LHC and HL-LHC

O. Brüning
CERN, Geneva, Switzerland

Presented by

M. Giovannozzi
CERN,Geneva, Switzerland

Introduction: LHC Performance Goals

A proton beam energy of 7 TeV within the existing LEP tunnel with a circumference of 27 km and an arc length of 22km
➔
Requires a peak magnet field in the dipoles of about 8.3 Tesla!!!
[ca. 300000 times the earth magnetic field]

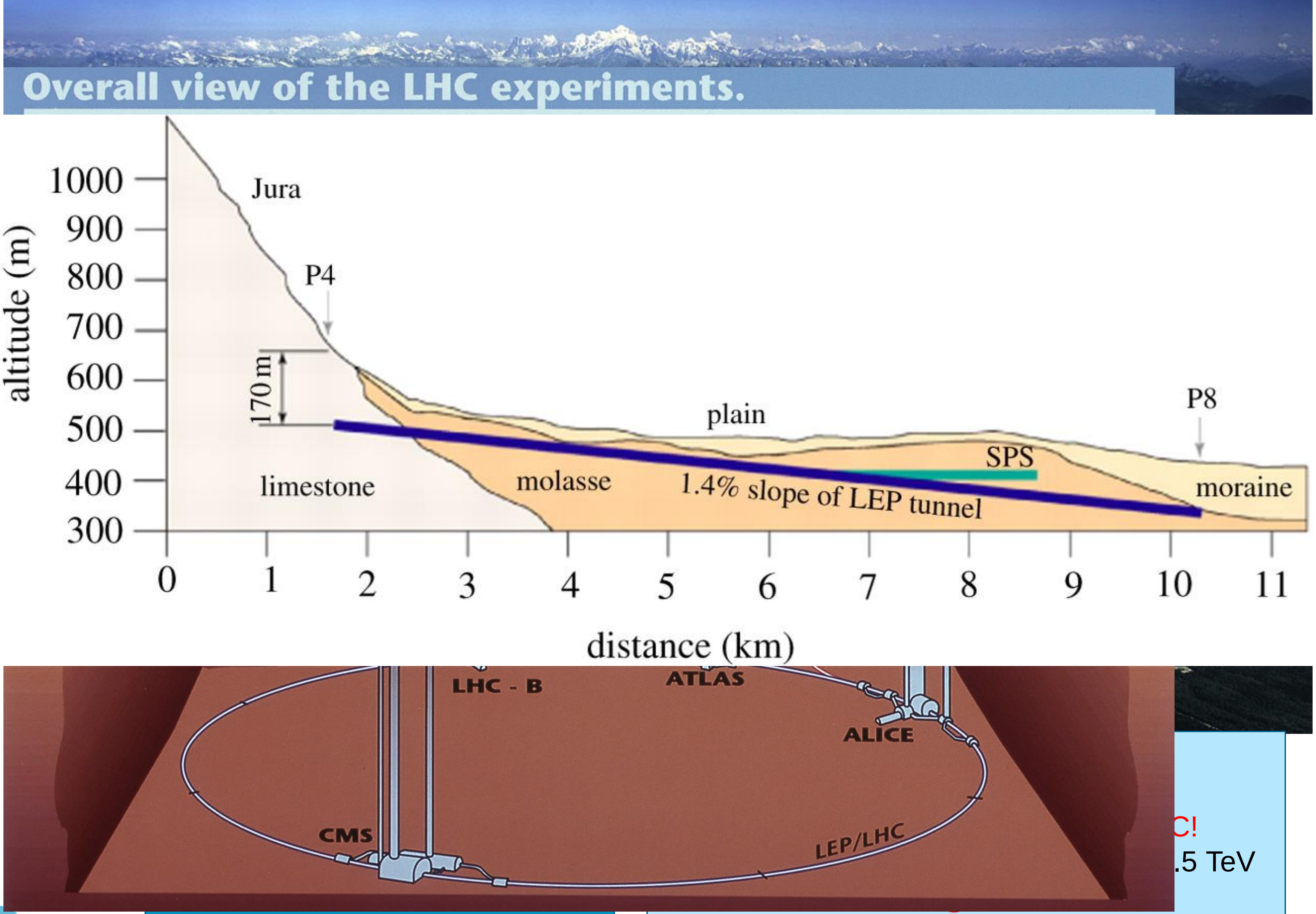
- Instantaneous luminosity: rate of events in detector $= L \times \sigma_{event}$

rare events ⟶ L > 10^{33}cm^{-2}s^{-1} ⟶ L = 10^{34}cm^{-2}s^{-1}

- Integrated luminosity: total number of events $\mathcal{L} = \int L(t)\,dt$

300 fb^{-1} with 1barn = 10^{-28} m^2 and femto = 10^{-15}

World hadronic luminosity production prior to the LHC: ca. 11 fb^{-1}


Overall view of the LHC experiments.
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)
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

C!
.5 TeV

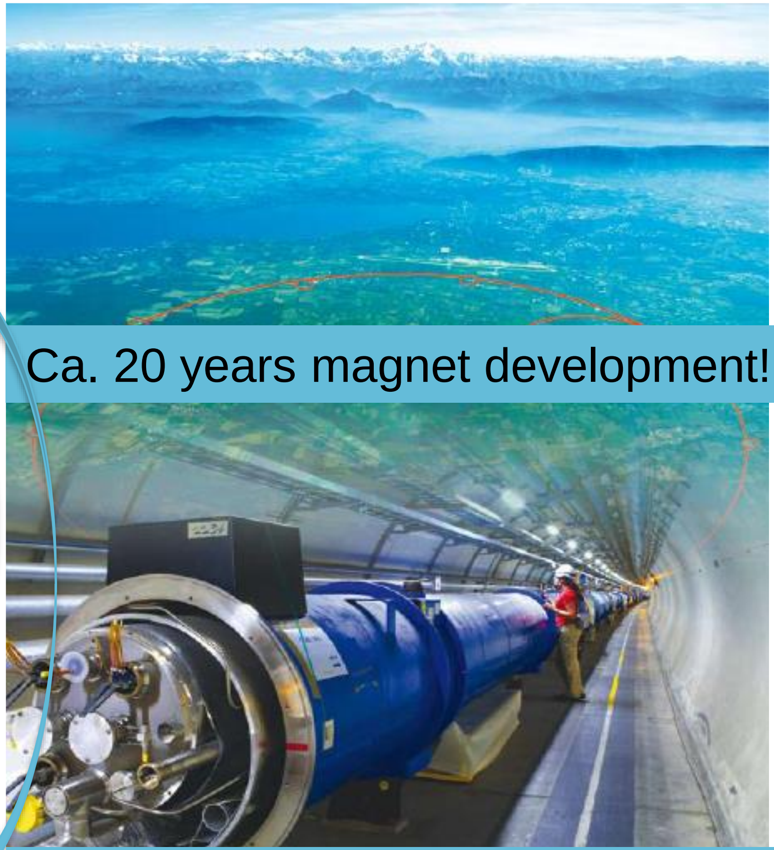
LHC (Large Hadron Collider)

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

2010-2037: Physics exploitation



Ca. 20 years magnet development!!!

Ca. 30 years machine development!!!

