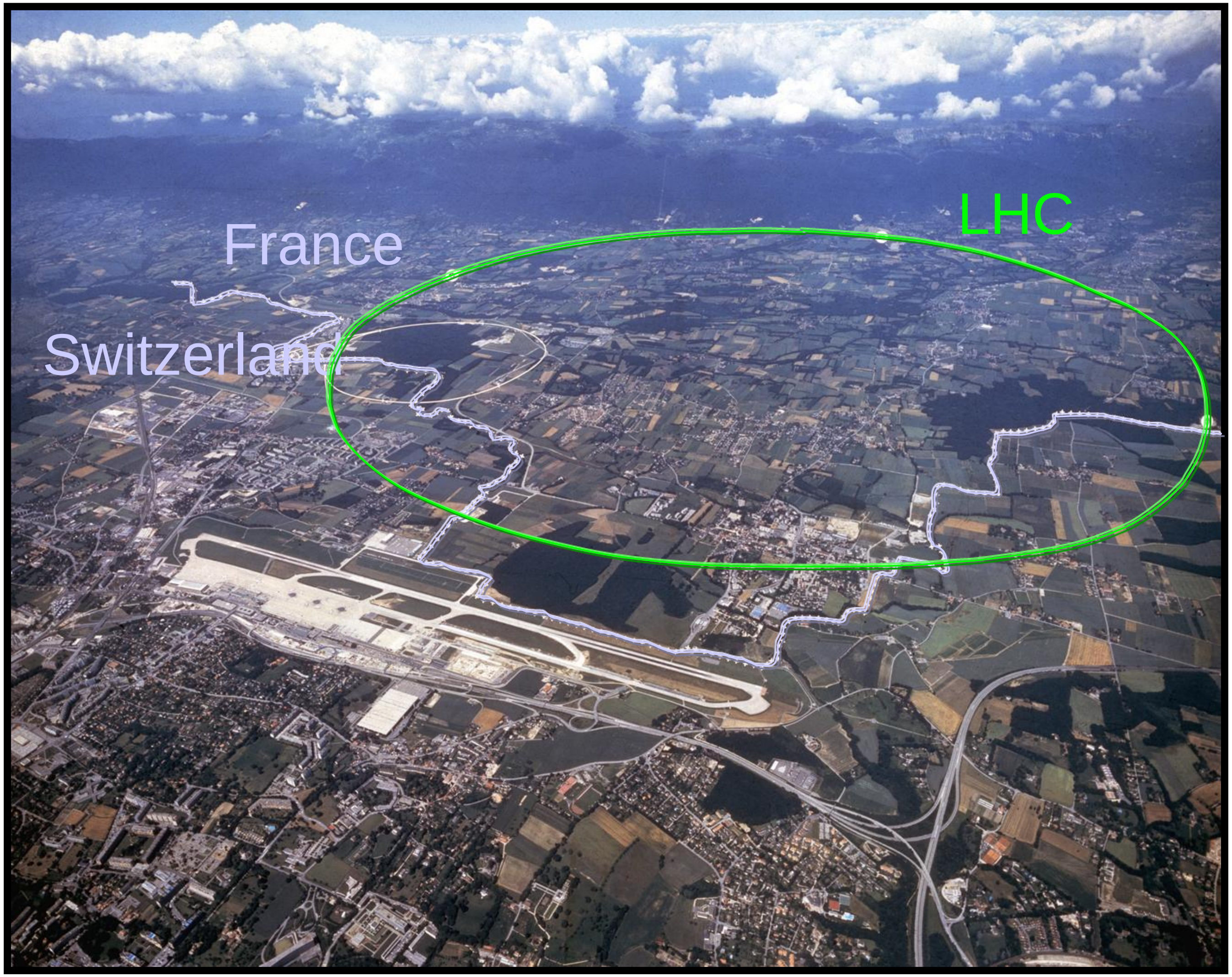
LHC collimation

R. Bruce

on behalf of the CERN LHC collimation team

CERN

- CERN is the world's largest particle physics centre, founded in 1954
- Located on the border between France and Switzerland
- 2600 employees, 7900 visiting scientists, 500 universities, 80 countries

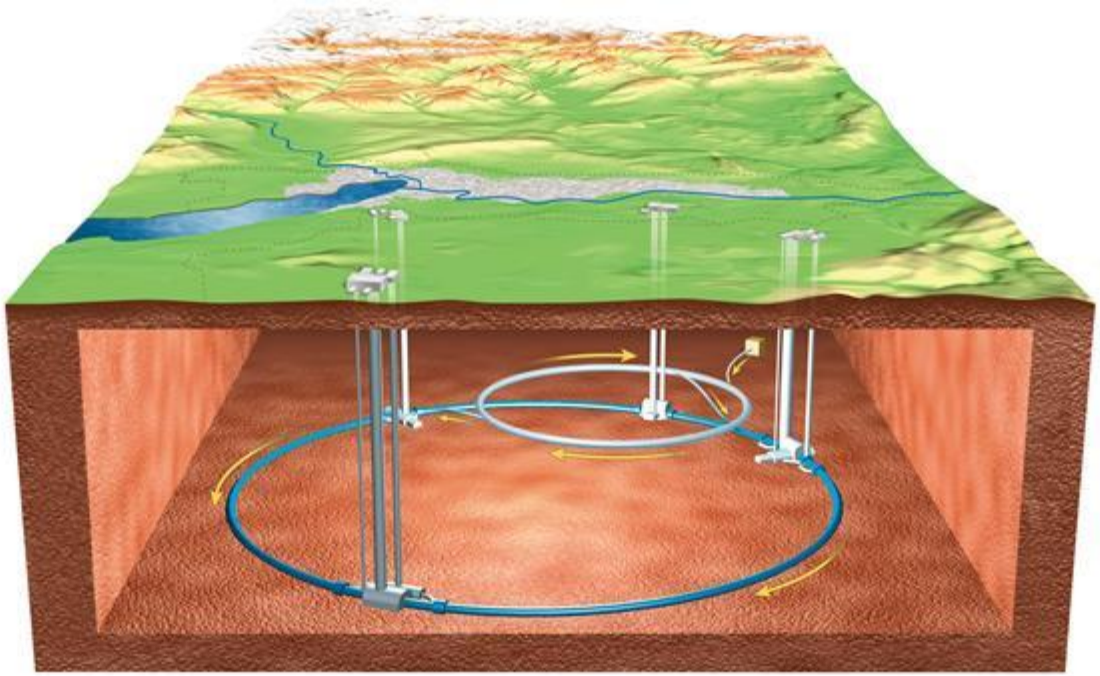


LHC (Large Hadron Collider)

