LHC and HL-LHC

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Contents:

- LHC design aspects and physics goals ➔ Synchrotron as the HEP workhorse

- Technology Challenges ➔ Superconducting magnet performance reach

- Luminosity optimization
  ➔ Operational challenges and limitations

  ➔ Machine efficiency and Turnaround Time

  ➔ Beam power and damage potential ➔ Machine Protection

  ➔ Operational challenges

- Operation experience: Unexpected Obstacles

Accelerators for Particle Physics Recap

- Collider Particle types:

  Leptons:

  'true' elementary particles ➔ well defined Center of Mass [CM] collision energy

  (precision measurement)

  'light' particles ($\gamma >> 1$) ➔ strong synchrotron radiation

  (size, damping, magnet type, limitation in energy reach)

  Hadrons:

  Composite particle collisions ➔ range of CM energies

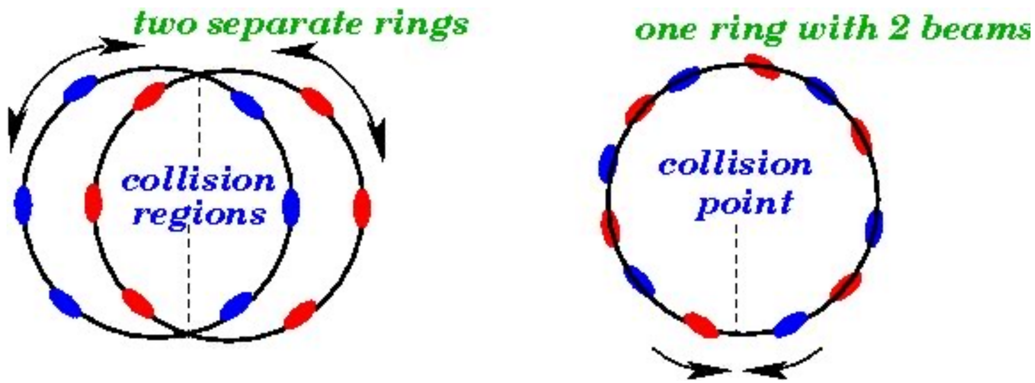
  (discovery potential ← → background)

  'heavy' particles ➔ suppressed synchrotron radiation

  (superconducting magnet technology, energy reach)

Accelerators for Particle Physics Recap

- collider ring design requires 2 beams:



- design with one aperture requires particles & anti-particles
  Not efficient for a hadron collider! (e.g. Tevatron, Chicago USA)
  But attractive for lepton colliders [LEP and Super KEK-B]

- 2-ring design implies twice the hardware

  → Allows higher beam intensities, more bunches and different particle species
  But more costly and potentially higher failure rate!

Key Goals of the LHC collider:

- Unitarity crisis of the Standard Model ➔ SM predictions yield over 100% probabilities in W-W interactions @ 1TeV CM collision energies without Higgs particle

  ➔ Probe 1TeV CM collision regime and look for SM discrepancies, or find the Higgs
  ➔ Higgs mass was not known ➔ need to cover a wide range of CM collision Energies!

- Challenges
  ➔ Small cross section events require large luminosity! ➔ $L > 10^{33}$ cm^{-2} s^{-1}

  ➔ As the mass of the Higgs was not know when the LHC was designed, one wants to cover a wide range of collision energies ➔ proton-proton collider

- Competition with Superconducting Super Collider in the US [80km circumference]
  ➔ LHC study was pushed in competition with the SS

  ➔ Needed to be substantially lower cost than the SS

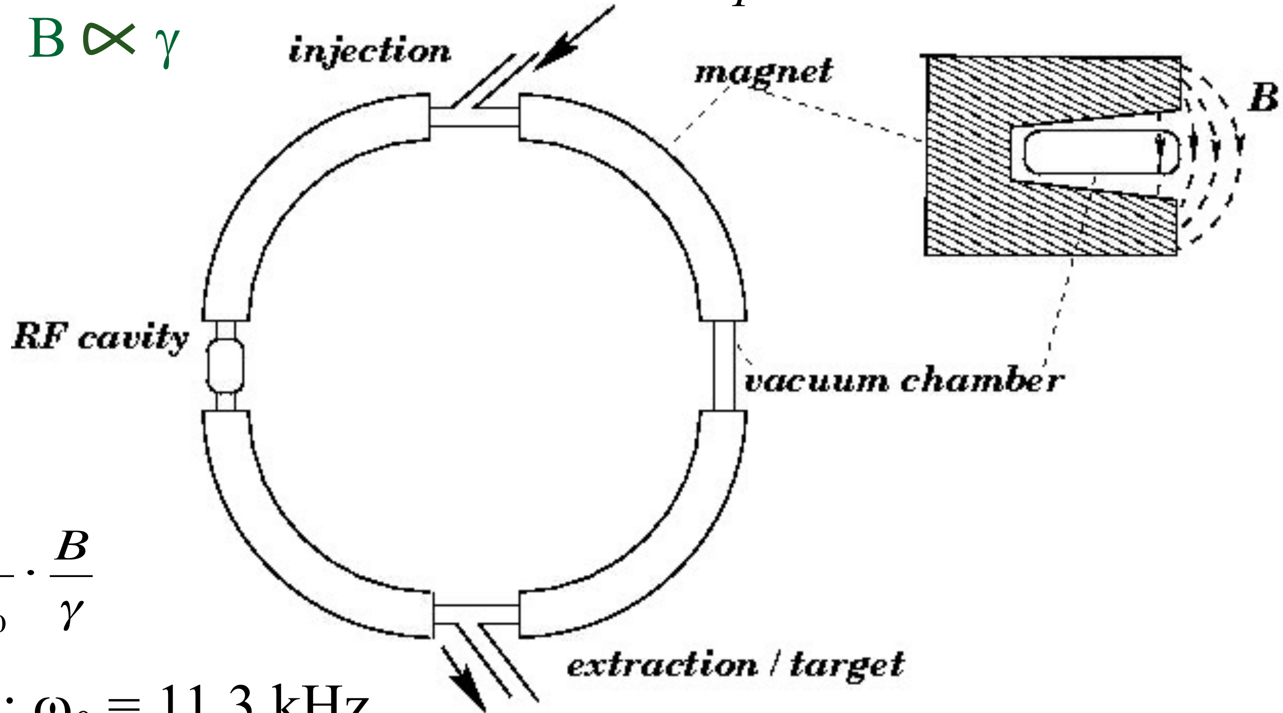
➔ re-use of the existing LEP tunnel and novel, compact magnet design!

Synchrotron concept: Work Horse for most HEP colliders

- R = constant:

$$r = \frac{m_0}{q} \cdot \frac{\gamma}{B} \cdot v$$

v = c → $B \propto \gamma$



$$\omega_0 = \frac{q}{m_0} \cdot \frac{B}{\gamma}$$

LHC / LEP: $\omega_0 = 11.3$ kHz

Synchrotron: magnet technology

- uniform B field: R = constant

$$p = q \cdot \frac{B \cdot circ}{2\pi} \approx E / c$$

for $E >> E_0$

- realistic synchrotron: B-field is not uniform

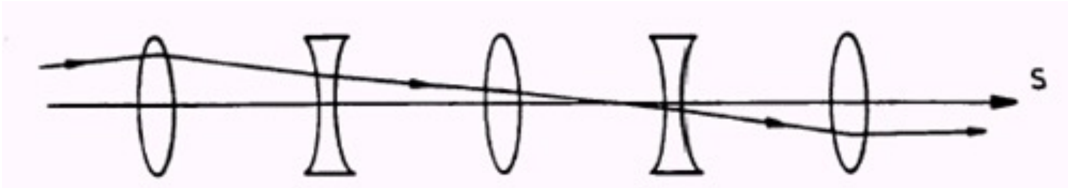
  -drift space for installation
  -different types of magnets
  -space for experiments etc

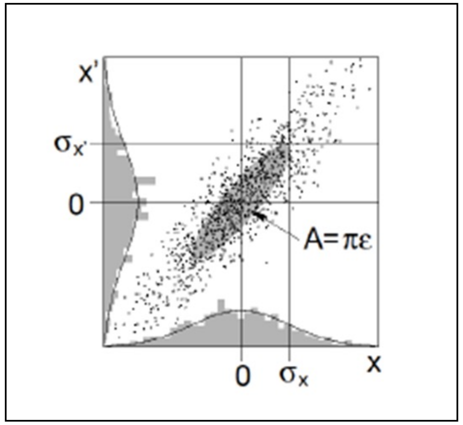
$$E = \frac{q \cdot c}{2\pi} \cdot \oint B \cdot ds$$

➔ high beam energies require: -high magnetic bending field
-large circumference
-large packing factor

Magnet aperture: Beam size in a FODO Lattice:

Optics: Overall focusing with alternate setup of focusing and de-focusing lenses ➔quadrupole magnets are the electro-magnetic lenses for particle beams





Ellipse area in (x,x') plane

Phase

Amplitude

$$x(s) = A\sqrt{\beta_x(s)}\cos\big(\phi(s)+\phi_0\big)$$

Emittance shrinks naturally as we go up in energy

Normalized emittance
(give or take blow-up from other sources)
remains constant

$$\varepsilon_n = \beta\gamma\varepsilon$$

Compromise between Bending and Focusing Fields

The aperture of a dipole magnet influences the maximum field strength:

➔ A smaller aperture allows for a stronger magnetic field for the same current in the coils
   ➔ Formulated differently: providing a given magnetic field in a larger aperture requires more current which requires more coil layers once the maximum acceptable current in the conductor has been reached ➔ higher cost for the magnet production

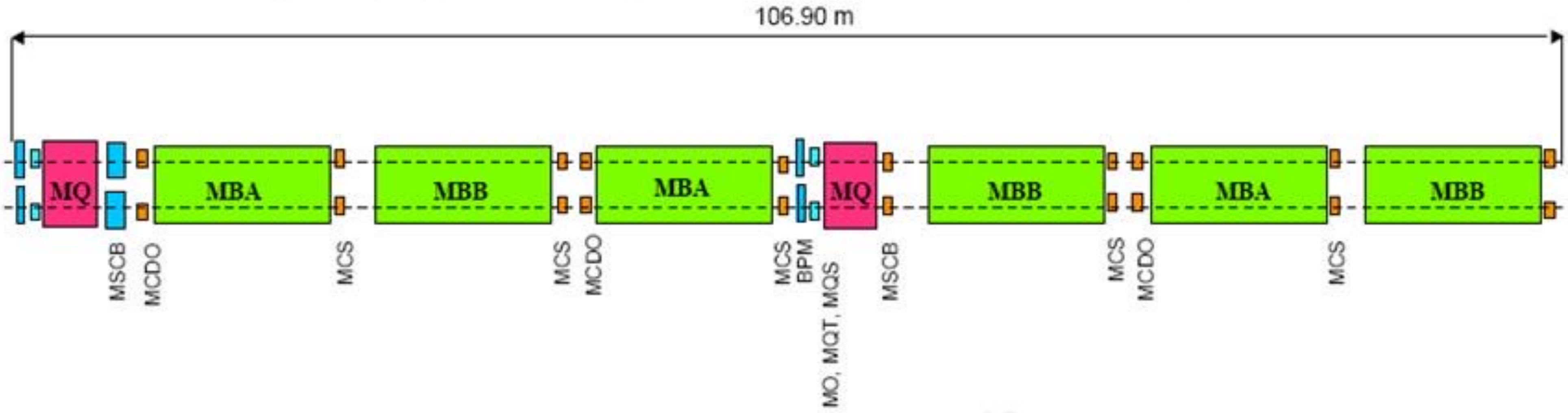
➔ The stored energy in a magnetic field is proportional to the square of the magnetic field and the volume of the field ➔ more challenging requirements for the machine protection

Optimizing the design of accelerator dipole magnets:
➔ Minimize the required aperture to allow for:
A maximum field at acceptable stored energies and acc

Balanced compromise for giving space for quadrupole and dipole magnets!

LHC Arc-Cell Layout

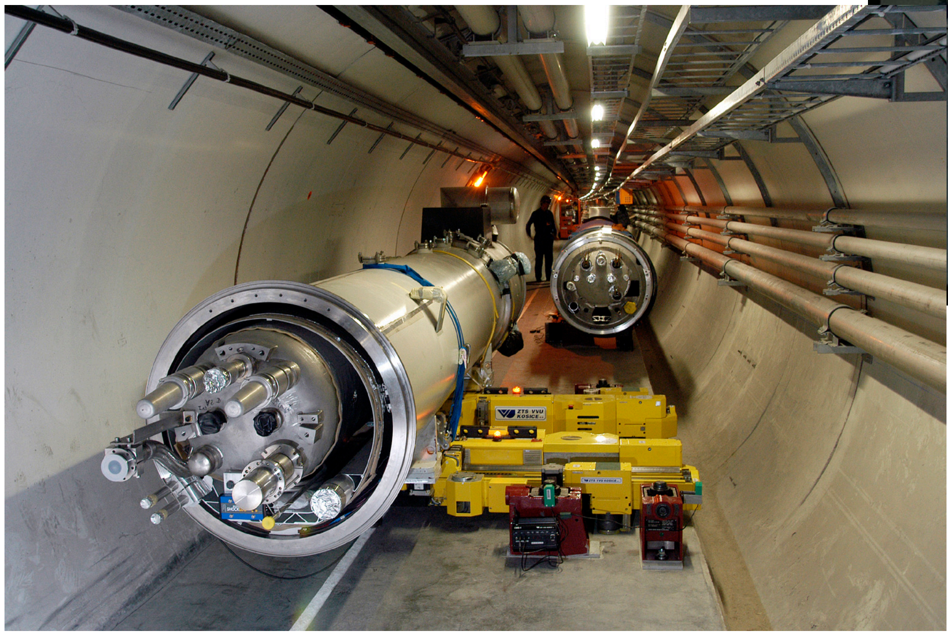
Maximize the space occupied by dipole magnet while providing sufficient focusing to keep the magnet aperture acceptable



➔ Three 15 meter long dipole magnets per 3.4 meter long quadrupole magnet; plus space for dipole and non-linear corrector magnets ➔ Packing factor of ca. 80%

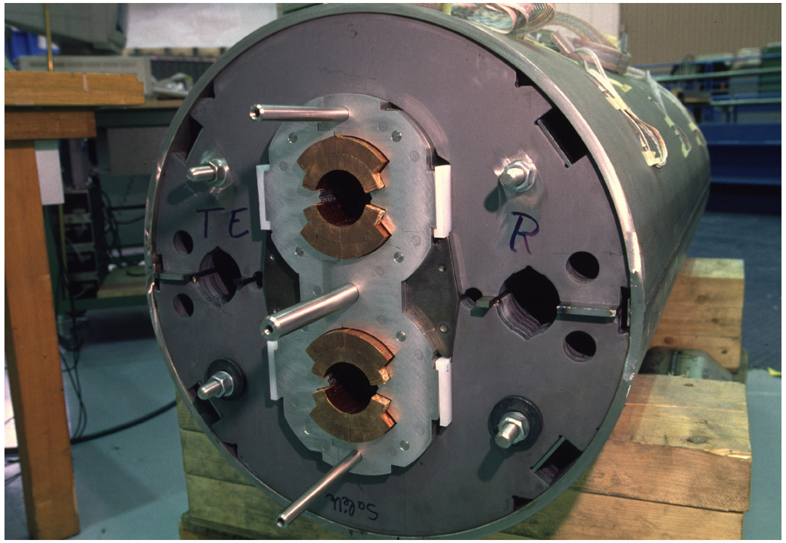
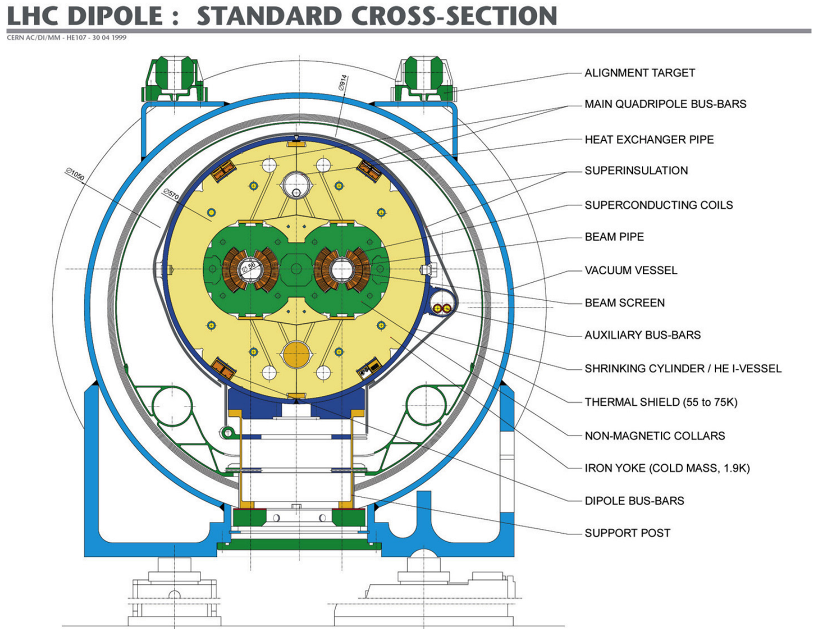
Maximizing the dipole 'Fill Factor'

- 15 m long, 30 Ton
  difficult transport & tight tolerances for installation



Magnet Technology

- 2-in-1 dipole magnet design with common infrastructure:

-15 m long → few interconnects (high filling factor)

-compact 2-in-1 design → allows p-p collisions in LEP tunnel

-corrector magnets at ends → tight mechanical tolerances

Challenges: magnet technology limit

- LHC physics goal: 1 TeV CME ➔ > 5 TeV beam energy ➔ 7TeV design

- existing infrastructure: LEP tunnel: circ = 27 km (ca. 17mi)
  with 22 km arcs (ca. 14mi)

- assume 80% of arcs can be filled with dipole magnets: F = 0.8

- required dipole field for the LHC:

$$\frac{2\pi}{q} \cdot \frac{E/c}{circ \cdot F} = B$$

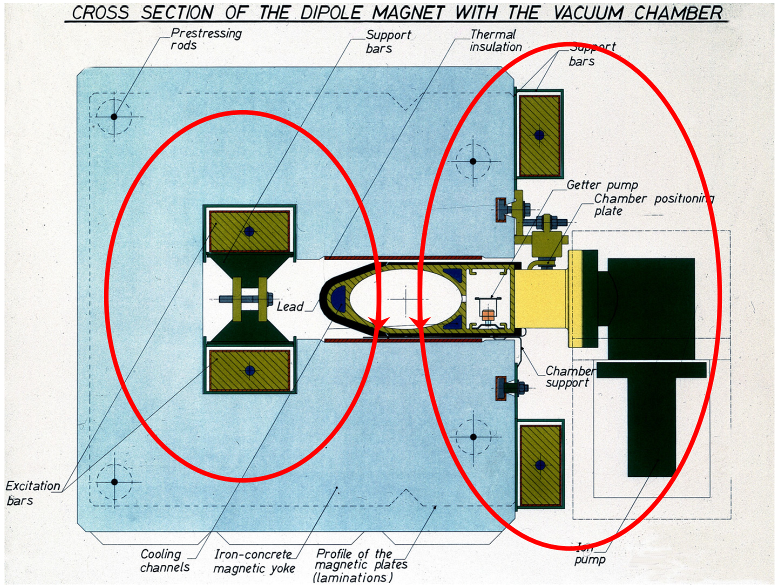
➔ B = 8.38 T

(earth: 0.3 10^{-4} T)

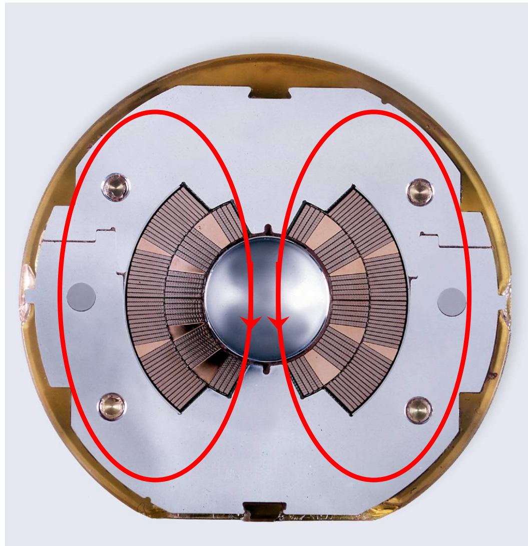
Magnet Technology Re-Cap

- high beam energies require large rings and high fields

1) Iron joke magnet design



2) air coil magnet design



-field quality given by pole face geometry
-field amplified by Ferromagnetic material
-iron saturates at 2 T
-Ohmic losses for high magnet currents

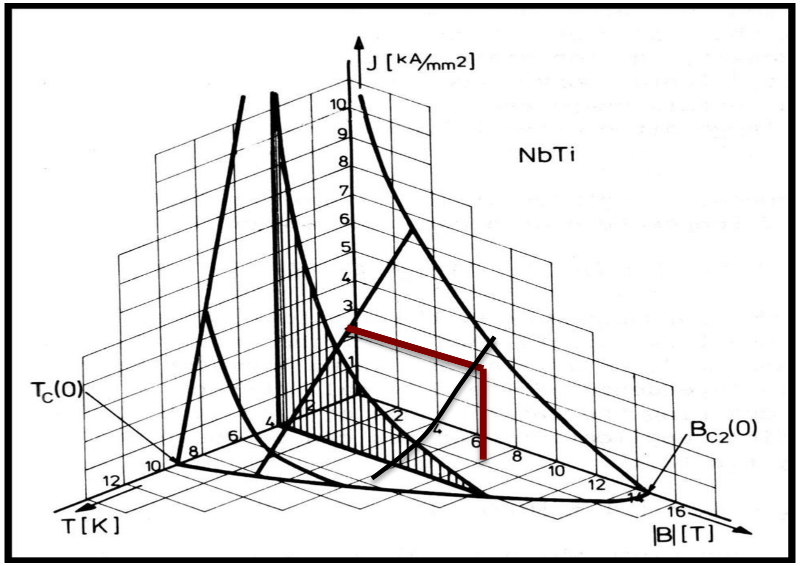
-field quality given by coil geometry
-SC technology avoids Ohmic losses
-not always superconducting ➔ risk of magnet quenches
-field quality changes with time

Introduction: Magnet Technology

- LHC Dipole Magnets: 8.3T, with 11850A ➔ not possible with Cu

  ➔ superconductor, but with high ambient magnetic field > 8 T @ coil

Critical Surface for NbTi

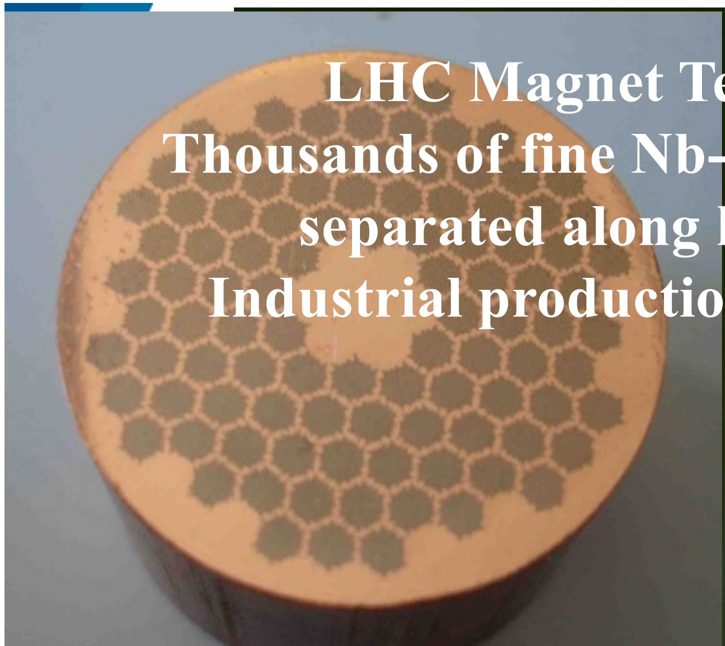


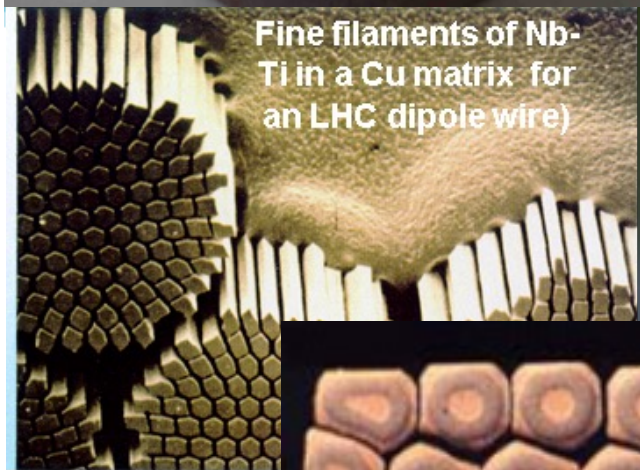
➔ 1.9 K cooling with superfluid He (thermal conductivity)

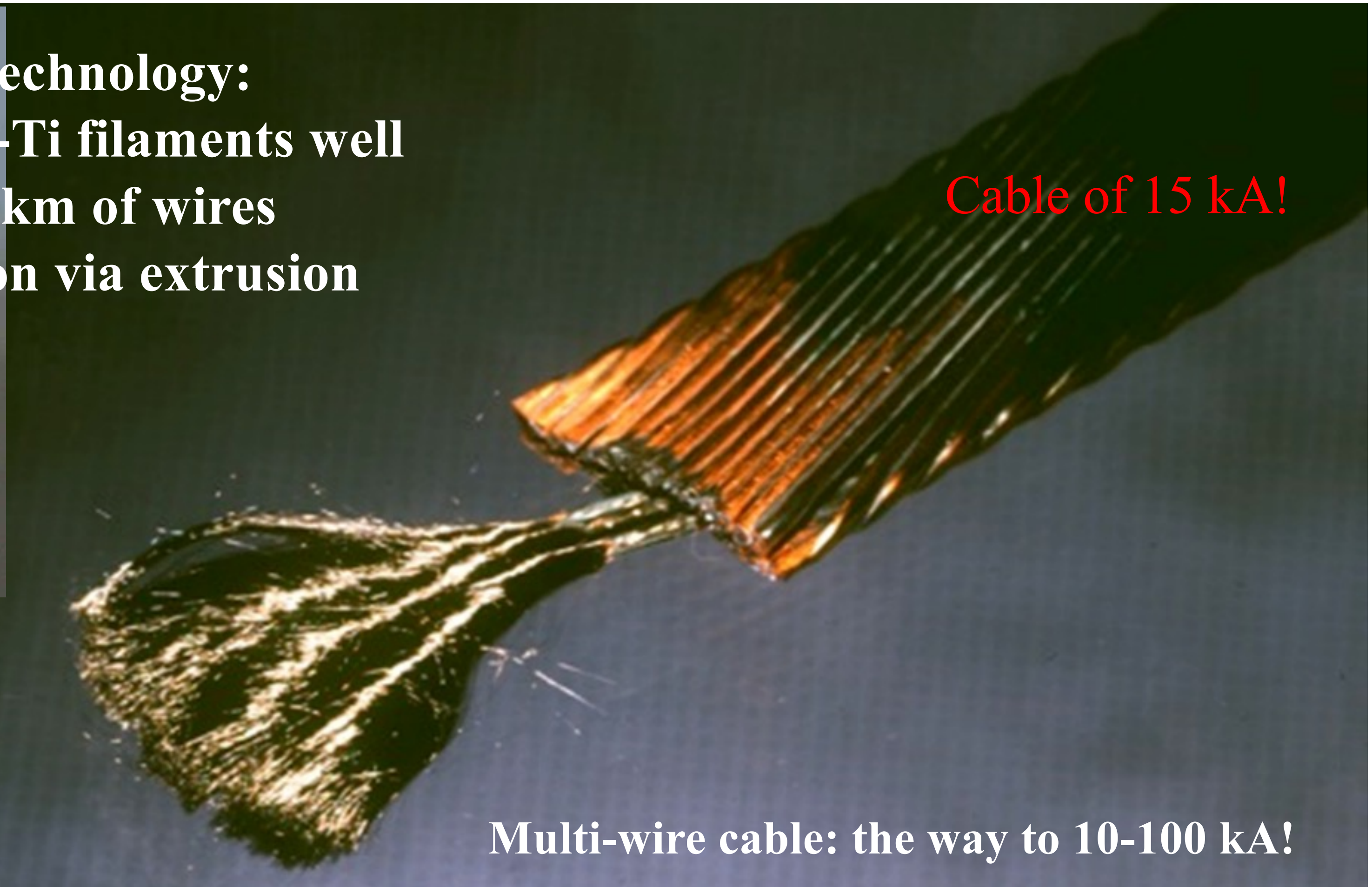
➔ current density of 2.75 kA / mm^2

At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!

LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well separated along km of wires
Industrial production via extrusion





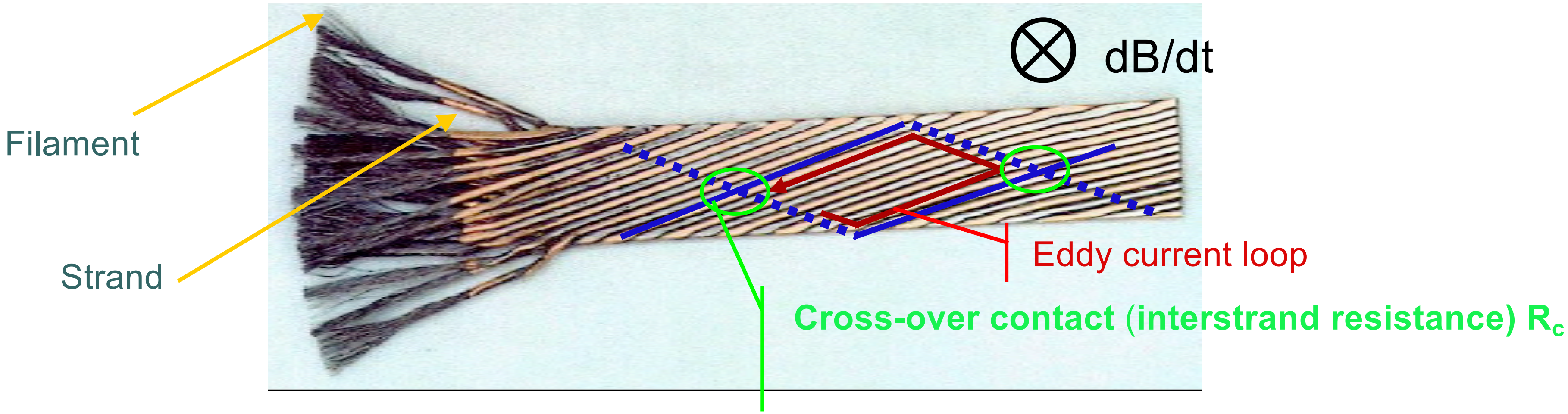


Cable of 15 kA!

Multi-wire cable: the way to 10-100 kA!

