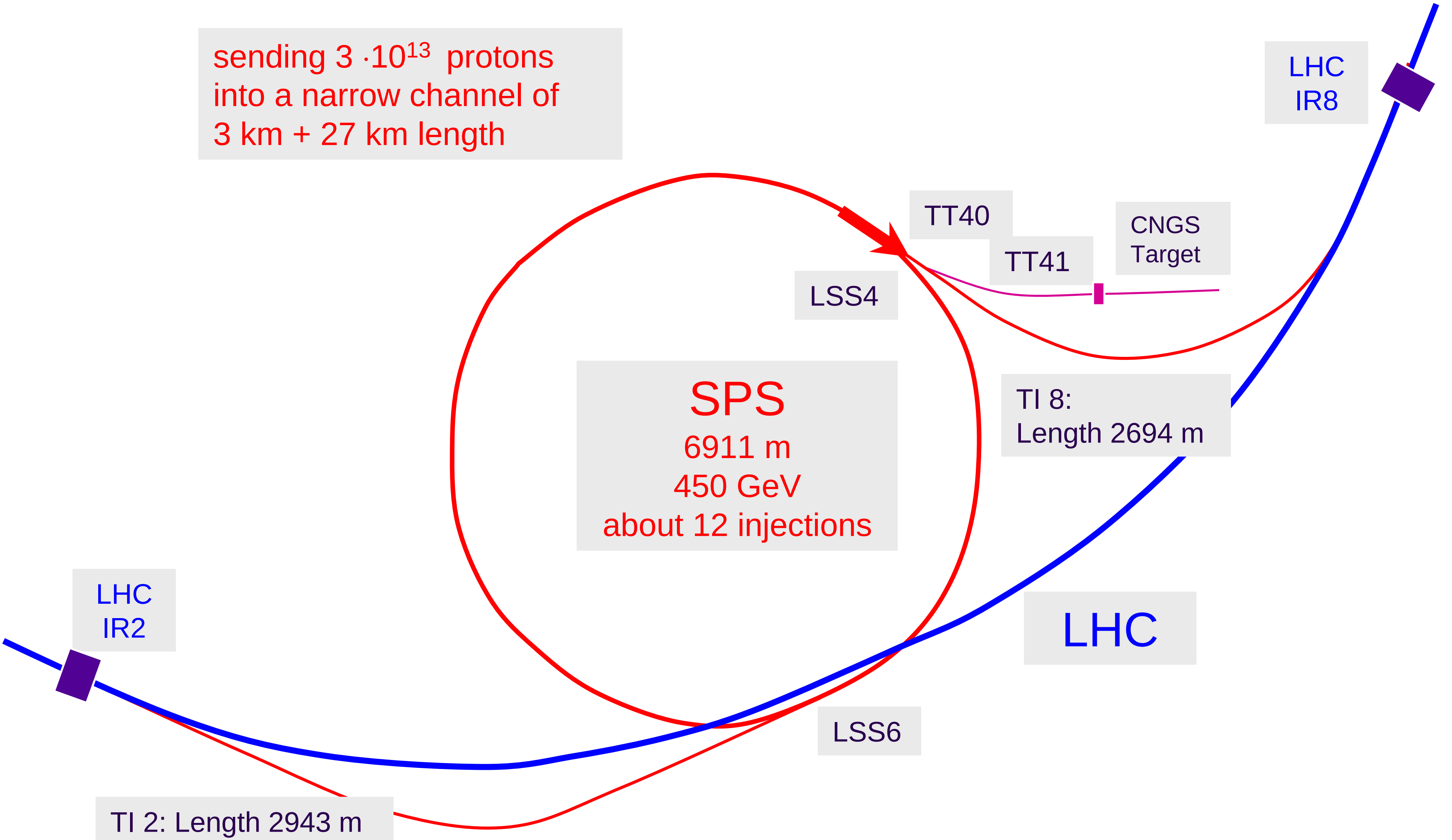
Failure mechanisms

- Failure of injection kicker and beam dump kicker
- Failure of kickers for tune measurements and aperture exploration
- During transfer and injection
  - wrong trajectory or mismatch of beam energy
  - obstruction of beam passage

Strategy for protection

- Avoid such failures (systems with high reliability)
- Beam trajectory after such failure is reasonably well defined
- **Passive protection: rely on collimators and beam absorbers**

Transfer and injection: SPS and transfer lines to LHC



Protection from high intensity SPS beams during the injection process

Interlock verifies correct settings of all elements

- Orbit in SPS before extraction
- Strengths of kickers, septa magnets, other magnets, etc.