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

Energy management challenges: Example LHC

Energy stored in the LHC magnet system [8.3 T]: ~10 GJoule

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage

Lifetime & Loss Spikes ➔ Distributed losses

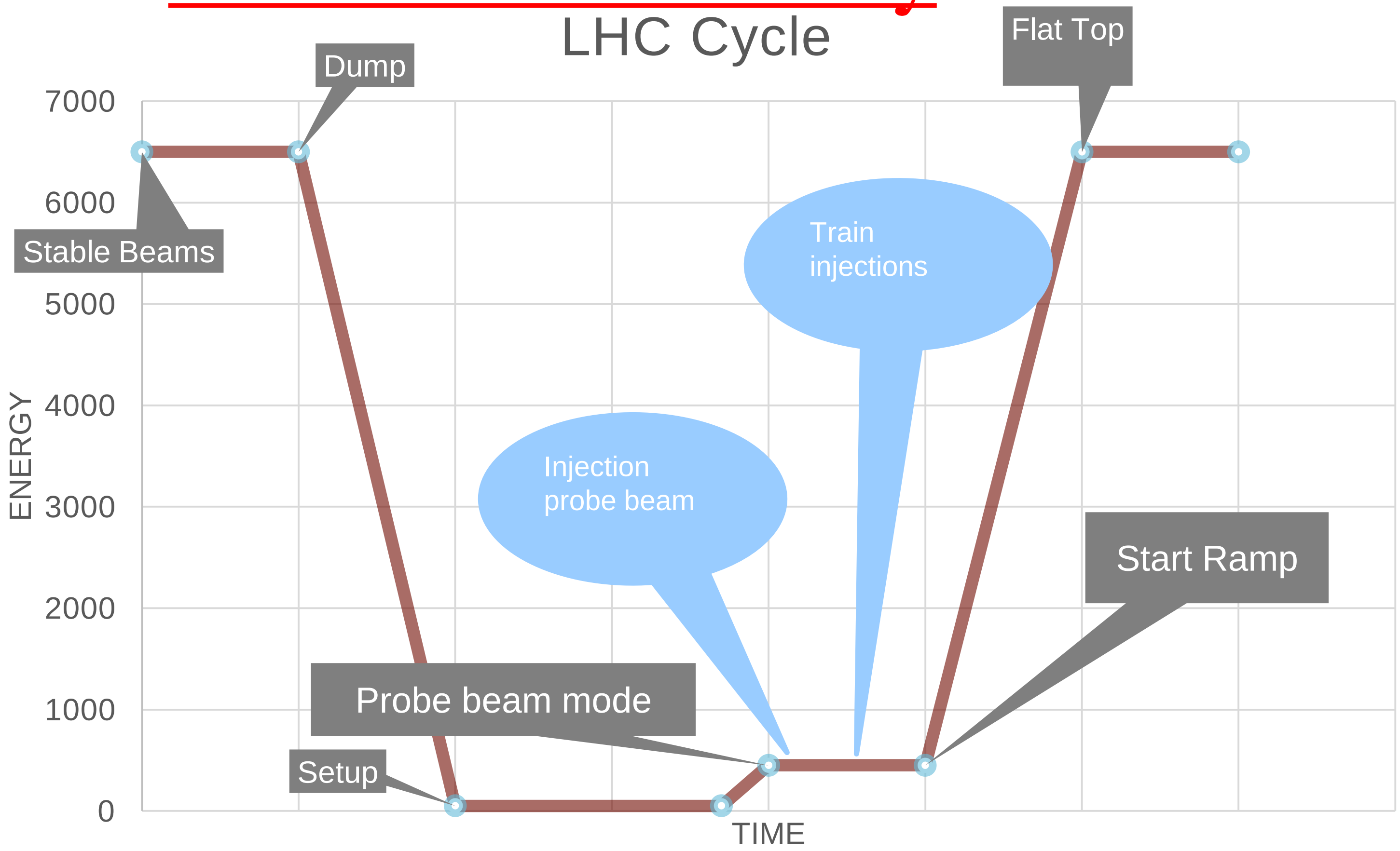
➔ Magnet Quench & QPS

➔ Machine efficiency

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

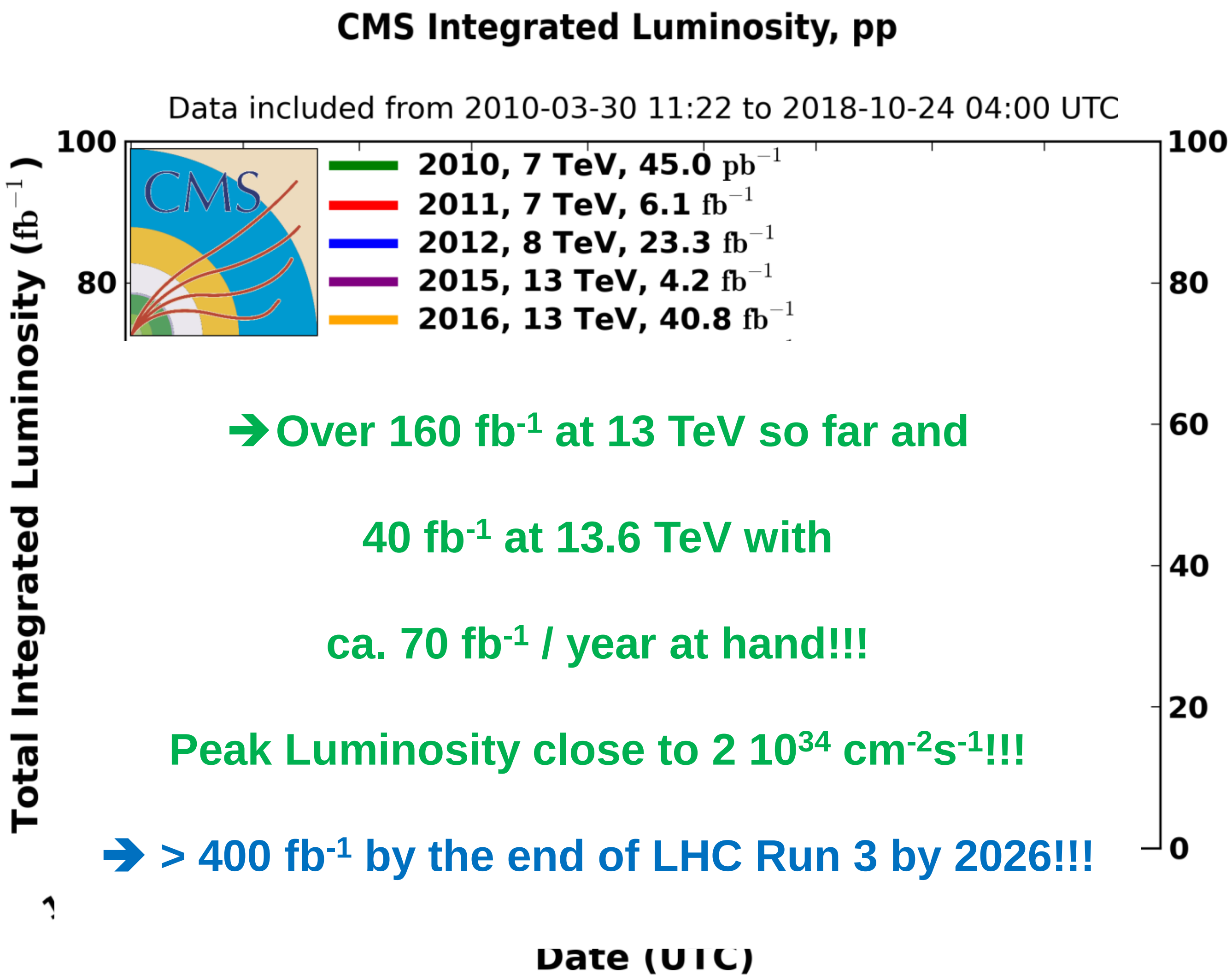
8 sectors ➔ [12 sectors ➔ 20 sectors]

Machine Efficiency



This becomes more challenging with increased Collider size and Requires even more powerful injector complex!!!!

➔ ca. 50% in LHC operation including faults at best conditions!



➔Over 160 fb^{-1} at 13 TeV so far and

40 fb^{-1} at 13.6 TeV with

ca. 70 fb^{-1} / year at hand!!!

Peak Luminosity close to 2 10^{34} $cm^{-2}s^{-1}$!!!

➔ > 400 fb^{-1} by the end of LHC Run 3 by 2026!!!

Higgs Discovery in July 2012 and 2013 Nobel Price for the Brout – Englert – Higgs mechanism

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at CEI

But many questions remain and the search continues!!!

➔ Higgs properties [coupling]
➔ More than one Higgs?
➔ BSM Physics? Dark Matter & Dark Energy?

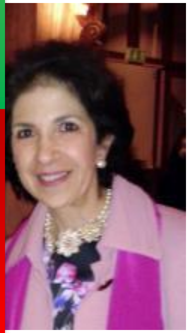
➔Need for more Data and Statistics!!
Doubling the Statistics requires 4 x more data!!!

➔ HL-LHC goal: 10 times the LHC data Volume

Implies overcoming several limitations in the existing LHC!!!

Not only experiments: cryo <u>cooling</u> of triplet magnets & <u>radiation damage</u> in triplet magnets & <u>machine efficiency</u>!

➔ Need for an Upgrade!



Goal of High Luminosity LHC (HL-LHC):

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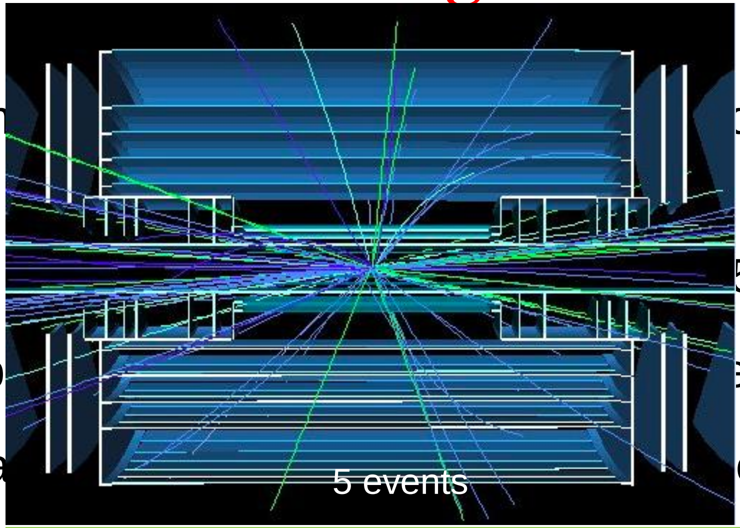
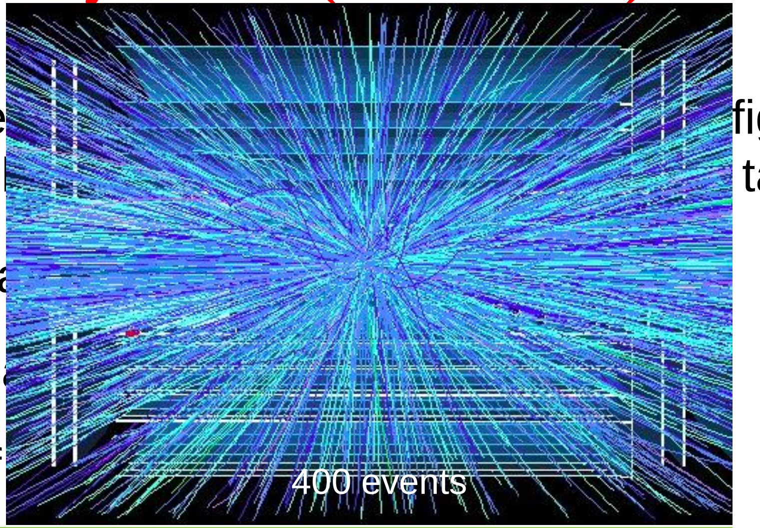
and … al … targets:

Prepare … 5 a

Devise b … ena

ena … of





Need to overcome several limitations in the existing LHC machine!!!

➔High machine efficiency and reliability are key upgrade ingredients!

Luminosity optimization:

- Luminosity Levelling at the luminosity frontier:

To cope

have been
strated in
the LHC!!!

Worry about beam losses!!!!