Superconducting Magnet Challenges: Field Quality

- SC Rutherford cable in transverse field



- The eddy currents loops generate a magnetic field that adds ("*field advance*") to the background field inside the aperture, proportional to: dB/dt and $1/R_c$
- Current ramps induce field distortions for all harmonics Δb^{rr}_n, Δa^{rr}_n
- Minimum specified **Rc** value for the machine **~ 15 μΩ** which gives (estimation):
  - ➔ b_1=6 units
  - ➔ b_2=15 units
  - ➔ multipoles errors ~ 0.1-1 units

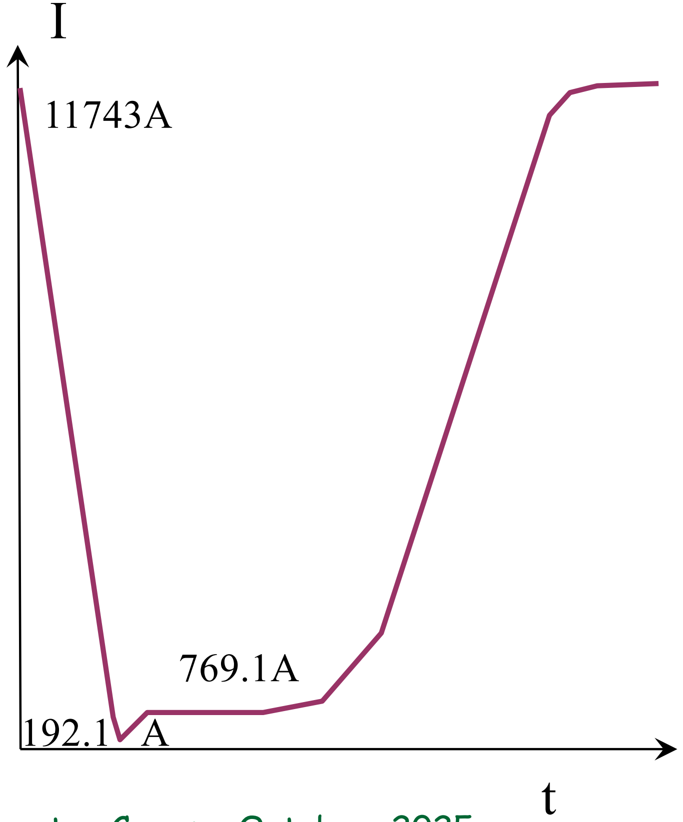
1 unit = 10^{-4} of the main field

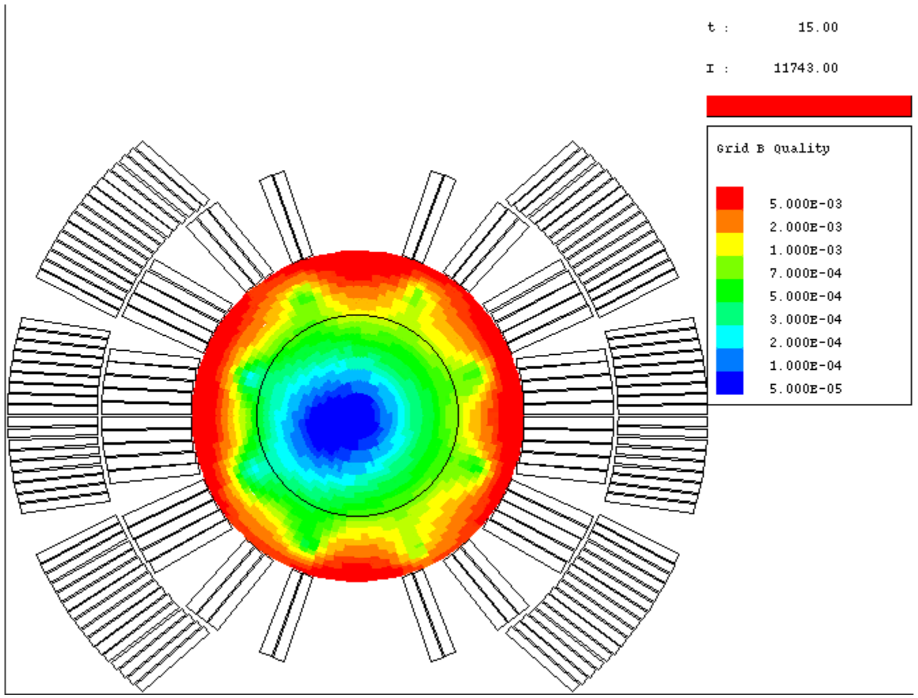
Field Imperfections: Super Conducting Magnets

- time varying field errors in super conducting magnets

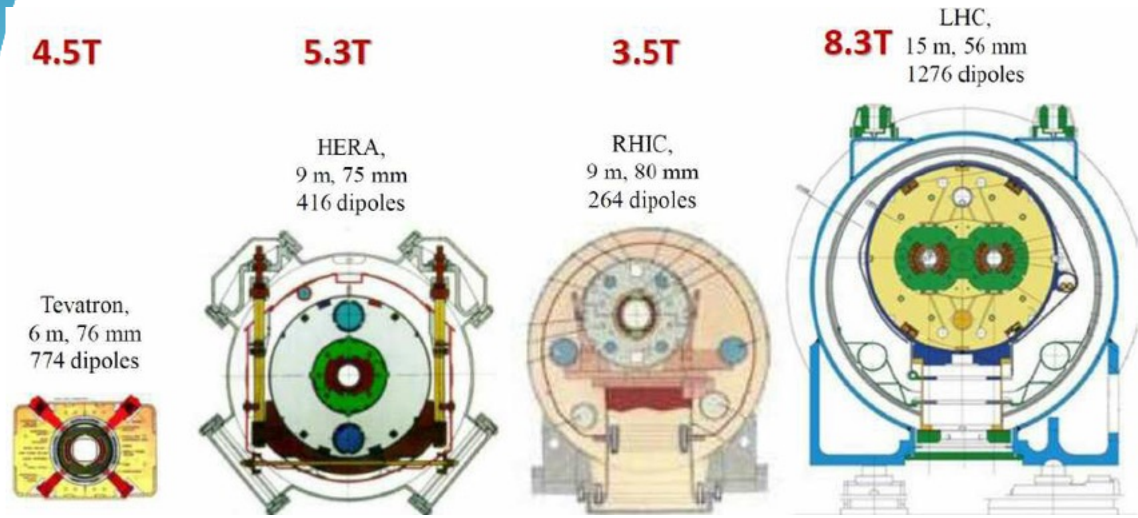
Luca Bottura CERN, AT-MAS

Beam stability requires Field Quality of a few units
➔ Black circle on the right

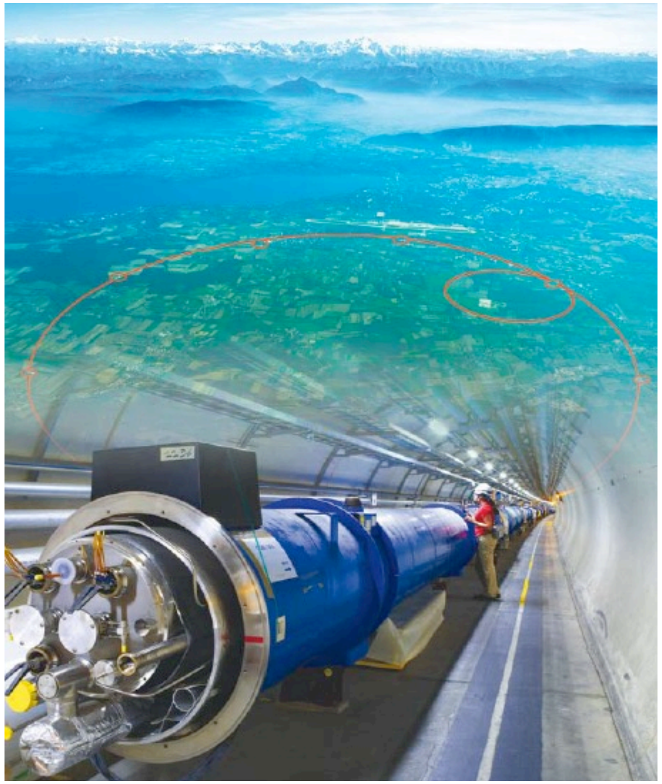




LHC (Large Hadron Collider): Magnet Technology



1983 1991 2000 2010



➔ The LHC dipole magnets mark the culmination of 30 years of superconducting NbTi magnet technology development!

➔ Requiring 1.9K [-271 degrees Celsius] operating temperature

Accelerators for Particle Physics

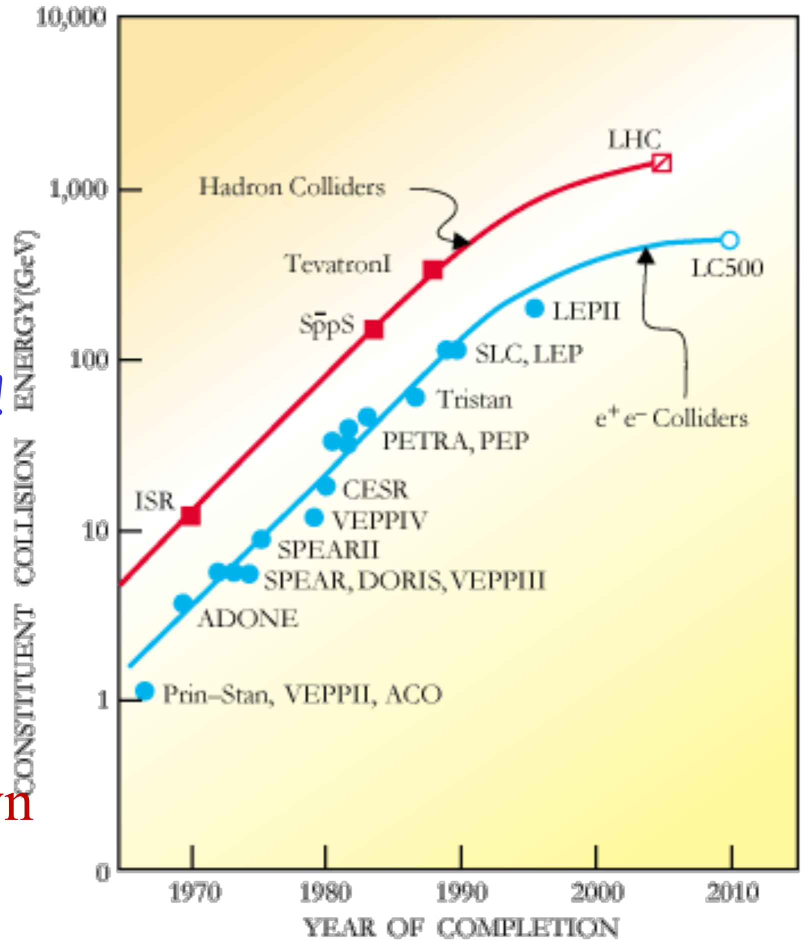
- Livingston Plot:

Accelerator energy:

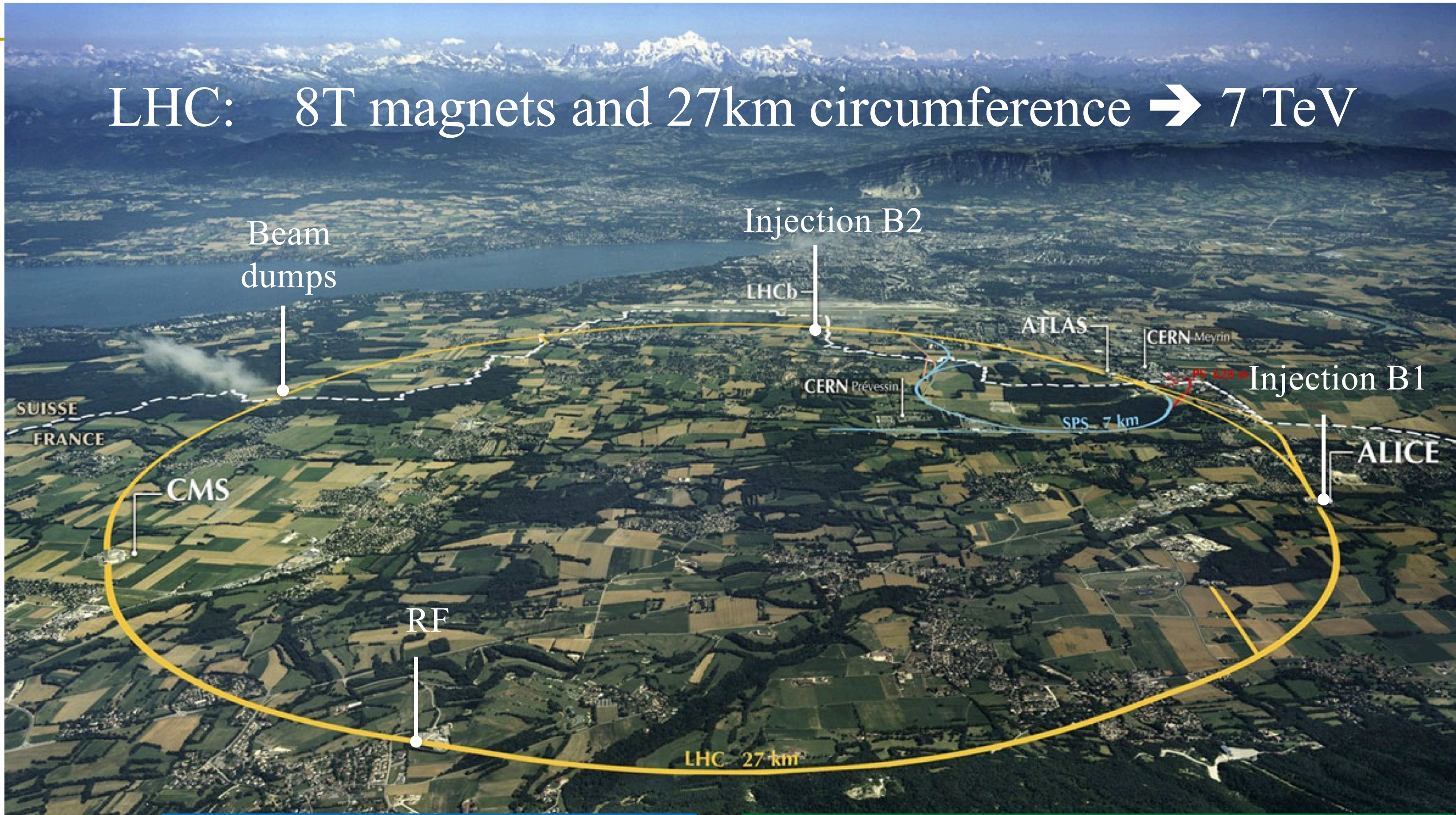
Energy reach has increased exponentially for over 40 years during the last century!!

➔ Foundation for the Standard Modell Triumph

➔ Performance increase seems to have slowed down over last decades!



LHC: 8T magnets and 27km circumference ➔ 7 TeV

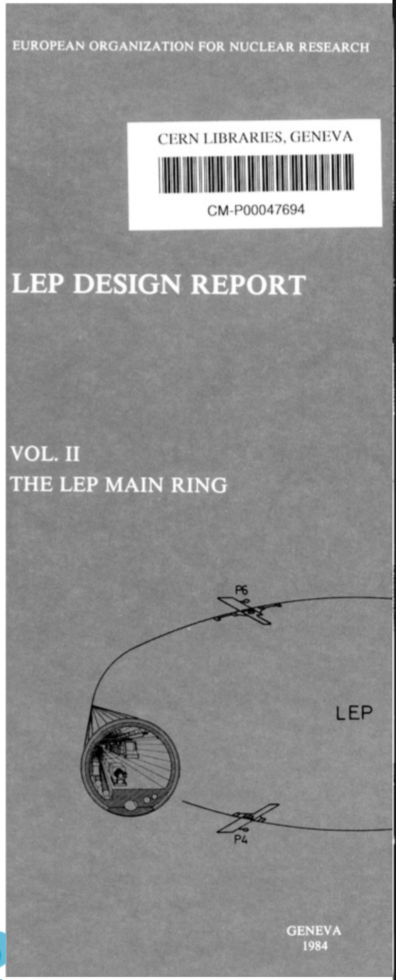


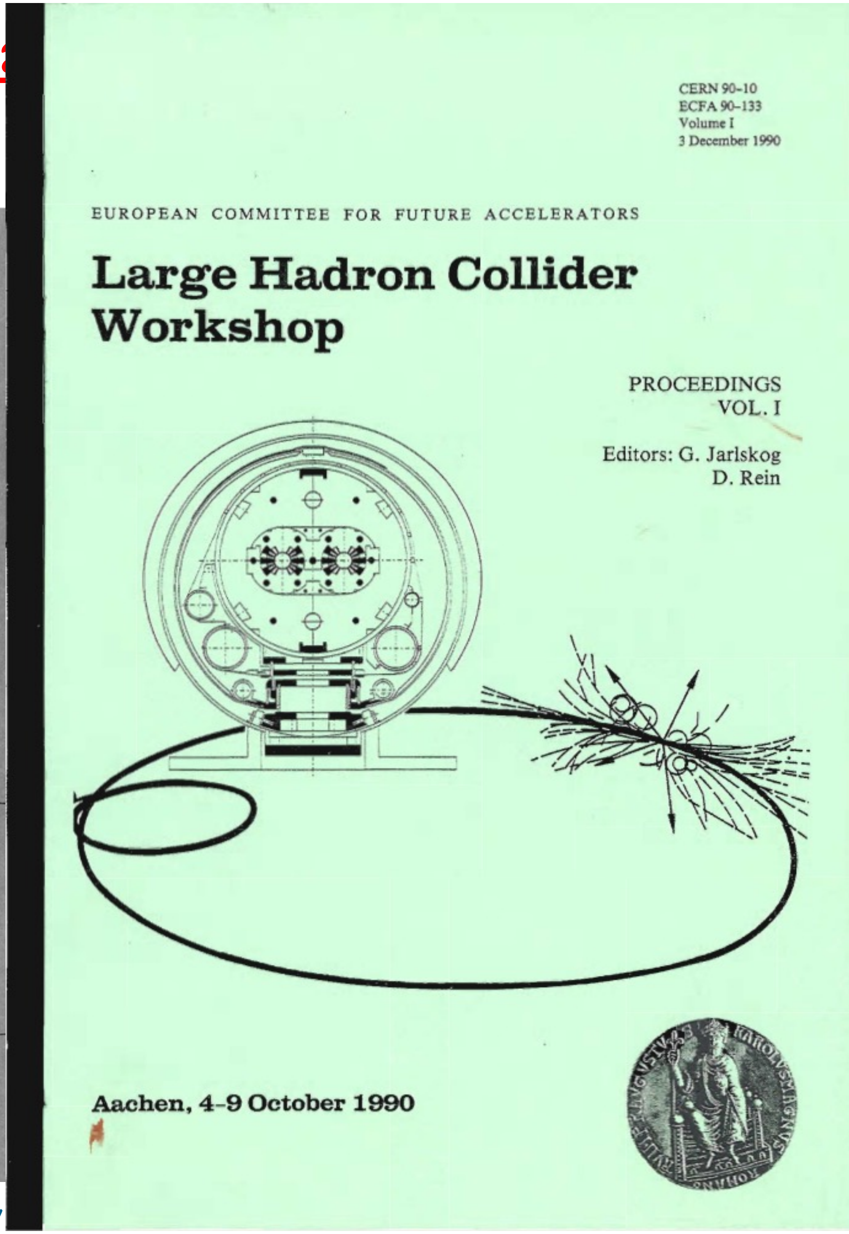
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

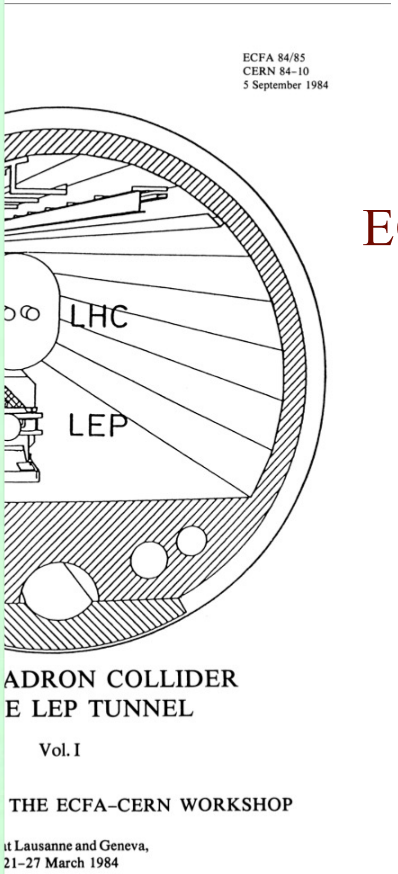
150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 700 MJ for HL-LHC!
830 MJ magnetic energy per sector at 6.5 TeV
➔ ≈ 10 GJ total @ 7 TeV

LHC: was alre Start of LEP 1989 to 2000

LEP
Design
Report
1984







Lausanne
ECFA-CERN
Workshop
1984

LHC (Large Hadron Collider)

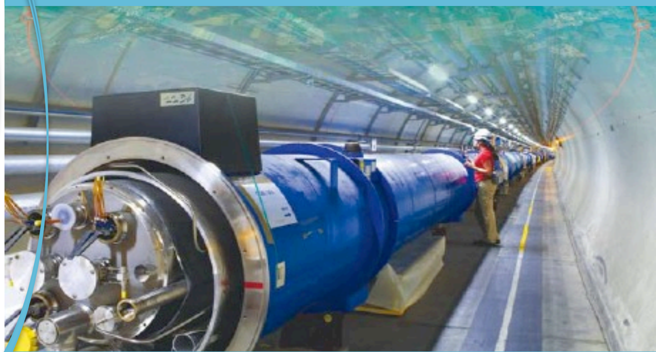
14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair

2010-2026 : Physics exploitation

Ca. 20 years magnet development!!!



Ca. 30 years machine development!!!

➔ Significant Time scale extending well beyond that of a physicist career!!!

LHC Performance Measures:

- Collision energy: e.g. LHC: probing limits of SM; $E_{CM} > 1$ TeV

  p collisions ➔ $E_{beam} > 5$ TeV ➔ LHC: E = 7 TeV

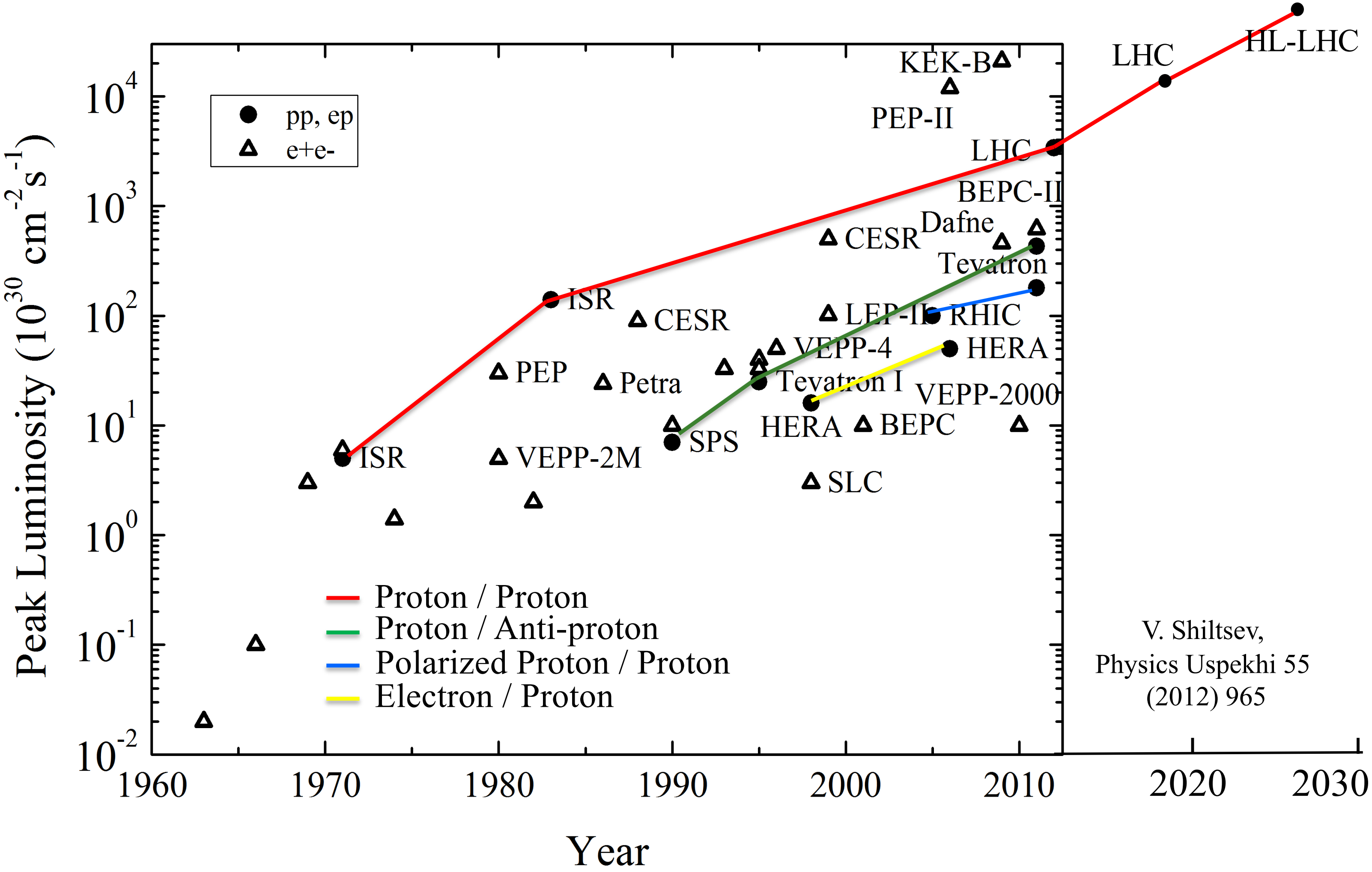
- Instantaneous luminosity: # events in detector $= L \cdot \sigma_{event}$

  rare events ➔ $L > 10^{33} cm^{-2} sec^{-1}$ ➔ $L = 10^{34} cm^{-2} sec^{-1}$

- Integrated luminosity: L $= \int L(t)\,dt$

  depends on the beam lifetime, the LHC cycle and 'turn around' time and overall accelerator efficiency ➔ designed for 300 $fbarn^{-1}$!!!
  [ca. 20 times the previously existing world production of hadronic collisions!]

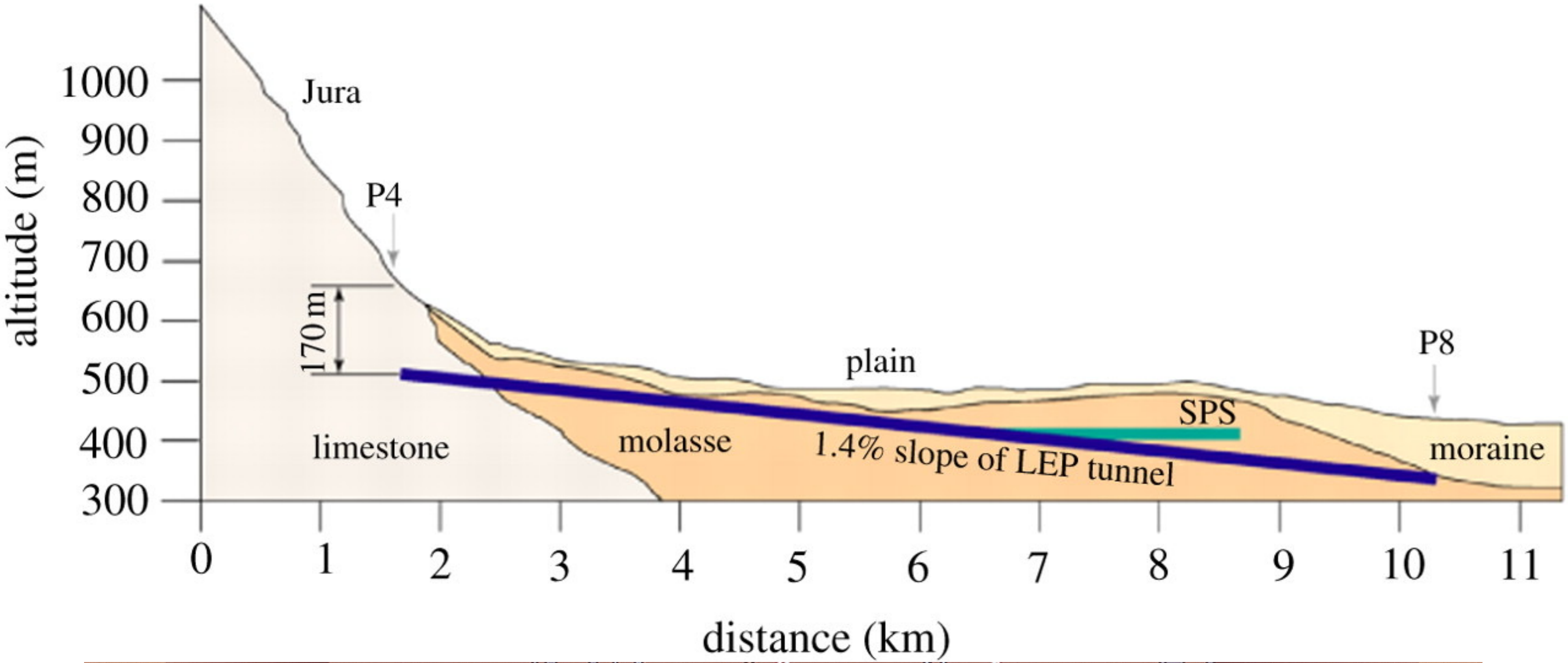
Peak luminosities of Hadron colliders



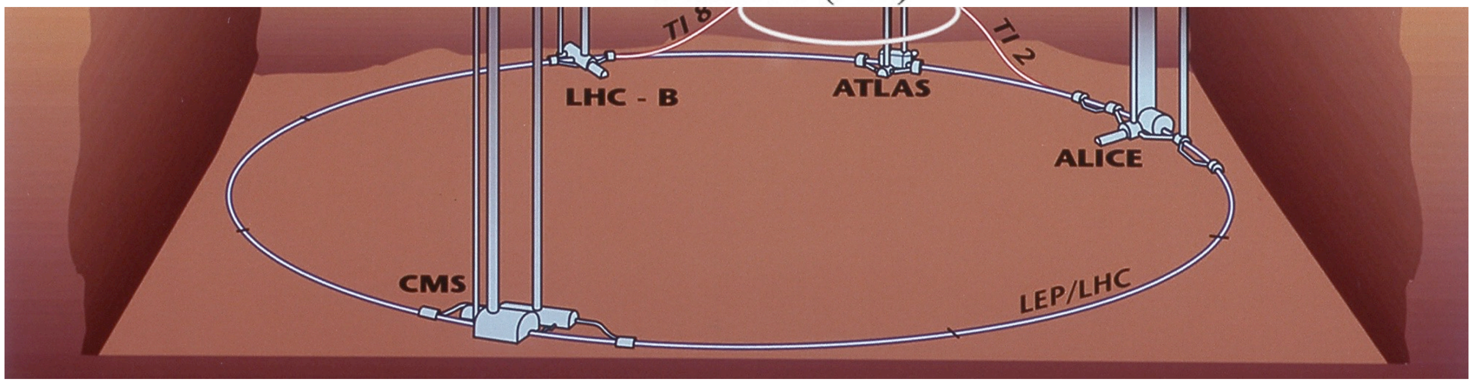
LHC in the Geneva Basin and its Experiments

Features proton-proton and Lead-Lead and Lead-proton collisions!

LHC ring:
27 km circumference
Super Conducting Magnets



altitude (m)
1000
900
800
700
600
500
400
300
Jura
P4
170 m
plain
P8
SPS
limestone
molasse
1.4% slope of LEP tunnel
moraine
0
1
2
3
4
5
6
7
8
9
10
11
distance (km)

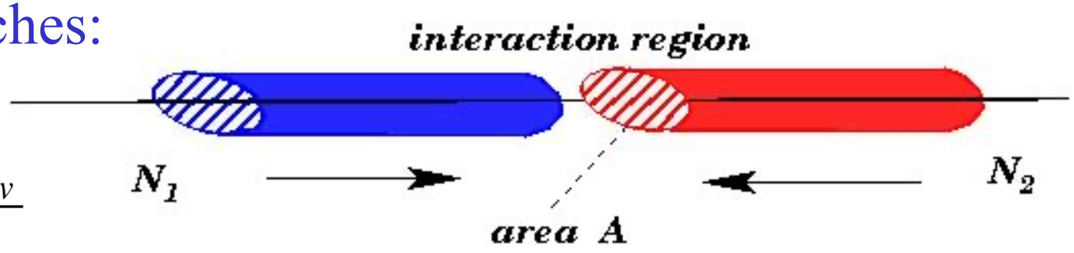


TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

Luminosity

colliding bunches:

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$



$$A = 4\pi \cdot \sigma_x \cdot \sigma_y \quad \text{with:} \quad \sigma = \sqrt{\beta \cdot \epsilon}$$

N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
F = geometric factor

β is determined by the magnet arrangement & powering

$\varepsilon = \varepsilon_n/\gamma$ ε_n is determined by the injector chain

goal: → high bunch intensity and many bunches

$L = 10^{34}\ cm^{-2}sec^{-1}$ small β at IP and high collision energy

Performance optimization: Peak Luminosity

- Luminosity recipe (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

1) maximize bunch intensities → Injector complex &
2) minimize the beam emittance — Losses and collimation
3) minimize beam size (constant beam power) → magnet aperture
4) maximize number of bunches (beam power) → X-ing angle
5) compensate for 'F' → Crab Cavities
6) Improve machine 'Efficiency' → Minimize number of beam aborts and maximize luminosity lifetime!

The LHC is NOT a Standalone Machine

The LHC performance fully relies on the **performance of its injector complex**

- By itself **one of the largest accelerator facility in the world** with its own diverse and, for many aspects, unique physics program

LHC Injector Upgrade Project

Installation finished in LS2 [2019 to 2022] and

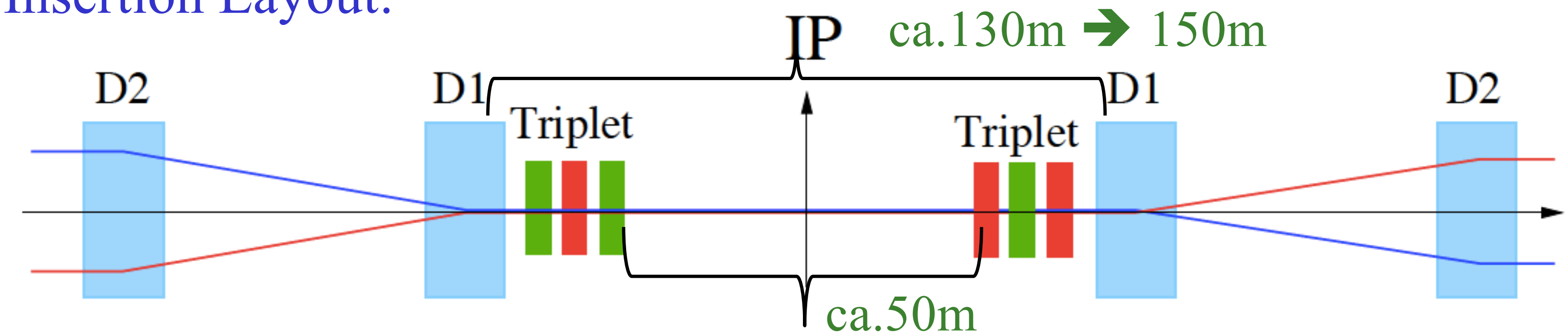
operational since 2022

➔ pre-requirement for HL-LHC!

