Introduction to Accelerator Protection Course

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Preface

Audience: This school is intended for physicists and engineers who are or may be engaged in the design, construction, and/or operation of accelerators with high power photon or particle beams and/or accelerator sub-systems with large stored energy.

Purpose: We will present the methods and technologies to identify, mitigate, monitor, and manage the technical risks associated with or operation of accelerators with high power beams or sub-systems with large stored energy the fault or failure modes of which can result in substantial damage to accelerator systems or significance interruption of facility operations. At the completion of the school the participants should be able understand the physical phenomena that can damage machine sub-systems or interrupt operations and to analyze an accelerator facility to produce register of technical risks and the corresponding risk mitigation and management strategies.

Preface

- First school on Beam Losses and Accelerator Protection
  - Throughout my lectures and in other lectures: **Machine Protection**
- For many topics in accelerator physics and technology….
  - Textbook material (e.g. beam dynamics, synchrotron radiation,….)
  - USPAS and CAS schools with an excellent set of proceedings
- Not the case for beam losses and protection of accelerators - no books available, no standard lectures
  - In the past a few lectures and conference talks (see references)
- This school does not yet have a defined syllabus … we hope to cover all relevant aspects
- It is not common to present what went wrong in accelerators…
  - Fastest learning is from past incidents and near misses
  - Some examples will be given

Some questions

- Protection for what accelerators?
- What needs to be protected?
- What are the hazards / risks?
- What are the consequences?
- What can be done about it?

Protection from Energy and Power

- Risks come from Energy stored in a system (Joule), and Power when operating a system (Watt)
  - "Very powerful accelerator" … the power flow needs to be controlled
- An uncontrolled release of the energy, or an uncontrolled power flow can lead to unwanted consequences
  - Damage of equipment and loss of time for operation
  - For particle beams, activation of equipment
- This is true for all systems, in particular for complex systems such as accelerators
  - For equipment, such as **RF system**, **power converters**, **magnet system** …
  - For **particle beams**
- Particle accelerators use large amount of power (few to many MW)
  - Where does the power go in case of failure?

Energy and Power / Power density

Many accelerators operate with high beam intensity and/or high particle energy

- For synchrotrons and storage rings, the energy stored in the beam increased over the years (at CERN, from ISR to LHC)
- For linear accelerators and fast cycling machines, the beam power increased
- For some accelerators, the emittance becomes smaller (down to a beam size of nanometer) – very high power / energy density (W/mm^2 or J/mm^2)
- This is important today, and even more relevant for future projects, with more powerful accelerators and increasingly complex machines
- Even small amount of energy can lead to some (limited) damage - can be an issue for sensitive equipment

What does it mean .... Joule, kJ and MJ?

The energy of pistol bullet: about 500 J

The energy of 1 kg TNT: about 4 MJ

The energy of 1 l gas: about 36 MJ

To melt 1 kg of steel (copper is similar): about 800 KJ

This lecture

- A personal approach from my past experience
- Performance of particle accelerators and hazards
- Performance of a particle accelerator and Machine Protection
- Introduction to Machine Protection
- An approach for accelerated learning…..

A personal approach from past experience

Storage rings / circular colliders for particle physics

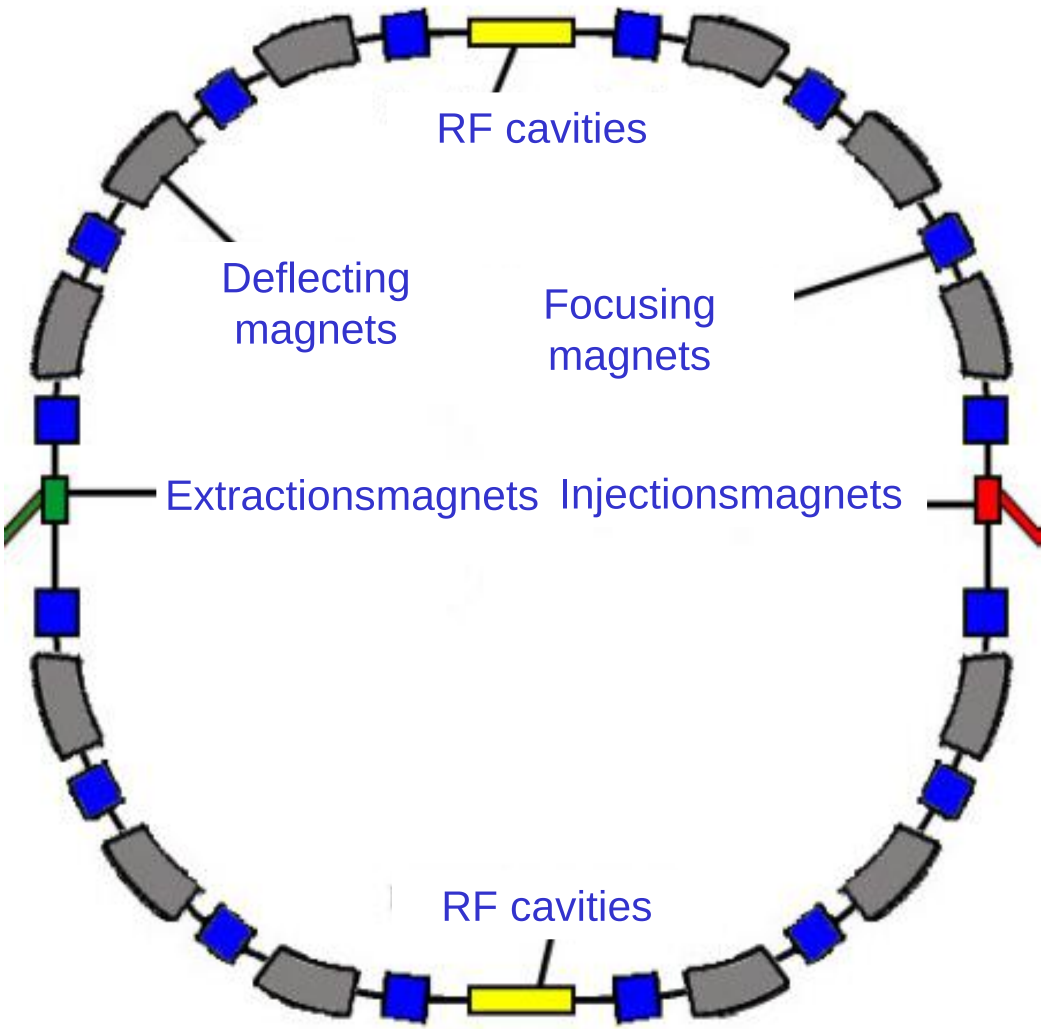
- DESY PETRA e+e- collider (1978 – 1986)
- CERN SPS Proton Antiproton Collider (1982 – 1990)
- CERN SPS Proton Synchrotron (1978 - …)
- CERN LEP Large Electron Positron Collider (1989 – 2000)
- CERN LHC Large Hadron Collider (2008 - …)

High intensity proton accelerator (spallation source) for neutron production

- ESS European Spallation Source at LUND (start of operation planned for 2019)

Circular accelerators

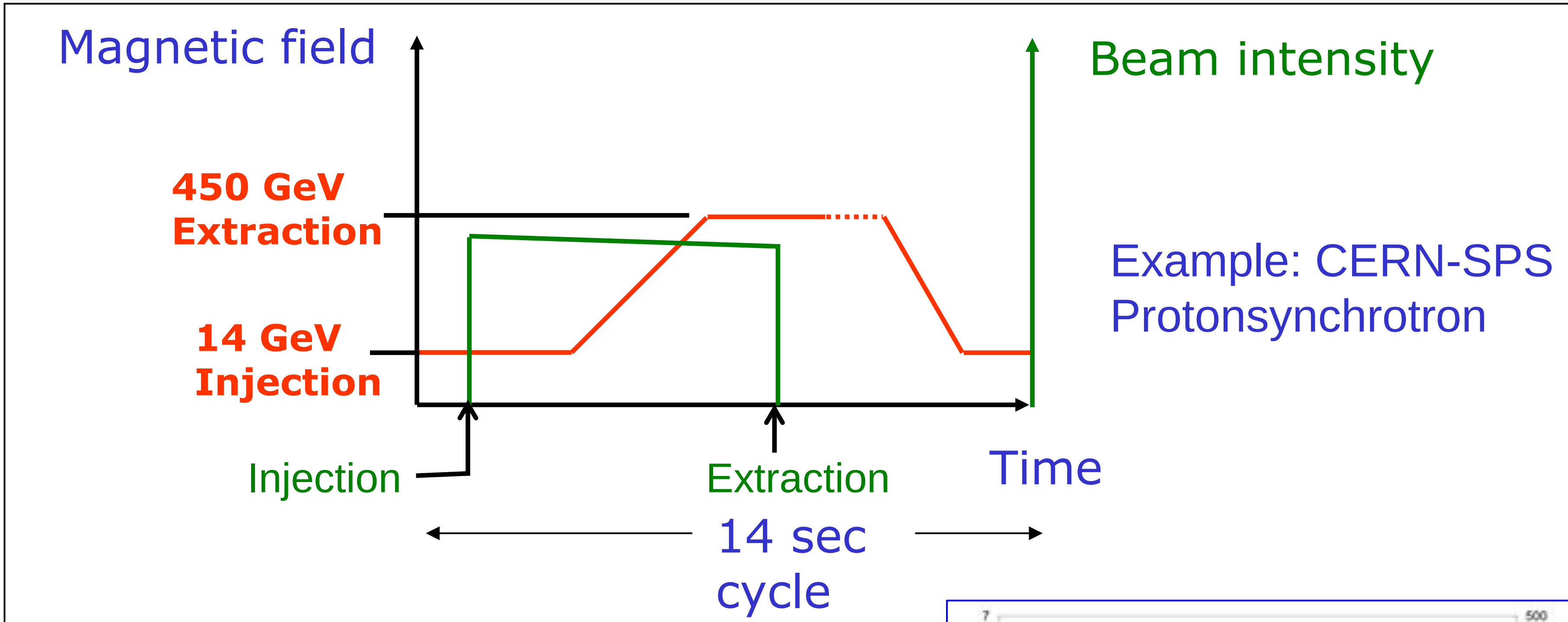
Components of a circular accelerator

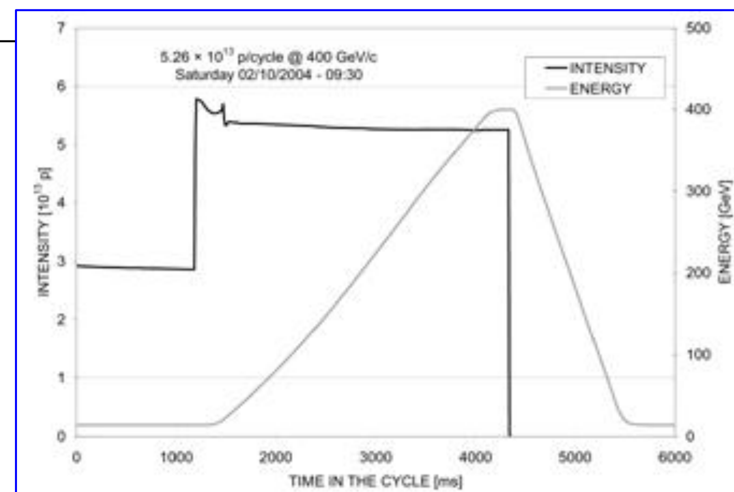


Components of a synchrotron:

- deflection magnets
- magnets to focus beams and other magnets
- RF cavities
- RF system
- vacuum system
- injection magnets (pulsed)
- extraction magnets (pulsed)
- beam instrumentation
- experiments
- control system
- power converter

Synchrotron





- From synchrotron to storage ring: “simply” extend the length of the extraction plateau to many hours
- Colliders use two beams, either in one or in two vacuum chambers

Circular colliders for highest energy….

- Operation as synchrotrons
- Beams are injected at "low" energy
- Beams are accelerated to "high" energy
  - In general, by a factor of 10 to 40
- Beam are brought into collisions
- Beams are colliding for many hours (depending on the accelerator, from 5 to several 10 hours)
  - This is what counts for particle physicists
- The fill is ended –next cycle starts - the magnets are ramped down to injection energy - what happens with the beam??
- The entire process from **end collisions** to **next collisions** takes some time (between, say 30 minutes and a few hours)
- If the beam is lost during a fill … time for physics lost

Luminosity and number of events

Number of „New Particles“ per unit of time:

$$\frac{N}{\Delta T} = L\left[cm^{-2} \cdot s^{-1}\right] \cdot \sigma\left[cm^{2}\right]$$

The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-2}s^{-1}$], HL-LHC about 5 10^{34} [$cm^{-2}s^{-1}$], other colliders (B-Factory at KEK, Japan) aim even at a luminosity of 10^{36} [$cm^{-2}s^{-1}$]

PETRA :	2 10^{31} [$cm^{-2}s^{-1}$] (?)
LEP (e+e-) :	3-4 10^{31} [$cm^{-2}s^{-1}$]
Tevatron (p-pbar) :	some 10^{32} [$cm^{-2}s^{-1}$]
B-Factories :	> 10^{34} [$cm^{-2}s^{-1}$]
Super-KEKB :	10^{36} [$cm^{-2}s^{-1}$]
FCC (Future Circular Collider):	5 10^{34} [$cm^{-2}s^{-1}$]

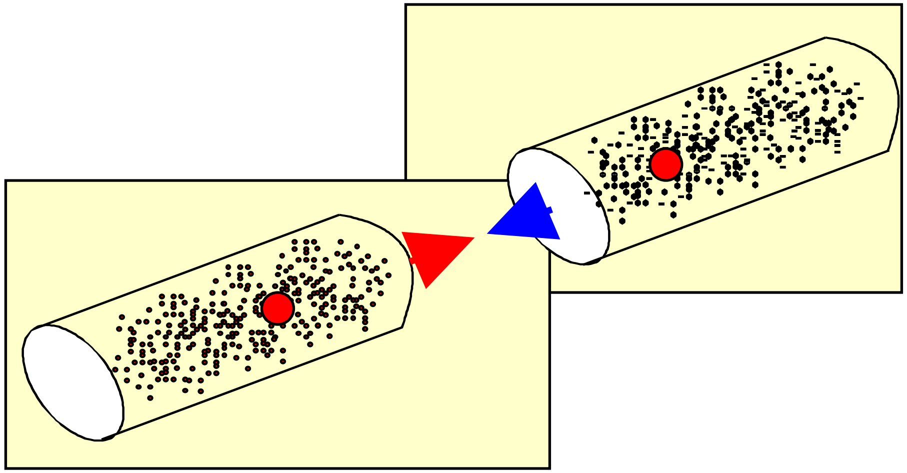
$$L = \frac{N^2 \times f_{rev} \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

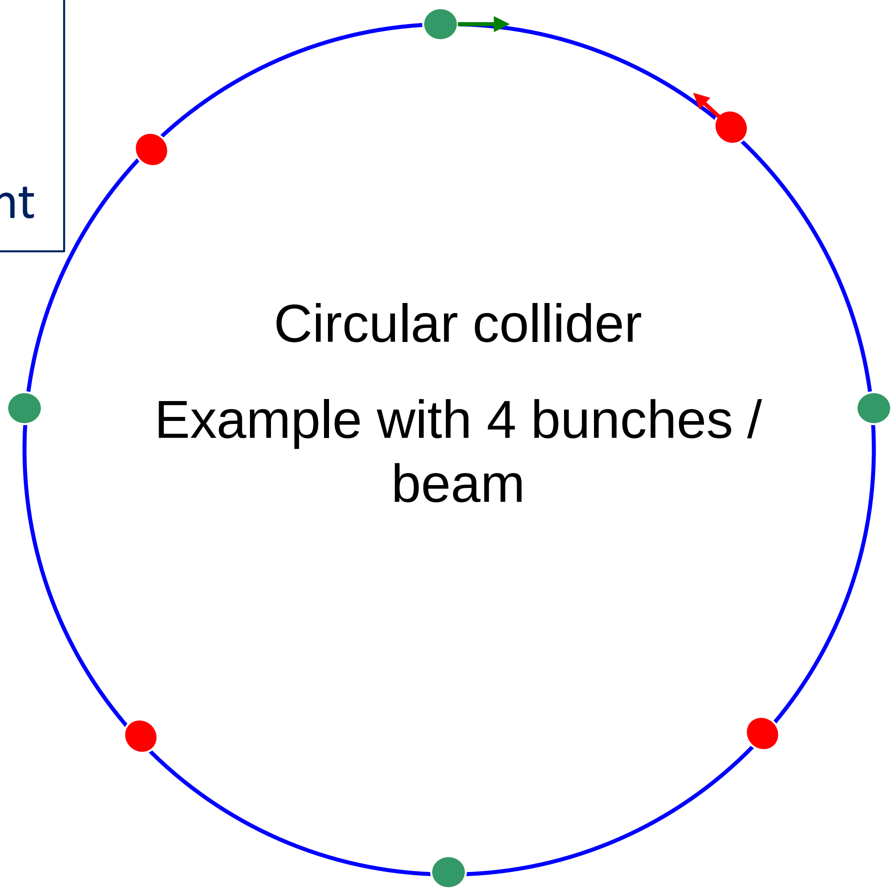
N … number of particles per bunch

f_{rev} … revolution frequency

n_b … number of bunches per beam

$\sigma_x \times \sigma_y$ beam dimensions at interaction point





Integrated Luminosity

- The total number of particles created at an accelerator (the total number of Higgs bosons) is proportional to the **Integrated Luminosity**:

$$\int L(t) \times dt$$

- It has the unit of [cm^{-2}] and is expressed in Inverse Picobarn or Inverse Femtobarn

- Example: https://lhc-statistics.web.cern.ch/LHC-Statistics/

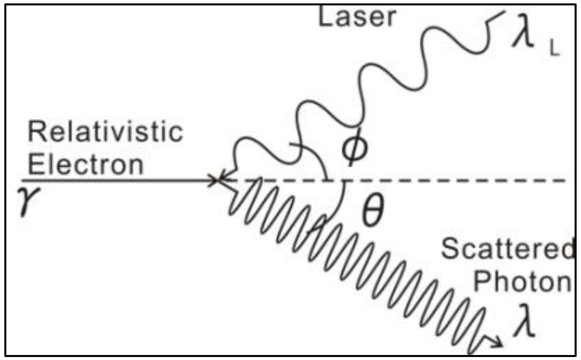
Observations at various accelerators

- My first experience in accelerators: PETRA at DESY
  - e+ e- collider with a length of 2304 m
  - Started operation in 1978
  - Four bunches per beam, each beam with about 6.5 mA
  - Normal conducting magnets
  - The beam was sometime lost, frequently for unknown reason, in particular during the energy ramp
  - No issues with protection from beam in case of beam loss (too little stored energy in the beam)
  - One way of getting rid of the beam is by switching off the RF – the beam gets lost over many ms to seconds (energy loss by synchrotron radiation)