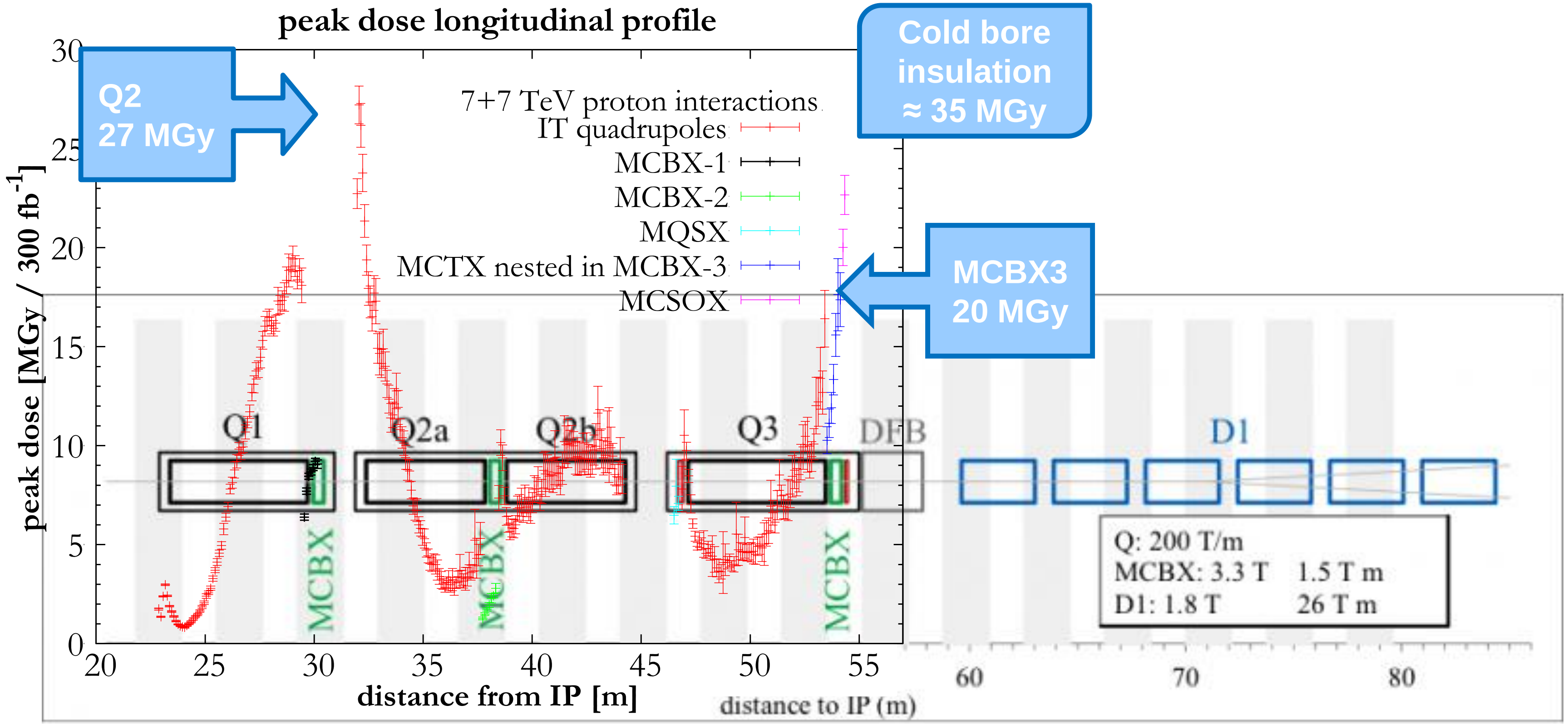
Radiation to Electronics!!! ➔ Beam aborts & Loss of efficiency!!!!

➔ Loss in integrated luminosity!

➔ Shielding, Additional Cooling and Removal of all active elements from the tunnel!!!

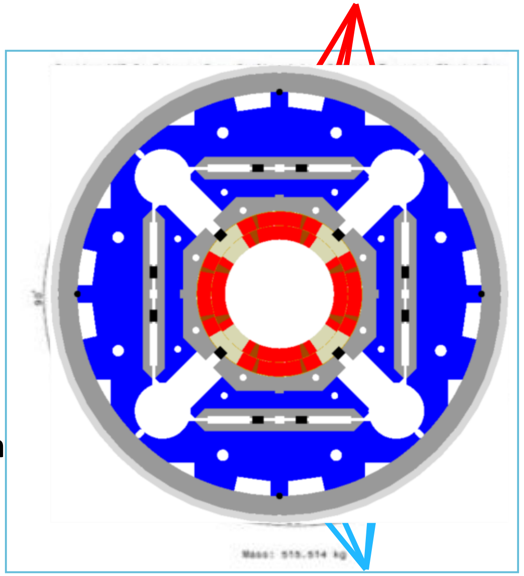
Worry filling patterns and unwanted colllsions!!!!

Luminosity Limitation: Debris from the IP
Radiation damage to magnets at 300 fb^{-1}



HL-LHC technical bottleneck: Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!! ➔ Shielding!



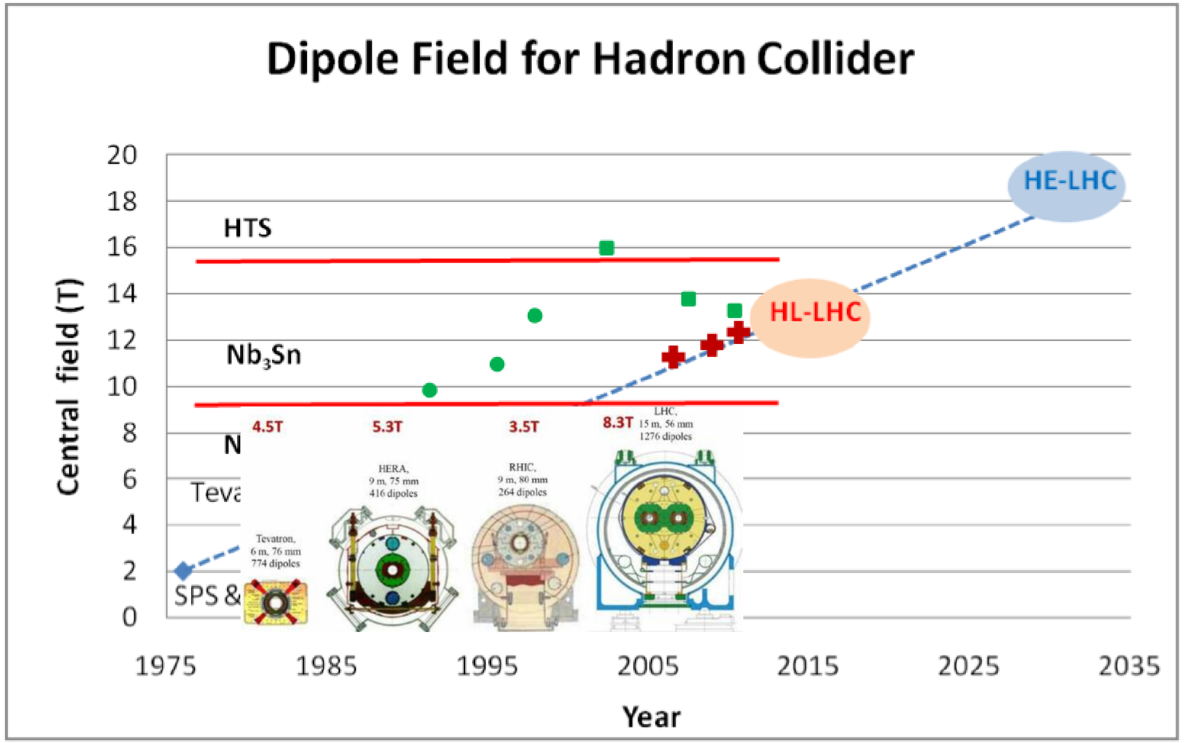
US-LARP MQXF magnet design Based on Nb_3Sn technology

- ➔ Requires larger aperture!
- ➔ New magnet technology!
- ➔ 70 mm at 210 T/m ➔150 mm diameter 140 T/m➔ Longer magnets

  8 T peak field at coils ➔ 12 T field at coils (Nb_3Sn)!!!

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



◆ Nb-Ti operating dipoles; ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles ✚ Nb3Sn cosϑ LARP QUADs

courtesy: L. Rossi (CERN)

Transition from Nb-Ti to Nb_3Sn: requires similar length of R&D!

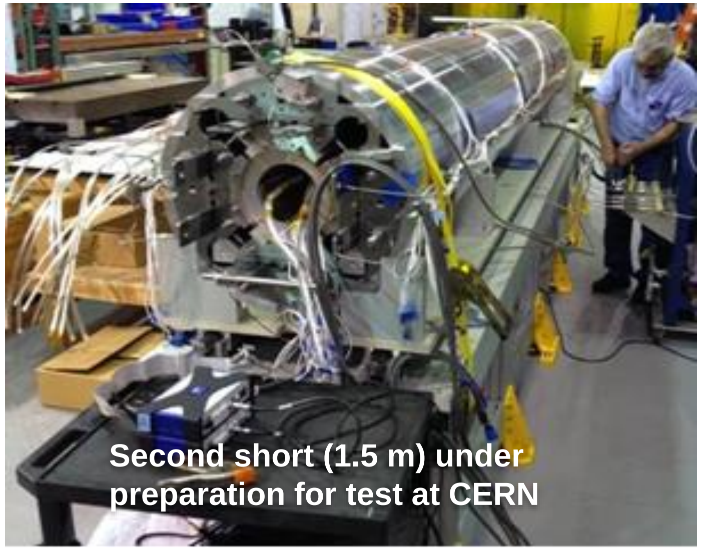
HL-LHC led the R&D for 11-15T magnets based on Nb_3Sn technology:

➔ Started in early 2000

➔ 15-20 years R&D program

➔ Ready by 2025

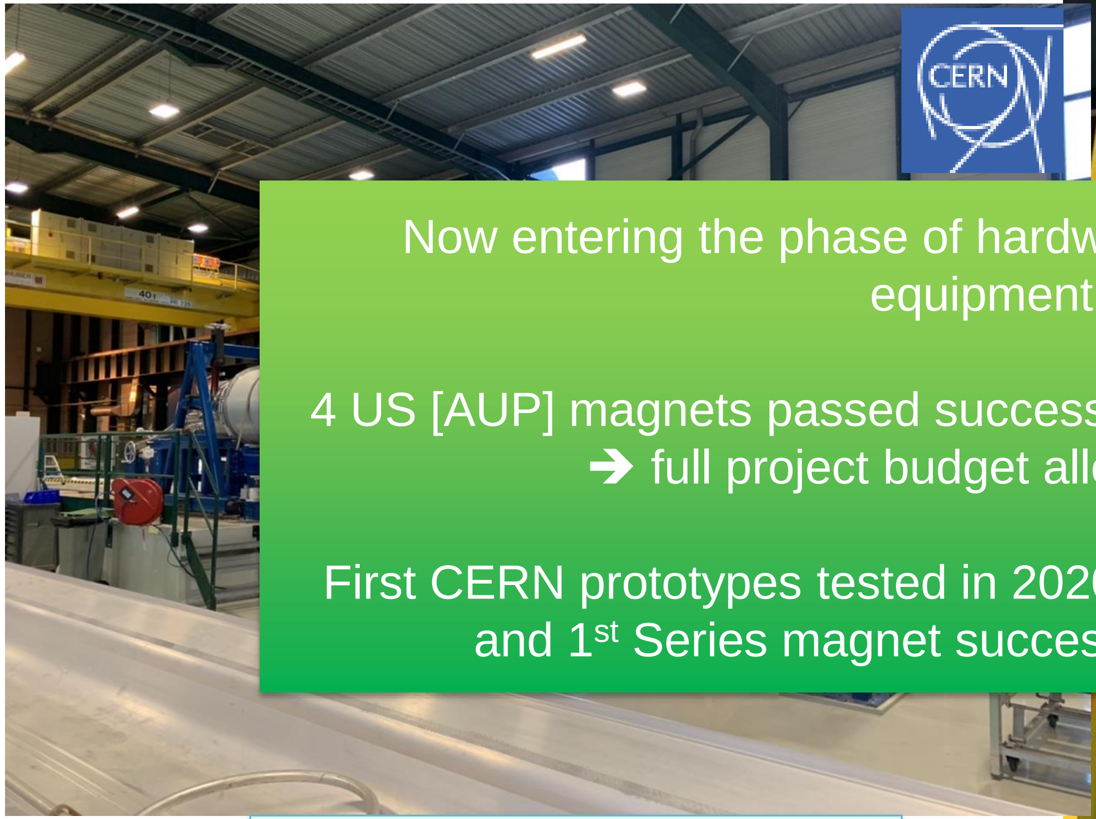
Nb_3Sn quadrupole: Transition from Prototype to Series production



Second short (1.5 m) under preparation for test at CERN

Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

Nb_3Sn quadrupole: Transition from Prototype to Series production



Q1/Q3: FIRST IT

Now entering the phase of hardware production for most equipment!!!

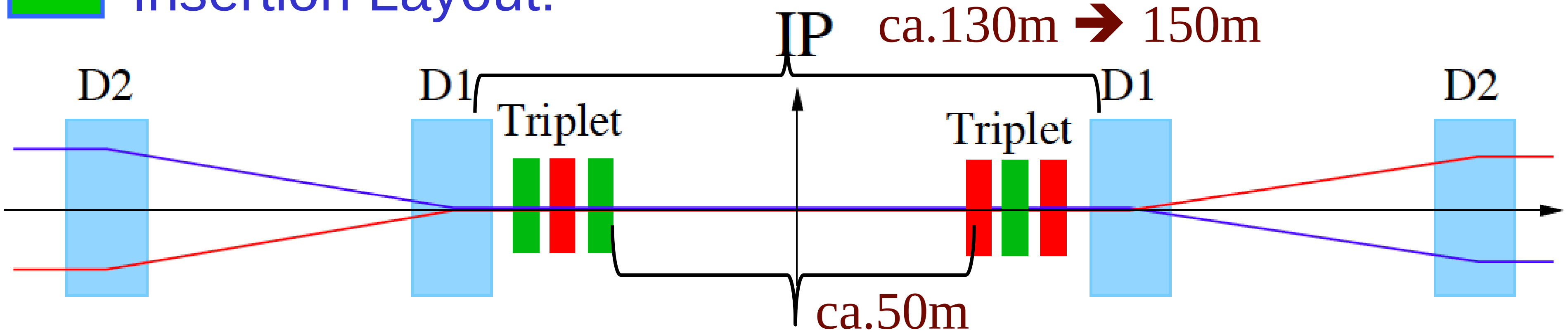
4 US [AUP] magnets passed successfully tests in 2020 and 2021
➔ full project budget allocation in 2020

First CERN prototypes tested in 2020 and 2021. Third prototype and 1st Series magnet successfully tested in 2022

Q2: IT QUAD prototype built and tested at CERN!!!

HL-LHC Challenges: Crossing Angle I

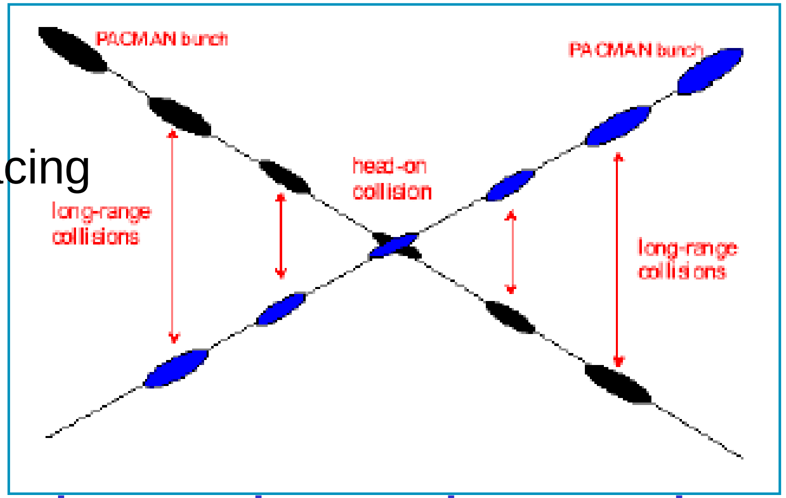
Insertion Layout:



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 ➔ large triplet apertures for HL-LHC!!

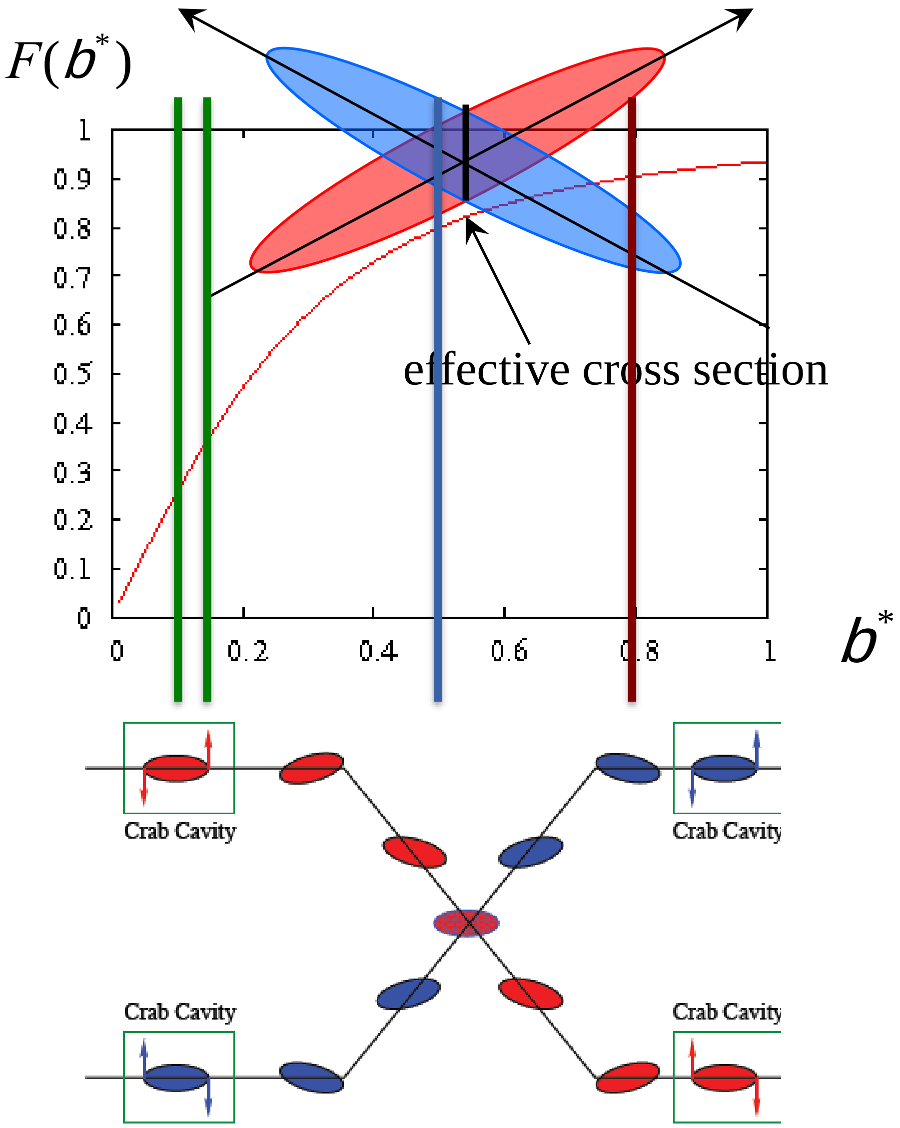
HL-LHC Upgrade Ingredients: Crab Cavities

- Geometric Luminosity Reduction Factor:
- Crab Cavities:
  - Reduces the effect of geometrical reduction factor
  - Independent for each IP

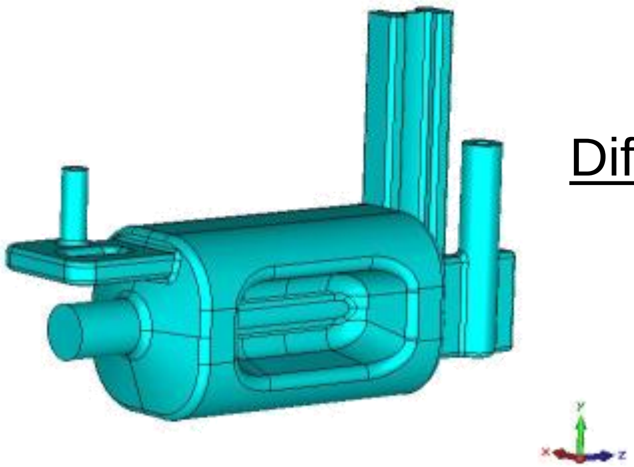
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

