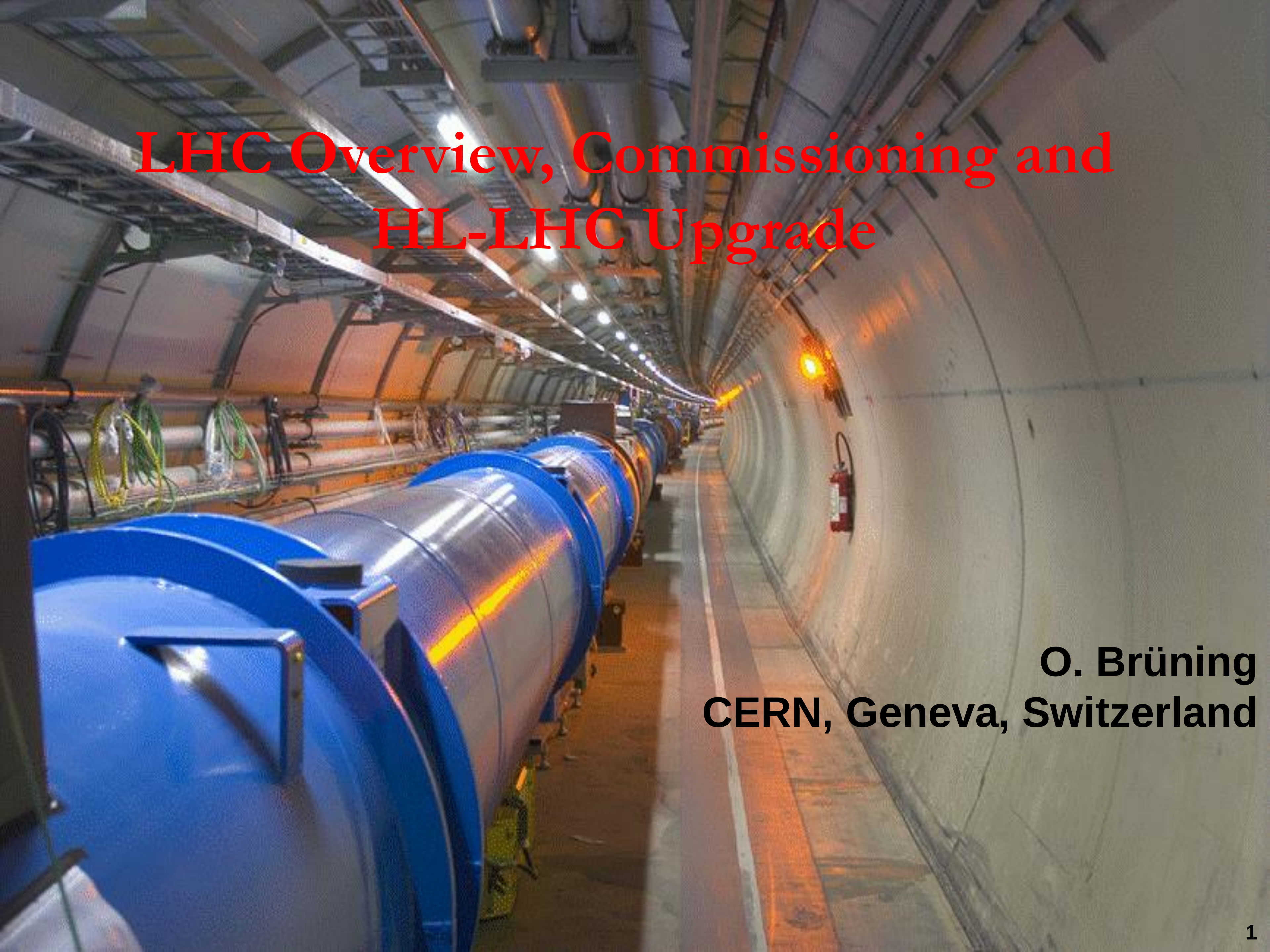


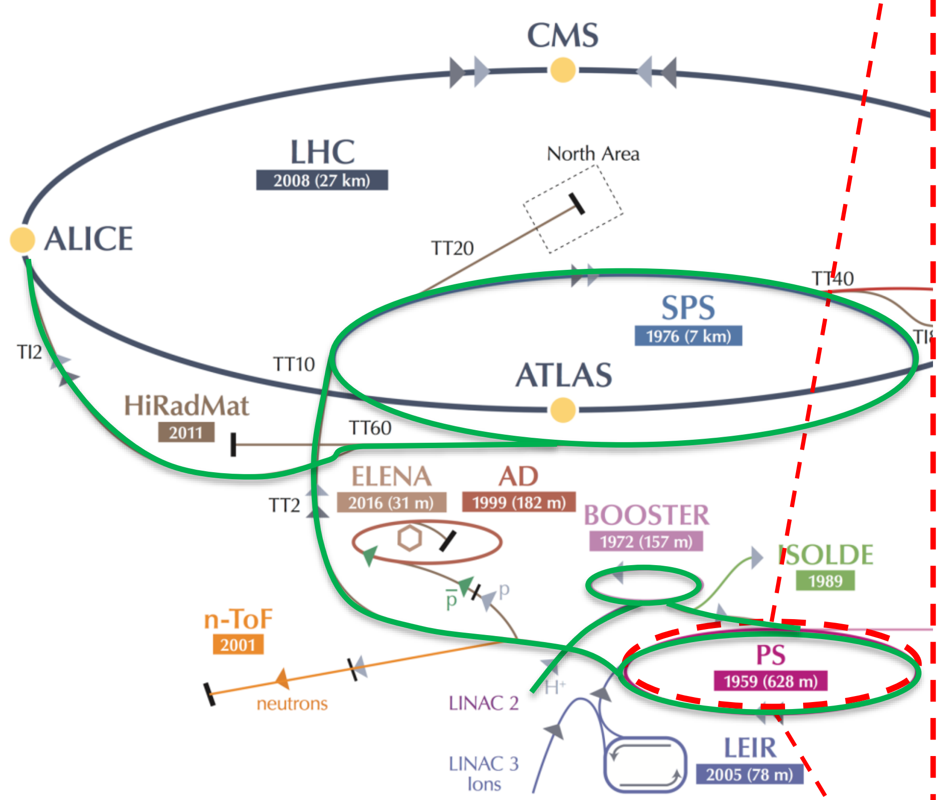
LHC Overview, Commissioning and HL-LHC Upgrade

O. Brüning
CERN, Geneva, Switzerland

An extra boost from the injectors

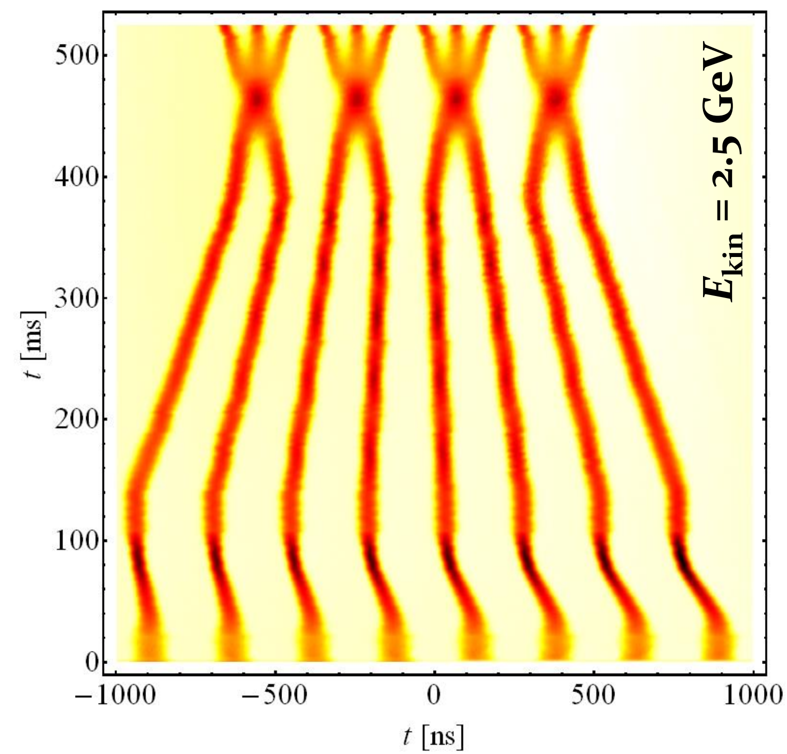
The LHC performance fully relies on the p

- By itself **one of the largest accelera** diverse and, for many aspects, uniqu



A **new production scheme** – the **"BCMS"** - was put in place in the PS

- RF cavities tuned at different frequencies play together to **compress merge and split bunches**
- Beams **~30% brighter** than standard scheme



→ $L \approx 2\ 10^{34}\ cm^{-2}s^{-1}$

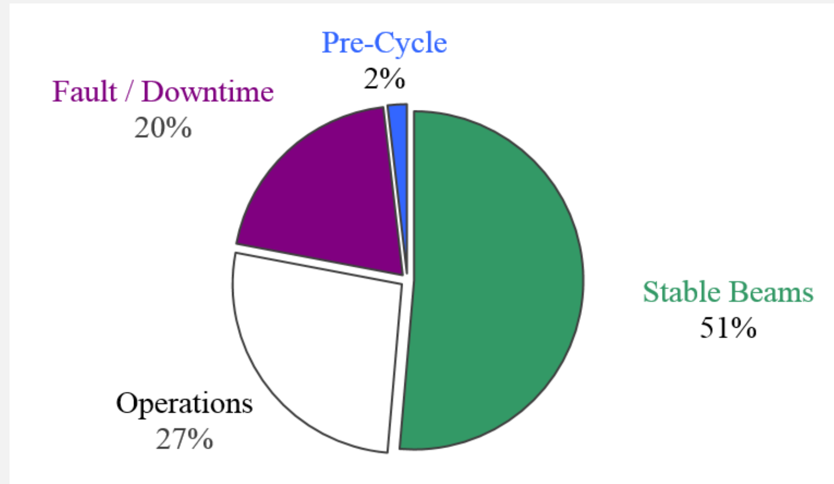
Impressive Machine Efficiency with 25ns

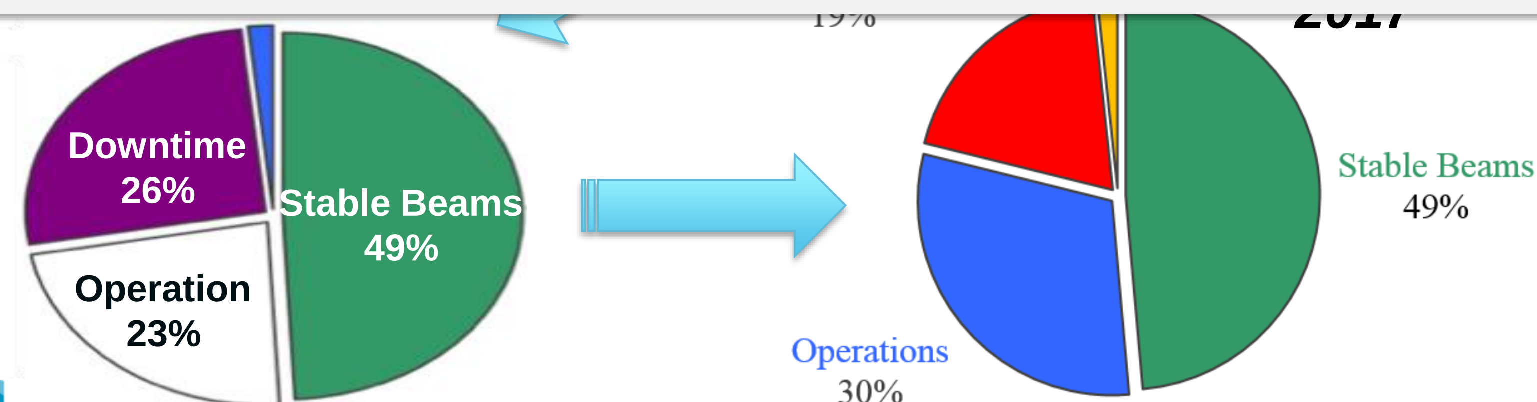
2018 up to Technical Stop in June:

≈55 days physics ≈ 1308.7 hours

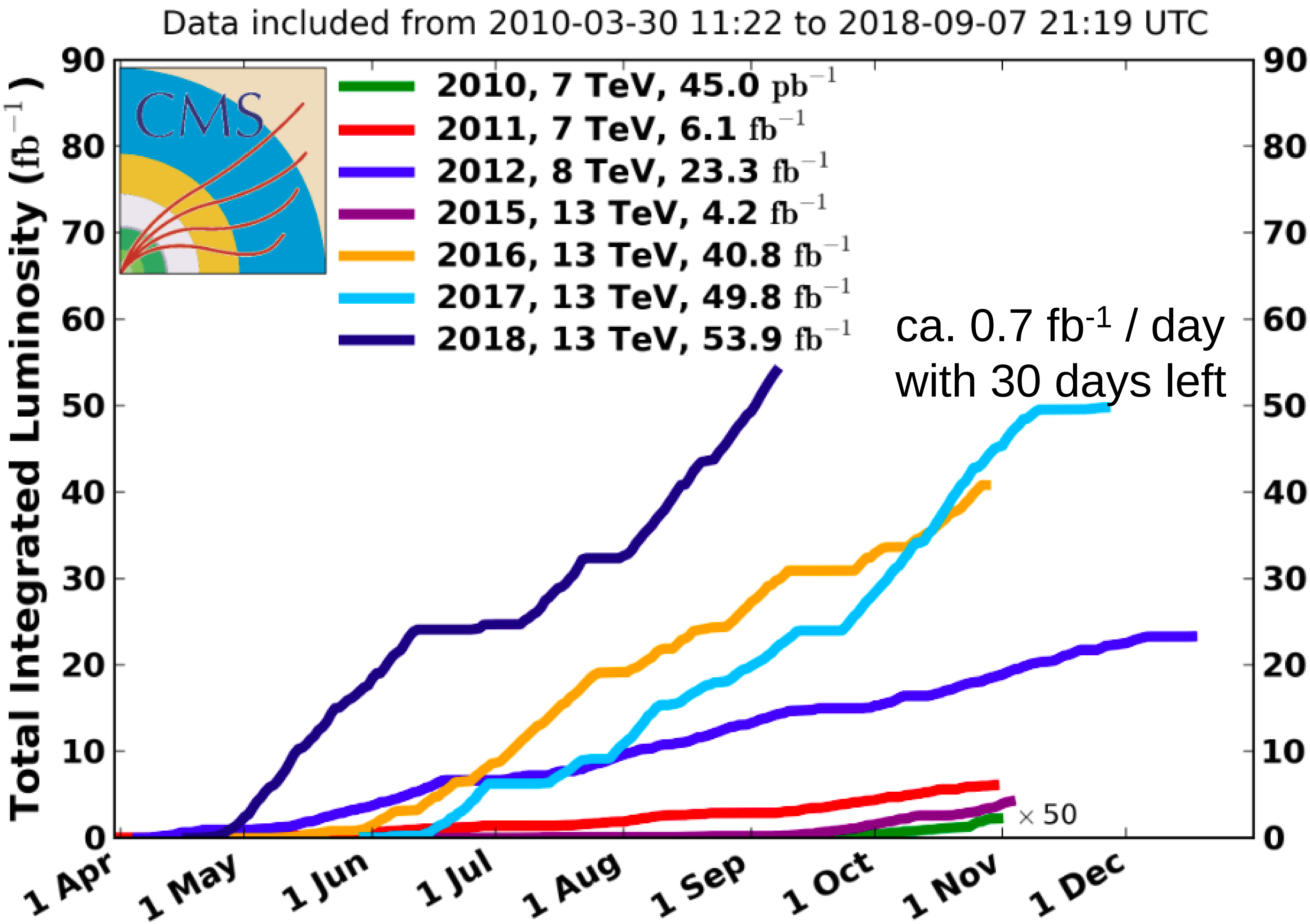
	Duration [h]
Stable Beams	672.2
Operations	348.4
Fault / Downtime	264.1
Pre-Cycle	24.0

= 1308.7

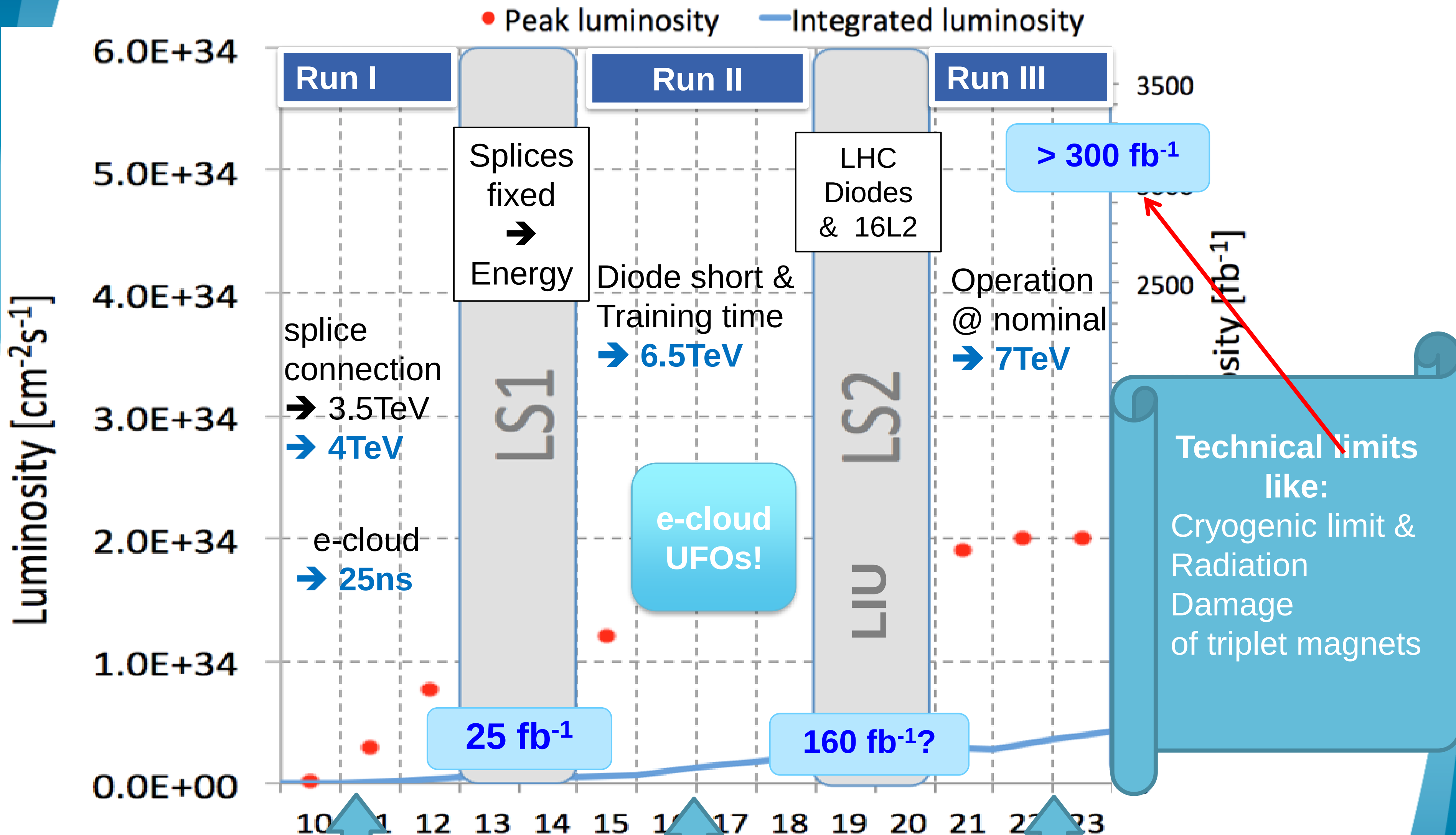




CMS Integrated Luminosity, pp



Performance Projections up to HL-LHC:

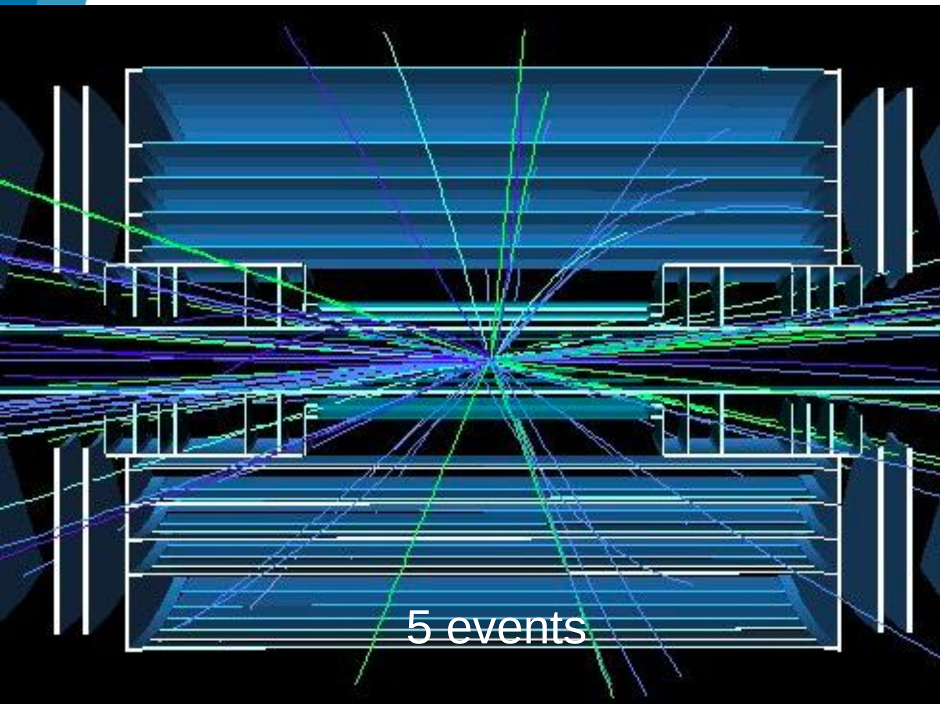


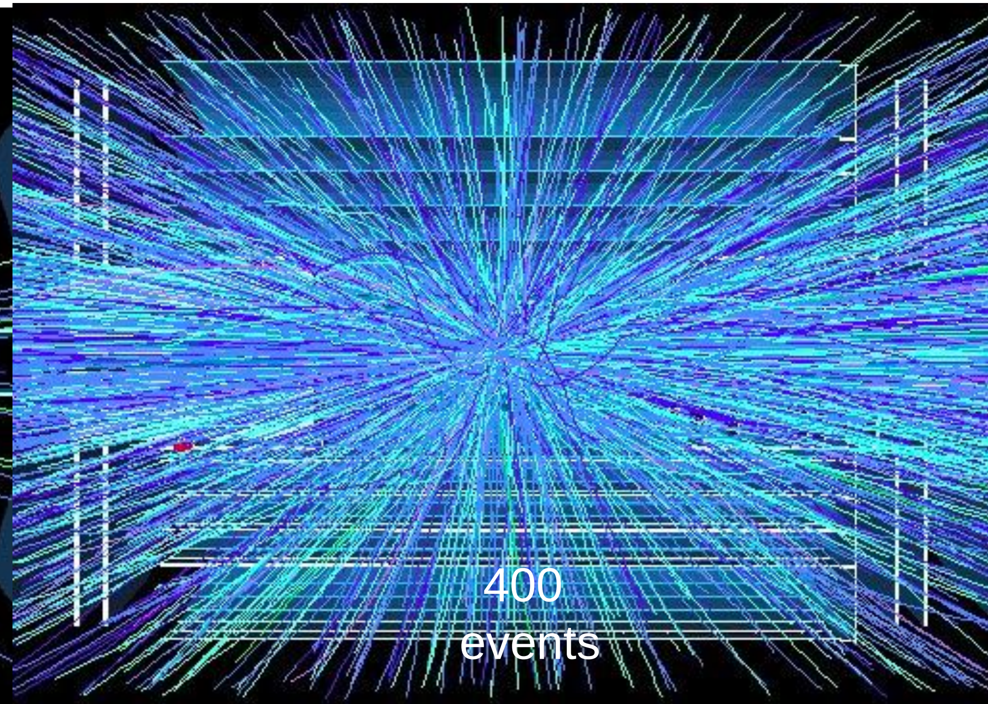
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
high pile up ~40

1.5 -2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

Goal of High Luminosity LHC (HL-LHC):





implying an integrated luminosity of **250 fb^{-1} per year**,

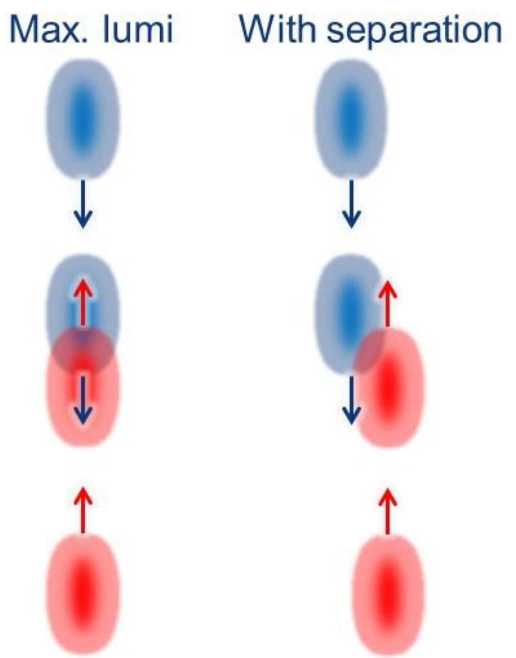
design oper. for μ δ **140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

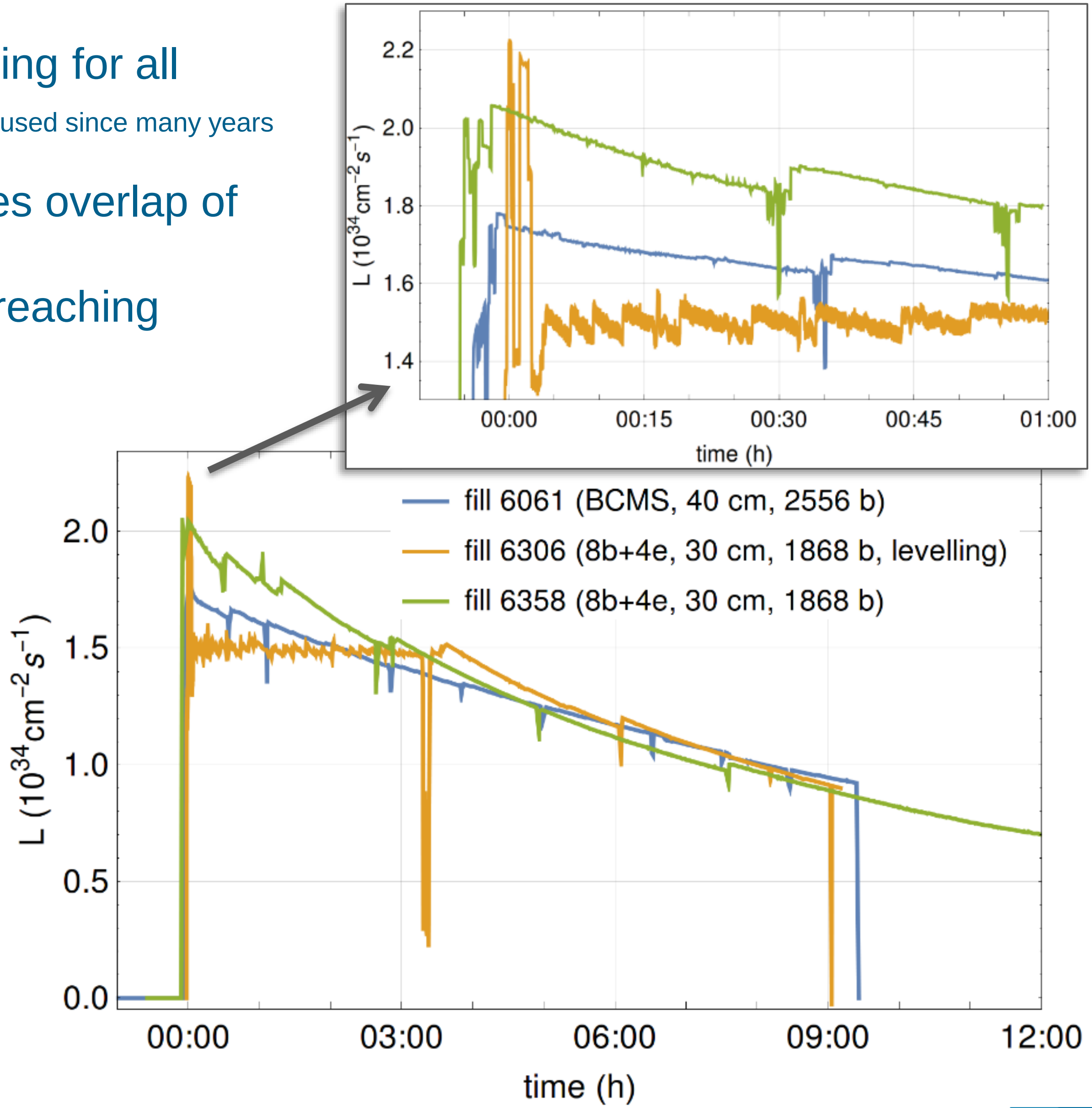
➔ Operation with levelled luminosity!

➔10x the luminosity reach of first 10 years of LHC operation!!

LHC 2017 : separation levelling

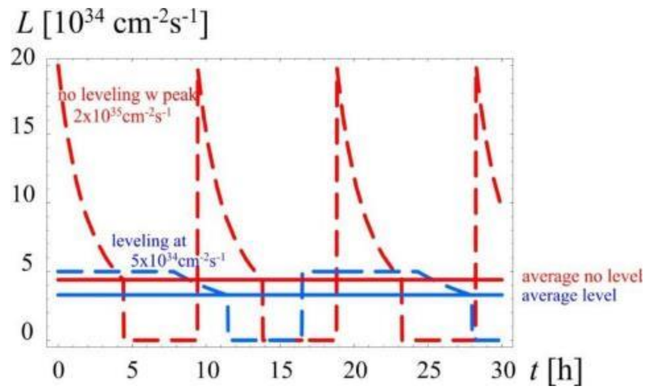
- Introduced separation levelling for all experiments (Separation levelling is used since many years for ALICE and LHCb)
- Dynamic orbit bump changes overlap of colliding bunches
- Initial spike before leveling reaching 2.2×10^{34} $cm^{-2}s^{-1}$





MDs on β* levelling

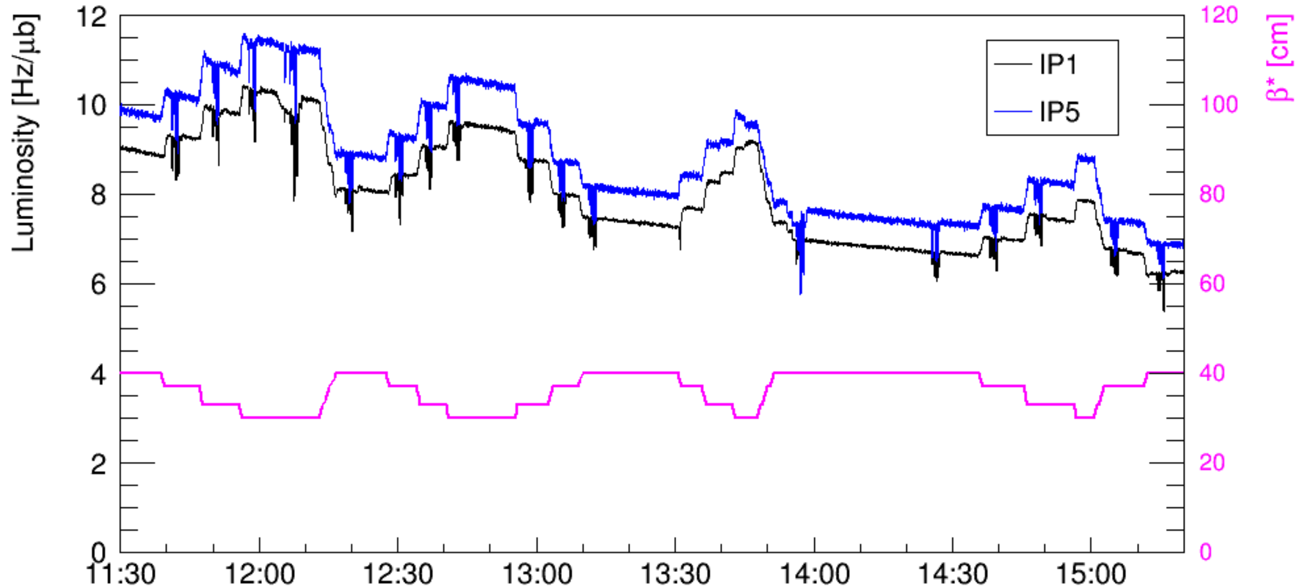
Levelling luminosity by β* should be the main levelling technique for HL-LHC



β* levelling in

LHC MD:

a possible tool for 2018 operation



Luminosity evolution during β levelling, moving back and forth between 30 cm and 40 cm. The beams remained head-on* ***within ~ 2 μm*** *!*

Upgrade Considerations: Beam Lifetime

F. Zimmermann, Chamonix 2011

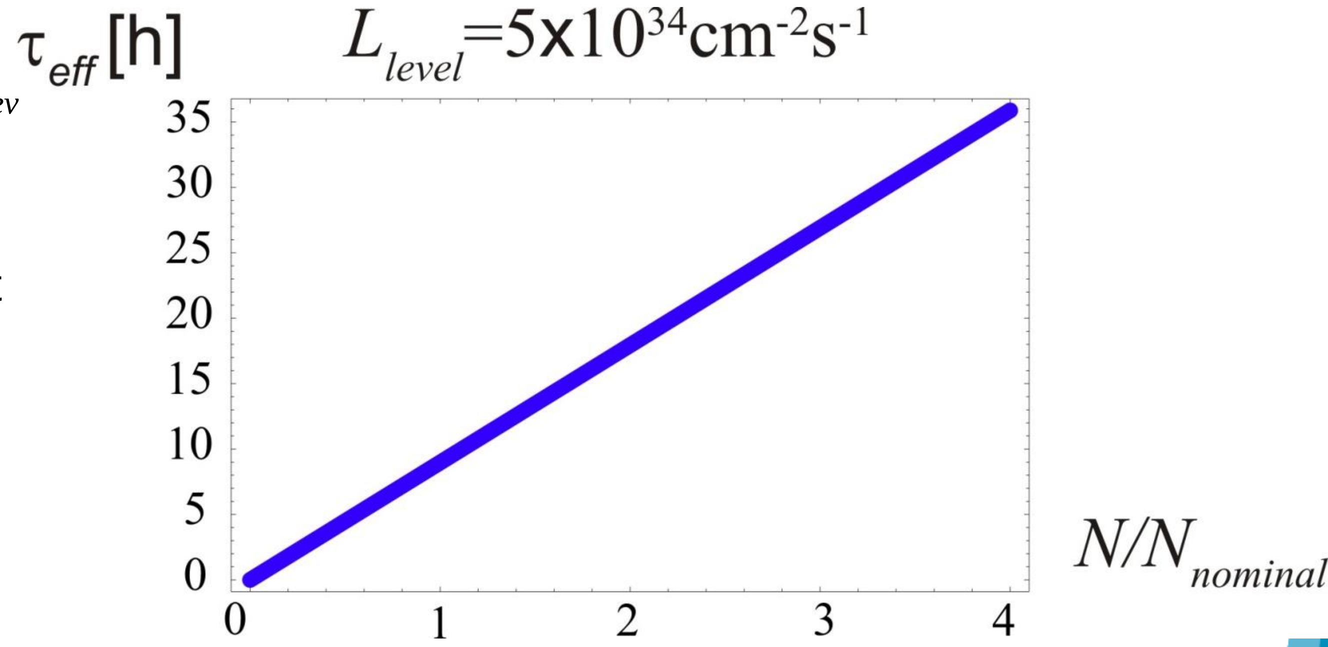
- For given luminosity τ_{eff} scales with total beam current

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = -n_{IP}\sigma L_{lev}$$

$$N(t) = (1 - t/\tau_{eff})\, N_{tot}$$

$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma L_{lev}}$$

(σ=100 mbarn)



➔ argument for HL-LHC scenarios with maximum beam current

➔ τ_{eff} = 13.9 hours for 5 10^{14} p/beam

➔ LIU Project for LS2!!!