PETRA Tunnel 1980 with bending magnets, quadrupoles and sextupole

PETRA Collider at DESY

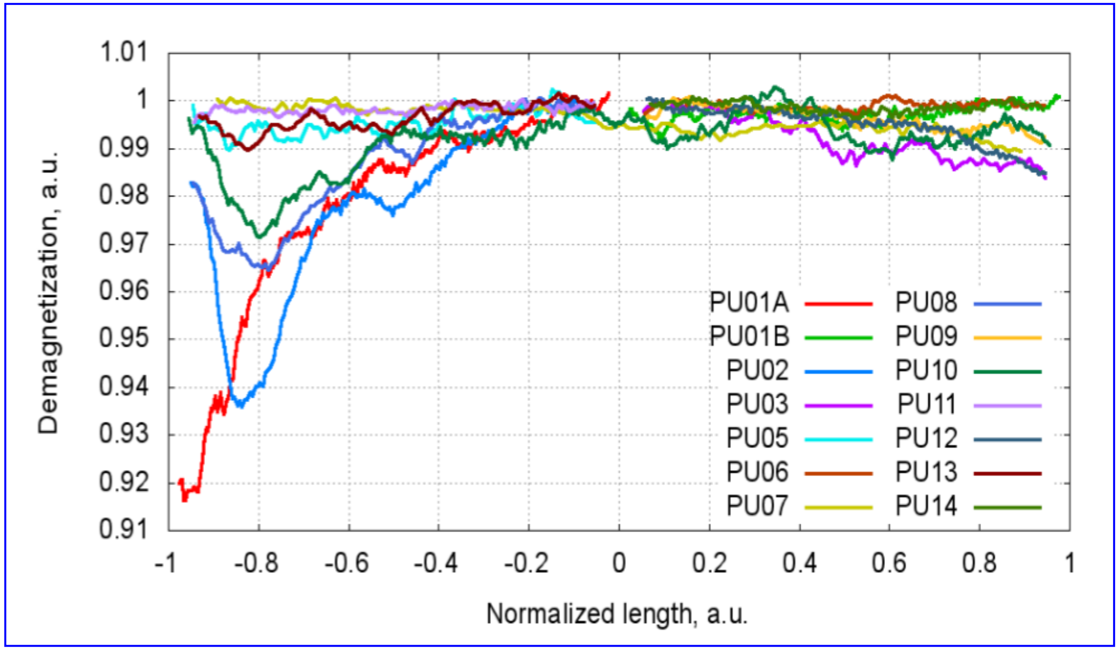
- My first (unfortunate) contribution to machine protection…….
  - Compton scattering of laser light to measure beam polarisation
  - Sending a high power laser beam into the vacuum chamber through a glass window: the glass cracked when the laser passed the window
  - Vacuum pressure increased, an intervention was required
  - The window could be sealed … and operation continued – no major incident
  - Watch out to leave the vacuum enclosure intact



PETRA at DESY

- Lesson from PETRA I:
  - The beam at PETRA I could hardly do any damage….
  - Watch out for protection of equipment due to the energy / power in the hardware systems
  - **Protect the beam**
  - **Provide the evidence** …. understand what happens

- PETRA III:
  - Operates since 2008 as a world-class synchrotron light source
  - Injection at operating energy, no energy ramp
  - Issues with the undulator magnets due to beam losses – de-magnatisation observed



CERN-SPS Proton Antiproton Collider

- Build as proton synchrotron, to accelerate protons to 450 GeV and direct the beam on a target for Fixed target experiments starting in 1978
    - Normal conducting magnets, no ultrahigh vacuum required
- Transformed the SPS accelerator from a Fixed Target Synchrotron into a Proton Antiproton collider in 1980 … 1982
- Operating as Proton Antiproton Collider until 1990
- **Antiprotons are very rare**, takes a **long time** to produce them
- **Lesson from SPS Proton Antiproton Collider: Protect the beam**
- Sometime the beams were lost …….. many hours to produce a new stack of antiprotons
- Once, injected beam went for 10 min into the UA2 experiment … not appreciated: do not forget the **protection of the experiments**

CRN-SPS Proton Synchrotron

- Very different parameters from Proton Antiproton Collider
  - Cycle time in the order of some seconds to some ten seconds, high intensity beams
  - Used for fixed target physics, neutrino production and as injector for LHC
  - Requirements for the vacuum system are moderate
- If the beam is lost … no big issue, wait for next cycle
  - However, beam losses should not lead to damage
- Beam current constantly being increased over the years
- Operating in different modes with different extraction lines
- Several (minor) accidents during the history of the SPS by beam induced damage
  - Damage, e.g. replacing a magnet, can be fixed in a short time (< one day)
- **Lesson from SPS Proton Synchrotron: Protect the machine from uncontrolled beam losses**

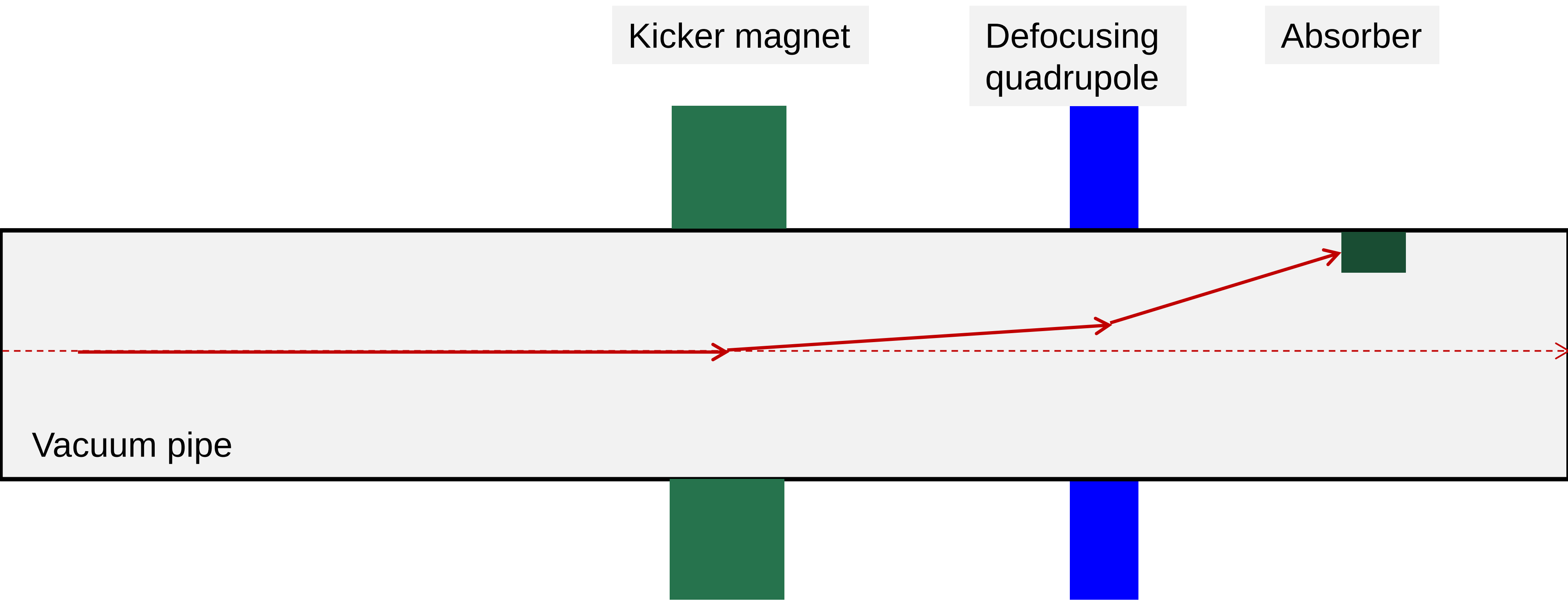
CERN-LEP Electron Positron Collider

- LEP, operating until 2000, was installed in the tunnel that is now used for LHC and energy of up to 104 GeV / beam, injecting at and energy of 20 GeV

- One vacuum chamber, normal conducting magnets for LEP I
- Superconducting RF cavities (for LEP II)
- Four to eight bunches per beam
- Background in the experiments was an issue for LEP, as for all colliders (not because of damage)
- Dumping the beam after a fill by switching off the RF during the first phase of LEP
- Total energy stored in the beam was small

LEP beam dump

- Improvement of LEP performance (higher energy, higher intensity): necessary to dump LEP beams in a fully controlled way.
- Fast kicker, close to defocusing QL8 quadrupole, vertically deflects bunches; other quadrupoles give additional vertical deflection to deflect beam into absorbers.



LEP surprises, another way to dump the beam ….

- In June 1996, operation was just about to begin with the upgraded machine when we ran into an unexpected problem. Operators were injecting beam, but it wasn’t getting around the whole accelerator.
- After careful investigation, we found the cause—a pair of Heineken bottles wedged into the beam pipe.
- Beam pipes were easily accessible and repairs could be made fairly quickly. This would have been **very different for a superconducting machine**, the consequence is a repair time of months

1996: Heineken Beam Stopper

UK advertising at the time:

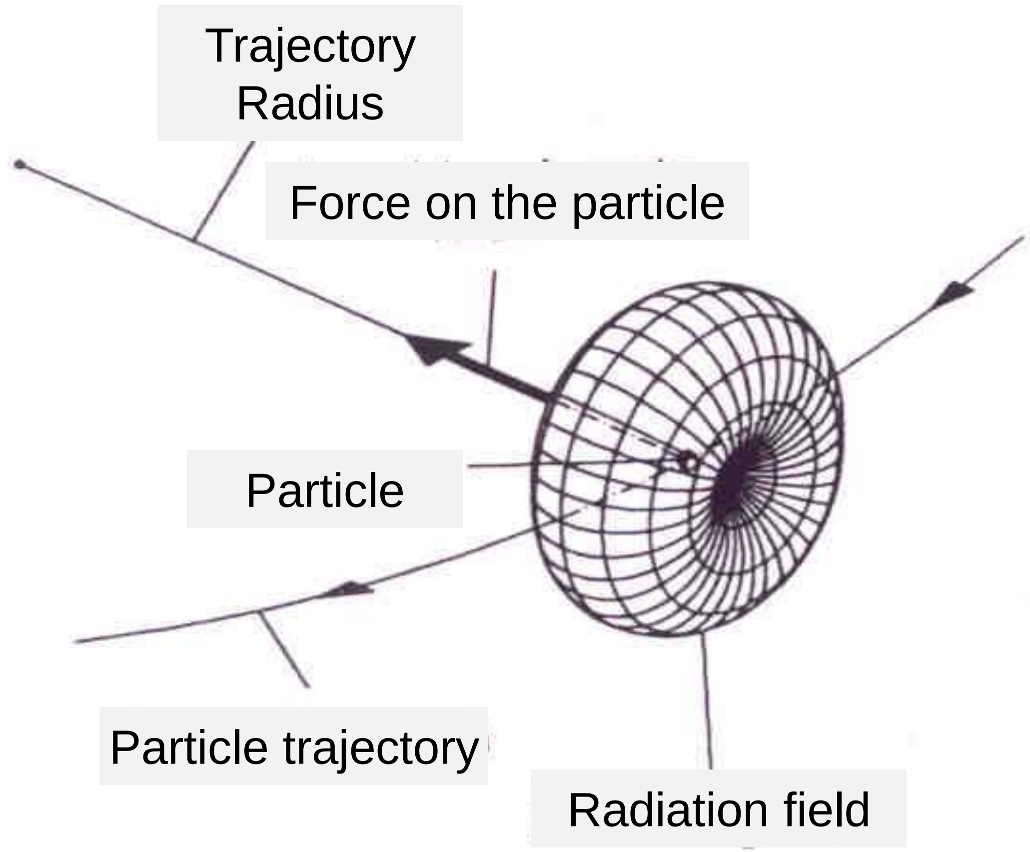
Heineken; the beer that gets to places no other beer can!

High electron energy and consequences for machine protection

Example for LEP

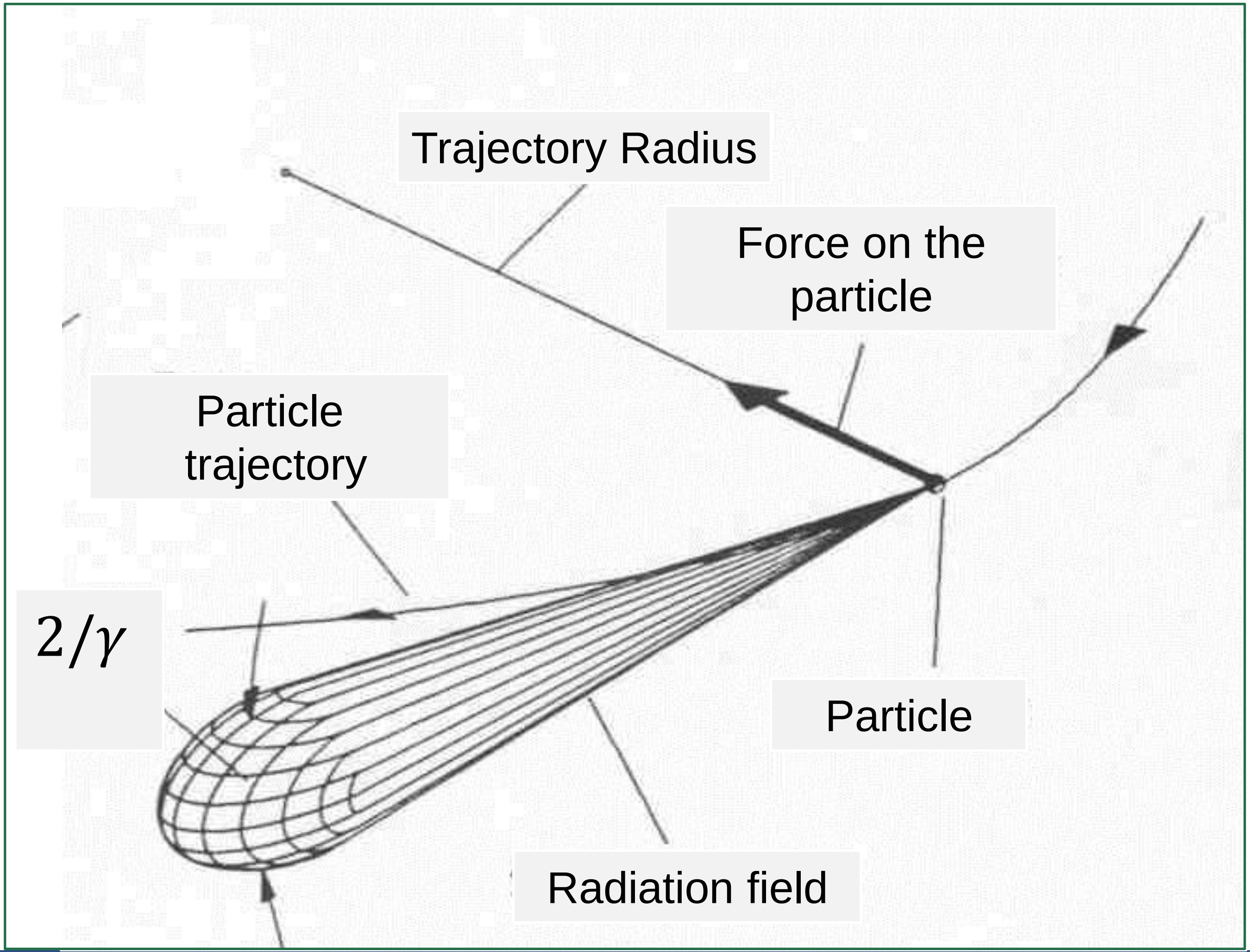
Synchrotron radiation

- An accelerated charged particle emits radiation.
- This is also valid for transverse acceleration in a deflecting field
- Calculation by a Lorentz Transformation



- Cone of synchrotron radiation in the lab frame
- The radiation is emitted in a very narrow cone with the angle γ

$$\gamma = \frac{E}{mc^2}$$



Power of synchrotron radiation

- Power of synchrotron radiation:

$$P_s = \frac{e_0^2 \times c}{6 \times \pi \times \epsilon_0 \times (m \times c^2)^4} \times \frac{E^4}{\rho^2}$$

Particle mass: m

Particle energy: E

Radius of the deflecting field: ρ

Speed of light: c

Elementary charge: ϵ_0

Power of synchrotron radiation at LEP

Compare LEP at 45 GeV and at 90 GeV

$$\rho = 3000\,\mathrm{m}$$

$$E_{lep45} := 45\mathrm{GeV}$$

Power for LEP (1 Electron):

$$P_{lep45} := \frac{e_0^{\,2}\cdot c}{6\cdot\pi\cdot\varepsilon_0\cdot\left(m_e\cdot c^2\right)^4}\cdot\frac{E_{lep45}^{\,4}}{\rho^2}$$

$$P_{lep45} = 3.079\times 10^{-7}\,\mathrm{W}$$

$$\gamma_{lep45} := \frac{E_{lep45}}{m_e\cdot c^2} \qquad U_{lep45} := e_0^{\,2}\cdot\frac{\gamma_{lep45}^{\,4}}{3\cdot\varepsilon_0\cdot\rho}$$

$$E_{lep90} := 90\mathrm{GeV}$$

Power for LEP (1 Electron):

$$P_{lep90} := \frac{e_0^{\,2}\cdot c}{6\cdot\pi\cdot\varepsilon_0\cdot\left(m_e\cdot c^2\right)^4}\cdot\frac{E_{lep90}^{\,4}}{\rho^2}$$

$$P_{lep90} = 4.927\times 10^{-6}\,\mathrm{W}$$

$$\gamma_{lep90} := \frac{E_{lep90}}{m_e\cdot c^2} \qquad U_{lep90} := e_0^{\,2}\cdot\frac{\gamma_{lep90}^{\,4}}{3\cdot\varepsilon_0\cdot\rho}$$

Power of synchrotron radiation at LEP

Energyloss for an electron per turn:

$U_{lep45} = 1.208 \times 10^{8} \cdot eV$ $\qquad$ $U_{lep90} = 1.934 \times 10^{9} \cdot eV$

Power of the synchrotron radiation:

Current in LEP: $I_{lep\_2\_beams} := 5 \times 10^{-3} A$

Revolution frequency: $f_{rev\_lep} := 12486 \cdot Hz$

$$N_{lep} := \frac{I_{lep\_2\_beams}}{e_0 \cdot f_{rev\_lep}}$$

Number of electrons / positrons in LEP: $N_{lep} = 2.5 \times 10^{12}$

$P_{total\_lep45} := N_{lep} \cdot P_{lep45}$ $\qquad$ $P_{total\_lep90} := N_{lep} \cdot P_{lep90}$