  - Noise from cavities to beam Beam size and losses?!?
  - Challenging space constraints:

    ➔ requires novel compact cavity design

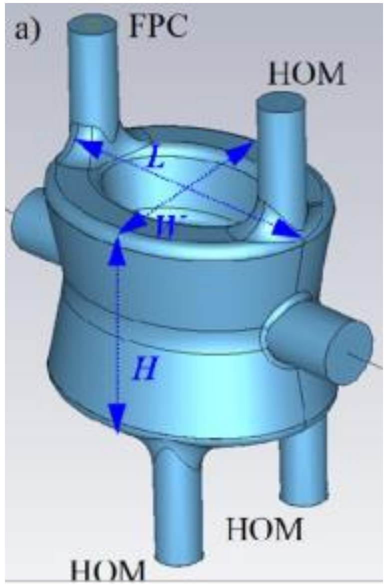


HL-LHC cavity designs



RF Dipole: Waveguide or waveguide-coax couplers

2 Designs with
Different Coupler concepts and
Deflection planes



Double ¼-wave:
Coaxial couplers with
hook-type antenna

DQW crab-cavity
Cryomodule for
SPS tests

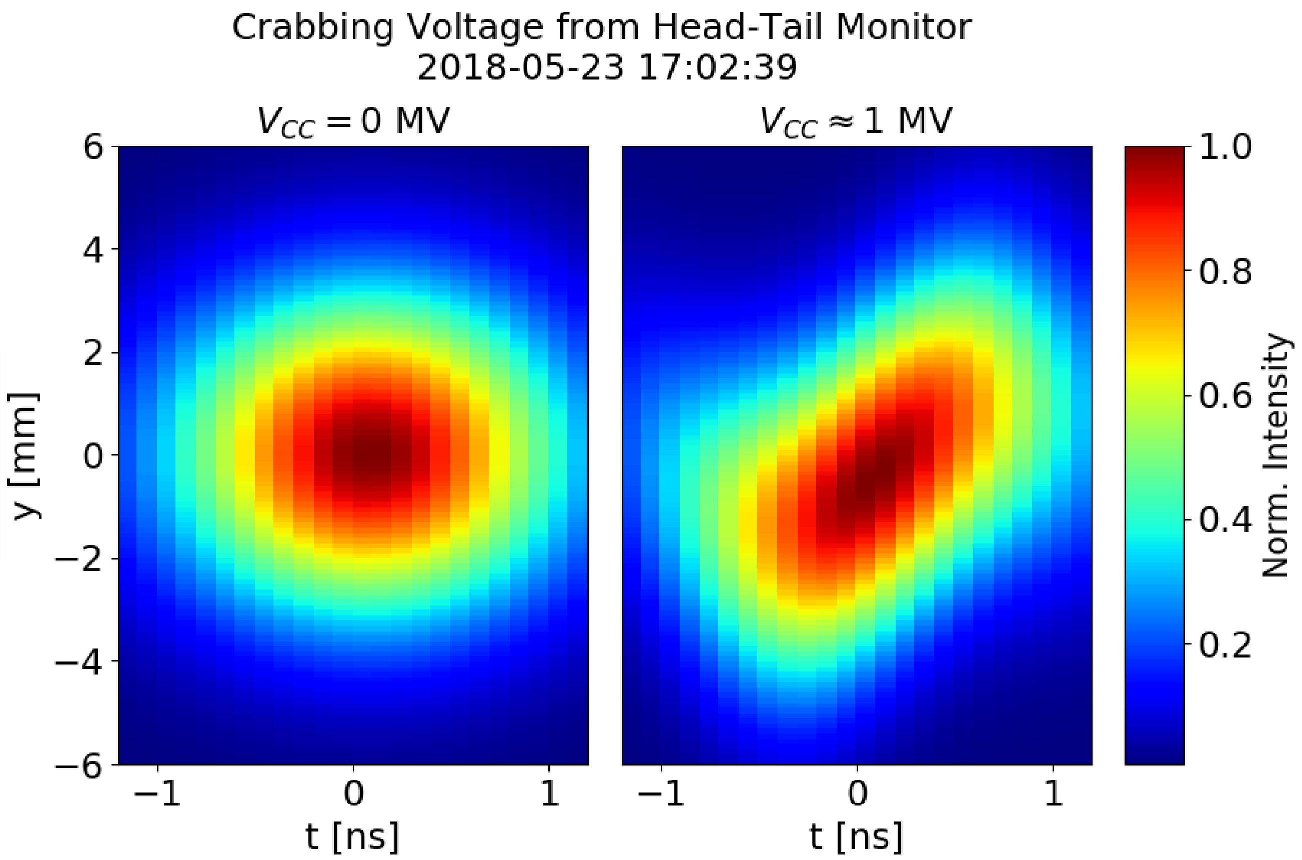
Present baseline: 4 cavities / IP / side → 16 total

Crab cavity cryo-module for installation in the SPS

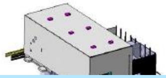
First proton crabbing ever!

TEST in SPS ongoing since 2018

Study and R&D has been very useful to obtain this result



IR1 & IR5 Civil Engineering:



New Underground areas for the HL-LHC:

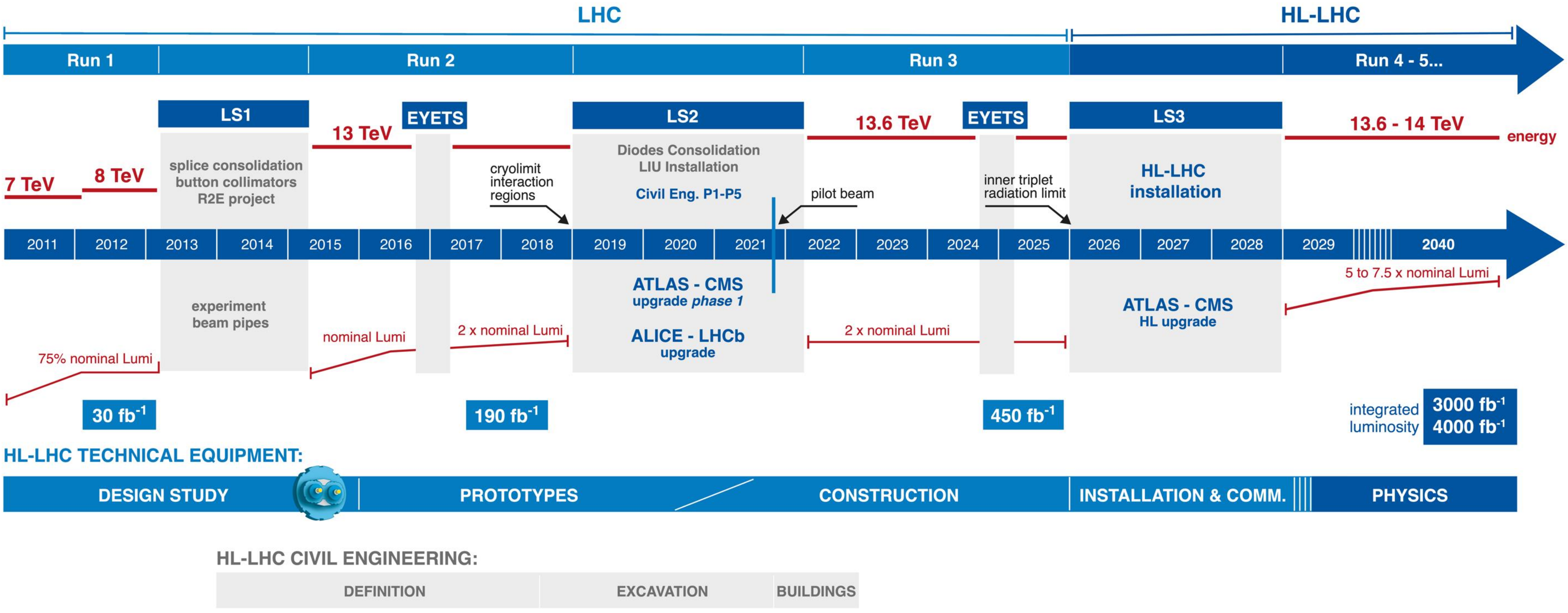
➔ Space for new HL-LHC equipment [e.g. cryo and power converter]

➔ Removal of all active components from the tunnel area
[R2E and equipment failure due to radiation]

➔ Remain accessible for equipment experts during beam operation
[Increase ring maintainability and decrease intervention times]

IR1 & IR5 Underground Civil Engineering: completed!

