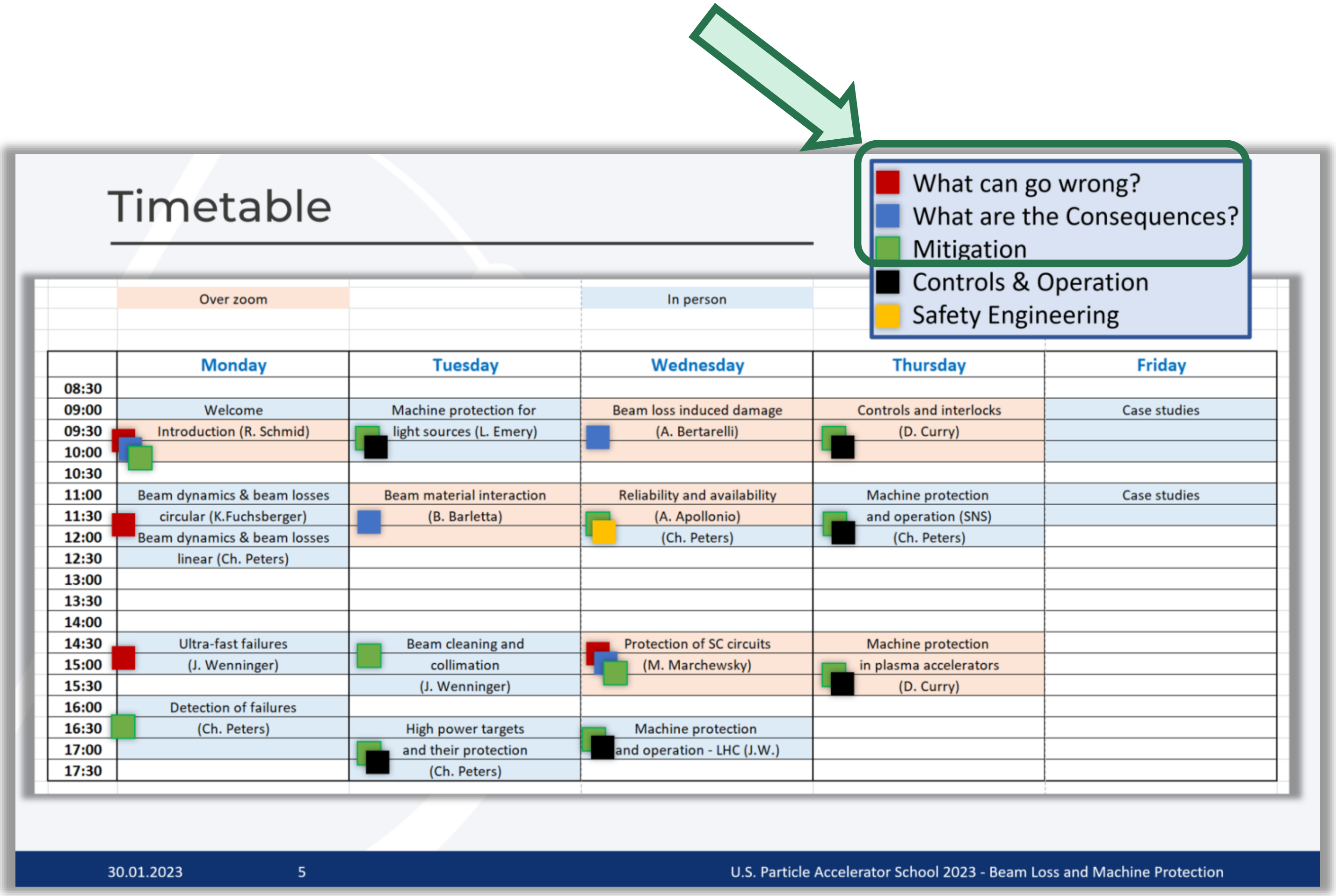
Beam Loss and Machine Protection
Introduction

Rüdiger Schmidt, CERN
U.S. Particle Accelerator School 2023

This lecture



Timetable

🟥 What can go wrong?
🟦 What are the Consequences?
🟩 Mitigation
⬛ Controls & Operation
🟨 Safety Engineering

Over zoom | In person

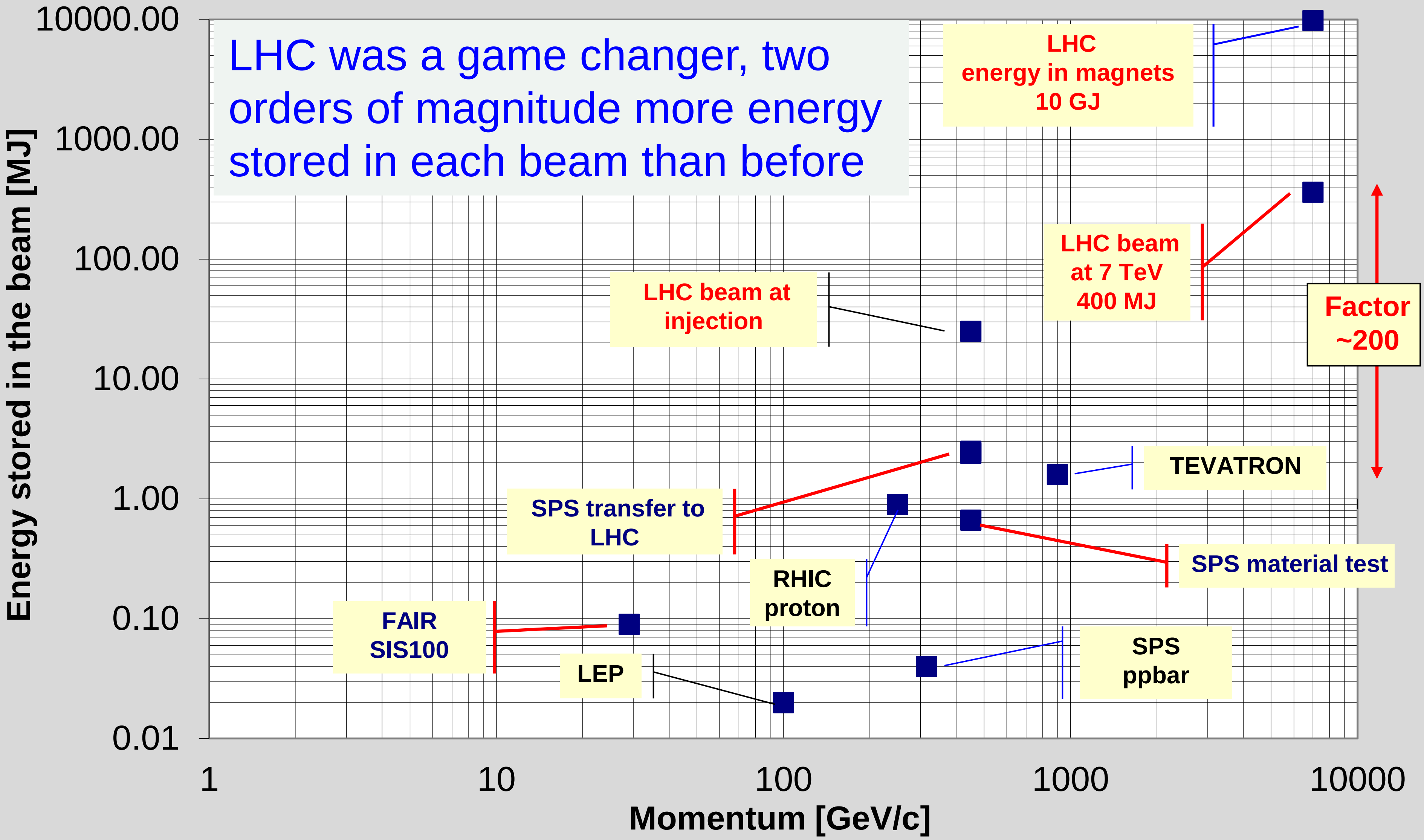
	Monday	Tuesday	Wednesday	Thursday	Friday
08:30					
09:00	Welcome	Machine protection for	Beam loss induced damage	Controls and interlocks	Case studies
09:30	🟥🟦🟩 Introduction (R. Schmid)	🟩⬛ light sources (L. Emery)	🟦 (A. Bertarelli)	🟩⬛ (D. Curry)	
10:00					
10:30					
11:00	Beam dynamics & beam losses	Beam material interaction	Reliability and availability	Machine protection	Case studies
11:30	🟥 circular (K.Fuchsberger)	🟦 (B. Barletta)	🟩🟨 (A. Apollonio)	🟩⬛ and operation (SNS)	
12:00	Beam dynamics & beam losses		(Ch. Peters)	(Ch. Peters)	
12:30	linear (Ch. Peters)				
13:00					
13:30					
14:00					
14:30	Ultra-fast failures	Beam cleaning and	🟥 Protection of SC circuits	Machine protection	
15:00	🟥 (J. Wenninger)	🟩 collimation	🟦🟩 (M. Marchewsky)	🟩⬛ in plasma accelerators	
15:30		(J. Wenninger)		(D. Curry)	
16:00	Detection of failures				
16:30	🟩 (Ch. Peters)	High power targets	Machine protection		
17:00		🟩⬛ and their protection	🟩⬛ and operation - LHC (J.W.)		
17:30		(Ch. Peters)			

30.01.2023 5 U.S. Particle Accelerator School 2023 - Beam Loss and Machine Protection

The performance of accelerators increased by orders of magnitude during the last 50 years, demonstrated by many parameters

Luminosity
Beam current
Emittance
…….
Energy stored in the beams
Beam Power

Energy stored in particle beams and magnets



LHC was a game changer, two orders of magnitude more energy stored in each beam than before

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

The energy of pistol bullet: about 500 J

The energy of 1 kg dynamite: about 4 MJ

The energy of 1 l gas: about 36 MJ

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

The kinetic energy of an 200 m long fast train at 160 km/hour corresponds to the energy of 400 MJ stored in one LHC beam.

Should we be worried ?

- As an example, if you heat your house with oil, you might have an oil tank of 4000 L in your basements
- **4000 L of oil ~ 120 GJ** **.....** I guess you would still sleep well at night

Hazards and Risks

Hazard and Risk

- **Hazard:** a situation that poses a level of threat. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **Incident / Accident**.
- **Accident:** An unfortunate event that happens unexpectedly and unintentionally, in general after a **Failure**, typically resulting in damage or injury.
- There is a certain **Probability** for a hazard becoming active. If the hazard becomes active, there are **Consequences.**
- Both together create **RISK** that can be quantified

RISK = Probability · Consequences

- The higher the **RISK**, the more **Protection** needs to be considered

Risk from Energy and Power

- Risks is related to the 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 beam operation
  - For particle beams, activation of equipment
- In particular relevant for complex particle accelerators
  - For equipment, such as **RF system**, **power converters**, **magnet system** …
  - For **particle beams**
- Particle accelerators use large amount of power (few MW to many MW) and store large amount of energy (to several 100 MJ)

Consequences: where does the energy go in case of failure?

Risks in many areas of an accelerator complex

- Risks for personnel
  - Electrical, Cryogenics, Radiation, Transport and Handling, …
- Risks for the environment
  - Radiation, release of (toxic) gases, fluids (e.g. oil spill), …
- Typical risks as for other technical installations, some examples
  - Normal conducting magnets
  - Power converters
  - RF-Systems
  - ……………………….

Most lectures in this school address **risks when operating with particle beams**, one lecture addresses **risks related to superconducting magnets**

Risks related to accelerator systems

- Normal conducting magnets
    - (Water) cooling, and interlocks to monitor if cooling works correctly
- Powering systems (power converters, power distribution, electrical network)
    - Interlocks to switch of the converter in case of failures
- 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 such transients
- High Voltage systems (e.g. kicker magnets) - risk of arcing

All equipment interlocks (LHC several 10000) risk to switch of equipment and cause beam loss, and need to be integrated in the Machine Protection System

Risks related to particle beams

- **Regular beam losses** during operation
  - Beam losses can lead to **activation of equipment** and quenches of superconducting magnets
  - **Radiation induced effects in electronics** (Single Event Effects) can lead to equipment failure, and can affect electronics for protection systems
- **Effects from electromagnetic fields and synchr** that potentially lead to damage of equipme
- **Understand mechanisms for non-regular**
  - Accidental beam losses due to failures: understa for accidental beam losses and their probability
  - Beam-losses due to instabilities and **unknown effects** (l dest part)

Consequences: see other lectures

- **Understand interaction of particle beams** with the environment
- **Understand mechanisms for damage** of components
  - Heating, activation, mechanical damage,…

If there are risks, protection is required to mitigate the risks

Energy and Power for particle beams

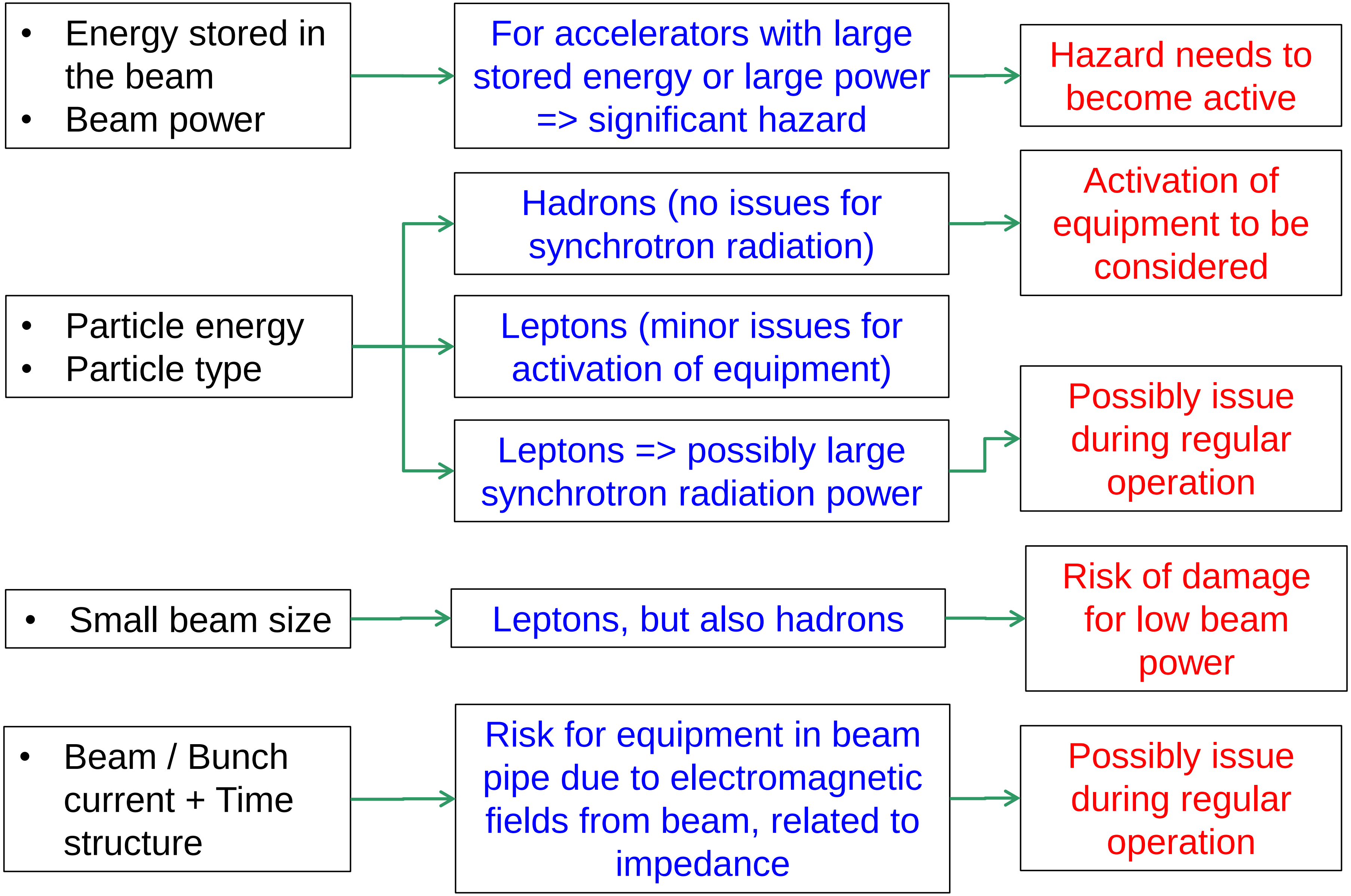
Many accelerators operate with high beam intensity and/or high particle energy

Energy stored in beam: $E_{beam} = N \cdot E_{particle}$

Beam power: $P_{beam} = \frac{N \cdot E_{particle}}{\Delta T}$

- For **synchrotrons and storage rings**, the energy stored in the beam increased over the years (at CERN, from SPS and LHC towards FCC)
- For **linear accelerators and fast cycling machines**, the beam power increased
- For **some accelerators**, the emittance becomes smaller (beam size down to nm for the International Linear Collider), very high power / energy density (W/mm^2 or J/mm^2)
- This is relevant today, even more relevant in the future, with more powerful accelerators and increasingly complex machines
- Small amount of energy can lead to some (limited) damage

Parameters for damage from beams



- Energy stored in the beam
- Beam power

For accelerators with large stored energy or large power => significant hazard

Hazard needs to become active

- Particle energy
- Particle type

Hadrons (no issues for synchrotron radiation)

Activation of equipment to be considered

Leptons (minor issues for activation of equipment)

Leptons => possibly large synchrotron radiation power

Possibly issue during regular operation

- Small beam size

Leptons, but also hadrons

Risk of damage for low beam power

- Beam / Bunch current + Time structure

Risk for equipment in beam pipe due to electromagnetic fields from beam, related to impedance

Possibly issue during regular operation

Machine protection for circular accelerators

Particle colliders

Accelerators for fixed target operation (e.g. neutrino factories)

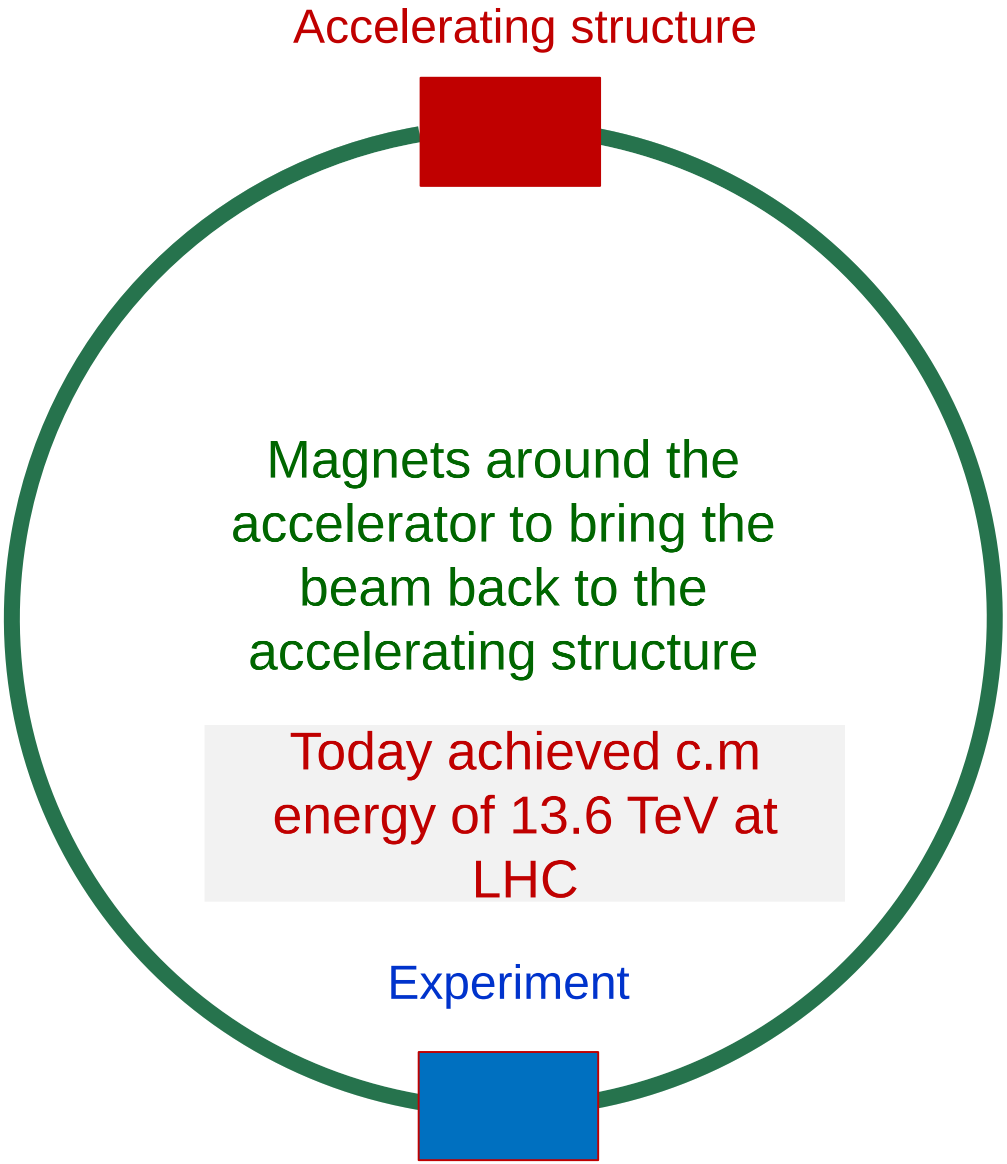
Synchrotron light sources

Cyclotrons

Synchrotrons: re-use accelerating structure

Accelerating beams to high energy in a synchrotron

- Beam are injected into the accelerator
- The particles make many turns
- The magnetic field is slowly increased, and particles are accelerated when travelling through the accelerating structure
- The beams is stored for many hours at top energy, bunches collide each turn (for colliders)
- **Major limitations: emission of synchrotron radiation (leptons) and strength of the magnetic field (hadrons)**