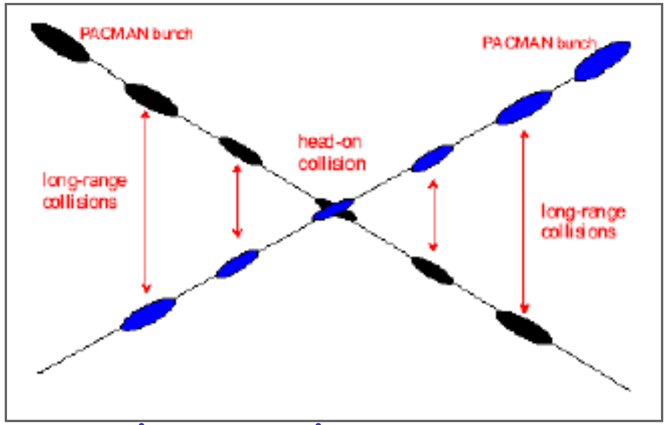
- **LHC : 2x(0.45 – 7) TeV**
- **SPS : 26 – 450 GeV**
  [RF Power]
- **PS : 1.4 - 26 GeV** / 2 - 26 GeV
  [RF and powering]
- **PSB : 0.05 - 1.4 GeV** / 0.16 - 2 GeV
- **Linac 2: 0-50 MeV** / Linac 4: 0-160 MeV H^-

Luminosity Optimization: Crossing Angle I

- Insertion Layout:



- Parasitic bunch encounters:



Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 30 unwanted collision per Interaction Region (IR).

➔ Operation requires crossing angle

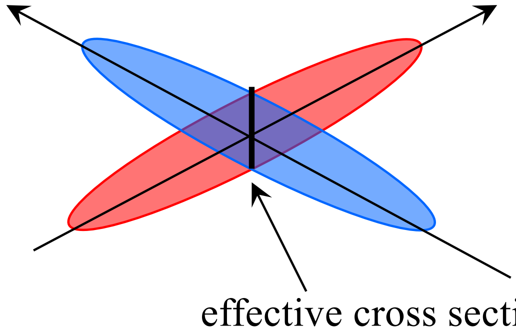
- non-linear fields from long-range beam-beam interaction:

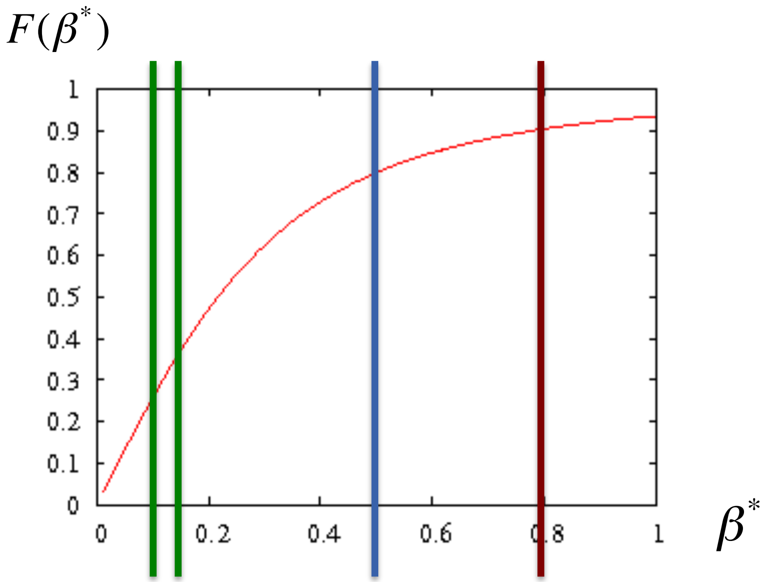
efficient operation requires large beam separation at unwanted collision points
➔ Separation of 10 -12 σ ➔ luminosity reduction and magnet aperture!!!

Luminosity Optimization: geometric reduction

- Geometric Luminosity Reduction Factor:

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$





Luminosity optimization: Beam Lifetime

- Fill length:

$$\frac{dN_{tot}}{dt} = -n_{IP} \cdot \sigma_{tot} \cdot L \quad \Rightarrow \quad \tau_{eff} = \frac{N_{tot}}{n_{IP} \cdot \sigma_{tot} \cdot L_0}$$

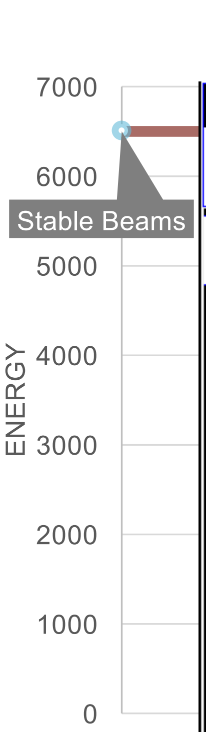
- Example LHC: $\sigma_{tot} \approx 100$mbarn [10^{-25}cm^2]; 2 IPs; $N_{tot} \approx 3\ 10^{14}$

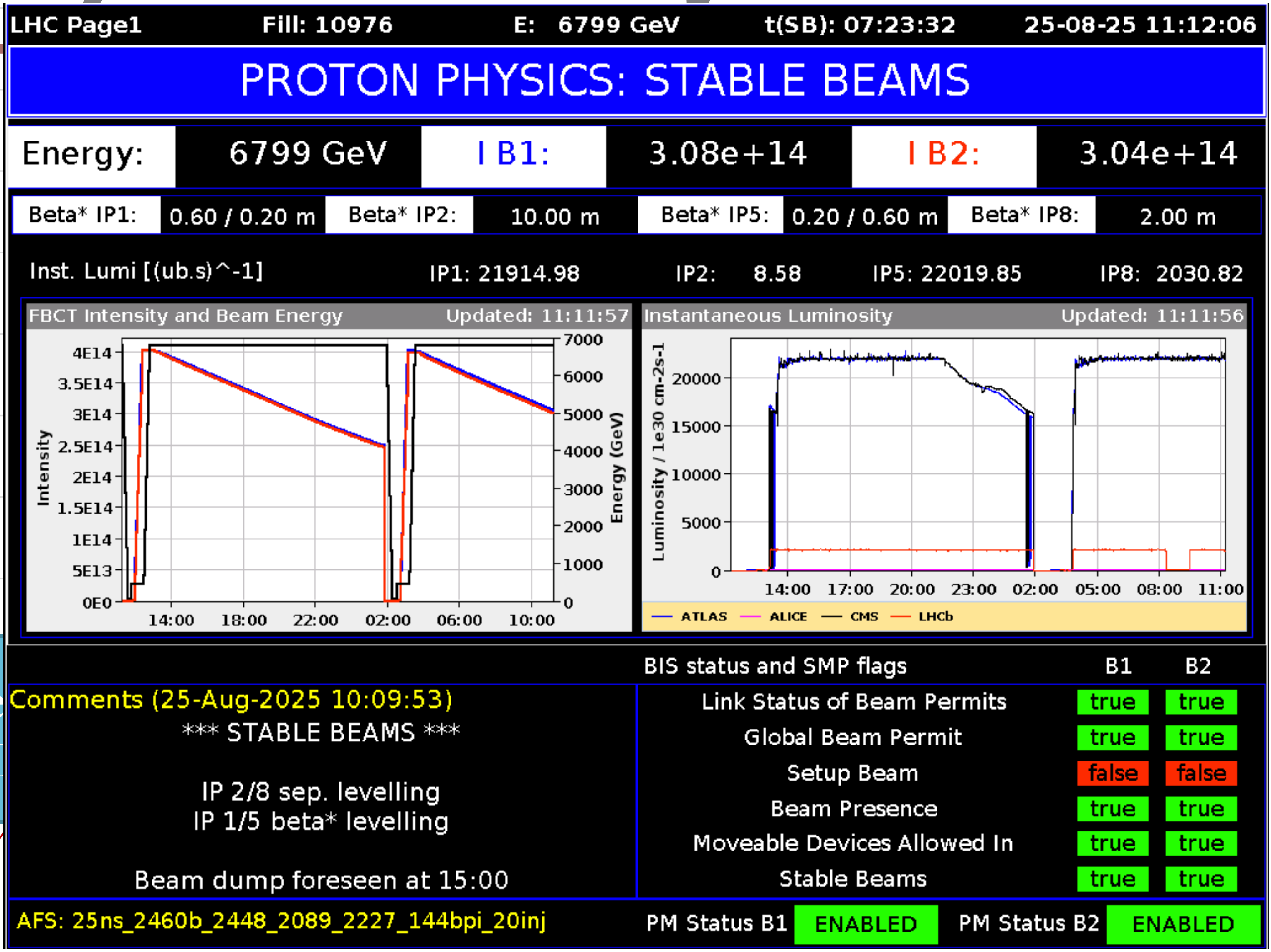
Nominal Luminosity: $L_0 = 10^{34}$ cm^{-2} s^{-1} ➔ $\tau_{eff} \approx 42$ hours

10 x Luminosity: $L_0 = 10^{35}$ cm^{-2} s^{-1} ➔ $\tau_{eff} \approx 4$ hours

➔ Efficient operation requires that the average fill length [data taking for physics] is significantly longer than the time required for preparing a new fill for physics!!!

Machine Efficiency

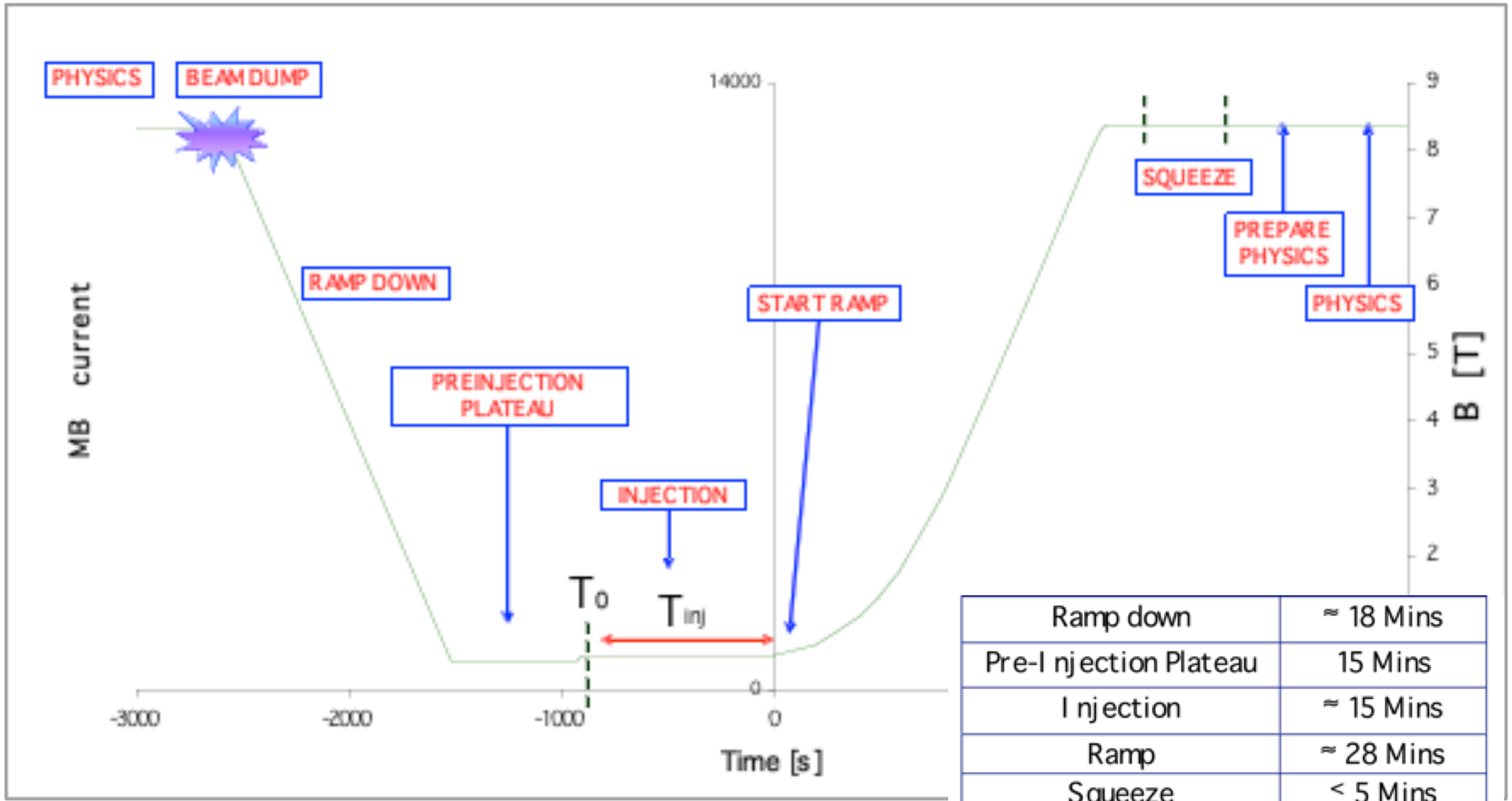




- ➔ Minimum of 2h
- ➔ Average LHC T
- ➔ LHC operation
  - ➔ ca. 70%

This be

LHC Operations Cycle Run 2



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Energy management challenges: Example LHC

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage

Lifetime & Loss Spikes ➔ Distributed losses

➔ Magnet Quench & QPS

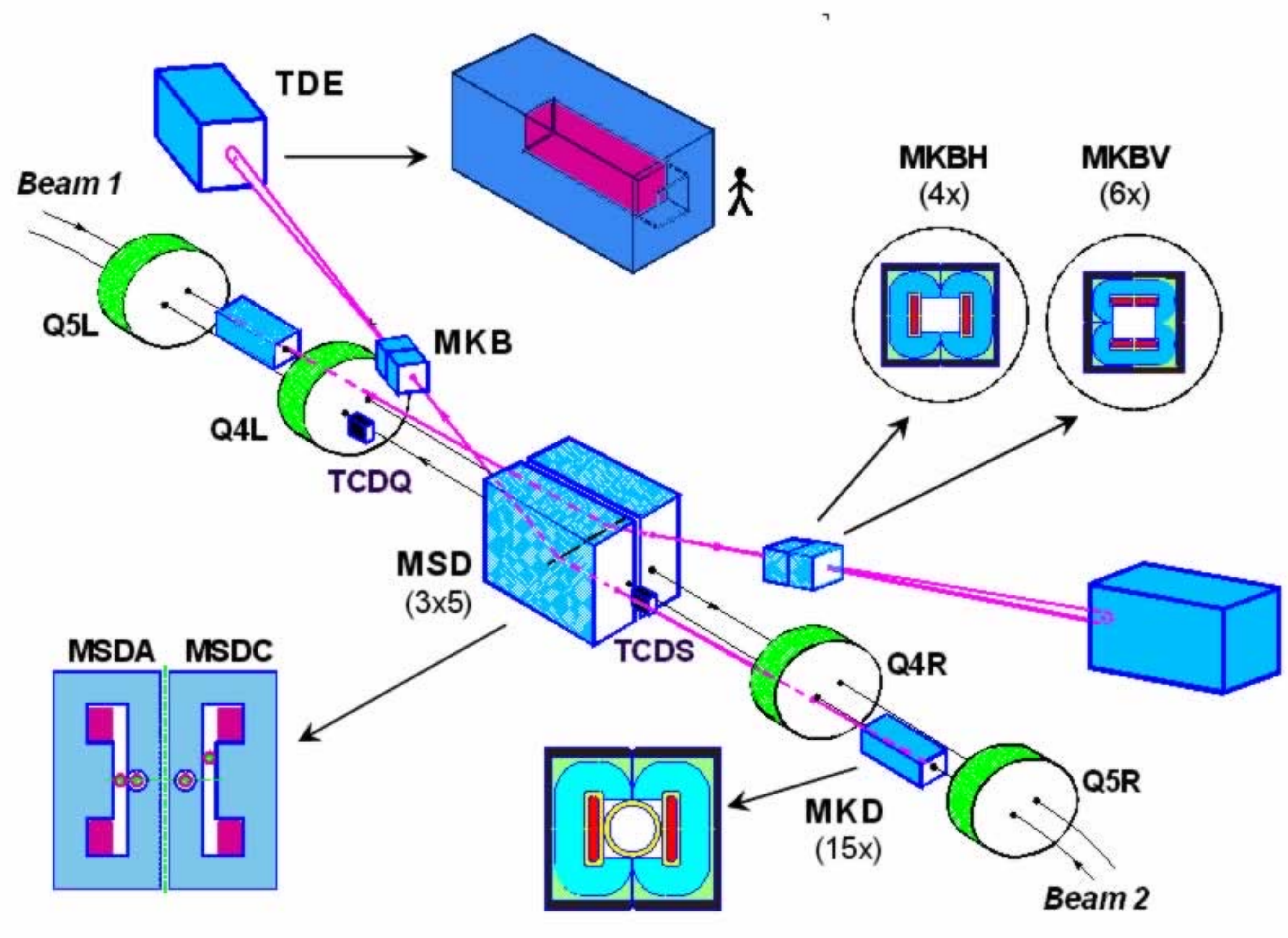
➔ Machine efficiency

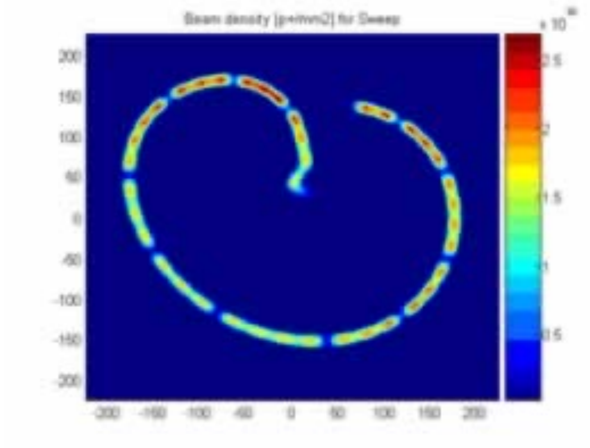
e.g. Cryo Sectors: 95% availability requires 99% with 8 sectors

LHC 8 Sectors ➔ Larger machine [12 Sectors ➔ 20 Sectors]

1 electron volt = 1,602 × 10^{-19} joule

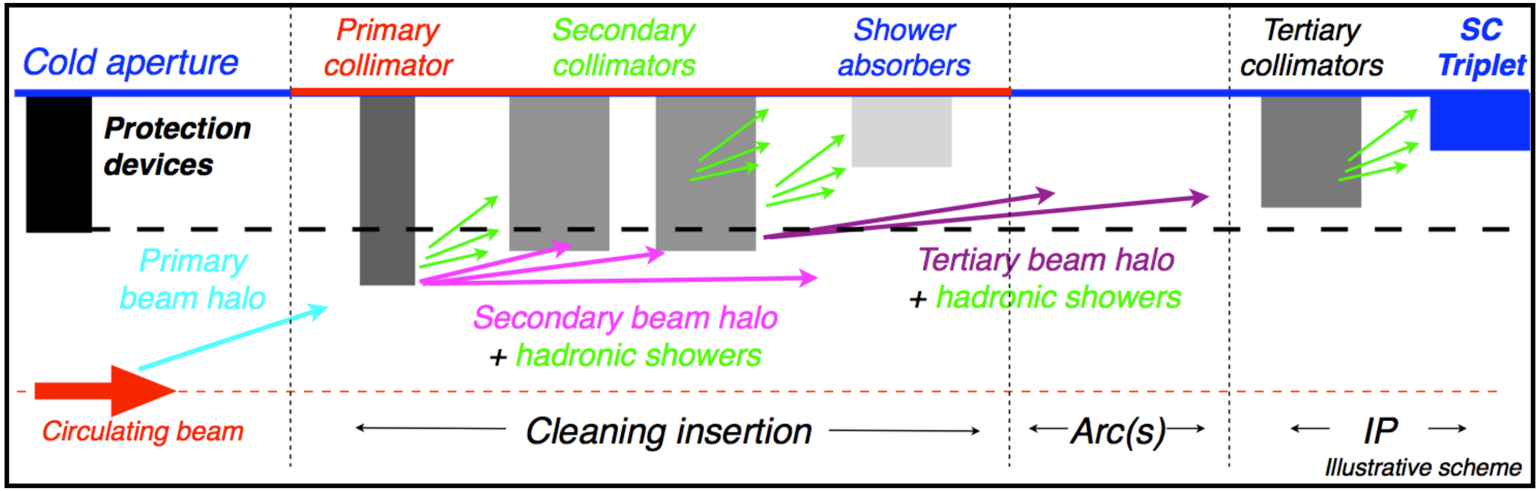
Beam Dump Dilution System

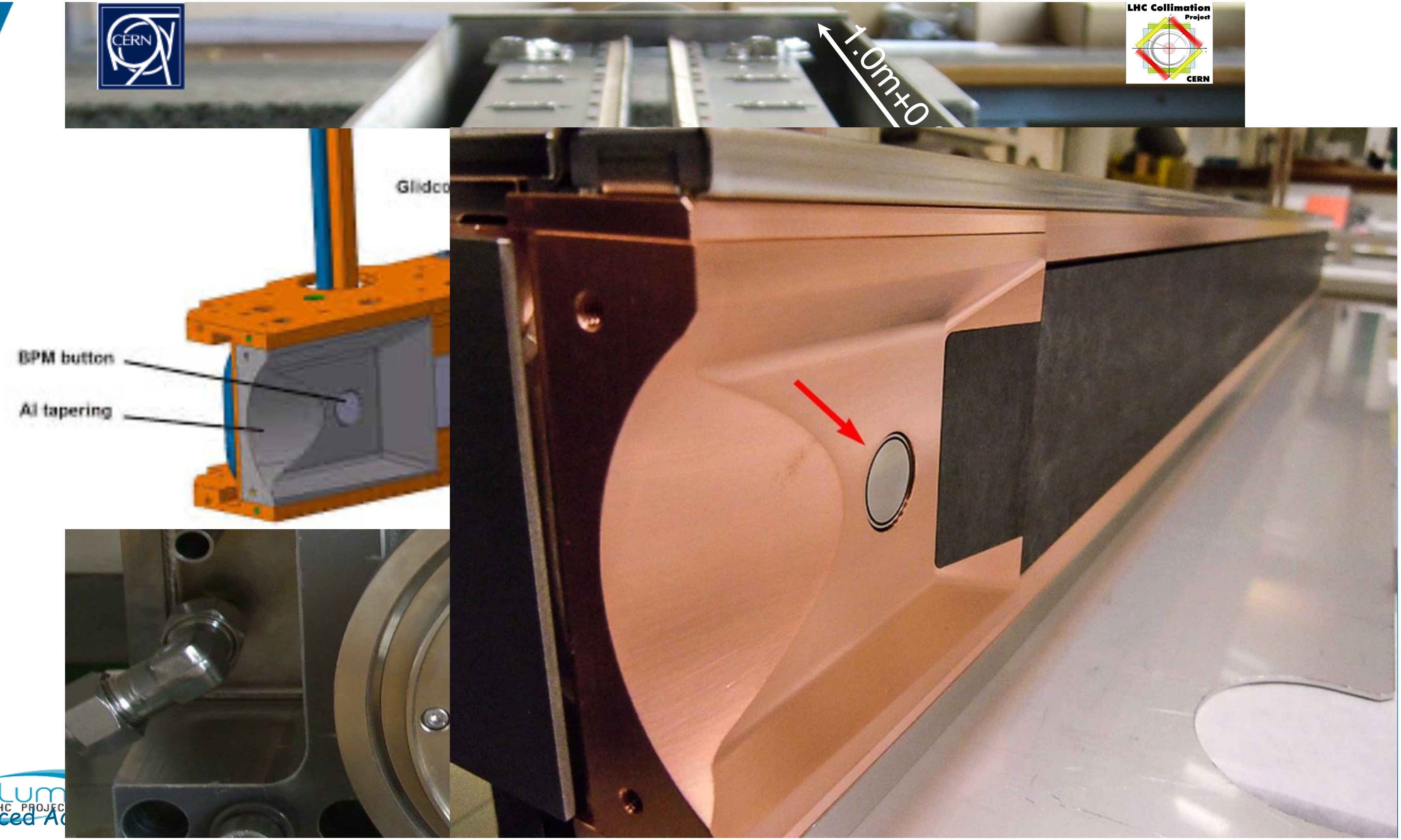




Assure high machine efficiency by protecting cold magnets

- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need **good statistical accuracy** at limiting loss locations;*
  - → *simulate only halo particles that interact with collimators, not the core.*
- Design challenge:
  - → *59 collimator per beam along 27 km; **multi-stage cleaning**;*
  - → *2 jaw design for 3 collimation planes: horizontal, vertical and skew;*
  - → *impact parameters in the sub-micron range;*
  - → *beam proton **scattering** with different collimator materials.*




BPM button
Al tapering

LHC collimation system layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

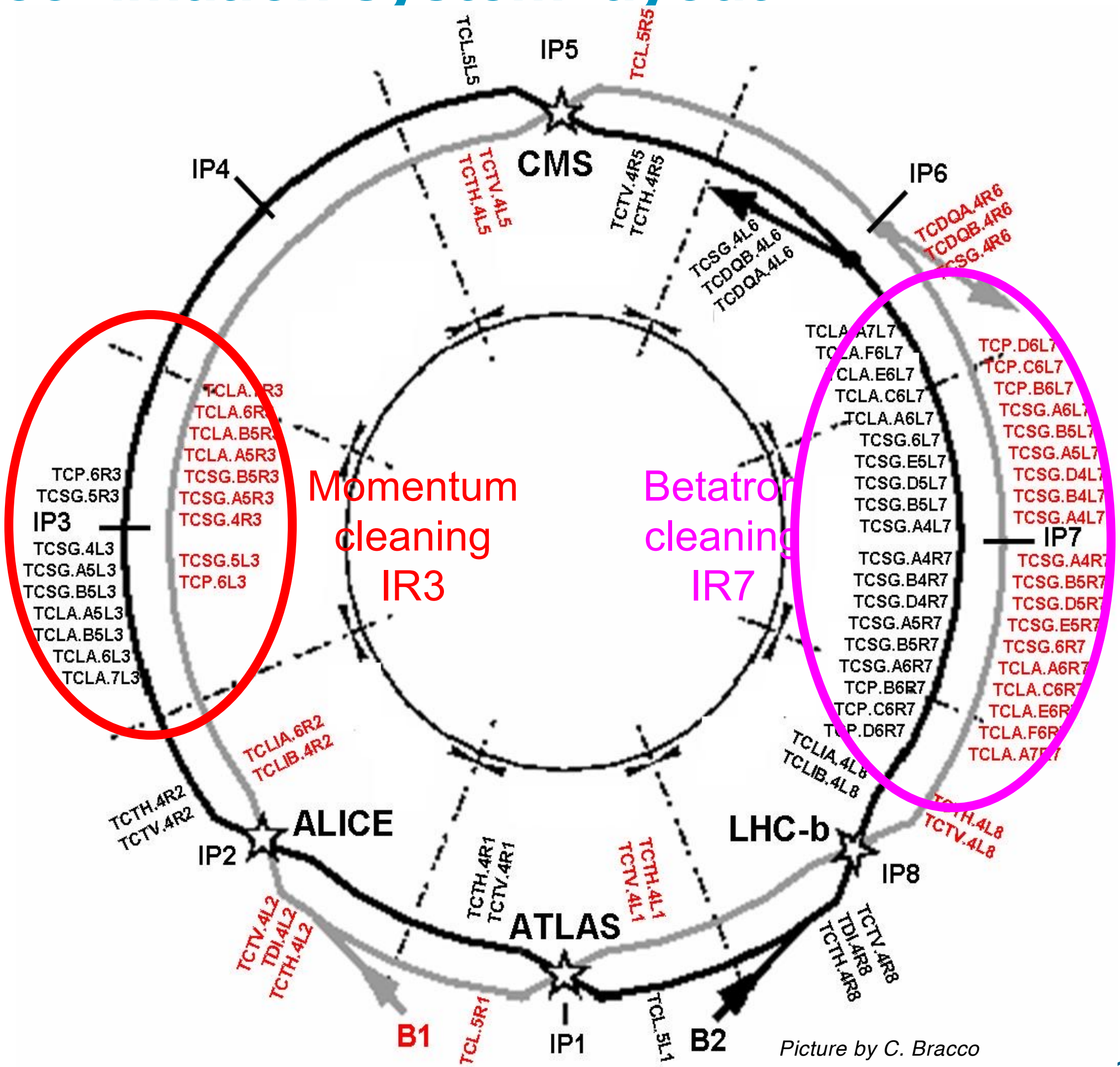
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

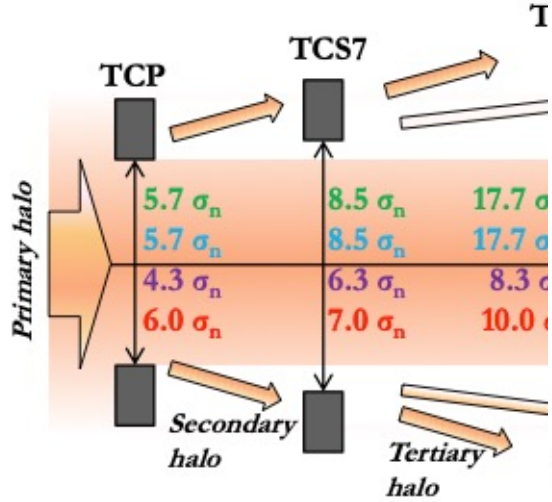
Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 118 collimators (108 movable).
Two jaws (4 motors) per collimator!