LHC / HL-LHC Plan



Beyond HL-LHC

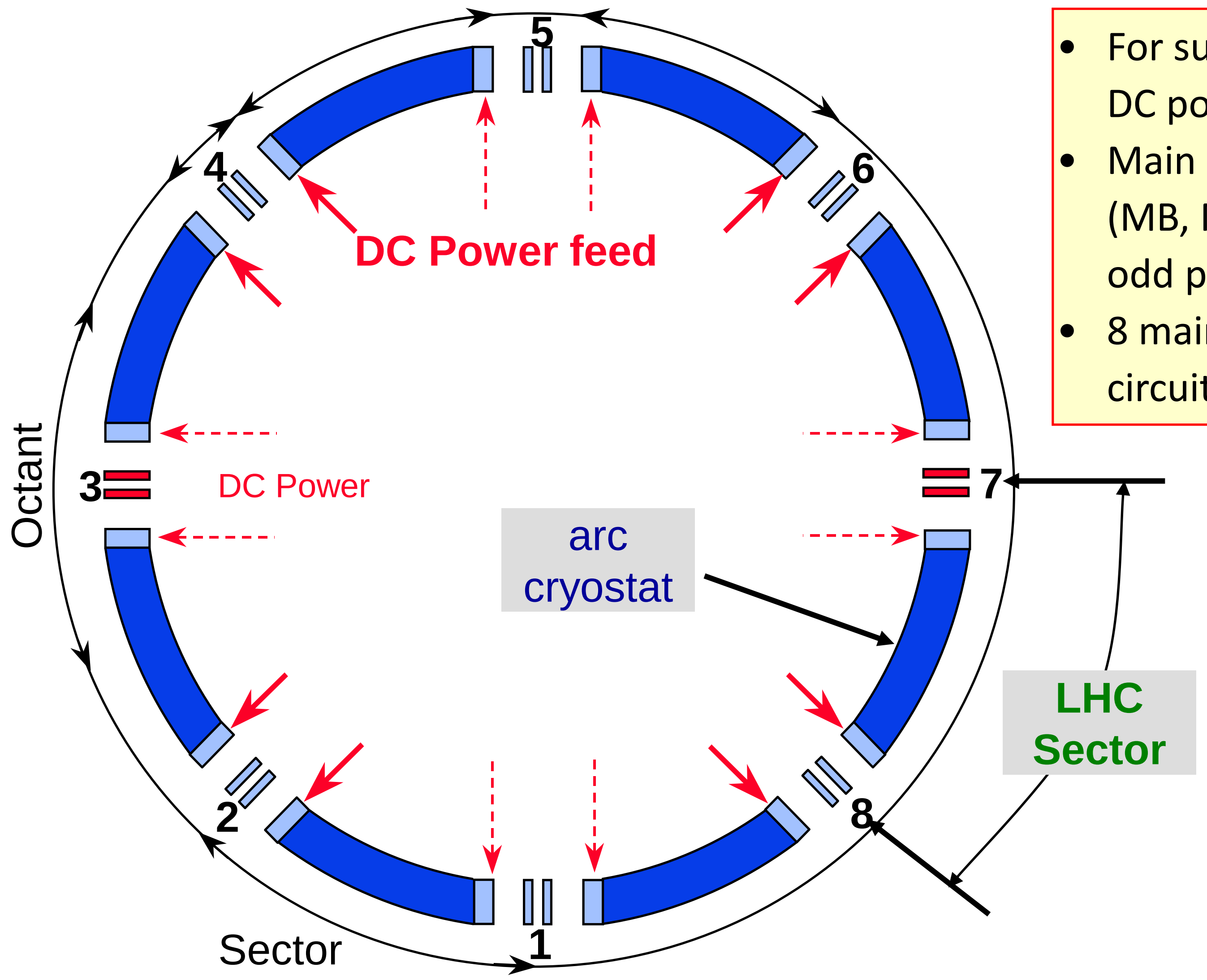
- 2031 after LS4: Full Energy Exploitation of the LHC?

- Beyond 2035: New project proposals!!!

Thanks a lot for your attention!!!

Back up slides

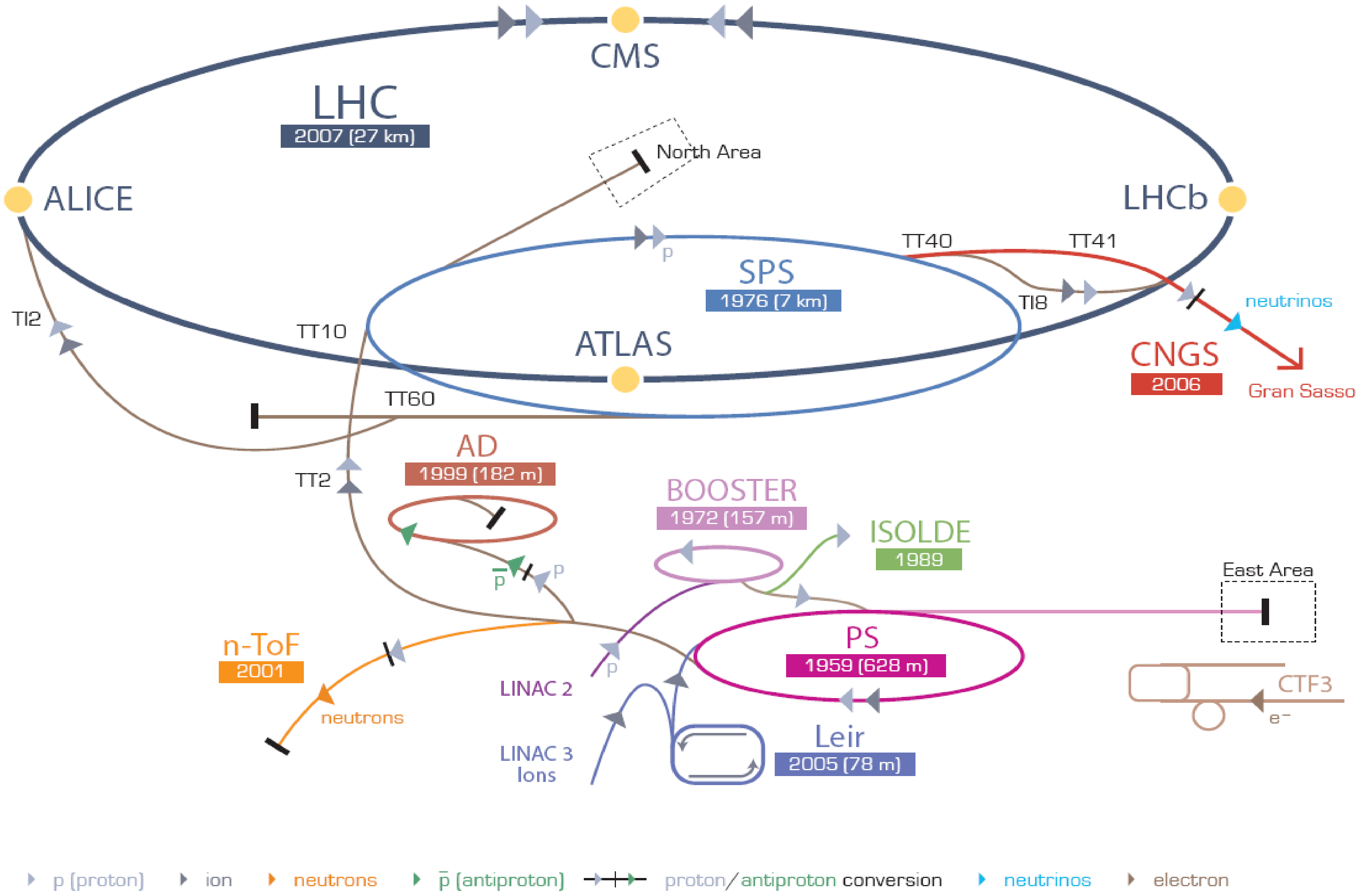
LHC machine sectorisation



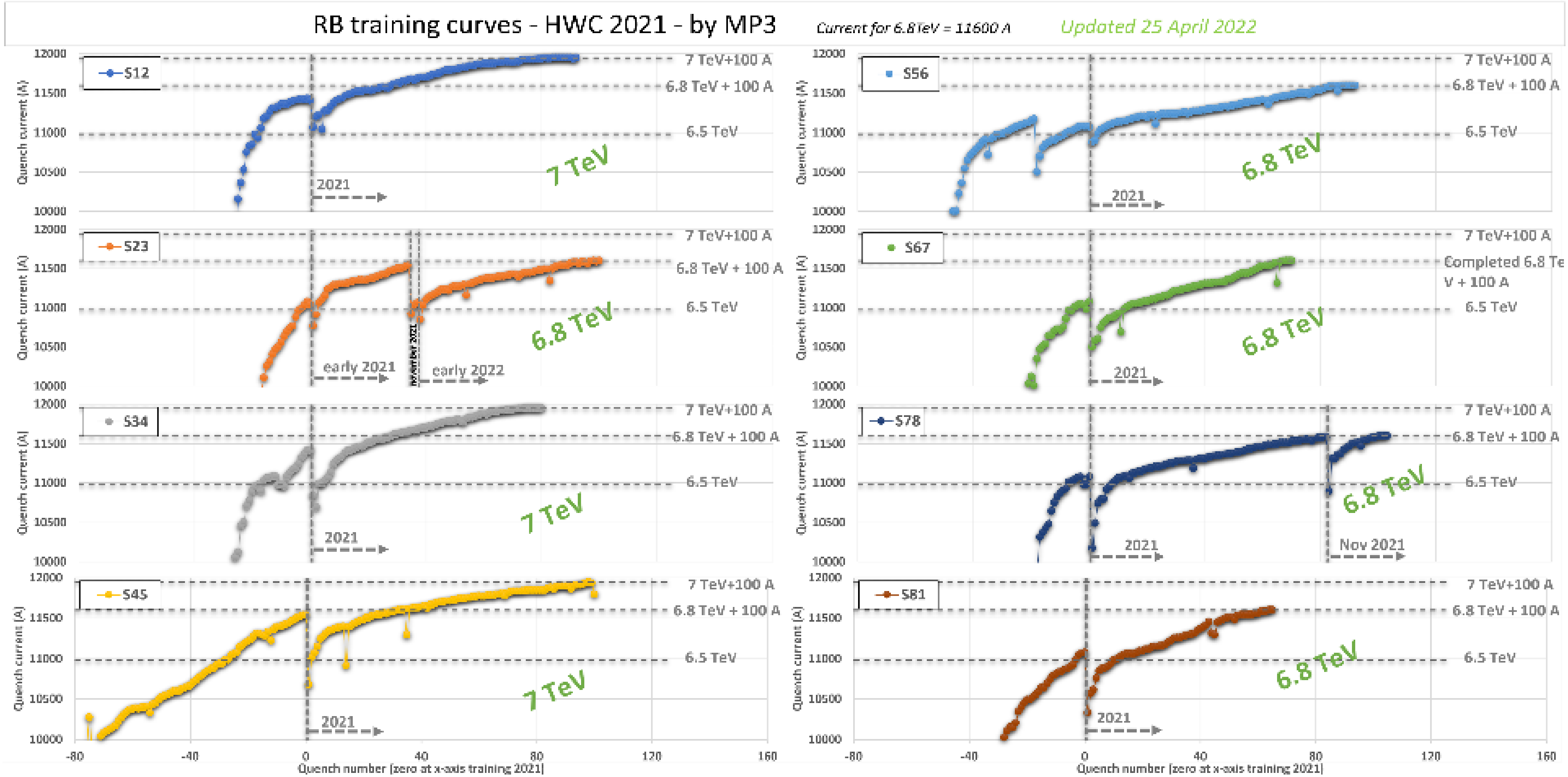
- For superconducting magnets, no DC powering across IPs
- Main DC power feed at even points (MB, MQ), some DC power feed at odd points
- 8 main dipole + 16 quadrupole circuits in LHC