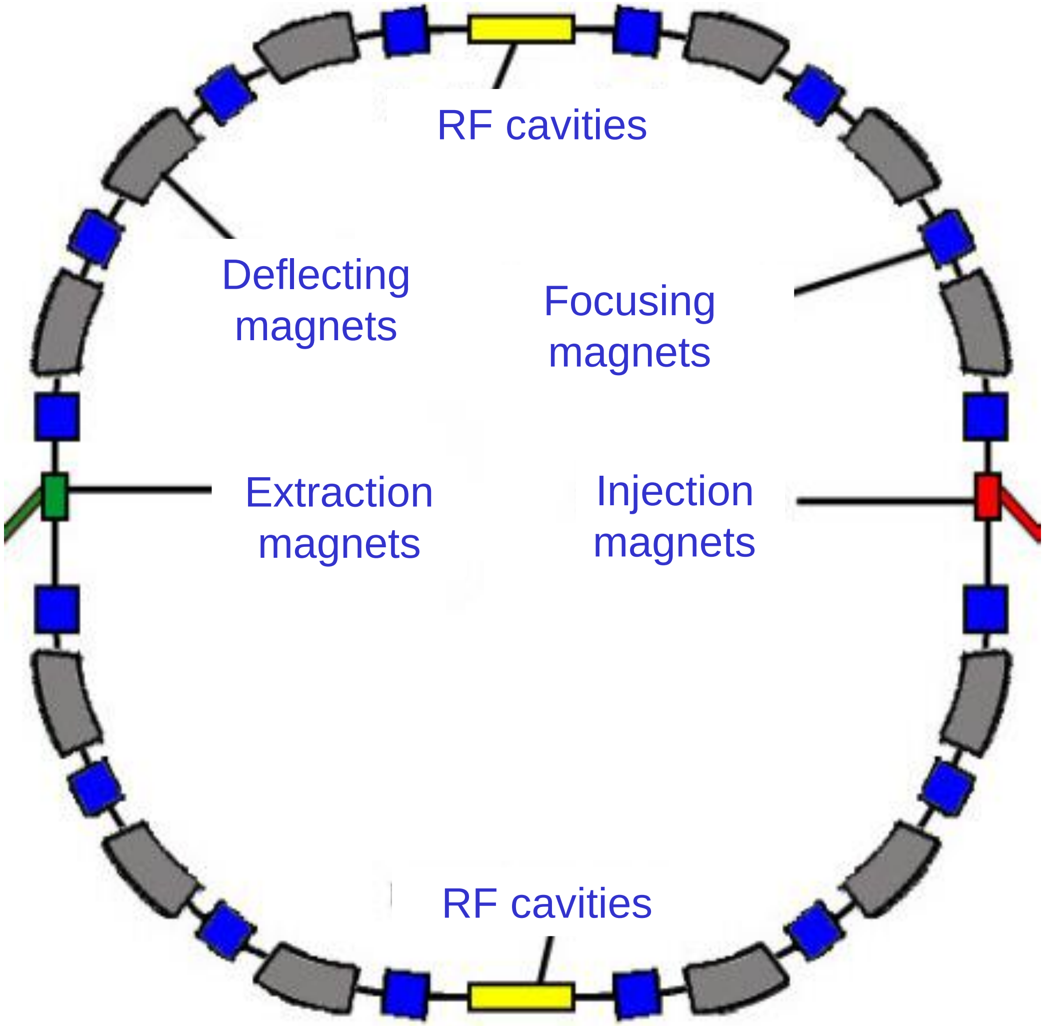
Accelerating structure

Magnets around the accelerator to bring the beam back to the accelerating structure

Today achieved c.m energy of 13.6 TeV at LHC

Experiment

Components of a synchrotron

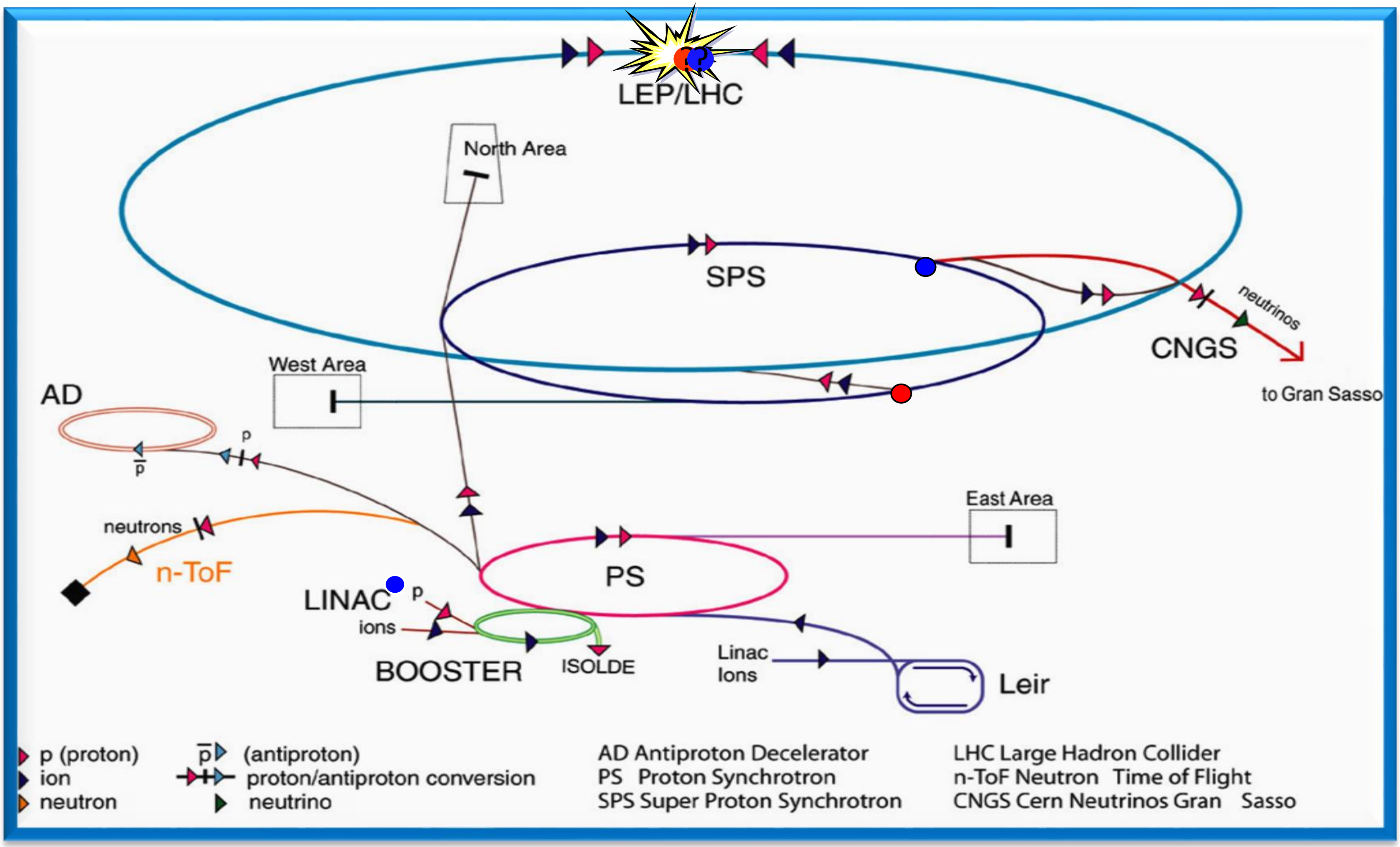


Components of a synchrotron:

- RF cavities
- Vacuum system
- Deflection magnets
- Magnets to focus beams and other magnets
- Injection magnets (pulsed)
- Extraction magnets (pulsed)
- Beam instrumentation
- Experiments (colliders)
- Control system
- Power converter

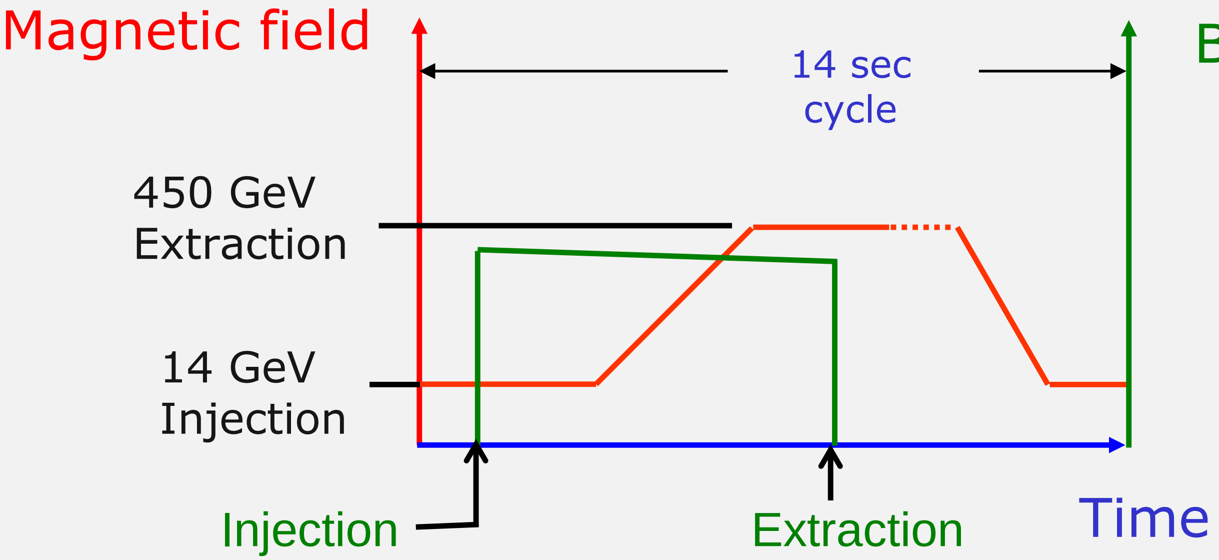
Mostly outside

CERN accelerator complex



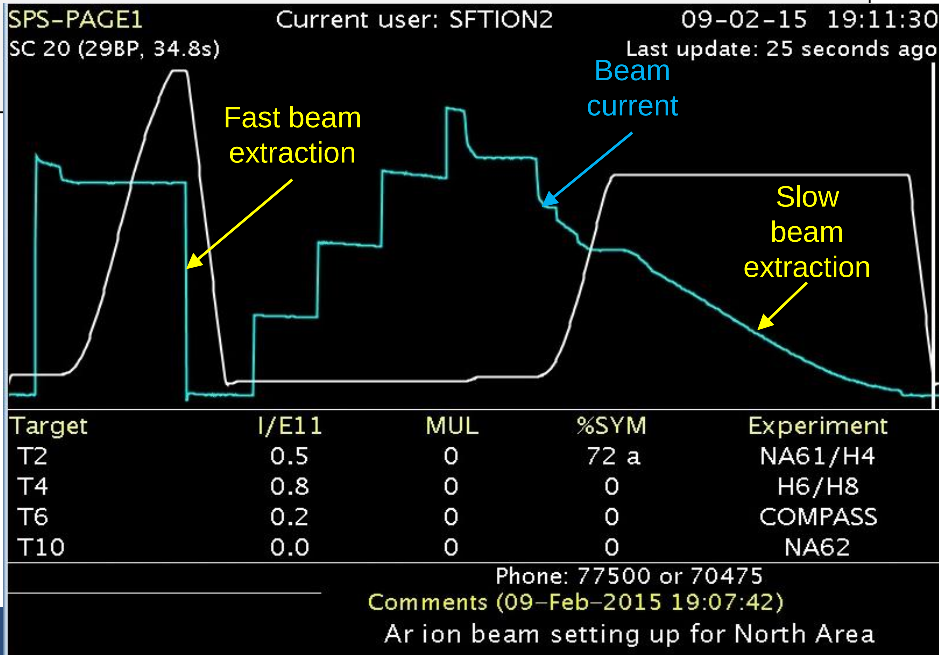
High intensity beam from SPS to LHC at 450GeV via TI2 and TI8, LHC accelerates to 6.8TeV

Synchrotrons and storage rings: SPS



Example: CERN-SPS Protonsynchrotron

- 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



SPS-PAGE1 Current user: SFTION2 09-02-15 19:11:30
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Target	I/E11	MUL	%SYM	Experiment
T2	0.5	0	72 a	NA61/H4
T4	0.8	0	0	H6/H8
T6	0.2	0	0	COMPASS
T10	0.0	0	0	NA62

Phone: 77500 or 70475
Comments (09-Feb-2015 19:07:42)
Ar ion beam setting up for North Area

Circular colliders for highest energy….

LHC collider, operating since 2009

- Proton-Proton and Ion-Ion collider
- 27 km long, operating at an momentum of 6.8 TeV/c per proton
- Very intense beams
- Very high luminosity
- Superconducting magnets (protection of superconducting magnets -> presentation on Wednesday)

FCC-hh, proposed as future collider at CERN

- Proton-Proton collider
- About 100 km long, for protons of about 100 TeV/c
- Very intense beams
- Very high luminosity
- Superconducting magnets

FCC-ee …. first phase of FCC-hh

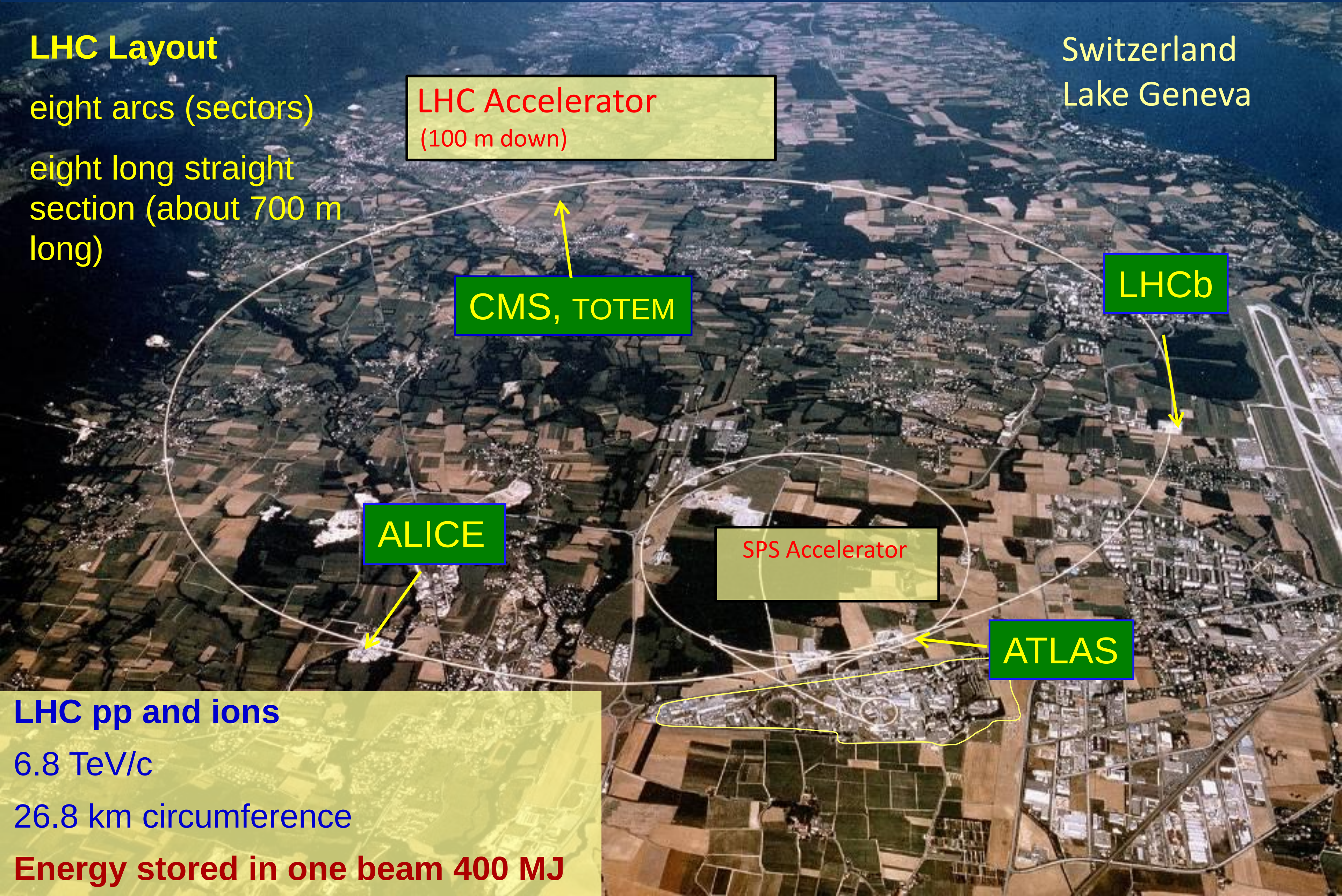
- Electron-Positron collider

LHC (Large Hadron Collider)

LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)