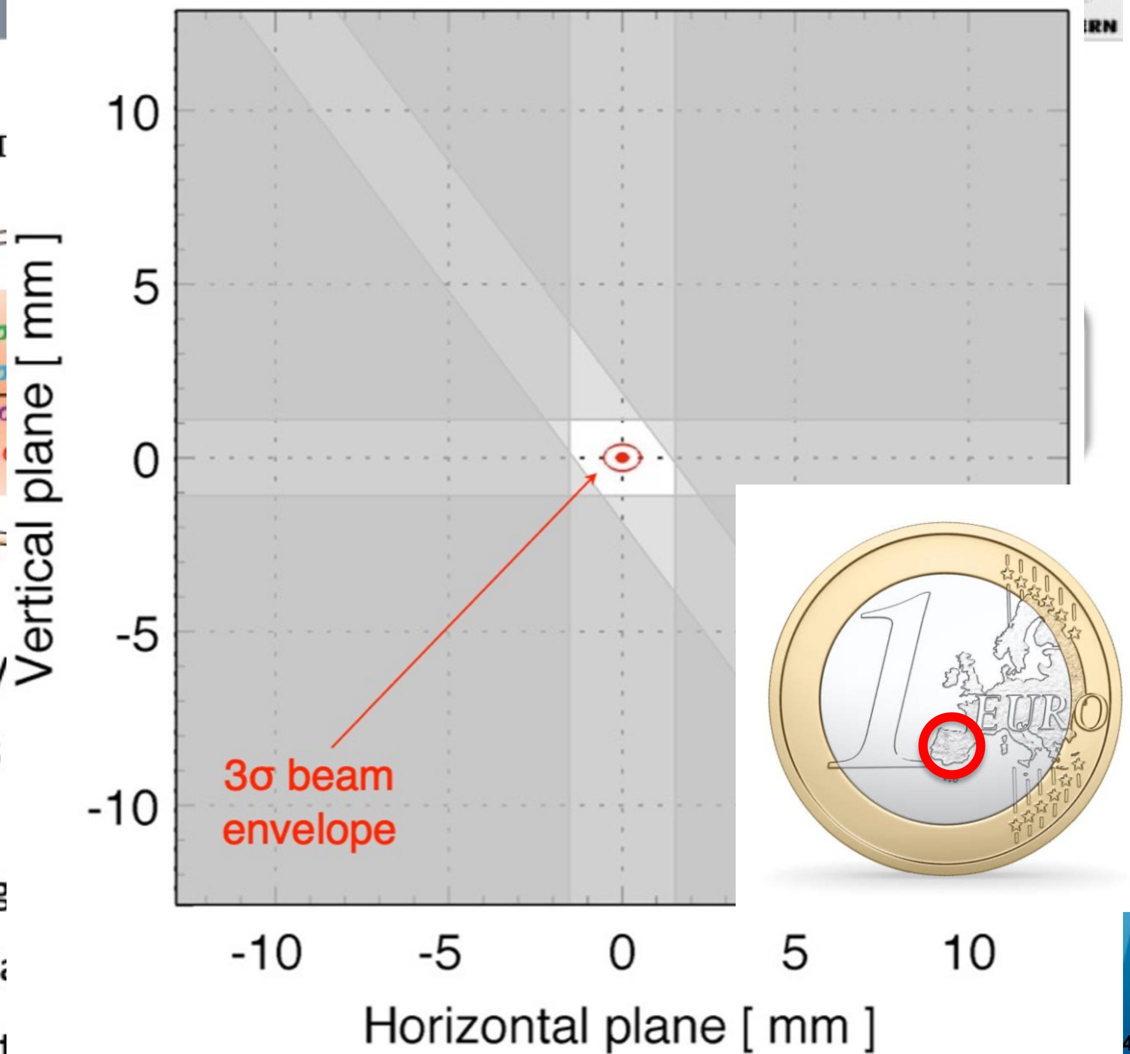
Picture by C. Bracco

σ calculated with emittance = 3.5μm

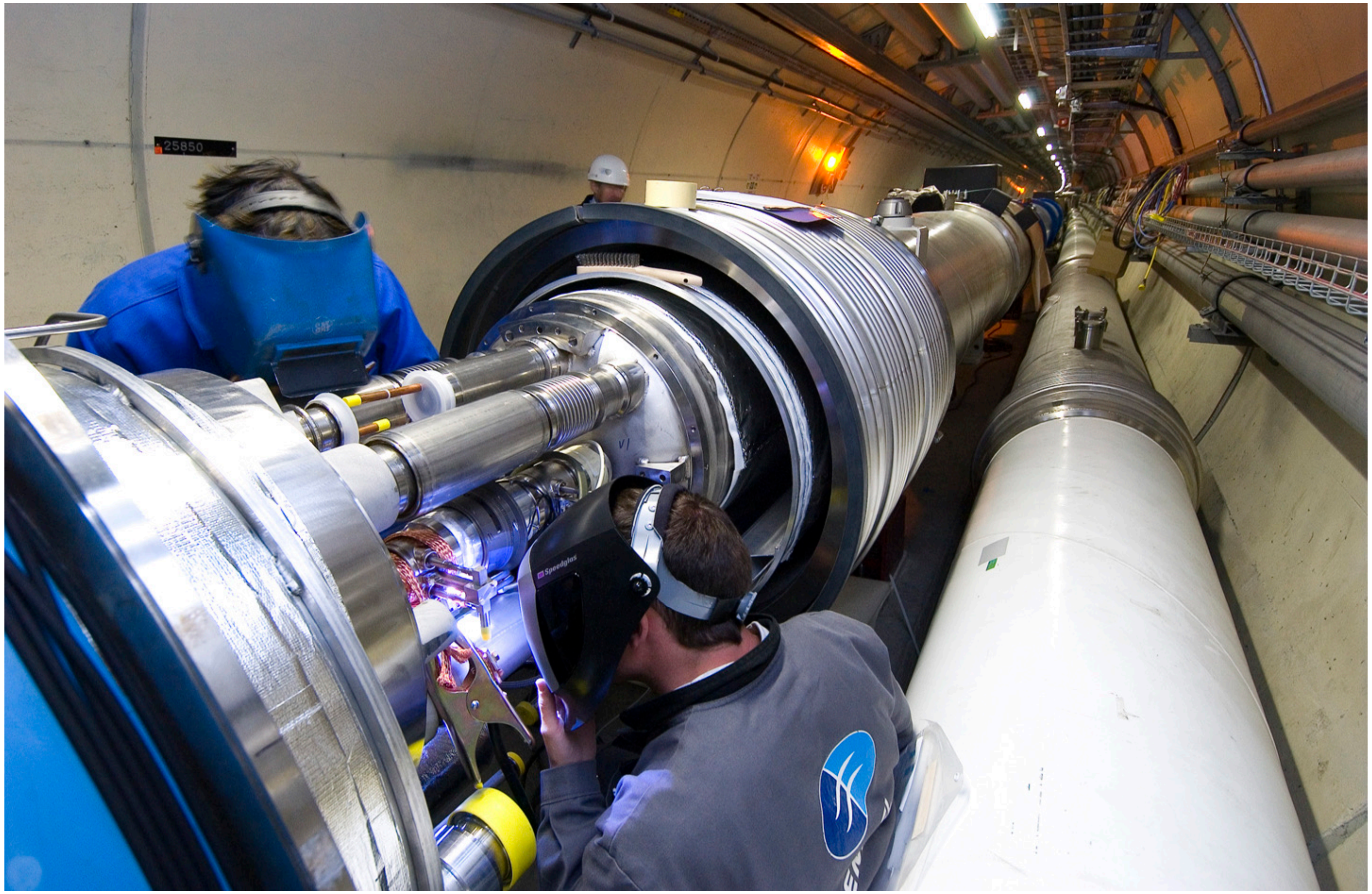


- Multi-stage collimation sy
- Collimation hierarchy has **protection and cleaning**
  - **Protection:** avoid damag
  - **Cleaning:** removal of un
- Aperture that we can prot

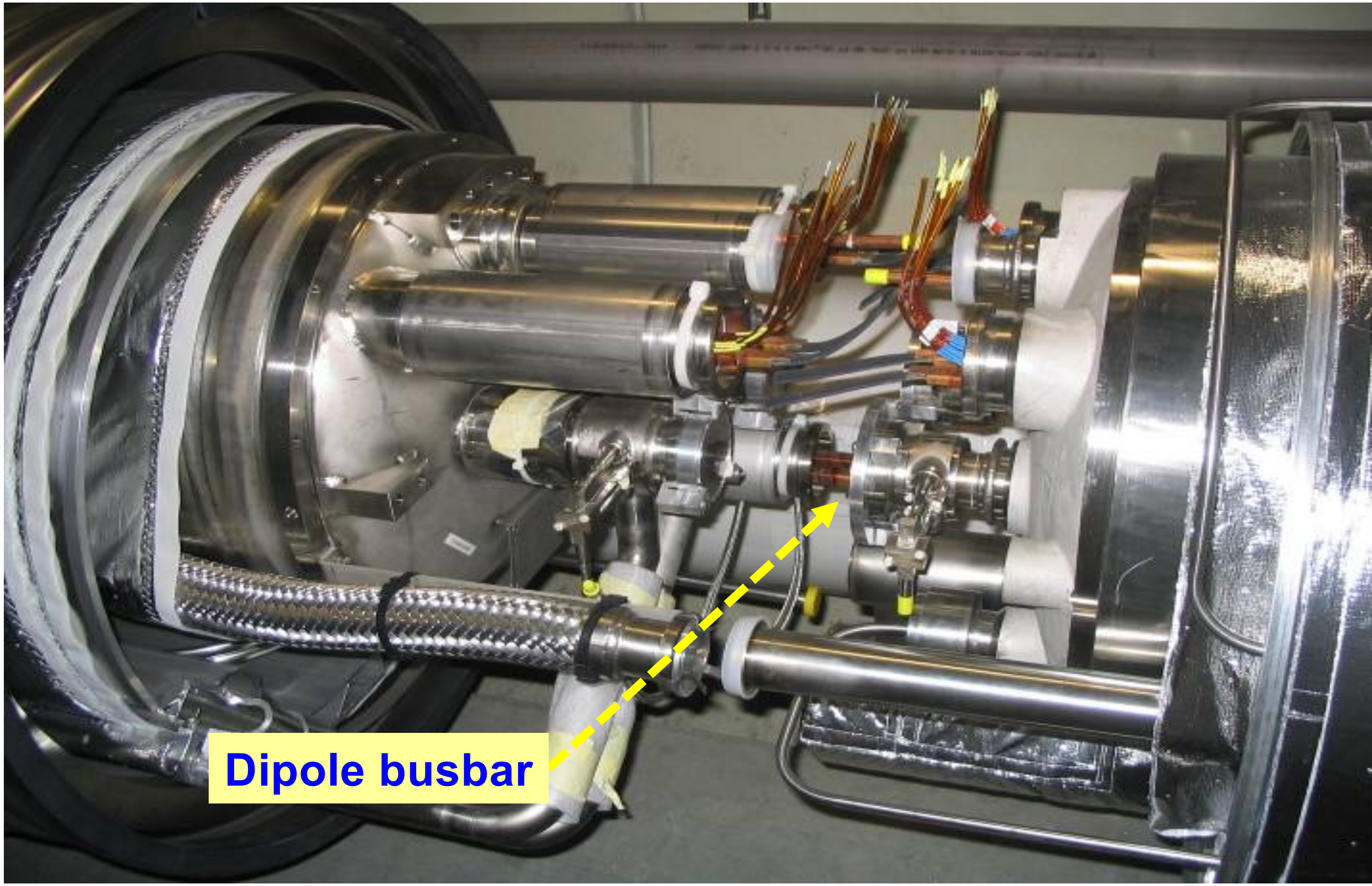
Transverse cuts from H, V and S primary collimators in IR7



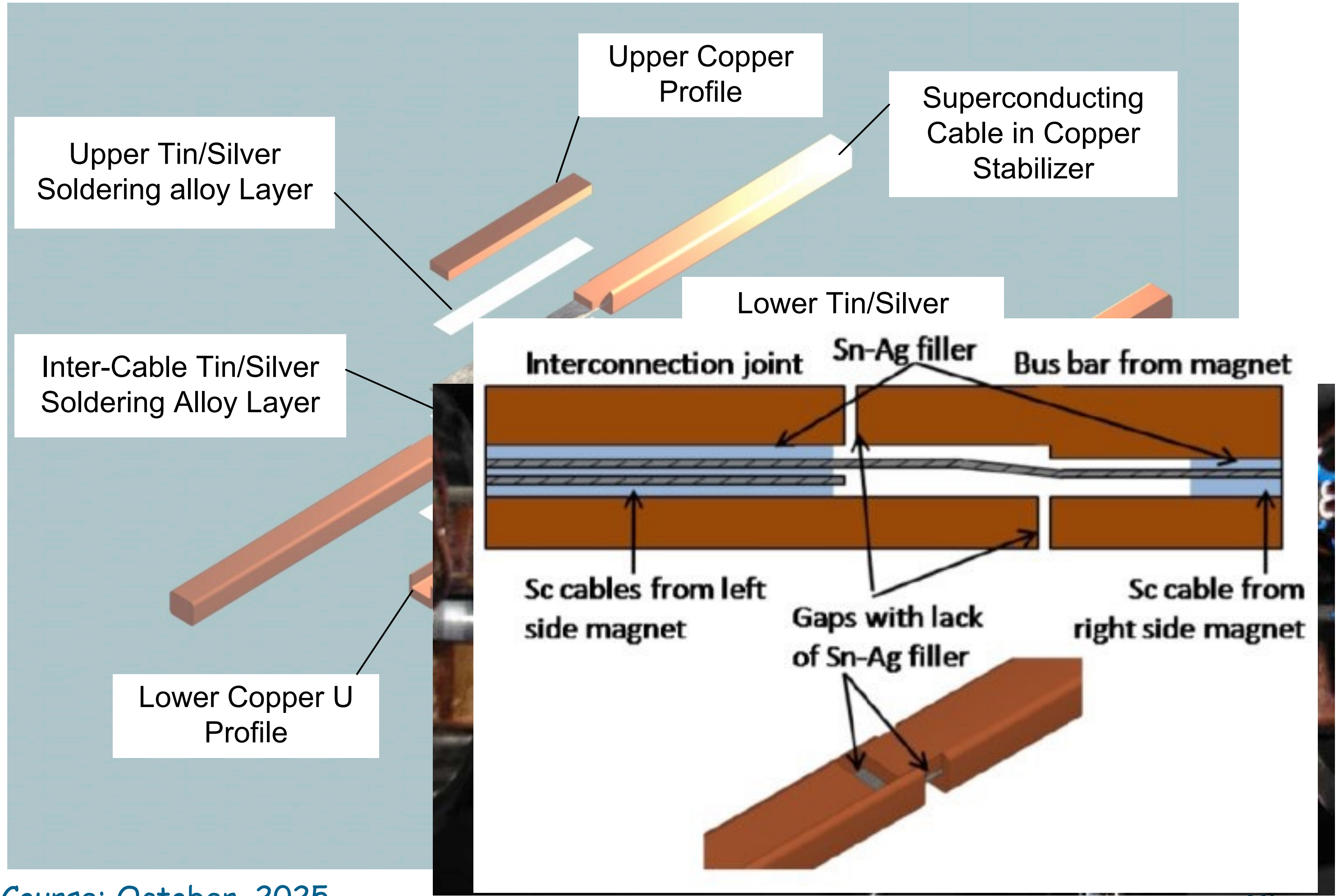
Operational Experience - 2008 Incident → Interconnects



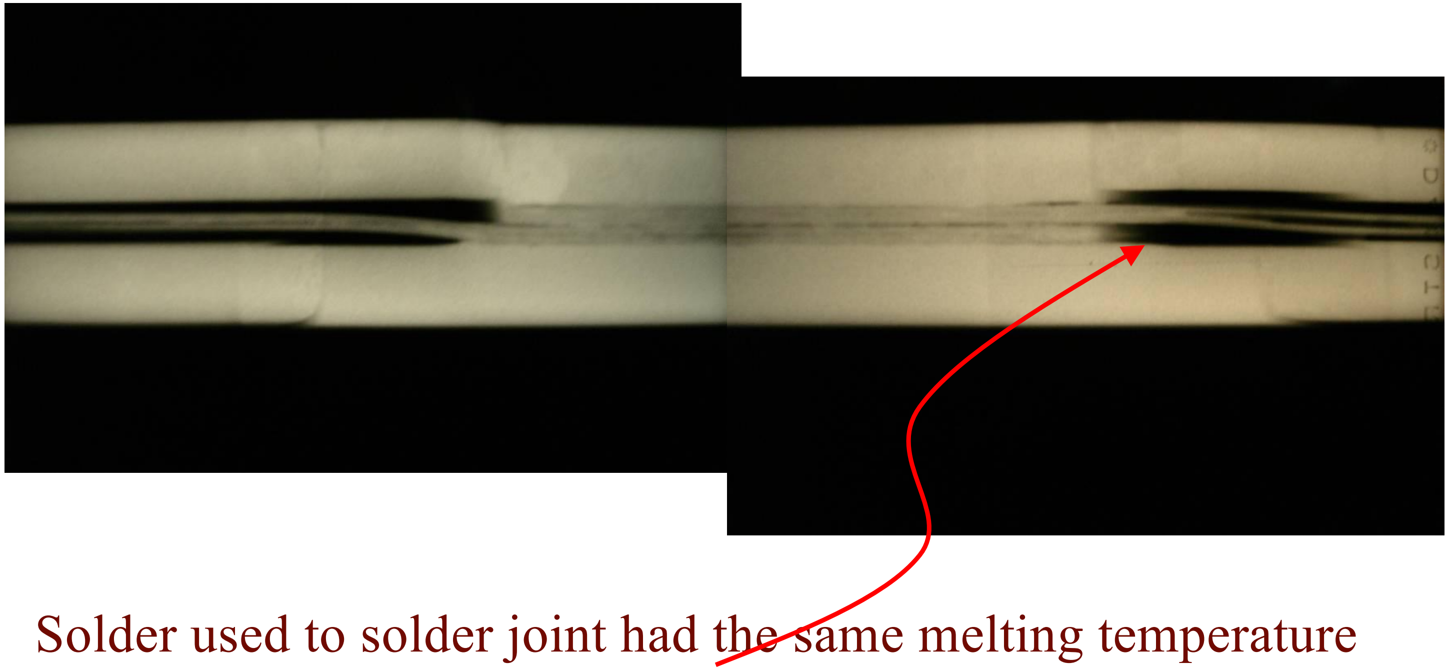
Magnet Interconnections:



2008 Incident: Busbar splice



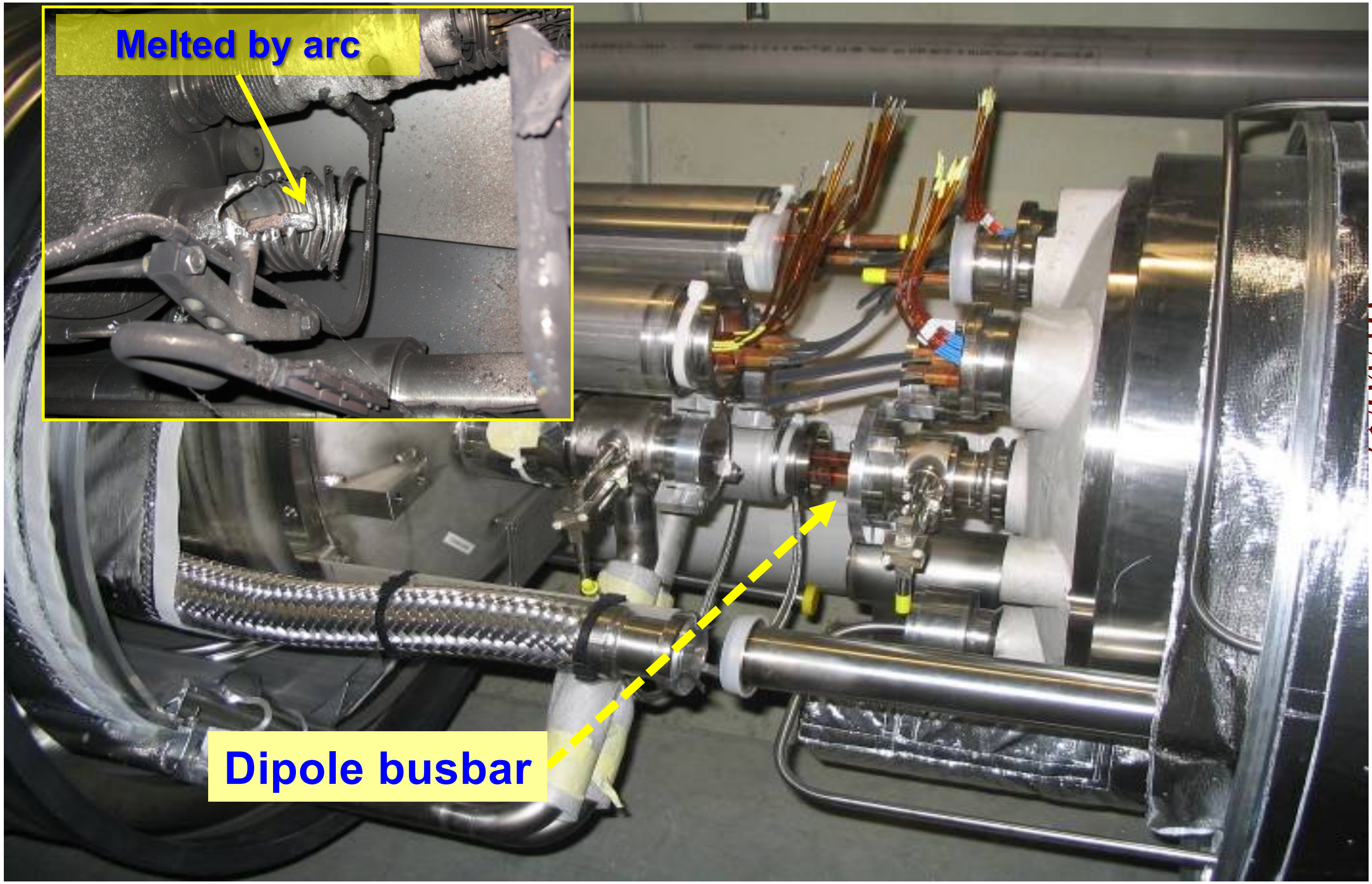
Joint Quality:



Solder used to solder joint had the same melting temperature as solder used to pot cable in stablizer

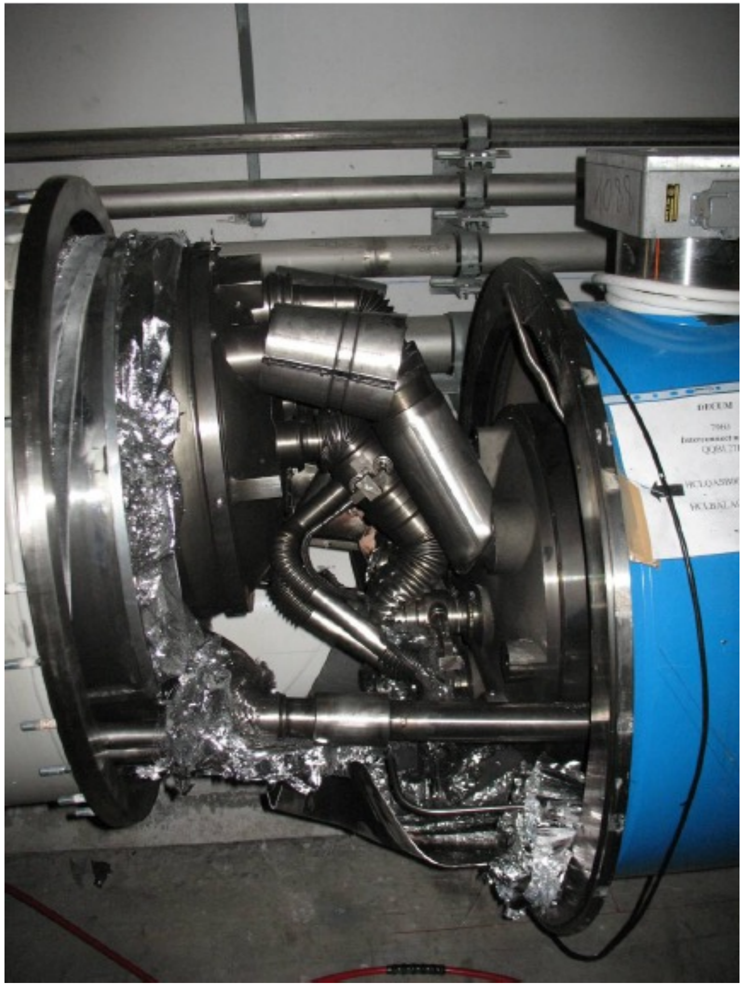
⇒Solder wicked away from cable

Magnet Interconnections:

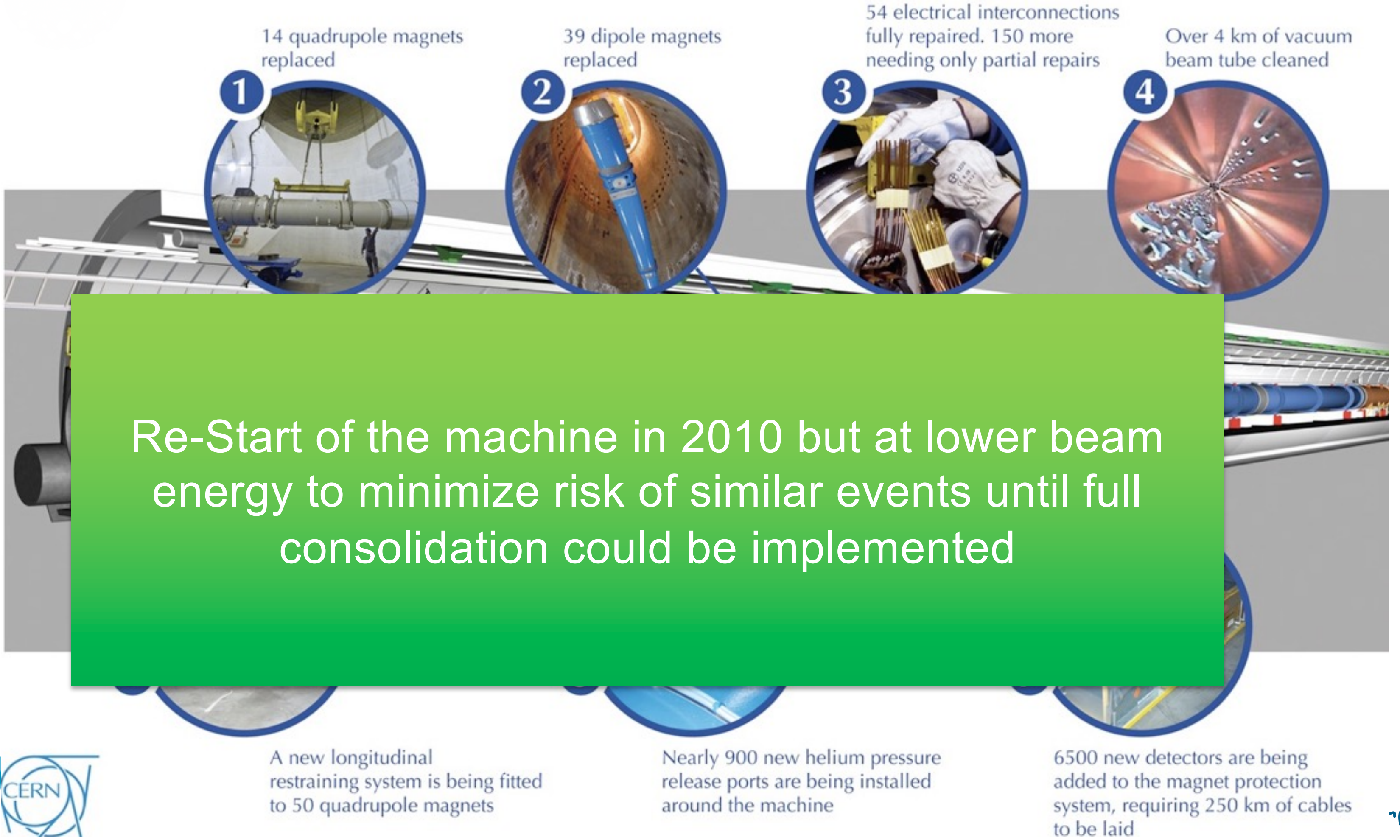


2008 Incident: Collateral Damage

2008 Incident: Collateral Damage



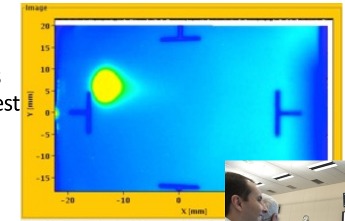
The LHC repairs in detail



Re-Start of the machine in 2010 but at lower beam energy to minimize risk of similar events until full consolidation could be implemented

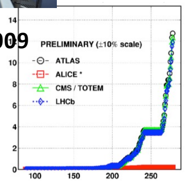
LHC RUN-I Timeline

August 2008
First injection test



September 10, 2008
First beams around

November 29, 2009
Beam back



October 14 2010
1e32
248 bunches

April 2010
Squeeze to 3.5 m

June 28 2011
1380 bunches (50ns)

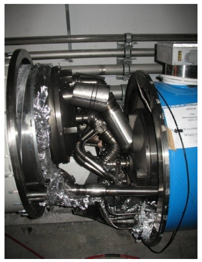
1380

6 June, 2012
6.8e33

4 July, 2012
Higgs discovery

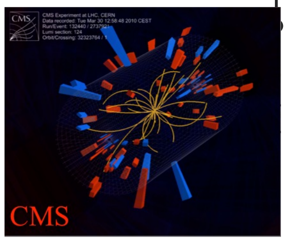
End of RunI
23.3fb^{-1}

2008 | 2009 | 2010 | 2011 | 2012

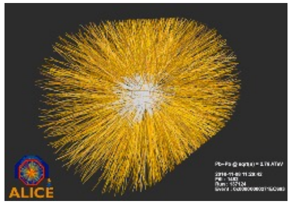


September 19, 2008
'Incident'
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at 3.5 TeV

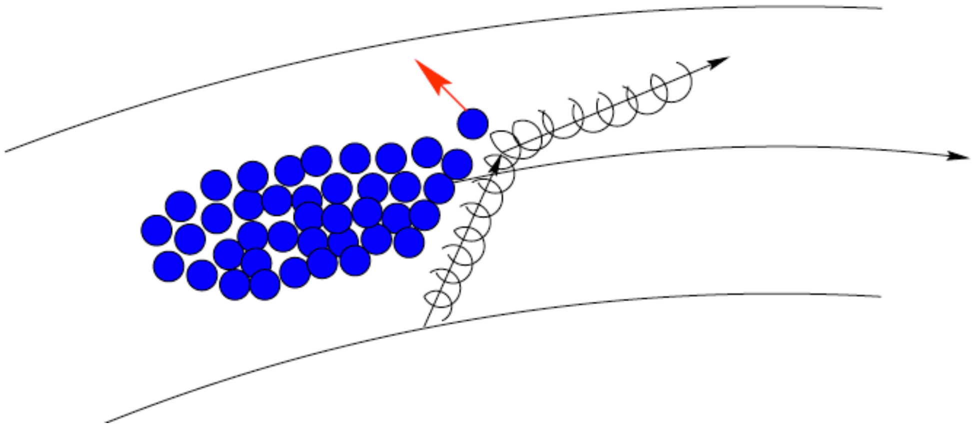


November 2010
Ions



18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

Accelerator Vacuum Requirements



Main gases desorbed from vacuum surface are:
H_2; CH_4; CO; CO_2; H_2O and noble gases

Ultra-High	< 10^{-7} Pa @ 5K
Vacuum	< 10^{-9} Pa @ 293K

[1 Pa = 0.0075 Torr]

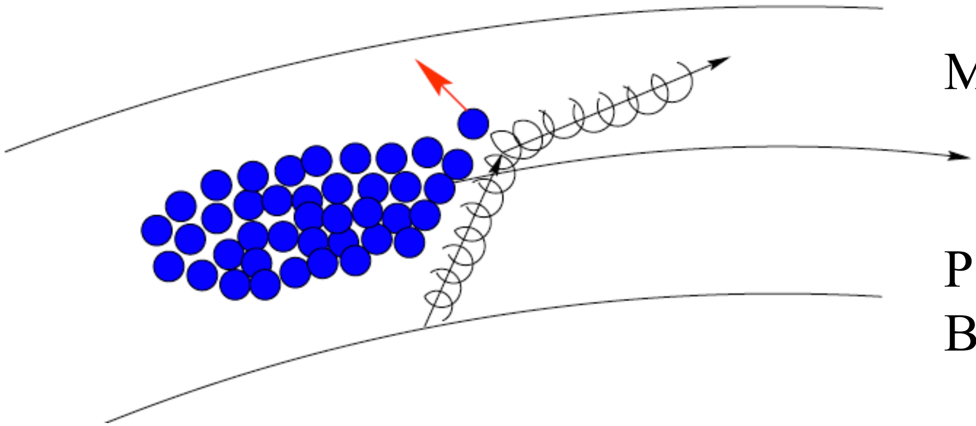
Ideal Gas: $P \cdot V = n \cdot R \cdot T$ [R = 8.31 J mol^{-1} K^{-1}; n = amount of substance in moles]

10^{-9} Pa @ 293K ➔ 2.4 10^{11} molecules / m^3; 10^{-7} Pa @ 5K ➔ 1.5 10^{15} molecules / m^3

➔ The pressure in the LHC beam pipes is about one hundred times lower than on the Moon

➔ **It is the emptiest space in the Solar System!**

Accelerator Vacuum Requirements



Main gases desorbed from vacuum surface are:
H_2; CH_4; CO; CO_2; H_2O and noble gases

Plus photons from
Black Body radiation and Synchrotron Radiation

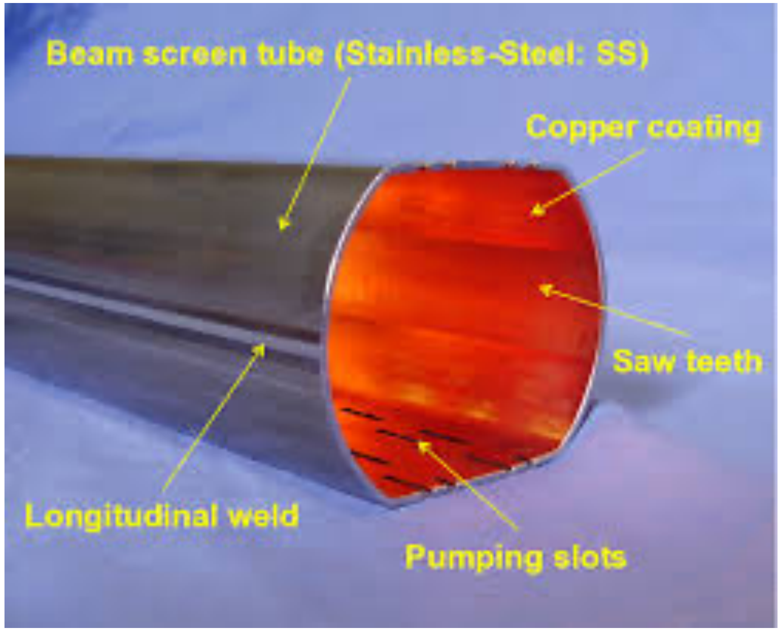
Ultra-High Vacuum $< 10^{-7}$ Pa @ 5K
$< 10^{-9}$ Pa @ 293K

[1 Pa = 0.0075 Torr]

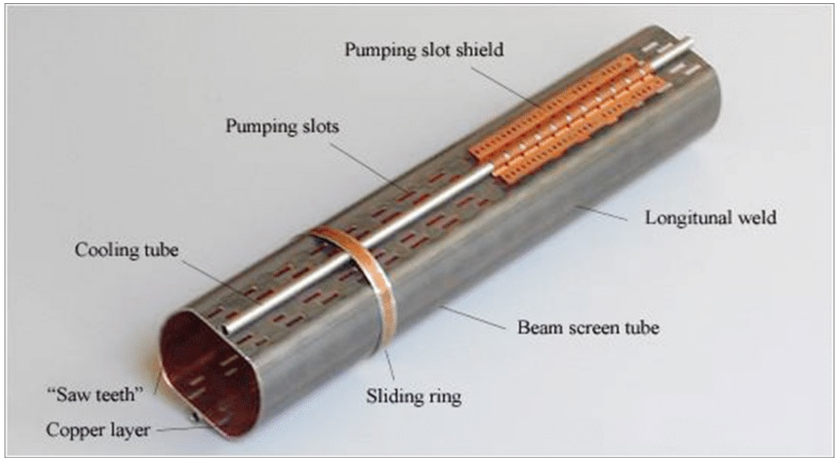
Example LEP

Beam Gas 10^{-10} Torr	τ_g = **200 hours**
Beam thermal photons	τ_{tp} = **80 hours**
Beam synchrotron photons	τ_{sp} = **134 hours**
Total	τ_{tot} = **40 hours**

LHC Beam Screen Concept



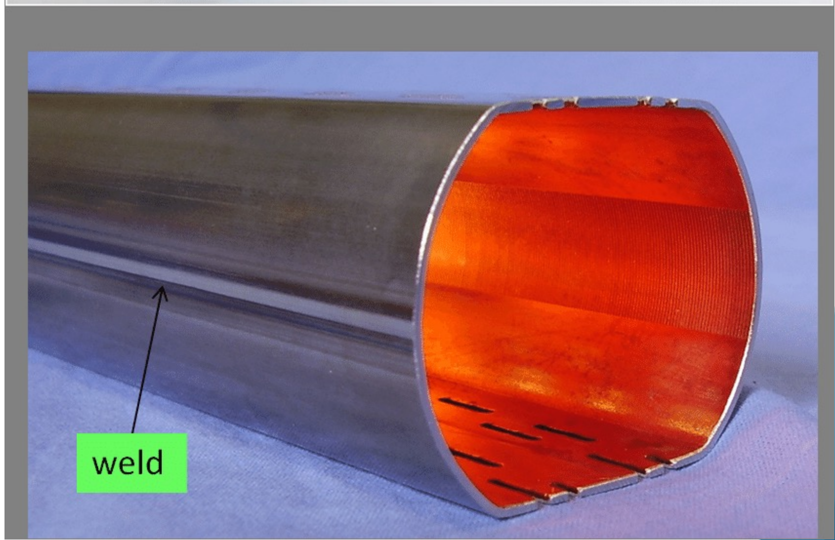
Cryo Pump



Cooled at 5K to 20K

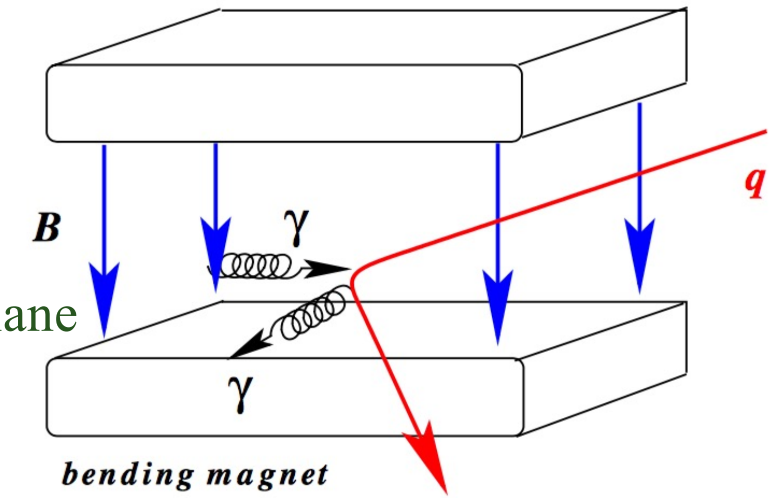
Delicate Impedance evaluations!