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

CERN accelerator complex



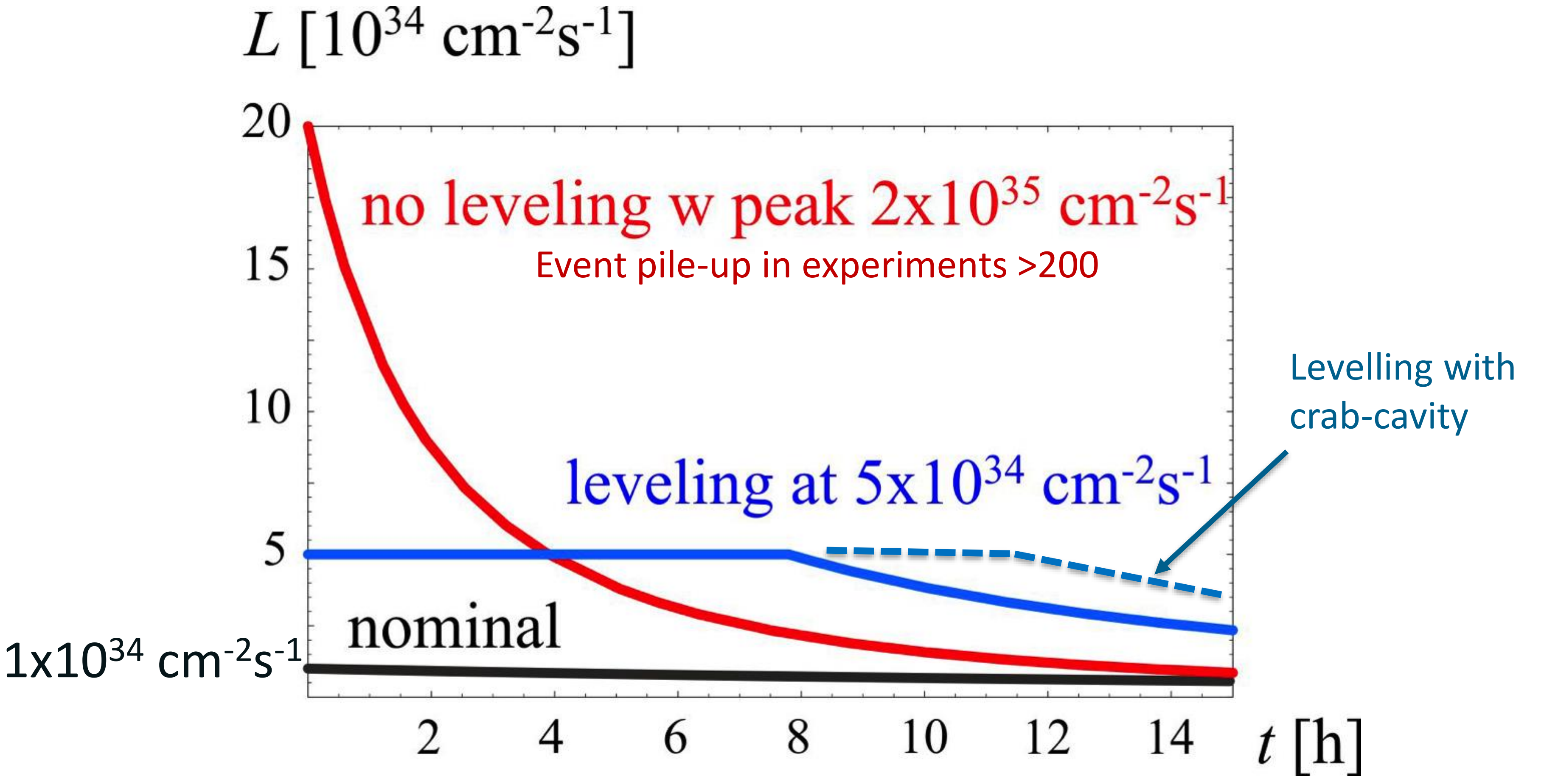
Training quenches RB Circuits



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

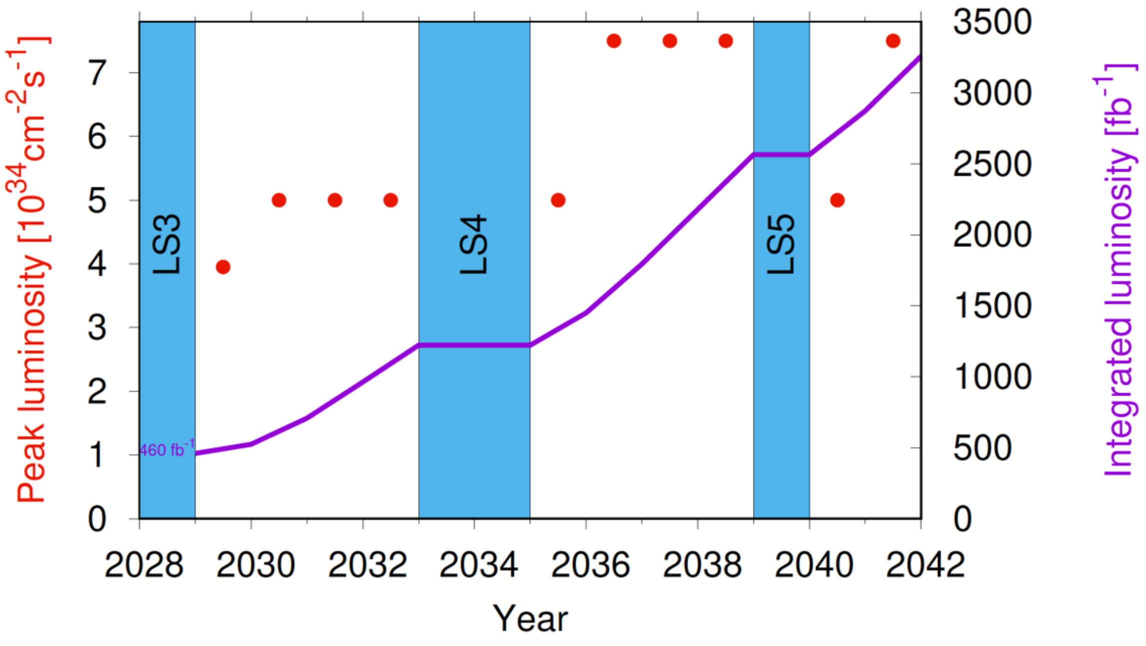
- 5 sectors reached 6.8 TeV equivalent, 3 sectors reached 7 TeV
- No sign of permanent degradation.