Collimation in transfer lines (~5 σ) and at LHC injection (~7 σ)

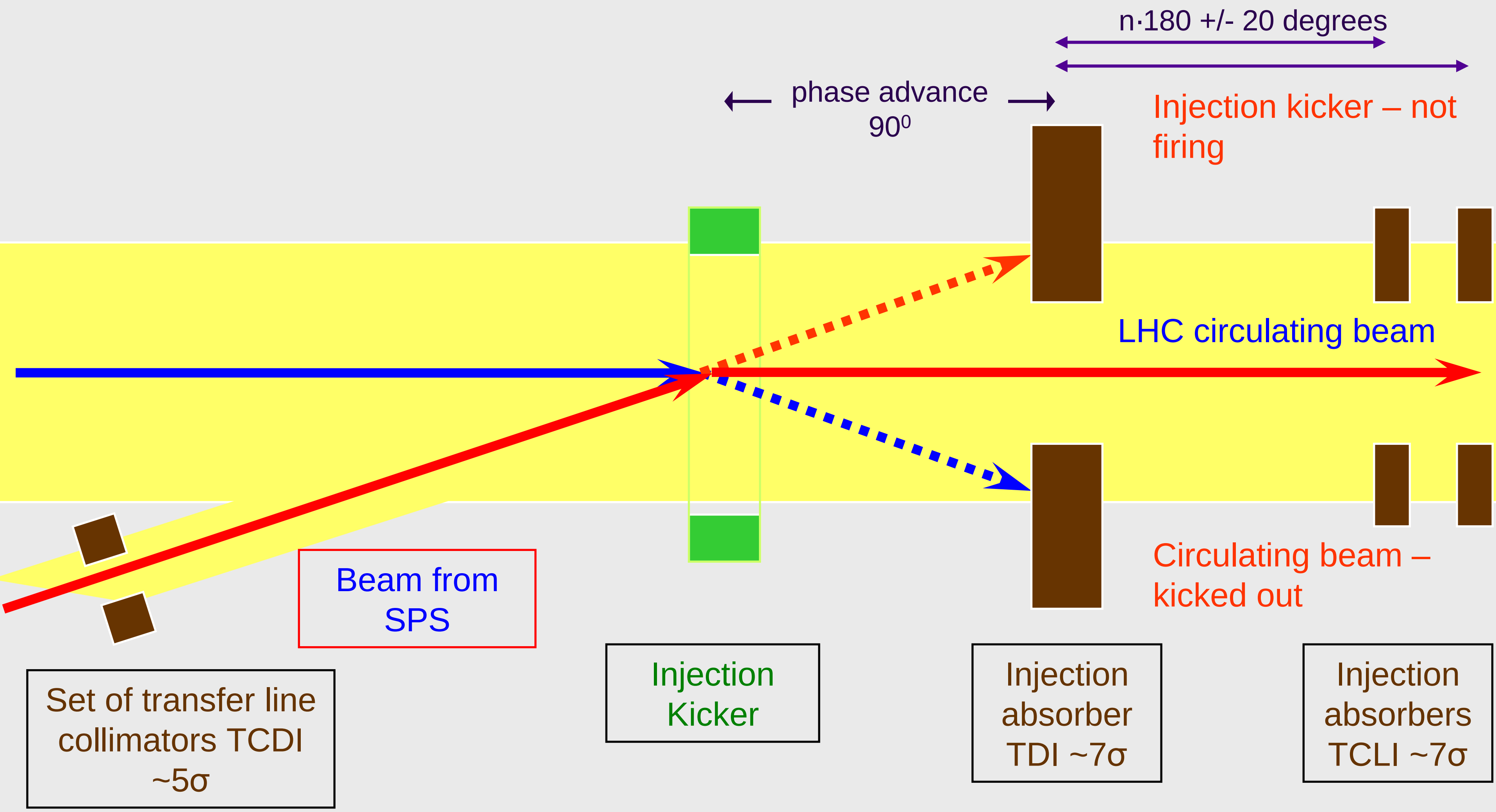
MOPLT022, H.Burkhardt et al.

MOPLT012, V.Kain et al.

