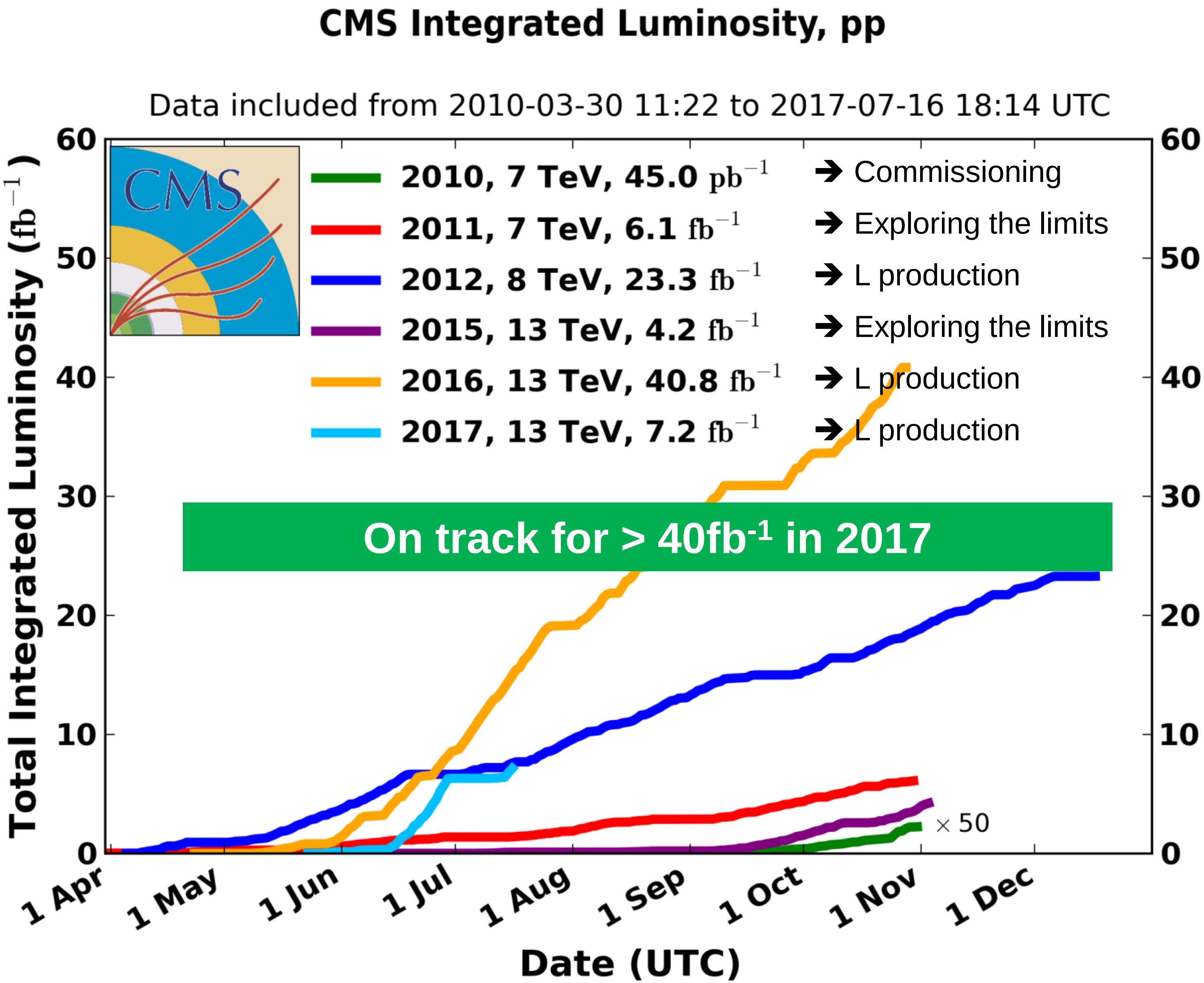
LHC Status and Energy prospects and HL-LHC Upgrade