Largest accelerator/collider (together with LEP) and highest energy ever

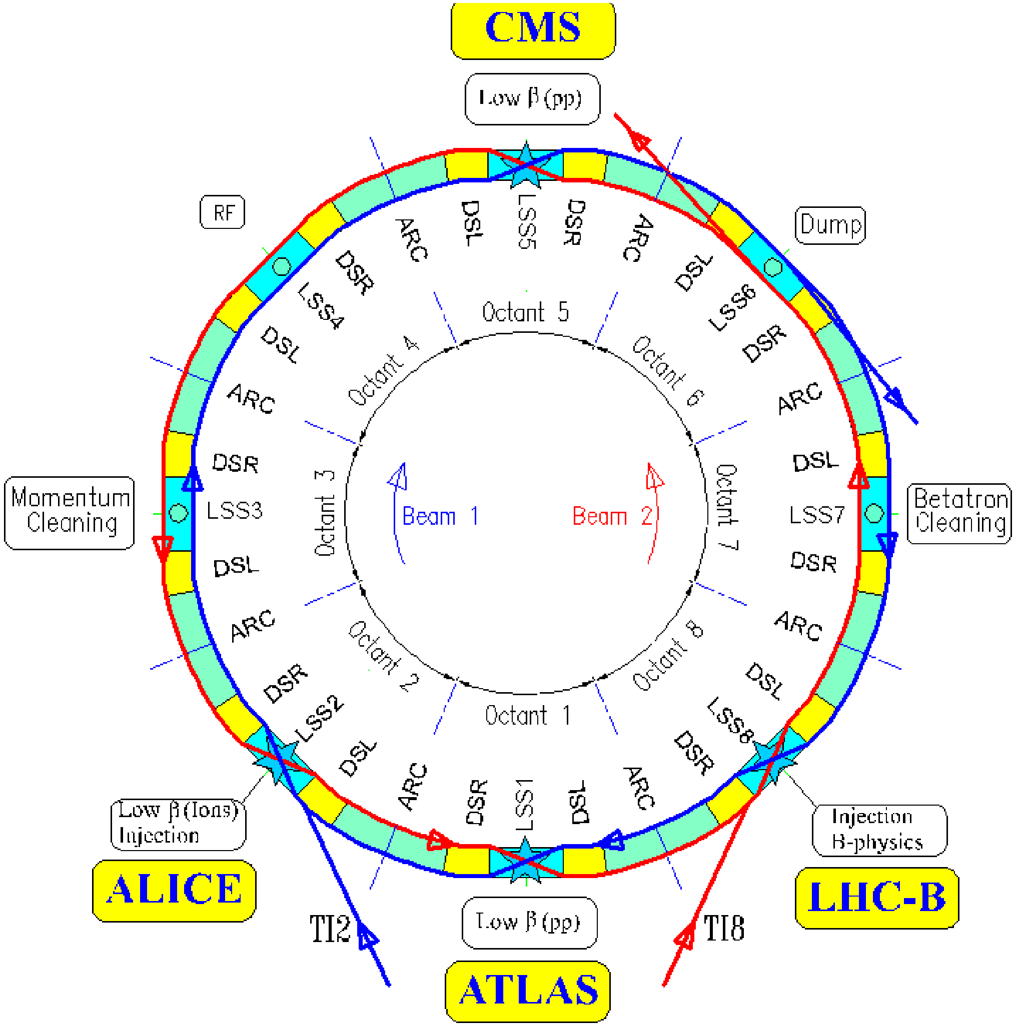
Design started in the early 1980's, approved in 1995

- Built in old LEP tunnel to collide
  - 7 TeV protons
  - 0.57 PeV Pb^{82+} nuclei (fully stripped ions)
- 4 interaction points (IPs) with experiments ATLAS, CMS, LHCb, ALICE
- 8 straight sect., 8 arcs



www.cern.ch

Some LHC figures



- 27 km circumference
- 100 m underground
- Almost 10 000 magnets, many superconducting
- 1.9 K working temperature of superconductors
- 10^{-13} atm vacuum pressure
- Nominal LHC: 362 MJ stored beam energy

Physics motivation

PROTONS

Find Higgs particle (ATLAS, CMS)

- Explain origin of mass

Search for supersymmetric particles (ATLAS, CMS)

- Unification of forces
- Dark matter

Balance between matter and antimatter in the universe

- Symmetry breaking in b-meson decay (LHCb)

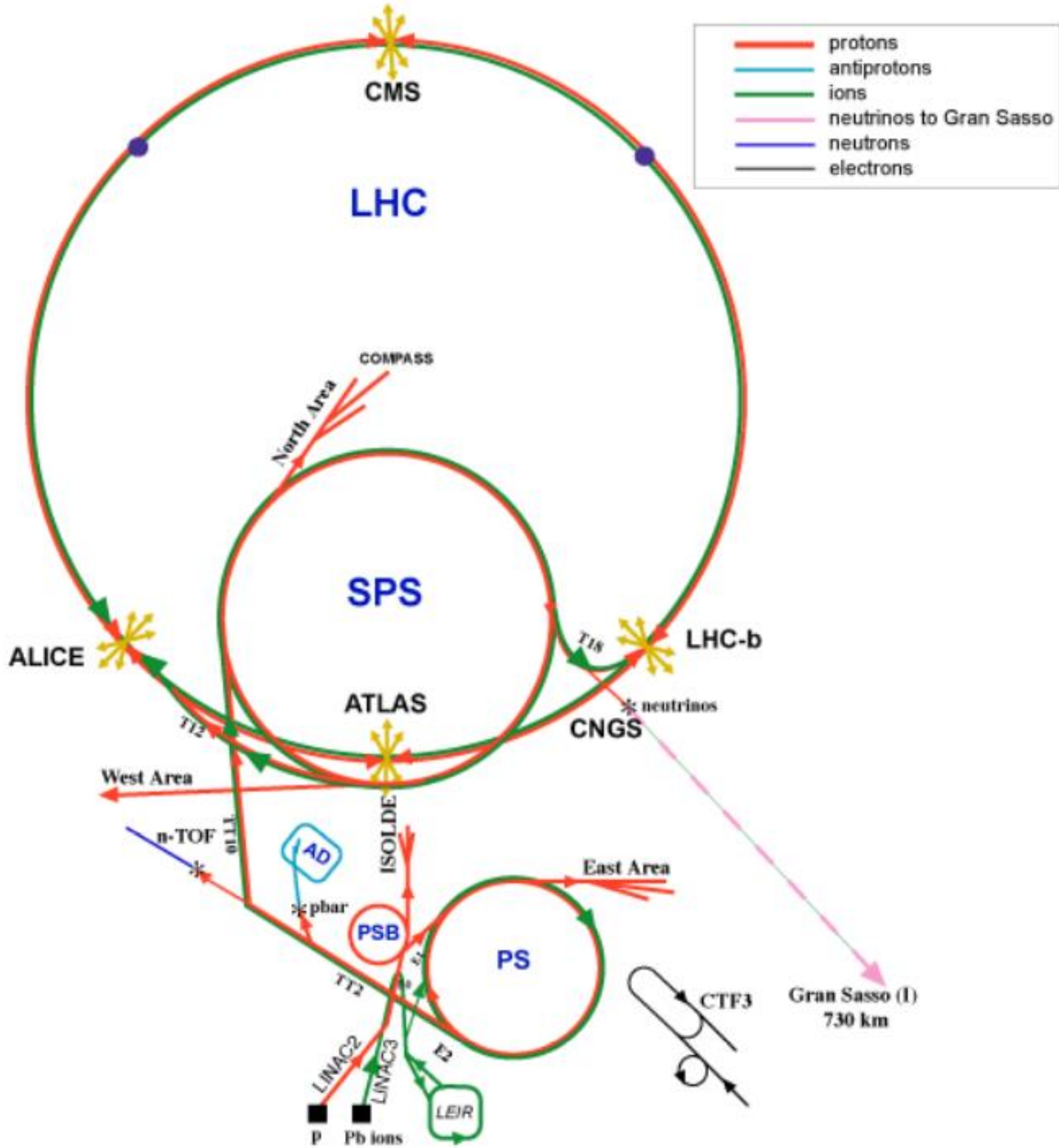
HEAVY IONS

Find and study quark-gluon plasma (ALICE)