HL-LHC Key Beam Parameters

- Increased Beam Brightness thanks to LIU upgrade

Ca. 2800 bunches with 2.2 10^{11} ppb and
a normalized transverse emittance of ca. 2.5μm

➔ ca. 3 times the nominal LHC beam brightness

➔ ca. 50% higher brightness as the one achieved during LHC Run2 with BCMS beams

➔ Beam current above 1A as compared to ca. 0.5A during LHC Run2 ➔ more than 500MJ stored energy per beam

LHC Challenges: Beam Power

- Unprecedented beam power:

Wo

Failu

Lifet

→ New collimators and absorbers for the HL-LHC

→ Remove all active components from the LHC tunnel [requiring new space underground]

→ Magnet Quench

→ R2E and SEU

→ Machine efficiency

HL-LHC Key Beam Parameters

- Increased Beam Brightness thanks to LIU upgrade

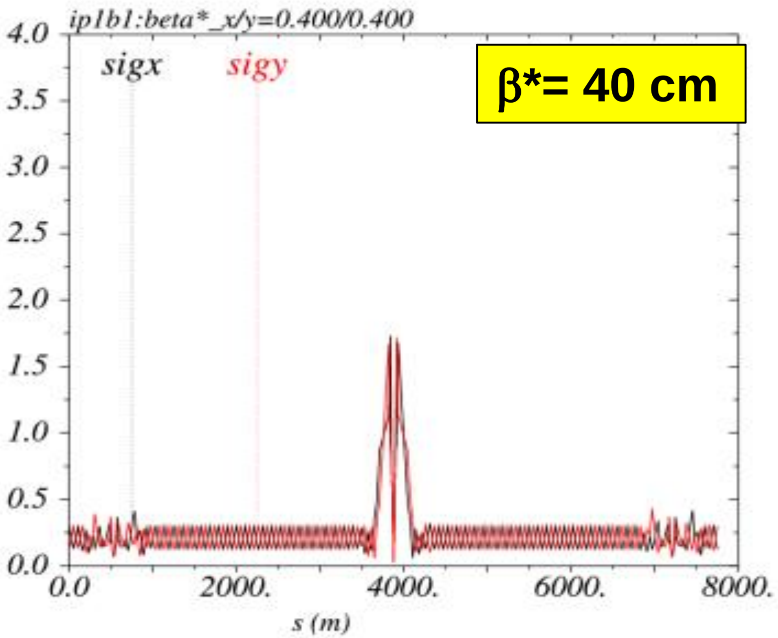
  Ca. 2800 bunches with 2.2 10^{11} ppb and
  a normalized transverse emittance of ca. 2.5μm
  ➔ ca. 3 times the nominal LHC beam brightness
  ➔ ca. 50% higher brightness as the one achieved during LHC Run2 with BCMS beams
  ➔ Beam current above 1A as compared to ca. 0.5A during LHC Run2 ➔ more than 500MJ stored energy per beam

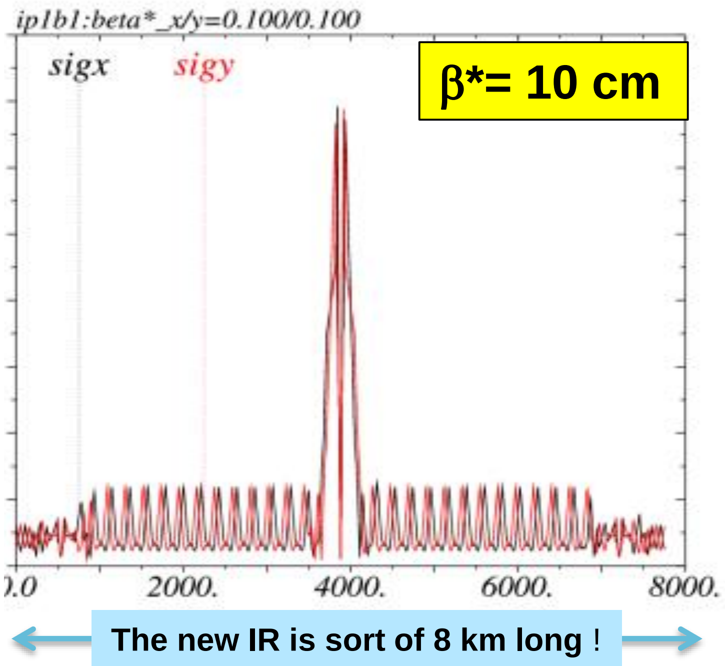
- Reduced β^* due to larger triplet aperture

  β^* = 15cm [perhaps down to 10cm] ➔ Chromatic aberrations
  ➔ Operation with novel ATS optics scheme

HL-LHC ATS Optics

Generalized Squeeze using 50% of the machine





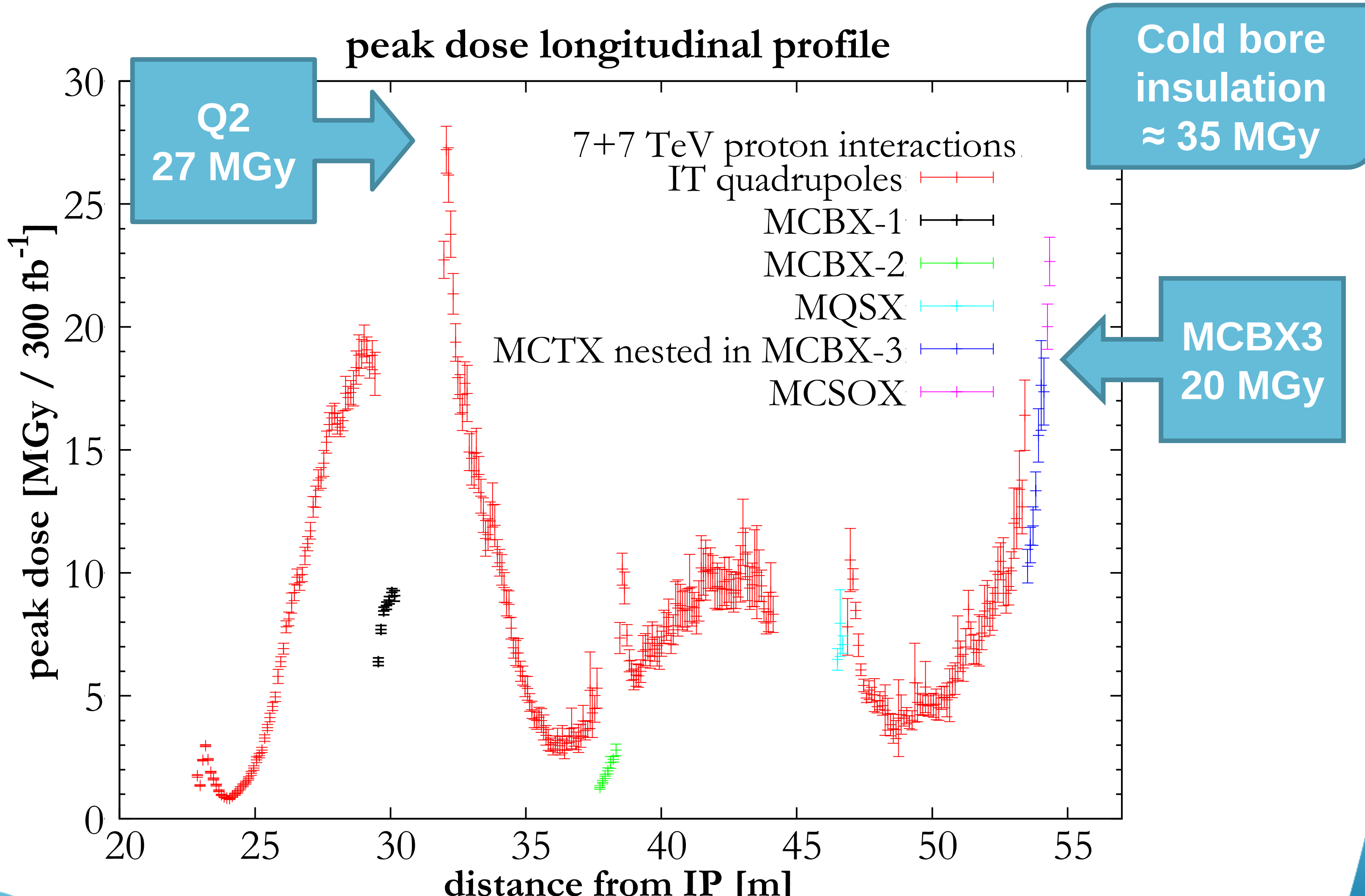
S. Fartoukh @ Chamonix 2018

➔ Increased efficiency of the arc correctors magnets [octupoles!!!]

➔ Optics 'machability' to the arcs

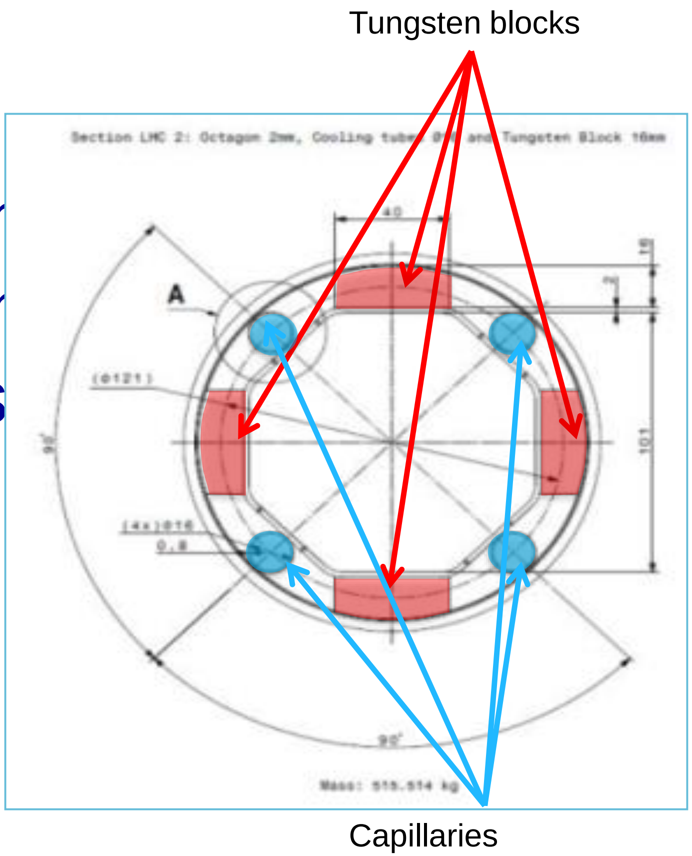
➔ Intrinsic correction of Chromatic aberrations from the triplets

HL-LHC technical bottleneck: Radiation damage to triplet 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 magn coils receive a similar radiation dos @ 10 times higher integrated luminosity!!!!! ➔ Shielding!

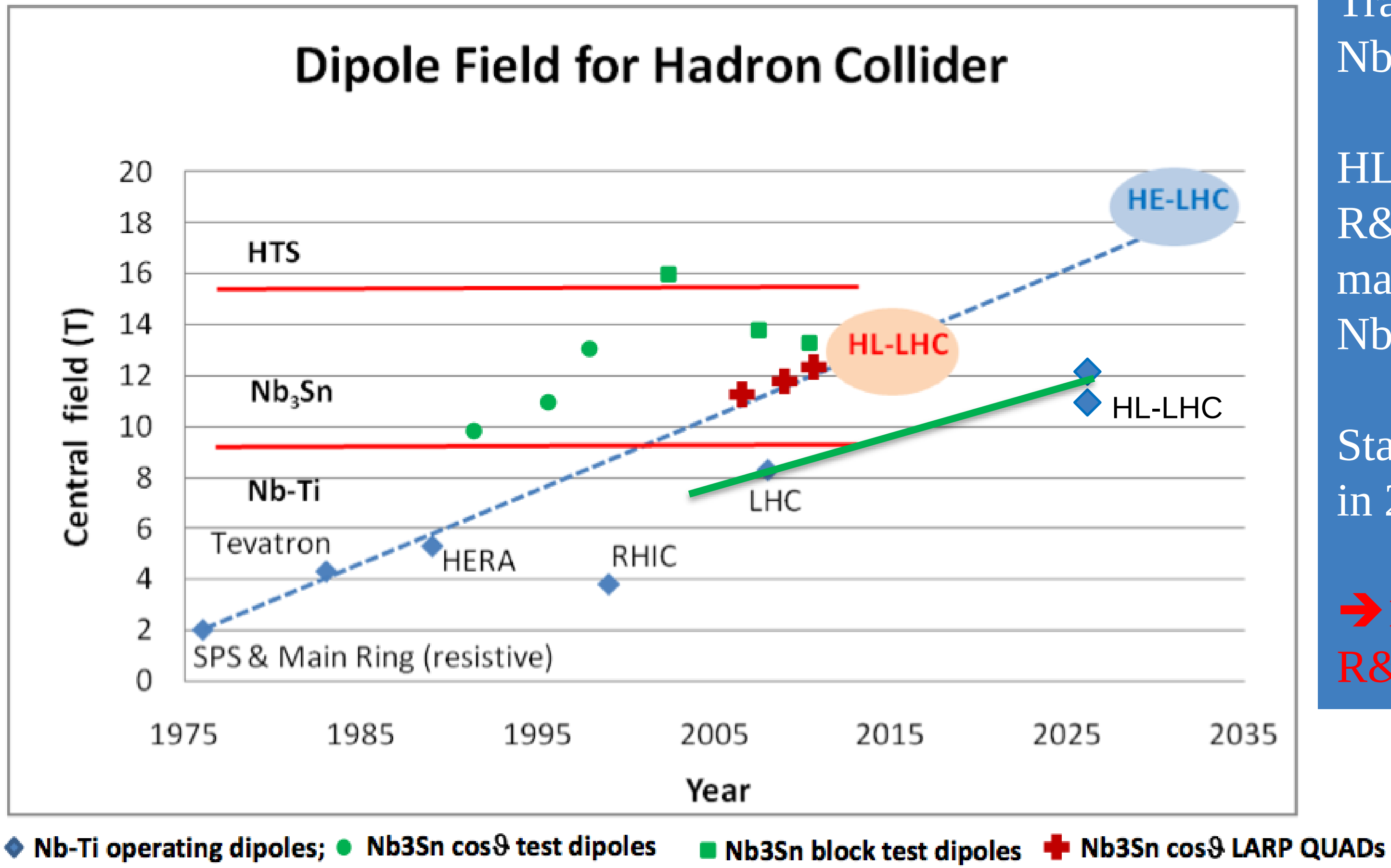


- ➔ Requires larger aperture!
- ➔ New magnet technology
- ➔ 70mm at 210 T/m ➔150mm diameter 140 T/m

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

pp colliders – High Field SC Magnets

How High can we go? Livingston plot revisited:



Transition from NbTi to Nb_3Sn:

HL-LH lead the R&D for 11-12T magnets based on Nb_3Sn technology:

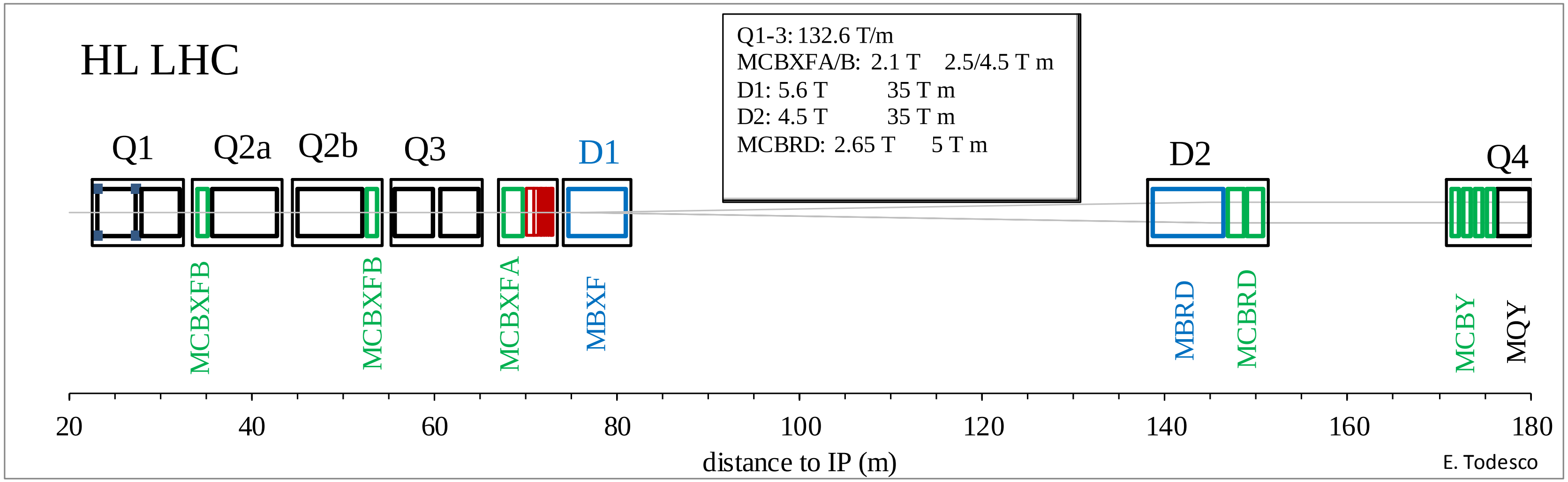
Started in earnest in 2004:

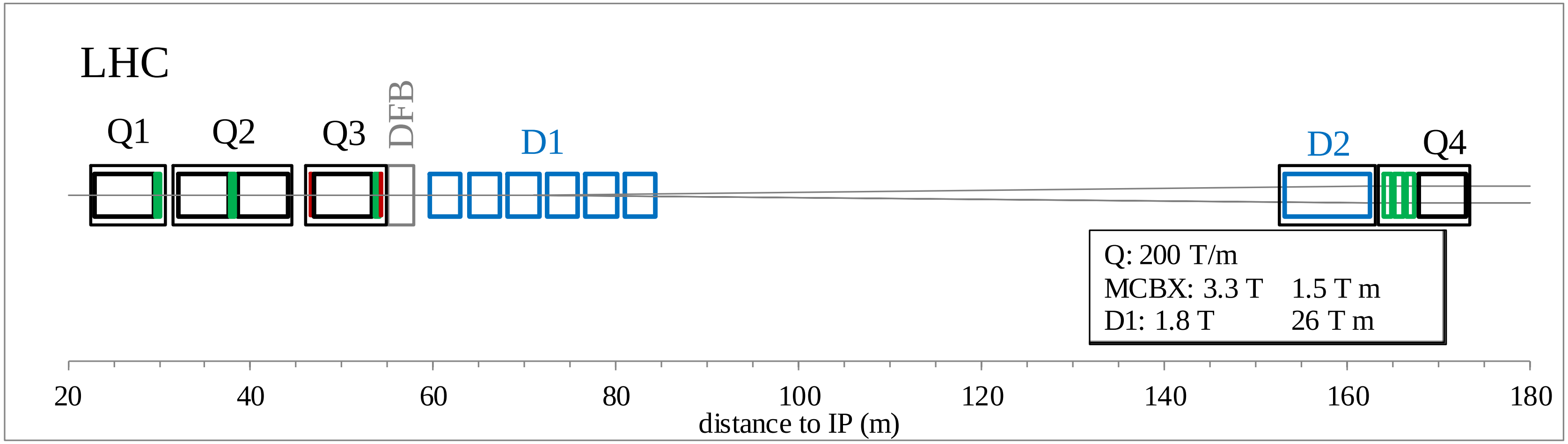
→15-25 years R&D program

courtesy: L. Rossi (CERN) from 2011-2012

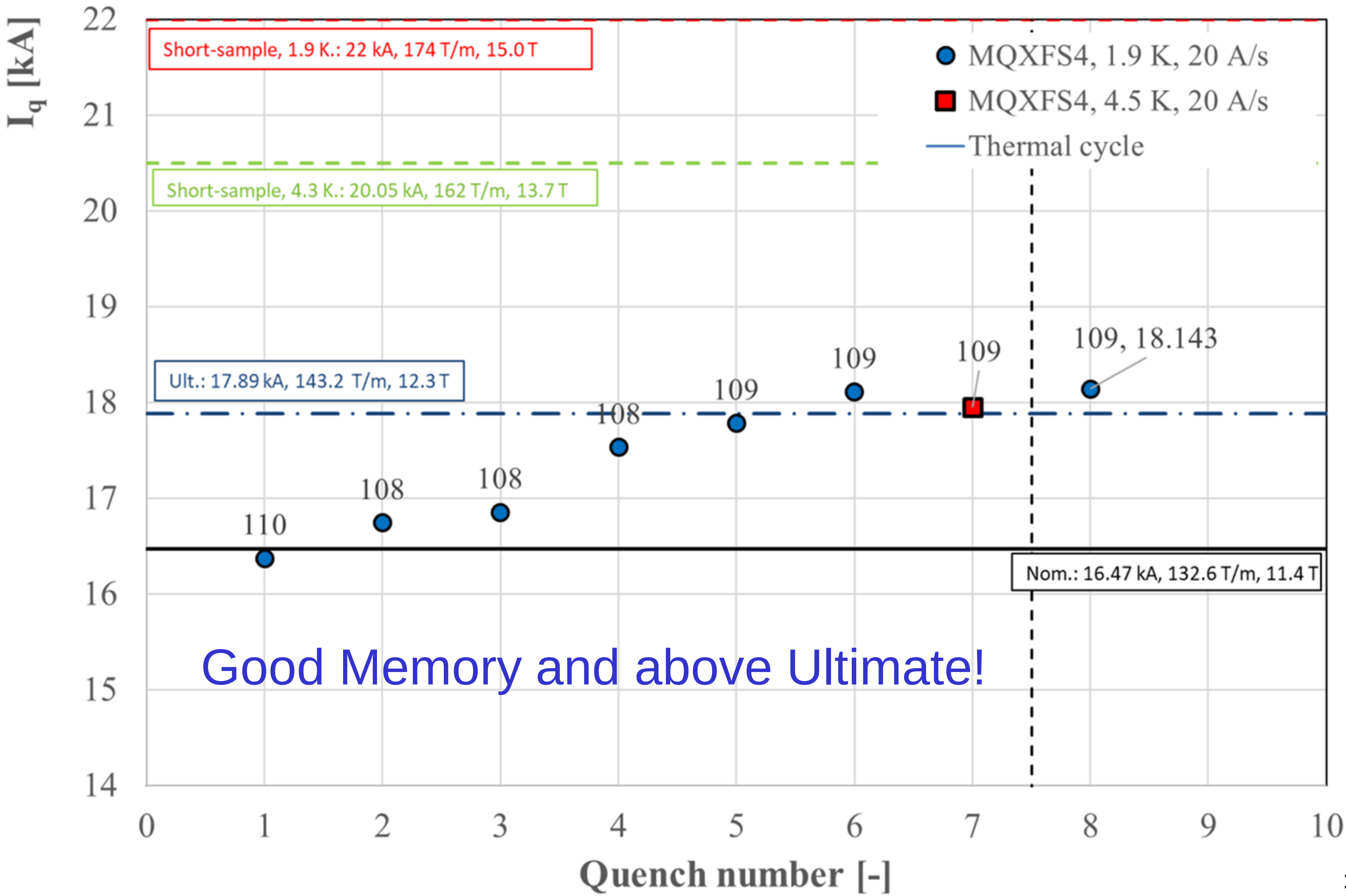
HL-LHC Triplet Layout

E. Todesco @ Chamonix 2018





Triplet Magnet Model Tests



HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

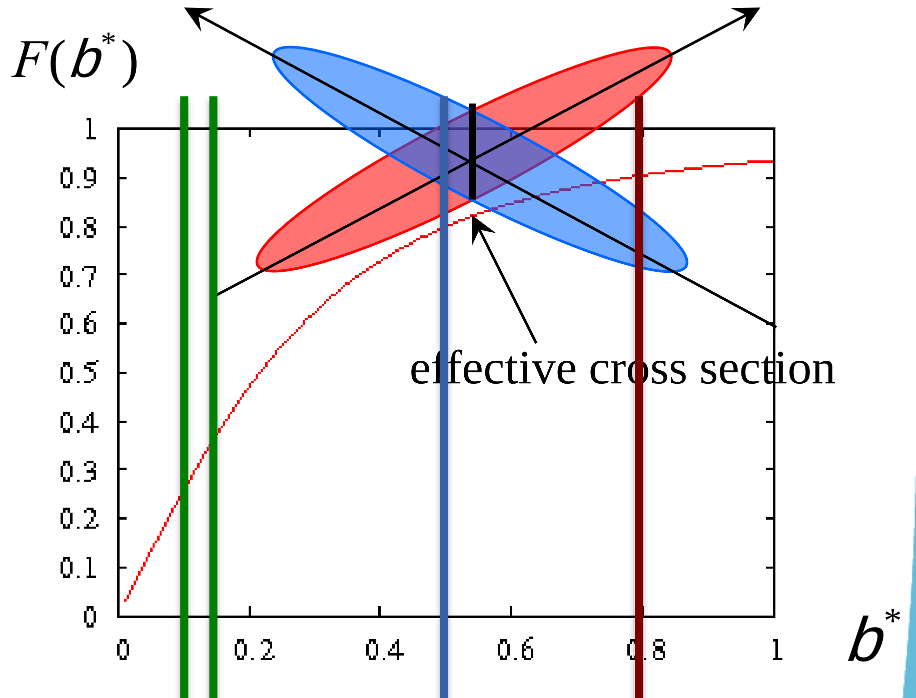
Crab Cavities:

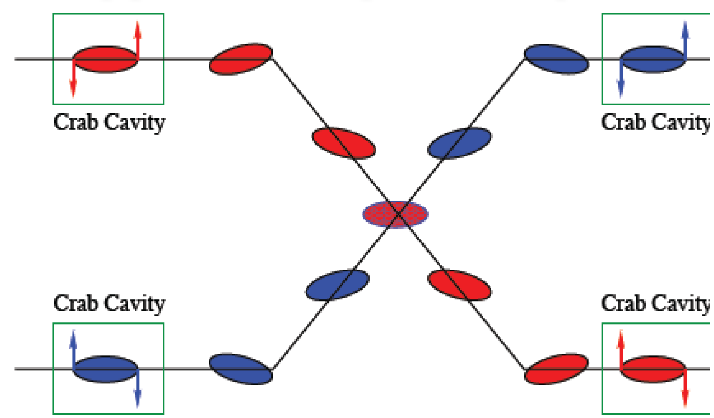
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+Q^2}}; \quad Q \text{ º } \frac{q_c s_z}{2 s_x}$$

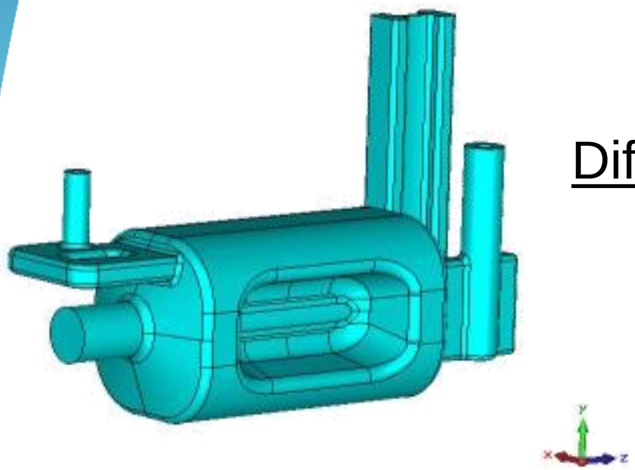
- Noise from cavities to beam & failure modes?!?
- Challenging space constraints:

➔ requires novel compact cavity design



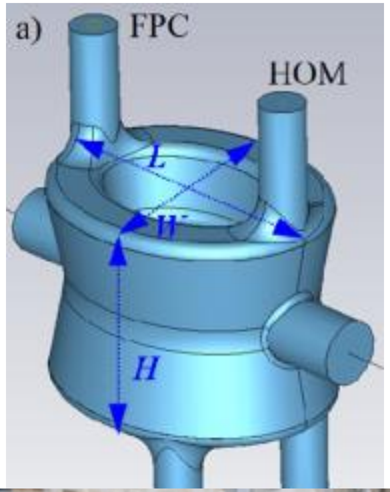


HL-LHC cavity designs



RF Dipole: Waveguide or waveguide-coax couplers

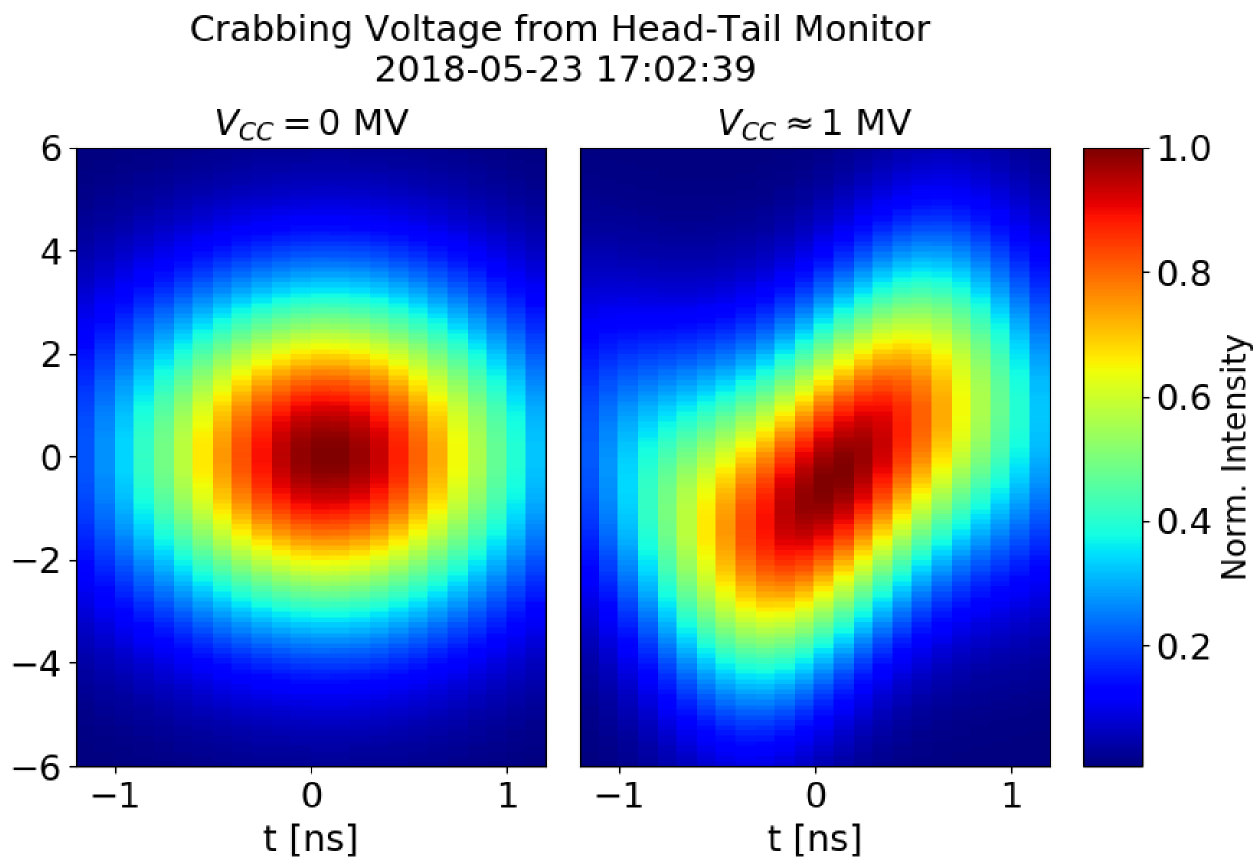
2 Designs with Different Coupler concepts and Deflection planes



DQW crab-cavity Cryomodule for SPS tests

Present baseline: 4 cavities / IP / side → 16 total
TEST in SPS ongoing in 2018 before LS2

First proton crabbing ever!



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

LHC Challenges: Beam Power

- Unprecedented beam power:

Worry about beam losses:

Failure S

Lifetime &

➔ New collimators and absorbers

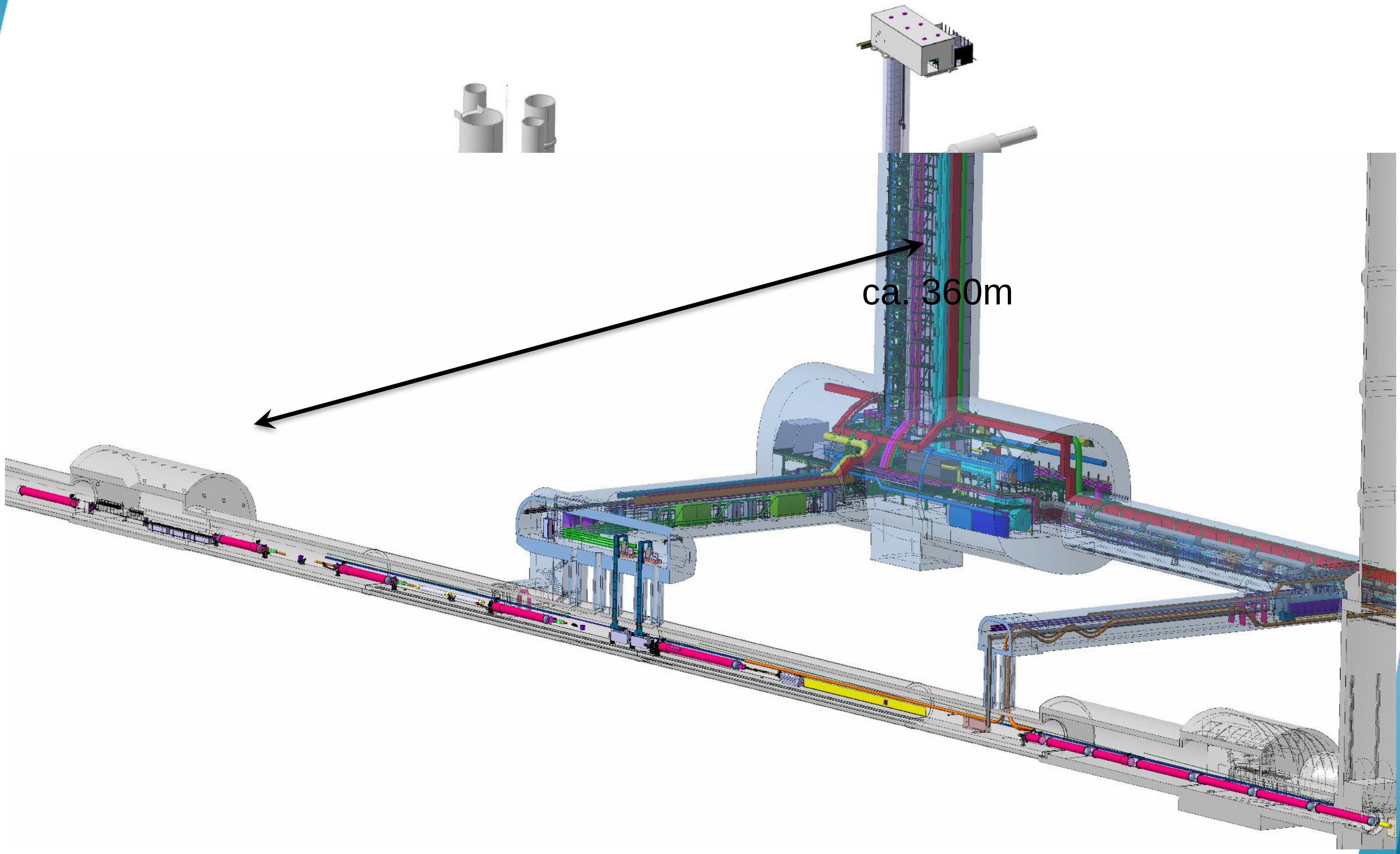
for the HL-LHC ✓

➔ Remove all active components from the

LHC tunnel

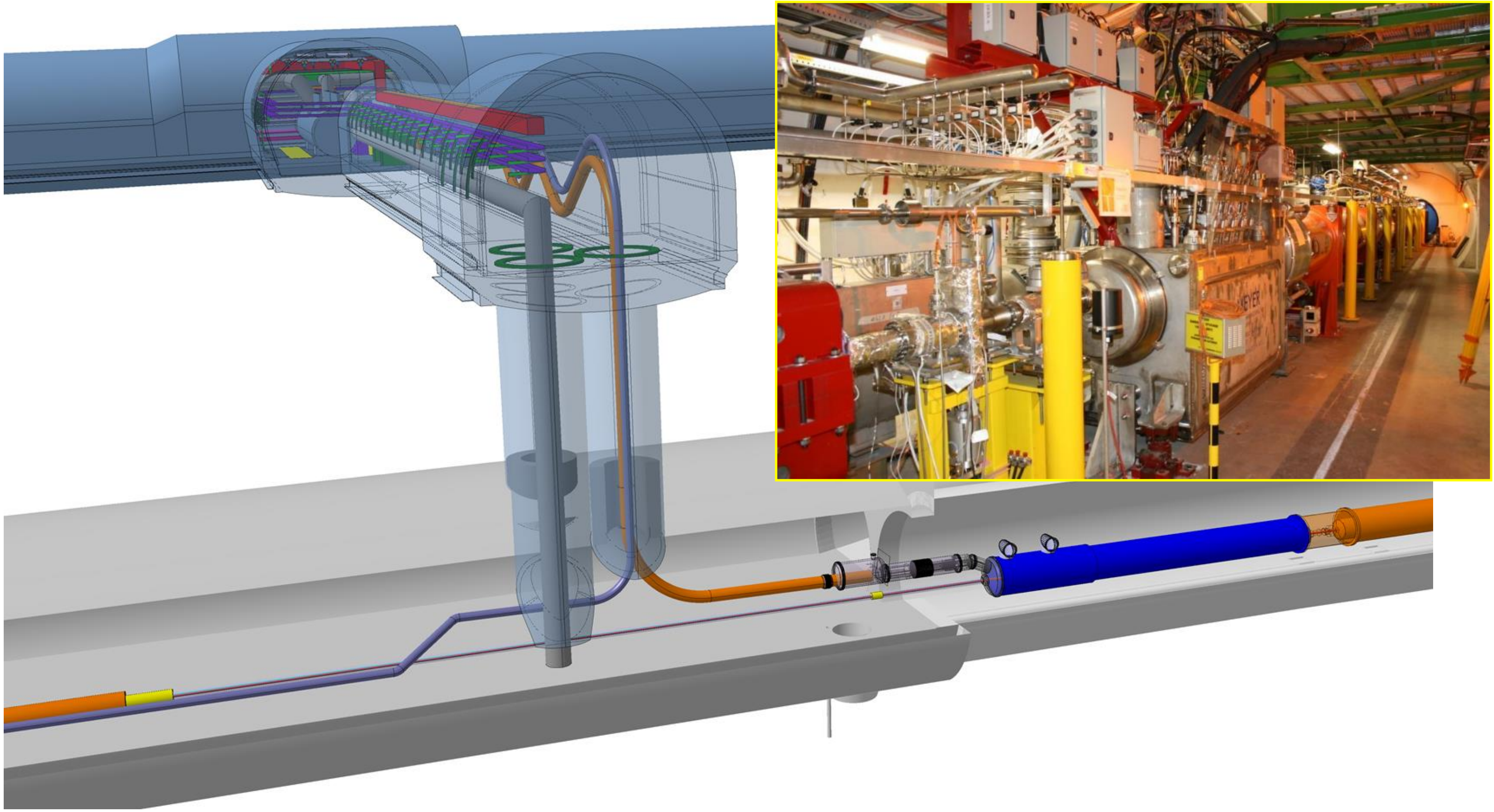
➔ Machine efficiency

IR1 & IR5 Civil Engineering:



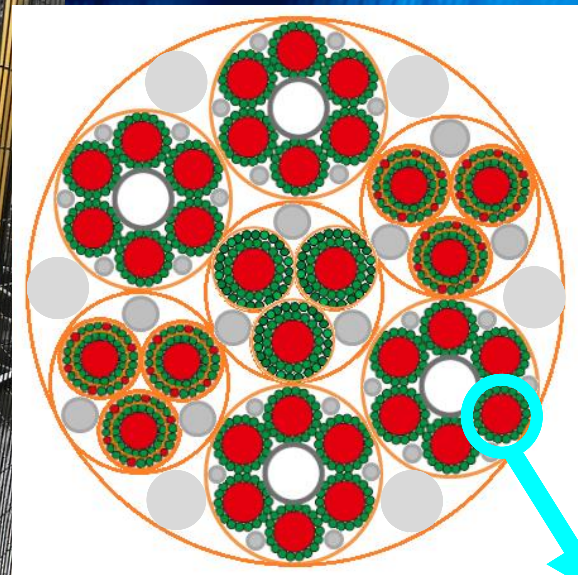
Superconducting Link Technology

- Mg_2B cable technology:



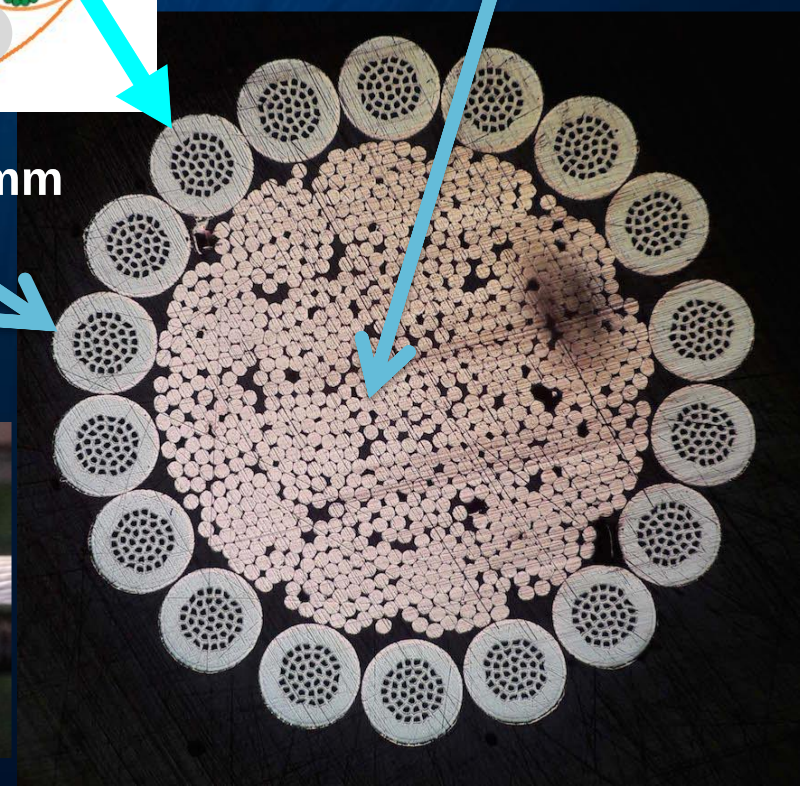
Production of CERN SC-Links MgB_2 cable

A. Ballarino @ Chamonix 2018



Core: 12 mm^2 Cu
Φwire=0.15 mm
46×19 wires
Tw=15/45 mm

Φcable=6.5 mm



Flexible SC Link Test Station in SM18

In 2017, adapted test station in the SM-18 for measuring the 60 m long cryostats – and for future system qualifications

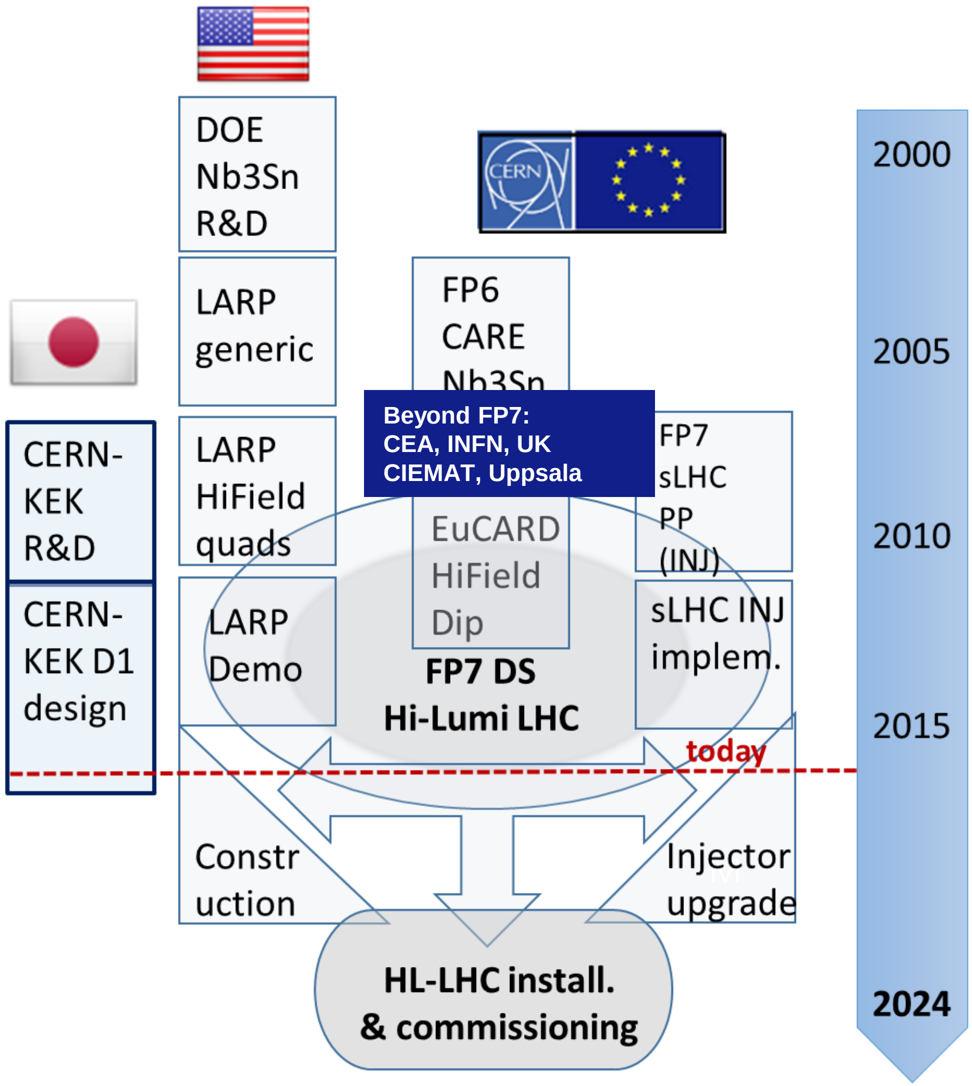
A. Ballarino @ Chamonix 2018

HiLumi & Collaborations: a strong effort

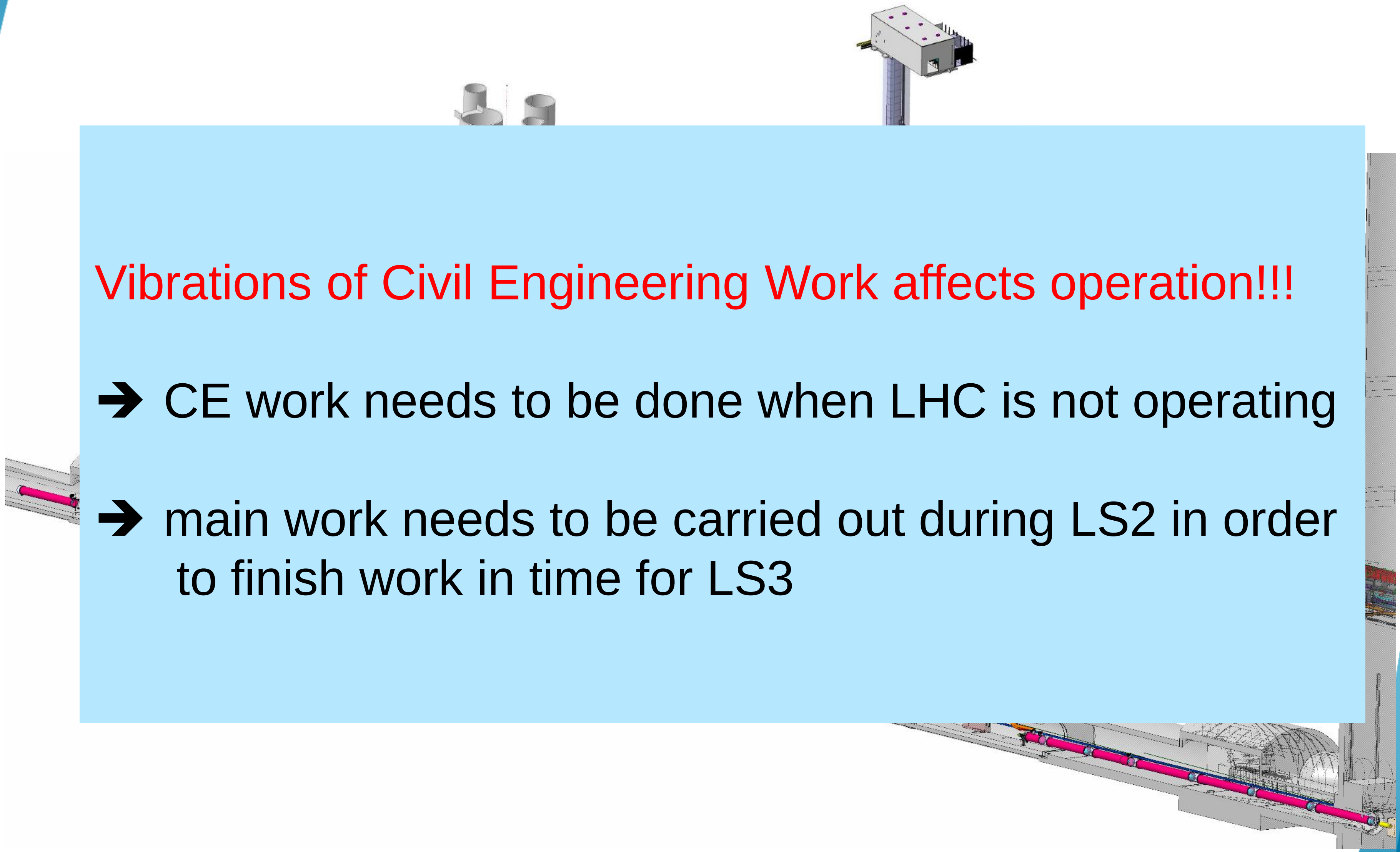
US-DOE (Q1-Q3 RFD-CC)
JP-KEK (D1 cold mass) are the biggest contributors

Special in-kind from:
ES – CIEMAT
IT – INFN
SE – Uppsala
UK – STFC & C.I. Univ.
(CC cryostat – half)

Canada/Triumf
(CC cryostat – half)
China/IHEP
Russia



IR1 & IR5 Civil Engineering:



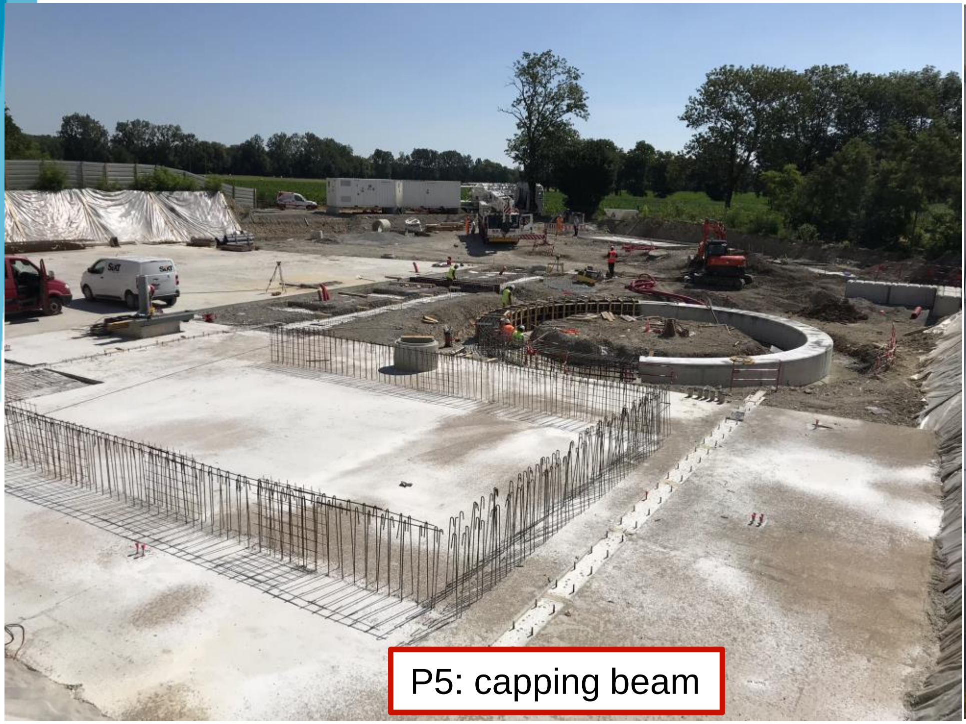
Vibrations of Civil Engineering Work affects operation!!!