O. Brüning
CERN, Geneva, Switzerland

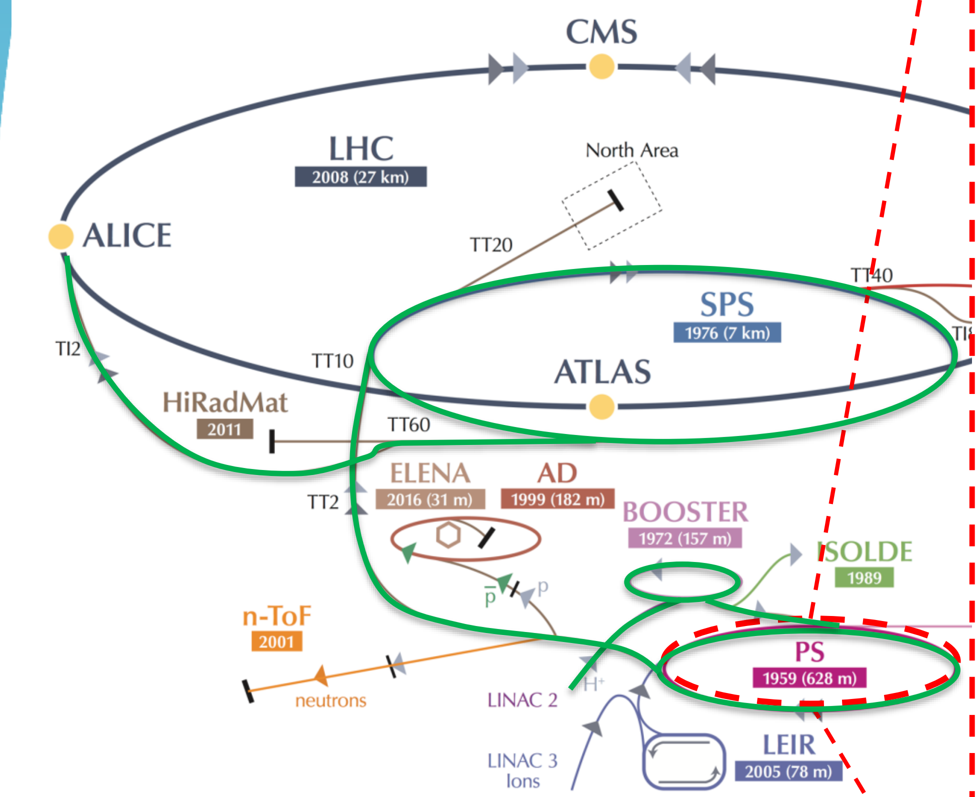
LHC Performance up to RunII:



An extra boost from the injectors

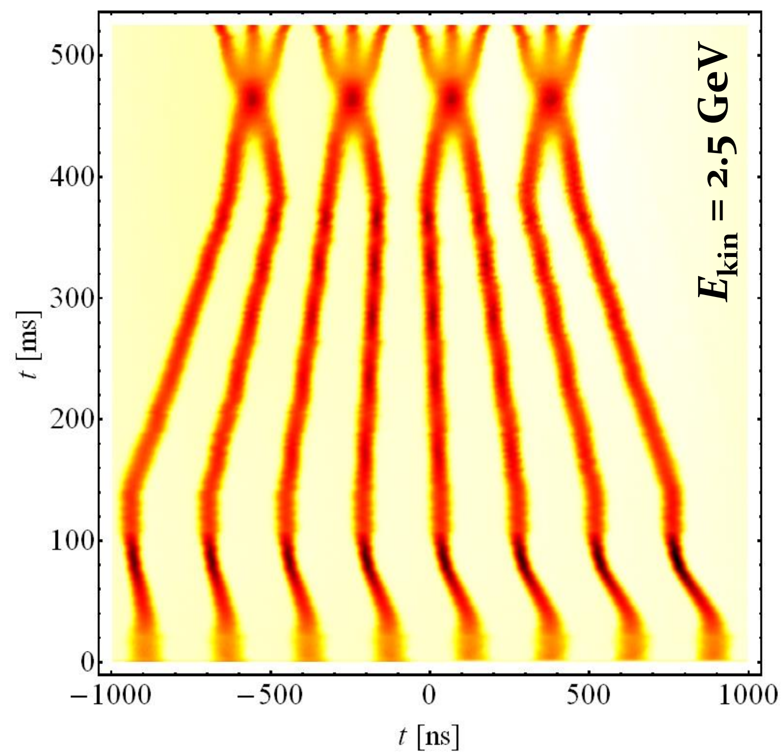
The LHC performance fully relies on the p