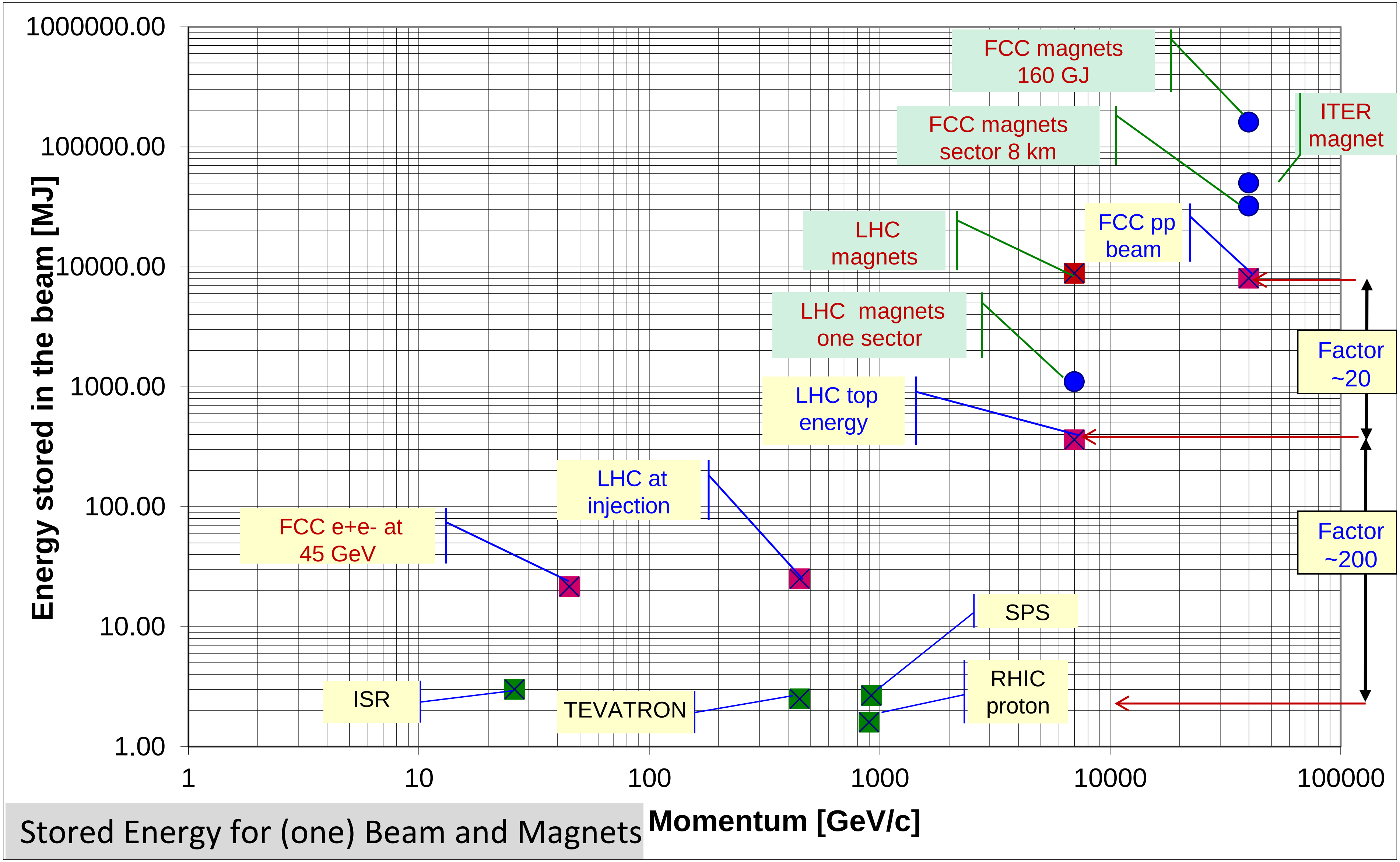
LHC pp and ions

6.8 TeV/c

26.8 km circumference

Energy stored in one beam 400 MJ

Energy stored in beam and magnets

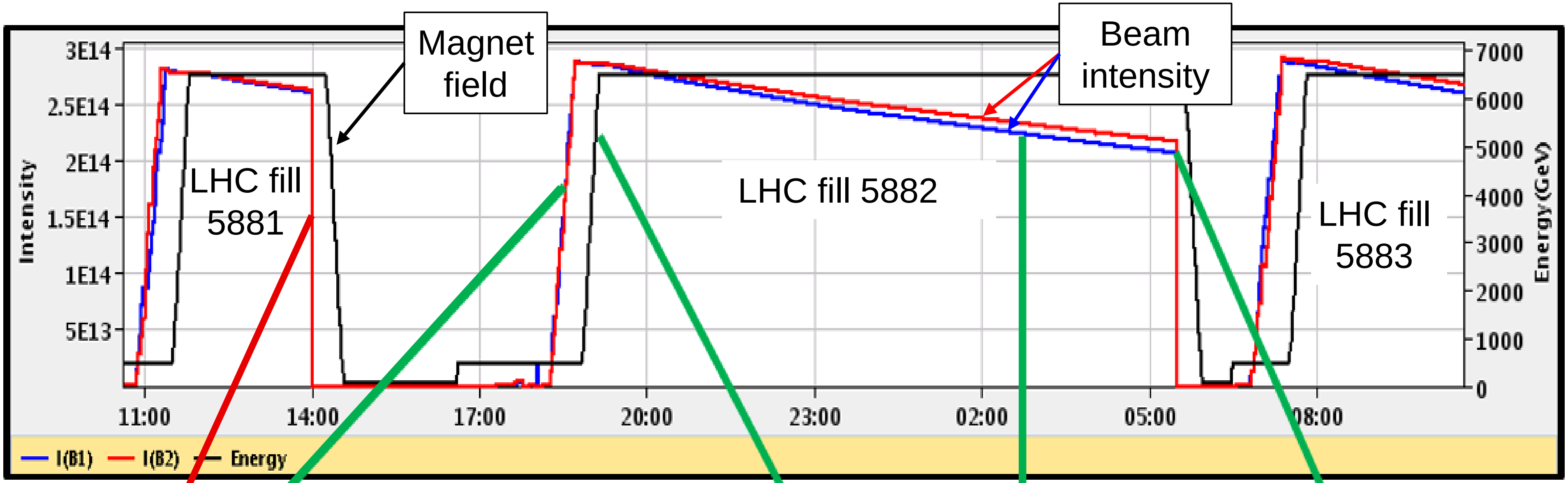


Stored Energy for (one) Beam and Magnets

LHC Operation

- Beams are injected at “low” energy
- Beams are accelerated to “high” energy
  - By a factor of 10 to 40 (LHC: 450 GeV to 6.8 TeV)
- Beam are brought into collisions
- Beams are colliding for many hours (depending on the accelerator, from a few to several 10 hours)
  - $\int Ldt$ integrated luminosity (~ number of collisions) is relevant for particle physicists
- The fill is ended - next cycle starts - the magnets are ramped down to injection energy - **what happens to a beam of 400 MJ?**
- 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 …**where does the beam go?**

LHC Operation



Injection of beam in batches of 144 bunches, in total about 2500 bunches, at 450GeV

Energy ramp from 450GeV to 6.5TeV. Beams are brought into collision

End of the fill: what to do with the two beams, each 300MJ?

A failure is detected, what to do with the two beams, each 300MJ?

Beams are colliding for many hours (depending on the accelerator, from a few to several 10 hours)

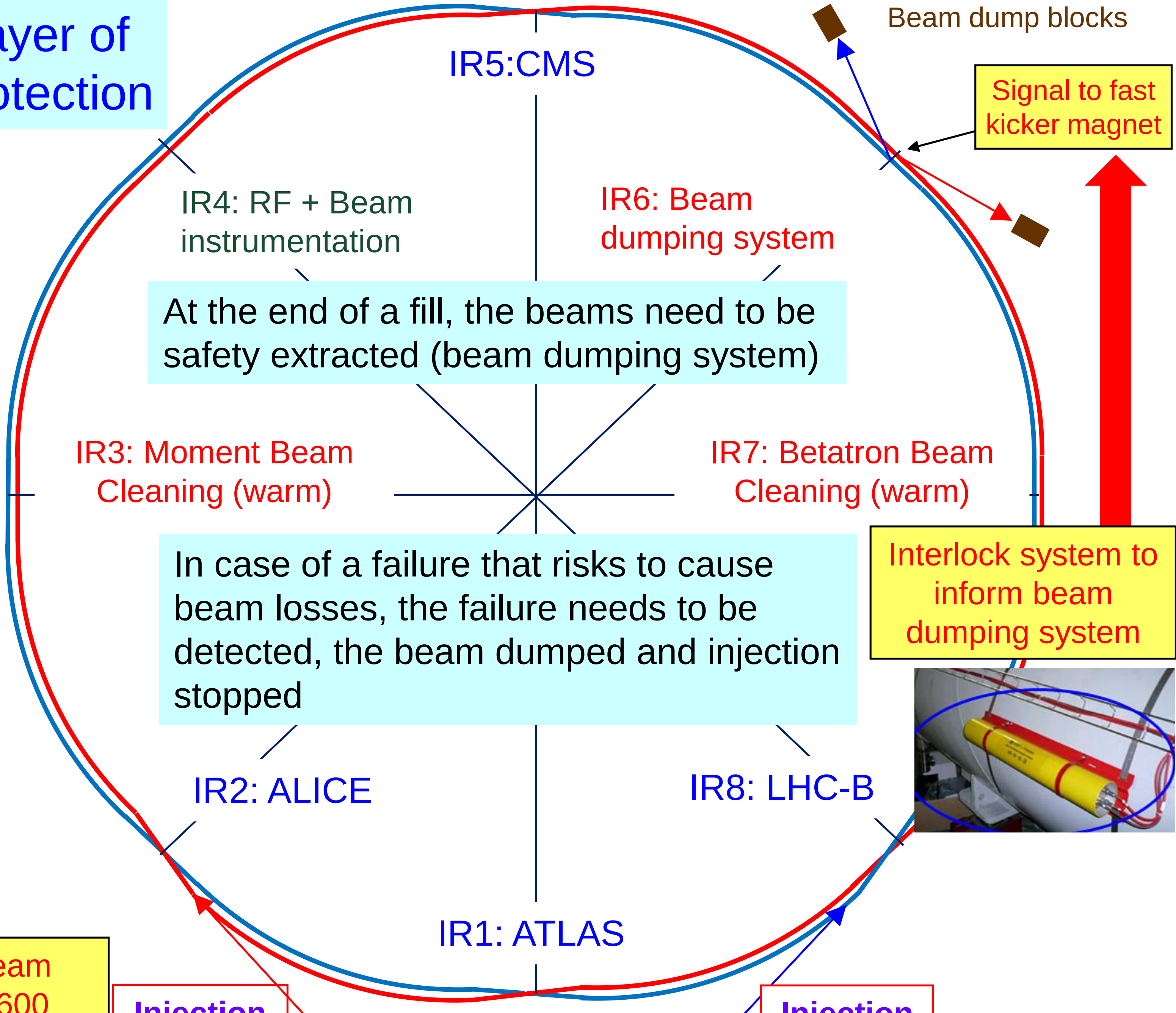
$\int L dt$ integrated luminosity counts for particle physicists (~number of collisions)

LHC Protection

- At the end of a fill, the beams must be dumped in a controlled way
  - Requires a performant beam dumping system correctly extracting the beams
- During the cycle, it is not tolerable to lose the stored beam in an uncontrolled way
  - Requires a performant system to detect failures, inform the beam dumping system and stop injection
- Correctly injecting beam from the SPS

A performant machine protection system is required, to protect from uncontrolled release of beam energy (....and uncontrolled release of magnet energy)

LHC first layer of machine protection



Signal to fast kicker magnet

At the end of a fill, the beams need to be safety extracted (beam dumping system)

In case of a failure that risks to cause beam losses, the failure needs to be detected, the beam dumped and injection stopped

Interlock system to inform beam dumping system

Detection of beam losses with >3600 monitors around LHC

Injection

STOP INJECTION

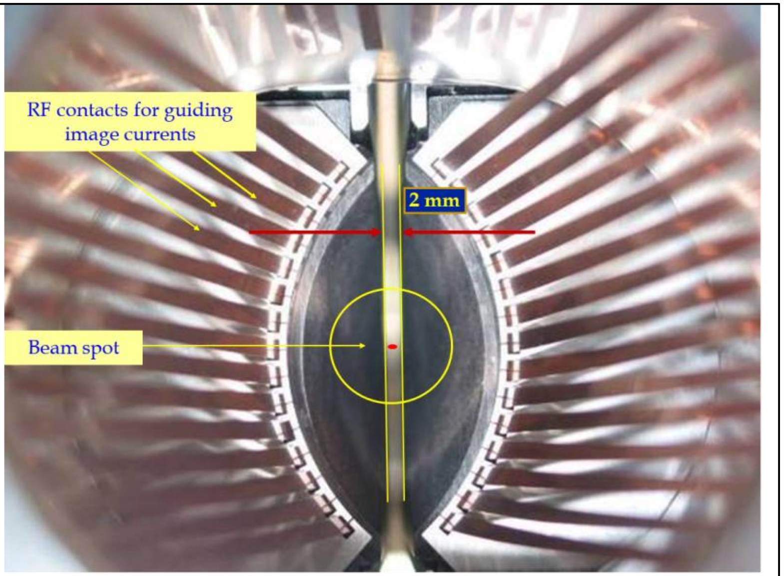
Injection

Circular accelerators: first layer of machine protection

- Beam dumping system
- Monitoring systems for beam losses and for failures of equipment
- Interlock system
- Beam cleaning system for capturing the beam halo

View of a two sided collimator

about 100 collimators are installed in LHC



Machine protection for single-path accelerators (including linear accelerators)

High power hadron accelerators

- Spallation sources
- Proton accelerators for neutrino production
- Rare Isotope Beams Production
- Accelerator Driven Spallation

Linear colliders

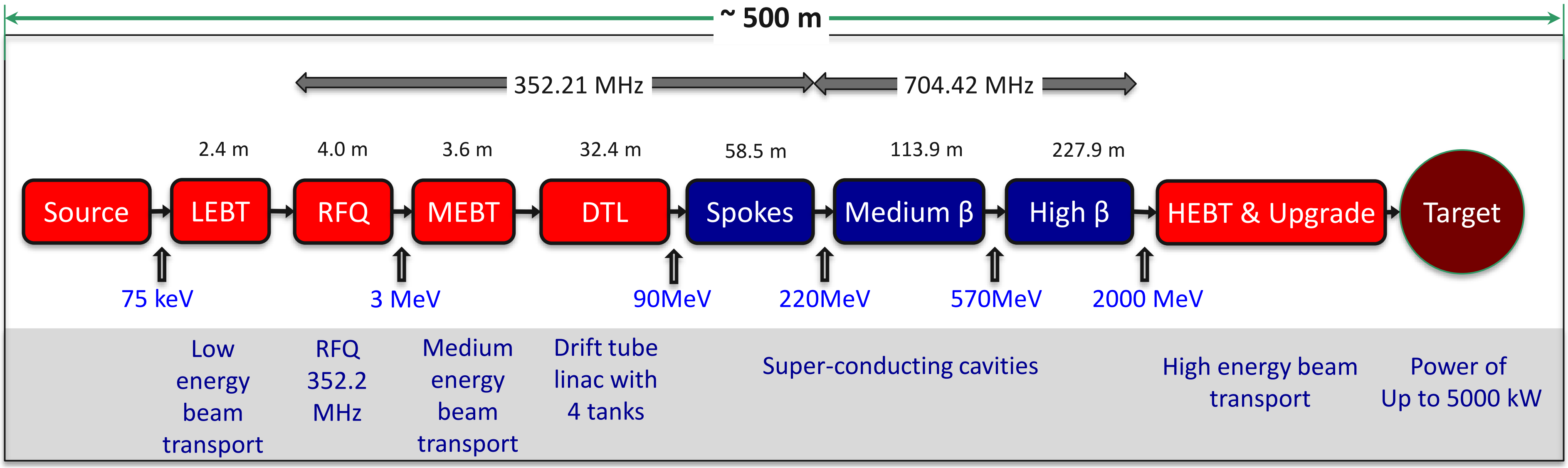
- ILC and CLIC

FEL Linear accelerators

- XFEL (DESY) and LCLS / LCLS II (SLAC)

Transfer lines

ESS (European Spallation Source) Lund / Sweden



~ 500 m

352.21 MHz

704.42 MHz

2.4 m

4.0 m

3.6 m

32.4 m

58.5 m

113.9 m

227.9 m

Source

LEBT

RFQ

MEBT

DTL

Spokes

Medium β

High β

HEBT & Upgrade

Target

75 keV

3 MeV

90MeV

220MeV

570MeV

2000 MeV

Low energy beam transport

RFQ 352.2 MHz

Medium energy beam transport

Drift tube linac with 4 tanks

Super-conducting cavities

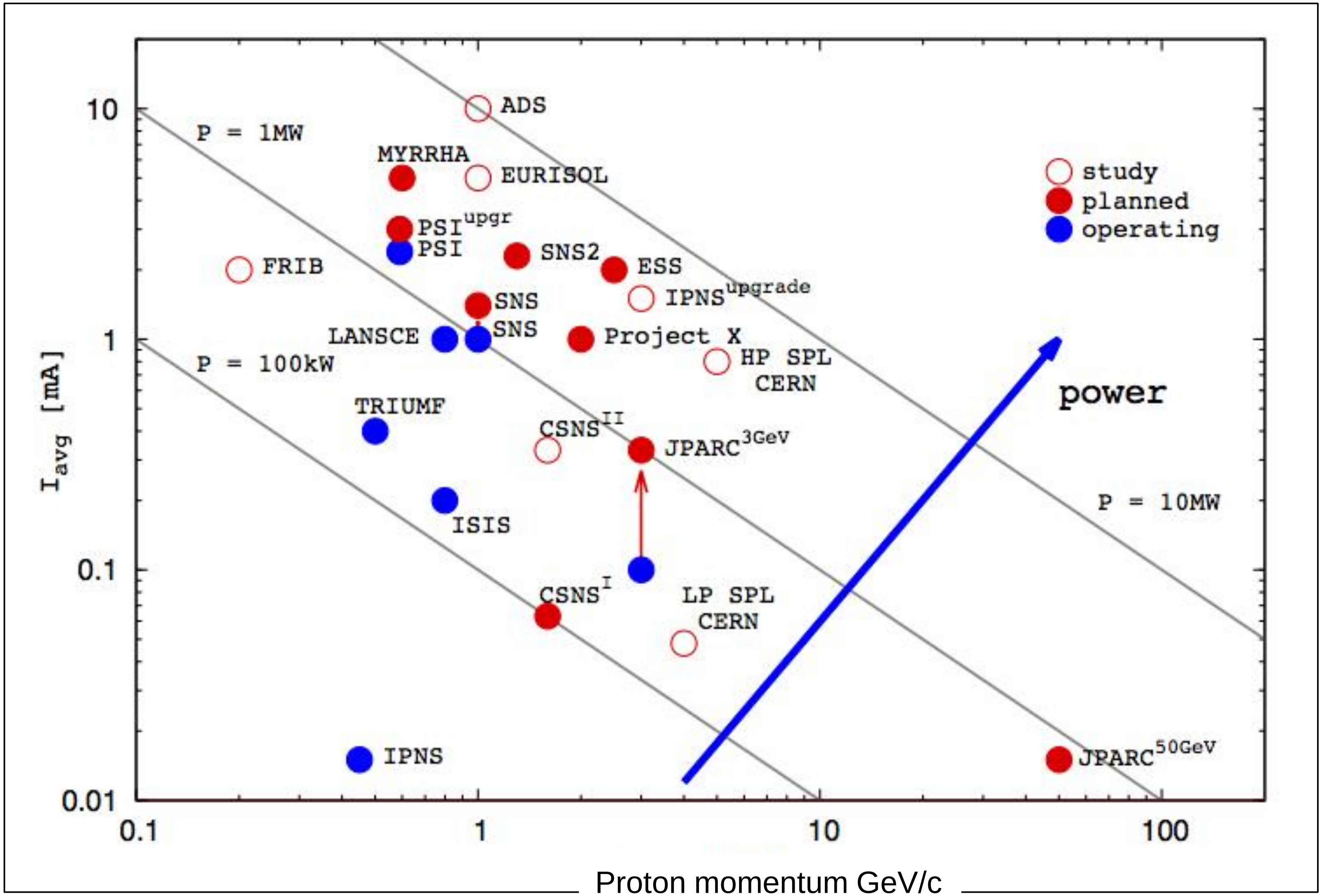
High energy beam transport

Power of Up to 5000 kW

- Operating with protons at 2 GeV/c
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Up to average beam power of up to 5 MW**
- Peak power of 125 MW
- Power per pulse 360 kJ