➔ CE work needs to be done when LHC is not operating

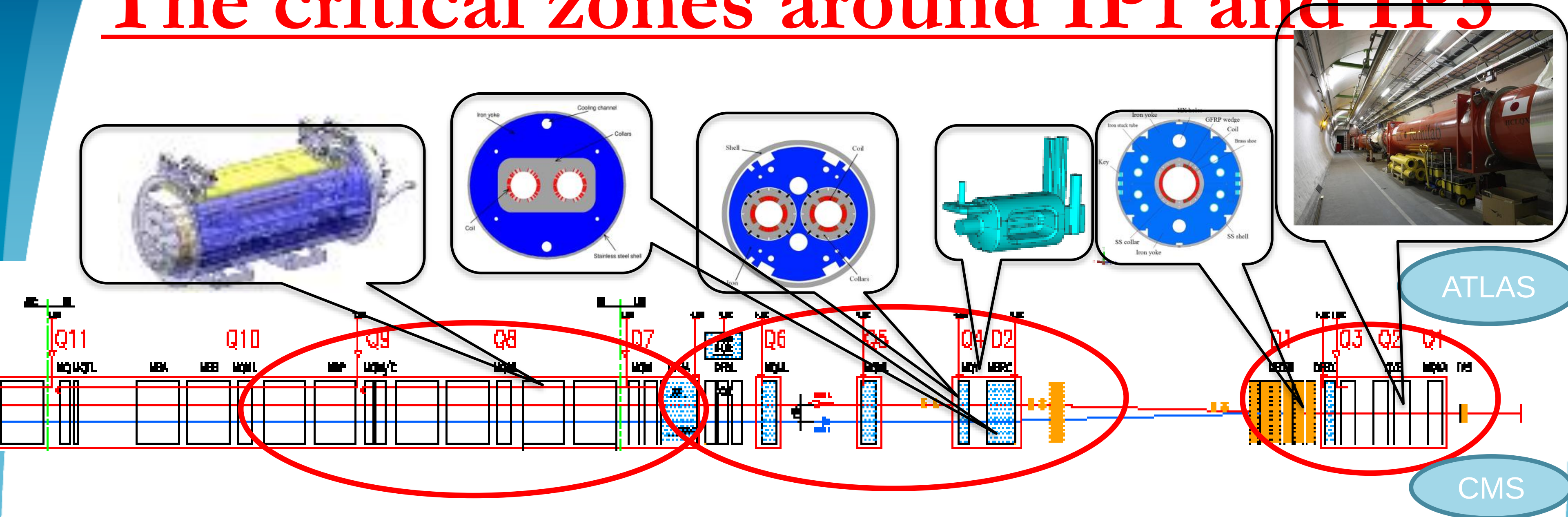
➔ main work needs to be carried out during LS2 in order to finish work in time for LS3

15 June 2015 : Groudbreaking Ceremony

Work is progressing fast…



The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. New triplet Nb_3Sn required due to:

-Radiation damage

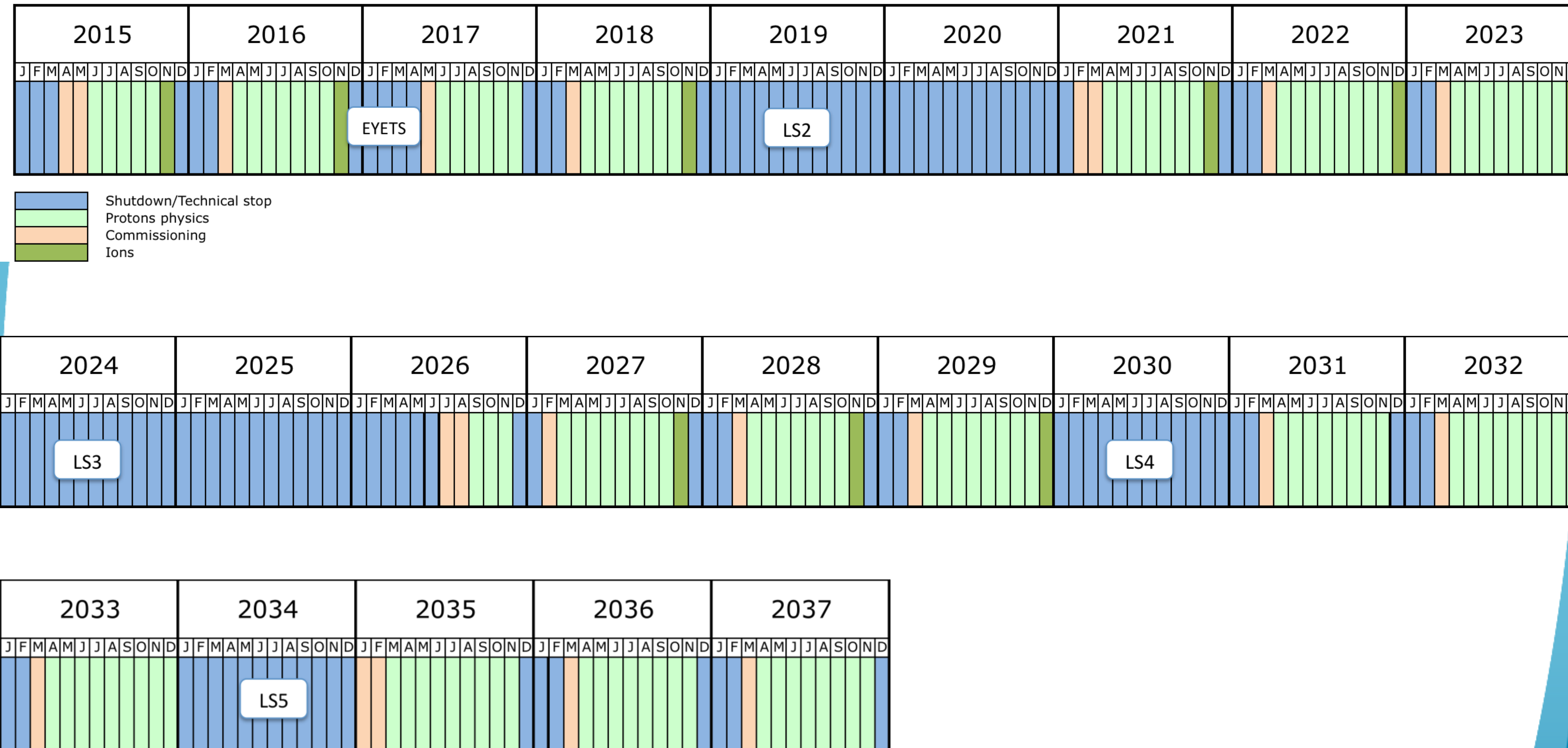
-Need for more aperture

Changing the triplet region is not enough for reaching the HL-LHC goal!

➔ **More than 1.2 km of LHC !!**

➔ **Plus technical infrastructure (e.g. Cryo and Powering)!!**

Schedule: ➔ HL-LHC CE during LS2



Reserve Transparencies

LHC Beam Energy during Run 2

Unforeseen Obstacles:

Short in the diode box following a training quench:

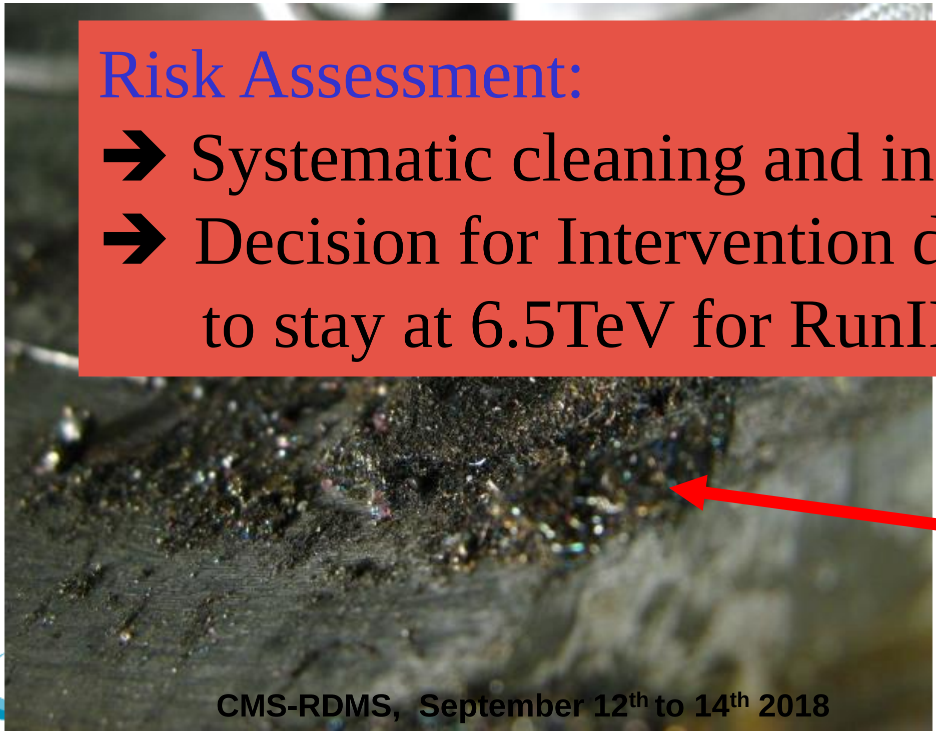
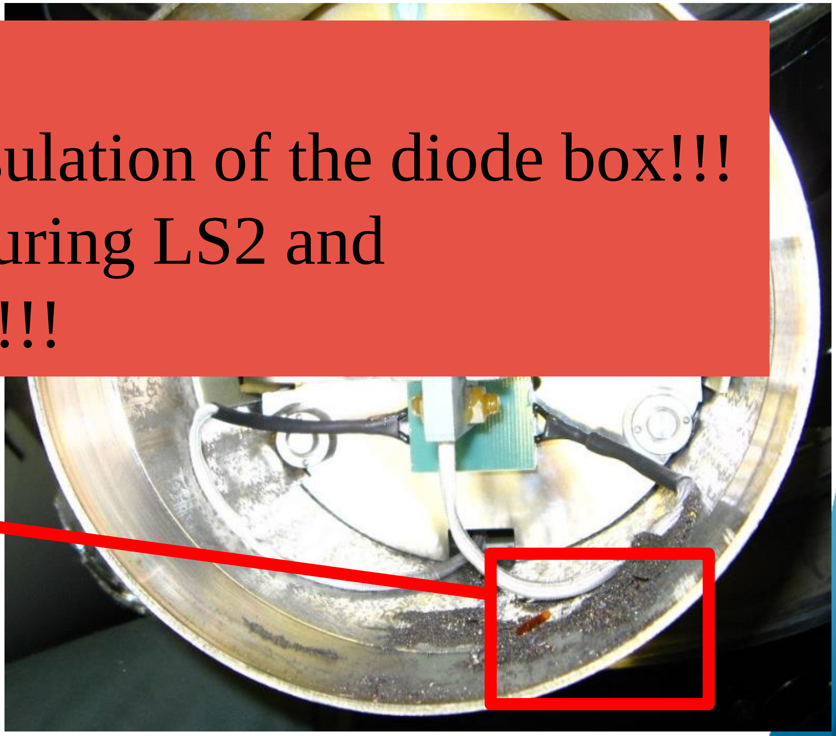
Earth Fault Burner:

Solution exists and could remove twice a short in the machine

But there is no guarantee that this method will always work!!!

Possibility of a double short on a given magnet!!!!

(but also had 5-6 shorts before LS1)

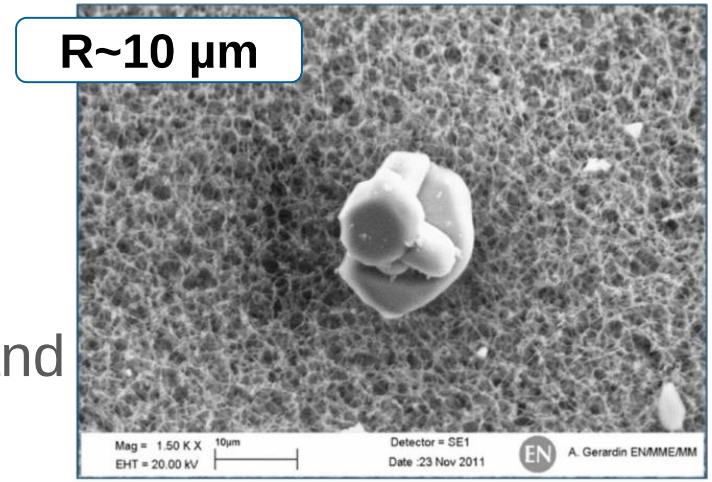
Risk Assessment:

➔ Systematic cleaning and insulation of the diode box!!!

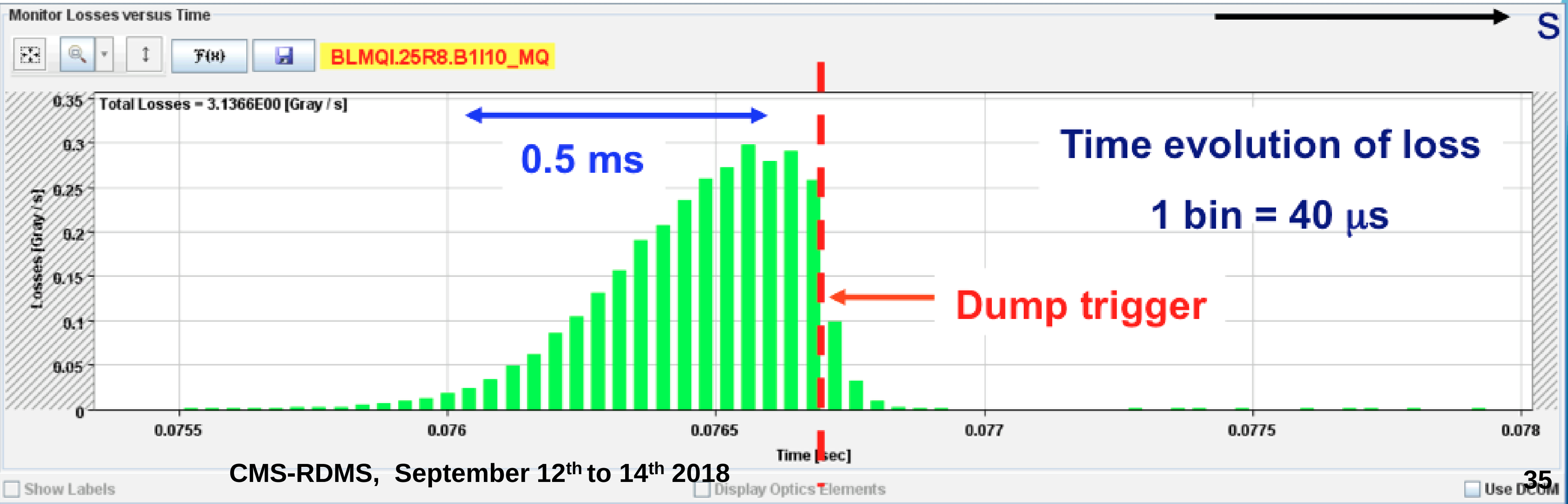
➔ Decision for Intervention during LS2 and to stay at 6.5TeV for RunII!!!

UFOs – Unidentified Falling Objects:

- Sudden local losses
- Rise time of the order of 1 ms.
- Potential explanation: dust particles falling into beam creating scatter losses and showers propagating downstream

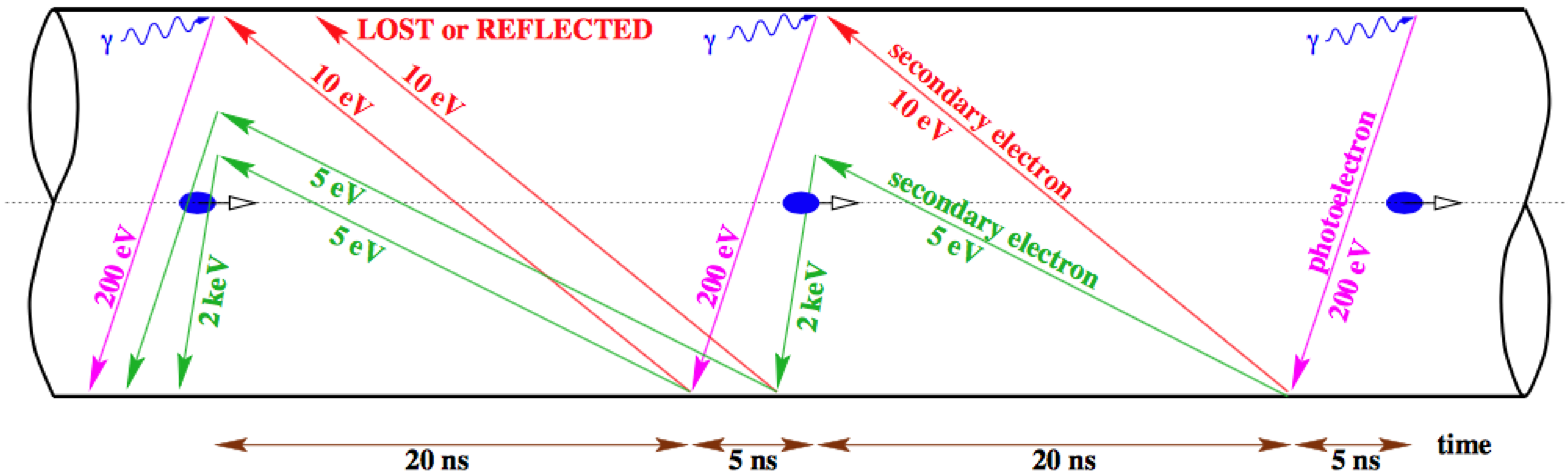


- Distributed around the ring – arcs, inner triplets, IRs
- Even without quench, preventive dumps by QPS