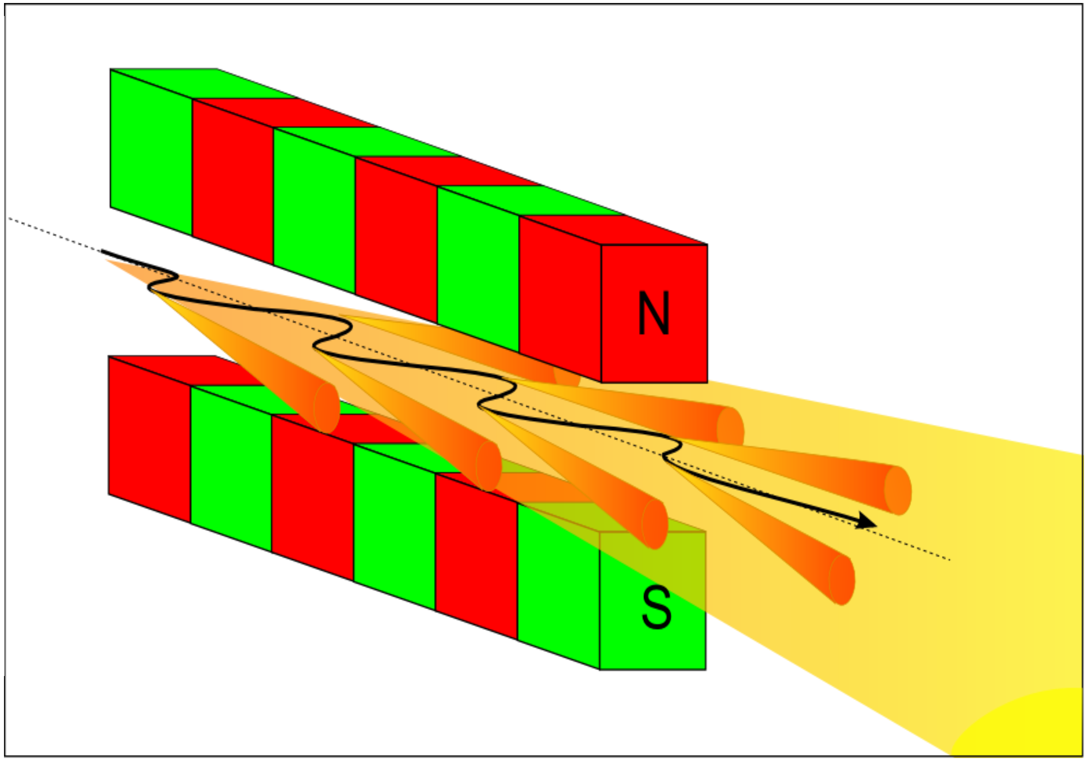
$P_{total\_lep45} = 7.697 \times 10^{5} W$ $\qquad$ $P_{total\_lep90} = 1.231 \times 10^{7} W$

The power of the synchrotron radiation in LEP is very large when operating at high energy

Even more intense when using a wiggler magnet

- Assuming we want to create very intense beam of light or X-rays
- Wiggler magnets or undulator magnet are used
- The light intensity is enhanced, possibly by orders of magnitude

- Using wiggler and undulators are not limited to circular accelerators
- The European X-Ray Laser Project XFEL is based on the use of undulators

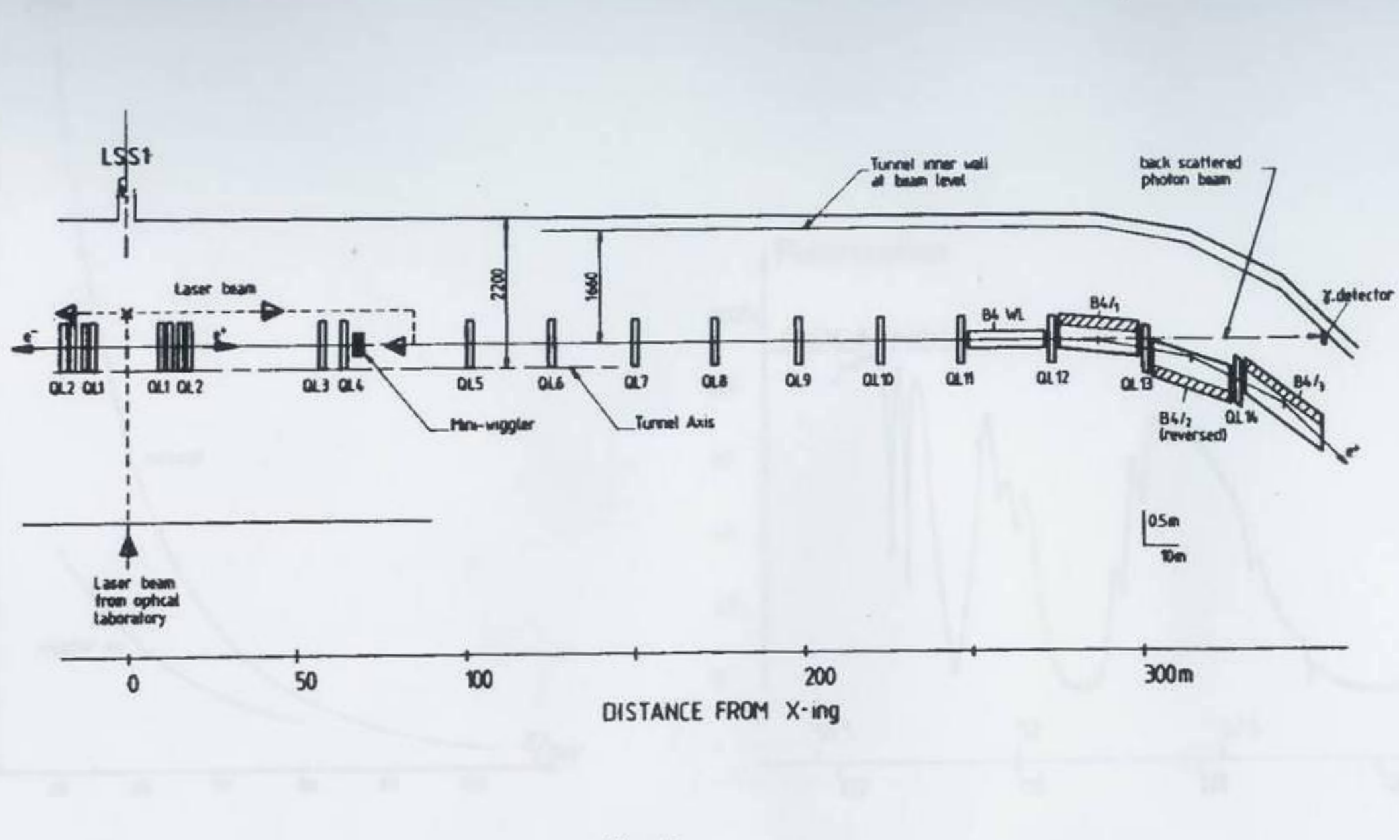


http://photon-science.desy.de/research/studentsteaching/primers/synchrotron_radiation/index_eng.html

LEP: damage from synchrotron radiation

- Initially operating at 45 GeV … later 80 GeV … 104 GeV
- The first equipment damaged: lead stoppers located in front of the aluminium windows of the polarimeter (to protect the device when it is not in use). After 30 days running at 80.5GeV per beam, several of these blocks were found melted and replaces with tungsten.
- Other damage: beam instrumentation, electrostatic separators, vacuum equipment, in particular from wiggler magnets

LEP: damage from synchrotron radiation



Lesson from LEP

- Dumping the beam without special equipment was at the limit: beam dumping system was later required
- Damage from beam losses in case of equipment failure was not an issue
- Frequently the beam was lost, e.g. during the energy ramp, without understanding the reason
  - No adequate diagnostic system to record beam and hardware parameters - **Post Mortem System**
  - Other colliders reported similar issues
- Emission of synchrotron radiation is a feature of normal operation.
  - Can damage equipment, needs to be foreseen in the design
- Also Very important for synchrotron light sources and XFELs

Hadron collider for high luminosity and energy: consequences for machine protection

LHC: Record energy of 7 TeV / beam
Very high luminosity
Superconducting magnets

Re-writing the luminosity equation ….

$$L = \frac{N^2 \times f_{rev} \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

$$E_{beam} = \frac{\sigma \times E \times C}{c} \sqrt{\frac{4 \times \pi \times L}{\delta T}}$$

Luminosity:	L
Bunch distance:	δT
Circumference:	C
Energy:	E
Beam size at IP (round beams):	σ
Speed of light:	c

This assumes that the ring is continuously filled with bunches – not quite possible

Energy stored in the beam: E_{beam} inceases with the particle energy, with the circumference, with the luminosity and the number of bunches

Energy and Luminosity for LHC

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy of 7 TeV
- In order to observe rare events, the luminosity should be in the order of 10^{34} [$cm^{-2}s^{-1}$] (challenge for the LHC accelerator)
- Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

- Assuming a total cross section of about 100 mbarn for pp collisions, the event rate for this luminosity is in the order of 10^9 events/second (challenge for the LHC experiments) - activation
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma ....)

Number of protons per bunch limited to about **1-3×10^{11}** due to the beam-beam interaction and beam instabilities

Beam size given by injectors and by space in vacuum chamber

f_{rev} = 11246 Hz

Beam size **16 μm**, for β = 0.5 m (β is a function of the lattice)

$$L = \frac{N^2 \times f_{rev} \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y} = 3.5 \times 10^{30}\ [cm^{-2}\ s^{-1}]$$ for n_b = 1

with **2808** bunches (every 25 ns one bunch)

L = 10^{34} [cm^{-2}s^{-1}]

$$E_{beam} = \frac{\sigma \times E \times C}{c} \sqrt{\frac{4 \times \pi \times L}{\delta T}}$$

$$E_{beam} = \sigma \times E \times \sqrt{\frac{4 \times \pi \times L \times n_b}{f_{rev}}}$$

Nominal LHC luminosity:	$L = 10^{34} \times \frac{1}{cm^2 s^1}$
Number of bunches per beam:	$n_b = 2808$
Revolution frequency:	$f_{rev} = 11\ kHz$
Energy:	$E = 7\ TeV$
Beam size at IP:	$\sigma = 16\ \mu$

Energy stored in the beam, exact result: $E_{beam} = 362\ MJ$

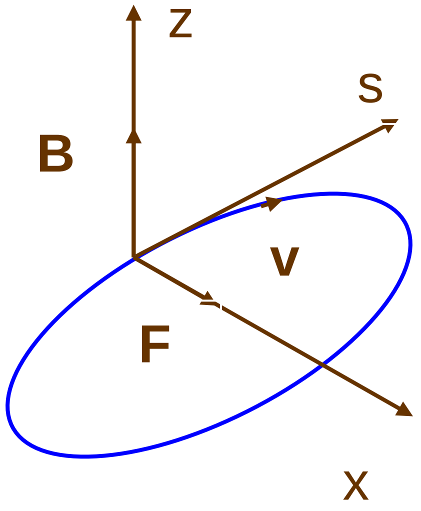
Energy stored in the beam, approx. result: $E_{beam} = 407\ MJ$

Particle deflection: superconducting magnets

The force on a charged particle is proportional to the charge, the electric field, and the vector product of velocity and magnetic field given by Lorentz Force:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$$B = \frac{p}{e_0 \cdot R}$$



- Radius determined by the tunnel
- Energy is proportional to the strength of the magnetic field
- Iron magnets are limited to a field of 2 Tesla
- Higher energy at fixed radius => higher field => superconducting magnets

Particle deflection: superconducting magnets

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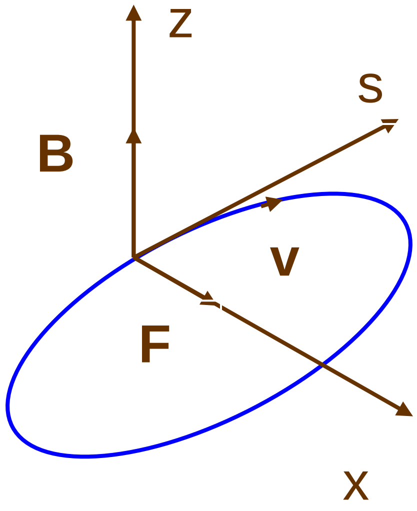


- Maximum momentum 7000 GeV/c
- Radius 2805 m fixed by LEP tunnel
- **Magnetic field B = 8.33 Tesla**
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions

Energy stored in superconducting magnets

The part of the energy in the magnet system inside the coil is given by (lower bound):

$$E_{magnets} \sim \frac{2 \times \text{Length} \times R^2 \times \pi \times B^2}{\mu_0}$$

$\text{Length} \sim 20\ \text{km}$

$\text{Radius vacuum chamber } R = 28\ \text{mm}$

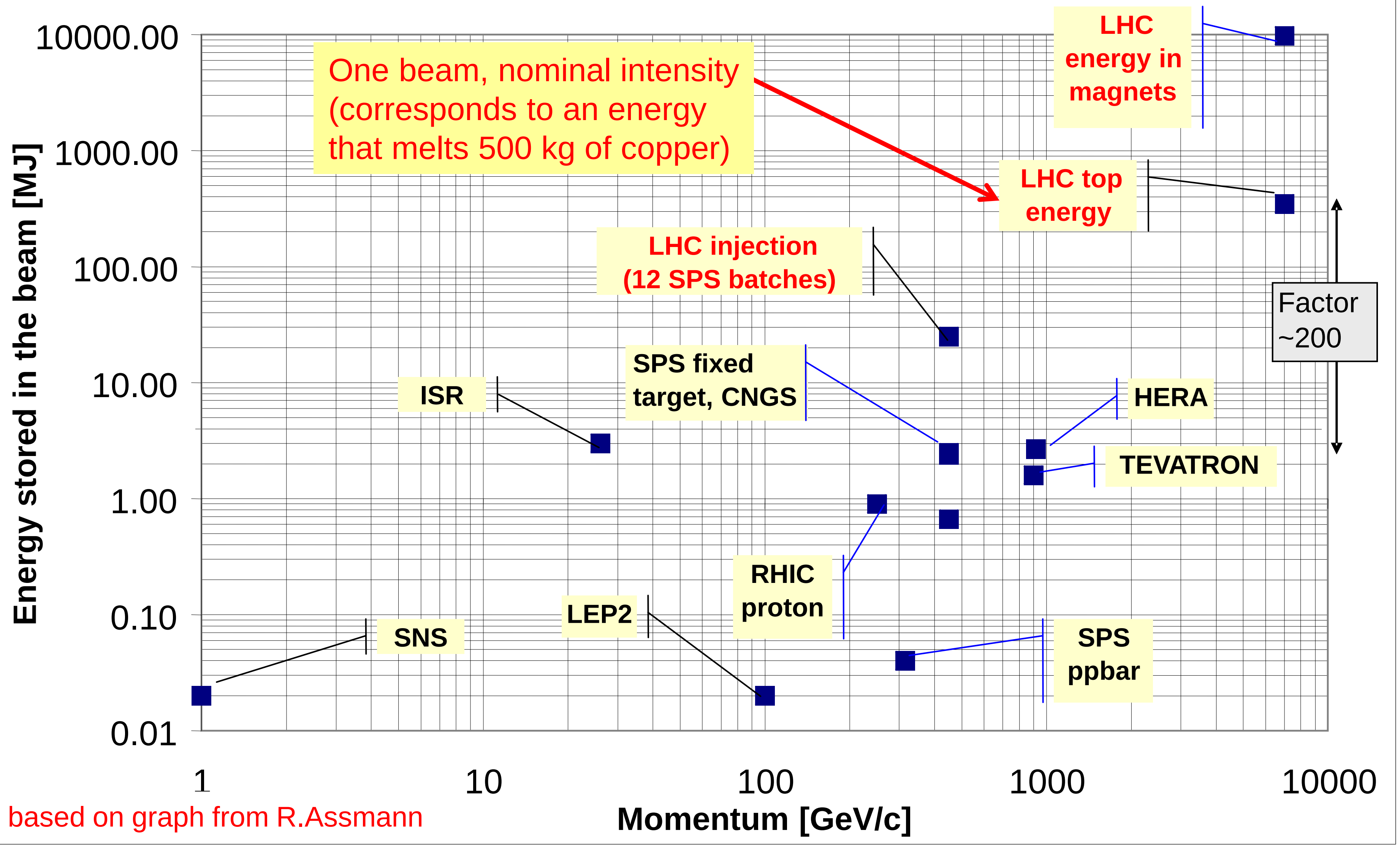
$B\ \ = 8.3\ \text{T}$

$\mu_0 = \text{permeability}$

$\mathbf{E_{magnets} \sim 4800\ MJ}$

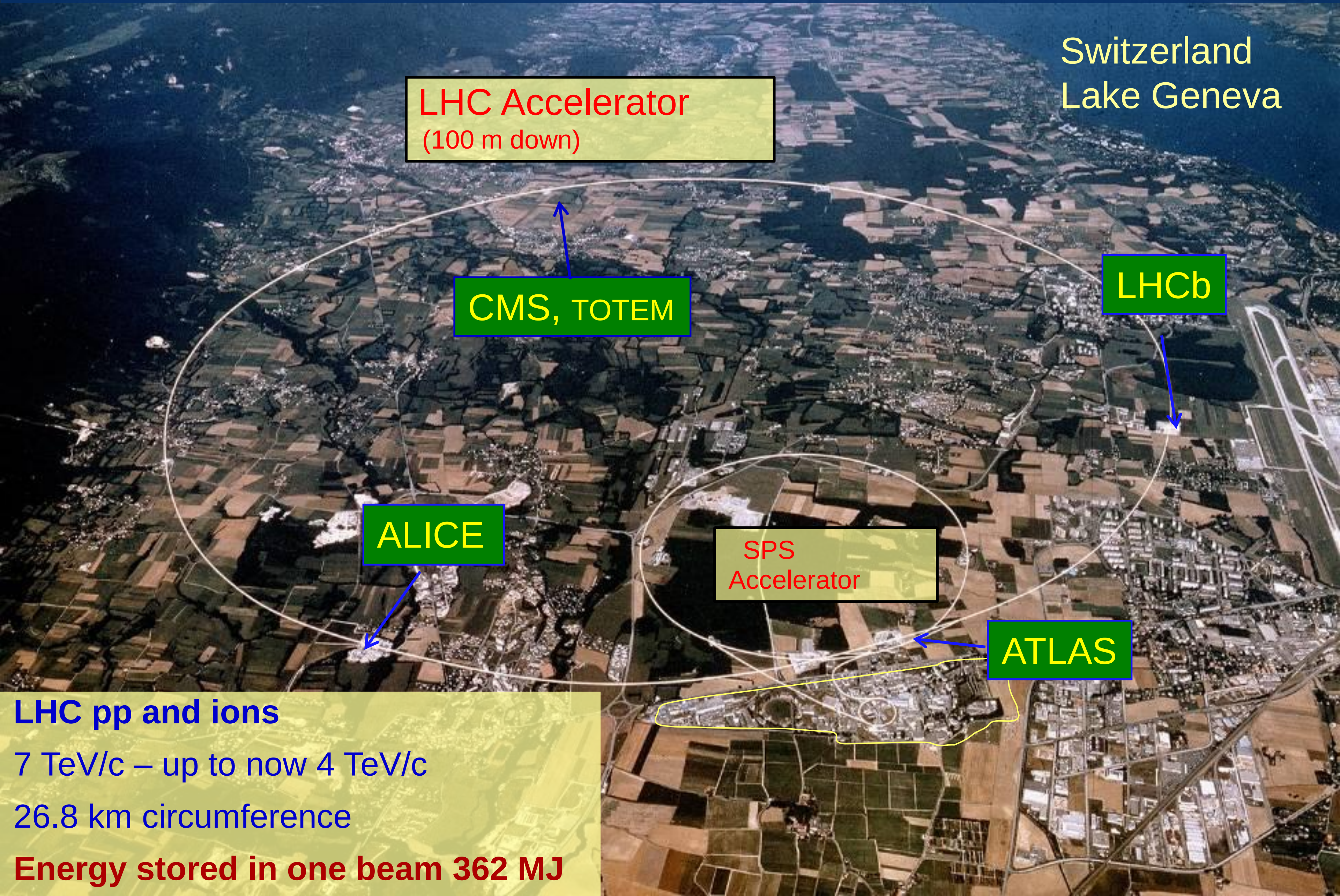
The exact calculation using the magnet inductance gives 8820 MJ