- State of matter believed to have existed in the early universe. No colour confinement

CERN complex

- LHC last in chain of accelerators



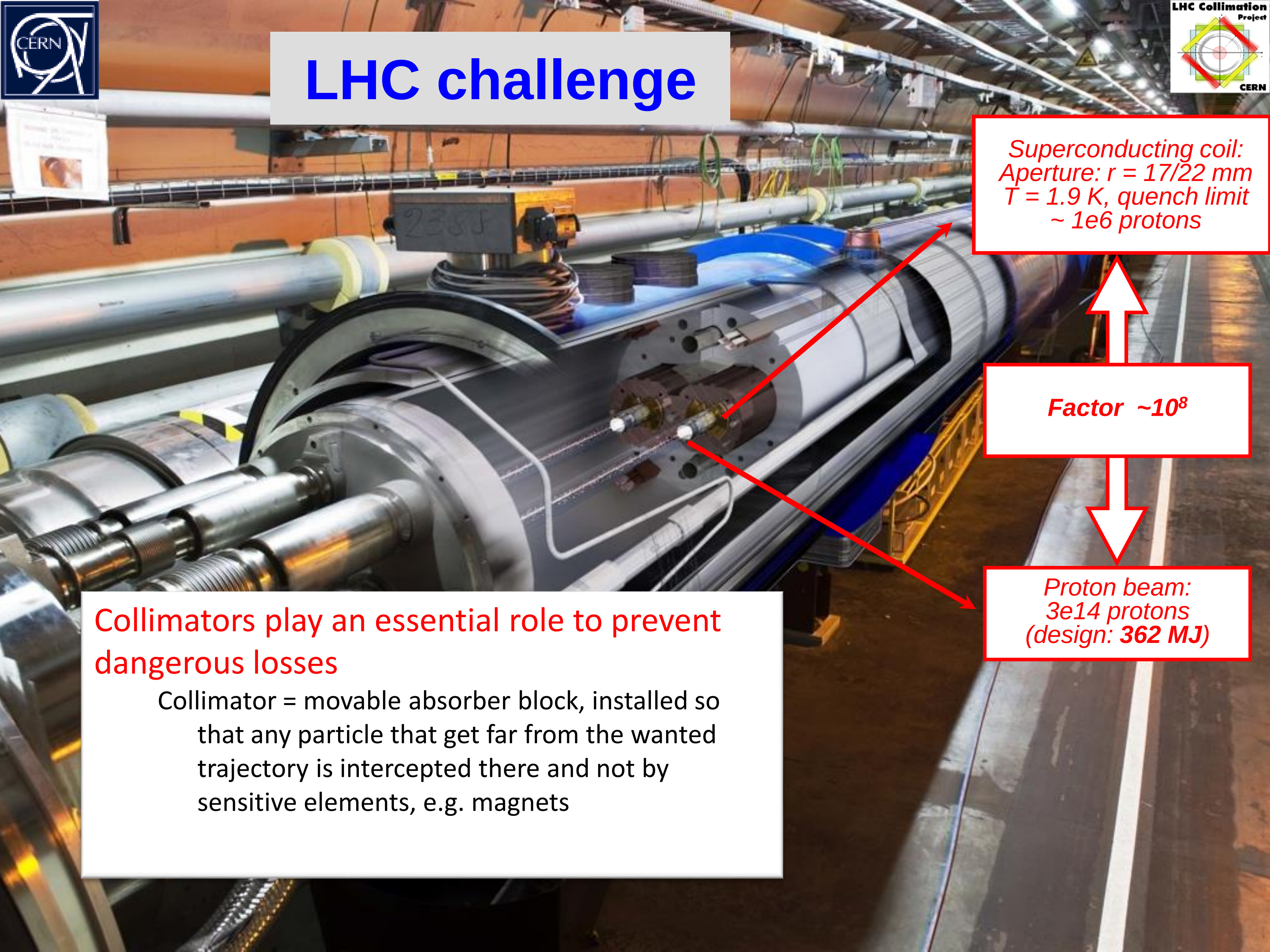
LHC stored energy

- Huge stored energy per beam : 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC

675 MJ = kinetic energy of USS Harry S. Truman cruising at 7 knots

- Beams could be highly destructive if not controlled well

LHC challenge

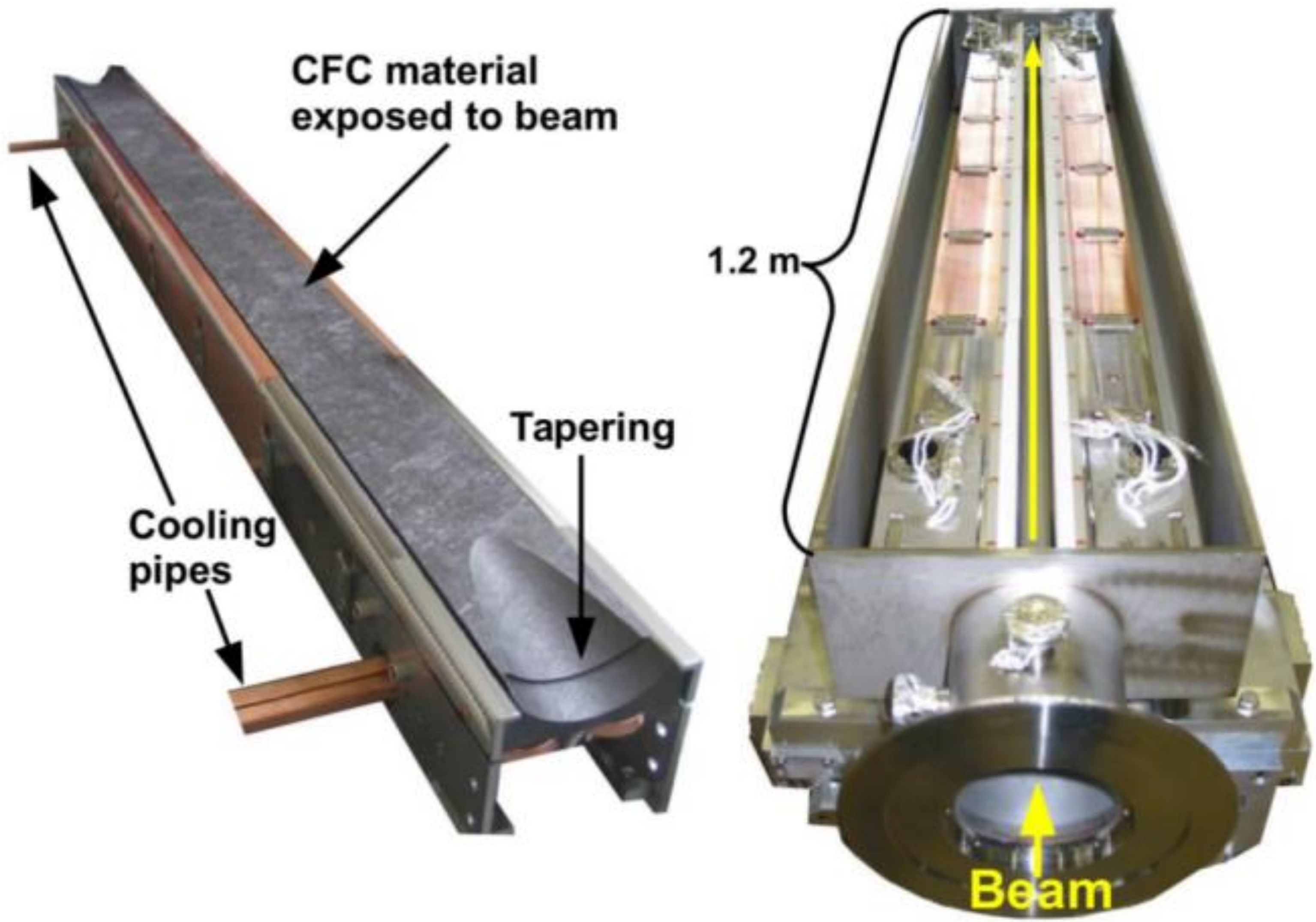


Collimators play an essential role to prevent dangerous losses

Collimator = movable absorber block, installed so that any particle that get far from the wanted trajectory is intercepted there and not by sensitive elements, e.g. magnets

LHC collimators

- Two jaws, beam passing in between, most are 1 m long



Roles of LHC collimation

- Beam halo cleaning: Safely dispose of unavoidable beam losses
  - allow high-intensity operation below quench limit of superconducting magnets
  - Confine losses in dedicated regions to minimize radiation doses to sensitive equipment or personnel.
- Passive machine protection: Absorb beam losses in case of beam failures
  - protect sensitive equipment from damage and/or quenches
- Physics debris cleaning: Catch losses from collision process in experiments.
  - As for halo cleaning: stay clear of quenches and confine losses
- Reduce background in experiments
  - Catch incoming losses upstream of the detectors.

Beam loss mechanisms

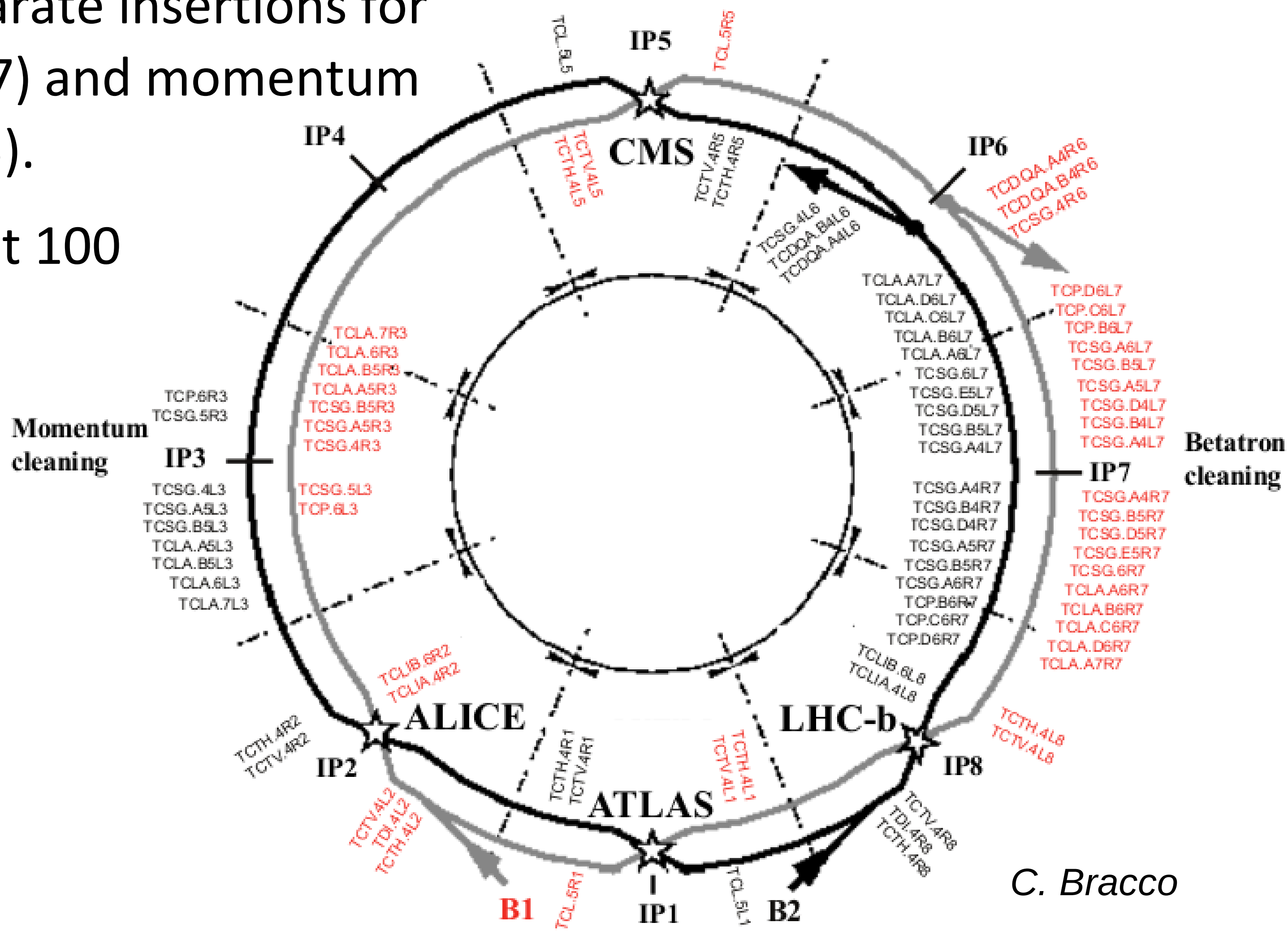
- Halo population and emittance growth from several sources:
  - Collisions in experiments, long-range beam-beam effect
  - Intra-beam scattering, Touschek effect, space charge
  - Scattering on rest gas
  - Beam acceleration, RF gymnastics
  - Imperfections on RF, magnets, feedback
  - Non-linearities, dynamic aperture
- Fast beam failures
  - Failure of magnets, RF cavities. Especially dangerous: bending dipoles and kickers

Where to add collimators

- Global protection of whole ring or transfer line from beam-halo
  - Possibly more cost-efficient than adding local protection to many elements
  - Collimators should be the smallest normalized aperture limitation
  - Which particles do we want to intercept – large betatron amplitudes or energy errors? *Betatron vs momentum collimation*
- Local protection in front of sensitive equipment or just downstream loss source, such as collider experiment or dump kicker
  - Simplest approach but often enough!
  - Collimator should have smaller physical aperture than the element. Often fixed mask

Global protection: LHC collimation layout

- LHC has separate insertions for betatron (IR7) and momentum cleaning (IR3).
- In total about 100 collimators!