Beam shaping in SPS – tail scraping at 3-3.5 σ

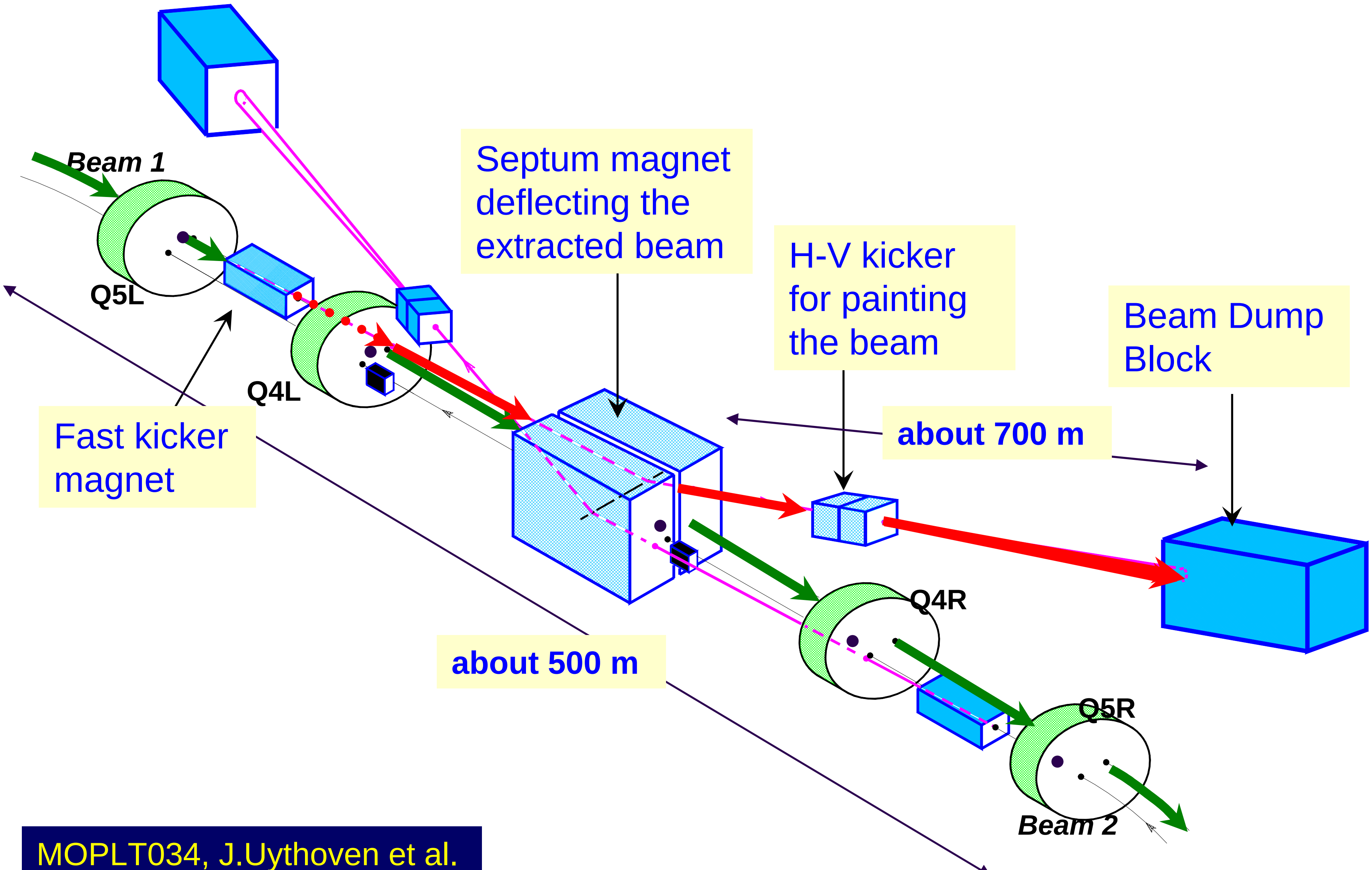
- In order not to quench the LHC magnets

Protection in case of kicker misfiring
Replacing low intensity beam by a full batch from SPS



Only when beam is circulating in the LHC, injection of high intensity beam is permitted

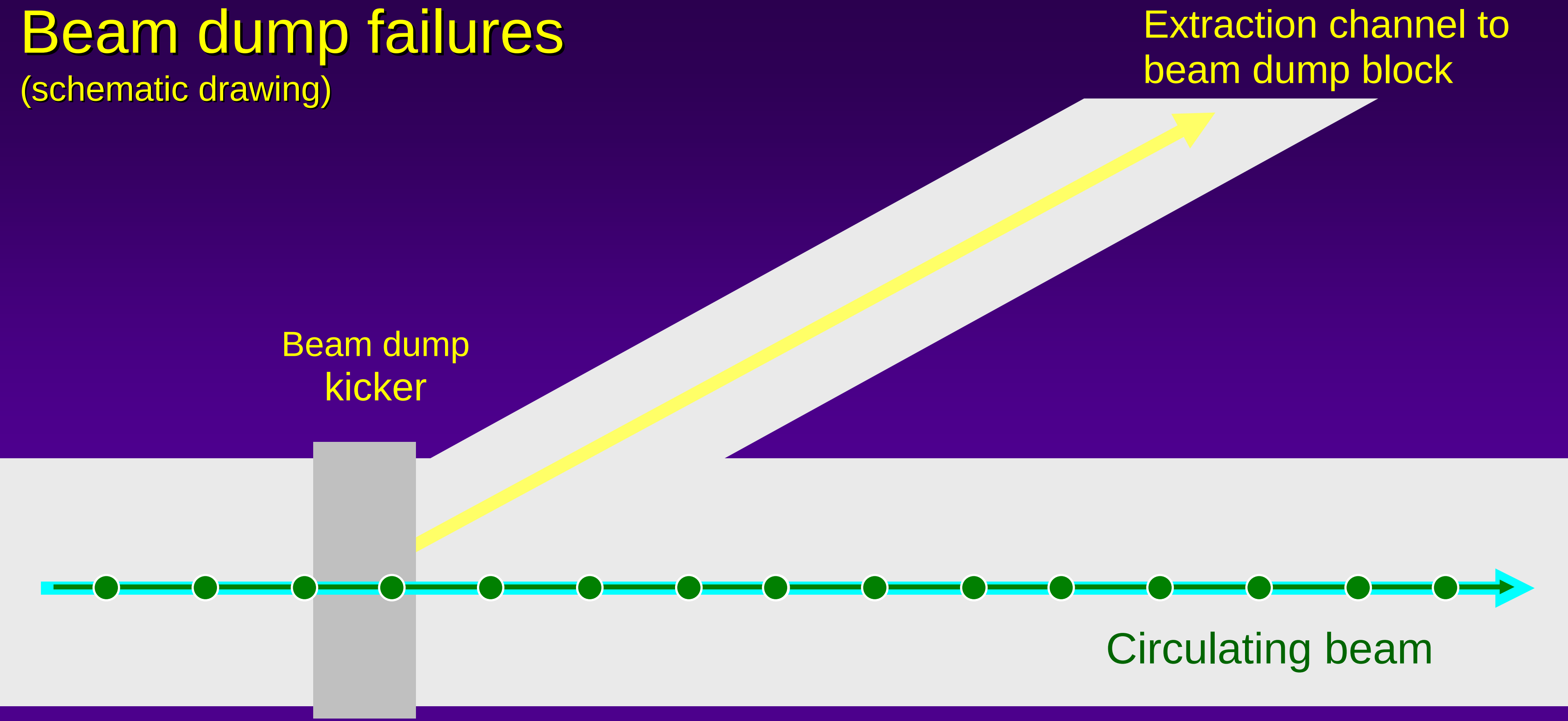
Schematic layout of beam dumping system in IR6