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

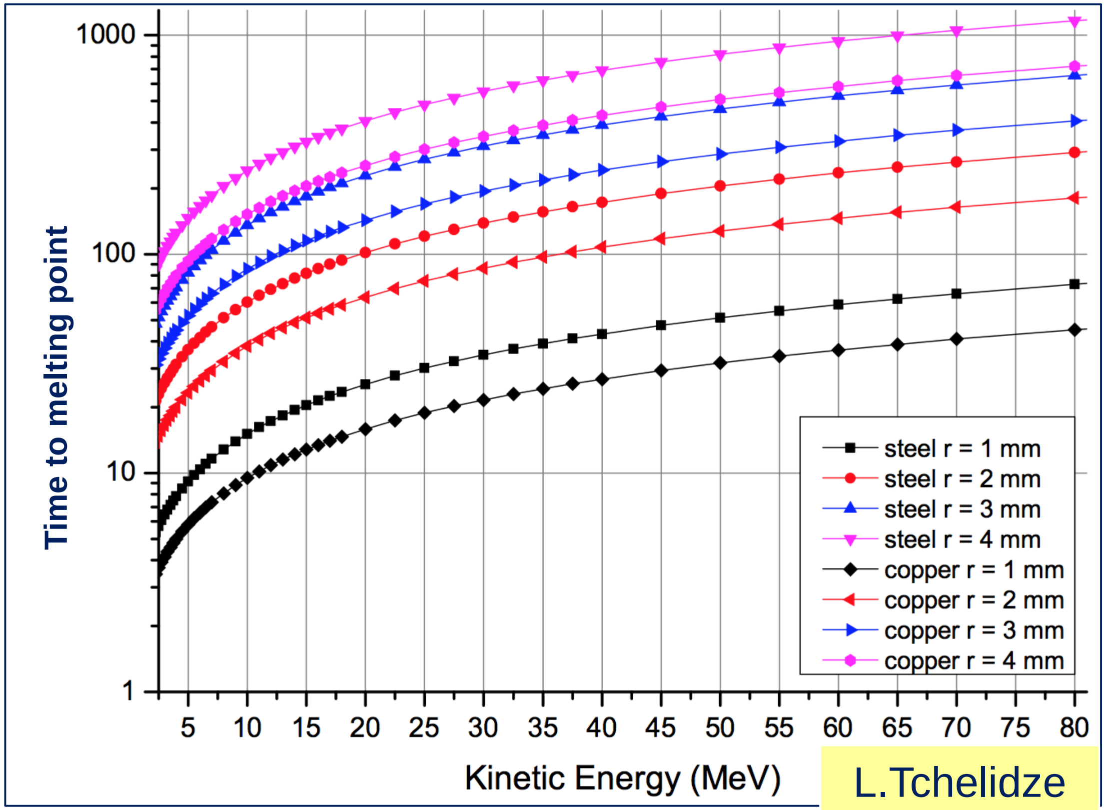
High intensity proton accelerators



Example for ESS, Lund, Sweden

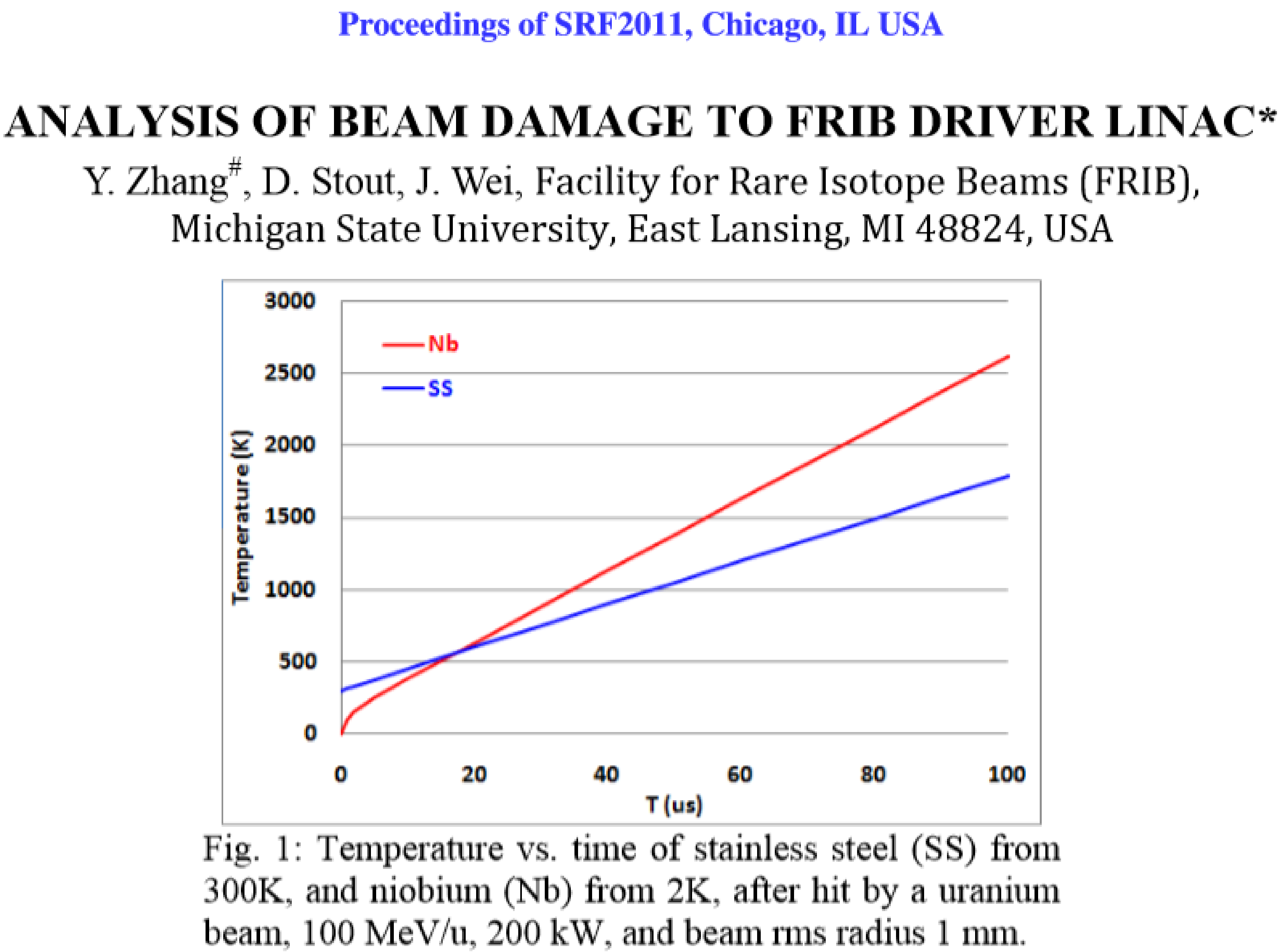
After the DTL normal conducting linac, the proton energy is 78 MeV. In case of a beam of 2 mm radius hitting material, melting would start after about 200 µs.

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



L.Tchelidze

Example for FRIB at MSU for uranium beams



Proceedings of SRF2011, Chicago, IL USA

ANALYSIS OF BEAM DAMAGE TO FRIB DRIVER LINAC*

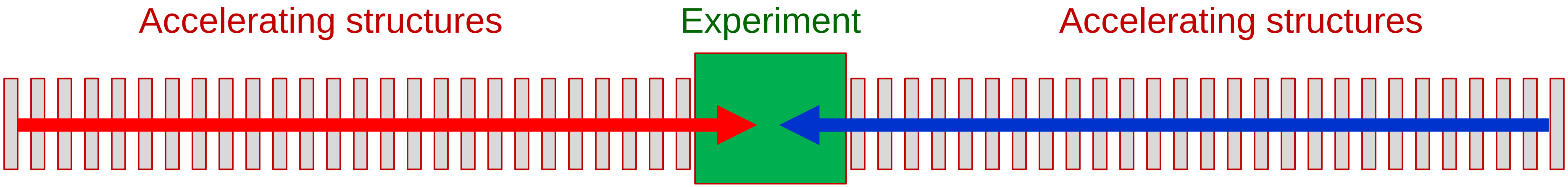
Y. Zhang[#], D. Stout, J. Wei, Facility for Rare Isotope Beams (FRIB),
Michigan State University, East Lansing, MI 48824, USA

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.

Linear collider: use accelerating structure once

Accelerating beams to high energy in a e+e- linear collider

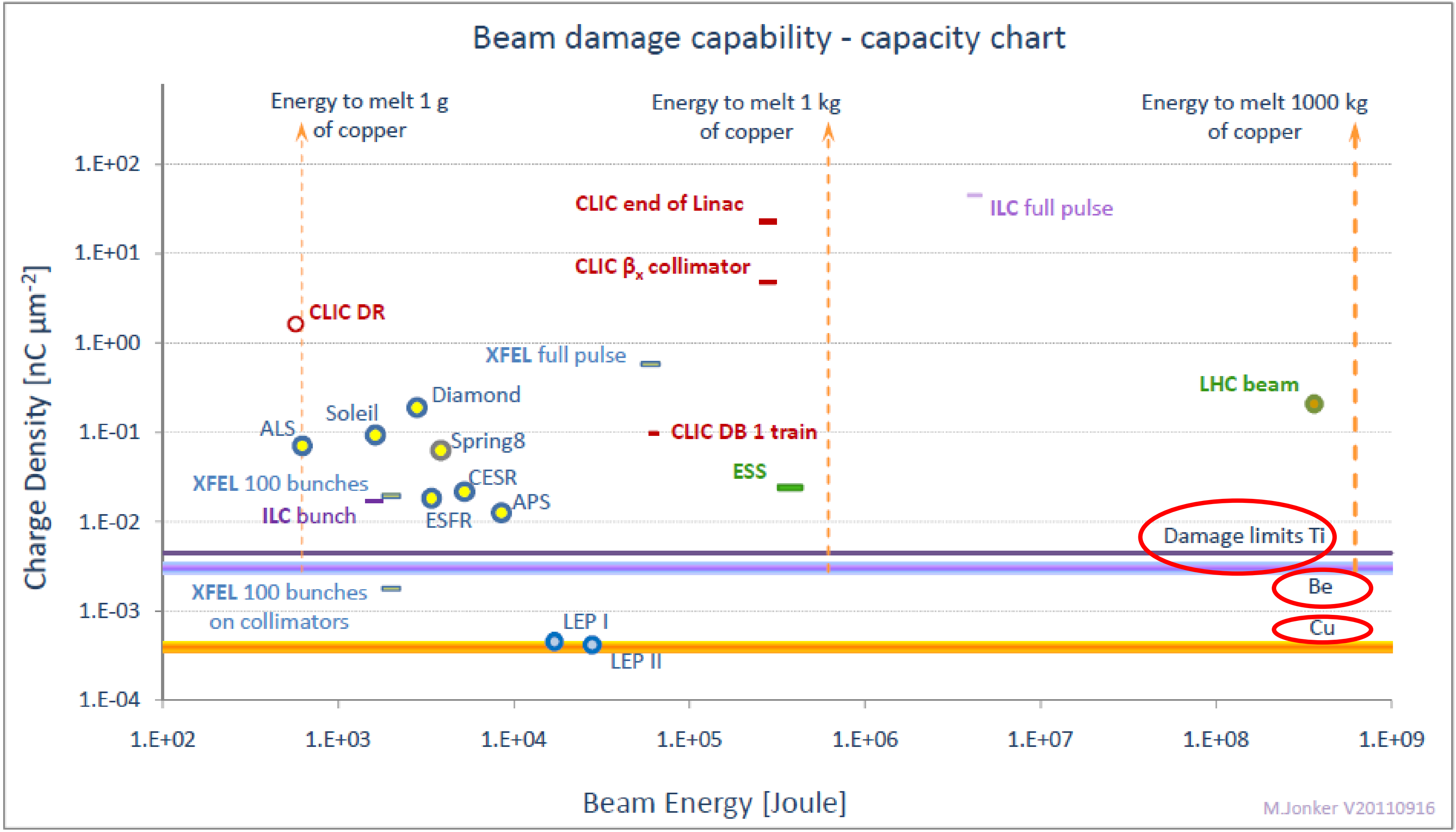
- The beams are accelerated during one passage and the bunches are colliding only once at the center of the experiment



Acceleration of particles with time-varying electrical field

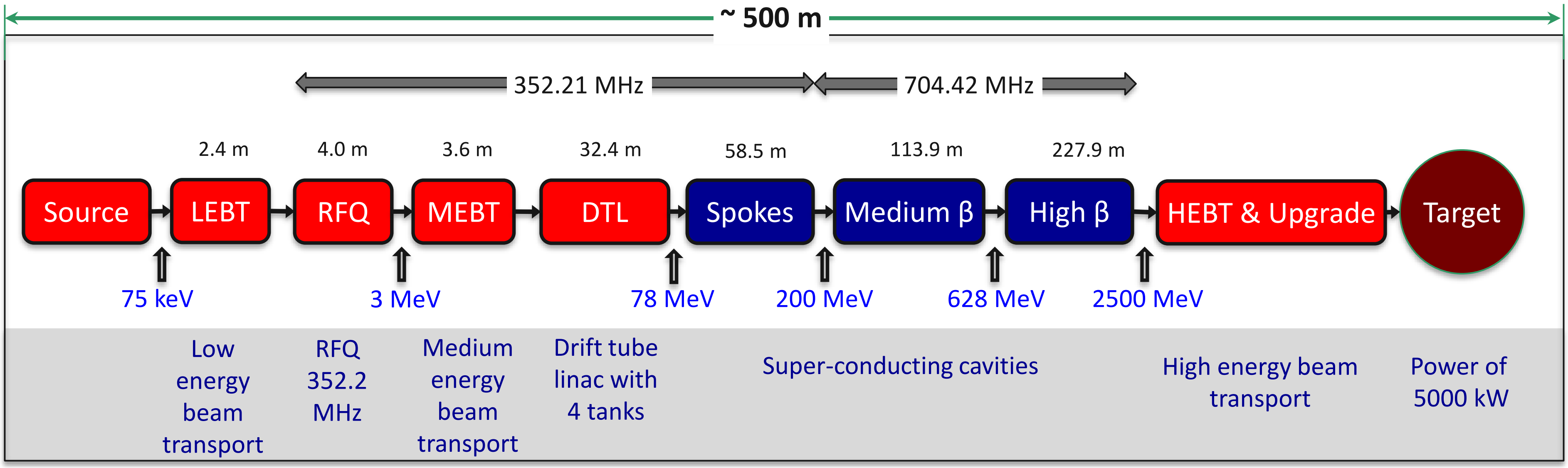
- Limit 30-40 MeV/m with superconducting cavities
- Limit about 100 MeV/m with other technologies, not yet used (CLIC)
- Some 100 MeV … ~TeV conceivable for e+e- colliders
- Reaching an energy of 14 TeV c.m. (such as LHC) would require an accelerator with a length > 400 km (with 40 MV/m)
- Long-term: acceleration in a plasma … not ready for a HEP collider
- **Challenge: operation with extremely small beams (few nm)**

Beam damage capabilities



M.Jonker

Main principles – example for ESS



Low energy beam transport

RFQ 352.2 MHz

Medium energy beam transport

Drift tube linac with 4 tanks

Super-conducting cavities

High energy beam transport

Power of 5000 kW

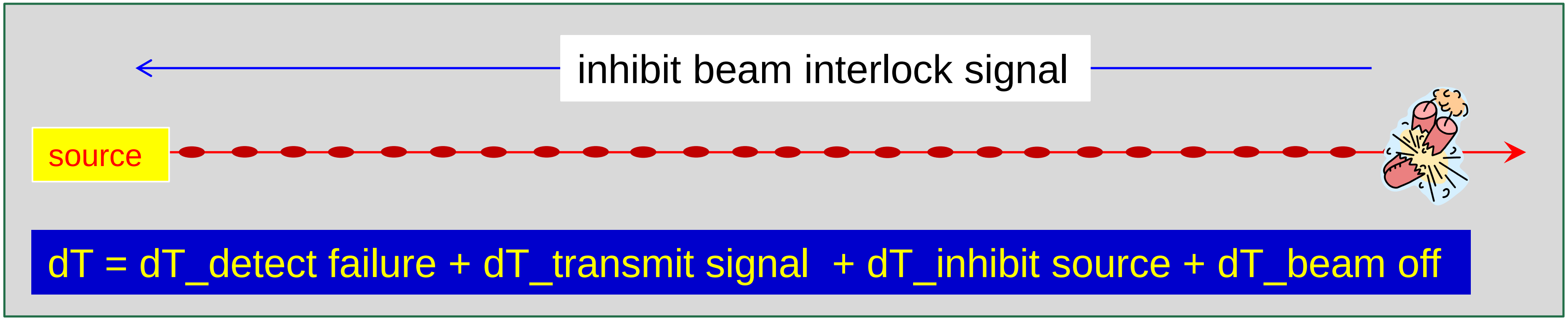
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms

- Only start pulse if it is sure that there is no obstacle (mechanical, RF, magnet field)
- If a failure is detected during the beam pulse, stop source

Single path accelerators: first layer of machine protection

- Monitoring for all equipment that can have an impact on the beam (RF, magnet power supplies, movable devices, ...)
- Interlock system that allows start of beam pulse production only if equipment monitoring gives "green light"

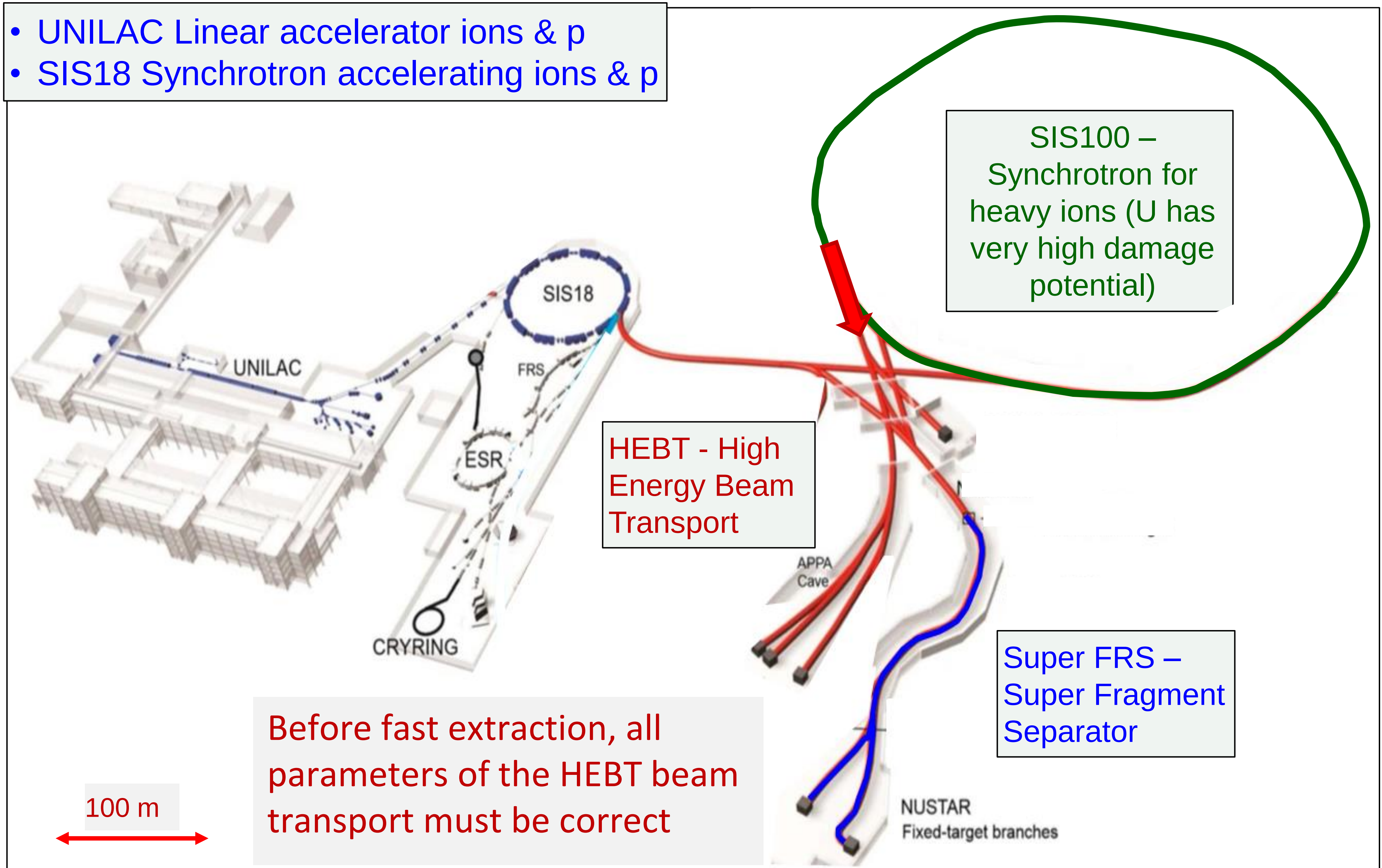
- Stop beam pulse at the source as fast as possible in case a failure is detected



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

FAIR at GSI (Darmstadt, Germany): transfer line

- UNILAC Linear accelerator ions & p
- SIS18 Synchrotron accelerating ions & p

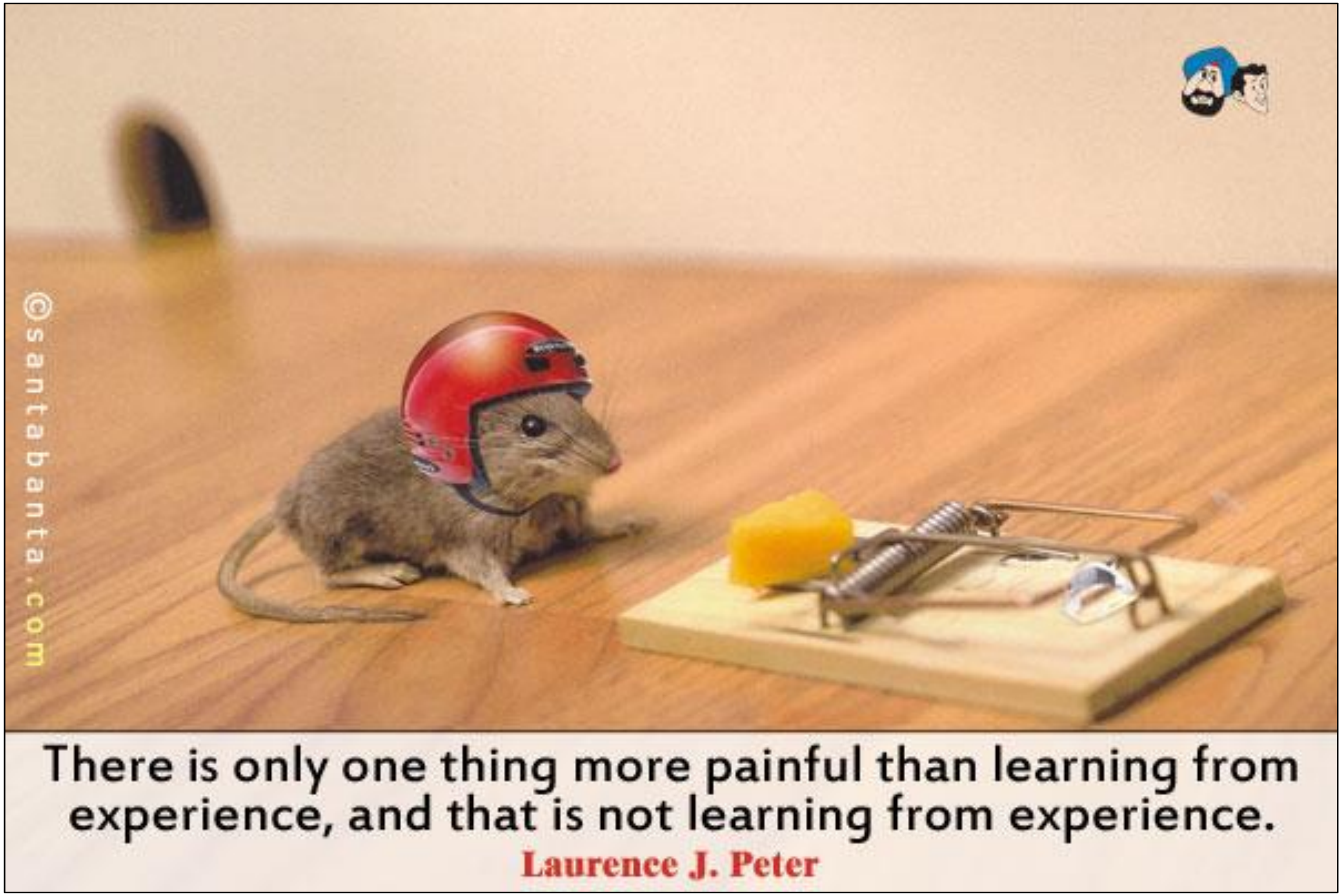


SIS100 – Synchrotron for heavy ions (U has very high damage potential)

HEBT - High Energy Beam Transport

Super FRS – Super Fragment Separator

Before fast extraction, all parameters of the HEBT beam transport must be correct



There is only one thing more painful than learning from experience, and that is not learning from experience.