C. Bracco

Betatron and momentum Collimation

- Transverse coordinates given by superposition of betatron oscillation and off-energy trajectory

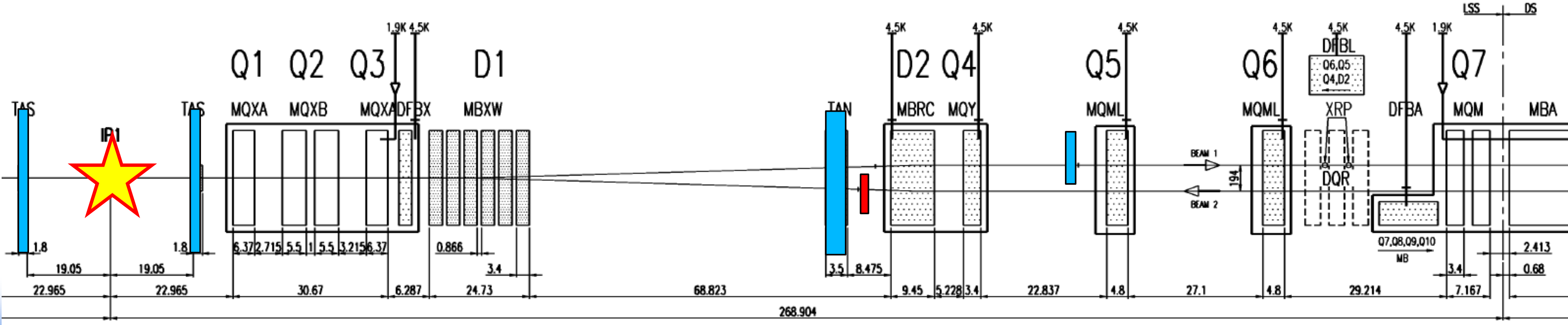
$$x = \sqrt{2\,J\,\beta}\cos(\mu - \mu_0) + D\,\delta$$

- Particles with high betatron amplitude caught by IR7 collimators
- Momentum collimation (installed in high-dispersion region) installed to clean particles with high energy offsets

Example of local protection

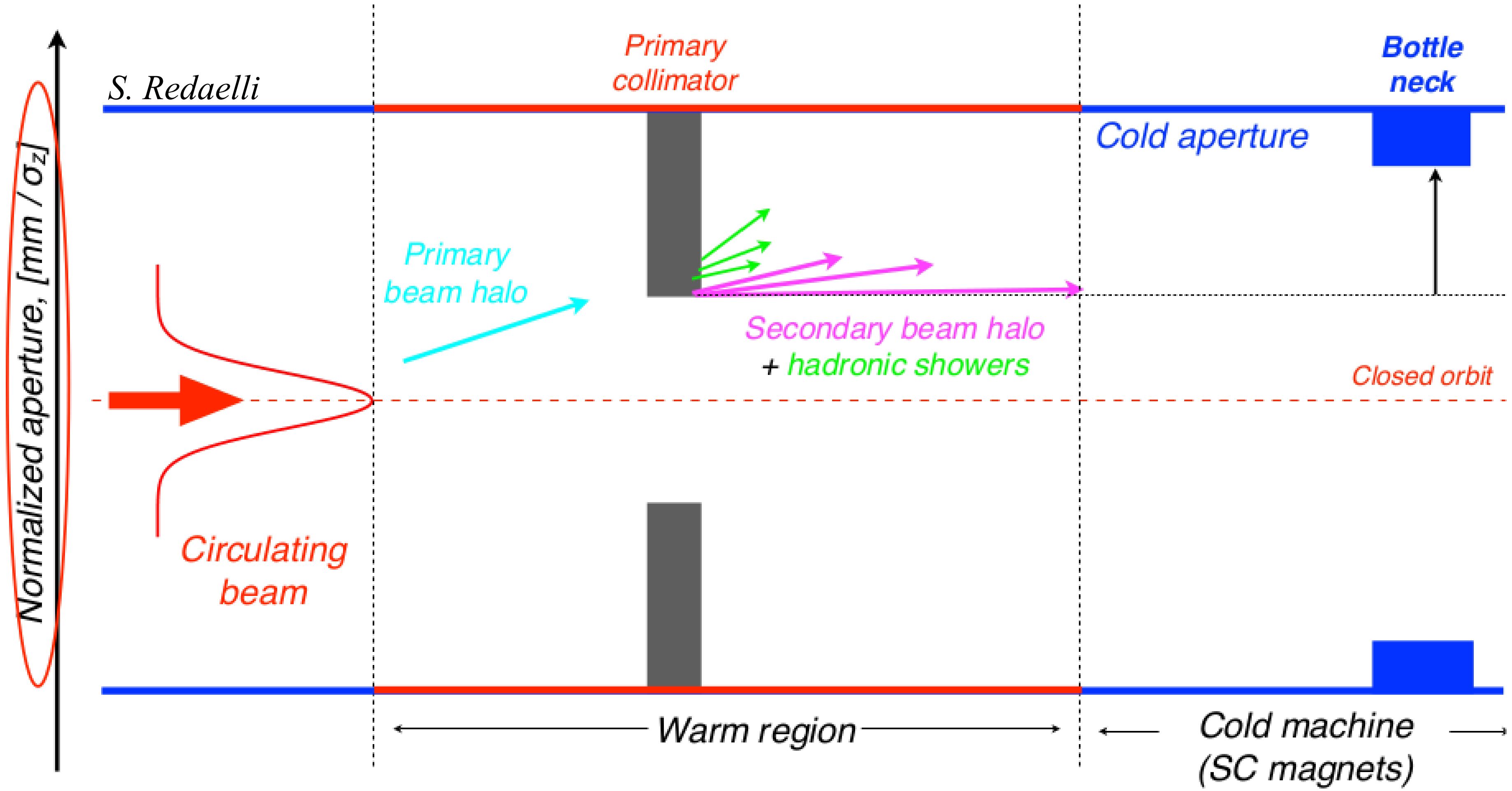
- LHC interaction point:
  - Local protection on outgoing beam to catch collision debris
  - Local protection on incoming beam to reduce background and shield aperture bottleneck