Energy stored in beam and magnets



based on graph from R.Assmann

Proton collider LHC – 362 MJ stored in one beam



LHC pp and ions

7 TeV/c – up to now 4 TeV/c

26.8 km circumference

Energy stored in one beam 362 MJ

LHC Large Hadron Collider

- Two ring collider (two different bending fields and vacuum chambers)
- Superconducting magnets
  - Protection of superconducting magnets is coming along with the development
- It is not tolerable to lose the beam in an uncontrolled way = > needs to be extracted from the machine
- A performant protection system is required, to protect from both, uncontrolled release of beam energy and uncontrolled release of magnet energy
- What triggers the extraction? Managing of interlocks is required.
- Task assigned to a team in 2000: Machine Protection Working Group

……the LHC

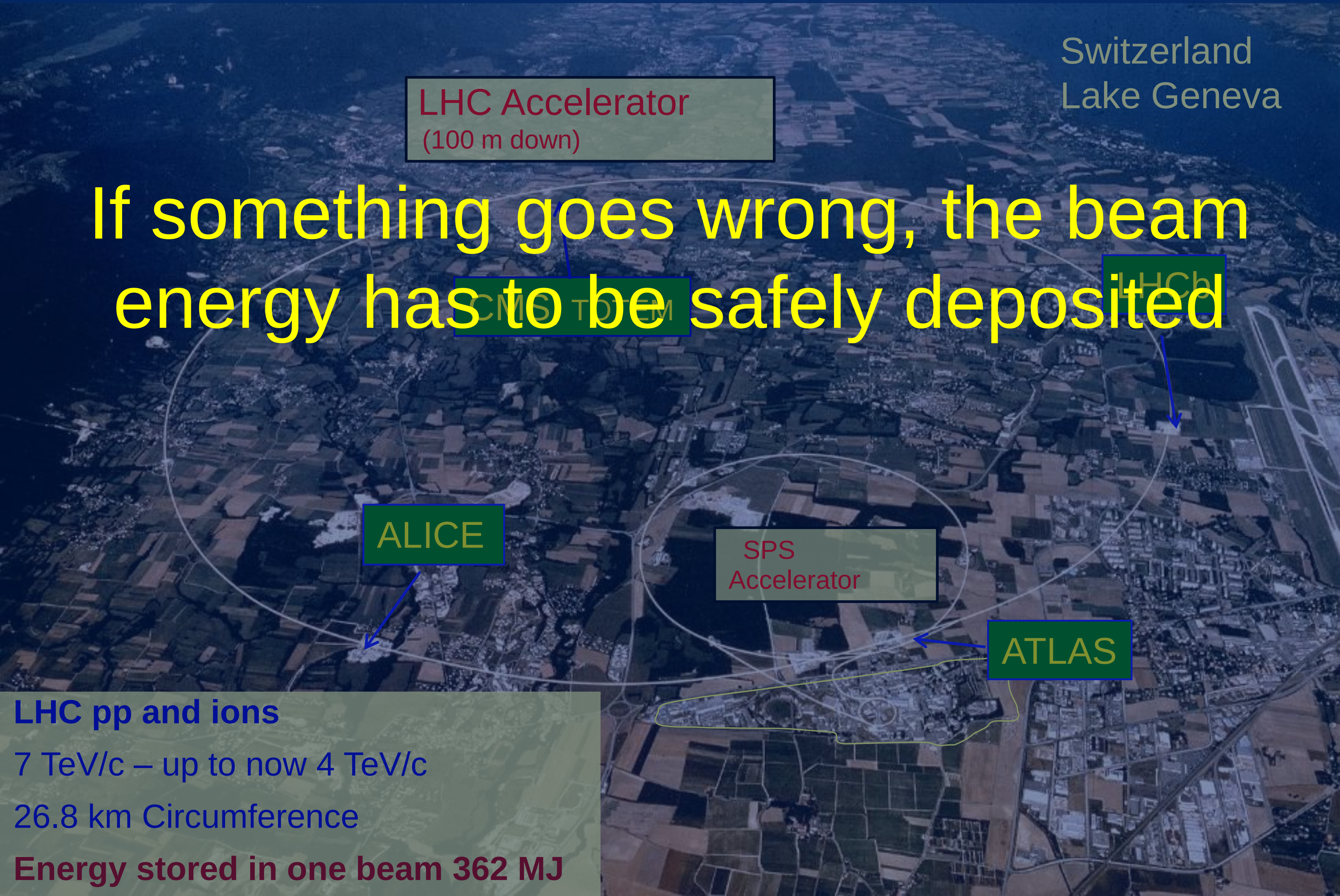
The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJ stored in one LHC beam.

360 MJ: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

It matters most how easy and fast the energy is released !!

Proton collider LHC – 362 MJ stored in one beam



If something goes wrong, the beam energy has to be safely deposited

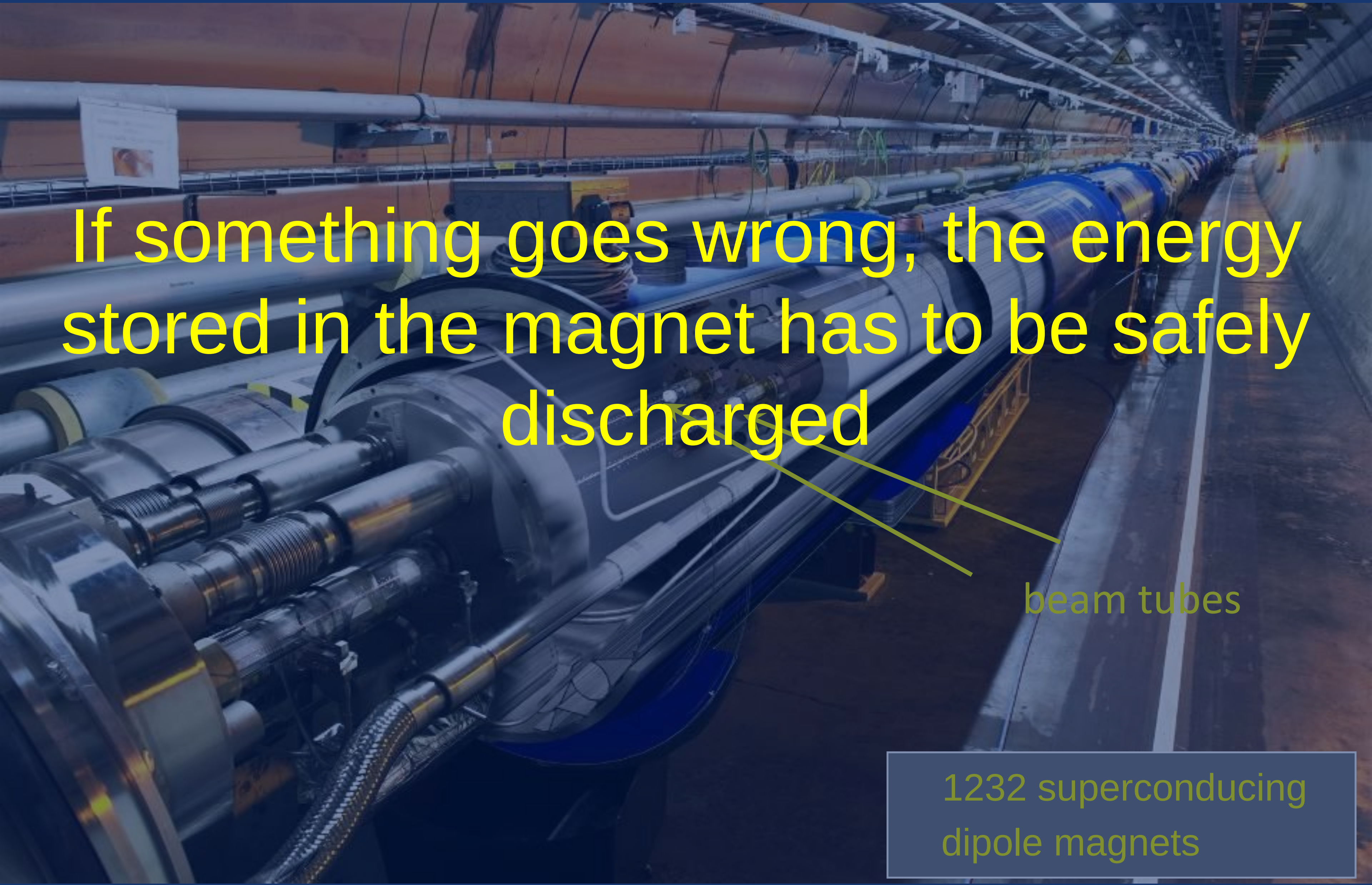
LHC pp and ions

7 TeV/c – up to now 4 TeV/c

26.8 km Circumference

Energy stored in one beam 362 MJ

LHC tunnel with dipole magnets



If something goes wrong, the energy stored in the magnet has to be safely discharged

For a few accelerators…..

	PETRA	LEP	LHC nominal
Max momentum [GeV/c]	19	98	7000
Bunch current [mA] per beam	9.00	3.10	2.07E-04
Circumference [m]	2304.00	26658.00	26658.00
Number of particles / bunch	1.08E+11	4.30E+11	1.15E+11
Number of bunches per beam	4	4	2808
Stored Beam Energy [kJ]	1.31E+00	2.70E+01	3.62E+05
Beam Average Power [kW]	7.29E-05	1.50E-03	20.09
Synchrotron Radiation Power per beam [kW]	1.00E+03	1.16E+04	1.50
Fill length [h]	10.000000	10.000000	10.000000

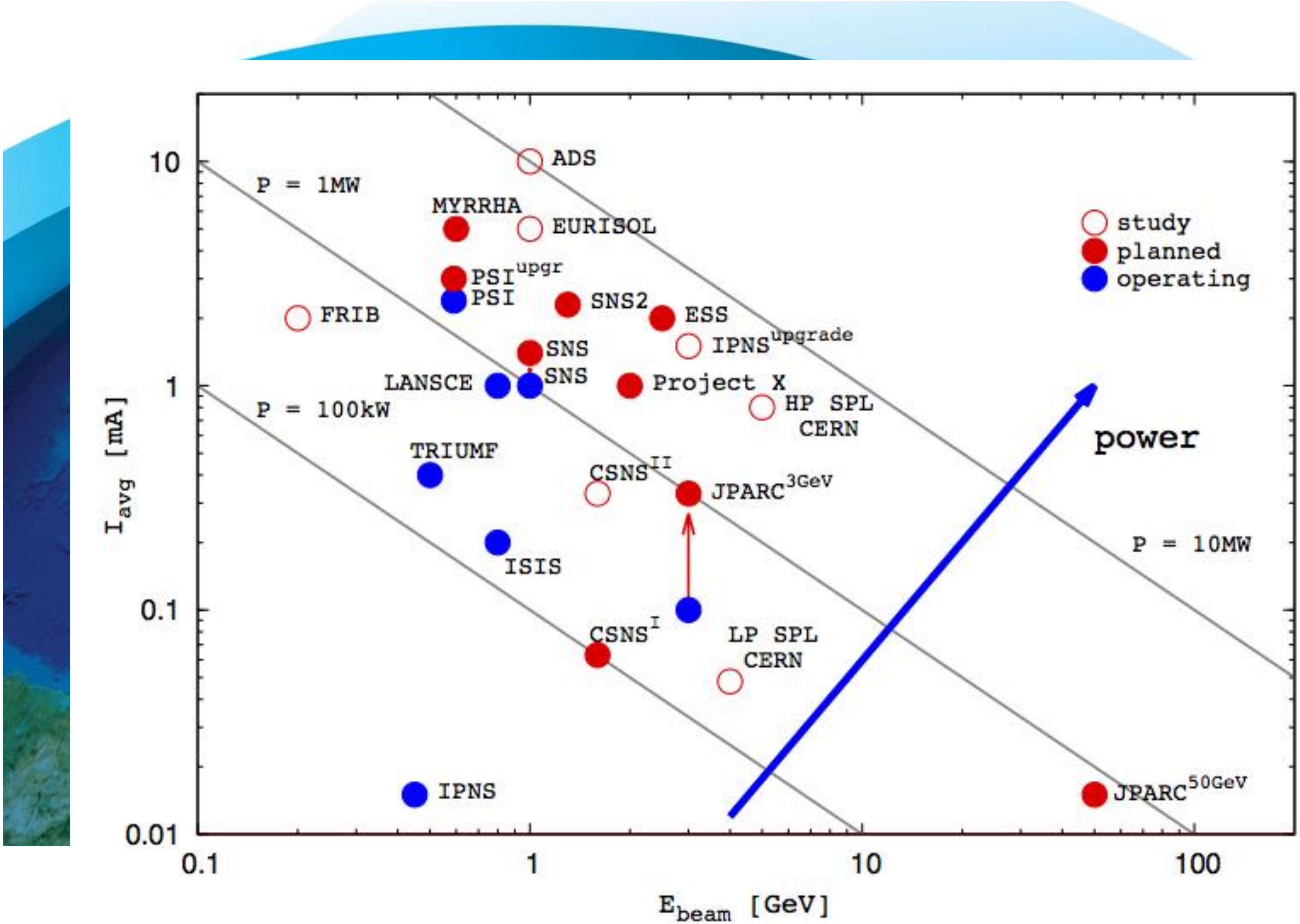
	SNS nominal	ESS
Max momentum [GeV/c]	1	2
Bunch current [mA]	20.00	62.50
Repetition rate [Hz]	60.00	14.00
Pulse length [ms]	1.00	2.86
Linac dutyfactor	0.06	0.04
Number of protons / s	7.49E+15	1.56E+16
Power [kW]	1200.00	5005.00

- For hadron colliders, the energy stored in the beams can be very high (LHC is very critical)
- For linacs, the power of the beam can be very high

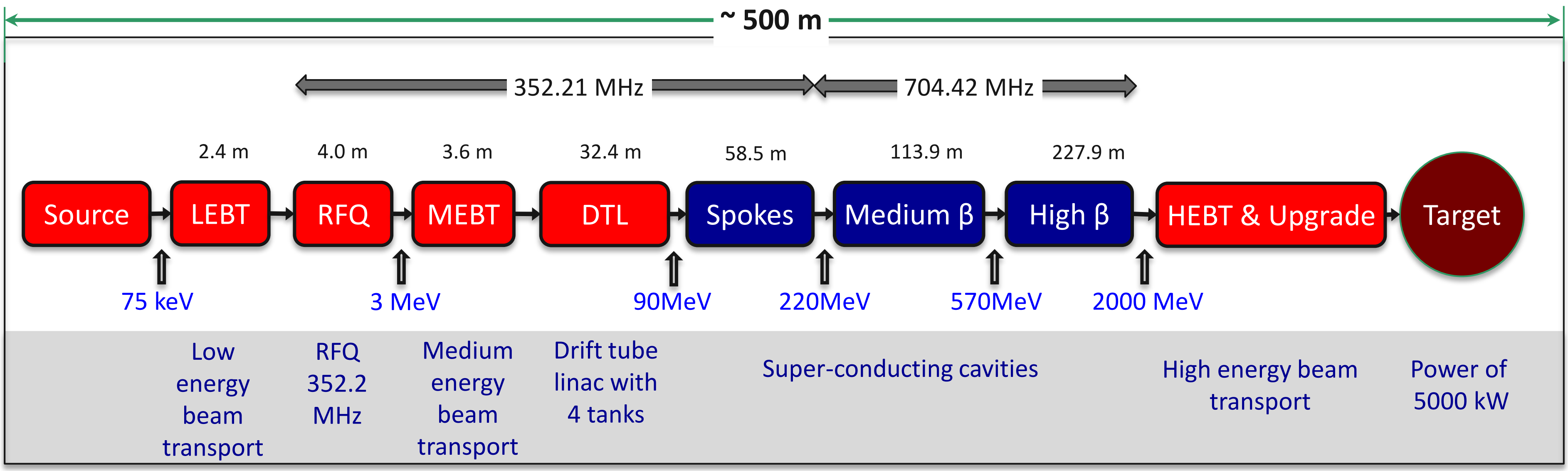
High power hadron accelerators

Spallation sources
Proton accelerators for neutrino production
Rare Isotope Beams Production (e.g. FRIB folded linac to accelerate ions)