MOPLT034, J.Uythoven et al.

Beam dump failures

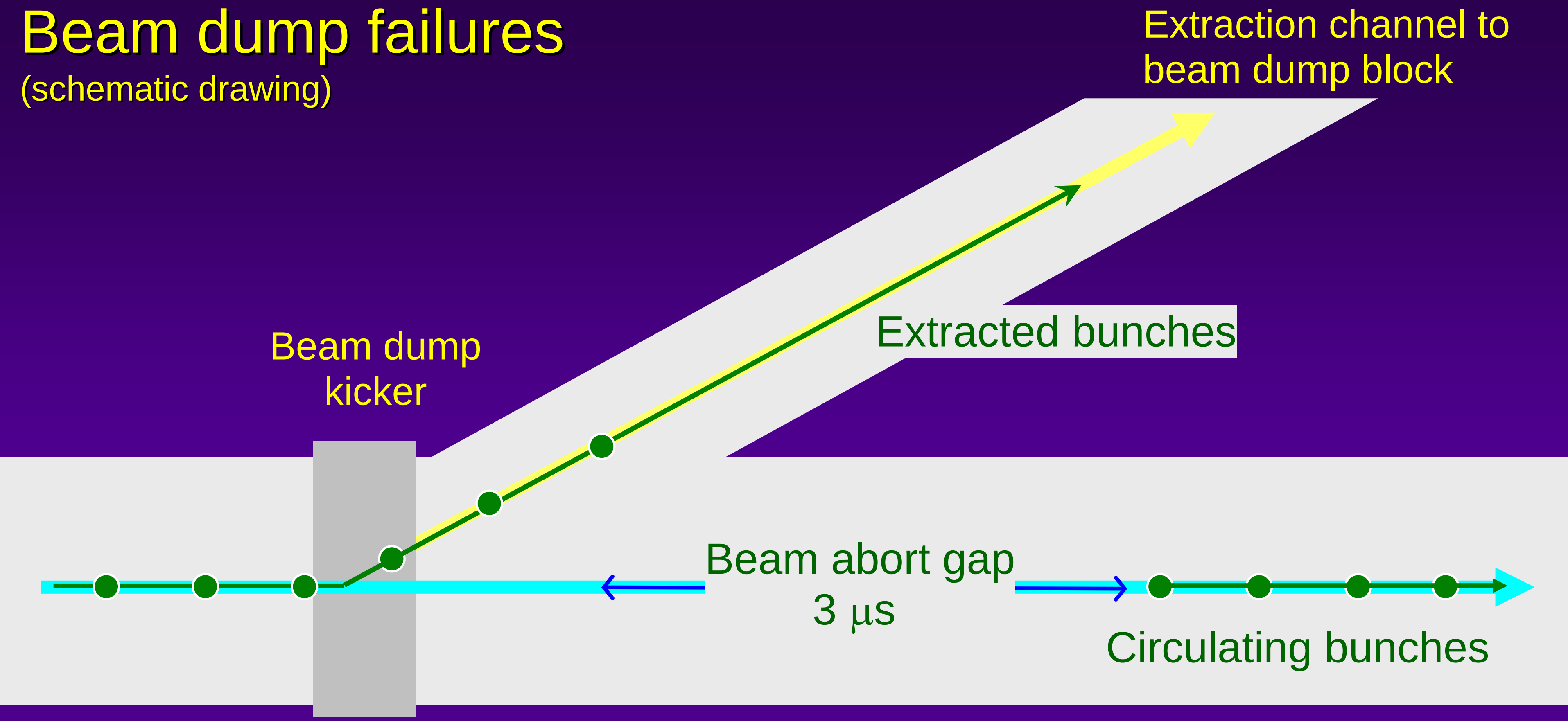
(schematic drawing)



Before beam dump request….