Run 2 operation: 25ns bunch spacing

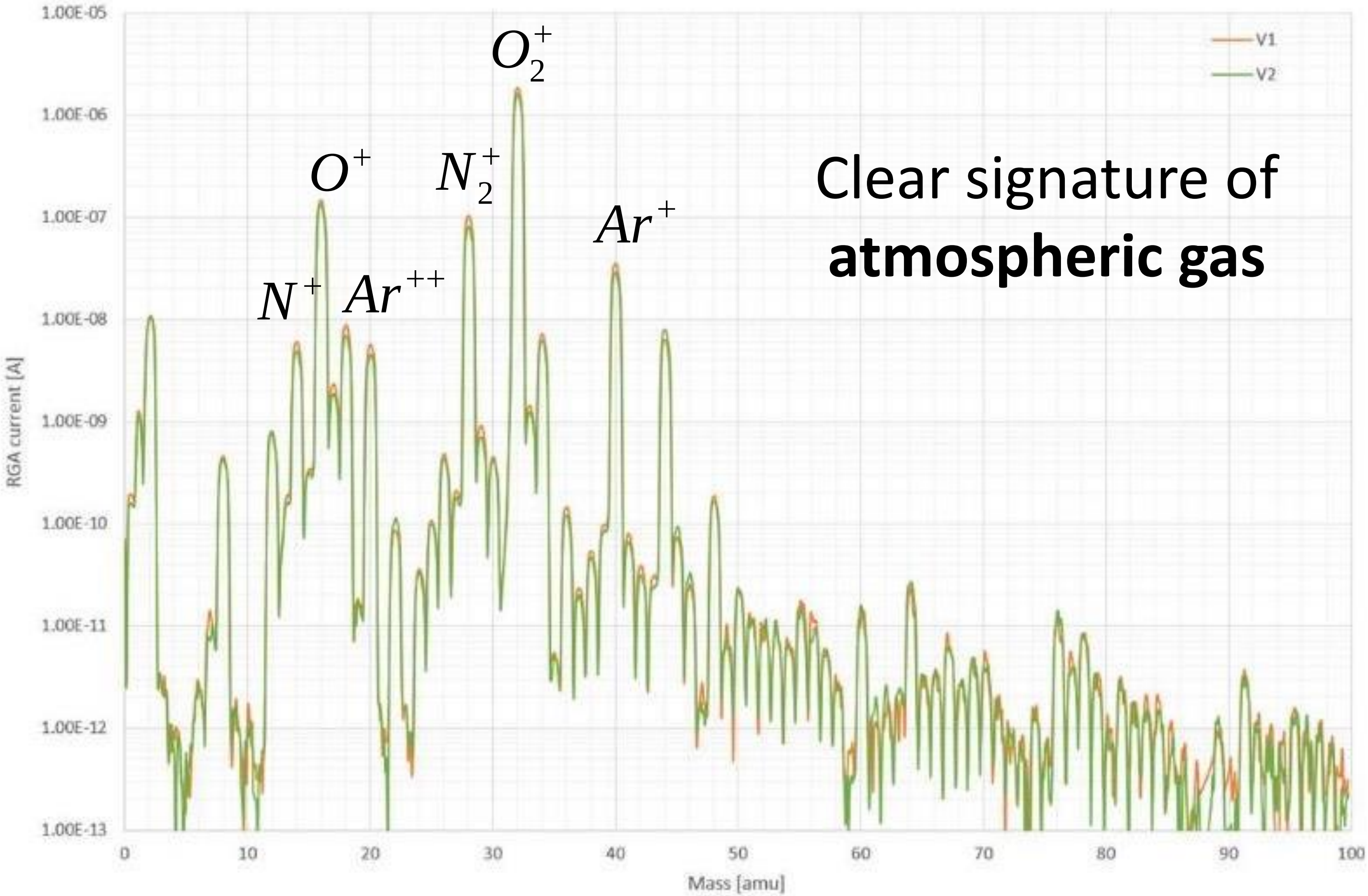
- Electron Cloud: strong suppresses of electron cloud effects!
  - → reduced beam conditioning times



16L2: Main Machine Limitation in 2017

- Sudden increase of losses in the half-cell **16L2** represented **"The machine limitation" in 2017**

→ **67 dumps** induced: only two at injection, one quench induced at high energy



LHC Performance optimization

- 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 Upgrade LIU

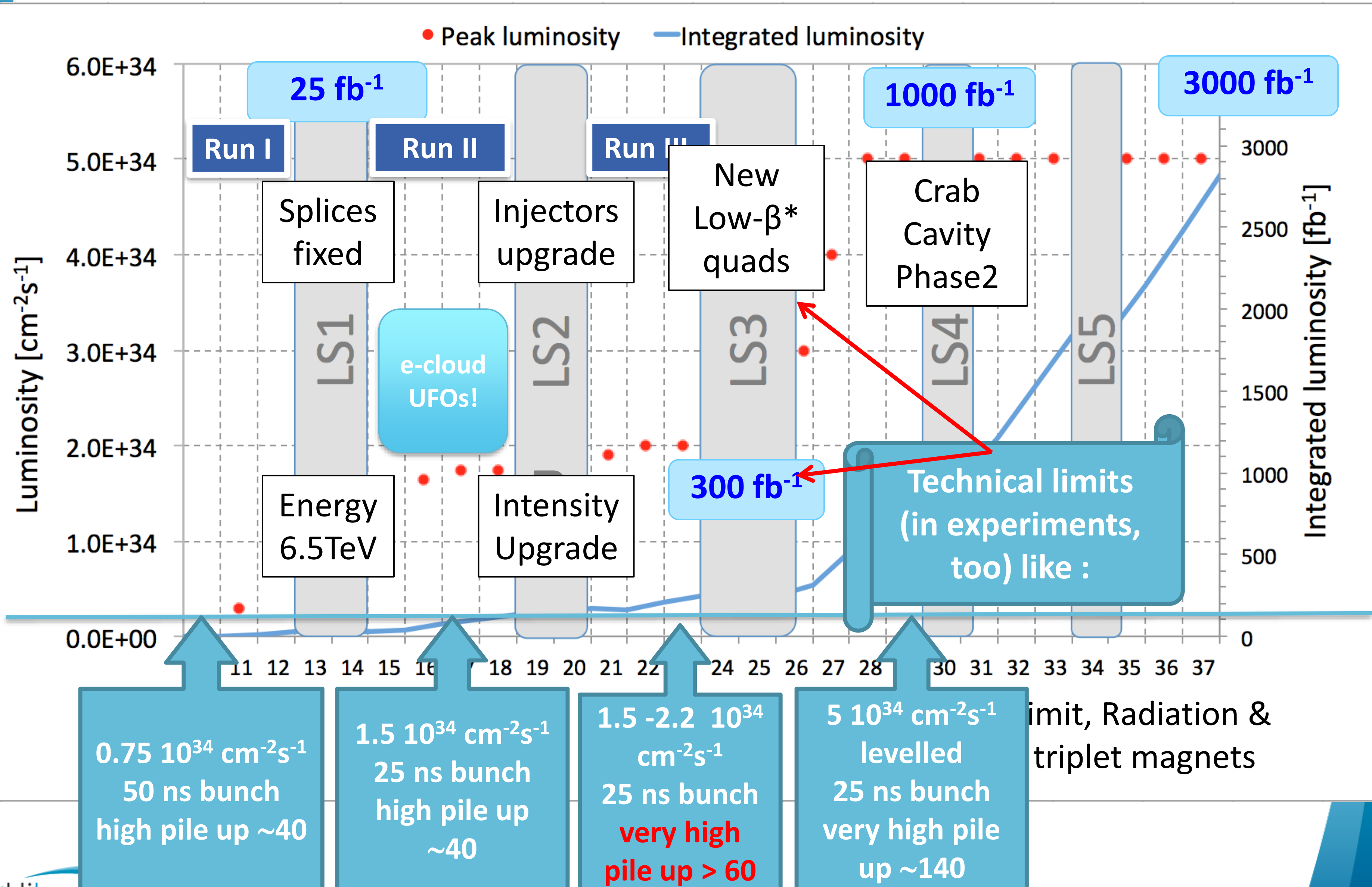
➔3) minimize beam size (constant beam power); ➔ triplet aperture

➔4) maximize number of bunches (beam power); ➔ 25ns

➔5) compensate for ‘F’; ➔ Crab Cavities

➔6) Improve machine ‘Efficiency’ ➔ minimize beam aborts and facilitate access to equipment

Performance Projections up to HL-LHC:



Technology Challenge: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture

➔ ca. 8 T @ coil

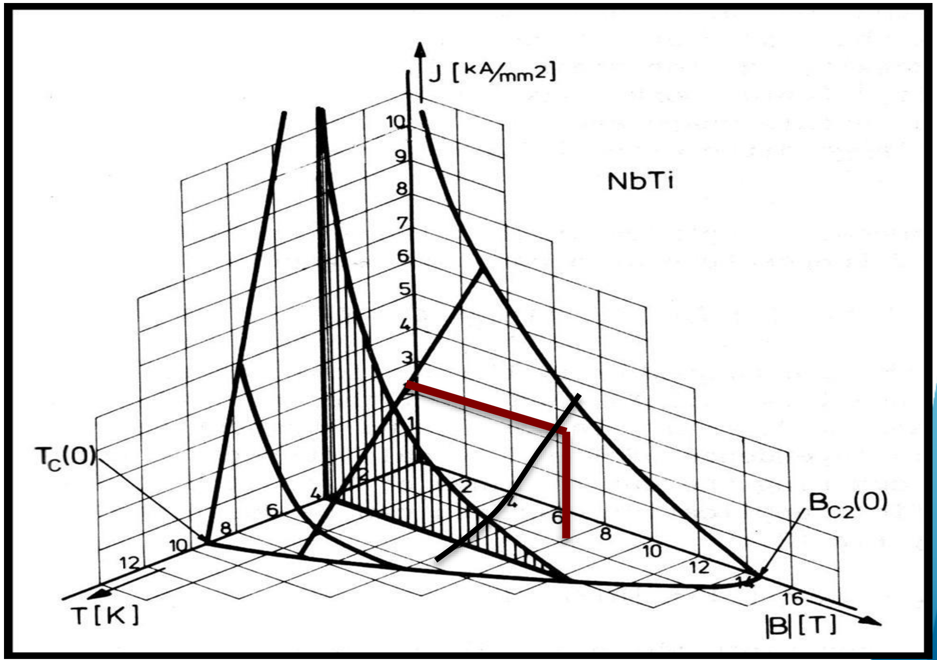
➔ 1.8 K cooling with superfluid He (thermal conductivity)

➔ 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

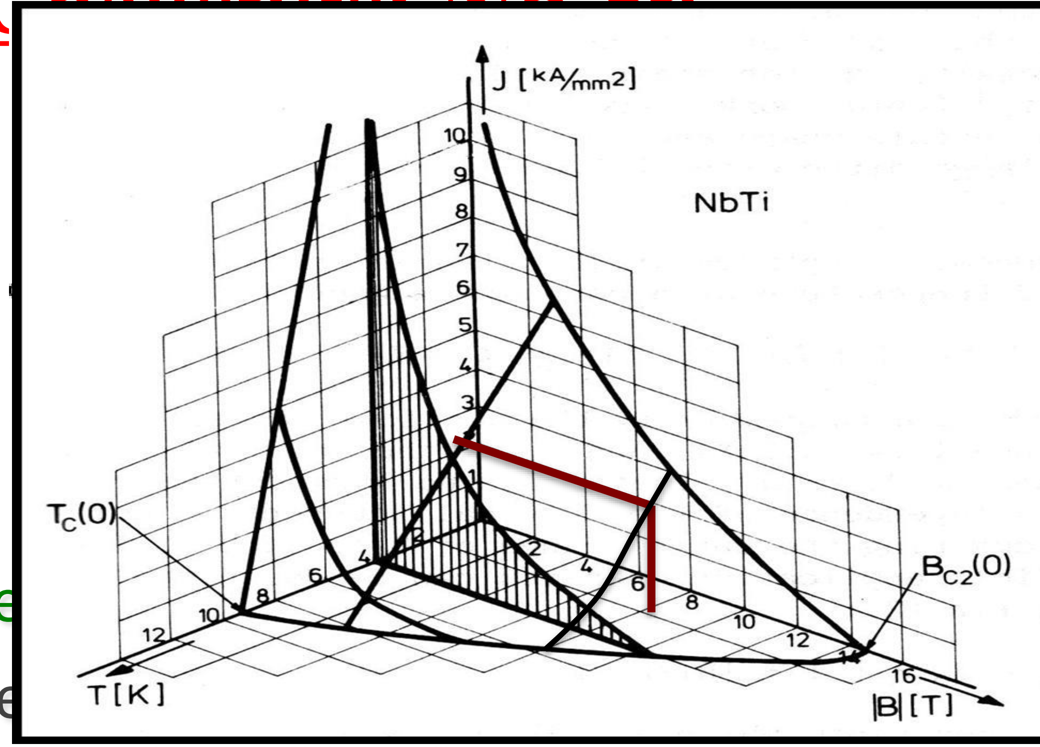
Critical Surface for NbTi



Technology Challenge: Nb Sn

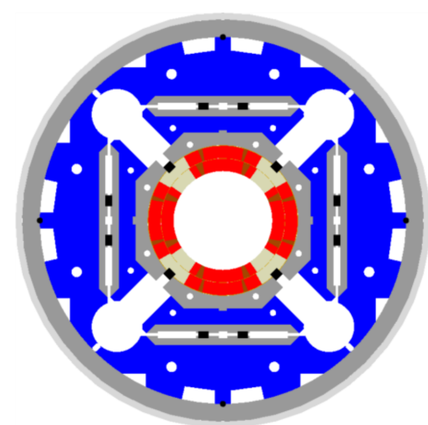
- LHC triplet: NbTi technology
  210 T/m, 70 mm bore aperture
  ➔ 8 T at coil with 2.75 kA/mm^2
  @ 1.8K ➔ limit of NbTi tech

- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  (shielding, β^* and crossing angle
  ➔ ca. 12 T @ coil ➔ 30% longer
  - Requires Nb$_3$Sn technology
    ➔ brittle material (fragile)
    ➔ ca. 25 year development for this new magnet technology!
  - US-LARP – CERN collaboration



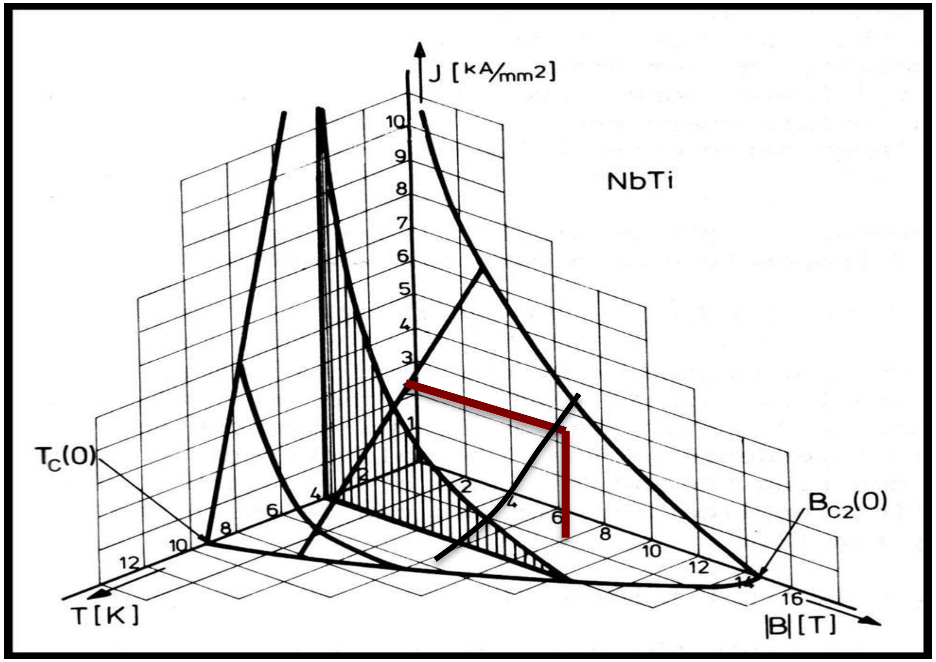
Magnetic field (T)

US-LARP MQXF magnet design Based on Nb$_3$Sn technology



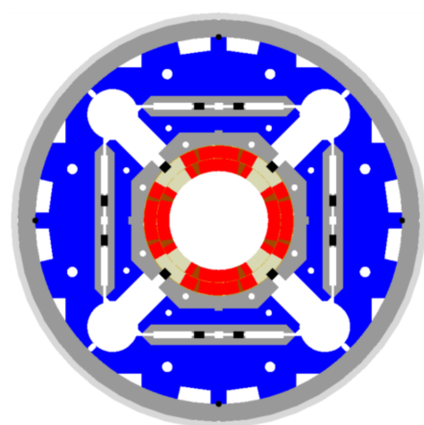
Technology Challenge: Nb_3Sn

- LHC triplet: NbTi technology
  210 T/m, 70 mm bore aperture
  ➔ 8 T at coil with 2.75 kA/mm²
  @ 1.8K ➔ limit of NbTi tech



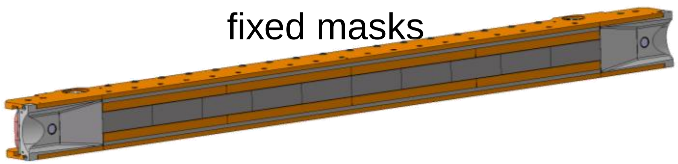
- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  (shielding, β^* and crossing angle)
  ➔ ca. 12 T @ coil ➔ 30% longer
  - Requires Nb_3Sn technology
    ➔ brittle material (fragile)
    ➔ ca. 25 year development for this new magnet technology!
  - US-LARP – CERN collaboration

US-LARP MQXF magnet design Based on Nb_3Sn technology



HL-LHC Collimation Upgrades

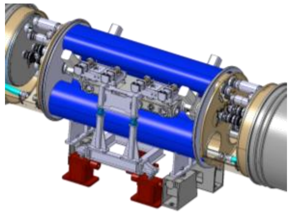
Completely new layouts
Novel materials.
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

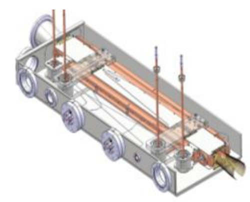


56 new collimators to be produced by LS3 in the present baseline!