Laurence J. Peter

Accidents at accelerators ...leading to damage

- CERN-ISR (Intersecting Storage Rings): 1973/1974
- CERN-SPS proton antiproton collider 1986: Damage of UA2
- FERMILAB TEVATRON p-pbar collider 2003: Damage of collimator
- SPS synchrotron 2004: Damage of transfer line TT40
- CERN-LINAC 4 (2013) at very low energy: Beam hit a bellow and a vacuum leak developed
- JPARC 2013: Damage of target – release of radioactive material
- SuperKEBb: damage of collimators and part of experiment due to beam losses
- CERN-LHC magnet powering: Severe damage of magnet system

Accidents in ISR 50 years

CERN-ISR (Intersecting Storage Rings): two intersecting proton synchrotron rings, each with a circumference of 942 m operating from 1971 to 1984.
The CERN PS injected 26 GeV/c proton beams into the two rings that could accelerate up to 31.4 GeV/c.

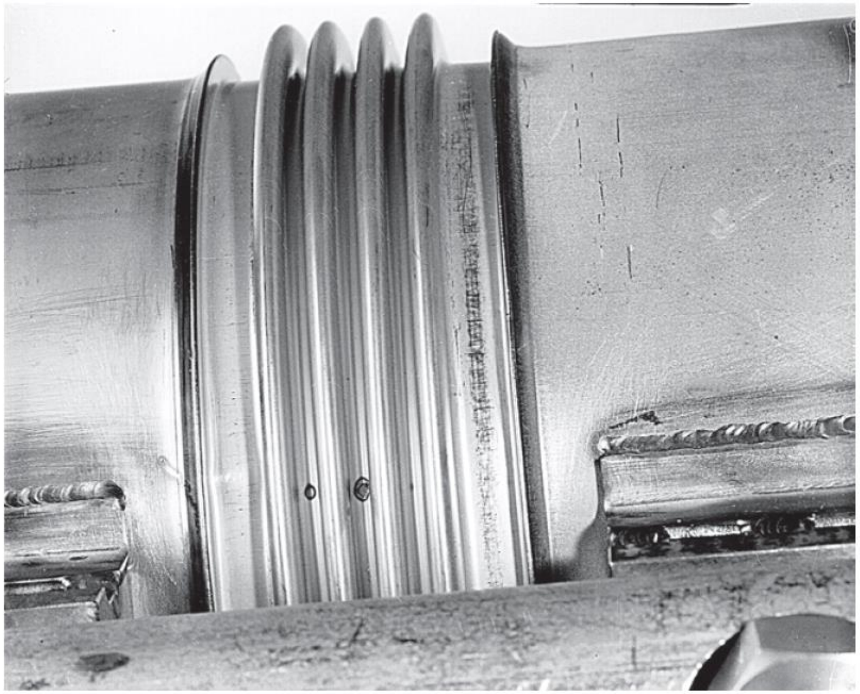
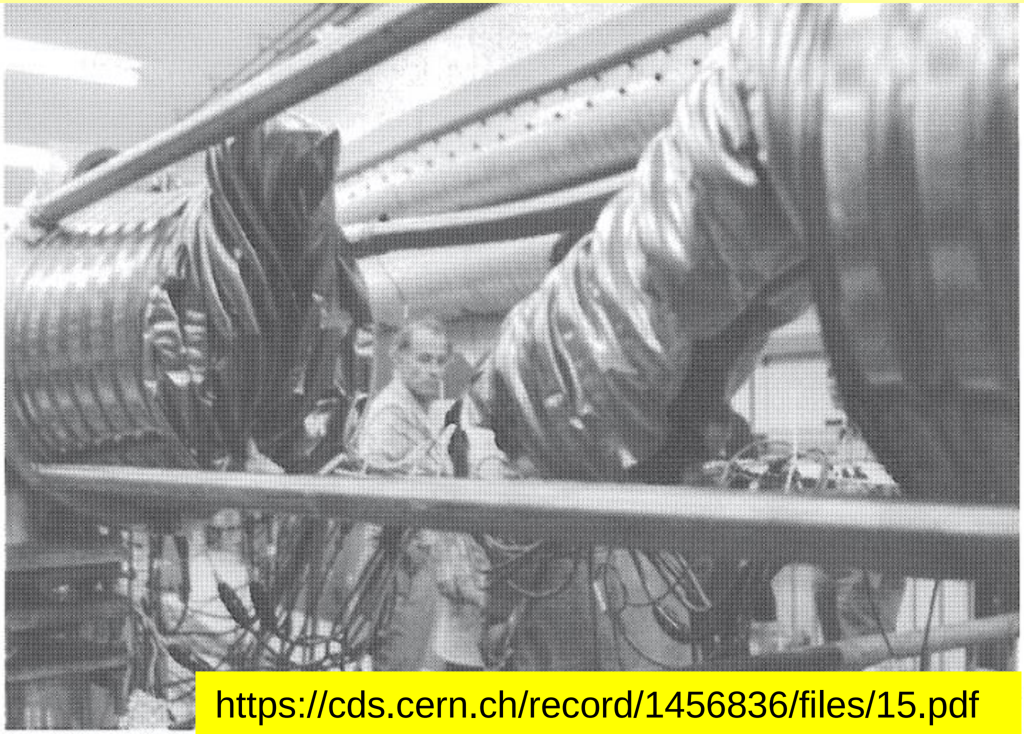


Fig. 14: Holes burnt by the beam in a bellows

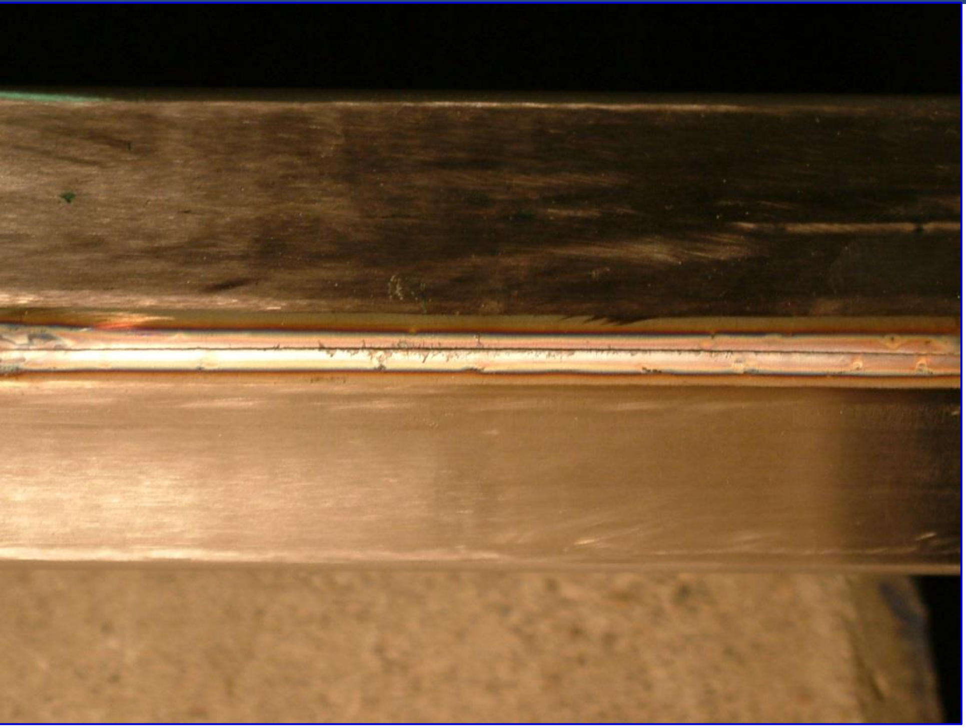
The ISR worked for physics with beams of 30–40 A over 40–60 hours with luminosities in its superconducting low-β insertion of 10^{31}–10^{32} cm-2 s-1. The ISR demonstrated the practicality of collider beam physics while catalysing a rapid advance in accelerator technologies and techniques



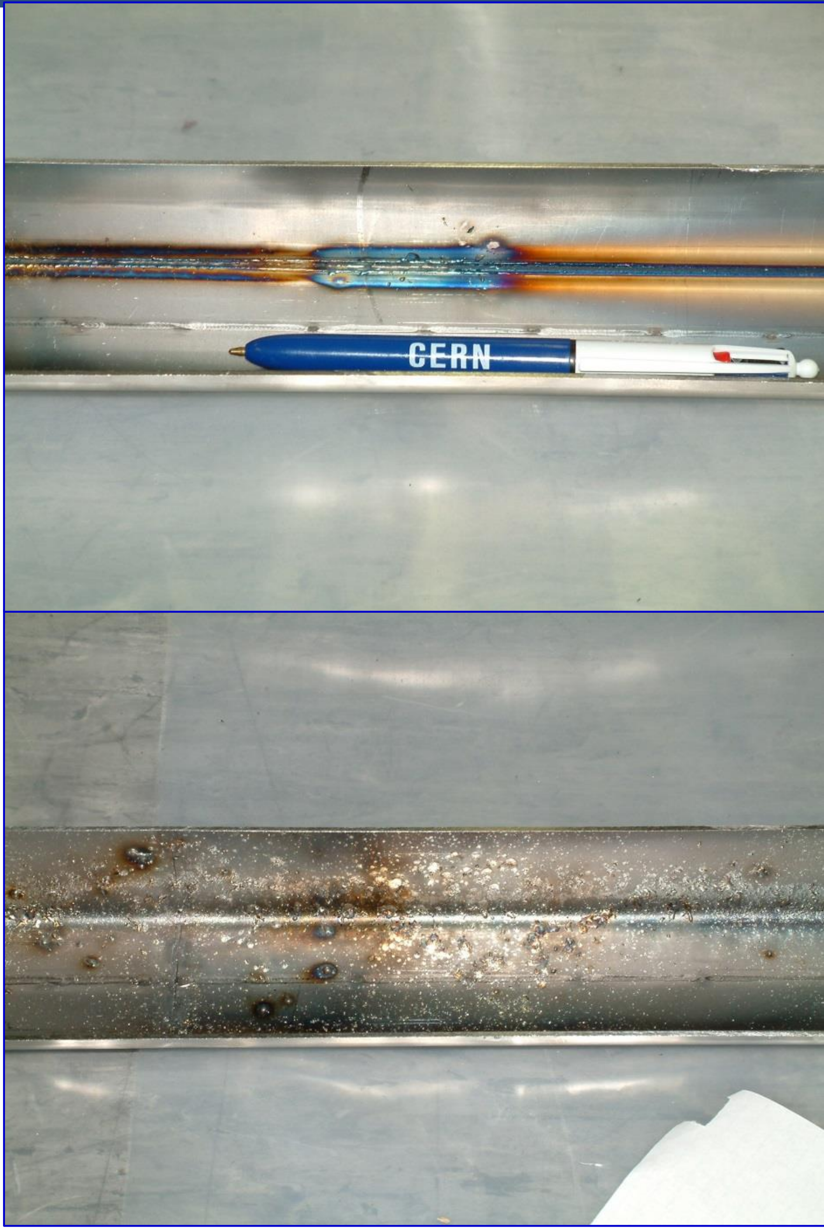
https://cds.cern.ch/record/1456836/files/15.pdf

Fig. 15: The thin-walled (0.3 mm) titanium chamber in Intersection 7 implodes (1975)

Vacuum chamber in SPS extraction line accident



- 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



CERN-SPS used as a proton antiproton collider

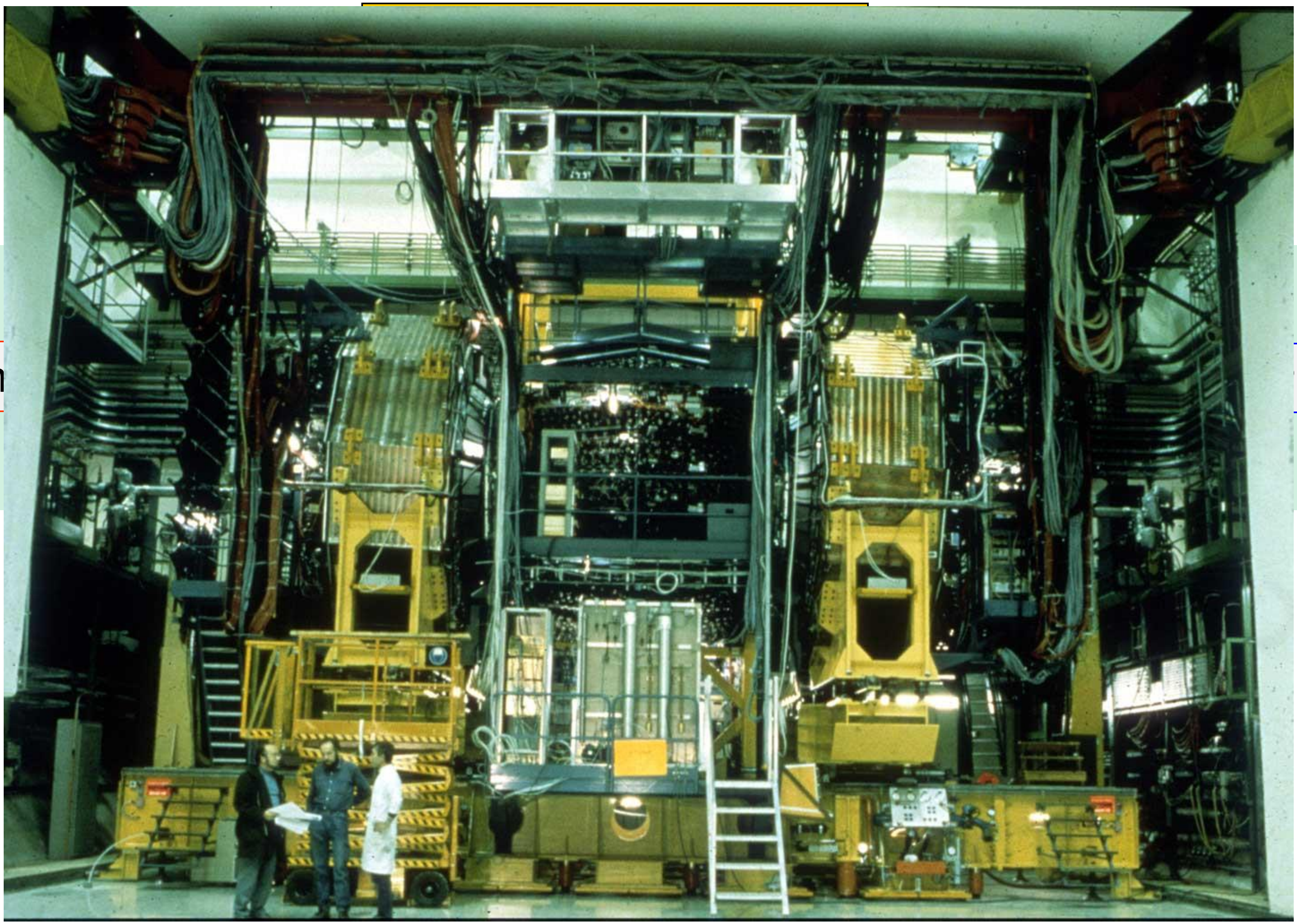
- Transformed the SPS accelerator from a Fixed Target Synchrotron into a Proton Antiproton collider in 1980 … 1982
- Operating as Proton Antiproton Collider until 1990
- **Antiprotons are very rare**, takes a **long time** to produce them
- Sometimes the beams were lost, frequently without knowing why …….. many hours to produce a new stack of antiprotons

- Once, beam was injected into the UA2 experiment.....