Beam dump failures

(schematic drawing)



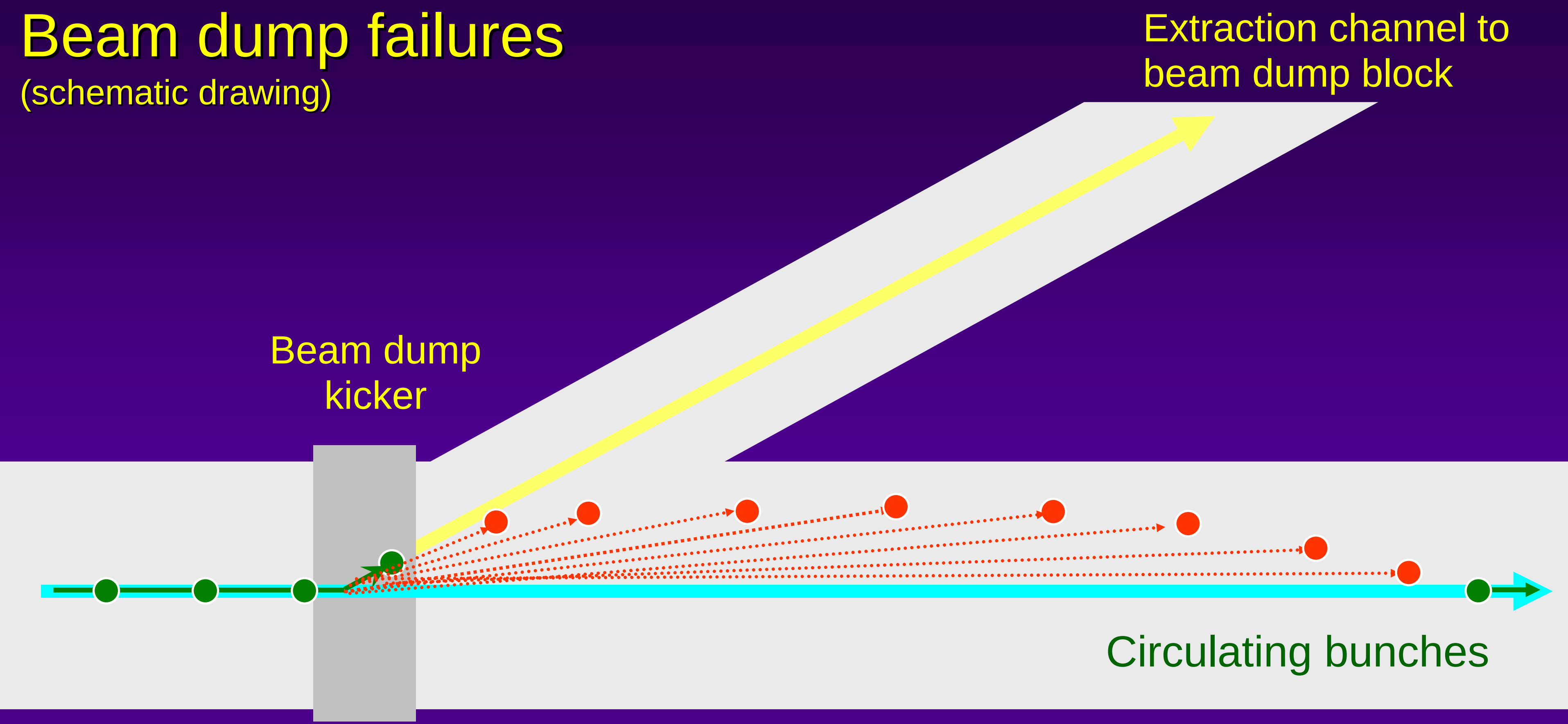
Beam dump must be synchronised with beam abort gap

Strength of kicker and septum magnets must match energy of the beam:
Ultrareliable energy tracking

Orbit excursions in IR6 < 4 mm to protect dump channel (interlock)

Beam dump failures

(schematic drawing)