➔ Random slot distribution



Synchrotron: Synchrotron Radiation

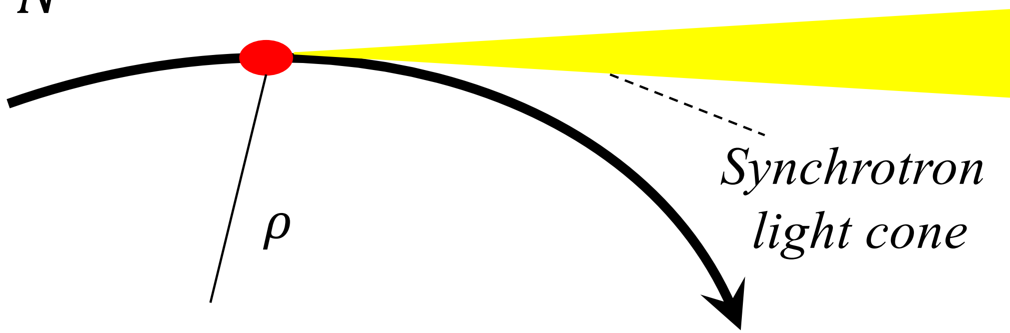
- Quantum Picture:



→ -radiation fan in the bending plane
-opening angle $\propto \frac{1}{\gamma}$

- $P \propto \frac{\gamma^4}{\rho^2} \cdot q^2 \cdot N$

- $\langle E_\gamma \rangle \propto \frac{\gamma^3}{\rho}$



- polarized

Synchrotron: Synchrotron Radiation

Examples:

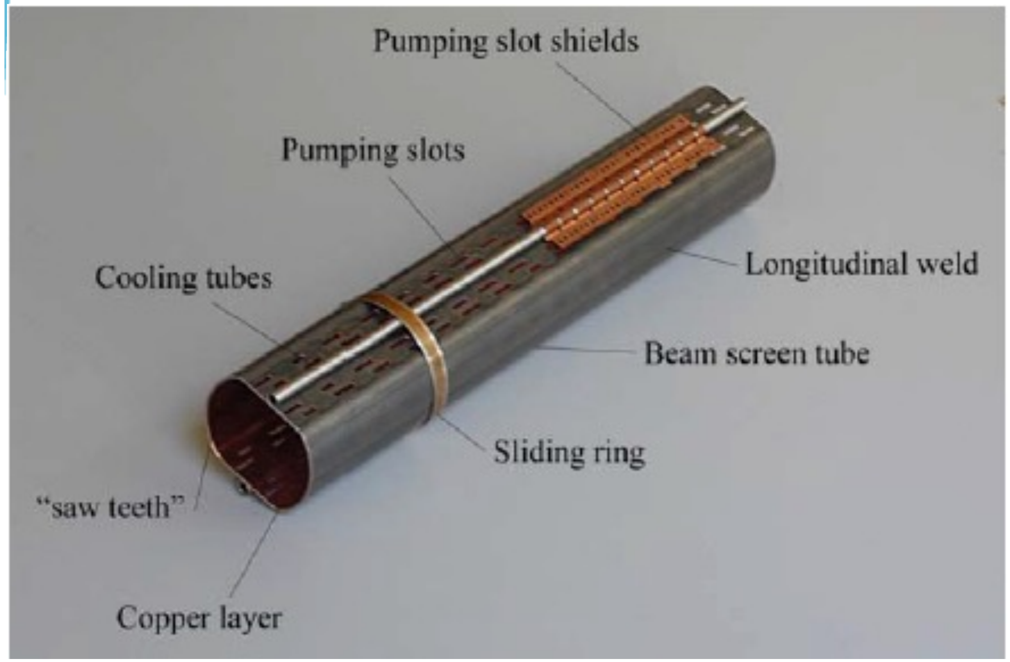
	E [GeV]	ρ [km]	*N* [10^{12}]	*U* [MeV]	*P* [MW]	E_γ [keV]
X-rays: *LEP 1*	45	3.1	4.7	260	2.1	90
γ-rays: *LEP 2*	100	3.1	4.7	2800	23	715
UV light: *LHC*	7000	3.1	312	0.007	0.005	0.04

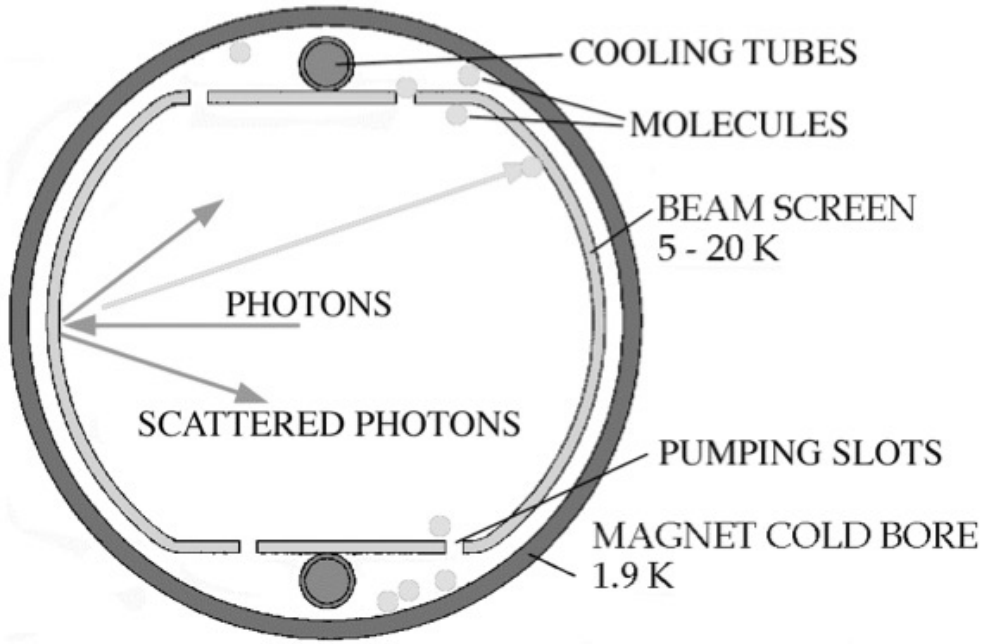
LHC is one of the first hadron colliders that features useful SR light!

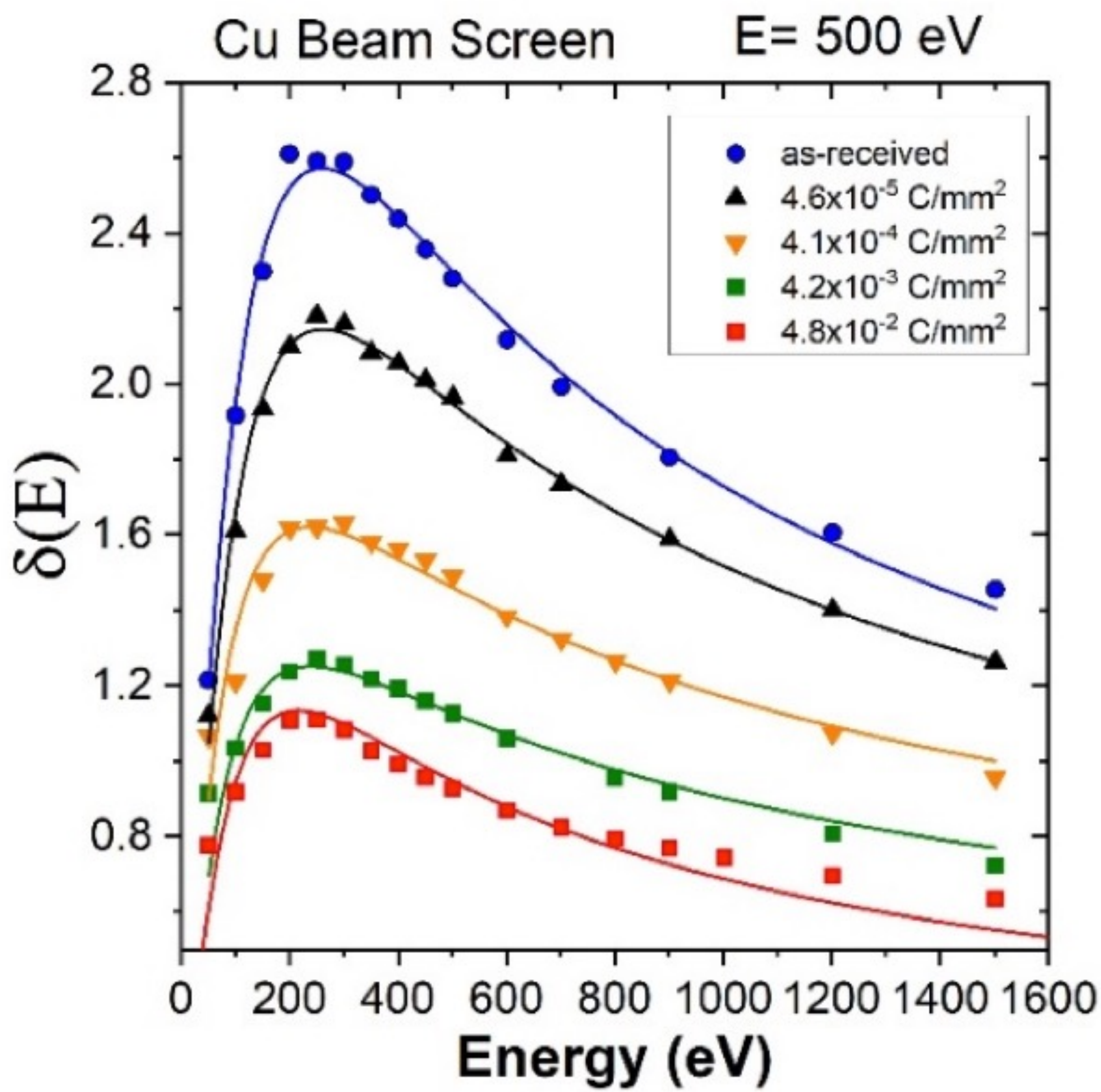
Higher energy machines will face the challenge of significant SR light in a superconducting environment!!!

SR inside SC Magnet and Beam Vacuum

- If hitting the cold bore of the magnets, the heat deposition of the SR photons will have to be compensated / cooled at 1.9K!



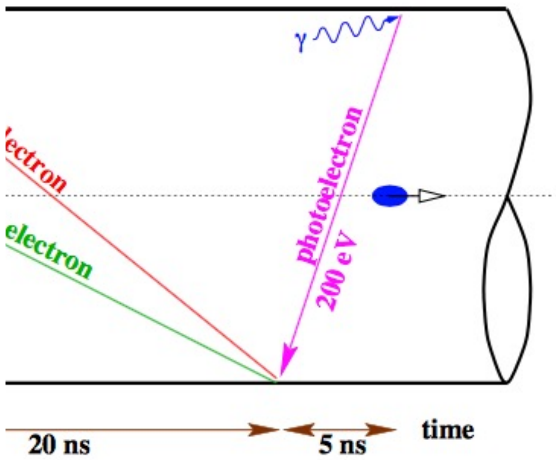




) in the LHC

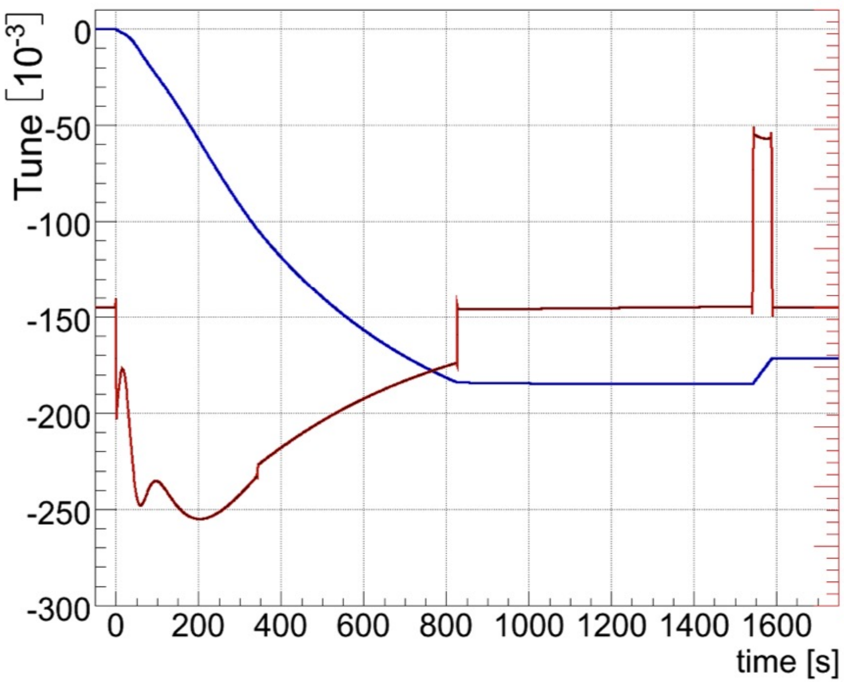
tipacting and electron cloud build up

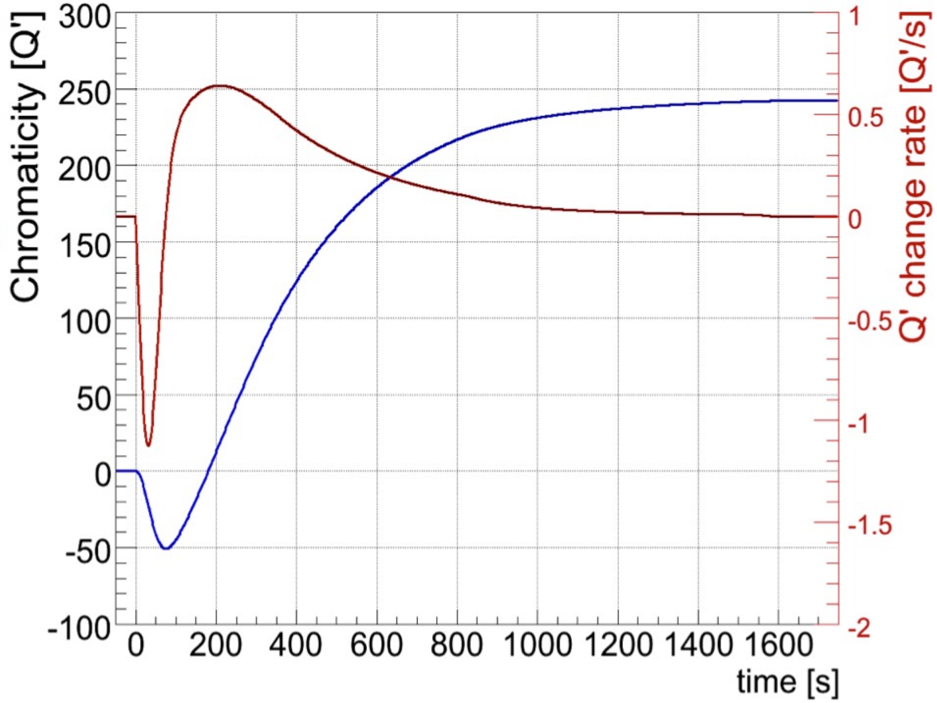
or beam instabilities and beam losses



Suppressed with large bunch spacing
➔ 50ns

Beam Diagnostics: Tune and Chromaticity

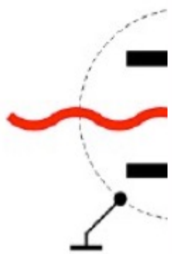


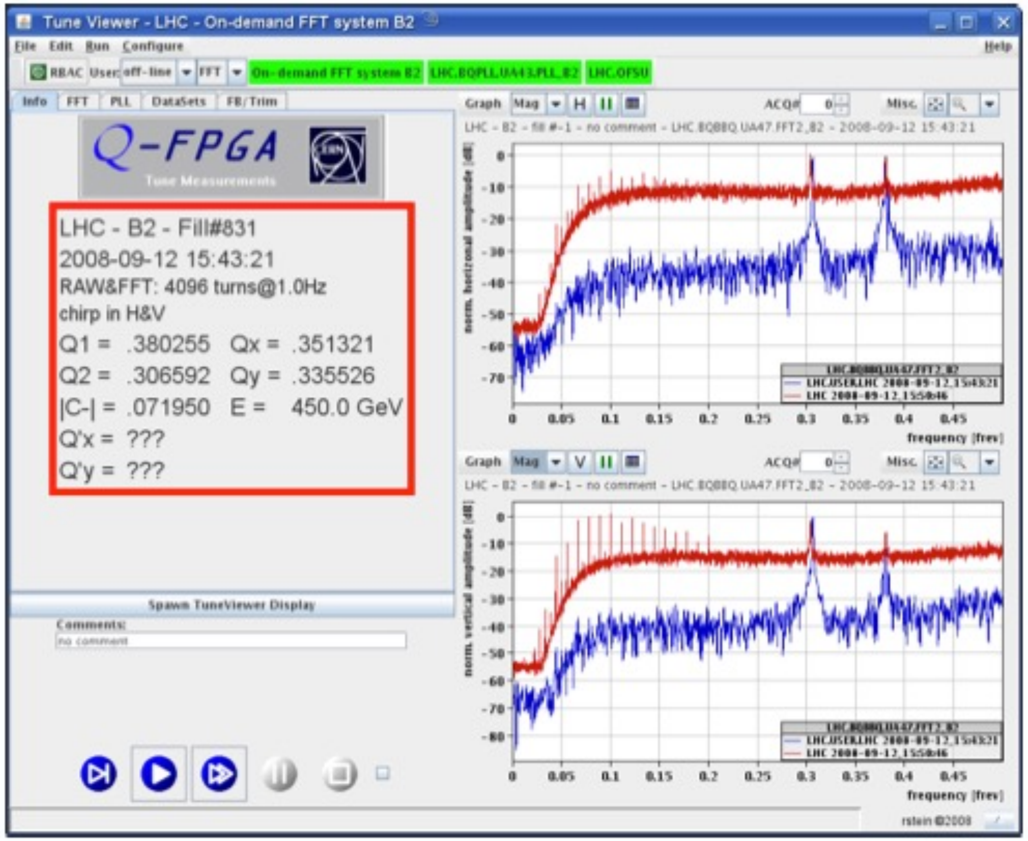


- Uncorrected perturbations are about 200 times the required stability!!!
- But change rates are relatively slow ➔ one can foresee a feedback loop, provided one can measure continuously the tune and chromaticity

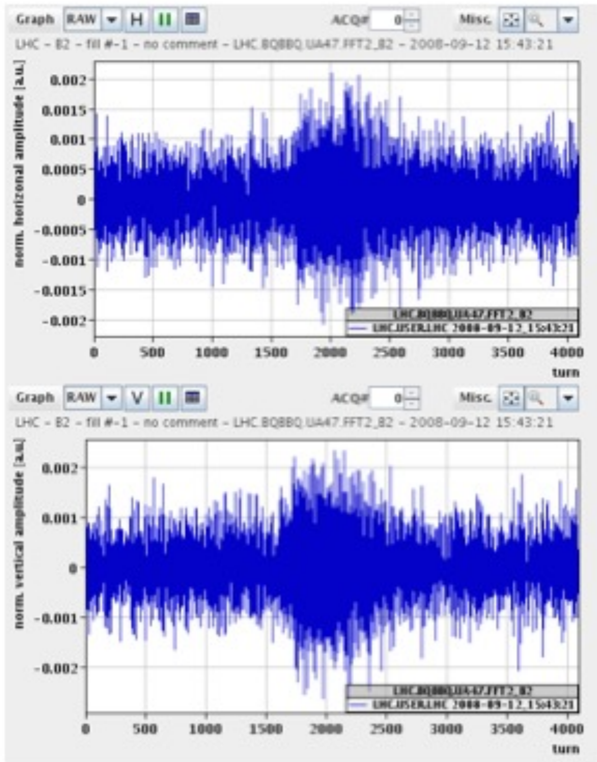
BBQ: Diode Based Base Band Tune

AC-coupled





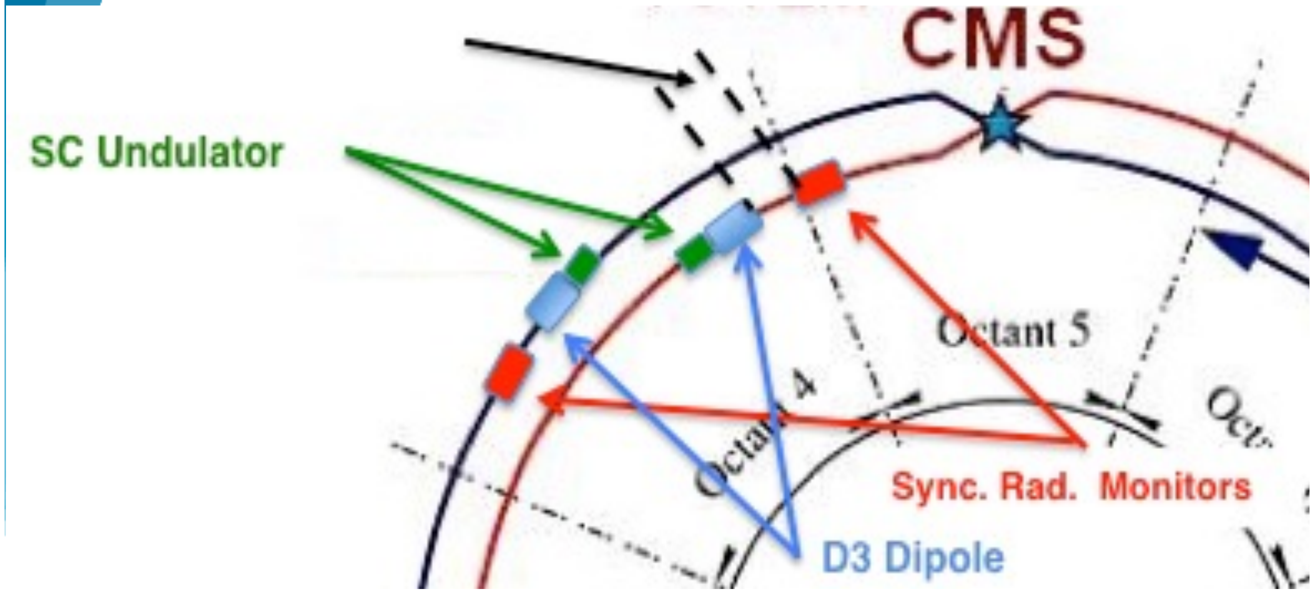
(a) TuneViewer Screen-shot - Beam Spectra

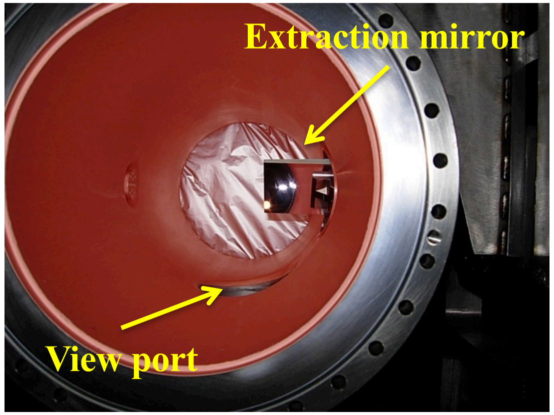


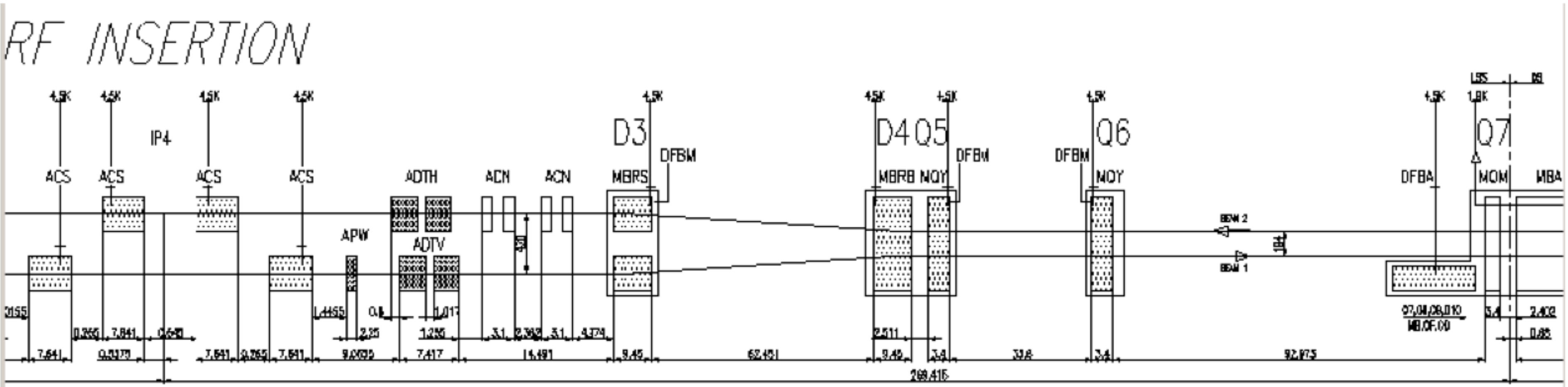
(b) Turn-by-Turn Data

FFT or PLL functionalities:

SR Diagnostics for LHC

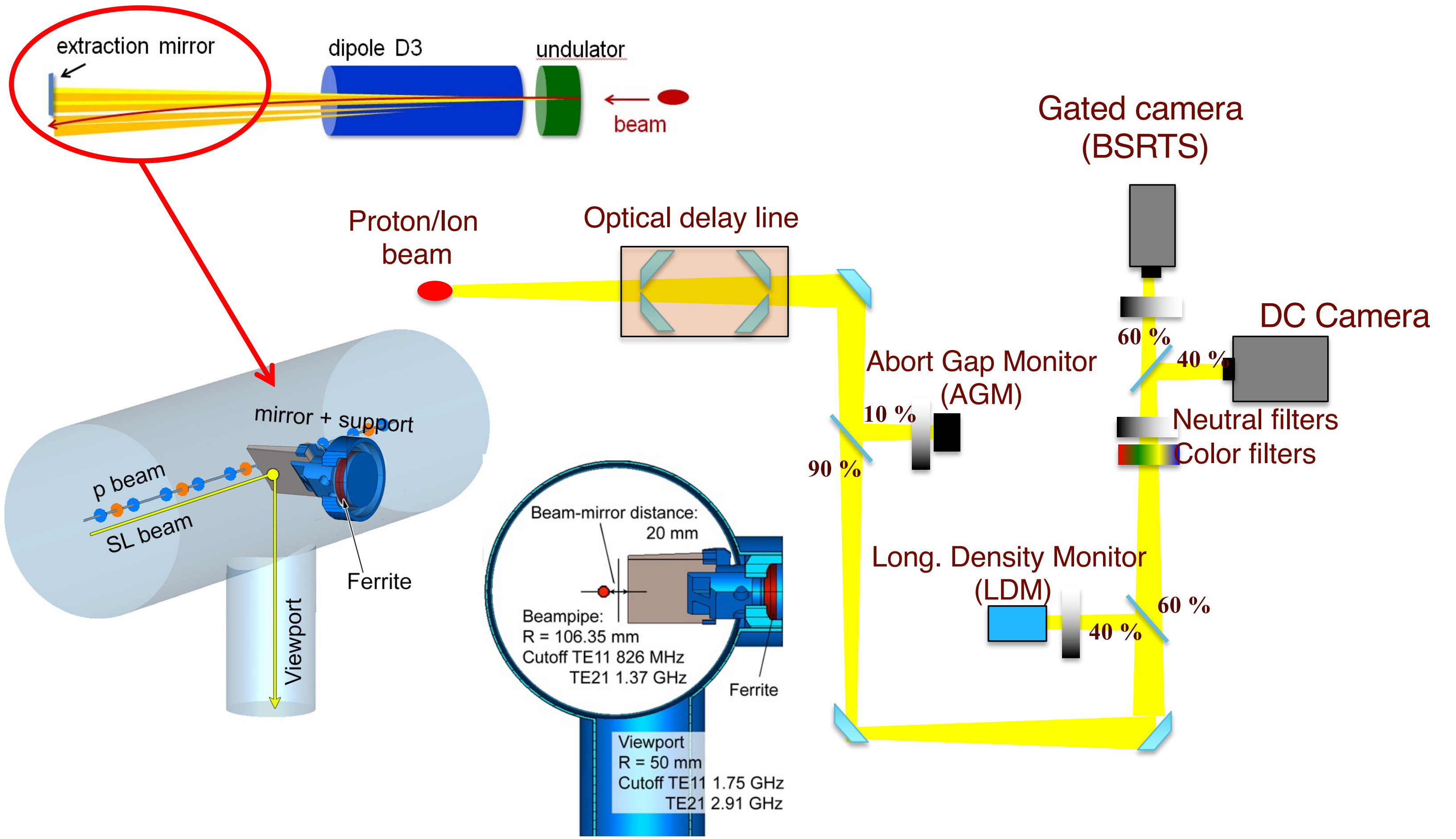




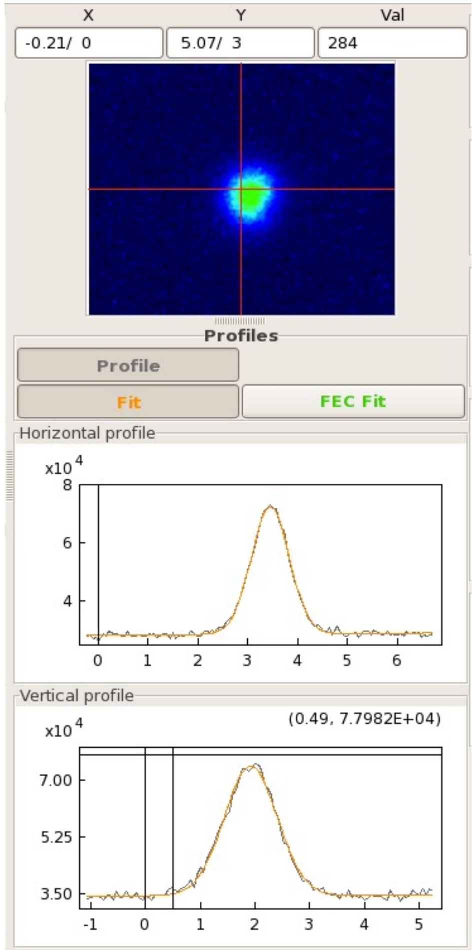


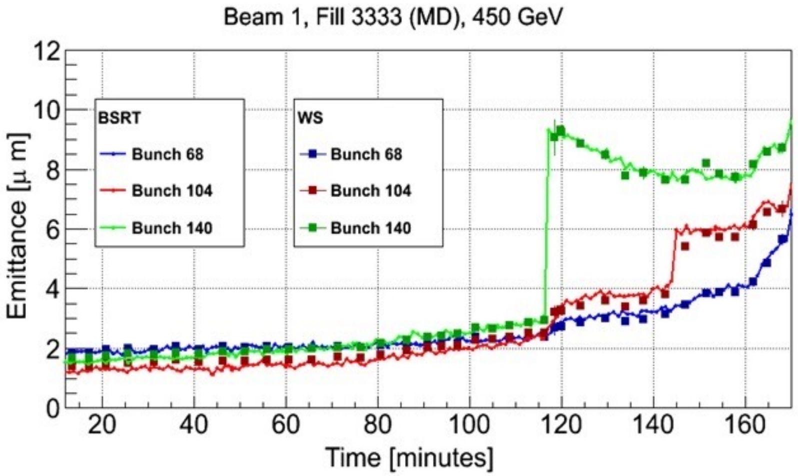
BSRT Hardware Schema

M. Wendt, ICFA mini-Workshop on Impedance, Erice 2014

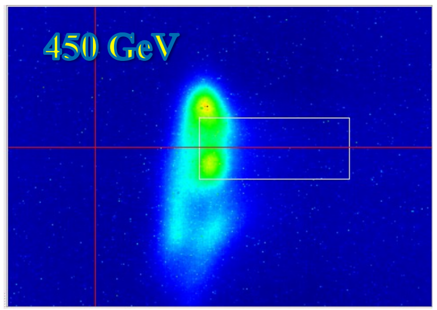


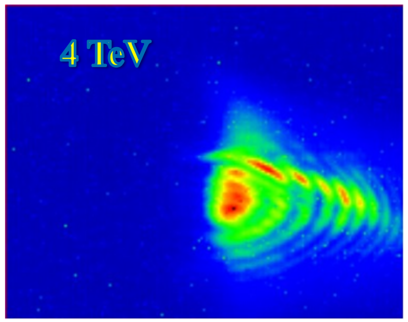
BSRT Operation





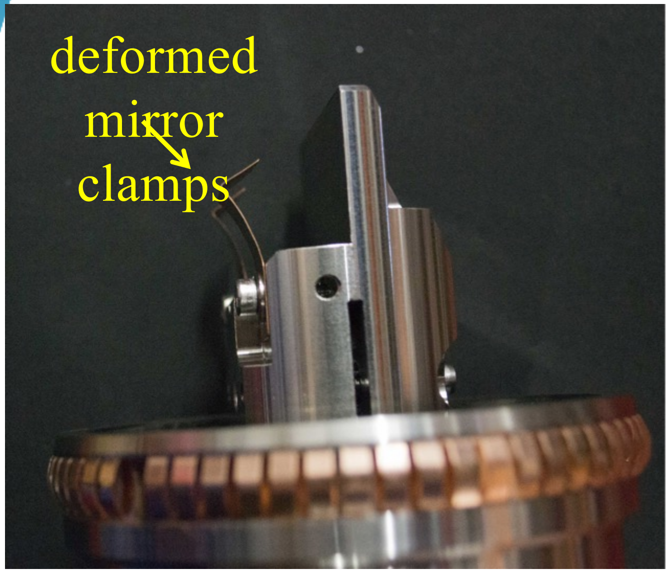
…however, the BSRT (particular system B2) showed "unphysical" beam profiles at the start of the operation!