Spallation sources + high intensity accelerators



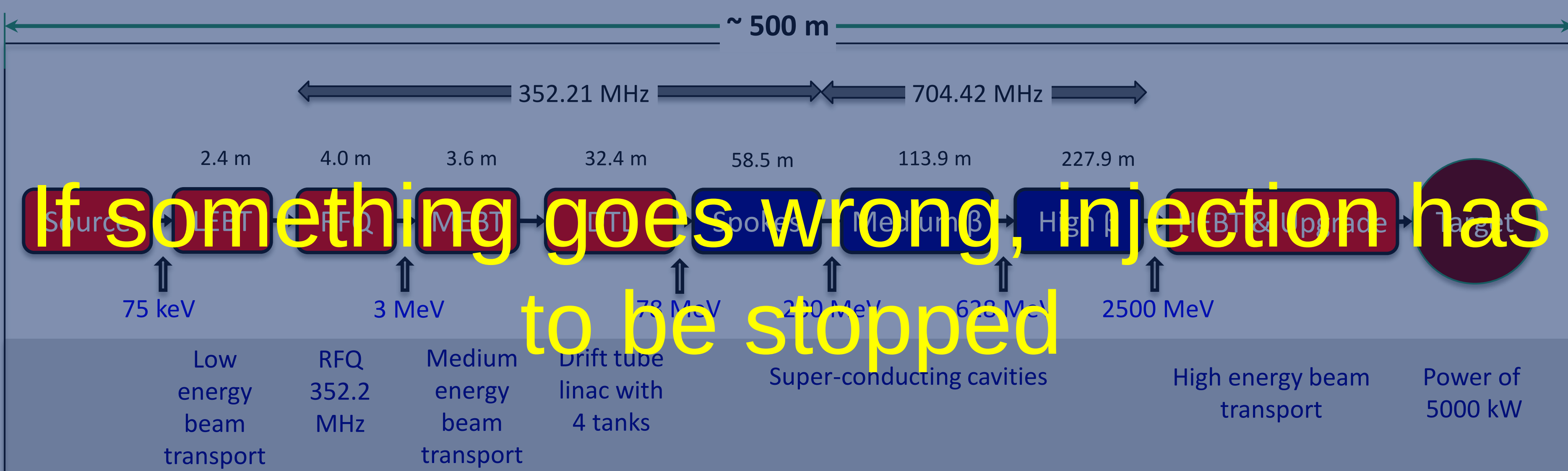
ESS Lund / Sweden – 5 MW beam power



As an example for a high intensity linear accelerator (similar to SNS and J-PARC)

- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average beam power of 5 MW**
- Peak power of 125 MW
- Power per pulse 360 kJ

ESS Lund / Sweden – 5 MW beam power



If something goes wrong, injection has to be stopped

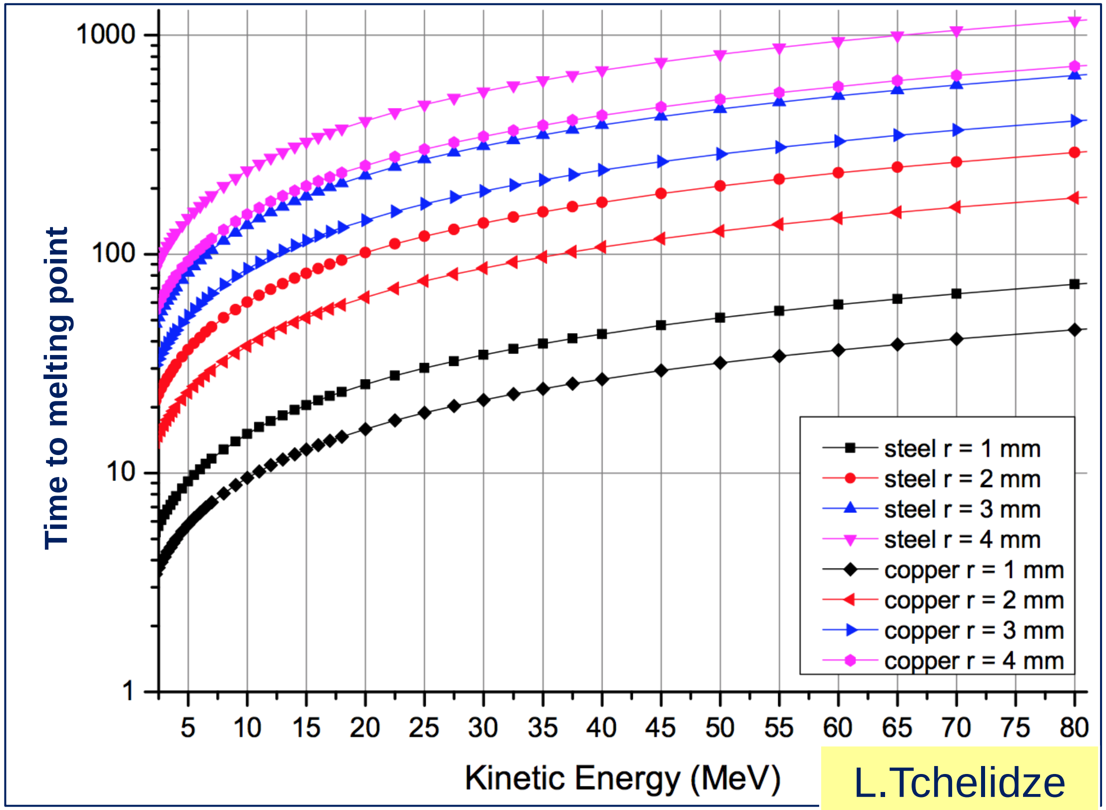
- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW

As an example for a high intensity linear accelerator (similar to SNS and J-PARC)

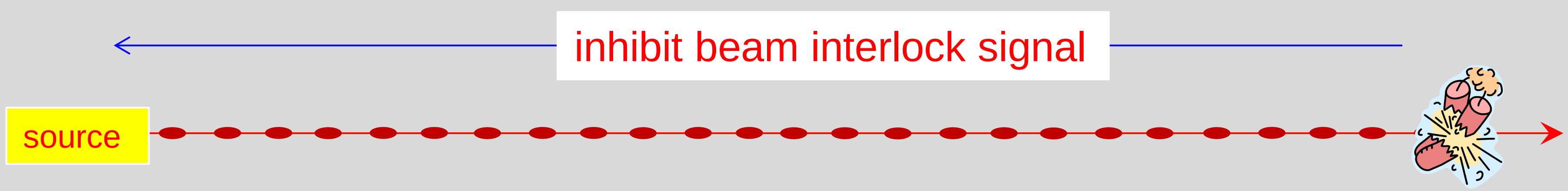
Example:

After the DTL normal conducting linac, the proton energy is 78 MeV. In case of a beam size of 2 mm radius, melting would start after about 200 µs.

Inhibiting beam should be in about 10% of this time.



L.Tchelidze



dT = dT_detect failure + dT_transmit signal + dT_inhibit source + dT_beam off

Example for FRIB at MSU for uranium beams

Proceedings of SRF2011, Chicago, IL USA

ANALYSIS OF BEAM DAMAGE TO FRIB DRIVER LINAC*

Y. Zhang[#], D. Stout, J. Wei, Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA

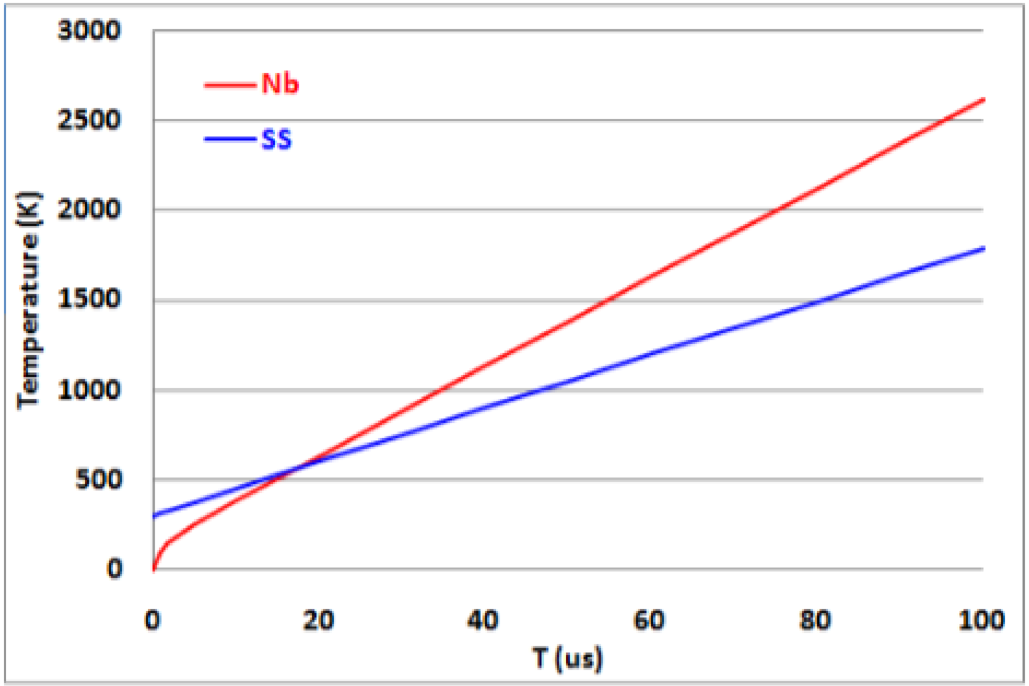


Fig. 1: Temperature vs. time of stainless steel (SS) from 300K, and niobium (Nb) from 2K, after hit by a uranium beam, 100 MeV/u, 200 kW, and beam rms radius 1 mm.

Measuring the performance of an accelerator

Figure of Merit and Availability

- Number of particles depends on integrated Luminosity for a collider:

$$N_{particles} = \sigma \times \int L(t) \times dt$$

- Number of neutron / neutrinos produced in a fixed target proton accelerator:

$$\int N(t) \times dt$$

- Similar quantities can be defined for other accelerators (e.g. synchrotron light sources)
- During repair: $\int L(t) \times dt = 0$ *and* $\int N(t) \times dt = 0$
- The **availability** of an accelerator is a key figure of merit

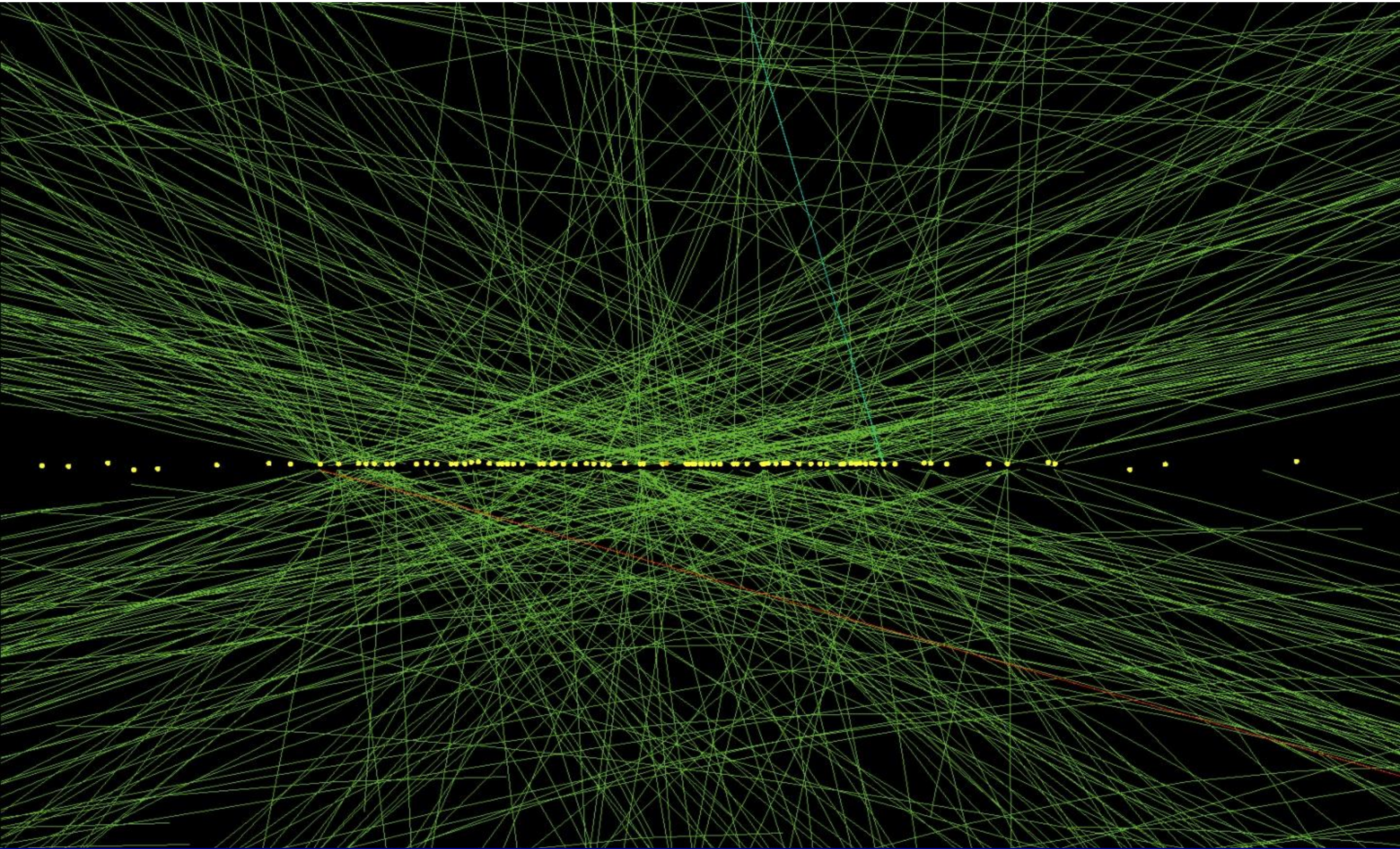
High Luminosity LHC – HL-LHC

Objective: Increase of the integrated luminosity

Target for integrated luminosity (very ambitious): 200 – 300 fb^{-1}/y (×10 today) starting in ~2025

......but

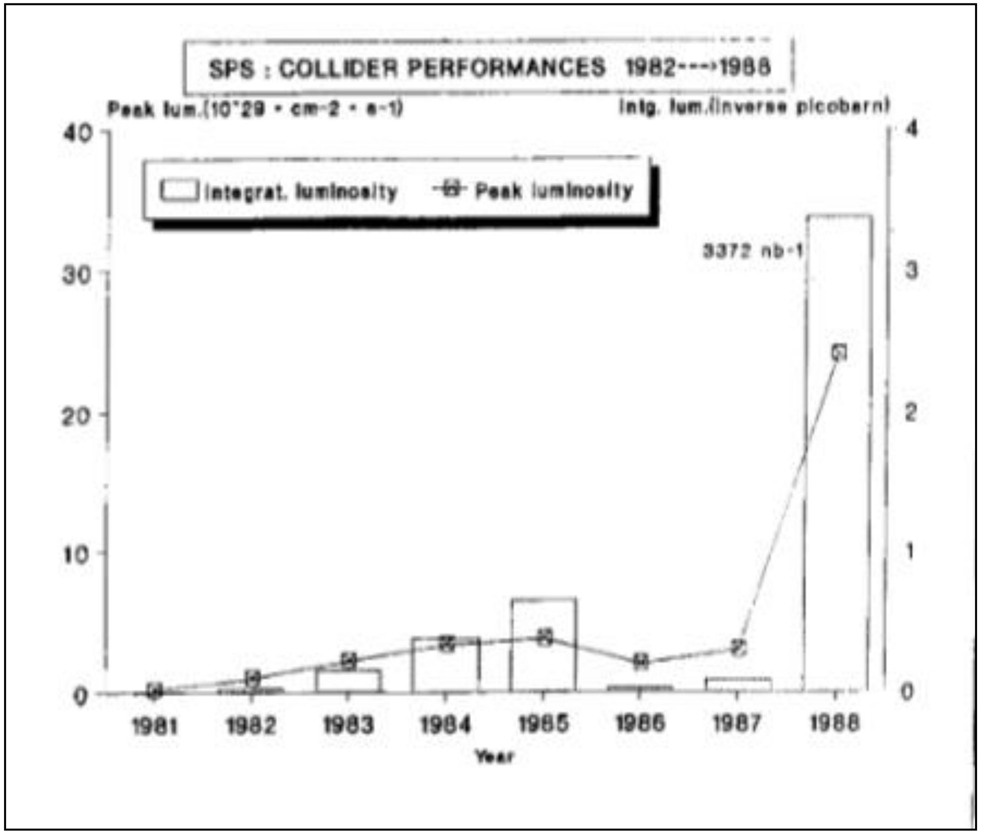
CMS event at LHC



The picture above shows a zoomed view of an event in the centre of the CMS detector where 78 proton-proton collisions took place simultaneously. The scale here is a few centimetres.

Colliders and availability

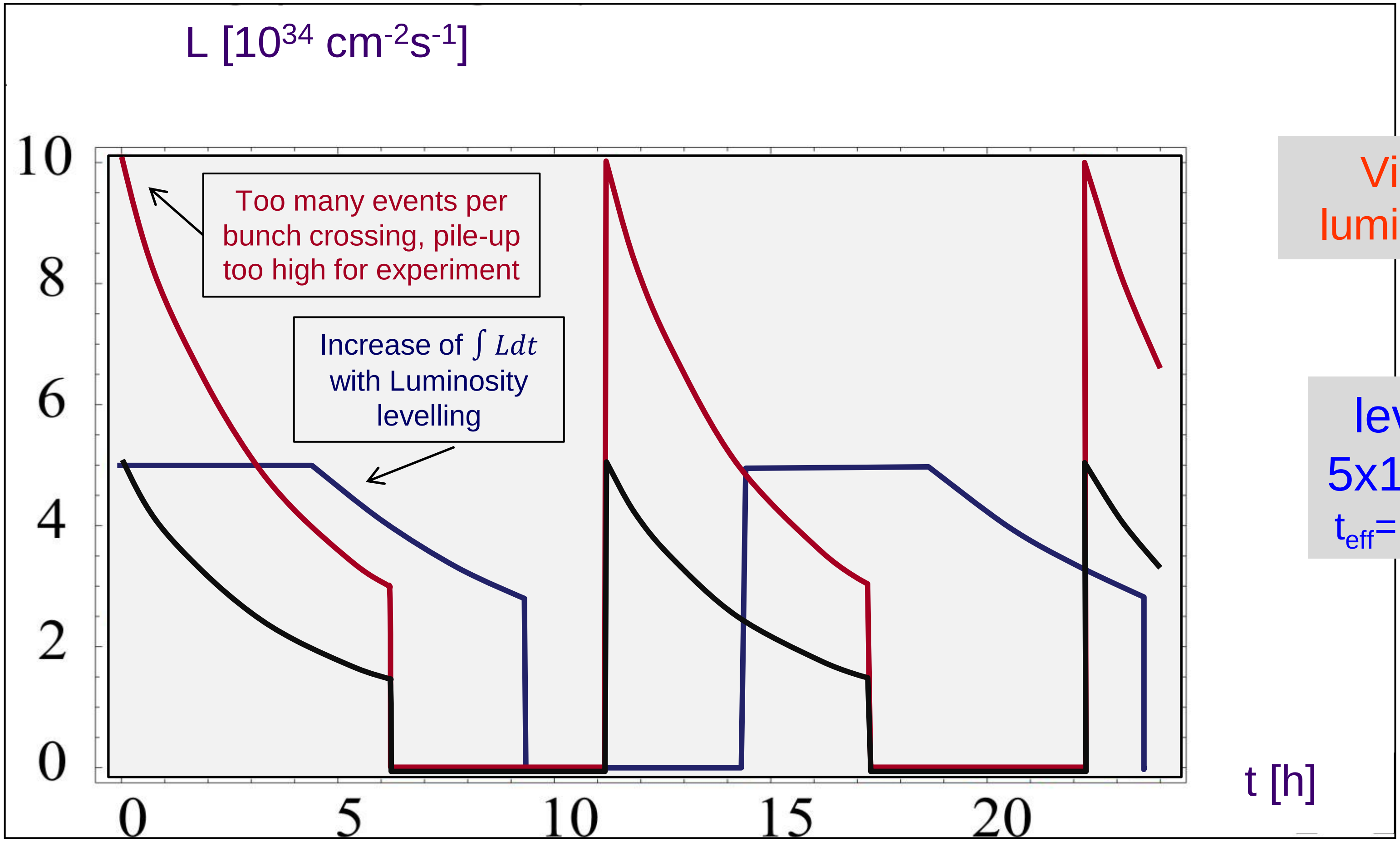
- SPS PPbar collider (left) and LEP (right) – the integrated luminosity was increased by increasing peak luminosity
- Physics experiments were not yet at the limit, could have taken higher Luminosity



Year	$\int \mathcal{L} dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

HL-LHC: Levelling luminosity

- $\int Ldt$ increase by increasing L_max not feasible (pile up too high): **Luminosity levelling** can increase $\int Ldt$
- **High availability** is required **(optimise length of fills)**



Virtual peak luminosity (F=1)

levelling at $5x10^{34}$ cm^{-2}s^{-1}
t_{eff}=15 h, T_{ta}=5 h

….for the LHC

- In the past, the most efficient way of increasing $\int \boldsymbol{L(t)} \times \boldsymbol{dt}$ was by increasing $\boldsymbol{L(t)}$.
- This is why colliders usually refer to $\boldsymbol{L\_max}$.
- There are many workshops and conferences around the world discussing how to increase $\boldsymbol{L(t)}$…..