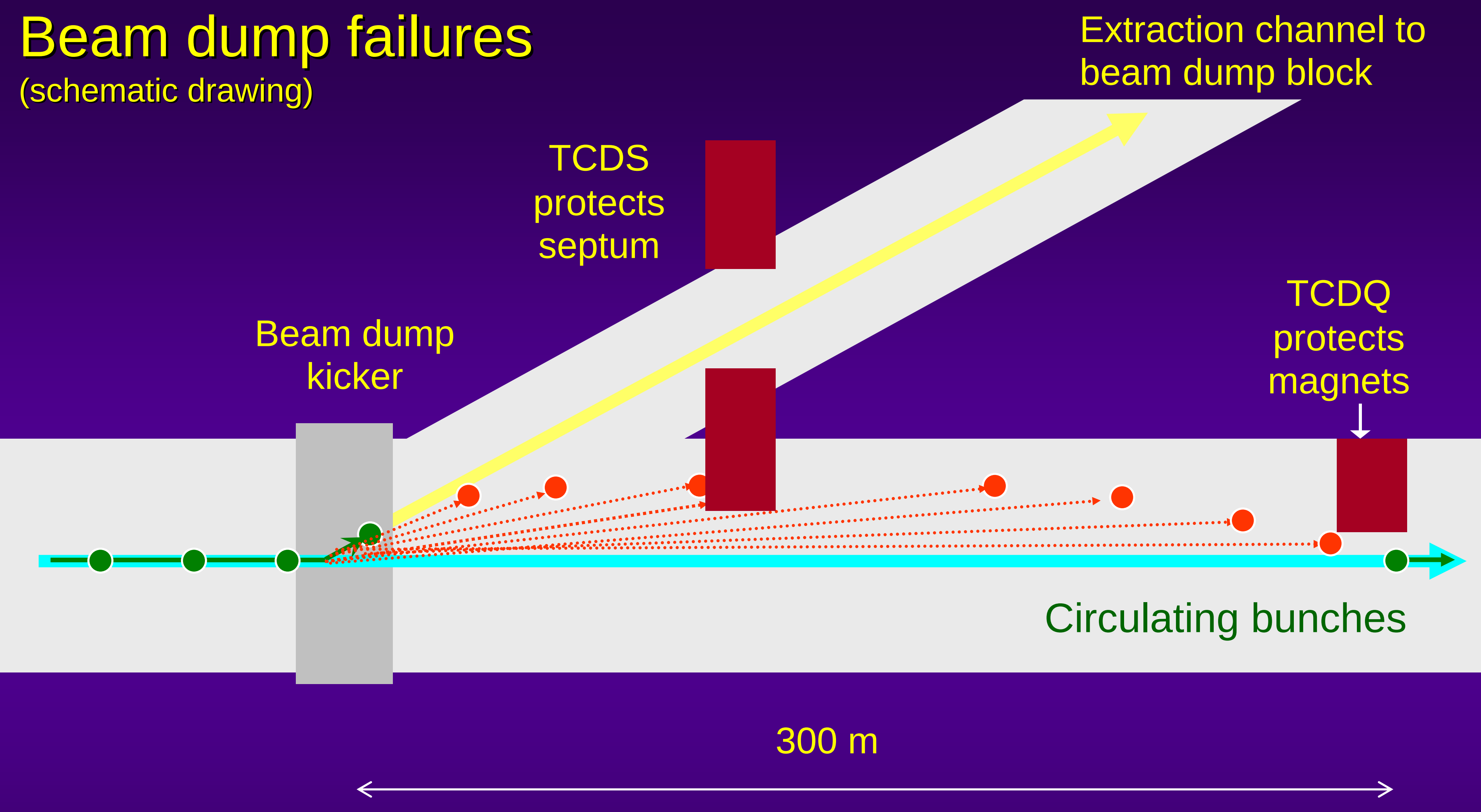


Example for accidental prefiring of kicker:

about 100 bunches are only partially deflected

Beam dump failures

(schematic drawing)



Set distance between closed orbit and TCDQ to protect aperture (10σ)

Capture bunches by beam absorbers

Eight Bunches that stays in the machine oscillates around closed orbit

Protection when dumping the beam

Optimisation of beam dump kicker parameters

- Minimise frequency of such failures
- Minimise kicker risetime
- After spontaneous firing of one kicker: fire 14 other kickers as fast as possible

Particles in the beam abort gap

- Protons at top energy lose energy by synchrotron radiation – absorbed by momentum collimators

MOPLT031, E. Shaposhnikova et al.