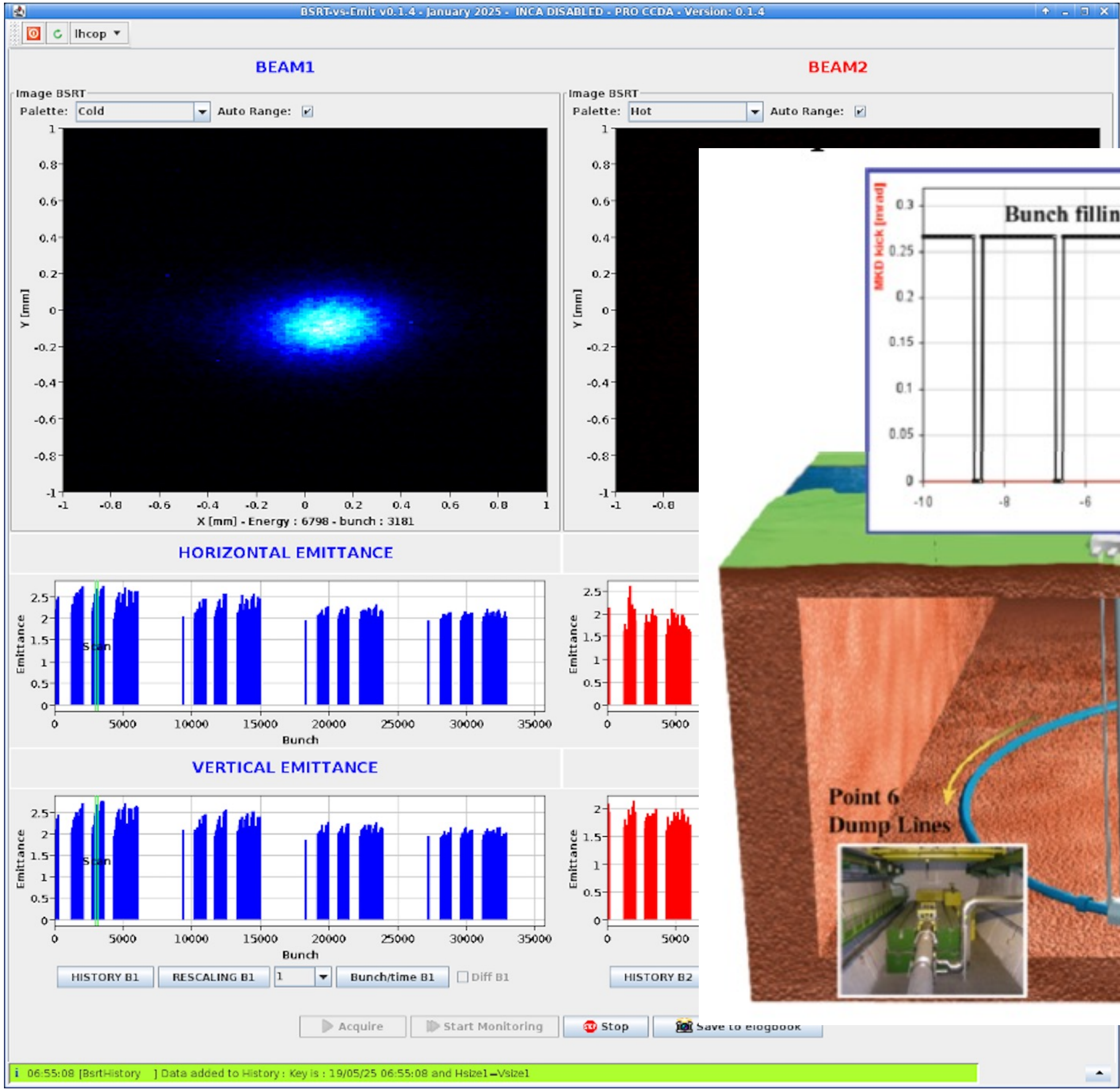


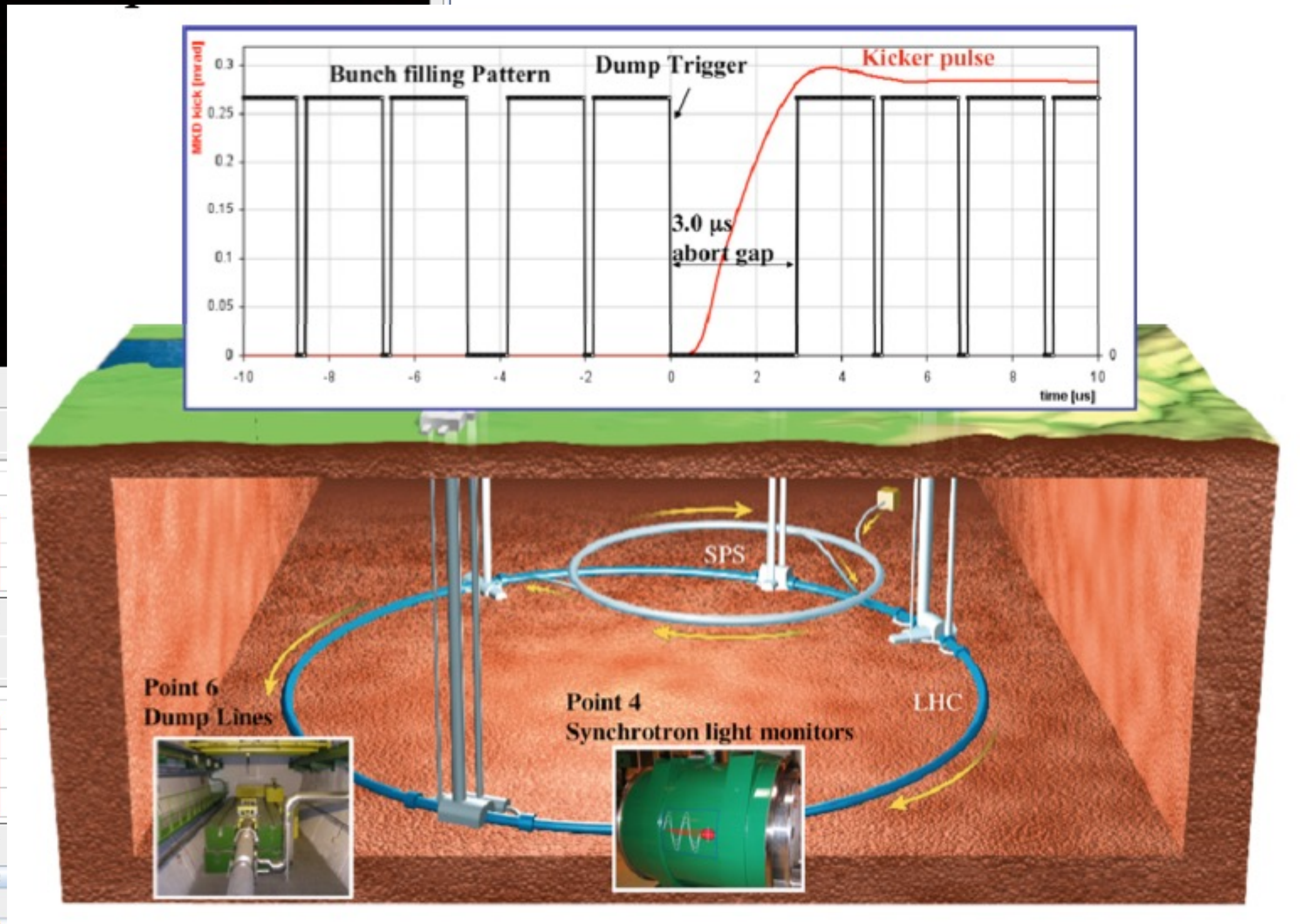
Extraction Mirror Issues

- Experimented with various mirror material options
  - Si & glass bulk, different coatings, etc.



Control Room Application

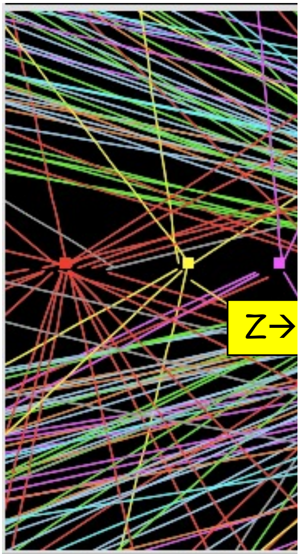


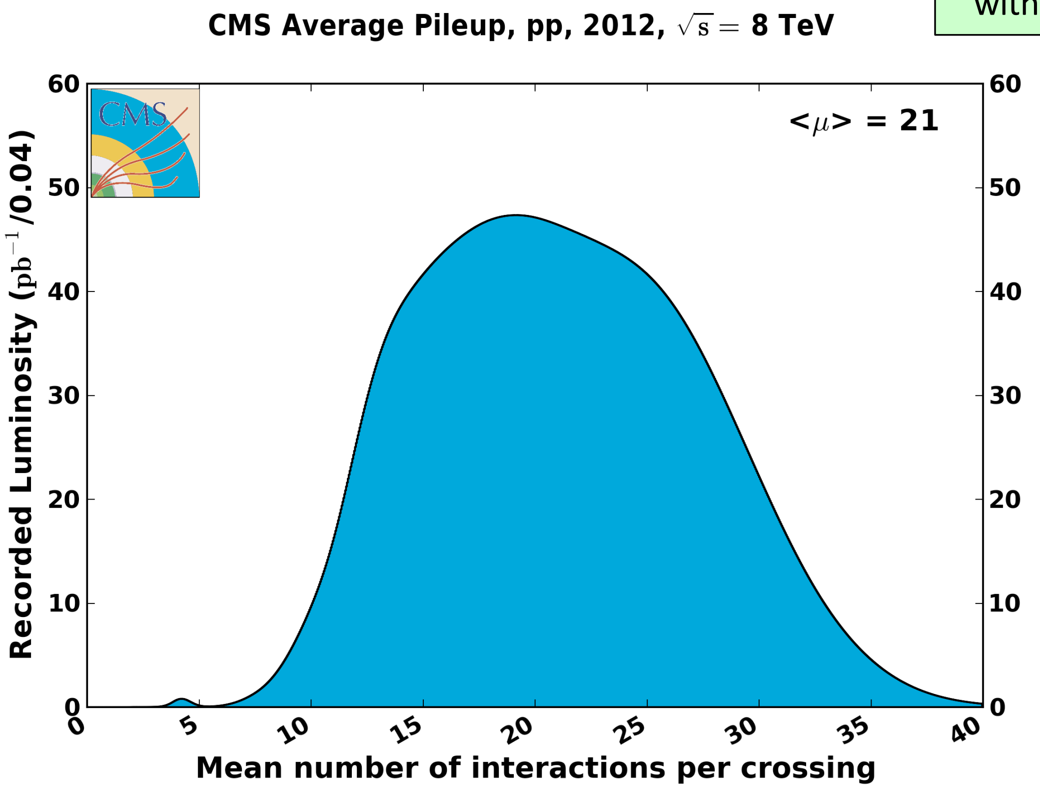


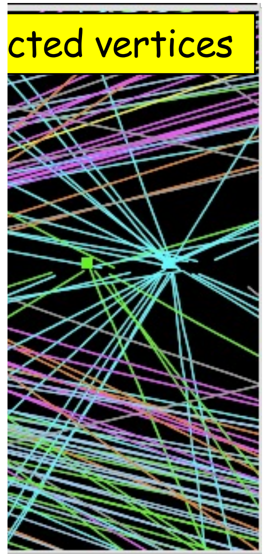
Run 1 operation: 50ns bunch spacing

- Electron cloud: strongly suppresses electron cloud effects!
  - → reduced beam conditioning times
- Highe[r]
  - → in… n^{-2} s^{-1}

2012: ~30 events/xing at beginning of fill with tails up to ~ 40.





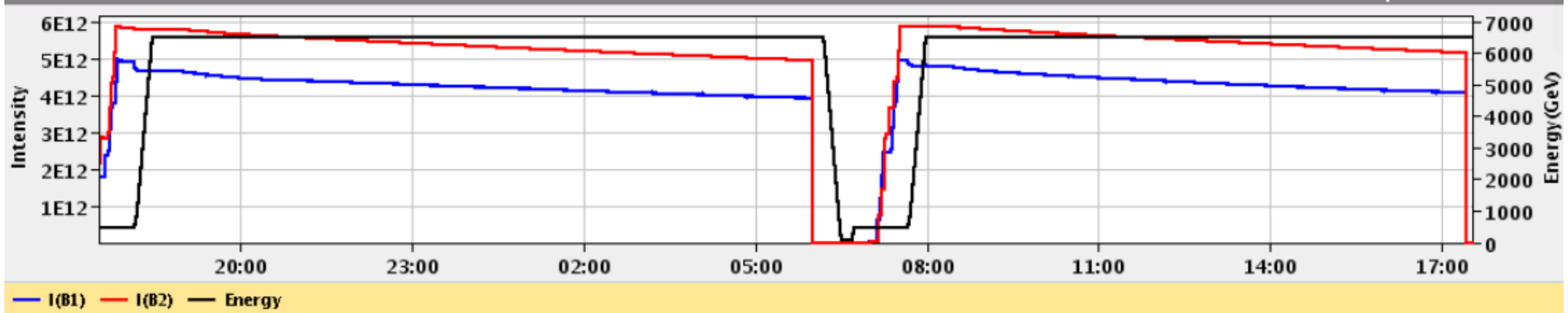


A nice day at the LHC: 50ns & low intensities

14–Jun–2015 17:31:07	Fill #: 3858	Energy: 6502 GeV	I(B1): 0.00e+00	I(B2): 0.00e+00
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi [(ub.s)^-1]	0.008	0.000	0.177	0.000
BRAN Luminosity [(ub.s)^-1]	0.0	0.0	0.0	0.0
Fill Luminosity (nb)^-1	3496.834	0.000	3279.892	191.862
BKGD 1	0.170	0.036	0.806	0.141
BKGD 2	0.000	0.000	3.384	3.144
BKGD 3	0.250	0.023	1.610	0.054

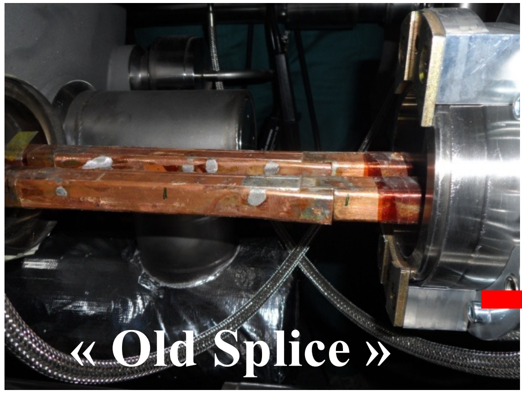
LHCb VELO Position OUT Gap: 58.0 mm | RAMP DOWN | TOTEM: PHYSICS

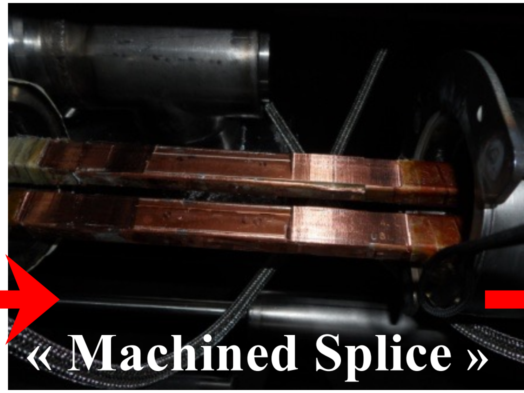
Performance over the last 24 Hrs | Updated: 17:31:07

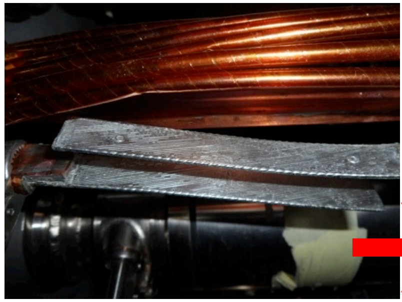


50 bunches @ 50ns per beam ➔ Two OP programmed dumps. About 20 hours in stable beams.

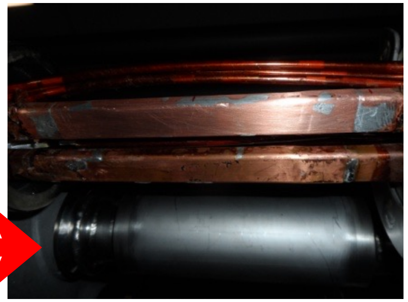
LS1 Consolidation:



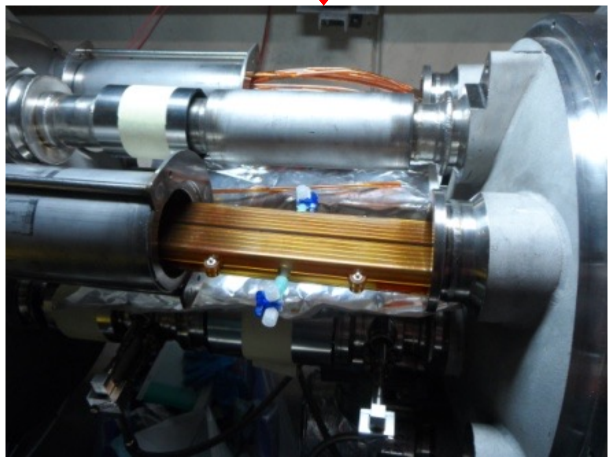




« Cables »



« New Splice »



« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

Long Shutdown 1: LS1

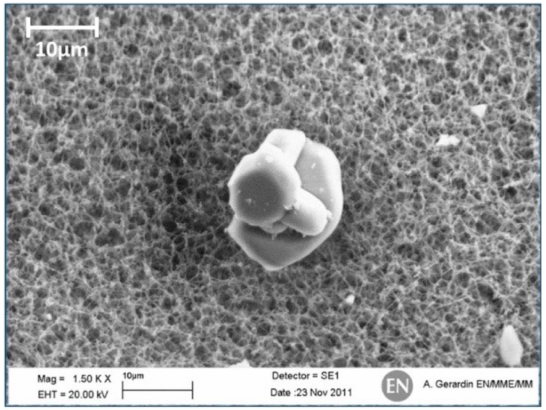
RunII: Main Concerns with 25ns bunch spacing operation:

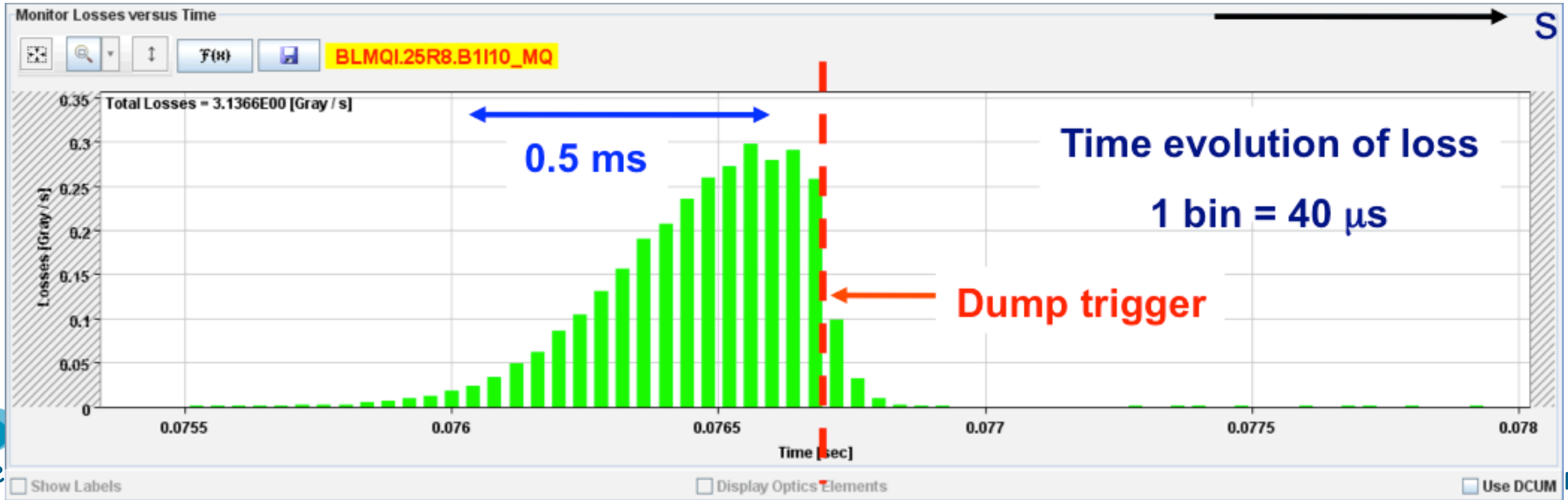
- Higher beam intensities and stored beam energies
- Higher electro-magnetic energy in the magnet system due to higher magnetic fields
- E-cloud scrubbing
- Cryo instability with 144+ bunch trains due to transients in the heat load
- Equipment heating (impedance)
- UFO rate
- QPS boards and R2E ➔machine availability and efficiency!
- Short circuits in protection diode box due to debris ➔ decision to limit energy in Run 2 and DISMAC for LS2

UFOs – Unidentified Falling Objects:

- Sudden local losses
- Rise time of the order of 1 ms.
- Potential explanation: dust particles
  interacting with beam creating scatter losses and
  showers propagating downstream
- Distributed around the ring – arcs, inner triplets, IRs
- Even without quench, preventive dumps by QPS

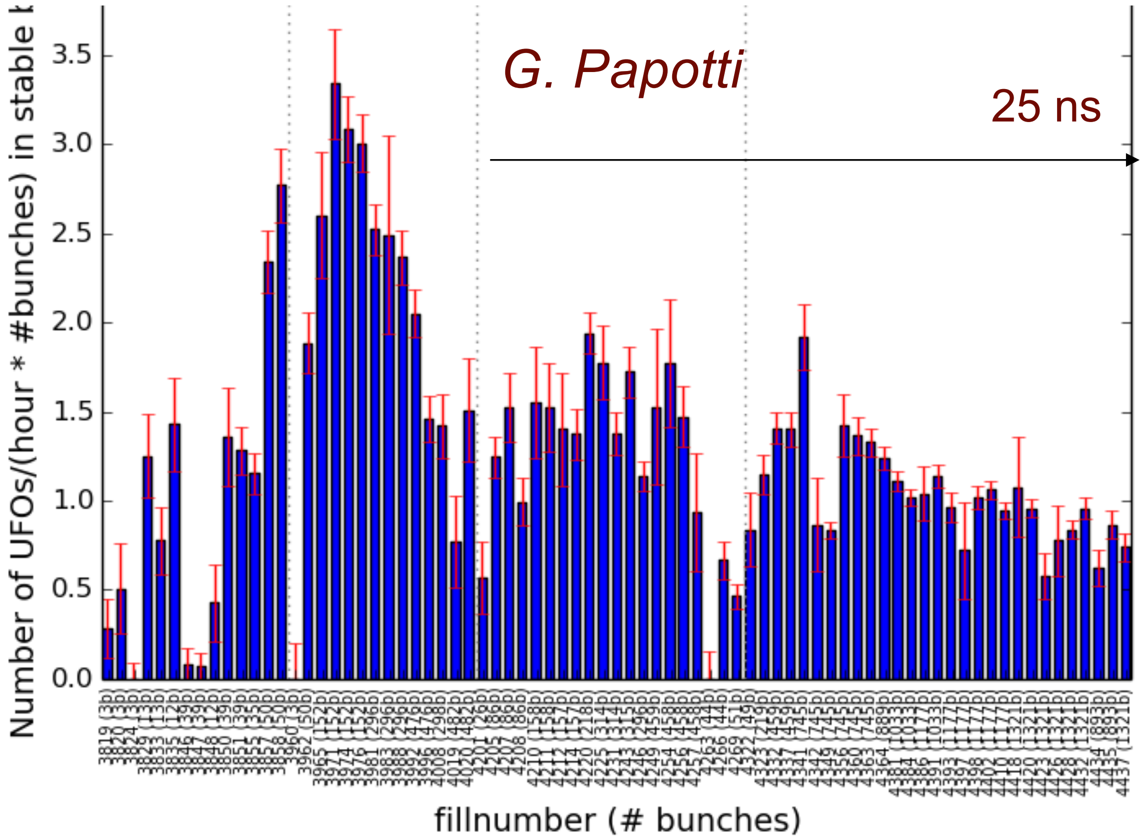
R~10 μm



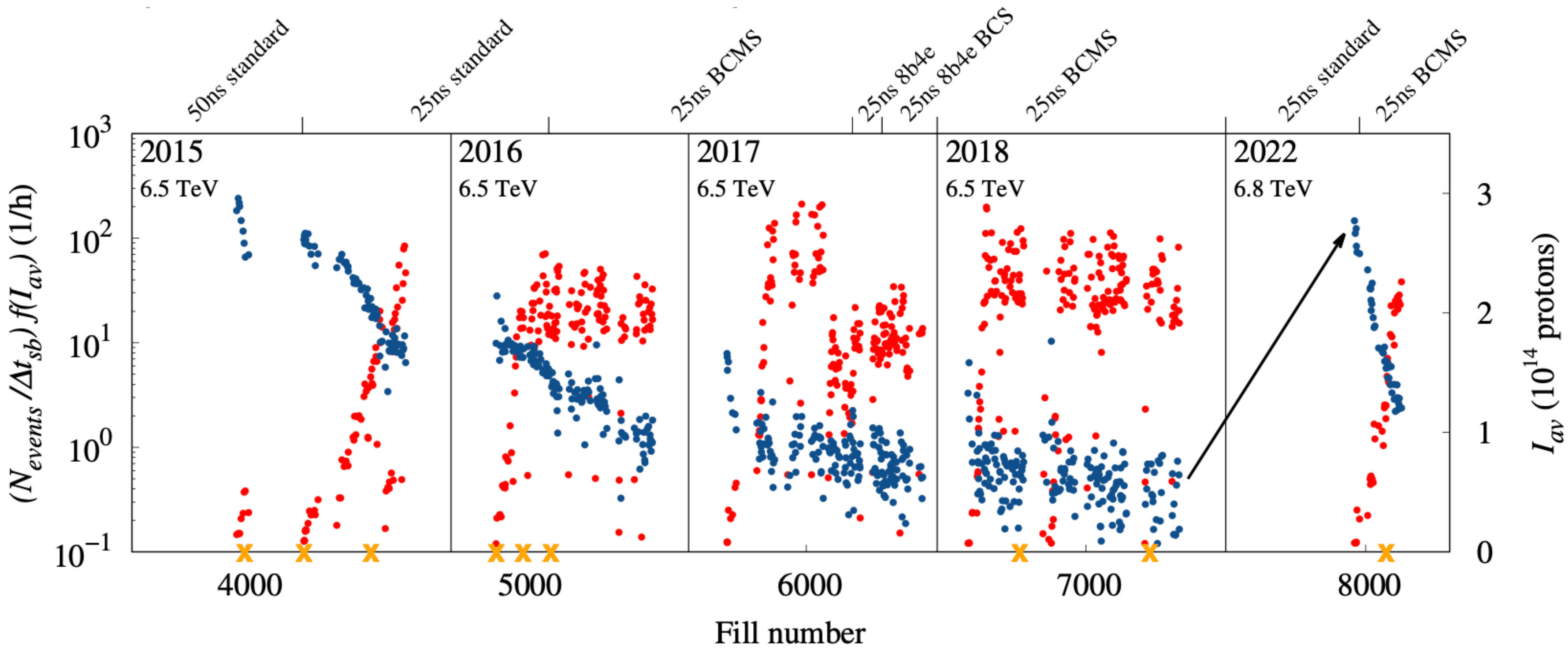


RunII Startup: UFO rates (September)

- There are many UFOs, a significant number > 1% of threshold
  - 0.07% of all UFOs actually dump the beam
- Slight signs of conditioning when normalizing rate by the total number of bunches