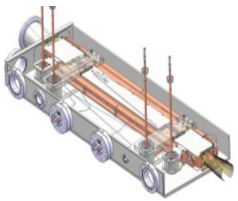
S. Redaelli
@ Chamonix 2018

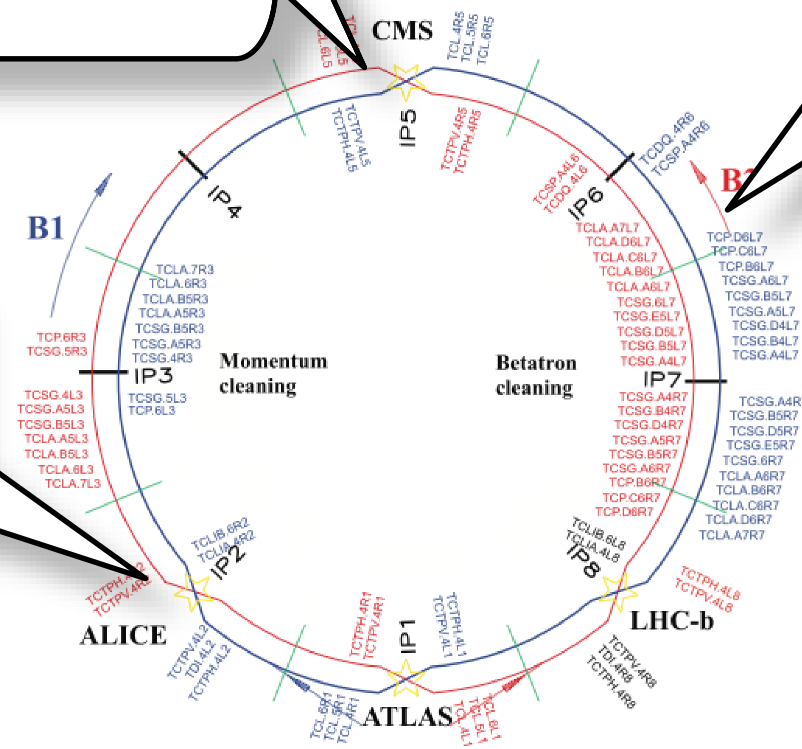
Cleaning: DS coll. + 11T dipoles, 2 units per beam



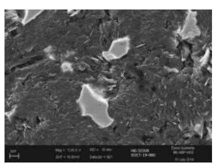


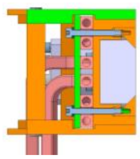
Ion physics debris:
DS collimation

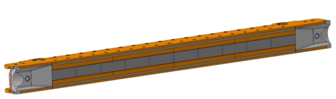




Low-impedance, high robustness secondary collimators







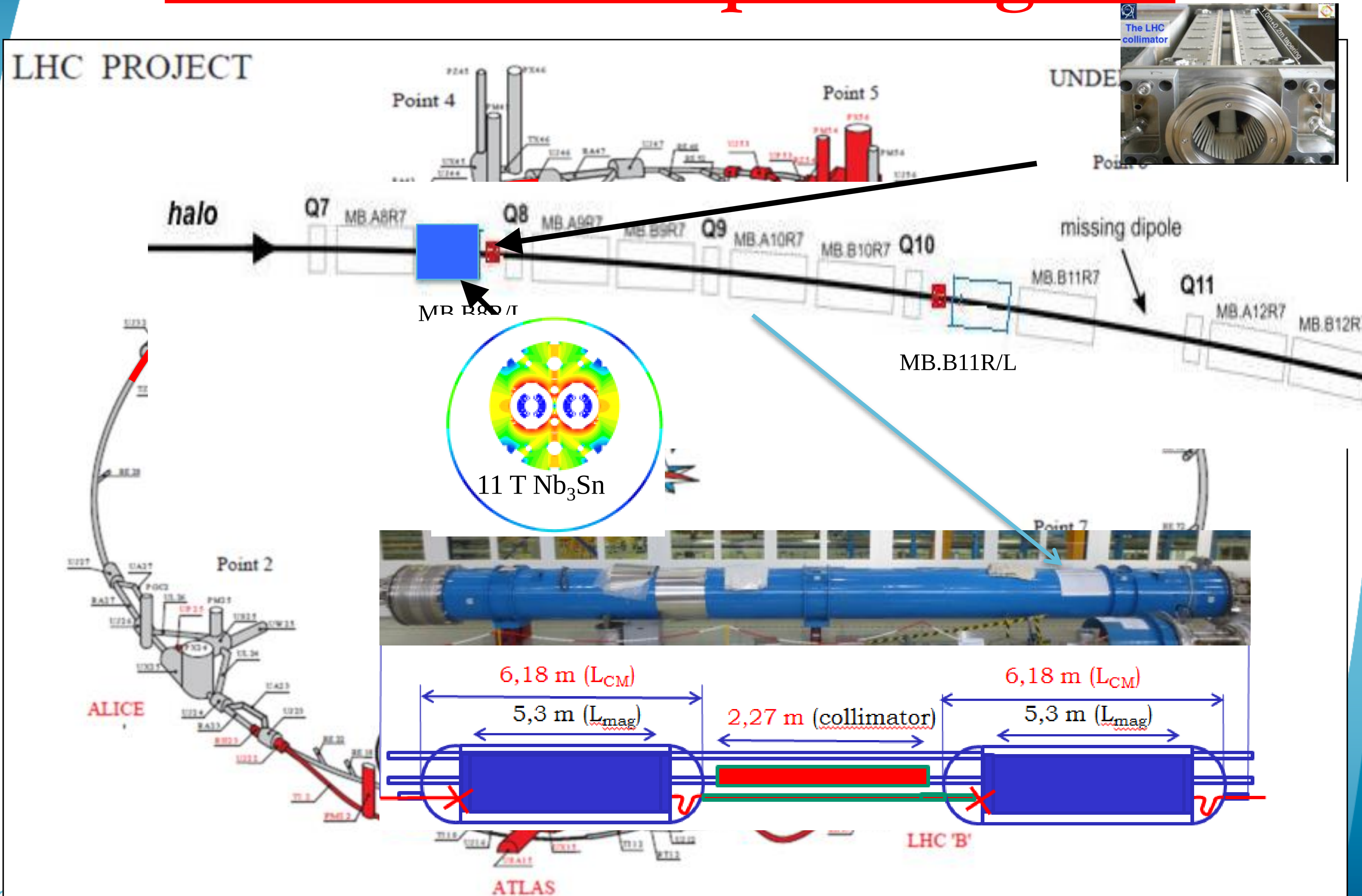
S. Redaelli,
Chamonix 2016, 28-01-2016

HL-LHC 11T Dipole Magnets

Prototyping of the by-pass crystostat (QTC) and 11T dipole for the installation of a warm collimator in the cold dispersion suppressors.

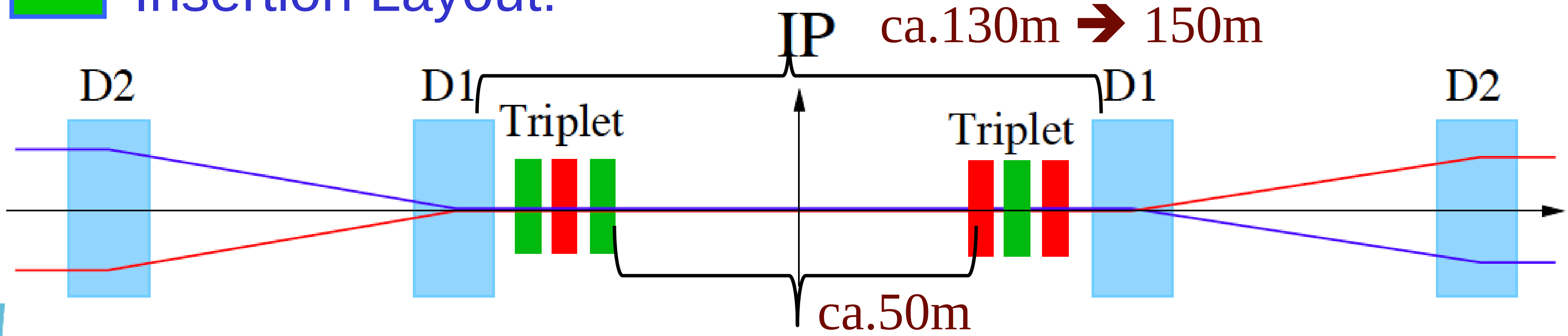
Magnet: prototypes reached 11 T field in March 2013!

HL-LHC 11T Dipole Magnets



HL-LHC Challenges: Crossing Angle

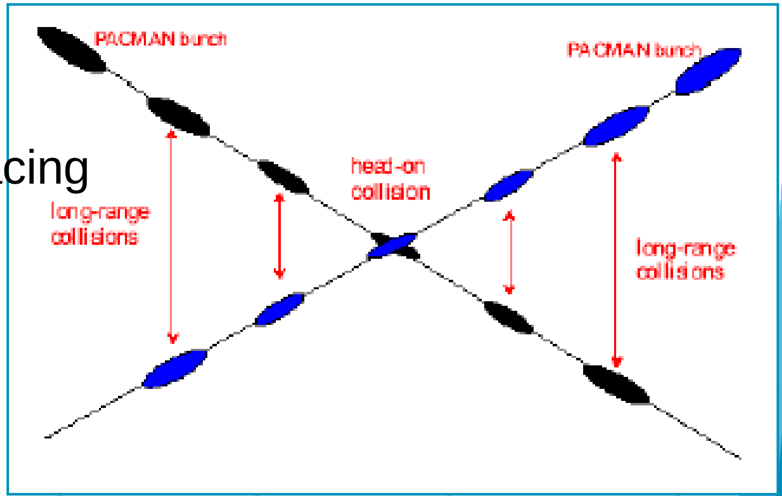
Insertion Layout:



Parasitic bunch encounters:

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

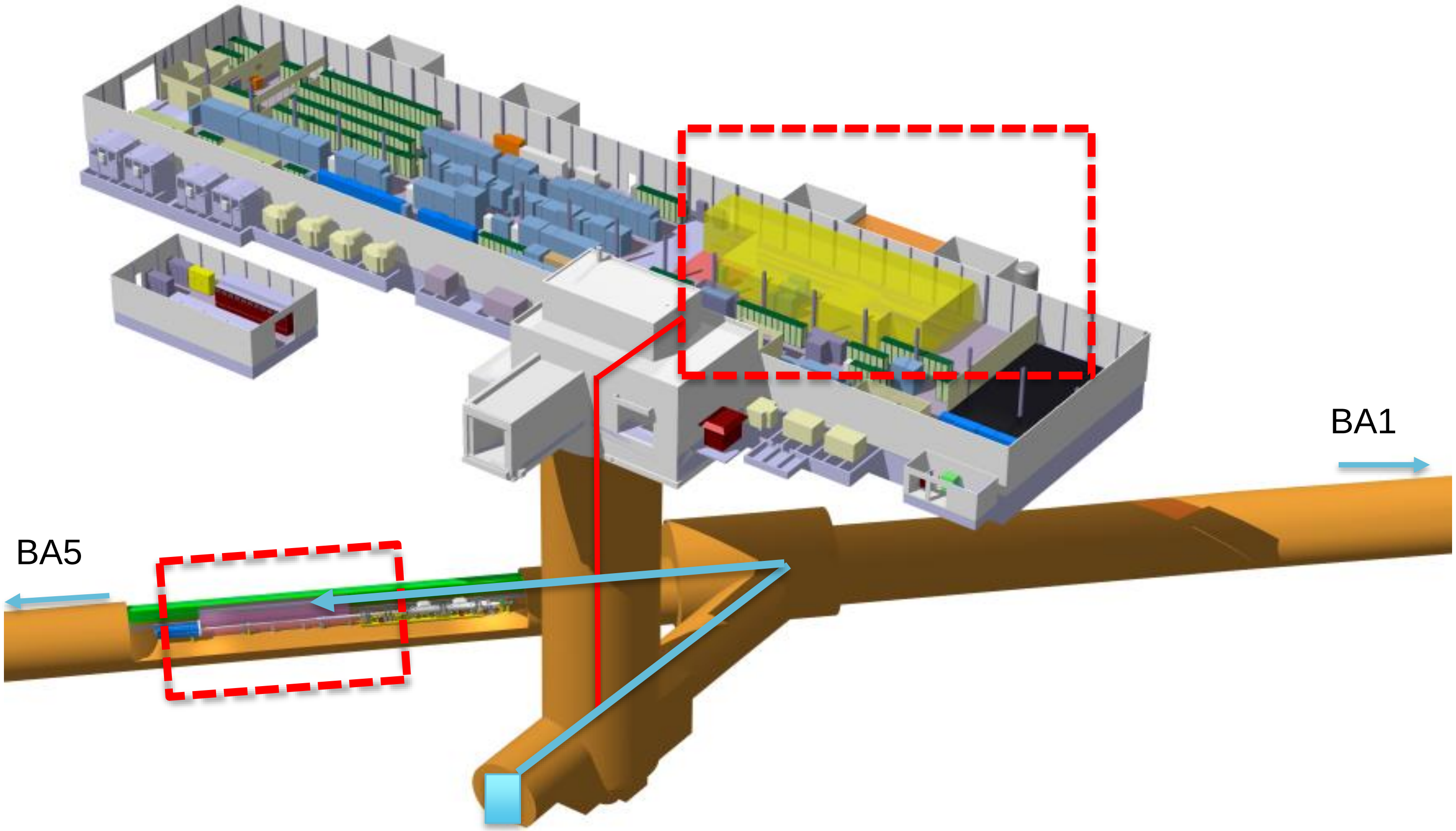
➔ Operation requires crossing angle



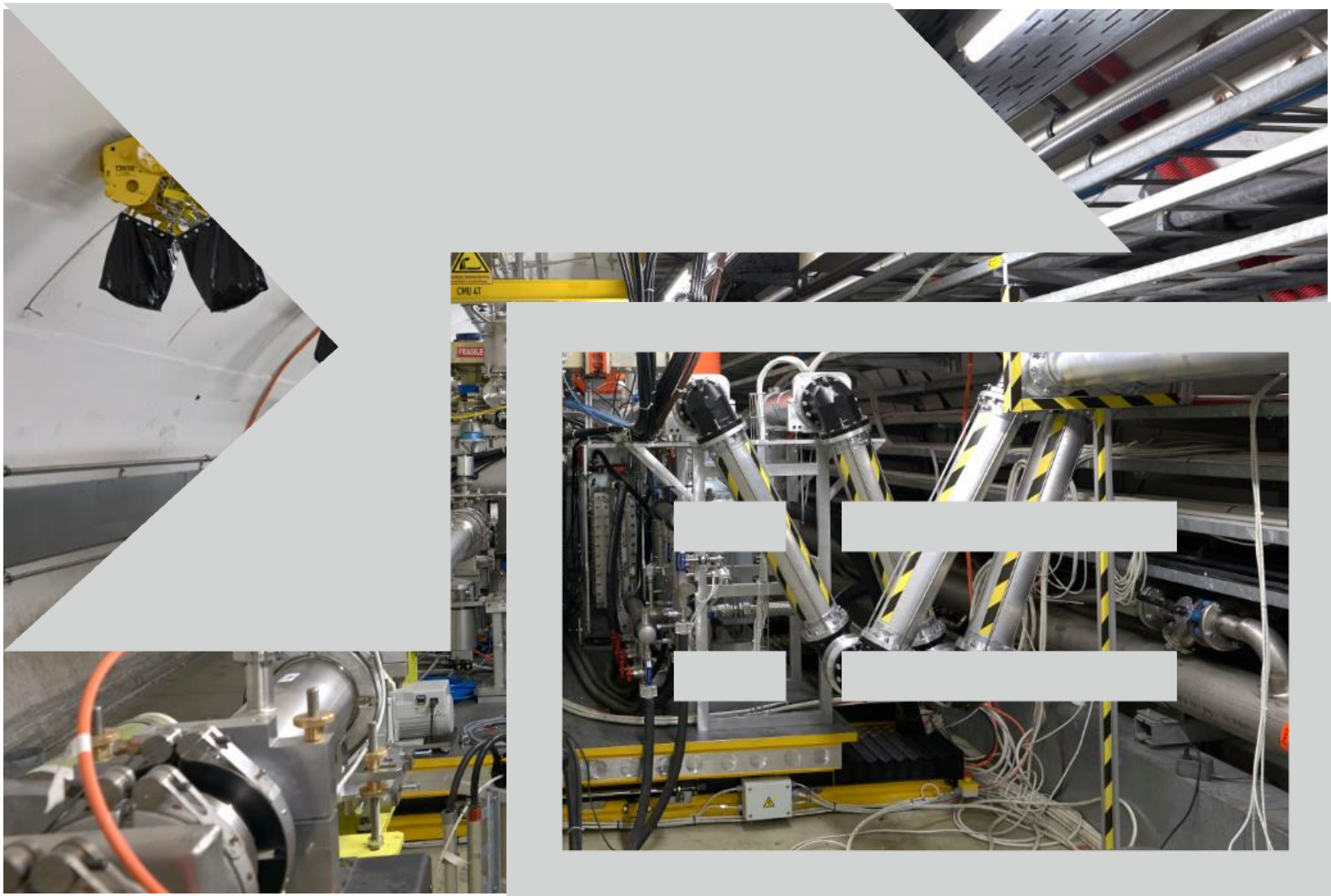
non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points ➔ Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC!!

Crab Cavity Test Stand in the SPS



Crab Cavity Test Stand in the SPS



LHC Overview

- Design Goals:

7TeV beam energy, L = 1 10^{34} $cm^{-2}s^{-1}$; 300fb^{-1} in 10 years

➔ 2008 'incident' limited beam energy to 3.5 / 4 TeV

➔ Got fixed during LS1

➔ After LS1 energy limited by: training time & shorts in diodes

➔ estimated 1000 magnet quenches for 7TeV [> 2 month]

➔ risk of double shorts and another 'incident'

➔ **Apart from energy, LHC surpassed all design goals!!!**

UFOs conditioned away and e-cloud scrubbing still ongoing

[with 8b4e as backup]