ATLAS



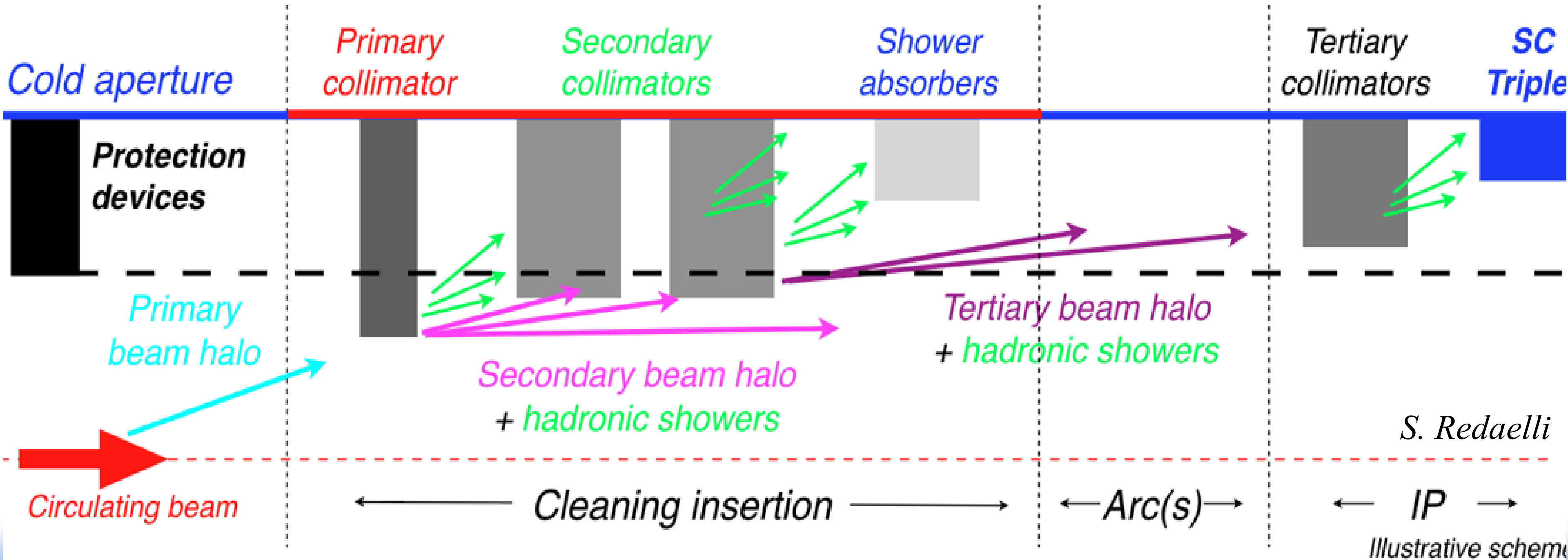
How many collimators?

- Simplest approach: single-stage cleaning.



Single or multi-stage

- If single stage does not provide sufficient cleaning (usually based on simulation studies): add more stages
- Two stages commonly used: scatterer intercepting primary halo, absorber catching out-scattered particles
- LHC: 5 stages including protection devices needed.



Placement of secondary collimators

- Secondary collimator must have retraction from primary collimator that is sufficient for not intercepting primary halo
  - Consider transfer line vs ring, phase advance
  - Consider imperfections, misalignments, drift of beam, β-beat
- Optimal phase advance from primary collimator
  - $\varphi_{opt} = arccos\left(\frac{n_1}{n_2}\right) \pm m\,\pi$ … with n_1 the opening of primary collimator, n_2 the opening of the secondary collimator in units of beam σ
  - Optimum in terms of covering the largest range of scattering angles

Movable vs fixed devices

- If collimator opening does not need to be changed, fixed masks could be considered
  - Fixed masks more sensitive to errors: alignment, optics, orbit. If problems, need to open machine to fix!

- LHC: very different beam sizes and normalized aperture to protect at injection energy and top energy. Movable devices necessary!
  - Movable devices allow optimization of cleaning by alignment using achieved orbit beta function. Robust vs imperfections!
  - Movable collimators significantly more challenging in terms of engineering design. Control system needed. More expensive!

Choice of material

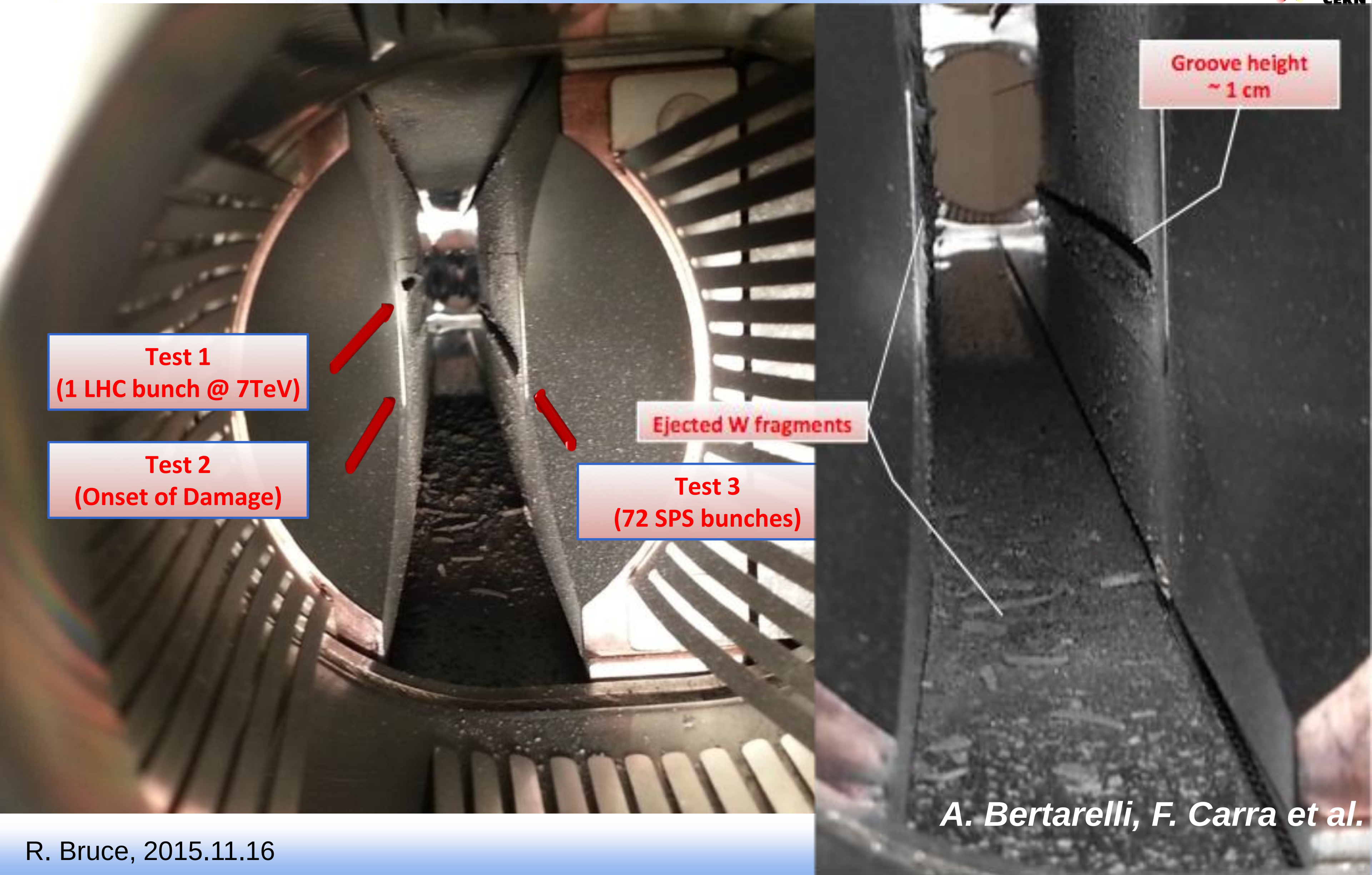
Several parameters influence choice of material