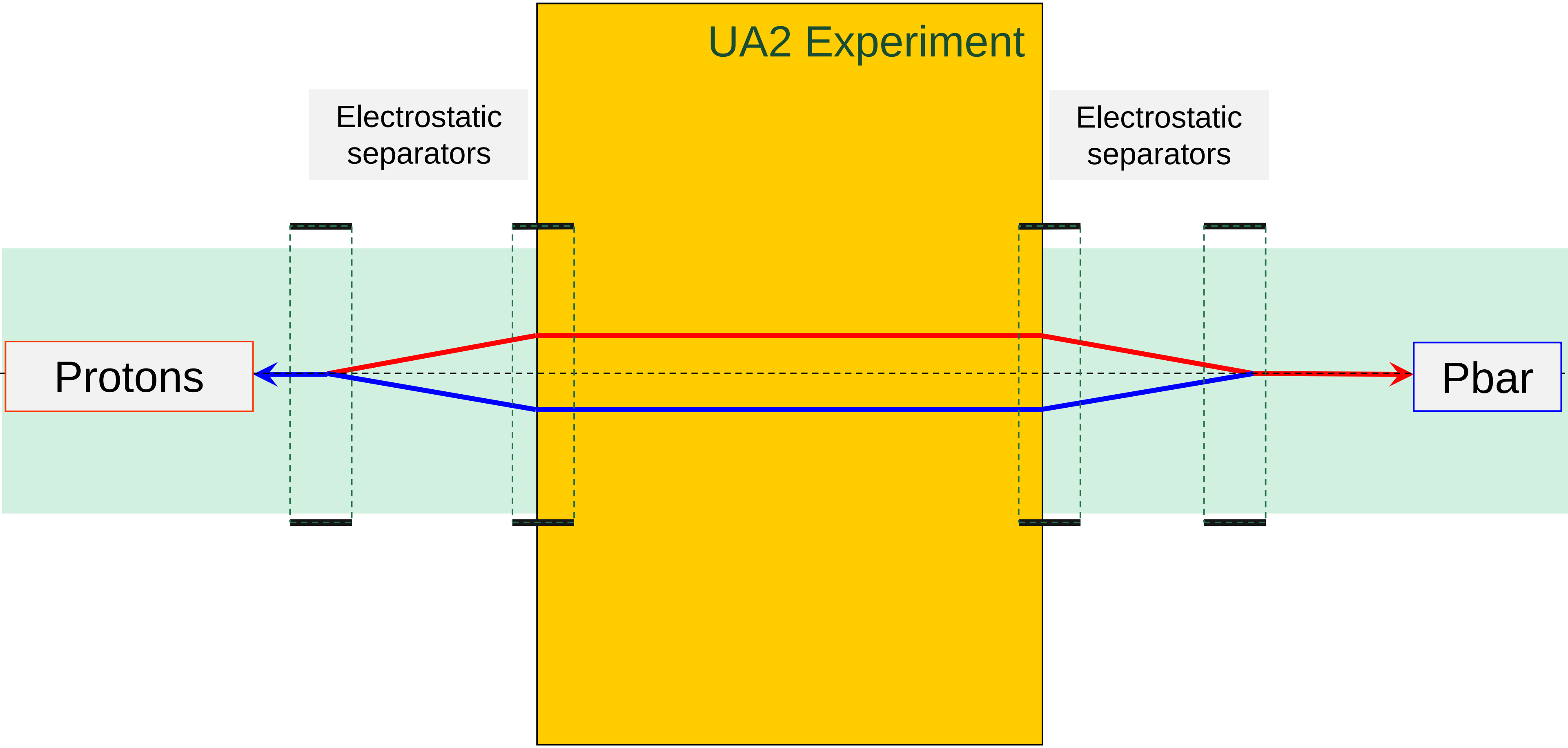
Colliding beams in UA2

Proton

bar

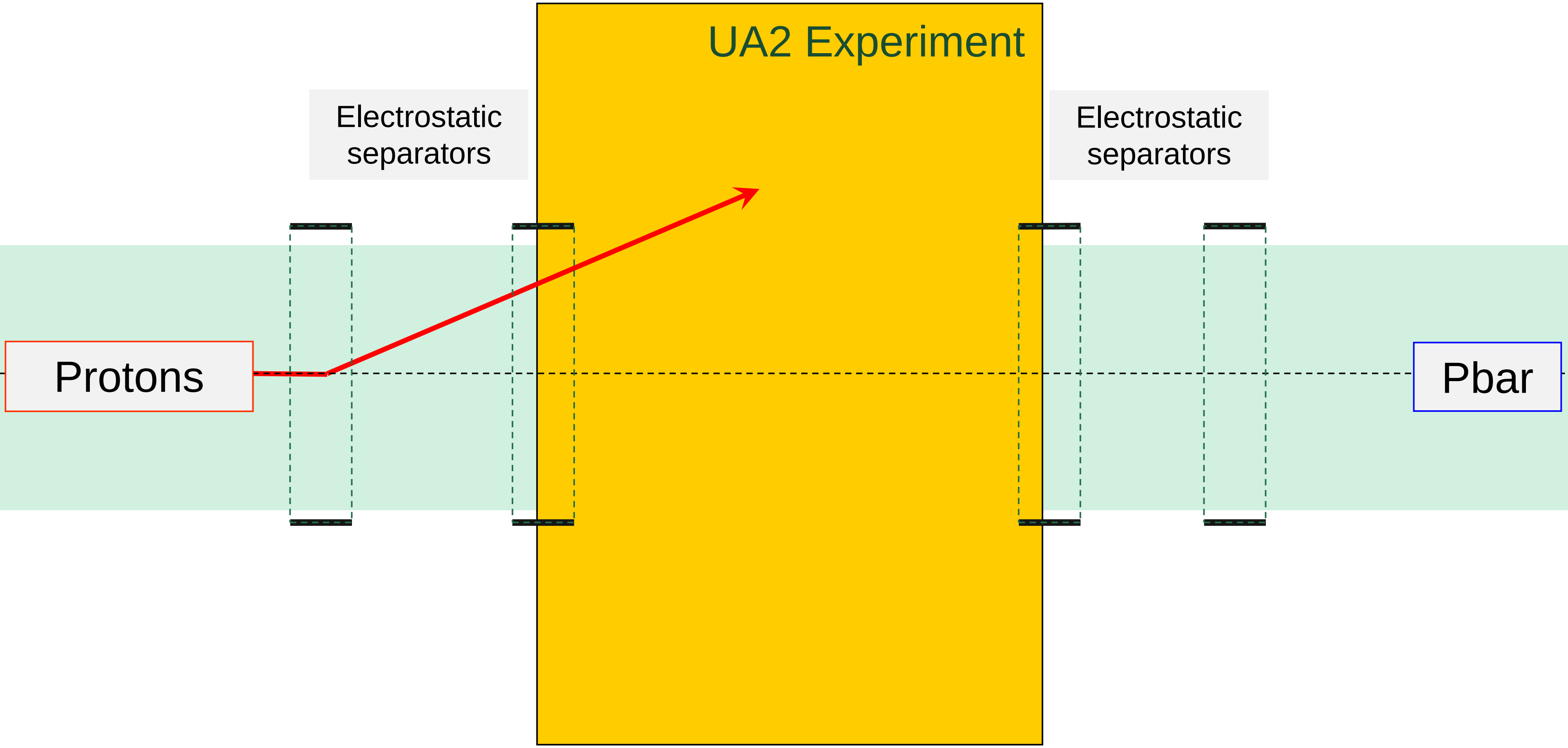


Separation bump when beams are not colliding



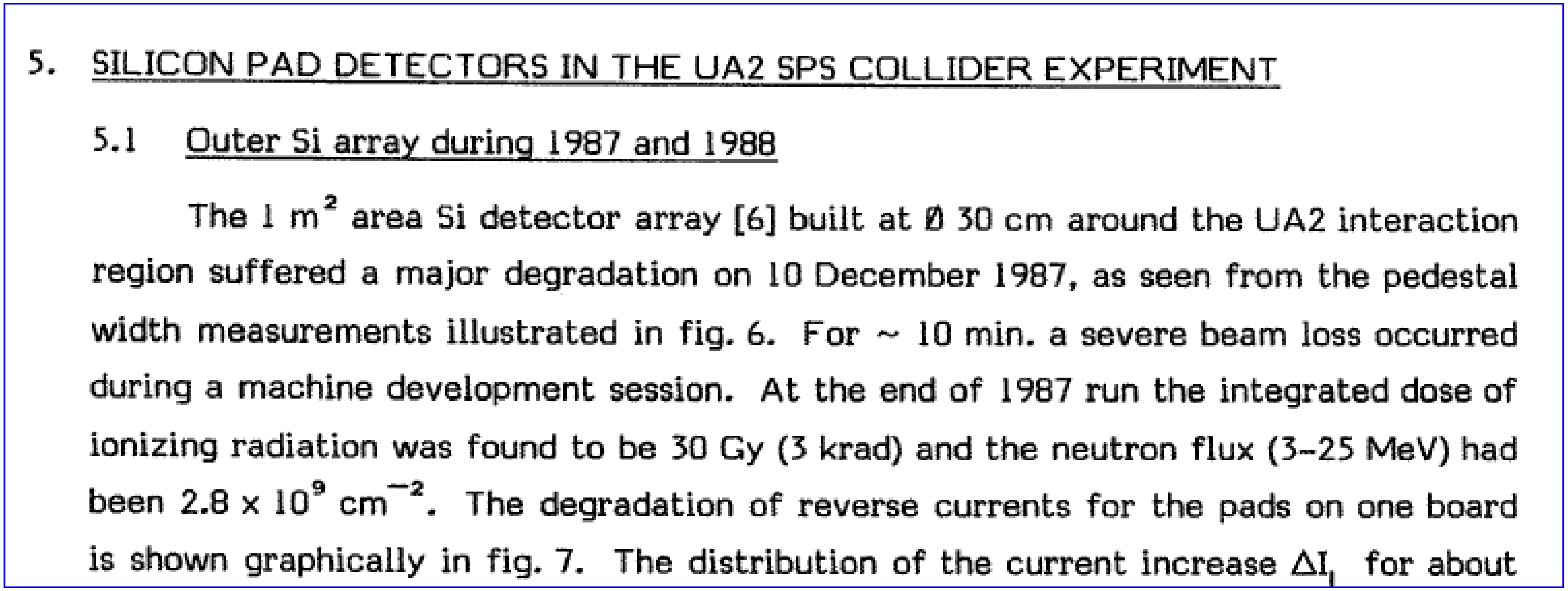
- The beam needed to be **separated at injection energy of 26 GeV and during the energy ramp to 315 GeV**
- Done with electrostatic separators, the voltage was increased

….try to inject beam



- One day, during **injection at 26 GeV**, the separators were **left at the setting for 315 GeV** – deflection angle much too large, operation was surprised to see not circulating beam **- using UA2 as beam dump**

Lessons from the CERN-SPS p-pbar collider



5. SILICON PAD DETECTORS IN THE UA2 SPS COLLIDER EXPERIMENT

5.1 Outer Si array during 1987 and 1988

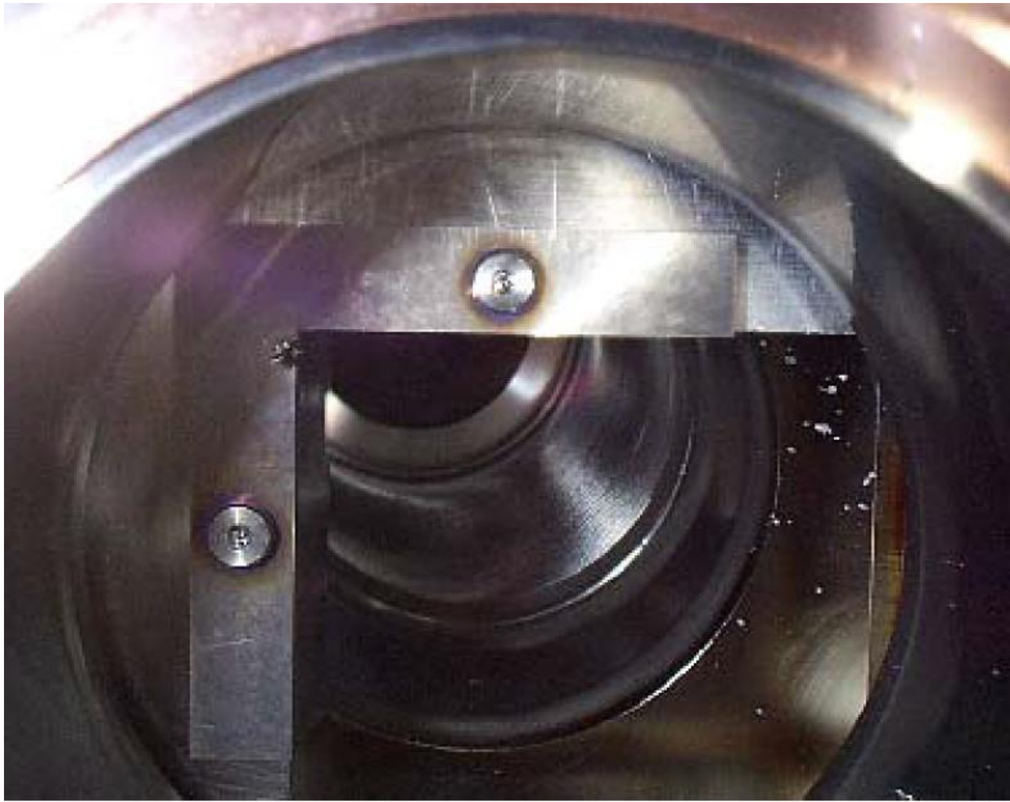
The 1 m^2 area Si detector array [6] built at Ø 30 cm around the UA2 interaction region suffered a major degradation on 10 December 1987, as seen from the pedestal width measurements illustrated in fig. 6. For ~ 10 min. a severe beam loss occurred during a machine development session. At the end of 1987 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

- **Protect the experiments**
- **Protect the beam**
- **Provide the evidence**

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
- Beam Loss Monitors were switched off during energy ramp ....



HERA at DESY proton collimator in 2003

- HERA (proton – e+ collider) collimators – 5 mm grove, never noticed during operation, only when machine was opened

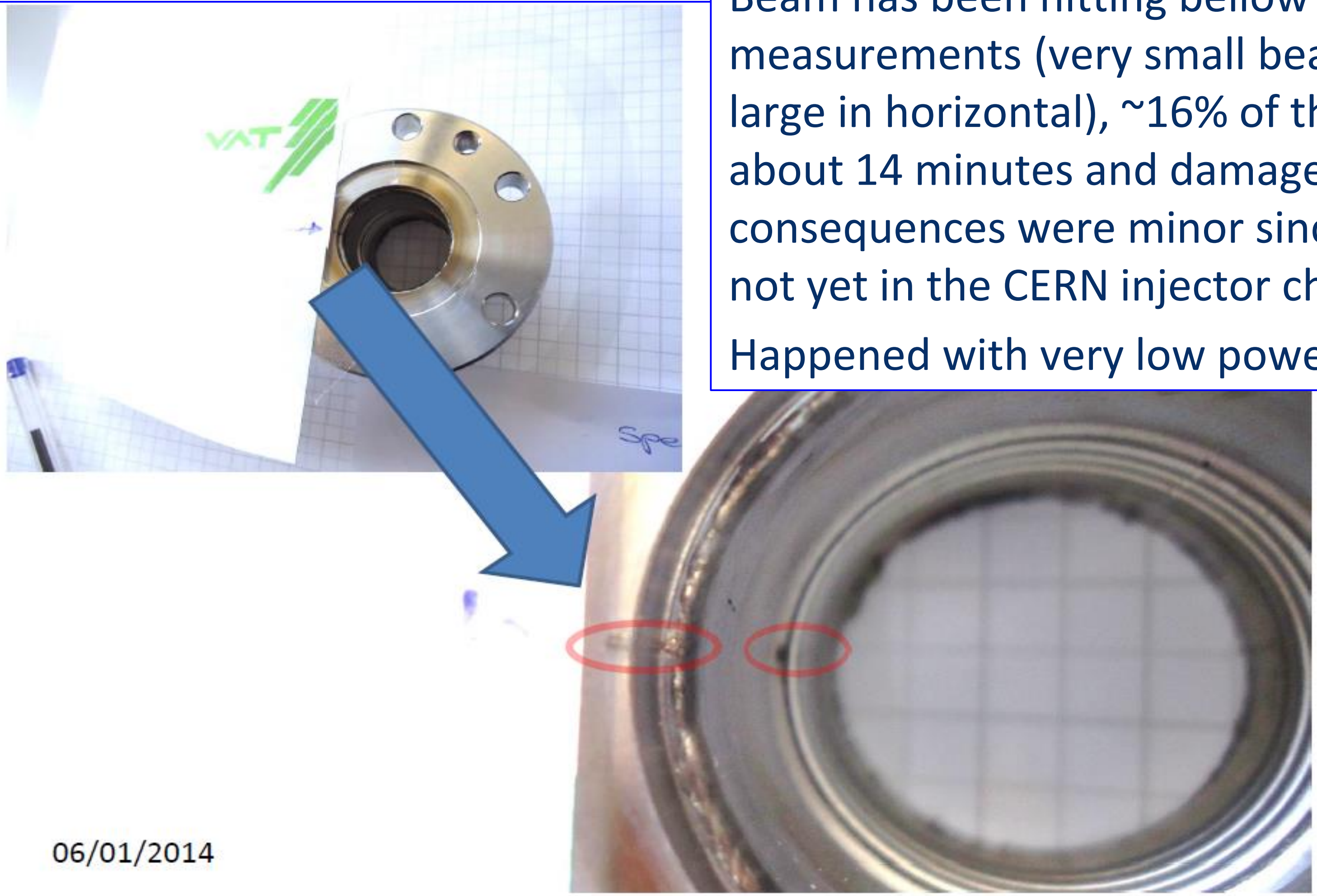
https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/talks/bjh_6_06_talk.pdf

CERN-LINAC 4 during commissioning at 3 MeV

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

Beam has been hitting bellow during special measurements (very small beams in vertical, large in horizontal), ~16% of the beam lost for about 14 minutes and damaged the bellow. The consequences were minor since LINAC4 was not yet in the CERN injector chain.

Happened with very low power beam (few W).



06/01/2014

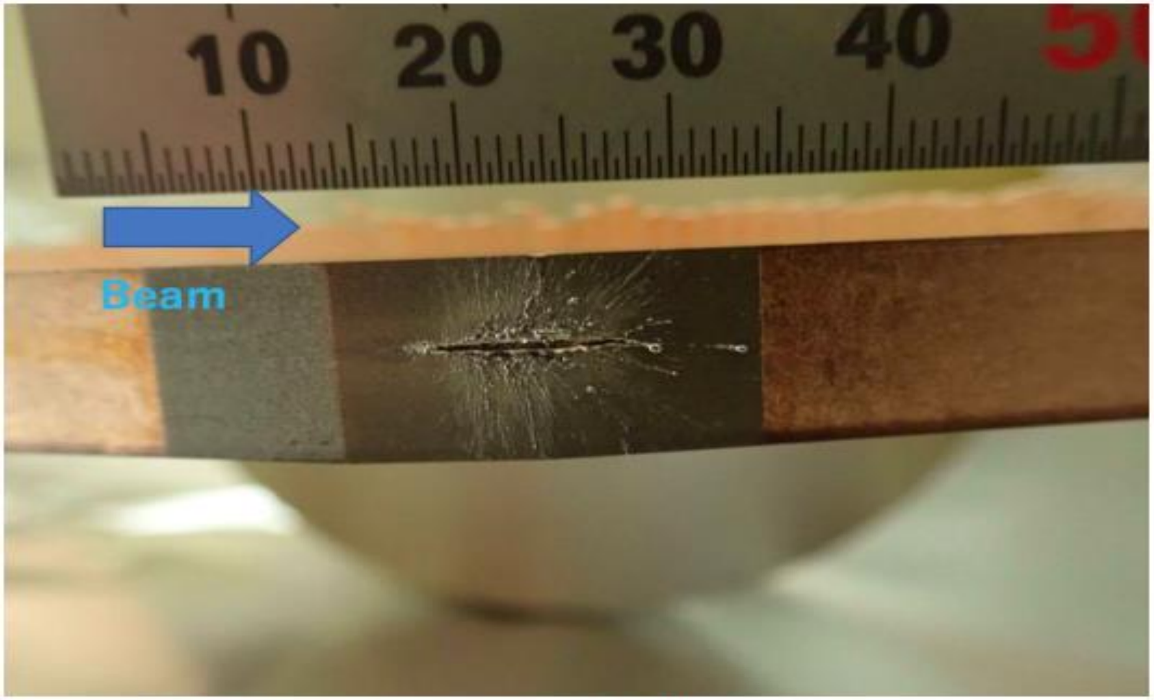
A.Lombardi

J-PARC (KEK) 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 instead of 2 s** and delivered to the gold target.
- **The 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.

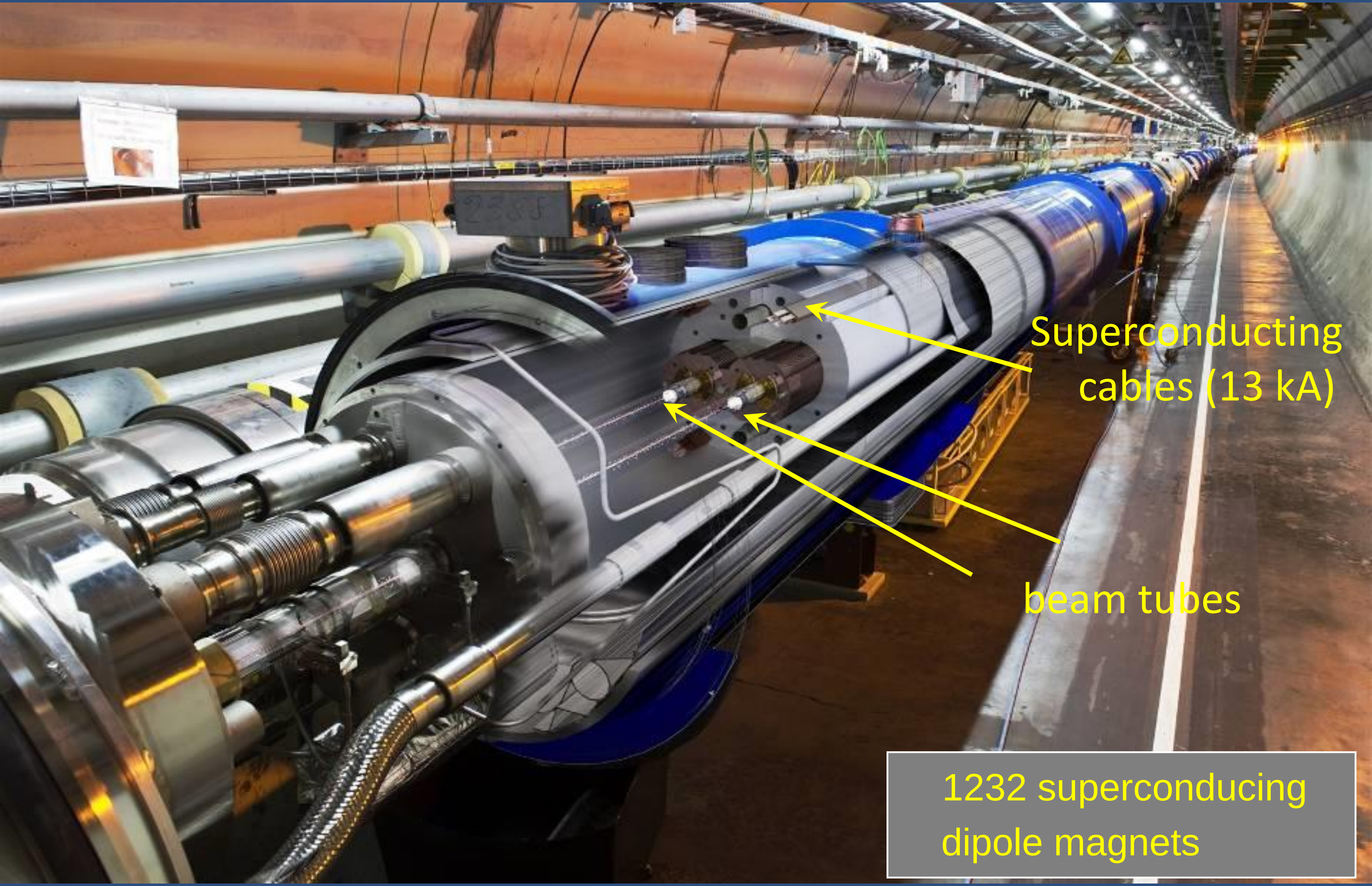
SuperKEKb: be prepared for the unknown !