- HL-LHC is a game changer: for the first time, $\boldsymbol{L\_max}$ is limited (due to pile-up).
- The only free parameters is the integral: how long can HL-LHC sustain operation a $\boldsymbol{L\_max}$?
- **Directly related to the availability of HL-LHC**

Hazards and Risks

Hazard and Risk for accelerators

- **Hazard:** a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **incident / accident**. **Consequences** and **Probability** of an accident interact together to create **RISK**, can be quantified:

RISK = Consequences · Probability

Related to accelerators

- Consequences of a failure in a hardware systems or uncontrolled beam loss (in Euro, downtime, radiation dose to people, reputation)
- Probability of such event
- The higher the **RISK**, the more **Protection** needs to be considered

What needs protection? From what?

- Protection of people – always highest priority
  - Main strategy to protect people during accelerator operation: keep them away from the accelerator when beam is running (access system)
  - There are several other hazards: electrical, pressure, oxygen deficiency, ..
- Protection of the environment
- Protection of accelerator equipment and experiments (including targets)
- This school focused on the protection of equipment
  - Similar methods for protection of people and environment
  - One presentation on protection of people
- Protection from what?
  - Particle beams and their effects
  - Electromagnetic energy stored in magnets and RF systems
  - Other sources of energy

Hazards related to accelerator systems

- Energy stored in superconducting magnets
  - Complex magnet protection system required
- Power in normal conducting magnets
  - (Water) cooling required, and interlocks to monitor if it works correctly
- Power in RF systems (modulator, klystrons, waveguides, cavities): high voltages, arcs can damage the structure
  - Requires complex and fast interlock systems
  - For high beam intensity: in case of transition from **beam on => beam off**, RF system has to cope with it
- High Voltage systems (e.g. kicker magnets) - in general risks of arcing
- Powering systems (power converters, power distribution, electrical network)

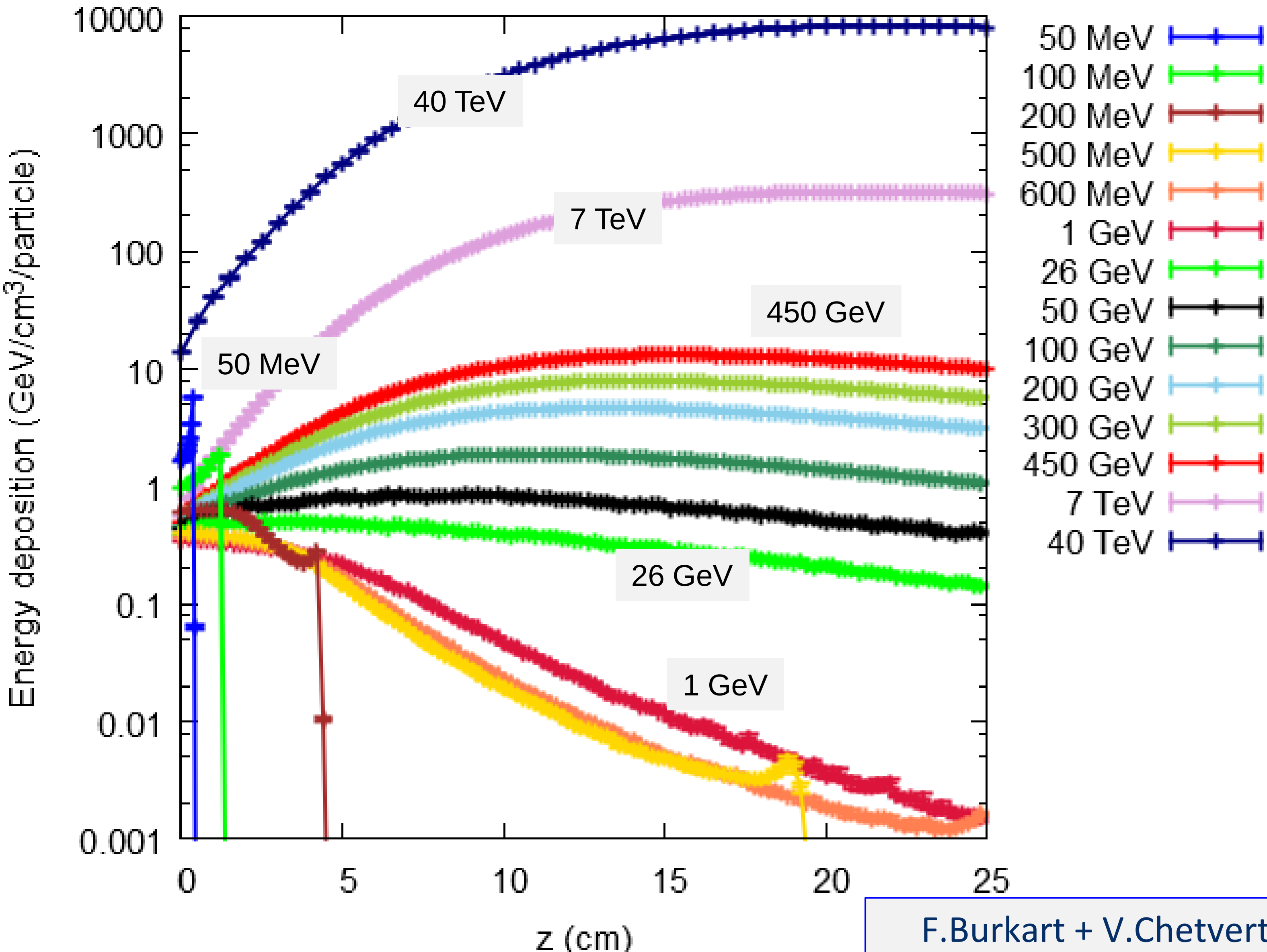
Hazards related to particle beams

- Regular beam losses during operation
  - To be considered since leads to activation of equipment and possibly quenches of superconducting magnets
  - Radiation induced effects in electronics (Single Event Effects)
- Accidental beam losses due to failures: understand hazards, e.g. mechanisms for accidental beam losses
  - Hazards becomes accidents due to a failure, machine protection systems mitigate the consequences
- Understand effects from electromagnetic fields and synchrotron radiation that potentially lead to damage of equipment
- Understand interaction of particle beams with the environment
  - Heating, activation, …
- Understand mechanisms for damage of components

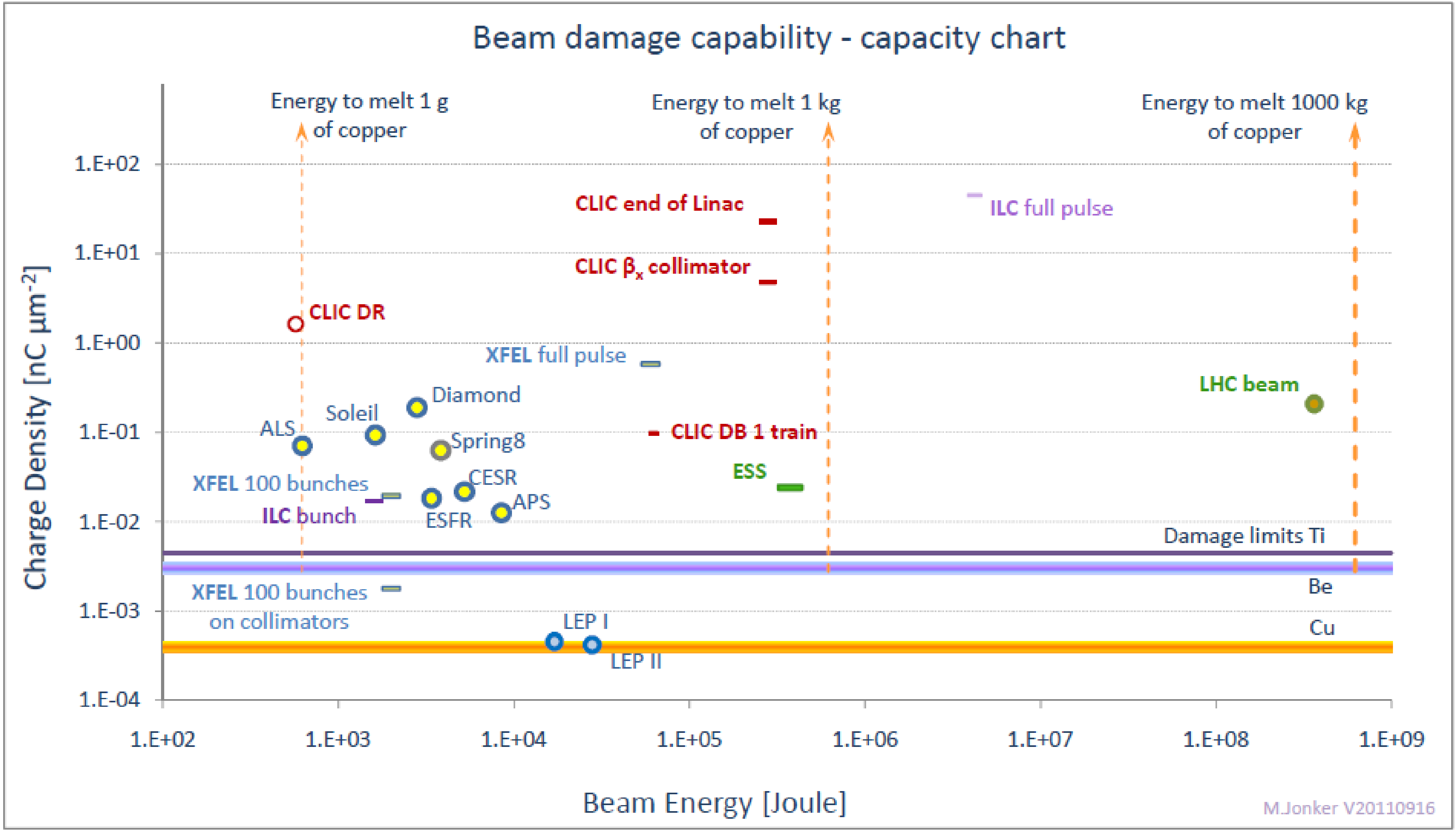
Parameters for damage from beam losses

Energy stored in the beam Beam power	For accelerators with large stored energy or large power => significant hazard	Hazard needs a failure to become active
Particle energy Particle type	Hadrons (no issue for synchrotron radiation)	Activation of equipment to be considered
	Leptons (little issues for activation of equipment)	
	Leptons => possible issue with synchrotron radiation	Possibly issue during regular operation
Small beam size	Leptons, but also hadrons	Risk of damage
Beam / Bunch current + Time structure	Determines risk for equipment in beam pipe due to electromagnetic fields related to impedance	Possibly issue during regular operation

Proton energy deposition for different energies



F.Burkart + V.Chetvertkova



Beam damage capability - capacity chart
Energy to melt 1 g of copper
Energy to melt 1 kg of copper
Energy to melt 1000 kg of copper
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
Charge Density [nC µm-2]
CLIC end of Linac
ILC full pulse
CLIC βx collimator
CLIC DR
XFEL full pulse
Diamond
Soleil
ALS
Spring8
LHC beam
CLIC DB 1 train
ESS
XFEL 100 bunches
CESR
ILC bunch
APS
ESFR
Damage limits Ti
Be
XFEL 100 bunches on collimators
LEP I
Cu
LEP II
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
Beam Energy [Joule]
M.Jonker V20110916

M.Jonker

Motivation for protection systems

1. All **technical systems** cause some **downtime**
2. A **protection system** will always **contribute to downtime**
3. If the **risk is small**, it might be **better to operate without protection system**
4. If the **risk is significant**, protection systems need to be considered
5. If the **downtime due to expected damage** is larger than the **downtime due to the protection system**, such system should be considered
6. Another motivation for protection systems is the **investment** required **for repair in case of damage**

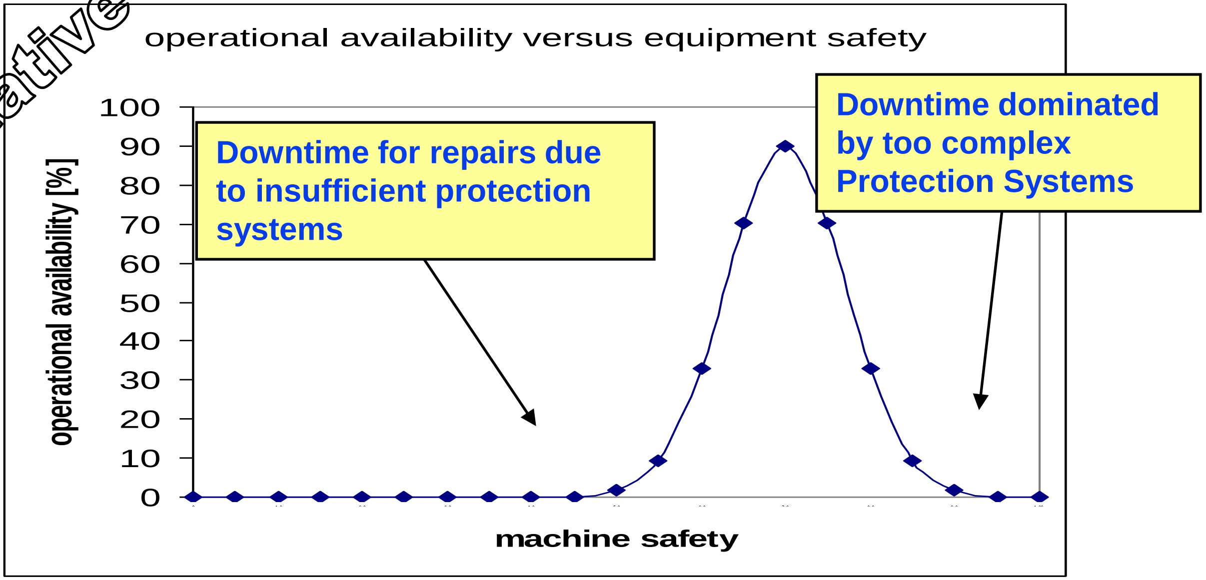
The LHC machine need protection systems, but….

Machine Protection is not an objective in itself, it is to

- maximise operational availability by minimising down-time (quench, repairs)
- avoid expensive repair of equipment and irreparable damage

Operations workshop
R.Schmidt - Villars
30/01/2001

Qualitative



Side effects from LHC Machine Protection System compromising operational efficiency must be minimised

Machine Protection

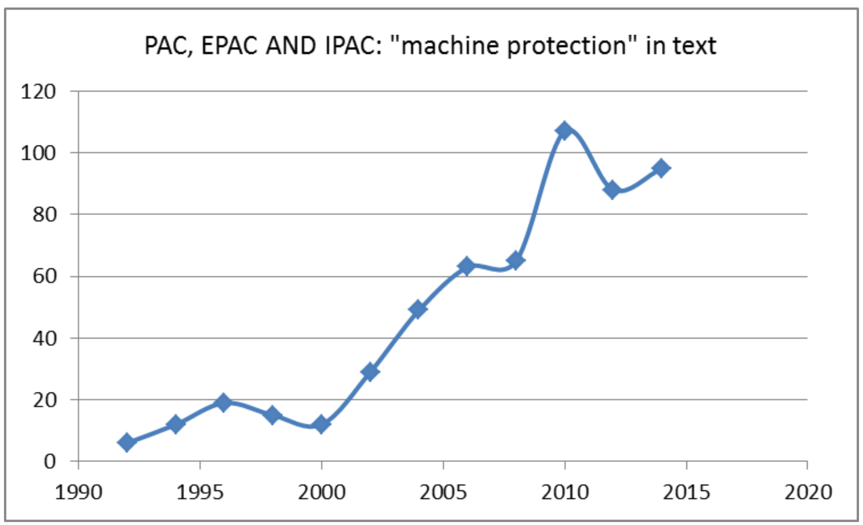
Machine protection during last 50 years

- Machine protection has been on the agenda since a long time
- Only in the last years it became significant in conferences

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, JUNE 1967

THE SLAC LONG ION CHAMBER SYSTEM FOR MACHINE PROTECTION*

Max Fishman and Daryl Reagan
Stanford Linear Accelerator Center, Stanford University, Stanford, California



Introduction

If missteered at high power, the SLAC electron beam can cause local melting of accelerator components in a fraction of a second. Even relatively low level irradiation of the accelerator waveguide will cause harm, gradually changing critical dimensions by altering the crystal structure of the copper. To protect the accelerator, a system has been installed which is based upon a single long ion chamber[1] that runs the whole 3 km length of the accelerator housing. The signal from the ion chamber operates equipment that turns off the beam when any local radiation level becomes too high.