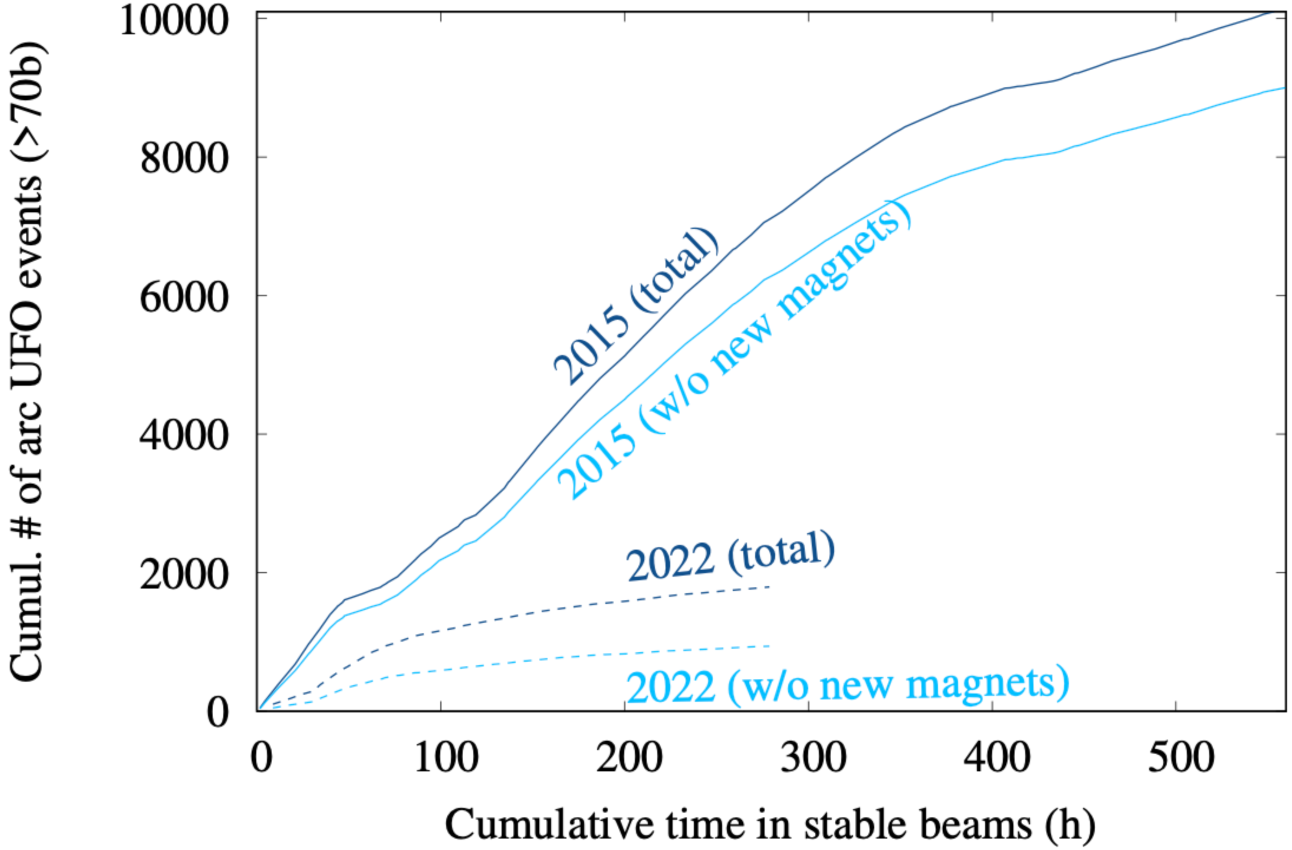


UFO conditioning in Run2 compared to 2022



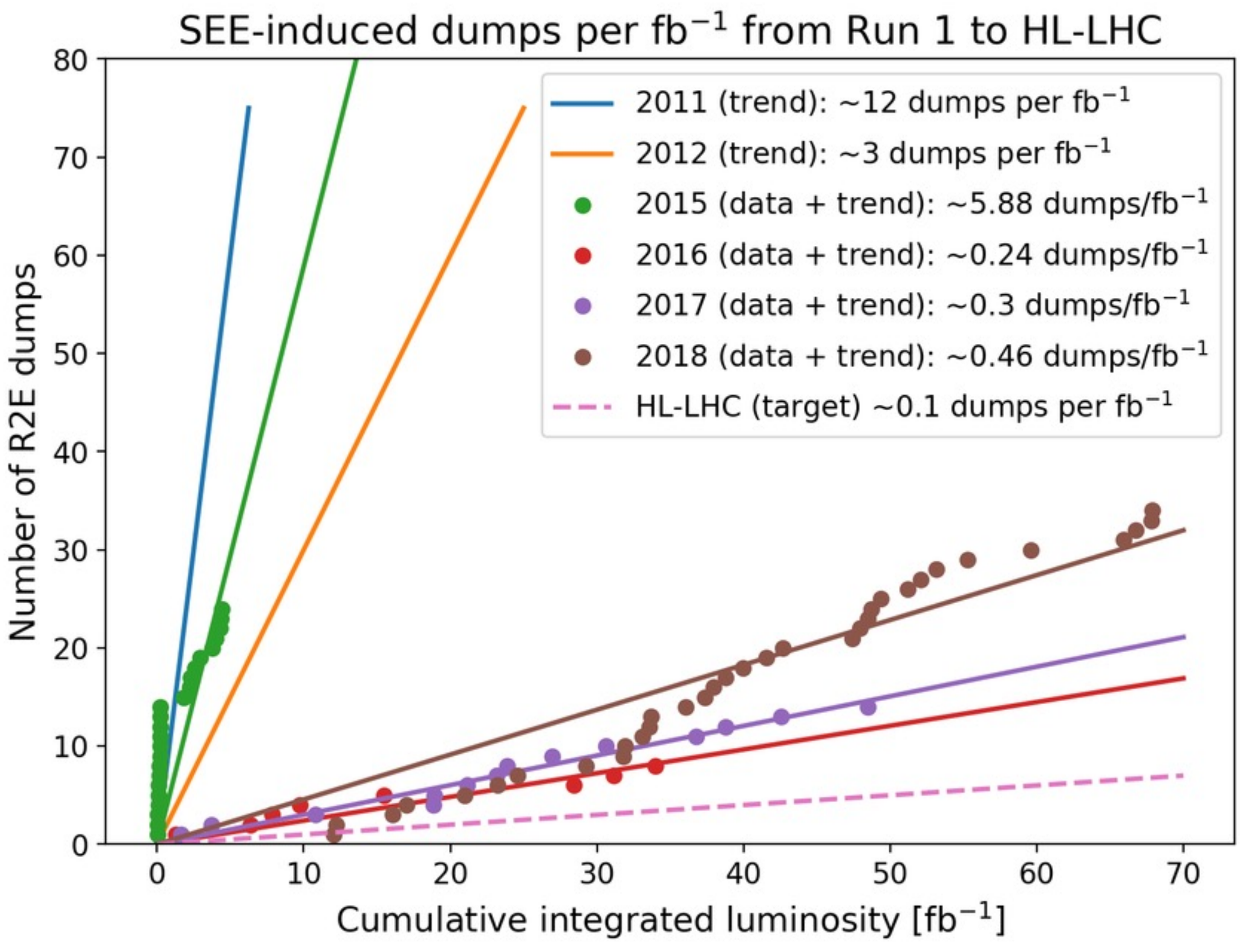
Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

UFO rate 2015 vs 2022



- In general, situation much better than in Run 2 due to the very fast conditioning of the UFO rate
- But the impact of UFOs evidently depends on the BLM threshold strategy

Radiation to Electronics R2E and Beam Aborts

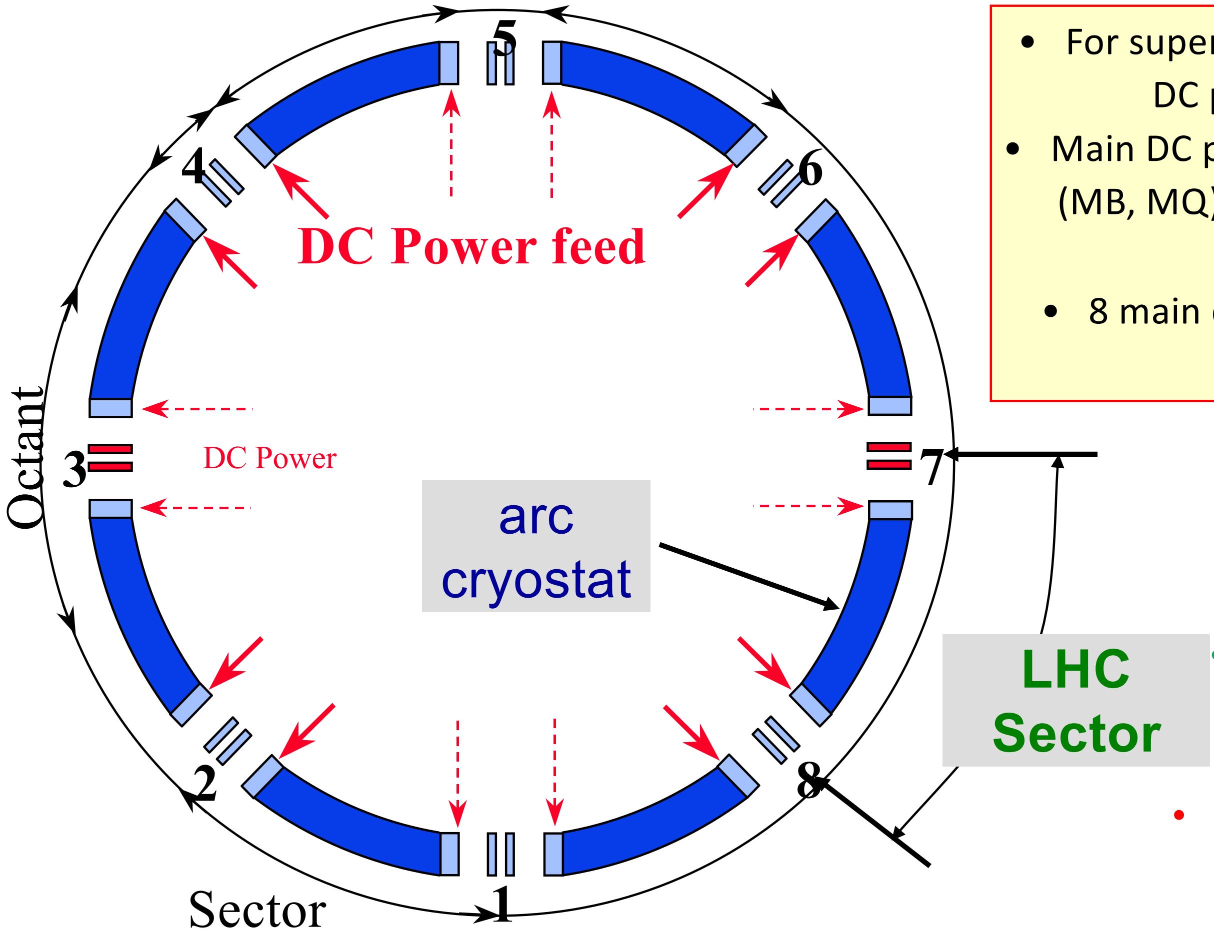


Required:

➔ Additional Shielding

➔ Relocation of electronics racks in the tunnel

LHC machine sectorisation

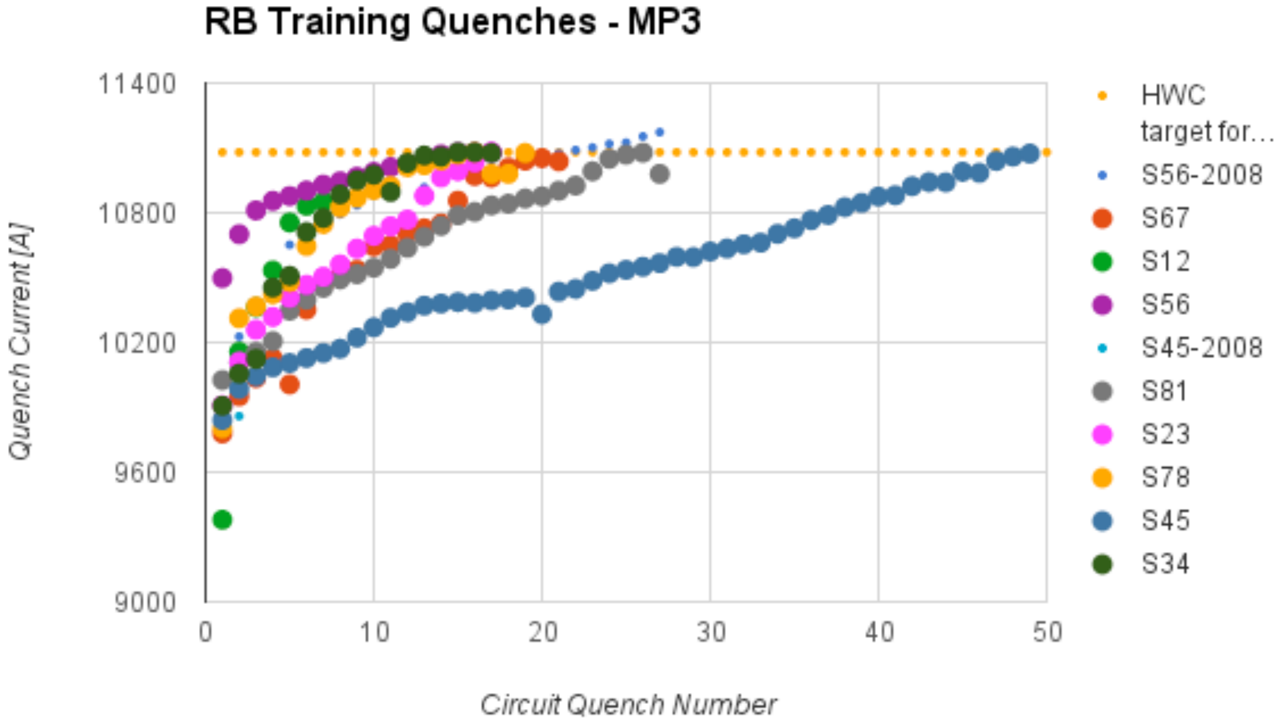


- For superconducting magnets, no DC powering across IPs
- Main DC power feed at even points (MB, MQ), some DC power feed at odd points
- 8 main dipole + 16 quadrupole circuits in LHC

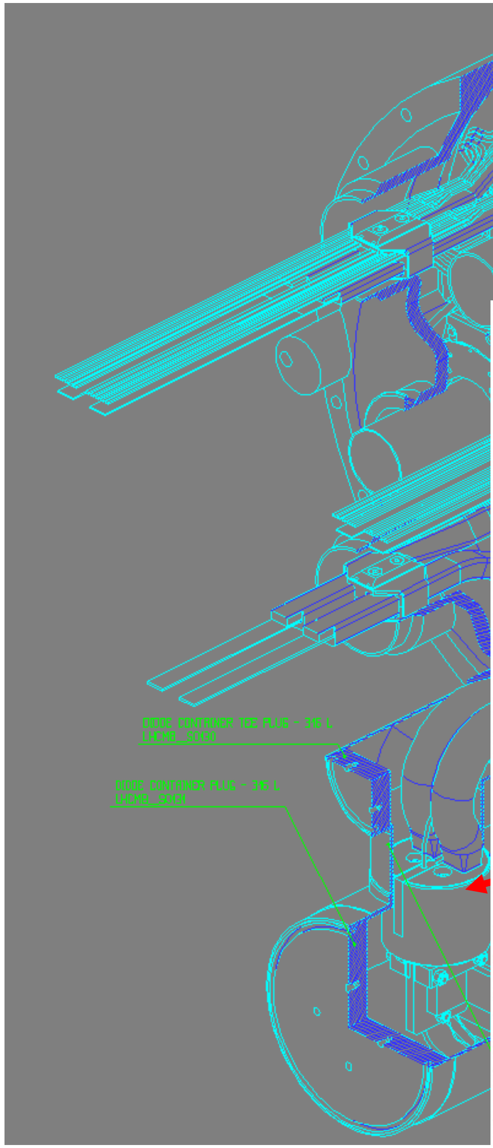
- Commissioning possible for each sector independent of other sectors
- More complex powering system and tracking between sectors

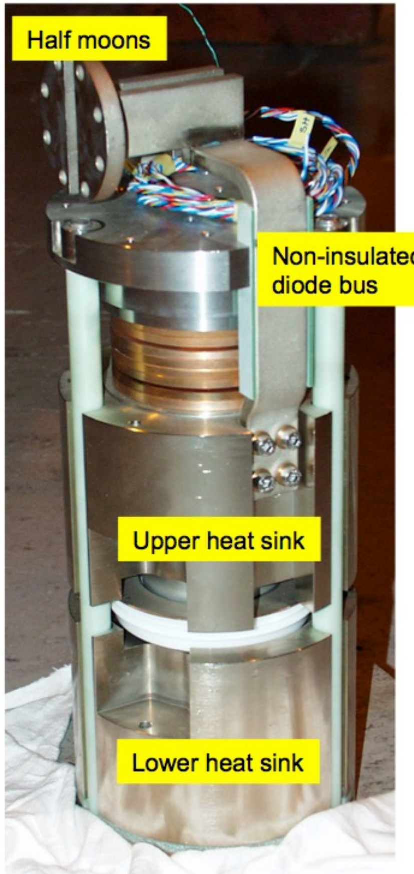
Hardware Commissioning: Dipole training

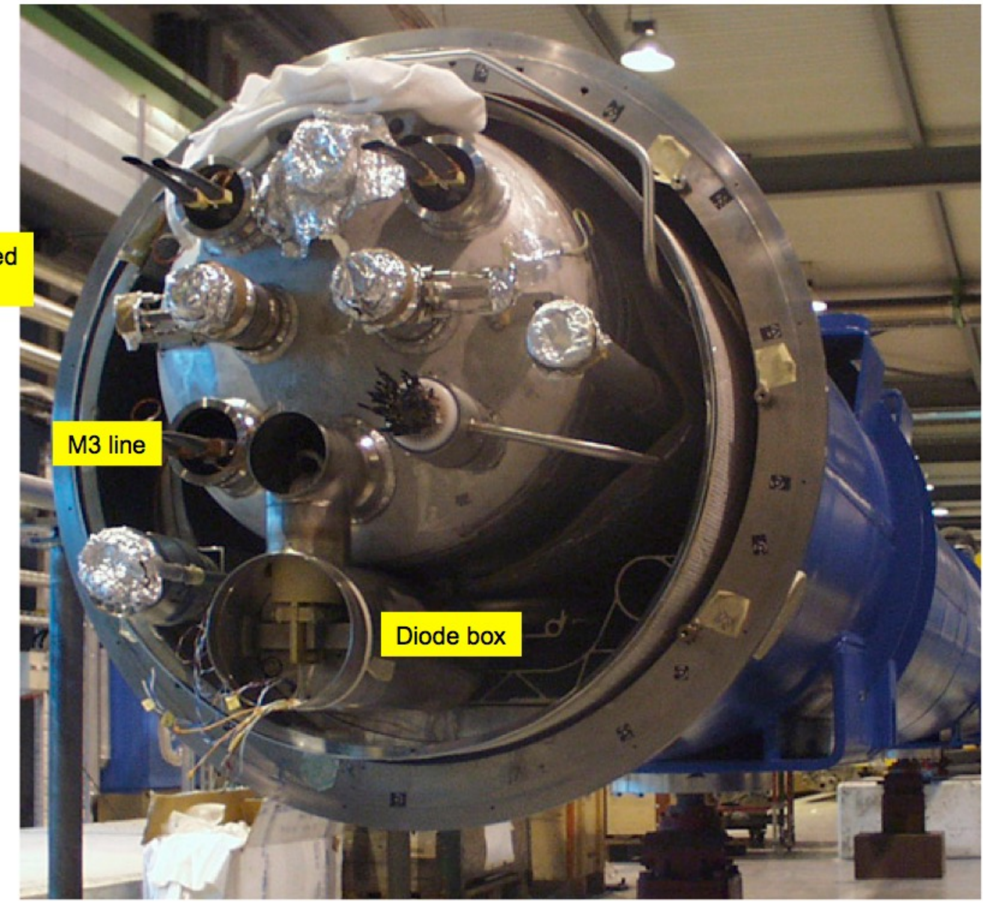
- 154 dipoles per sector, powered in series
- Ramp the current until single magnet quenches - "training quench"
- Usually quench 3 – 4 other dipoles at the same time
- Cryogenics recovery time: 6 – 8 hours
- RB34 earth fault ➔ controlled burn off using capacitive discharge



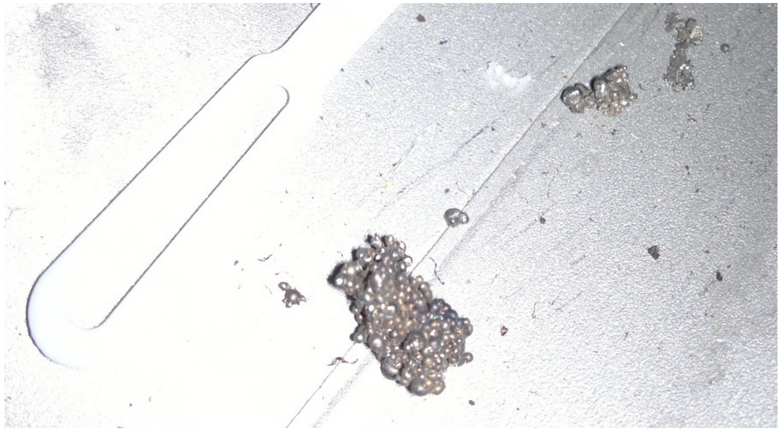
Connection side of MB and diode



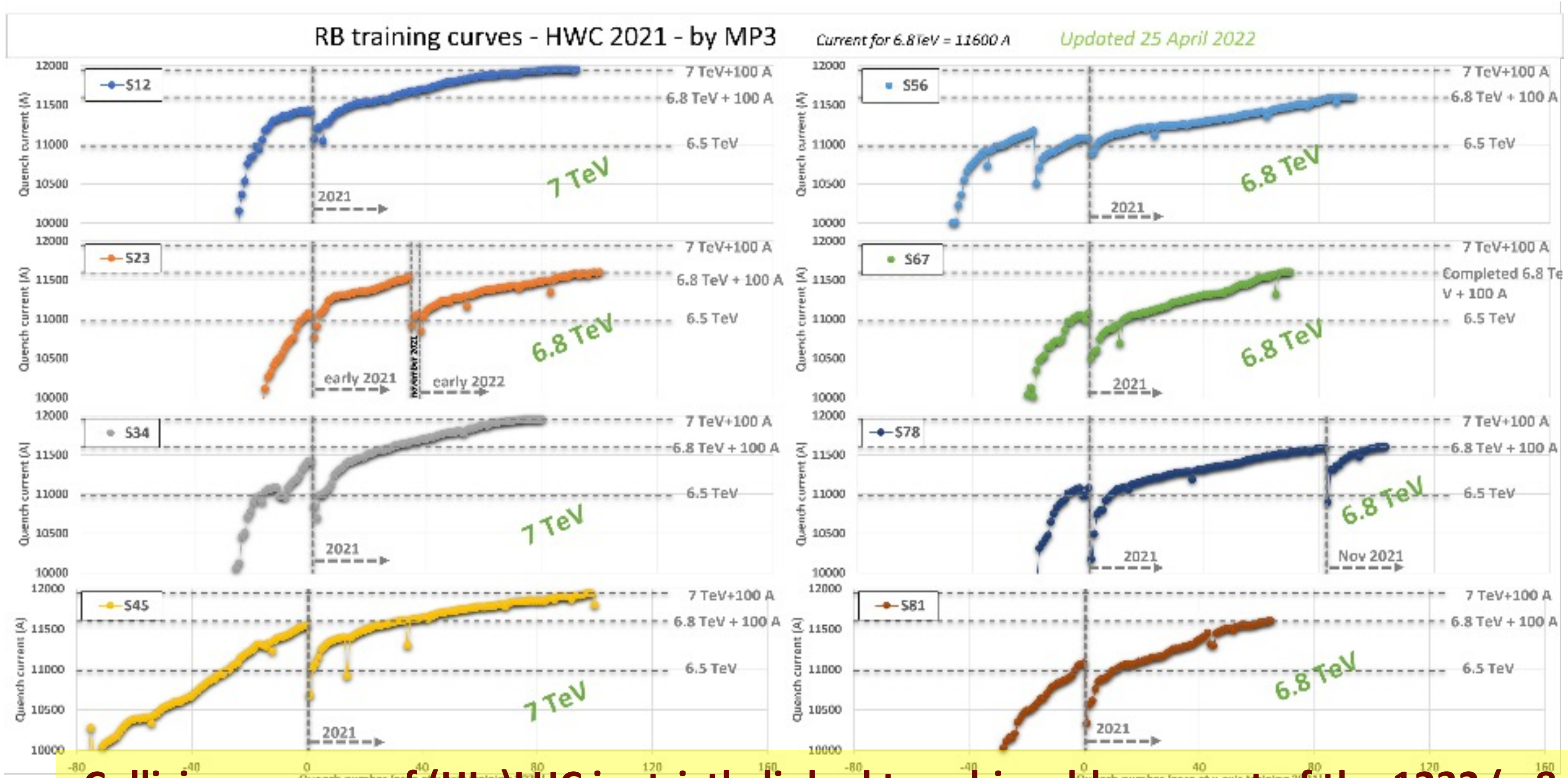




Metal chips and pieces found in the past



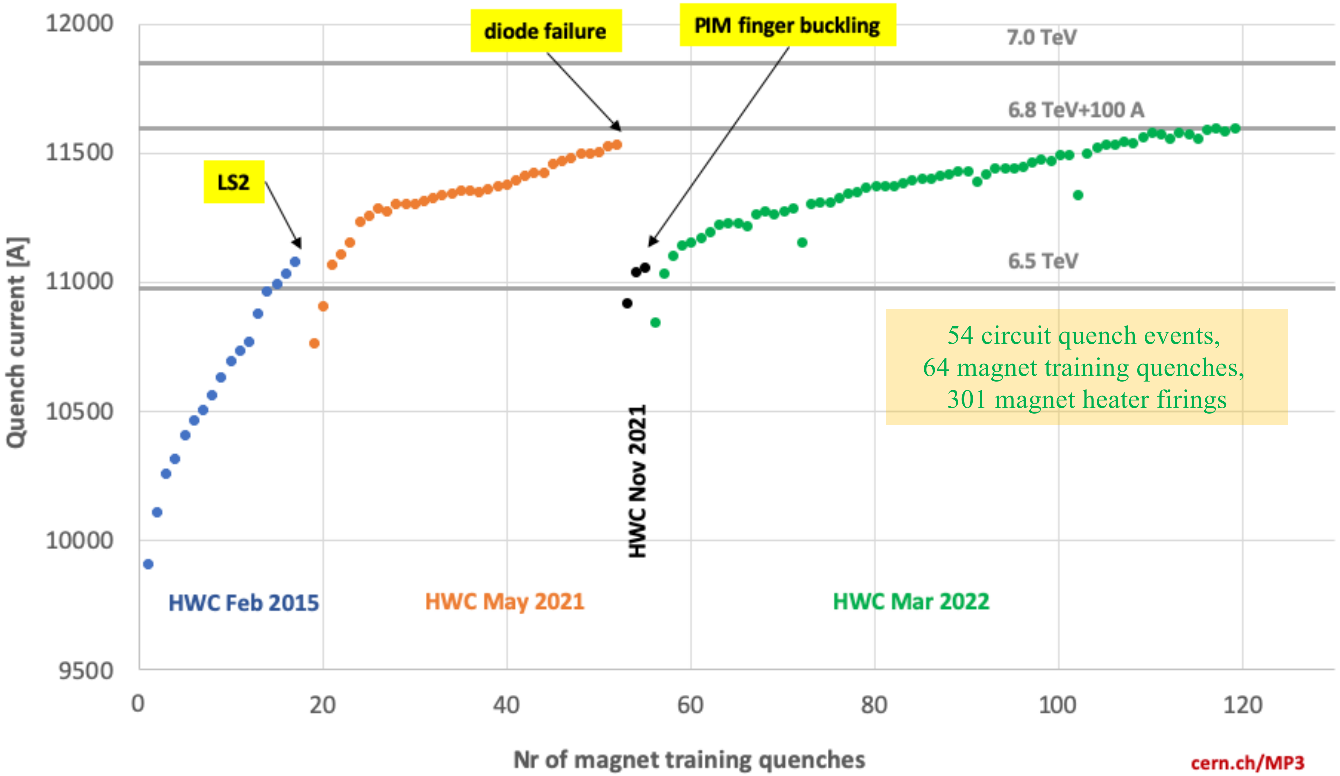
Training quenches RB Circuits



Collision energy of (HL-)LHC is strictly linked to achievable current of the 1232 (= 8 x 154) LHC main dipole magnets

- 5 sectors reached 6.8 TeV equivalent, 3 sectors reached 7 TeV
- No sign of permanent degradation.

Training history RB.A23



- The 64 quenches in S23 after the 2nd additional TC came as a surprise, as usually training goes faster after a TC
- Detailed analysis of the dipole training campaigns is ongoing, including results from reception tests in SM18.

Total number of quenches in LHC main dipoles

Nr of quenches in the same dipole magnet	Nr of dipole magnets
5	3
4	11
3	56
2	154
1	446
0	562

Conclusion:

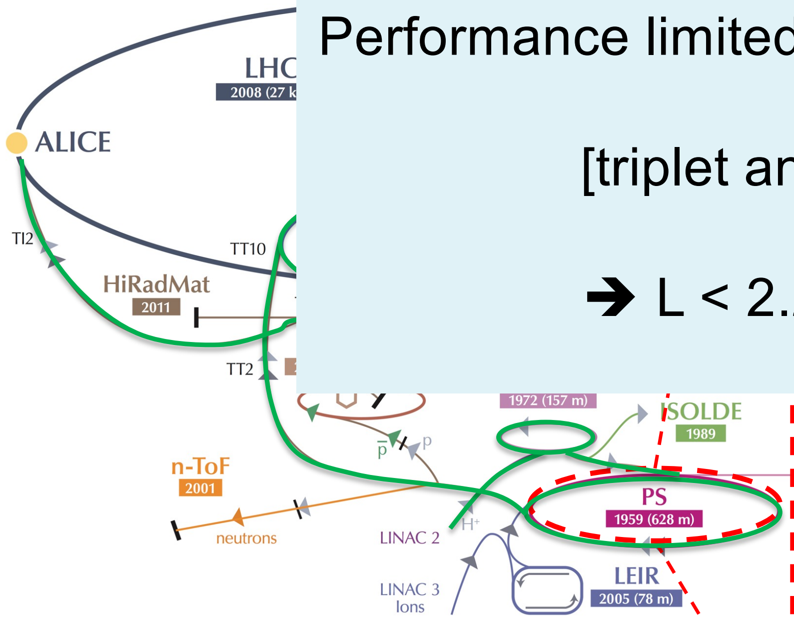
- Still 562 dipole magnets (45%) never experienced a training quench in the LHC since 2008.
- Some circuits (including corrector circuits) showed much longer training than in previous campaigns, and their behavior will be closely monitored in the coming years.
- Desired operating currents can still be reached (with only a few exceptions) 14 years after the start of the LHC, with several thermal cycles, numerous current cycles, radiation, and large number of quenches.
- a quench is a very violent process (especially in the high-current circuits), and that each quench implies a certain unavoidable risk (short-to-gnd, internal short, quench heater failure, etc).
- Decision of collision energy post LS3 will inevitably involve a cost/benefit analysis of required re-training effort (which implies technical risks and considerable time!)

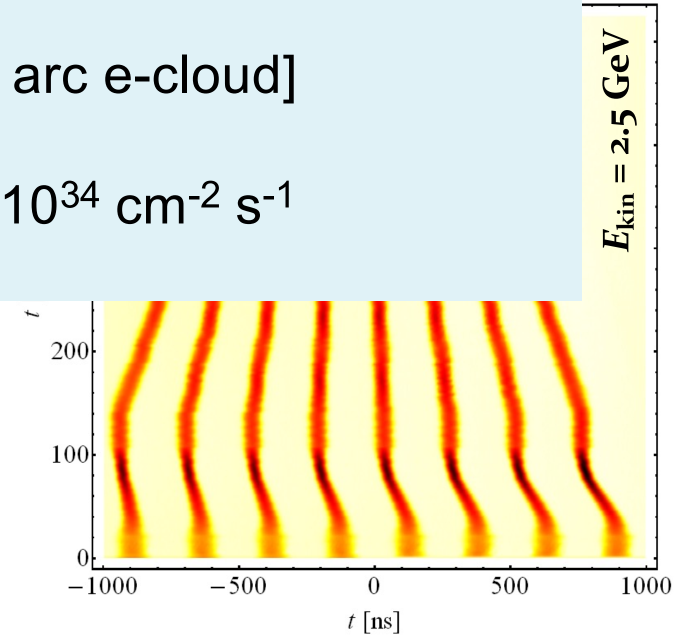
An extra boost from the injectors

The LHC performance fully relies on the p…

- By itself c… diverse a…

A **new production scheme** – the **"BCMS"** - was put in place in the PS …uencies …e and … ard





➔ Higher than nominal beam brightness!

Performance limited by LHC cooling power!!!