- 2500 colliding electron and positron bunches in two rings, 4 GeV and 7 GeV
- Machine performance is limited by beam losses and damage to equipment (e.g. collimators)



D02V1 bottom side (38 μSv/h)

LHC tunnel with dipole magnets

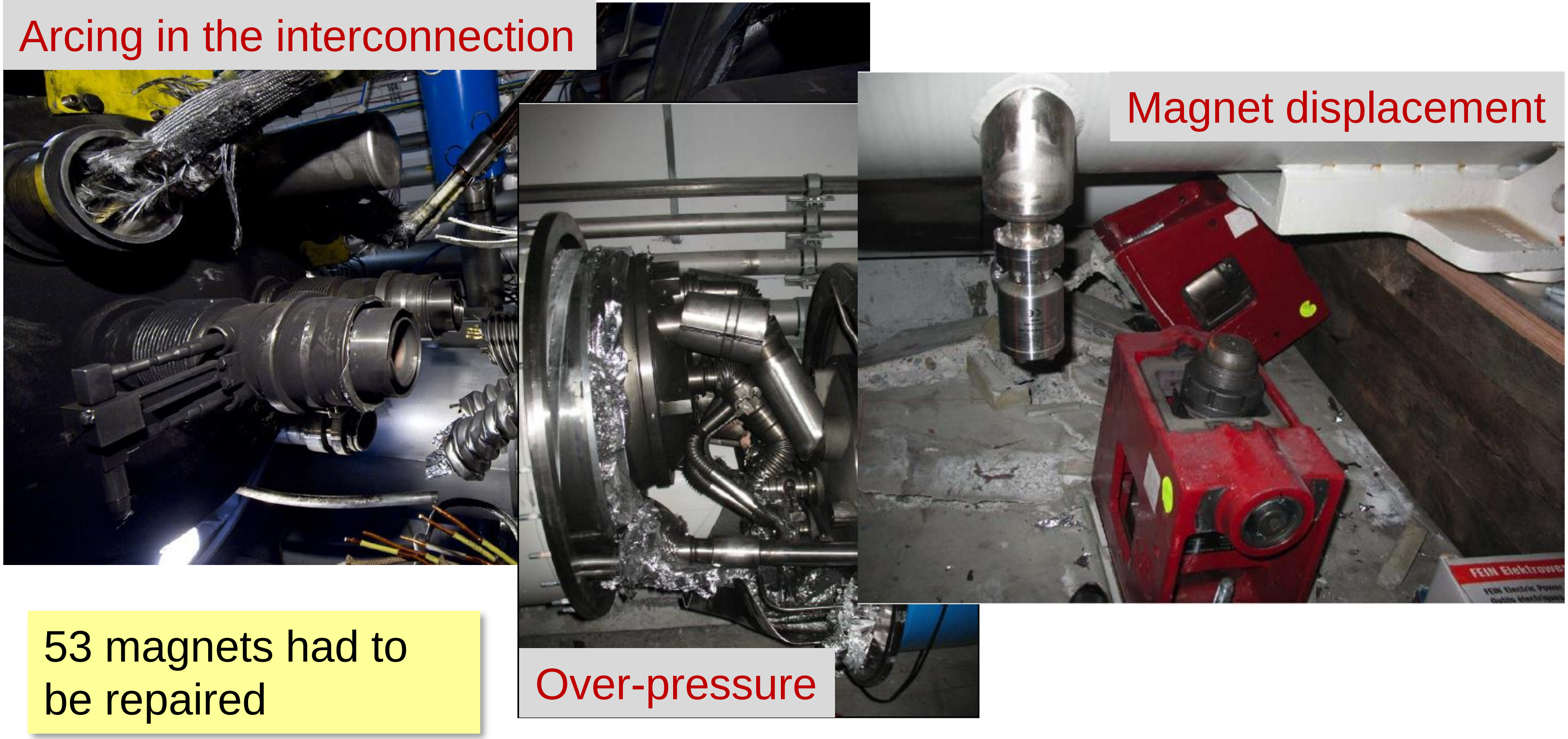


1232 superconducing dipole magnets

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 the release of an energy of several 100 MJ. A He pressure wave damaged ~600 m of LHC, polluting the beam vacuum over more than 2 km.



Arcing in the interconnection

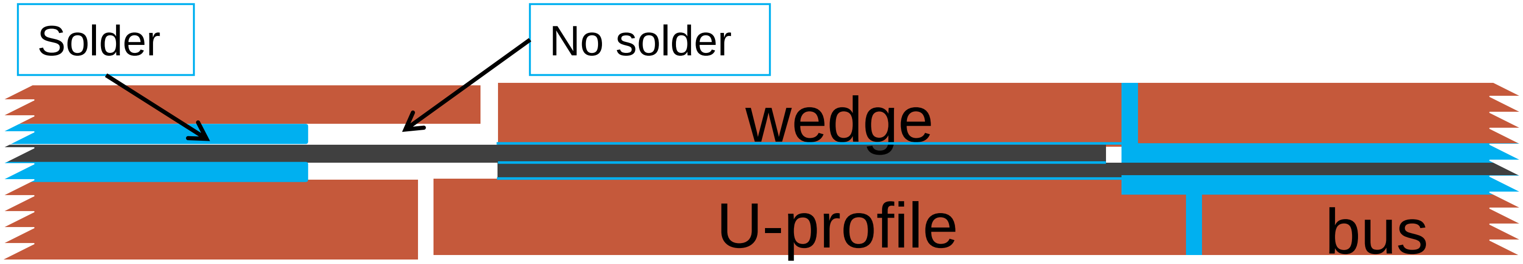
Magnet displacement

Over-pressure

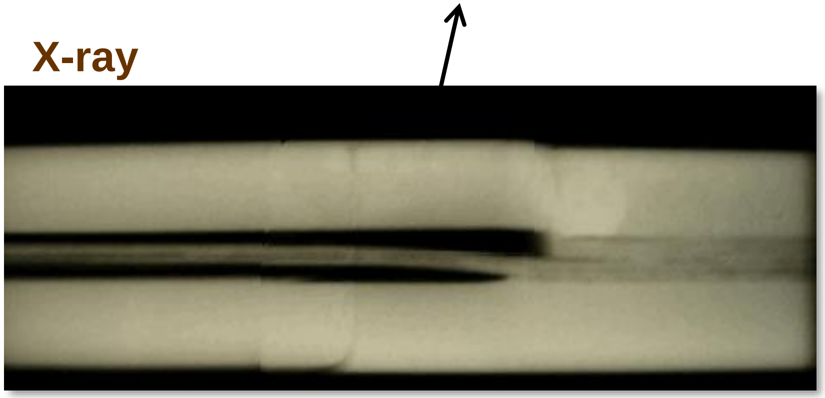
53 magnets had to be repaired

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



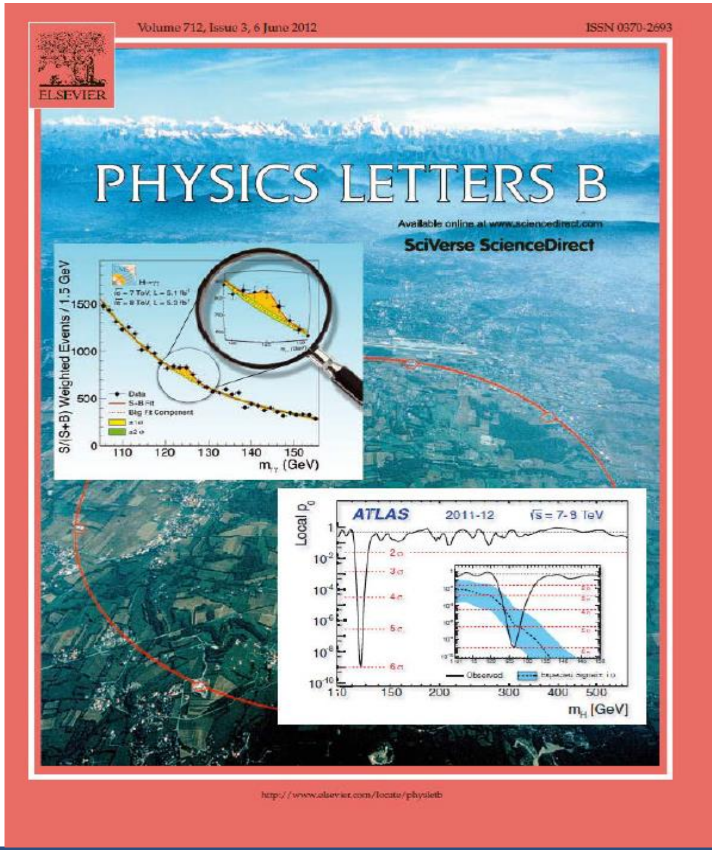
During repair work, inspection of the joints revealed systematic voids caused by the welding procedure.

→ 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 about one year to repair the magnets

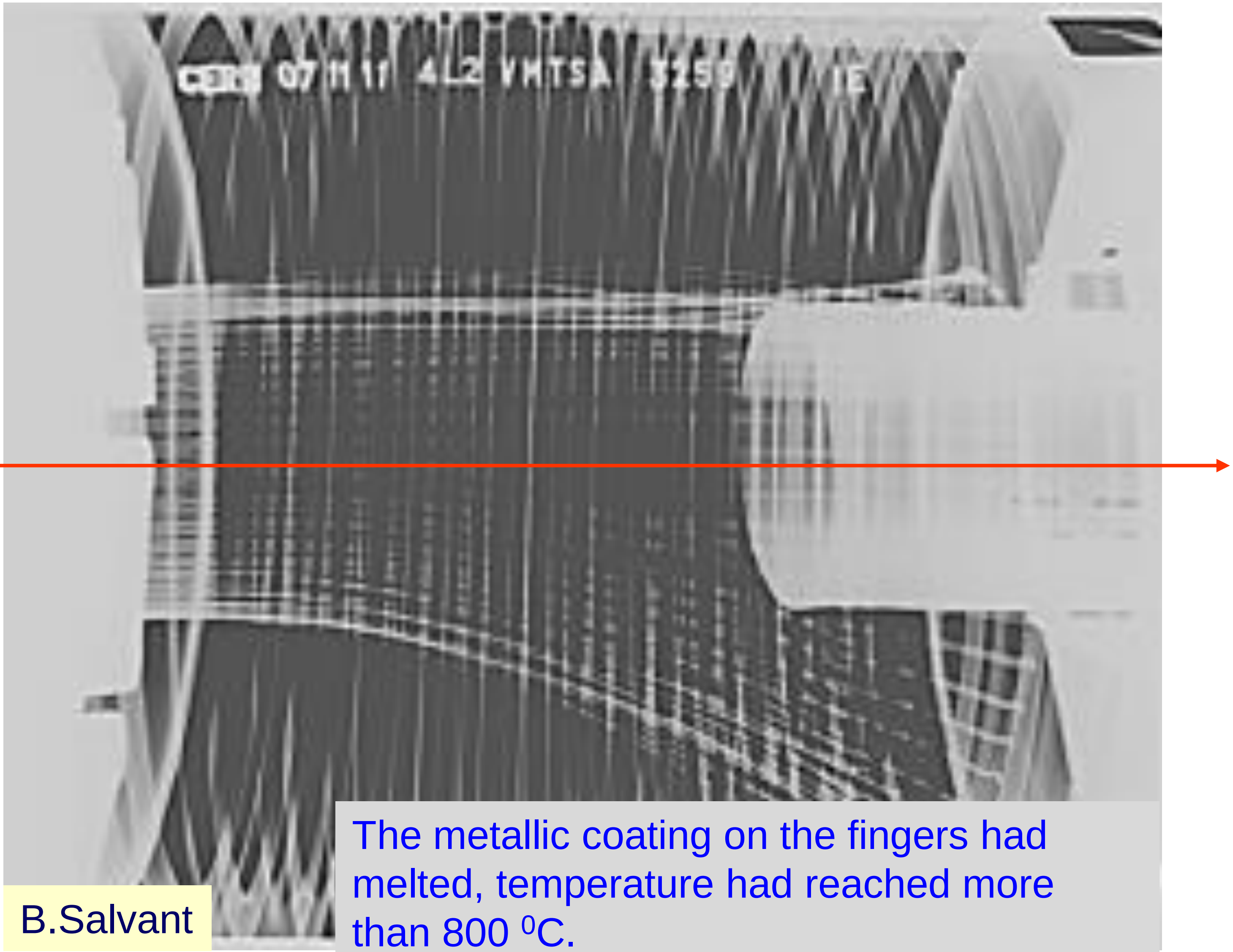
- A new layer of protection system for the superconducting magnets and bus-bars was installed
- Energy was limited to 3.5 TeV, later to 4 TeV
- Re-start up about one year later
- **Performance was excellent**
- During a two years shut-down from 2013-2014 the interconnects were finally repaired, then operation at 6.5 TeV and today at 6.8 TeV



Indirect energy transfer from beam to equipment

- Power deposited by electromagnetic interaction between beam and environment (RF, beam instrumentation, vacuum chamber, kicker magnets, …)
  - Depends on the beam intensity and bunch structure
  - Depends on the impedance (geometry, resistance) of the beam tube
- Power of synchrotron radiation emitted by the beam, to be considered for electron / positron accelerators
  - The power increases with the particle energy: $P = const \times E^4$
  - The power of synchrotron radiation can be very high (10s of MW)
  - The radiation can be very focused
  - Wiggler and undulator magnets can increase the power by orders of magnitude (e.g. for FELs)
  - This is considered in the design of the accelerator and experiments – however, there are a number of failure scenario that can lead to accidents

LHC interconnects



Beam

B.Salvant

The metallic coating on the fingers had melted, temperature had reached more than 800 ^{0}C.

Machine Protection

Understanding the damage level

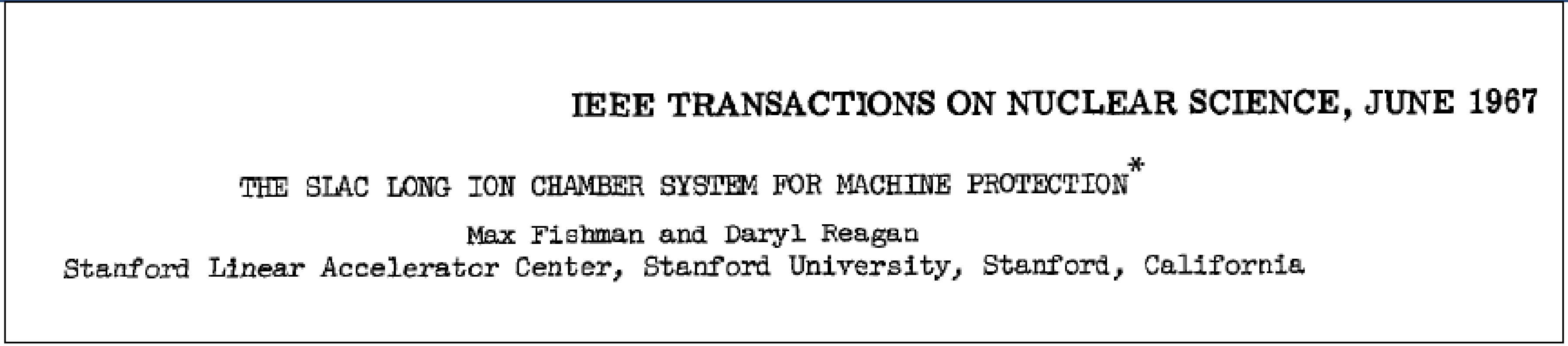
Beam losses time scale

Active protection

Passive protection

Understanding damage limits

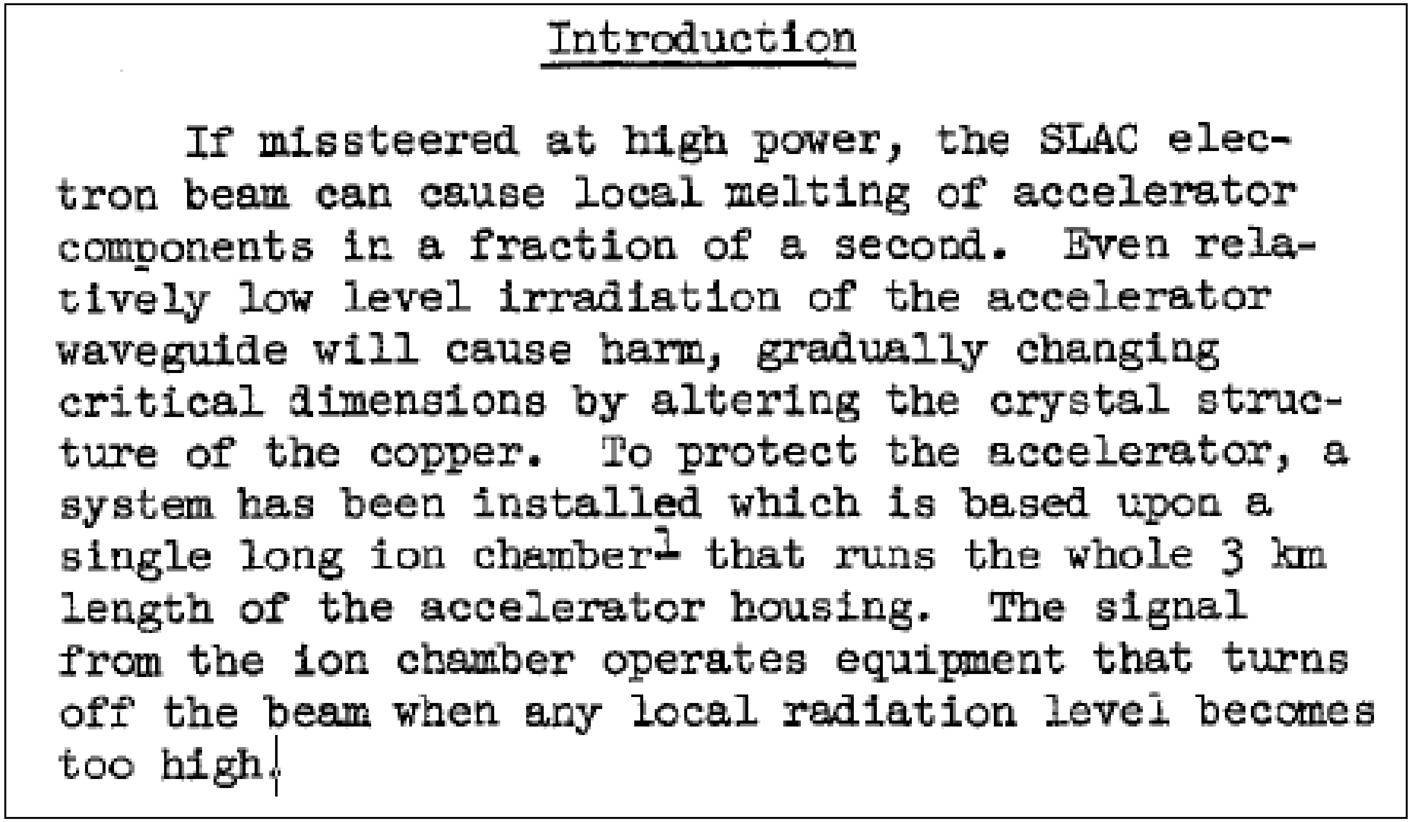
More than 50 years ago



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

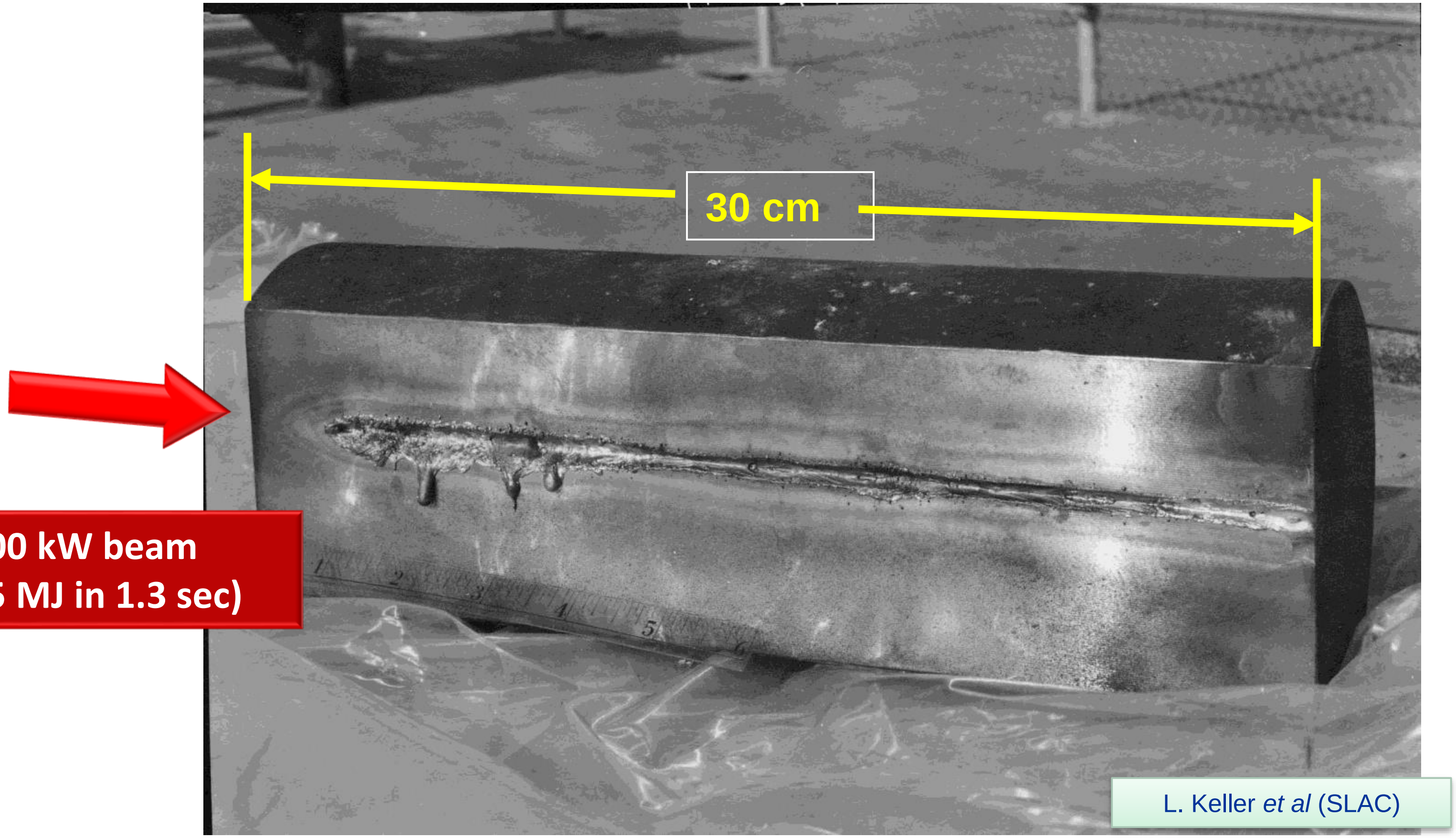


Introduction

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.