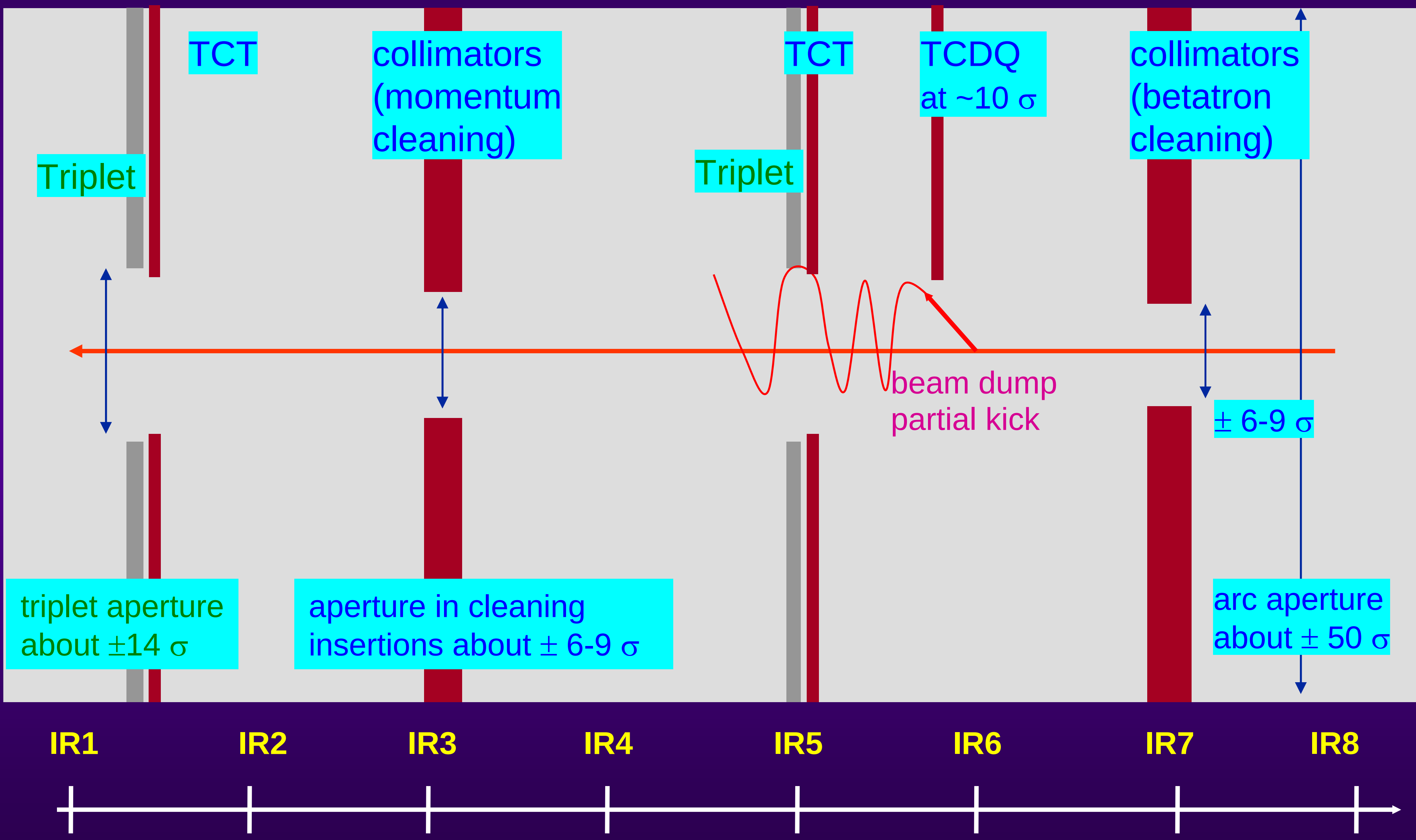
- Active gap cleaning is planned (using the transverse damper) – protons absorbed by betatron collimators

MOPLT019, W.Hofle

Critical apertures around the LHC (illustration drawing)

in units of beam size σ

7 TeV and β* = 0.55 m in IR1 and IR5



Collimators and beam absorbers

Beam could hit the collimator jaws in the beam cleaning insertions

- At 7 TeV, eight bunches escaping through the TCDQ
- At injection, a full batch from the SPS with 288 bunches
- High Z materials would be damaged (copper, but even aluminium)
- Collimators must be robust

Carbon-based materials has been chosen for the jaws of collimators

MOPLT036, V.Vlachoudis et al.

After a failure: Multiturn beam losses

- Closed orbit grows and moves around the ring (follows free betatron oscillation with one kick)
- Beam size explodes

Can happen very fast (for example, after a magnet quench)