[triplet and arc e-cloud]

➔ $L < 2.2\ 10^{34}\ cm^{-2}\ s^{-1}$

➔ **$L > 1.75\ 10^{34}\ cm^{-2}s^{-1}$**

LIU beams from the injector complex

Hybrid beam: used in 2023

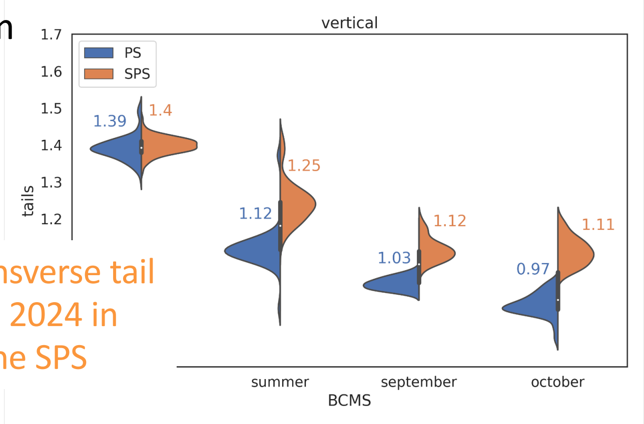
- Interleaving "8 bunches 4 empty slots" (8b4e) with standard 25 ns beam
- As a mitigation of e-cloud and cryo heat load

Standard 25 ns beam: used early 2024

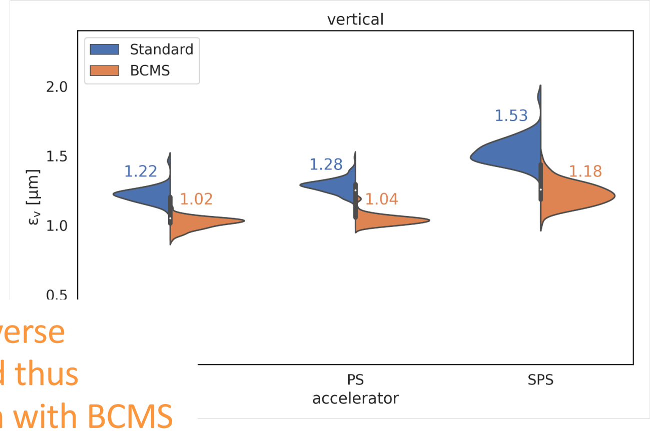
- Used for beam commissioning with 3x36b trains
- Intensity: (1.6-1.65)x10^{11} p/b at injection

BCMS beam: used since mid-2024

- PS producing this high brightness beam using the "batch compression, merging, and splitting" scheme
- Intensity: (1.6-1.65)x10^{11} p/b at injection
- Longest batches: 3x36b (2024) and 4x36b (2025)
- Significant work on reducing tails and emittance blow-up



Reduced transverse tail content over 2024 in the PS and the SPS



Smaller transverse emittance and thus brighter beam with BCMS

The less expected… 2/2

BIRDS & WEASELS

- Electrical fault in 66kV surface substation
- Mitigated by repair and additional protection

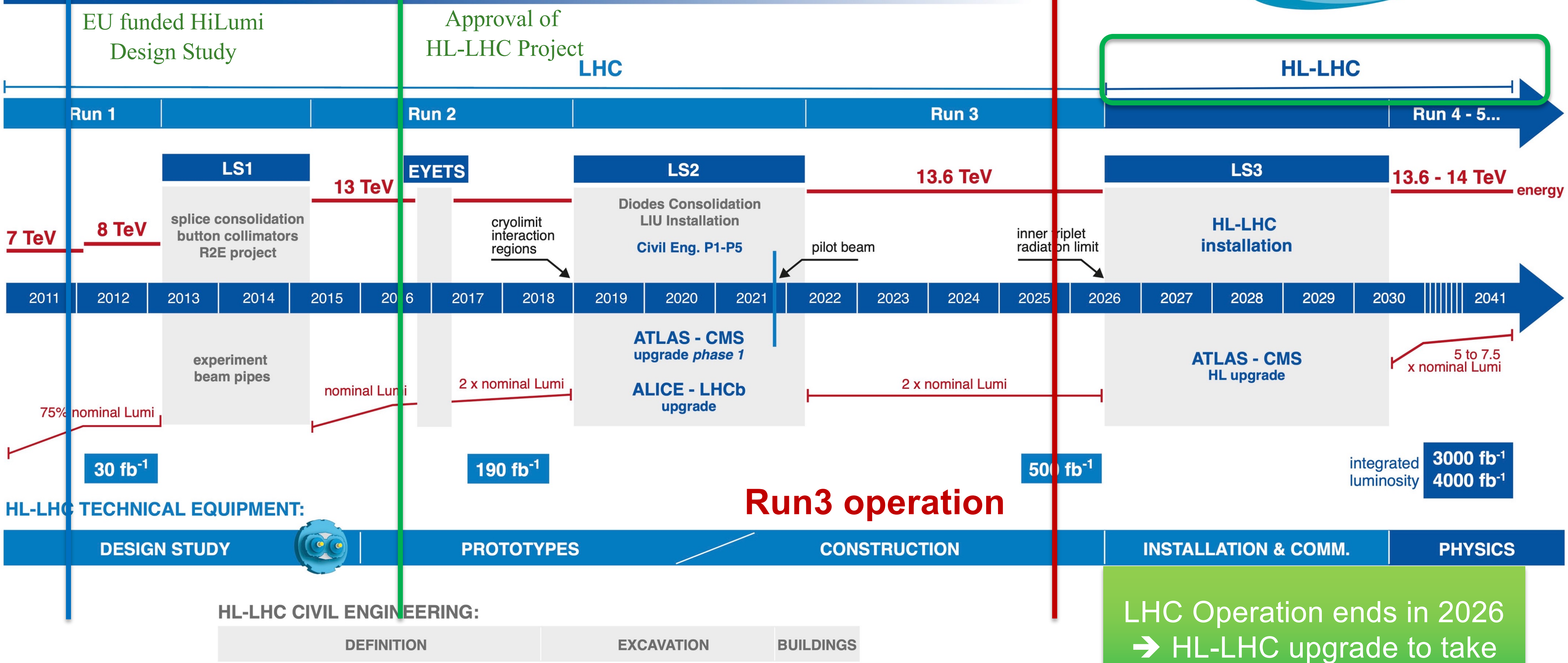
PS MAIN POWER SUPPLY

- Short in capacitor storage bank
- Mitigated by network reconfiguration and operation of rotating machine

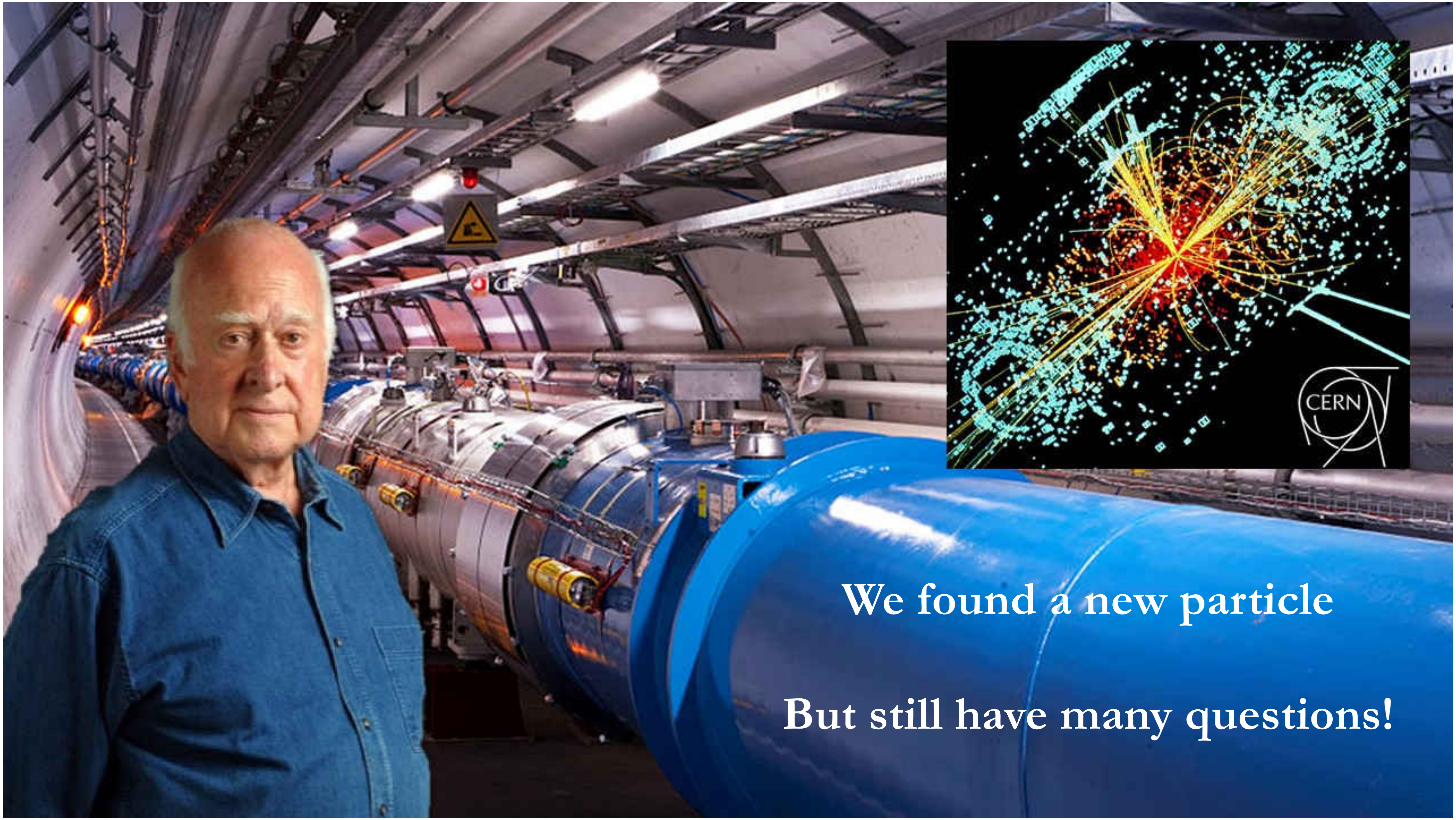
SPS BEAM DUMP

- Limited to 96 bunches per injection
- 2076 (2200) bunches per beam cf. 2750
- Replacement during EYETS

LHC / HL-LHC Plan



LHC Operation ends in 2026
➔ HL-LHC upgrade to take over as of 2030 after LS3


CERN
We found a new particle
But still have many questions!

Questions?

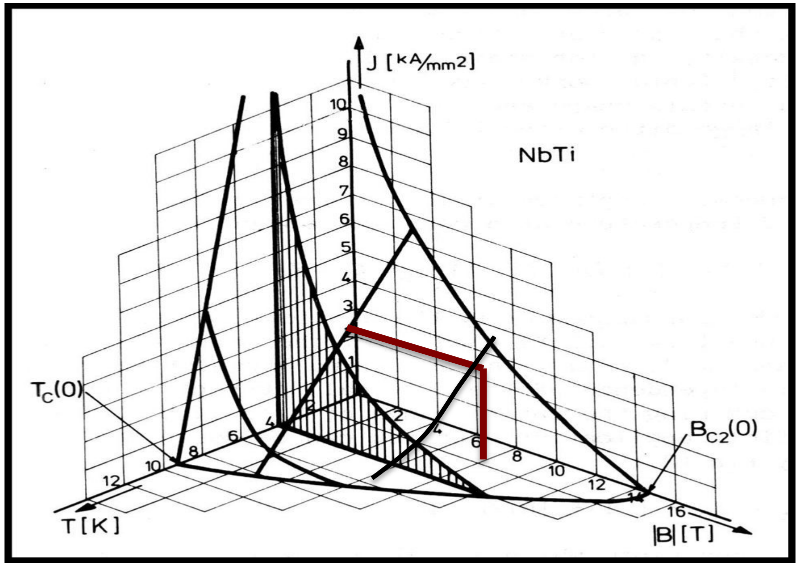
Technology Challenge: Magnets for High energy

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  ➔ ca. 8 T @ coil
  ➔ 1.8 K cooling with superfluid He (thermal conductivity)
  ➔ current density of 2.75 kA / mm^2

- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!!

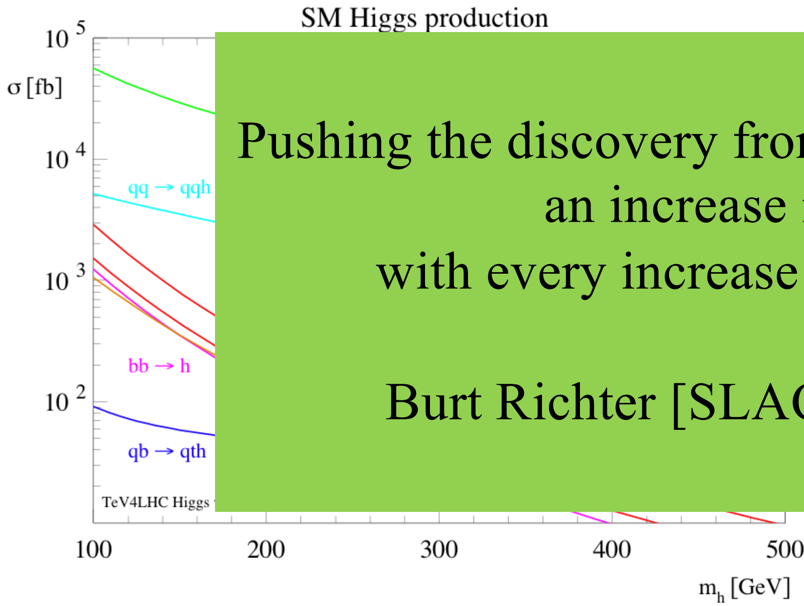
LHC Production in collaboration with USA and KEK

Critical Surface for NbTi



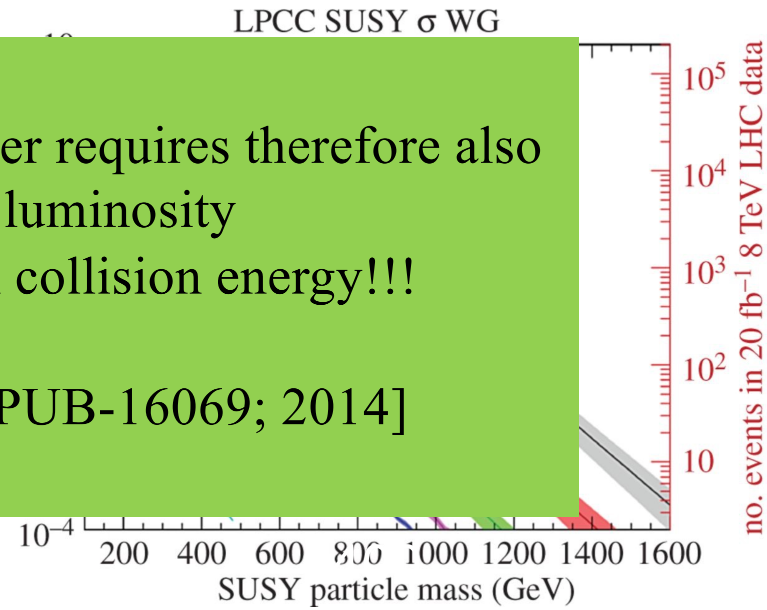
Performance Optimization: 2 Competing Effects:

- Discoveries: production of new particles requires CM energy above the production threshold: Z → 45GeV, W → 80GeV, H → 125GeV
  → discovery of the unknown implies highest possible CM energy!
- Production rate: cross section decreases with particle mass!



Pushing the discovery frontier requires therefore also an increase in luminosity with every increase in collision energy!!!

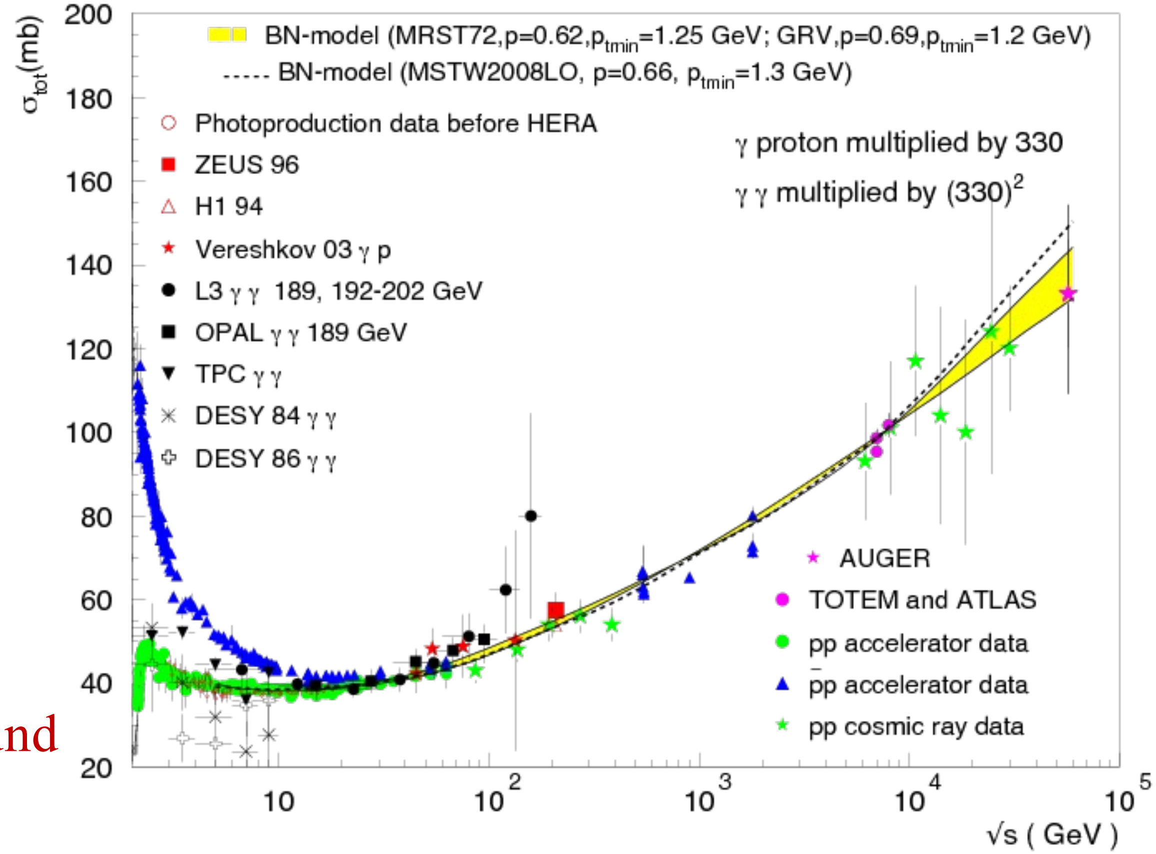
Burt Richter [SLAC-PUB-16069; 2014]



Performance Optimization: 2 Competing Effects:

Beam Burn off: total cross section increases with CM Energy!!!

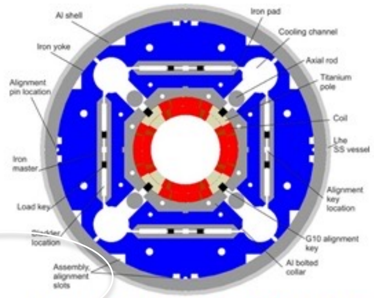
- ➔ The beam lifetime decreases with increasing Luminosity AND E
- ➔ Shorter fills which imply reduced efficiency and reduced integrated Luminosity
- ➔ Increased background in the detectors!



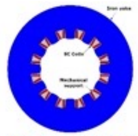
Hadron Collider Limitations / Challenges:

- Beam energy and luminosity:
  ➔ Beam lifetime and operation efficiency
- Event rate and pile up:
  [number of events per luminous region length]
  ➔ Detector challenge and efficiency and data quality
- Beam energy and intensity = beam power & stored EM energy
  ➔ Damage potential and machine protection
- Debris from the IP
  ➔ Quench protection; heat load and radiation damage
- Beam energy:
  ➔ Magnet technology [maximum B] and accelerator size & FQ

THE HL-LHC MAGNET ZOO:

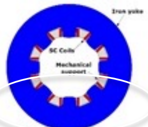


Triplet [G. Ambrosio, P. Ferracin et al.]

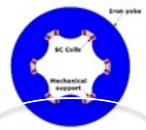


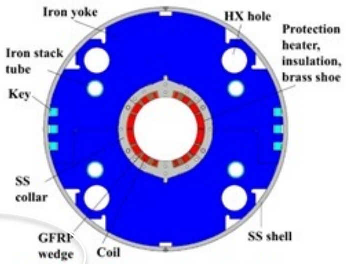
Dodecapole

Decapole

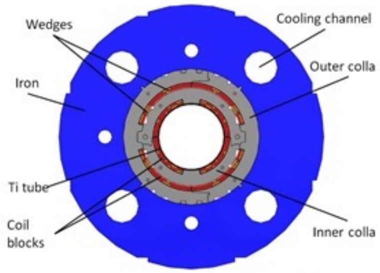


Octupole

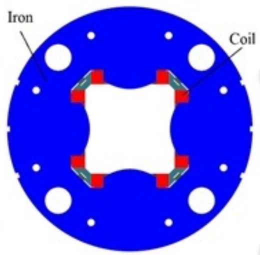




D1 [T. Nakamoto, et al.]

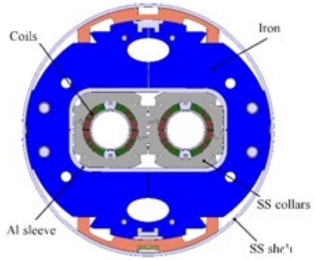


MCBXF [F. Toral, et al.]

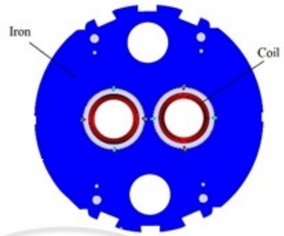


Skew quad

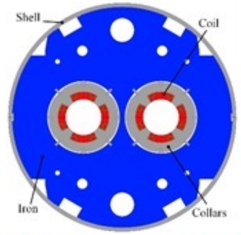
[M. Sorbi, M. Statera, et al.]



D2 [P. Fabbricatore, S. Farinon, et al.]

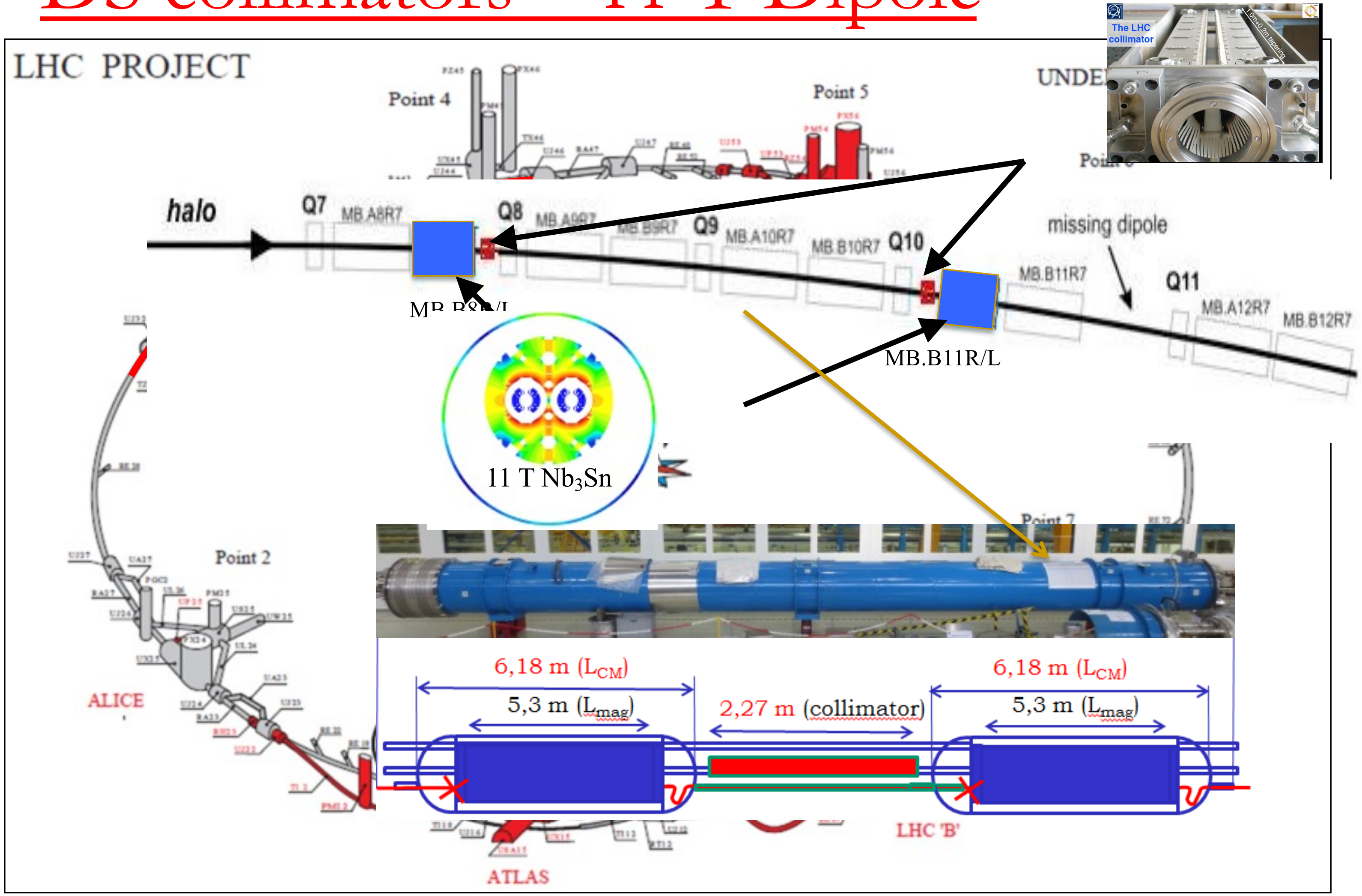


D2 correctors [G. Kirby]



MQYY [H. Felice, et al.]

DS collimators – 11 T Dipole



Example LEP: SR limit

- physics: LEP1 = 45.6GeV; LEP2 = 80.5GeV; LEP_{end} > 100GeV

  m_Z = 91GeV m_W = 91GeV m_H = 125GeV

- LEP Tunnel: circumference = 27 km (ca. 17mi)

  with 22 km arcs (ca. 14mi)

- LEP limitations:

  → P_{SR} > 20MW

  → E_{turn} > 2.8GeV

  → P_{RF} > 40kW (> 10MW)

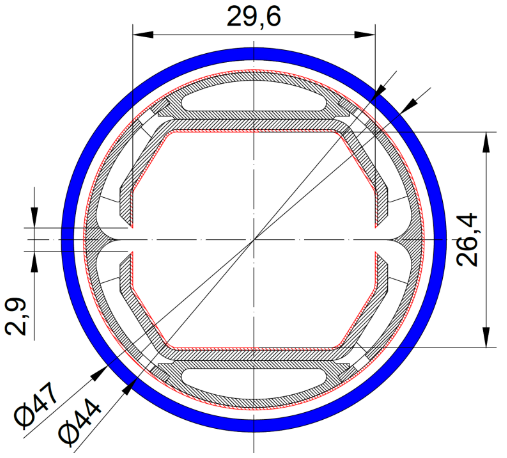
Synchrotron Radiation in Superconducting Magnets

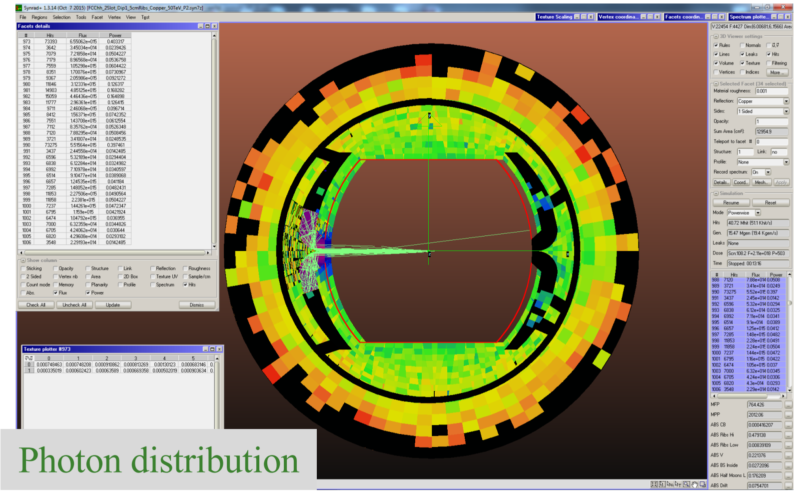
High synchrotron radiation load of protons @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs**

New Beam screen with ante-chamber

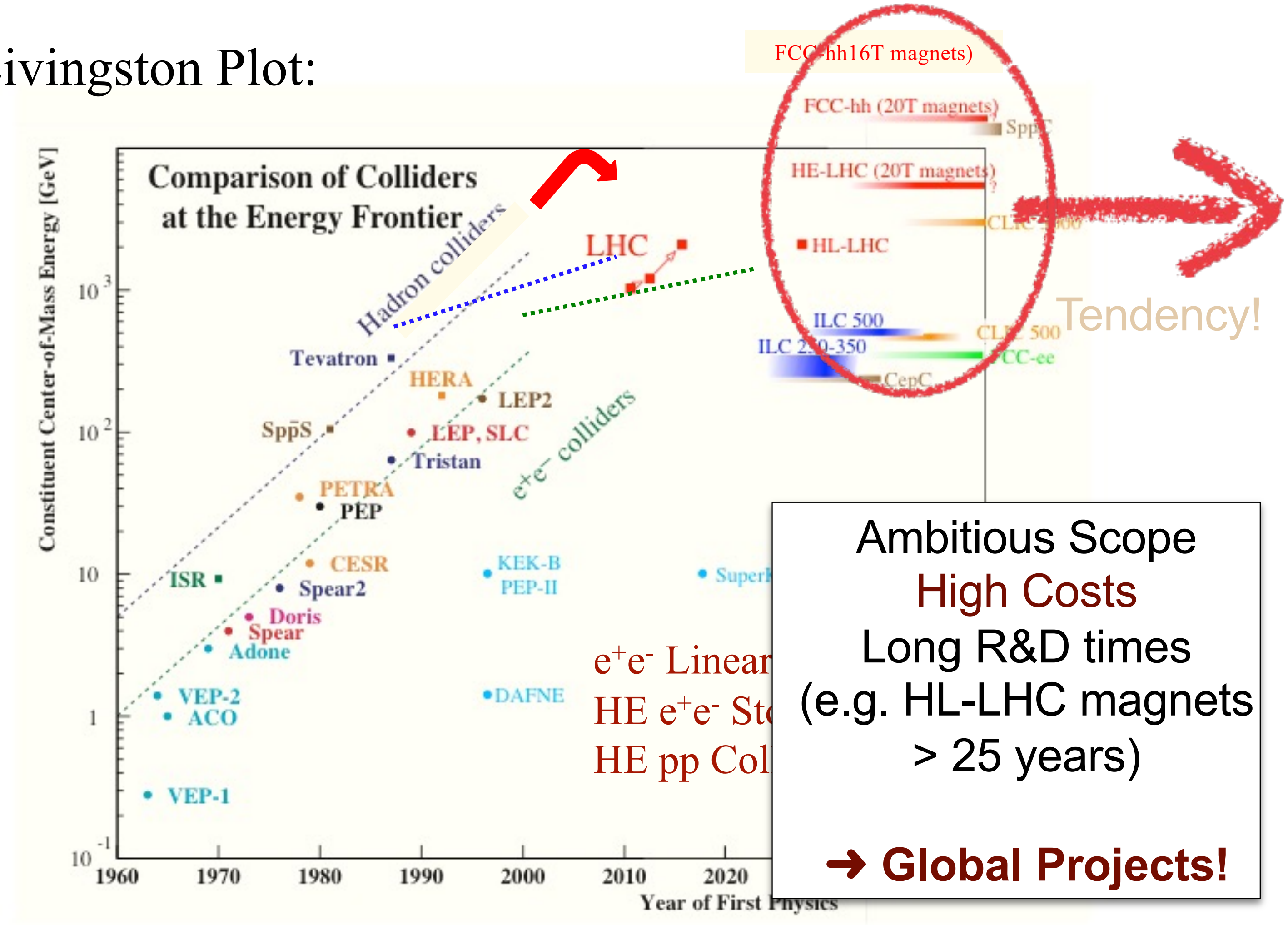
- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum





Past, Present, Future

- Livingston Plot:



Ambitious Scope
High Costs
Long R&D times
(e.g. HL-LHC magnets
> 25 years)

➜ **Global Projects!**

Accelerator for Particle Physics: Goals

- Luminosity Frontier:

  ➔ Luminosity and Beam lifetime (>> than fill time)

  ➔ accelerator size, total number of particles, burn-off!!!

  ➔ Data density & cleanliness: luminous region and pileup

  Beam intensity and stored beam energy

  Detector background

  Operation efficiency

➔ Challenging operation modes at luminosity frontier

Accelerator for Particle Physics: Goals

- Luminosity Frontier:
  - ➔ Luminosity and Beam lifetime
  - ➔ accelerator size, total number of particles, burn-off!!!
  - Data density and cleanliness: luminous region and pileup
  - Beam intensity and stored beam energy for Hadron beams
  - ➔ 500MJ!! / beam for HL-LHC
  - Operation efficiency
- Energy Frontier:
  - ➔ Technology driven / limited!!!

Phase 1 Intensity Limit vs Loss Rate at 7 TeV

Loss map simulations and LHC design values