Damage test at SLAC – 1971

- Damage test of a 30 cm long **Copper** Block
- A ~2-mm 500 kW electron beam enters a few mm from the edge.
- It took about 1.3 sec to melt through the block (slow accident).



500 kW beam
(0.65 MJ in 1.3 sec)

L. Keller *et al* (SLAC)

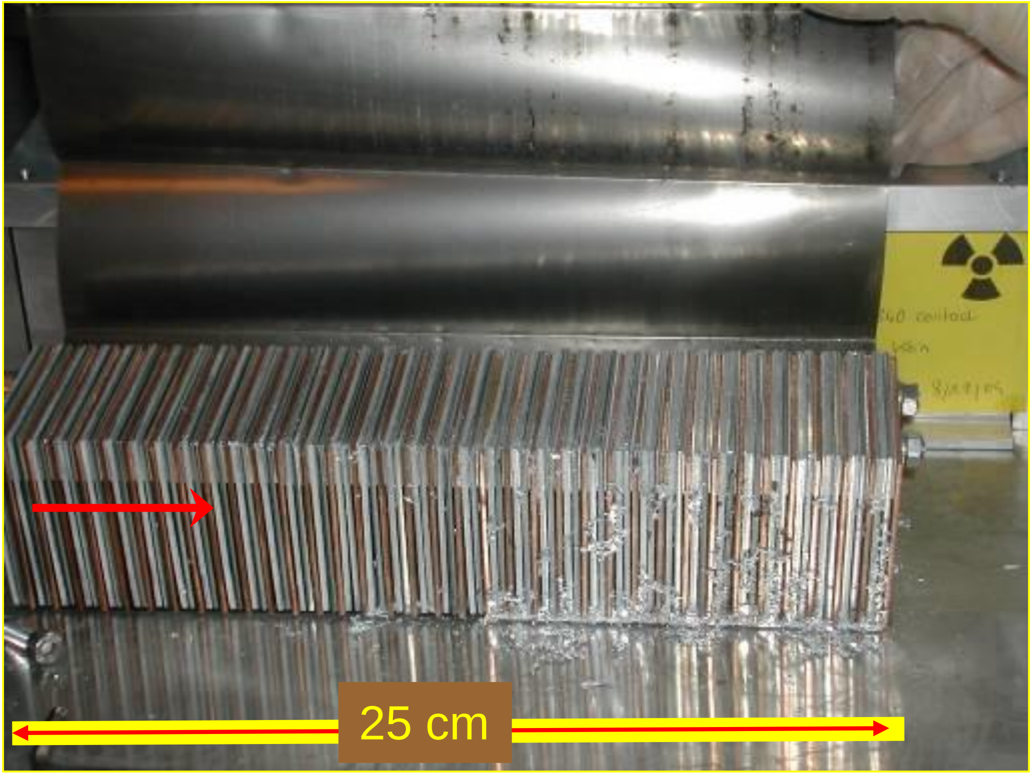
SPS experiment: Beam damage with 450 GeV protons

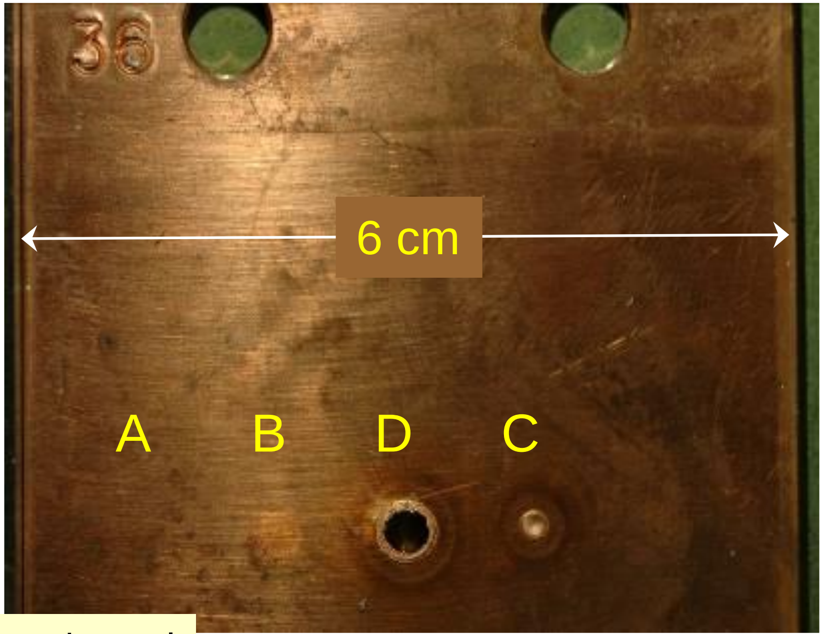
Controlled SPS experiment

- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

stainless steel no damage

- $2 \cdot 10^{12}$ protons



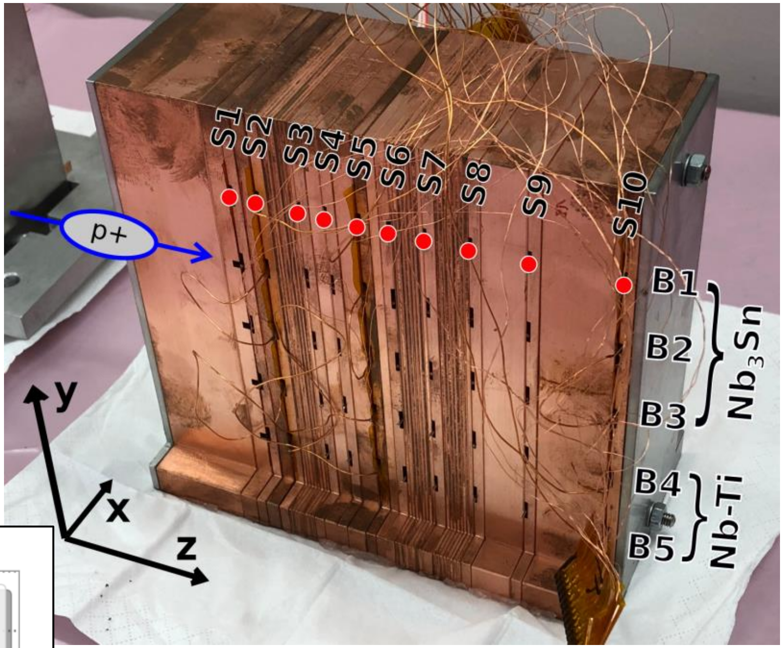


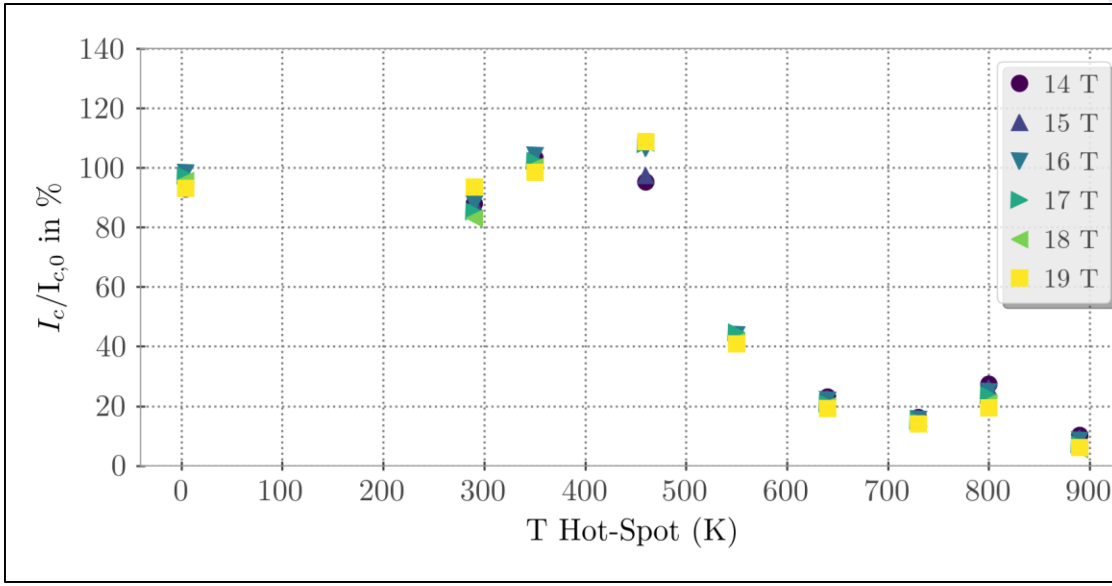
- 0.1 % of the full LHC 7 TeV beams
- factor of three below the energy in a bunch train injected into LHC
- damage limit ~200 kJoule

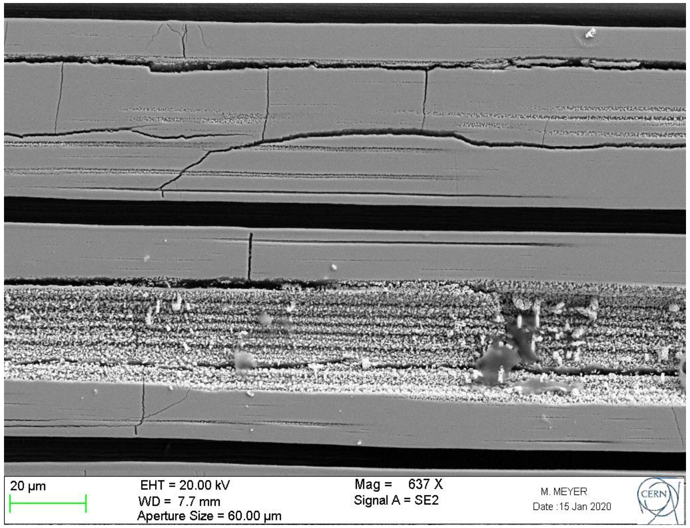
V.Kain et al

Impact of 440 GeV SPS proton beam on sc wires

- Nb-Ti strand (LHC)
- Nb3Sn strand (HL-LHC)
- Short beam impact at cold, heating the strands up to 1200 K
- Very little degradation of NbTi strands
- Strong degradation of Nb3Sn strand for temperatures exceeding 500 K

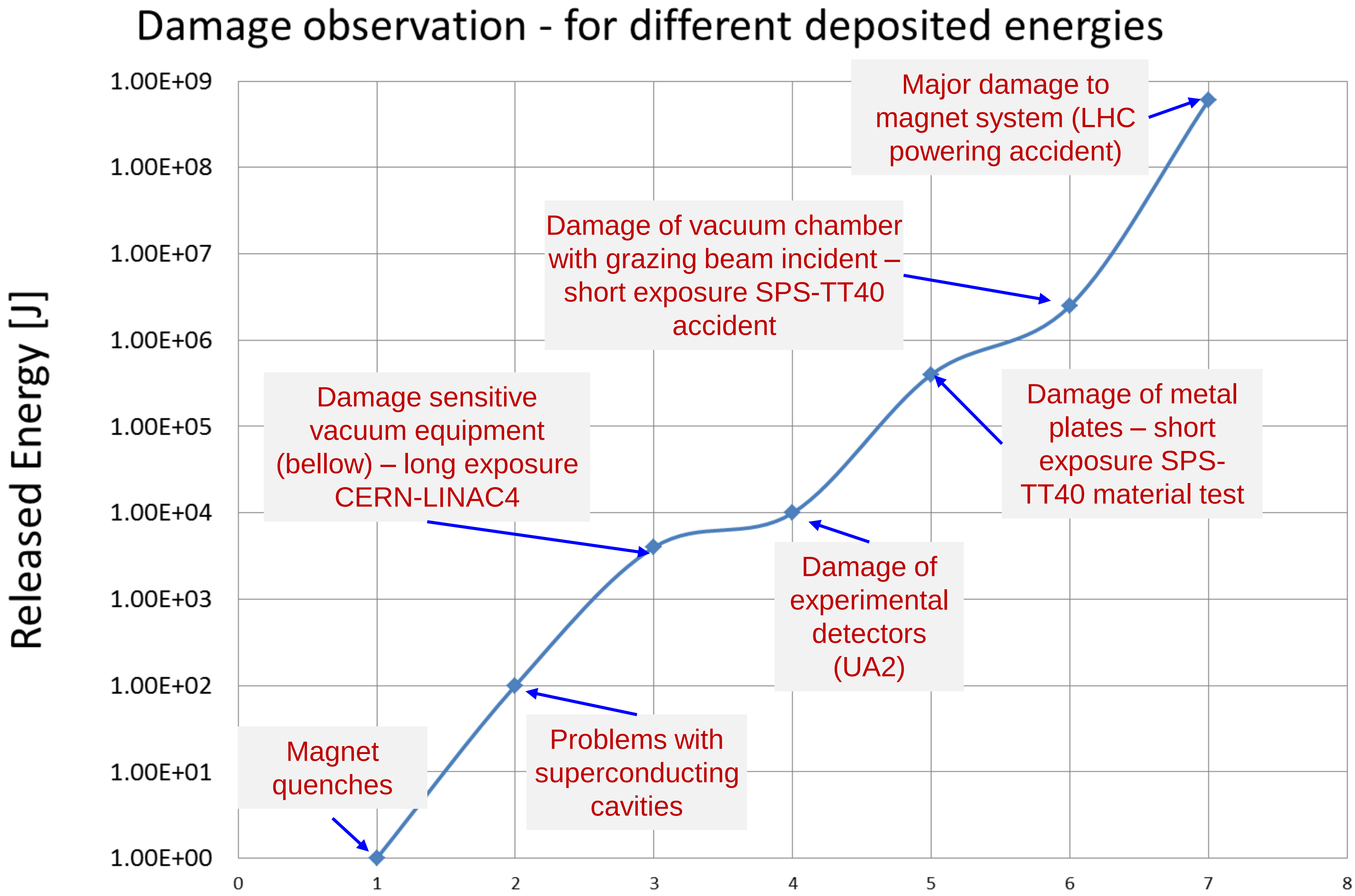






A. Will et al., 2018

Observed damage for deposited energy



Damage observation - for different deposited energies

Magnet quenches

Problems with superconducting cavities

Damage sensitive vacuum equipment (bellow) – long exposure CERN-LINAC4

Damage of experimental detectors (UA2)

Damage of metal plates – short exposure SPS-TT40 material test

Damage of vacuum chamber with grazing beam incident – short exposure SPS-TT40 accident

Major damage to magnet system (LHC powering accident)

Beam losses time scale

No-regular (accidental) beam losses

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, RF systems, magnets, ...
- 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

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 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 circulating beam, stop injection, ….)
- The information has to travel from the monitor to the activator (extraction system, injection system, source, …) => interlock system
- There is some **reaction time required for the response** (depending on the system this can range between ns and seconds)

Example for Passive Protection - Traffic

- 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)
- One example is the **fast extraction of a high intensity beam** from an synchrotron
  - The extraction is performed with a fast kicker magnet
  - A kicker failure leading to a wrong deflection angle needs to be addressed (wrong field, wrong timing, ...)
  - The range of plausible failures (=deflection angles) needs to be defined
  - If the beam can damage hardware, protection absorbers are required
  - For absorbers that can move to the beam: need to be made sure that they are at the correct position

- Might simplify the protection system

Coming to an end

A few guidelines for machine protection

For circulating beams in a synchrotron

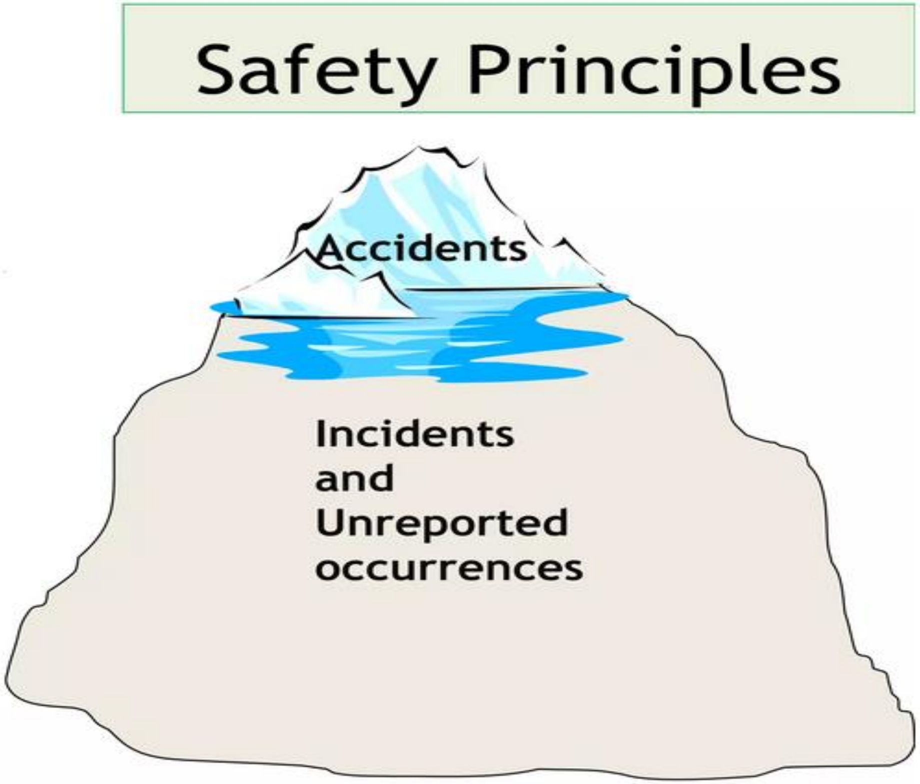
- In case a failure is detected, dump the beam and inhibit injection
- In general, beam loss monitors and beam current monitors are most efficient for detection of a failure
- Other monitors of hardware systems are equally important and can detect failures that would lead to beam losses, before the beam is affected
- For fast extraction into a transfer line, a downstream accelerator or a target station: only extract the beam if all equipment downstream of the fast kicker confirms that it is in the correct state

For single path accelerators (linear accelerators, transfer lines, ...)

- Only start a beam pulse if all equipment in the beamline confirms that it is in the correct state
- In case a failure is detected: Stop the beam pulse as fast as possible and inhibit the next pulse

P^3 for Machine Protection

You only see the tip of the pyramid.



- Protect the machine
  - Beam dumping system
  - System to stop the particle source
  - Beam and equipment monitoring systems
  - Interlock system
  - Passive absorbers / collimators
- Protect the beam
  - Only stop operation when there is a real risk (not trivial with many 10000 interlock channels)
- Provide the evidence
  - All monitors that can stop operation should have a "Post-Mortem" transient recorder
  - Recording data from all systems that can have an impact on the beam
  - All beam stops by the protection system should be analysed to understand if the Machine Protection Systems worked as expected

Thanks and have fun !

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