Ideal (HL-)LHC operation…. vs…

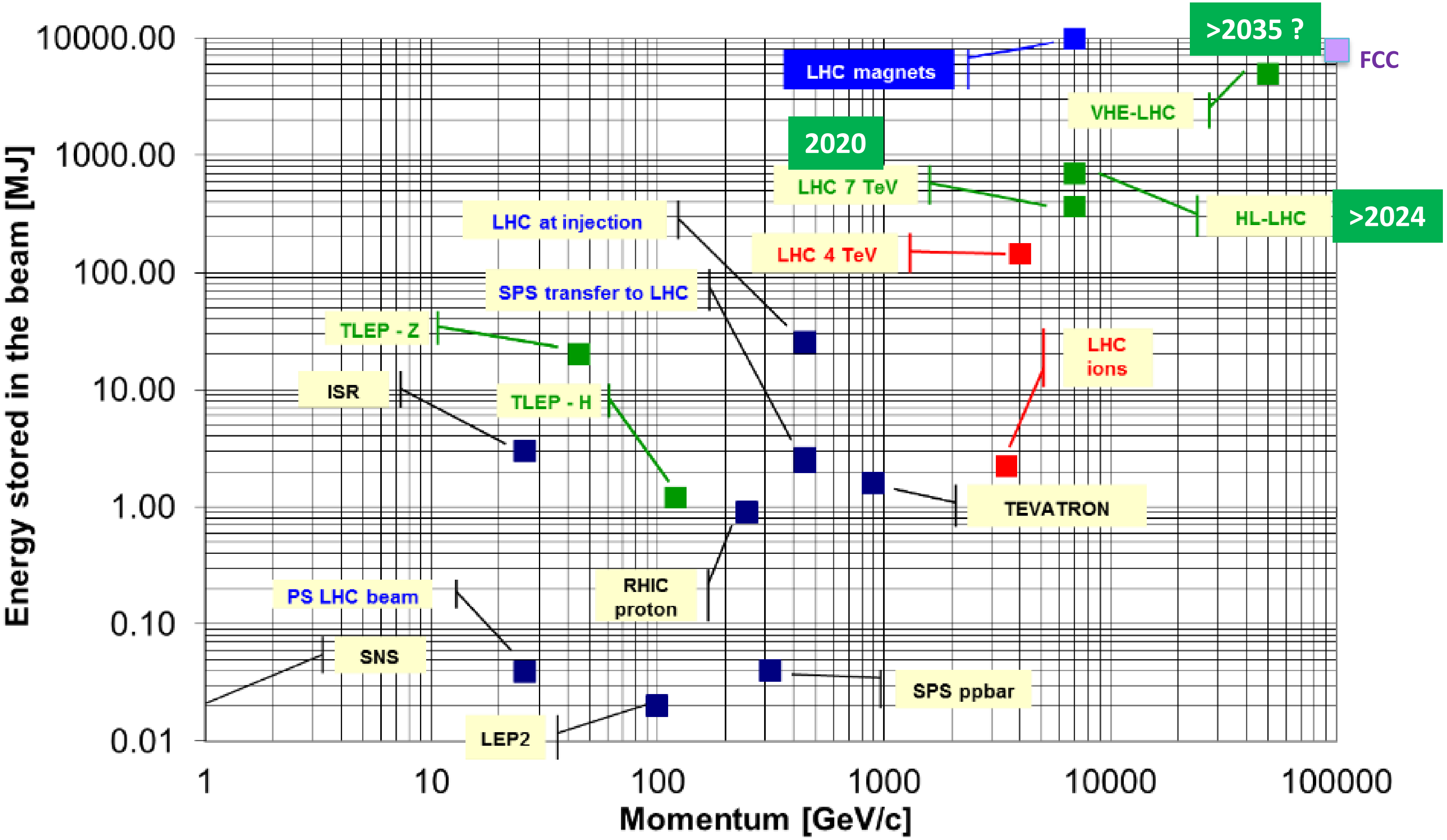


Start of HL-LHC exploitation and performance ramp-up

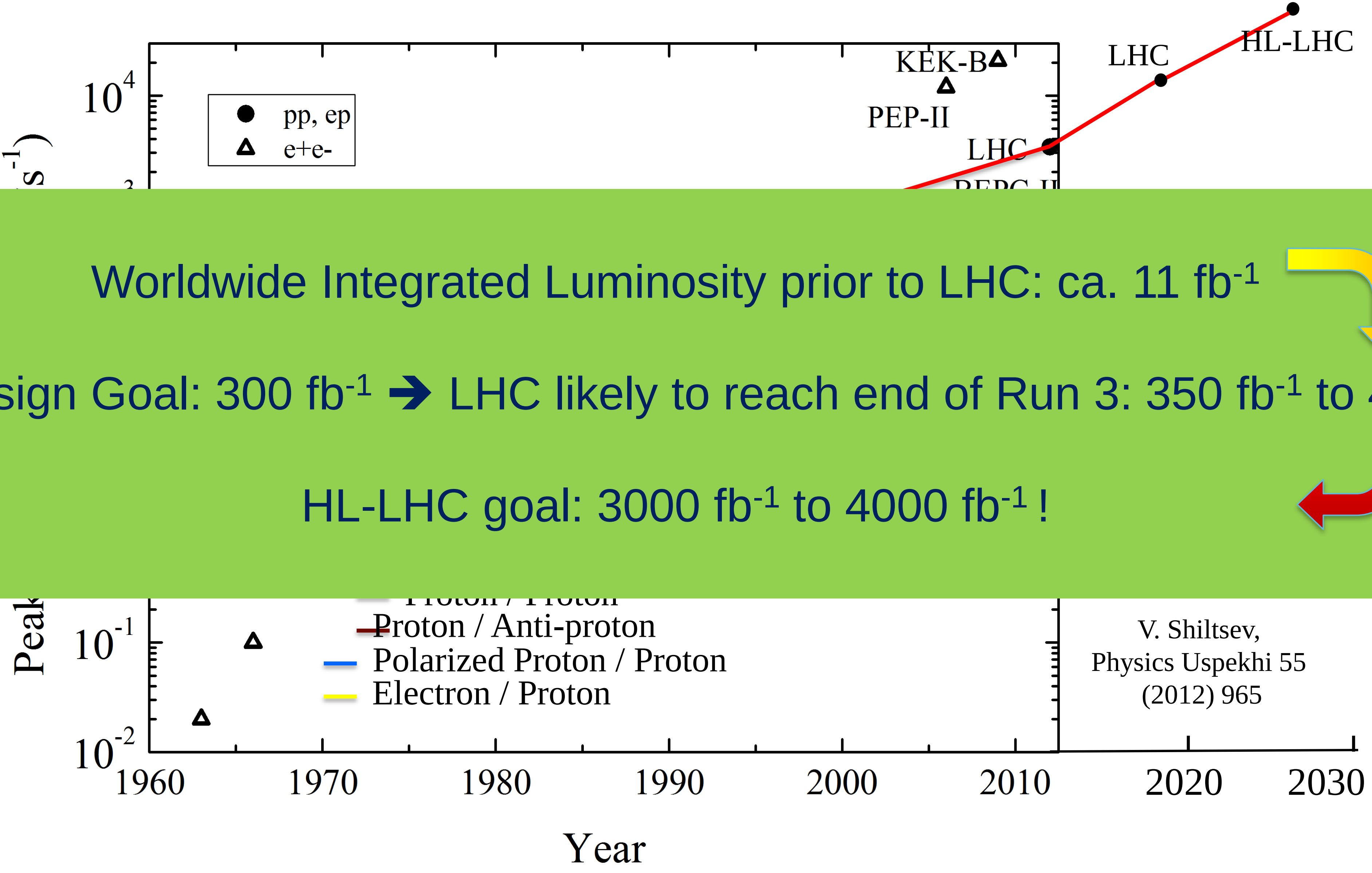
Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	Days in physics	θ $[\mu\text{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200



Stored energies- the future



Peak luminosities of Hadron colliders



Worldwide Integrated Luminosity prior to LHC: ca. 11 fb^{-1}

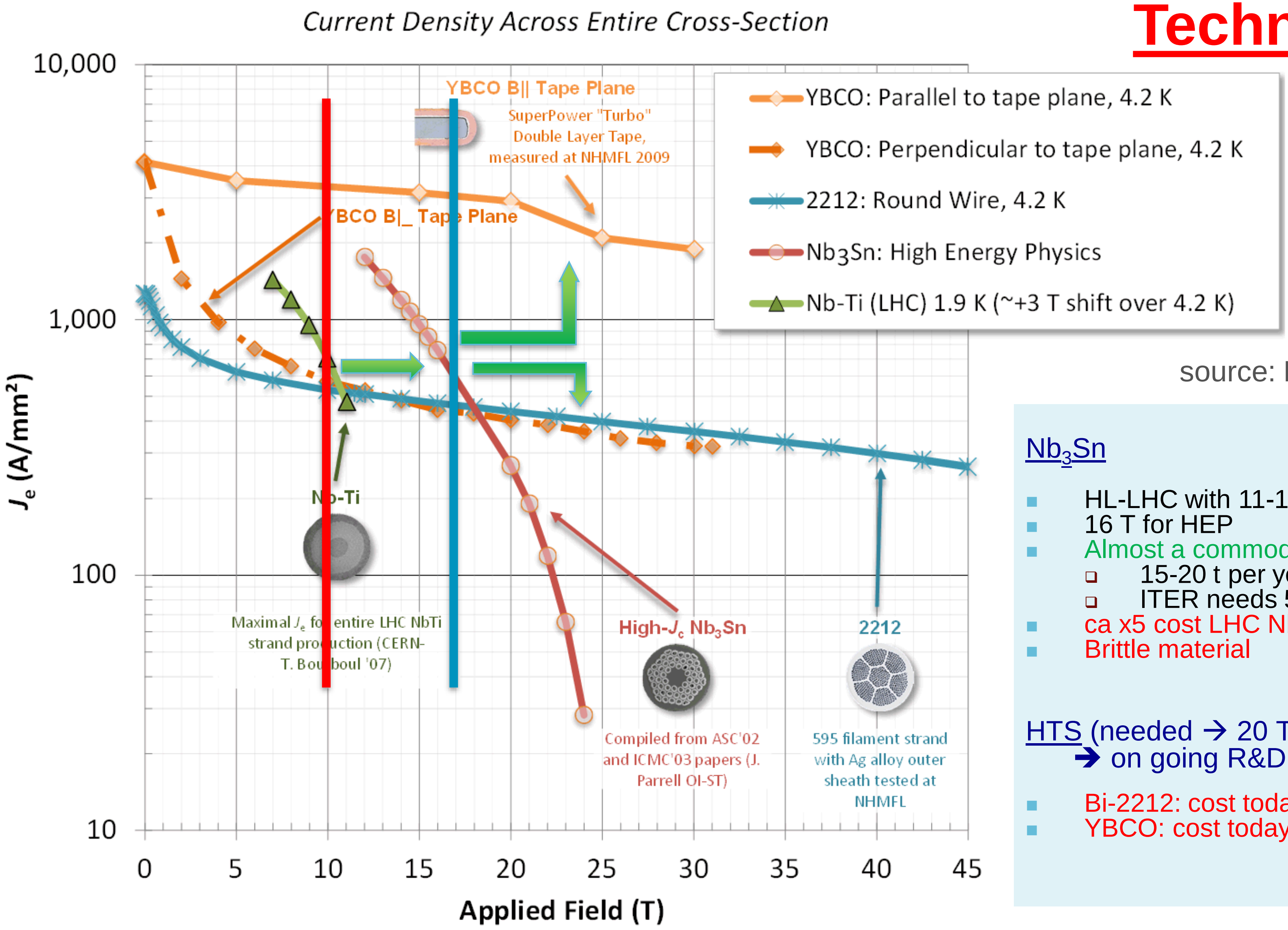
x 35

LHC Design Goal: 300 fb^{-1} ➔ LHC likely to reach end of Run 3: 350 fb^{-1} to 400 fb^{-1}

x 10

HL-LHC goal: 3000 fb^{-1} to 4000 fb^{-1} !

SC Magnet Technology



source: L. Rossi

Nb$_3$Sn

- HL-LHC with 11-12T
- 16 T for HEP
- Almost a commodity!
  - 15-20 t per year for MRI
  - ITER needs 500 t
- ca x5 cost LHC Nb-Ti
- Brittle material

HTS (needed → 20 T)
→ on going R&D!

- Bi-2212: cost today 2-5x Nb$_3$Sn
- YBCO: cost today 10x Nb$_3$Sn