- Cleaning efficiency (absorption rate) – short interaction length better
- Robustness in case of high impacts or accidents
- Resistance to radiation damage effects, activation
- RF impedance: Maximize Electrical Conductivity
- Mechanical properties: thermal behavior, brittleness, stability, easy to machine
- Vacuum behaviour: minimize outgassing
- Availability, price

LHC collimator materials

- Tertiary collimators made of tungsten for optimal absorption. Not optimal robustness
- Advanced R&D ongoing to find materials for future collimators (A. Bertarelli et al.)
  - Molybdenum Graphite composite, possibly with molybdenum coating, seems to be most promising option at the moment
  - Experimental program on radiation resistance in collaboration with GSI, BNL, Kurchatov
  - Experimental program at CERN to verify robustness - HiRadMat

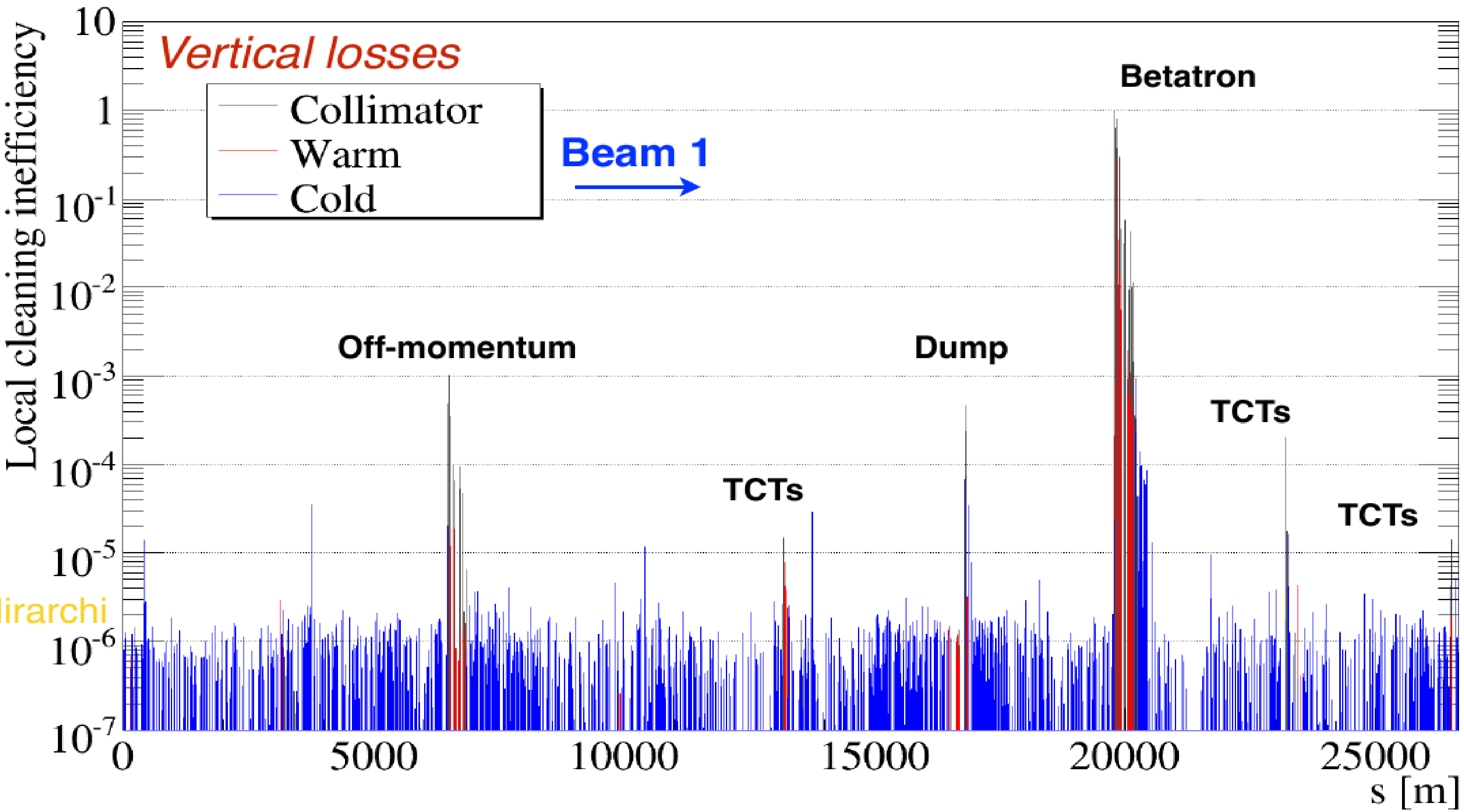