Accidental beam losses: Machine Protection

Single-passage beam loss in the accelerator complex (ns - μs)

- transfer lines between accelerators or from an accelerator to a target station (target for secondary particle production, beam dump block)
- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- failures in linear accelerators, in particular due to RF systems
- too small beam size at a target station

Very fast beam loss (ms)

- e.g. multi turn beam losses in circular accelerators
- due to a large number of possible failures, mostly in the magnet powering system, with a typical time constant of ~1 ms to many seconds

Fast beam loss (some 10 ms to seconds)

Slow beam loss (many seconds)

Active and passive protection

Active protection

- A system is monitored, the monitor delivers some values (e.g. beam loss monitors measuring beam losses)
- The acceptable range of values is predefined (e.g. maximum beam losses within a time interval)
- If a value is out of the predefined range (e.g. after an equipment failure): take action (dump the circulating beam, stop injection, ….)
- The information has to travel from the monitor to the activator (extraction system, injection inhibit, …) => interlock system
- There is some **reaction time required for the response** (depending on the system this can range between some ns and many seconds)

Example for Active Protection - Traffic

- A monitor detects a dangerous situation


- An action is triggered

- The energy stored in the system is safely dissipated

Active and passive protection

Active protection

- A system is monitored, the monitor delivers some values (e.g. beam loss monitors measuring beam losses)
- The acceptable range of values is predefined (e.g. maximum beam losses within a time interval)
- If a value is out of the predefined range (e.g. after an equipment failure): take action (dump the circulating beam, stop injection, ….)
- The information has to travel from the monitor to the activator (extraction system, injection inhibit, …) => interlock system
- There is some **reaction time required for the response** (depending on the system this can range between some ns and many seconds)

Example for Passive Protection

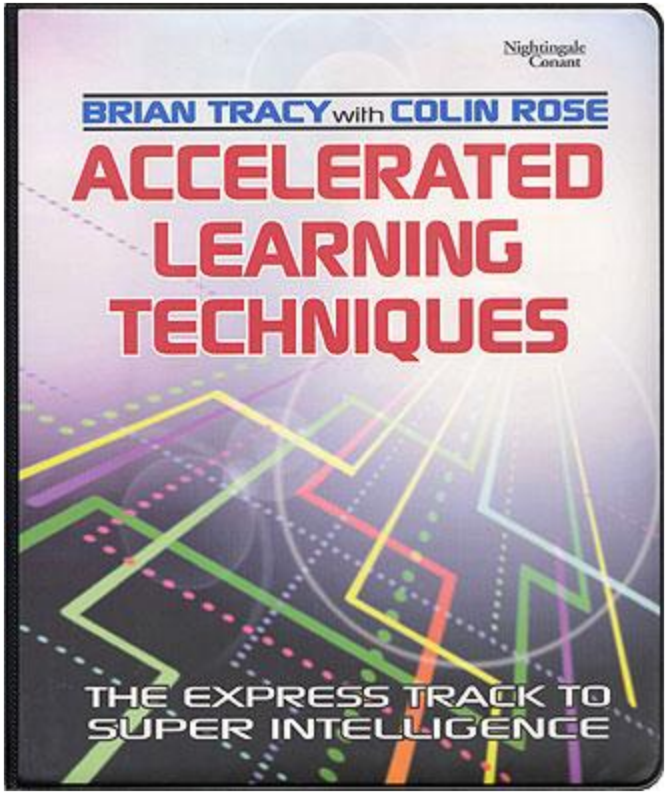
- The monitor fails to detect a dangerous situation
- The reaction time is too short
- Active protection not possible – passive protection by bumper, air bag, safety belts

Passive protection

- Is always necessary when the time required for the response is too short (…remember the limitation of the speed of light)
- Might simplify the protection system
- One example is the **fast extraction of a high intensity beam** from an synchrotron
  - The extraction is performed with a fast kicker magnet
  - It cannot be guaranteed that there is not kicker failure leading to a wrong deflection angle of the beam
  - The range of plausible failures (=deflection angles) needs to be defined
  - If the beam could damage hardware, protection absorbers are required
  - For movable aborbers: need to be made sure that they are at the correct position

Accelerated learning

Accelerated learning about machine protection



Accidents at accelerators: looking into the past

Accident: **An unfortunate incident** that happens unexpectedly and unintentionally, typically **resulting in damage** or injury.

- SPS proton antiproton collider
- SPS synchrotron
- Tevatron proton antiproton collider
- LHC magnet powering
- LINAC 4 (2013) at very low energy: beam hit a bellow and a vacuum leak developed
- JPARC

- LHC wire scanner (not an accident…)

Damage to silicon detector in UA2 at SPS

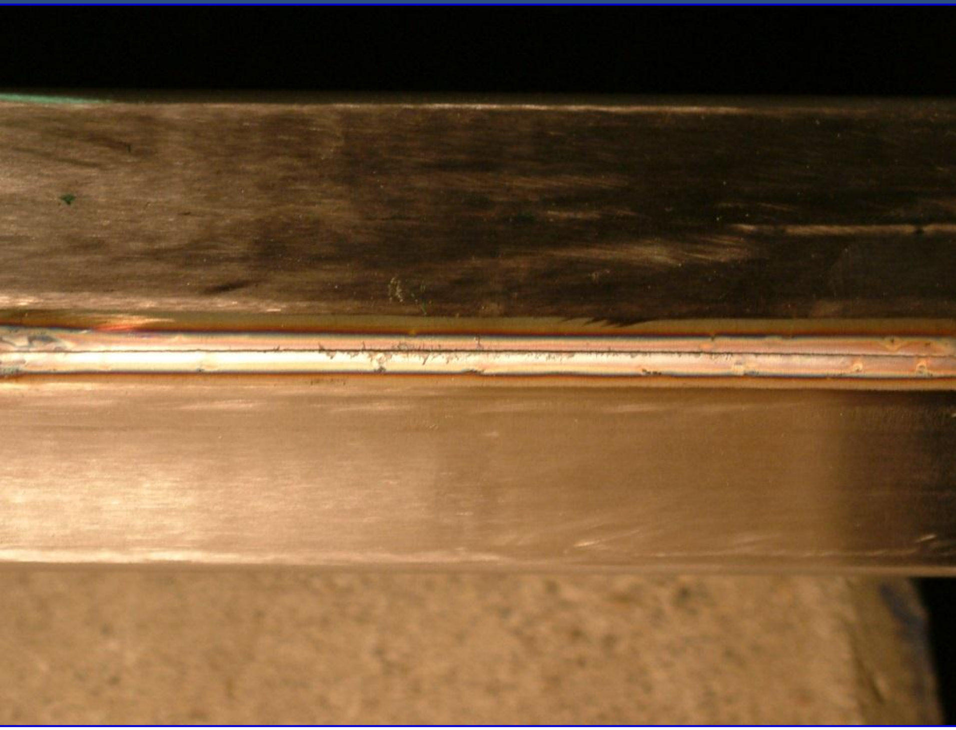
- Damage to the silicon detector in the UA2 experiment at the Proton Antiproton Collider
- The beam was injected for about 10 minutes
- The electrostatic separators, normally used to create an orbit bump at the experiment, were still set to high energy
- The bump directed the beam directly into UA2

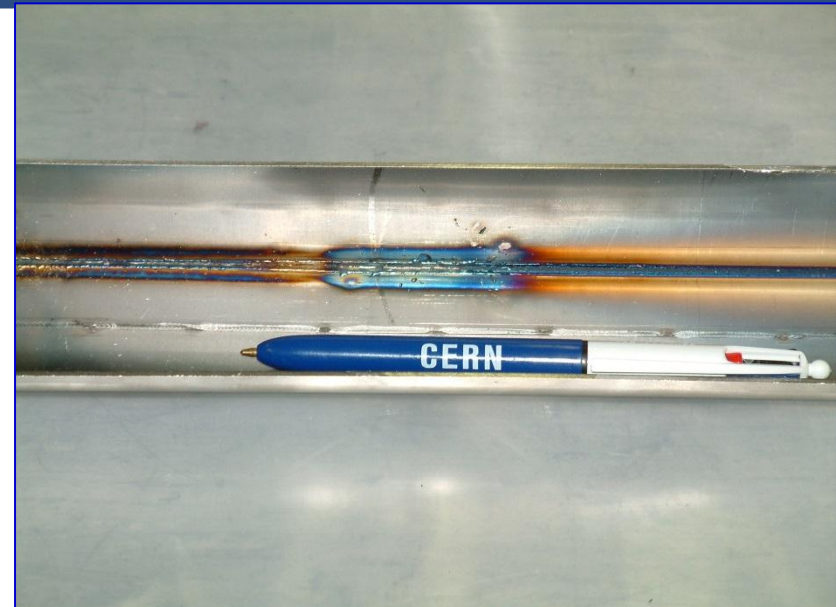
5. SILICON PAD DETECTORS IN THE UA2 SPS COLLIDER EXPERIMENT

5.1 Outer Si array during 1987 and 1988

The 1 m^2 area Si detector array [6] built at Ø 30 cm around the UA2 interaction region suffered a major degradation on 10 December 1987, as seen from the pedestal width measurements illustrated in fig. 6. For ~ 10 min. a severe beam loss occurred during a machine development session. At the end of 1987 run the integrated dose of ionizing radiation was found to be 30 Gy (3 krad) and the neutron flux (3–25 MeV) had been 2.8×10^9 cm^{-2}. The degradation of reverse currents for the pads on one board is shown graphically in fig. 7. The distribution of the current increase ΔI_l for about

Vacuum chamber in SPS extraction line incident



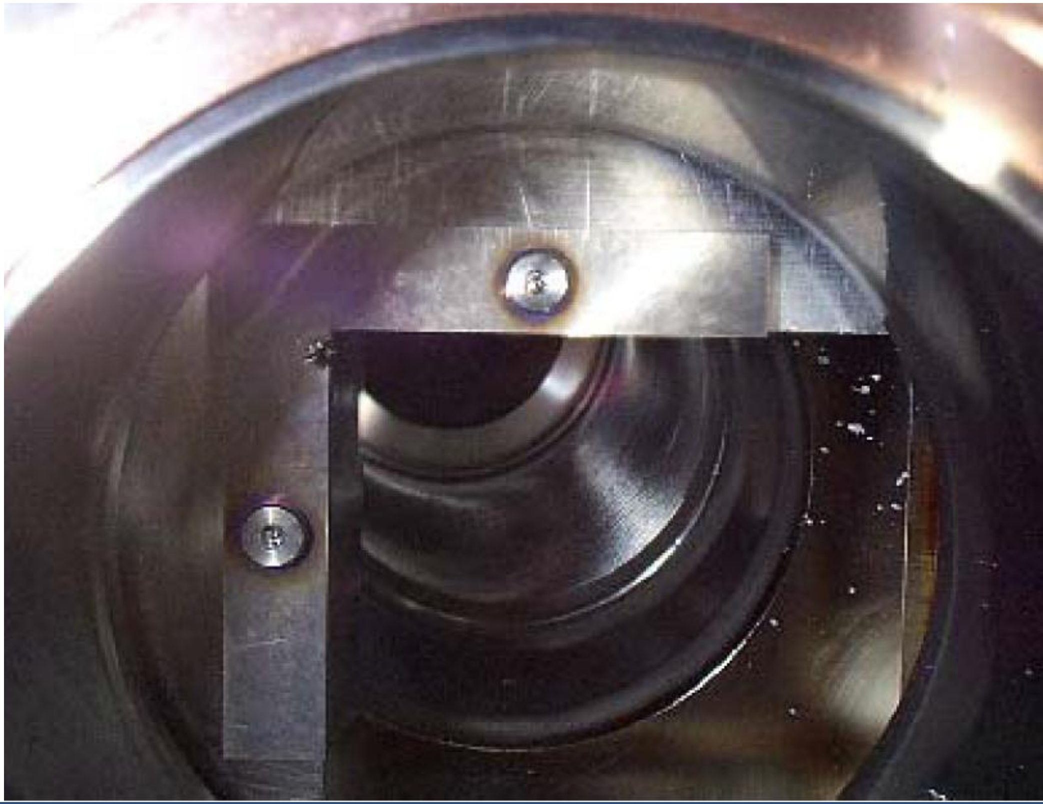


- 450 GeV protons, 2 MJ beam in 2004
- Failure of a septum magnet
- Cut of 25 cm length, groove of 70 cm
- Condensed drops of steel on other side of the vacuum chamber
- Vacuum chamber and magnet replaced

Tevatron accident

December 5, 2003, 16 house quench during the end of a proton-antiproton colliding beam store followed by the damage of two collimators used for halo reduction at the CDF and DØ interaction points. A cryogenic spool piece that houses correction elements was also damaged as a result of helium evaporation and pressure rise during the quench, requiring 10 days of Tevatron downtime for repairs.

- A Roman pot (movable device) moved into the beam
- Particle showers from the Roman pot quenched superconducting magnets
- The beam moved by 0.005 mm/turn, and touched a collimator jaw surface after about 300 turns
- The entire beam was lost, mostly on the collimator
- BLMs were switched off during the ramp

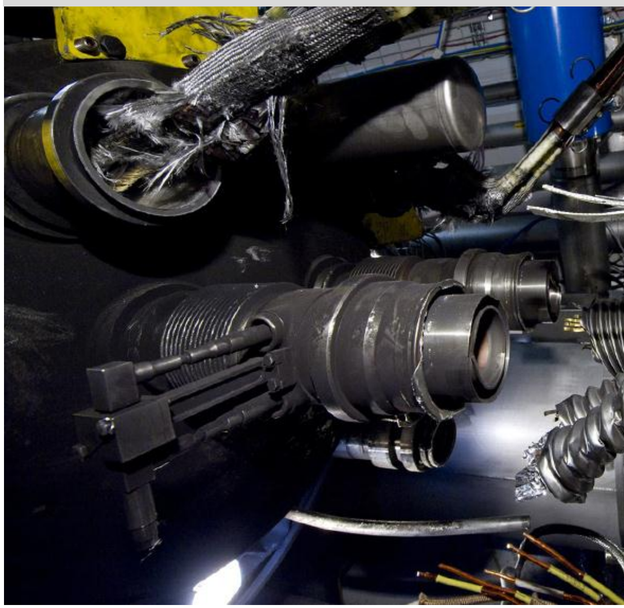


Consequences of a release of 600 MJ at LHC

The 2008 LHC accident happened during test runs without beam.

A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.

Arcing in the interconnection



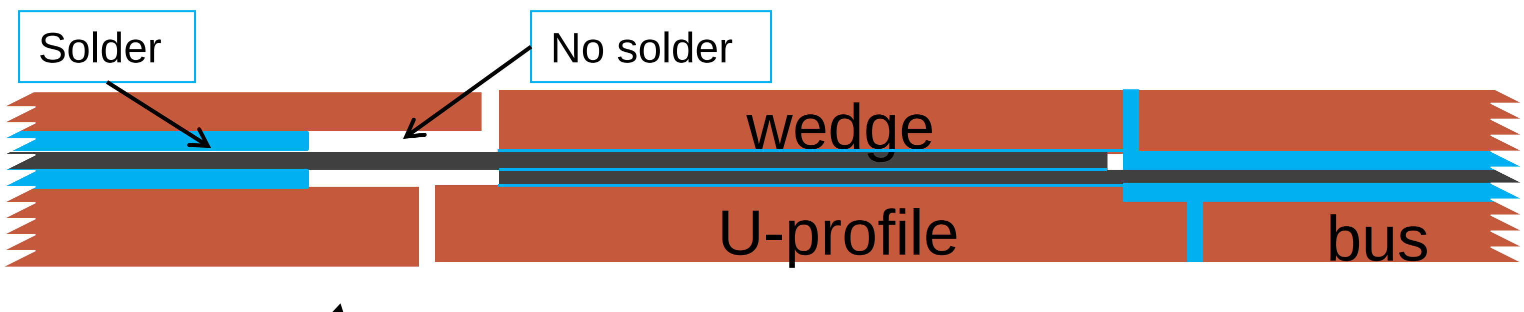
Over-pressure

Magnet displacement

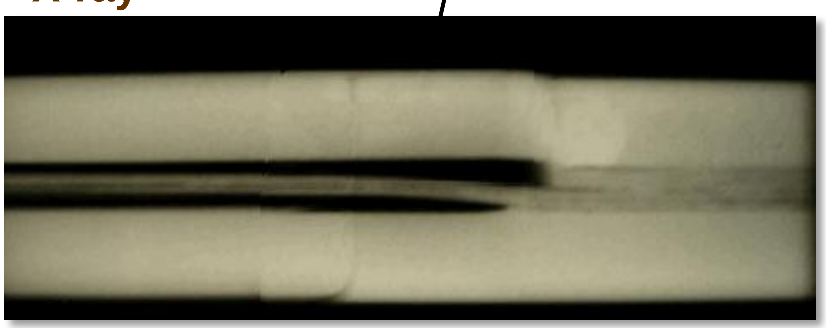
53 magnets had to be repaired

Problems on the joints between magnets

- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).
- Protection system in place in 2008 not sufficiently sensitive.
- A copper bus bar with reduced continuity coupled to a badly soldered superconducting cable can lead to a serious incident.



X-ray

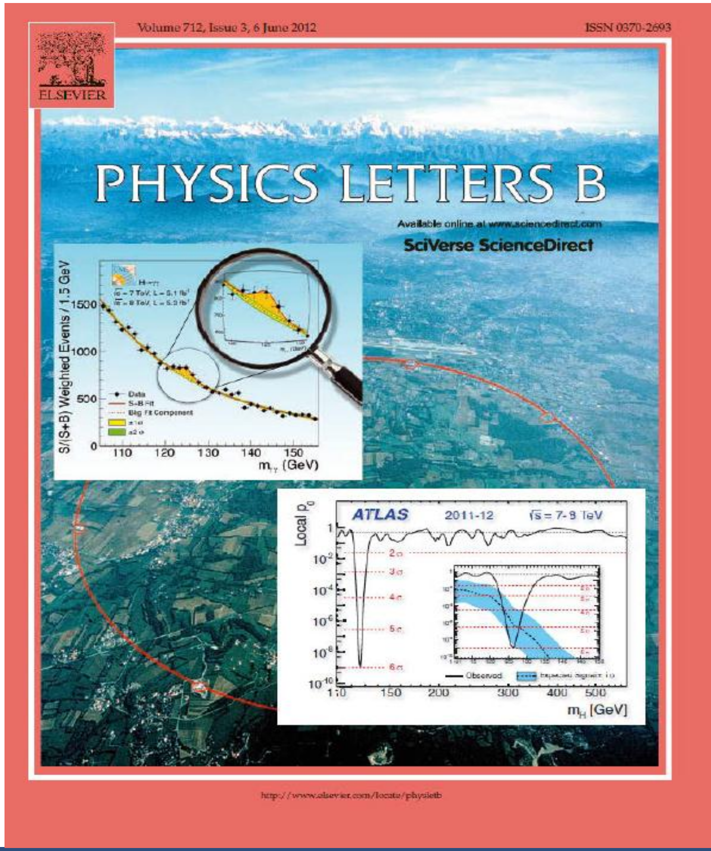


During repair work, inspection of the joints revealed systematic voids caused by the welding procedure.