Can be detected around the entire accelerator

- Local orbit bump

Cannot happen very fast

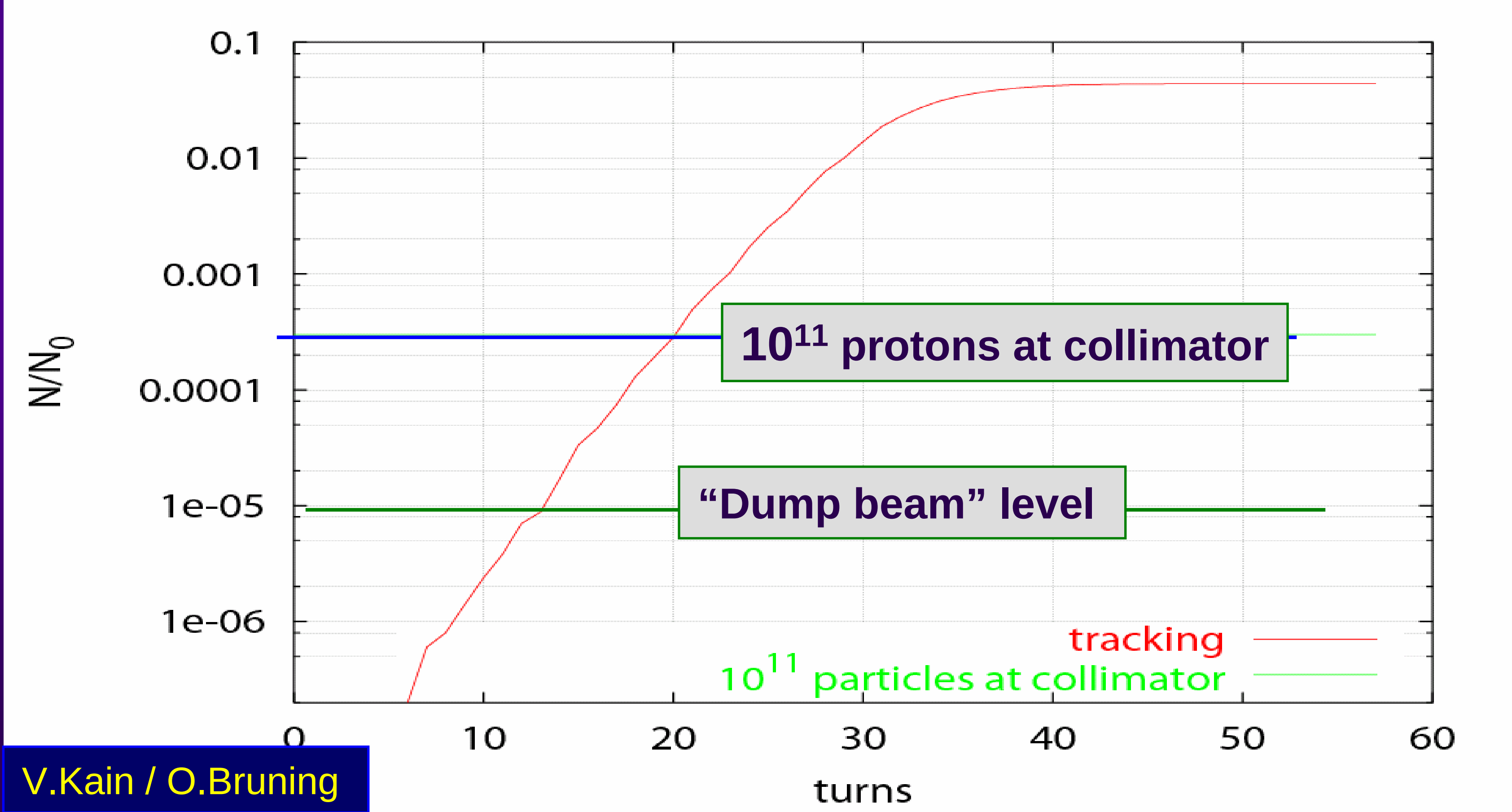
Might be detected only locally

Protection: Detect failure and dump beam

Detection by beam monitors and equipment monitoring

Particles 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



V.Kain / O.Bruning

Beam Loss Monitors

Very fast beam losses

- Collimators are limiting the aperture during all phases of LHC operation
- Beam loss monitors at all aperture restrictions continuously measuring beam losses
  - Losses can be detected within less than a turn
  - Aperture limitations are essentially collimators

Fast or slow beam losses

- Beam loss monitors around the ring (mainly in arcs) continuously measure beam losses
  - Losses can be detected within 2.5 ms

THPLT011, THPLT012, E.B.Holzer et al.

Design principles for machine protection

No erroneous manipulation on protection systems should compromise the accelerator safety

No single equipment failure should lead to equipment damage

- Redundant systems
- At least two channels should capture a failure (for example, by equipment monitoring and by beam monitoring)
- Failsafe systems: “Fail safe” leads to a beam dump in case of a failure in the protection systems – downtime of the accelerator but no damage

Quantification of risks coherent across systems – using standards (Safety Integrity Level - SIL)

Safe operation AND availability of LHC

Safety increases using two channels in parallel, each channel could dump the beam

- This increases the number of false beam dumps

Reducing number of false beam dumps by voting strategy

- For example “2 Out Of 3” or “2 Out Of 4”
- Not always possible (for example, for beam dumping system)
- Keep cost under control

Introduce flexibility by making the system “rigid but flexible”

- “Safe Beam Flag”: relaxing protection when operating with beam below damage threshold
- Masking interlocks permitted due to Safe Beam Flag

New ideas and future developments

Future work: detecting failures in less than one millisecond

Very fast detection of power converter / magnet failures

- Monitors current change in an electrical circuit (Hall probes)
- Prototype “quick and dirty” gave promising results

WEPLT043, M.Zerlauth et al.

Very fast beam current monitor, could detect beam losses within down to one turn

- Challenge: must be **fast and accurate** – to be explored

Detection of very fast orbit drifts (1 m/s – 1 mm/ms)

Sacrificial absorbers ?

Incentive from HERA: beam losses on this timescale are of concern

Conclusions

- Protection for LHC starts before extraction from SPS
- Protection is required during the entire cycle
- Collimators / Beam absorbers have an important role in machine protection and must define the aperture from injection to colliding beams

Availability of the machine due to the complex protection is challenging

- Large energy: stringent protection required - too few interlocks could lead to severe damage of the LHC
- Unprecedented complexity too conservative interlocking of the machine protection systems required - but could prevent LHC exploitation

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