Experimental tests of beam impact



A. Bertarelli, F. Carra et al.

LHC cleaning performance

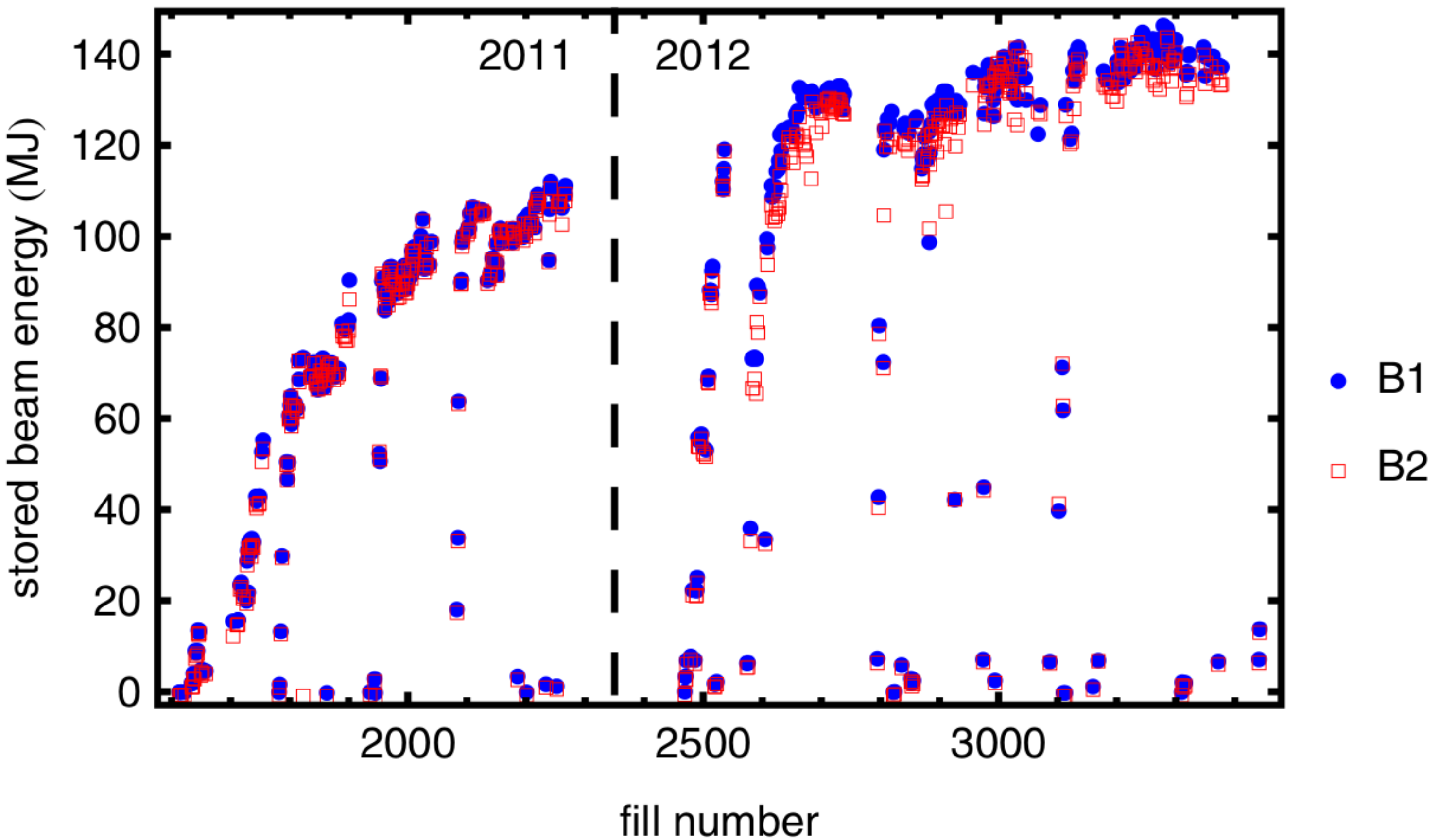
- Collimation cleaning qualified by provoked losses (loss map)Loss distribution around ring measured



D. Mirarchi

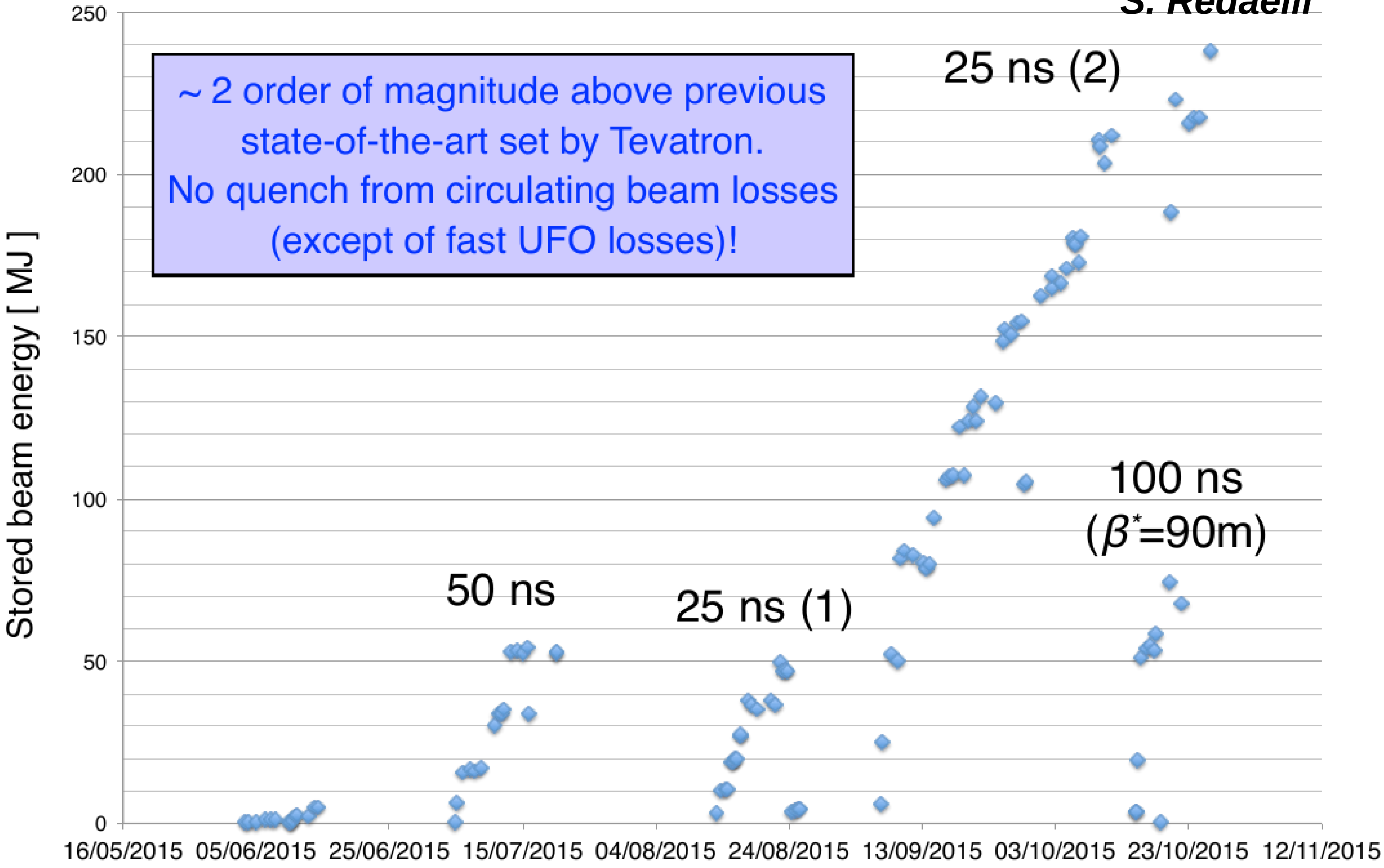
Stored energy in Run 1

- LHC collimation worked very well in Run 1 (2010 – 2013)
- Routinely stored ~140 MJ beams over hours. No beam-induced quenches during physics operation



Stored energy in 2015

S. Redaelli



Summary

- LHC collimators have a wide range of applications: protect against quenches, radiation damage, experimental background, direct damage from beam impact…
  - About 100 collimators
  - Operational experience: No beam-induced quenches (yet) with circulating beam during physics operation
  - Handled losses of ~1 MW without quench
- More challenges ahead: doubled stored energy in HL-LHC