→ Energy limitation for run 1 !!

Recovery from the accident

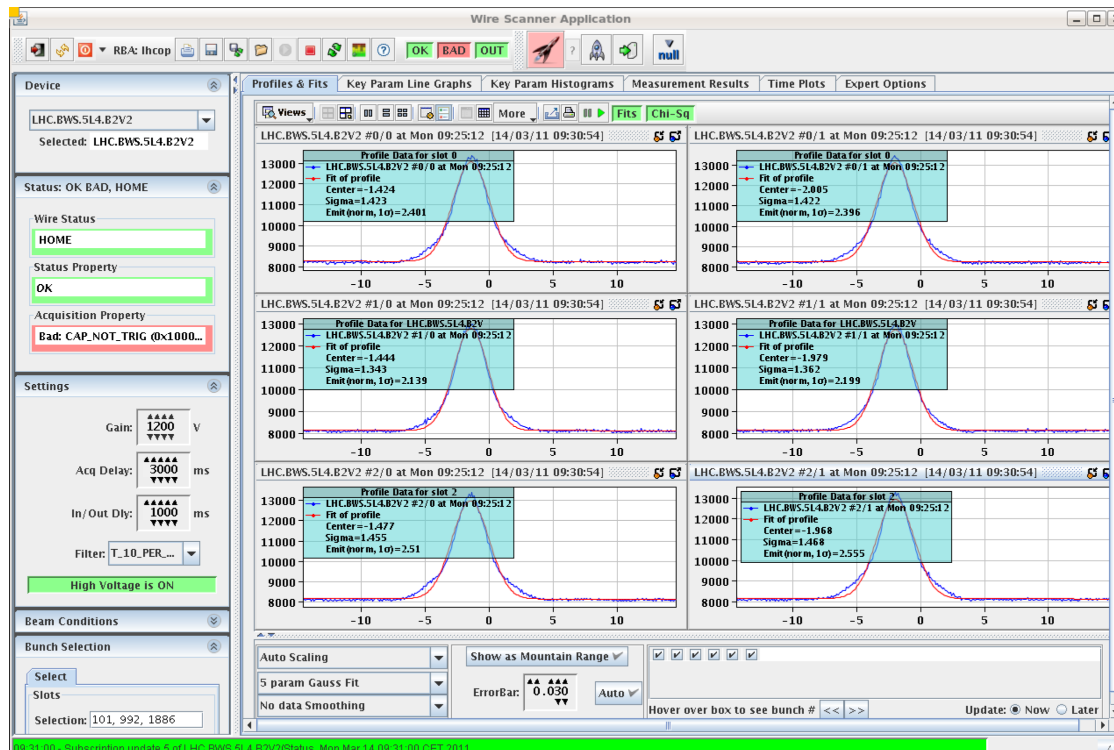
- Damage has a large impact on the availability of an accelerator
- For the LHC, it took a long time (about one year) to repair the magnets
- A new layer of protection system for the superconducting magnets and bus-bars was installed
- Energy was limited to 3.5 TeV, later to 4 TeV
- Re-start up about one year later
- **Performance was excellent**
- During a two years shut-down from 2013-2014 the interconnects were finally repaired



Wire scanner at LHC

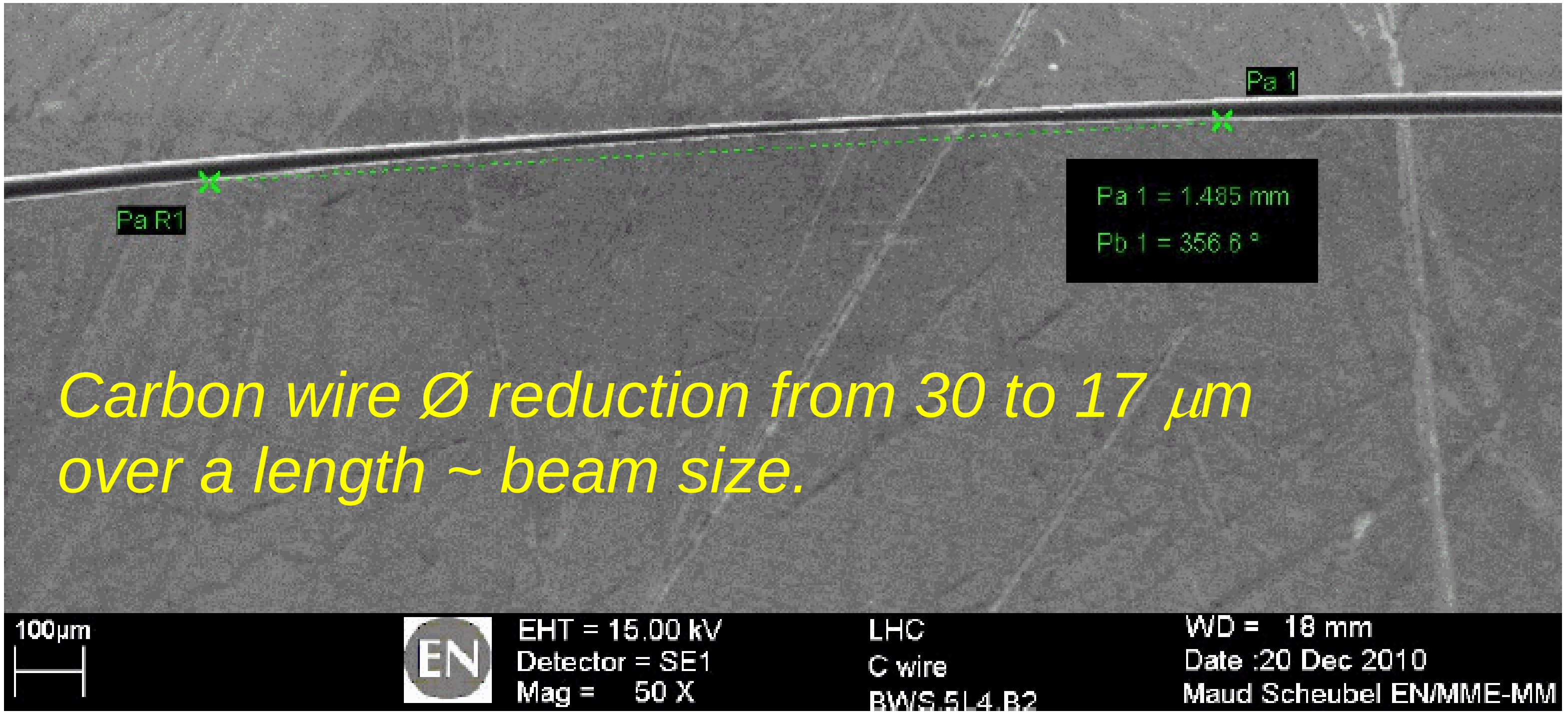
- Wire-scanners have long been the workhorse for emittance measurements for operations, but their range is limited to low intensity due to risk of damage (injection) or quench (3.5 TeV) – max. ~150 bunches.
- Wire scans can presently only be used at start of filling and for machine experiments with moderate intensity.
- Wire scanners are our reference devices for absolute emittance measurements.

Example of bunch by bunch wire scans



Damage of wire scanner

- The only (known) damage to LHC equipment from the beam.
- Beam 2 wire-scanner almost evaporated during a quench test when the wire speed was reduced to 5 cm/s (from 1 m/s) to quench a magnet.
- Almost fatal to the wire – the magnet seems to be in good shape!

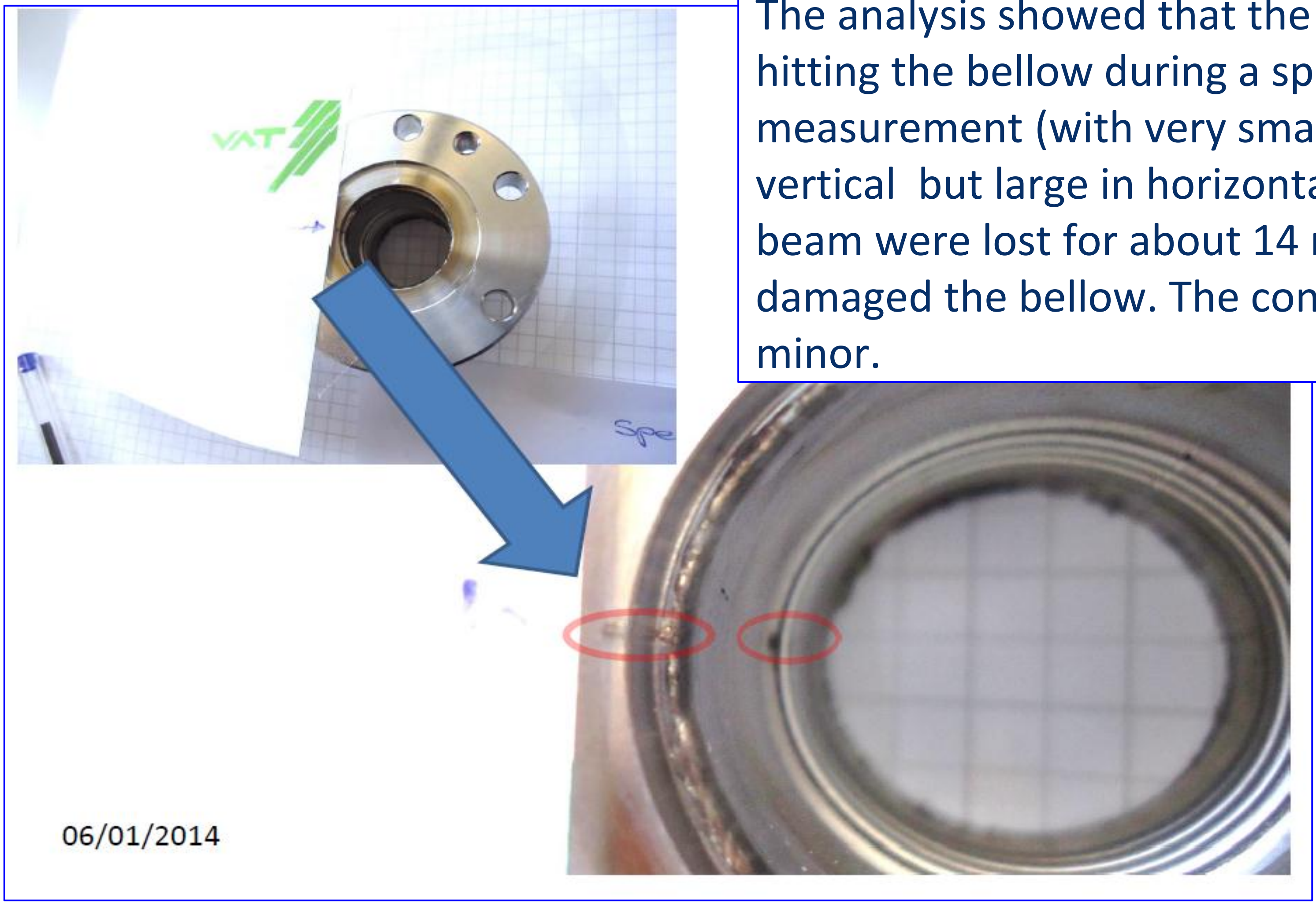


Courtesy M. Scheubel / A. Lechner

CERN-LINAC 4 during commissioning at 3 MeV

On 12 December 2013 a vacuum leak on a below developed in the MEBT line.

The analysis showed that the beam has been hitting the bellow during a special measurement (with very small beams in vertical but large in horizontal), ~16% of the beam were lost for about 14 minutes and damaged the bellow. The consequences were minor.



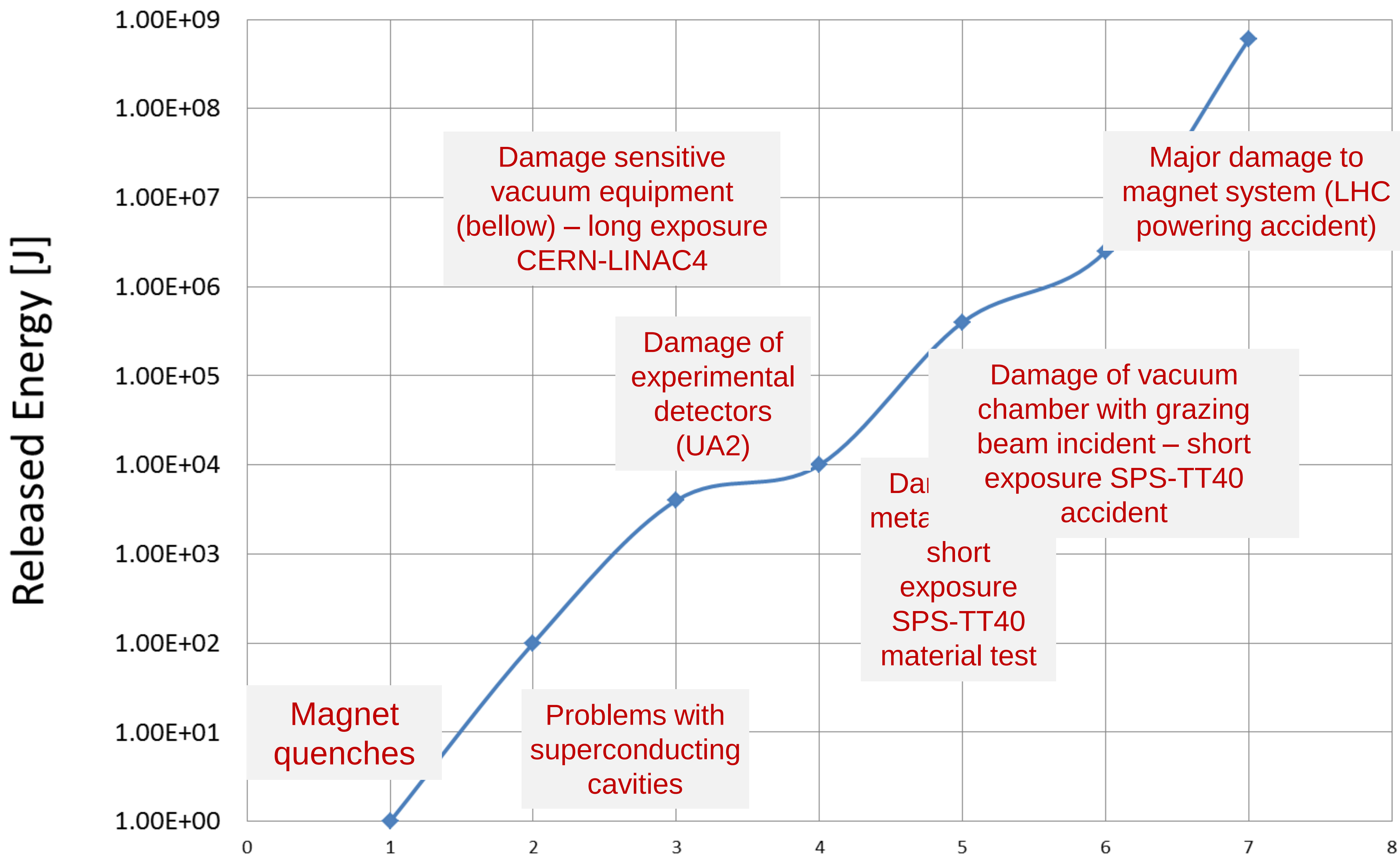
A.Lombardi

J-PARC radioactive material leak accident

- A radioactive material leak accident occurred at the Hadron Experimental Facility on May 23, 2013.
- The accident was triggered by a **malfunction of the slow extraction system** of the Main Ring synchrotron (MR). May 2013, one of the spill feedback quadrupole magnets, Extraction Quadrupole (EQ), malfunctioned.
- A beam consisting of $2x10^{13}$ protons was extracted within a very short time of 5 ms and delivered to the gold target in the HD facility, normally a total of $3x10^{13}$ protons were extracted for 2 s. T**he gold target was instantaneously heated up to an extraordinarily high temperature** and partially damaged. The **radioactive material dispersed from the gold target** and **leaked into the primary beam-line room**, because the target container was not hermetically sealed.
- After **seven-month long shutdown** due to the accident, beam operation of the linac was restarted in December 2013.

Observed damage for deposited energy

Damage observation - for different deposited energies



Thanks and have fun !

Joint International Accelerator School on Beam Loss and Accelerator Protection

November 5-14, 2014

Time	Wednesday Nov. 5	Thursday Nov. 6	Friday Nov. 7	Saturday Nov. 8	Sunday Nov. 9	Monday Nov. 10	Tuesday Nov. 11	Wednesday Nov. 12	Thursday Nov. 13	Friday Nov. 14
8:30 10:00	A R R I V A L D A Y	Introduction to Accelerator Protection Course Rudiger Schmidt	Beam Material Interaction, Heating & Activation Nikolai Mokhov (2 hrs)	Beam Transfer and Machine Protection Verena Kain	F R E E D A Y	Detection of Equipment Failures Before Beam Loss John Galambos	Machine Protection and Interlock Systems for LHC Rudiger Schmidt	Machine Protection and Operation for LHC Jorg Wenninger	Personnel Protection Systems Sayed Rokni	D E P A R T U R E D A Y
		COFFEE				COFFEE				
10:30 12:00		Beam Dynamics and Beam Losses - Circular Machines Verena Kain	Beam Material Interaction, Heating & Activation Francesco Cerutti (1 hr)	Beam Induced Damage Mechanisms and Their Calculation (Part I) Alessandro Bertarelli		Controls and Machine Protection Enzo Carrone	Machine Protection and Interlock Systems - Linear Machines Marc Ross	Machine Protection and Operation for Linear Machines Marc Ross	Medical Facilities Anthony Mascia	
		LUNCH				LUNCH				
13:30 15:00		Beam Dynamics and Beam Losses - Linear Machines Mike Plum	Intro to Risk Management of Complex Systems John Thomas	Beam Induced Damage Mechanisms and Their Calculation (Part II) Alessandro Bertarelli		Beam Instrumentation for Machine Protection Tom Shea (2 hrs)	Protection of Hardware: Powering Systems (PC, NC and SC Magnets) Howard Pfeffer	Beam Cleaning and Collimation Systems Stefano Redaelli (2 hrs)	Present Case Studies	
		STUDY				STUDY				
17:00		High Intensity Synchrotron Radiation Effects Yusuke Suetsugu	Reliability and Availability Ferdinand Willeke	Protection Related to High Power Targets Mike Plum		Beam Loss Monitors at LHC Bernd Dehning (1 hr)	Protection of Hardware: RF Systems Sang Ho Kim	Advanced Collimators for Future Colliders Tom Markiewicz (1 hr)		

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