- 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 > 1.6 10^{34} $cm^{-2}s^{-1}$**

LHC Full Energy Exploitation Study:

- Organized in 3 Stages:

1) Operation at nominal energy of 7TeV (8.3T)
   -powering tests in S34 and S45 before EYETS 16/17
   ➔ observation of multiple quenches at high fields
   ➔ observation of a second short to ground after quench

➔ Decision to consolidate the LHC diode boxes in LS2 and to plan for 7TeV operation only after LS2

2) Operation at ultimate beam energy of 7.56TeV (9T)
   Ongoing and preparing for discussion at Chamonix 2018

3) Operation with beam energies beyond 'ultimate'

LHC Energy Exploitation Session

Chamonix 2017
Sandrine Le Naour

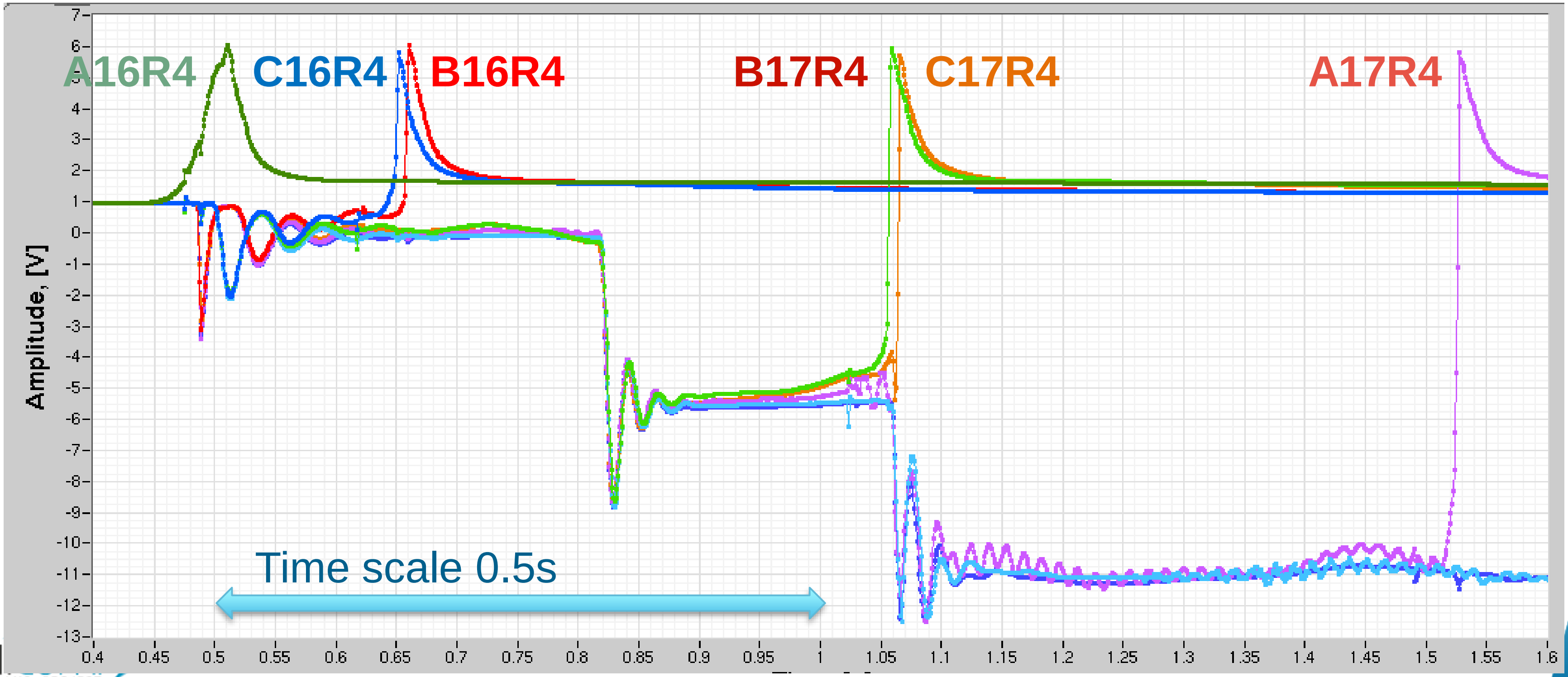
Observations from the training campaign:

Multiple magnet quenches during a given training quench event:

➔ Multiple training quenches and / or EM coupling (timescale < 1s)
+ heat propagation at lower current ➔ multiple quenches!!

➔ Possible cascade effect for quenches at higher magnet current!!!

Example: I=11521 A with 6 quenches triggered by nQPS and iQPS

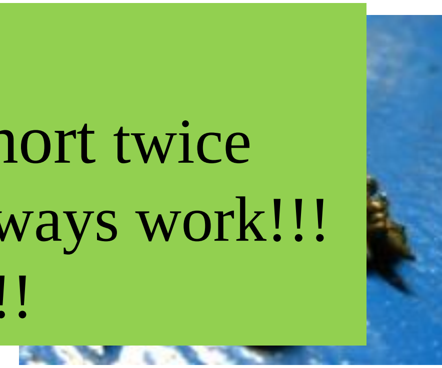


LHC Energy Exploitation Session

Mateusz Bednarek

Unforeseen Obstacles:

Short in the diode box following a training quench:



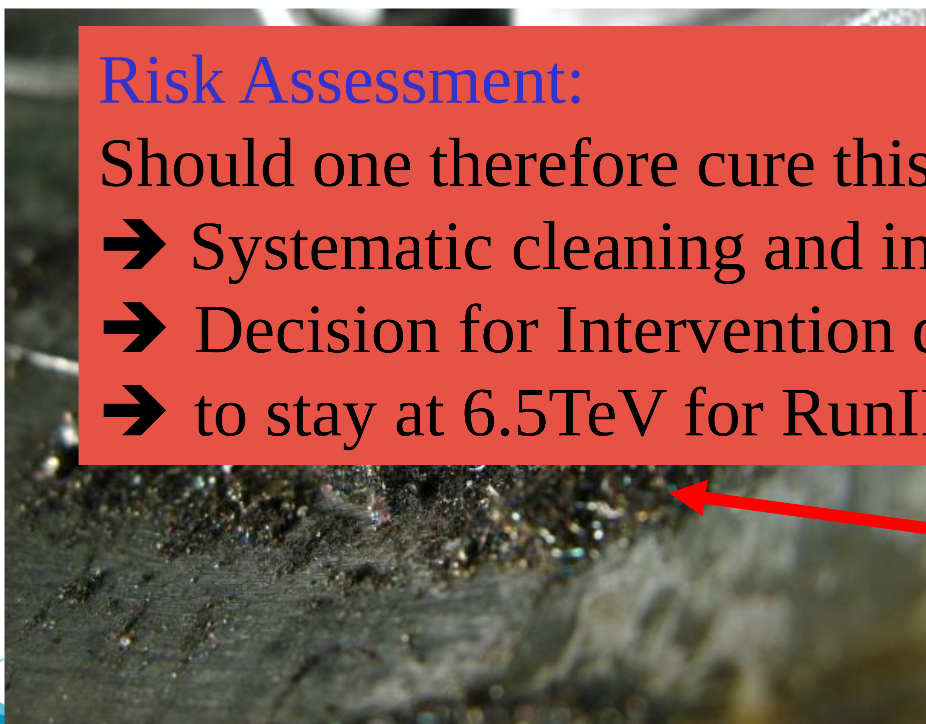
Earth Fault Burner:

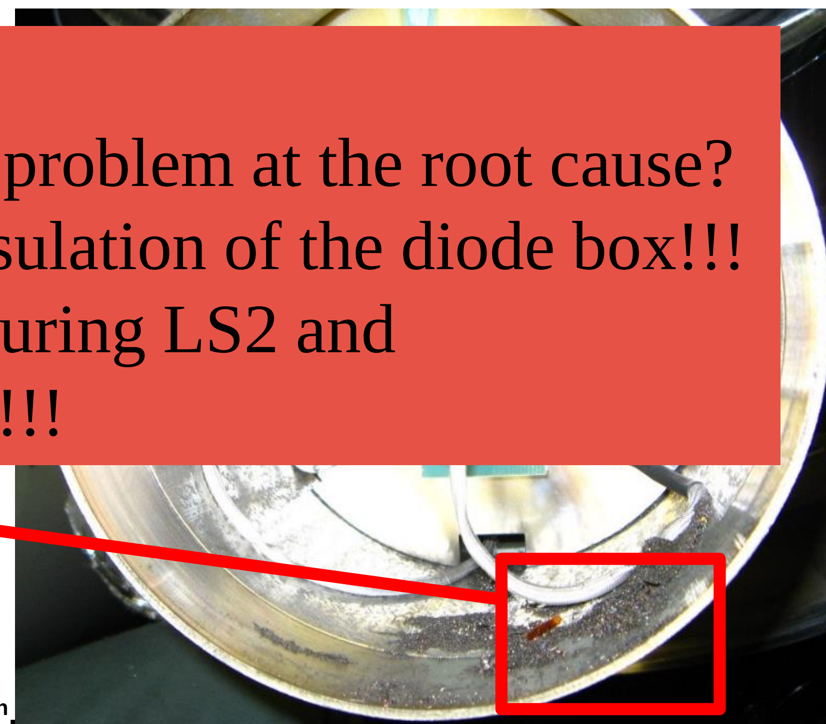
Solution exists and could by now remove a short twice

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:

Should one therefore cure this problem at the root cause?

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

➔ Decision for Intervention during LS2 and

➔ to stay at 6.5TeV for RunII!!!

LHC Energy Exploitation Session

- All magnets re-tested in SM18 did not show intrinsic limitations to reach ‘ultimate’ field (including 26MBs from tunnel)

Chamonix 2017
Gerard Willering

- Statistical analysis of all training quenches:
  - 95% of all quenches are 1st quenches (magnets quench only once)

Beam Energy for RunIII:

Probable to push beam energy towards 7 TeV after LS2 for RunIII

However, several equipment components might reach their performance limits @ 7TeV

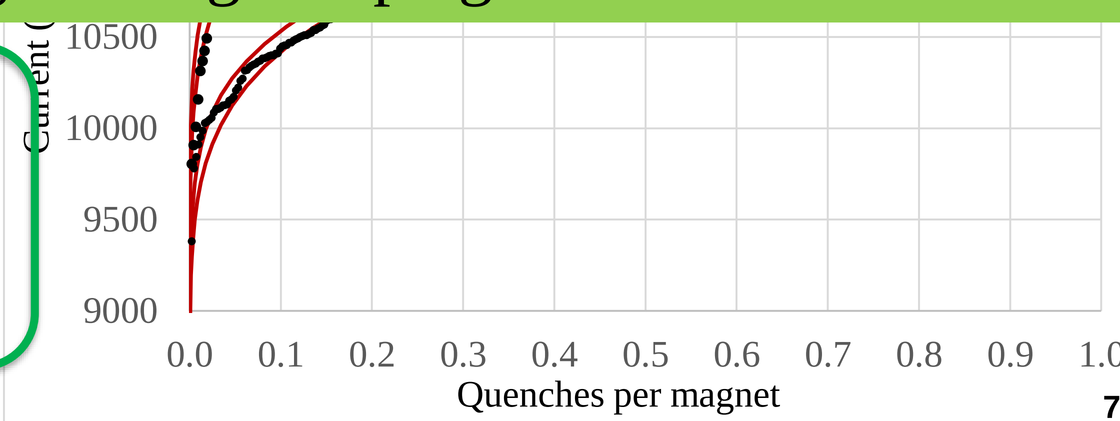
➔ needs validation during training campaign after LS2

~370 quenches

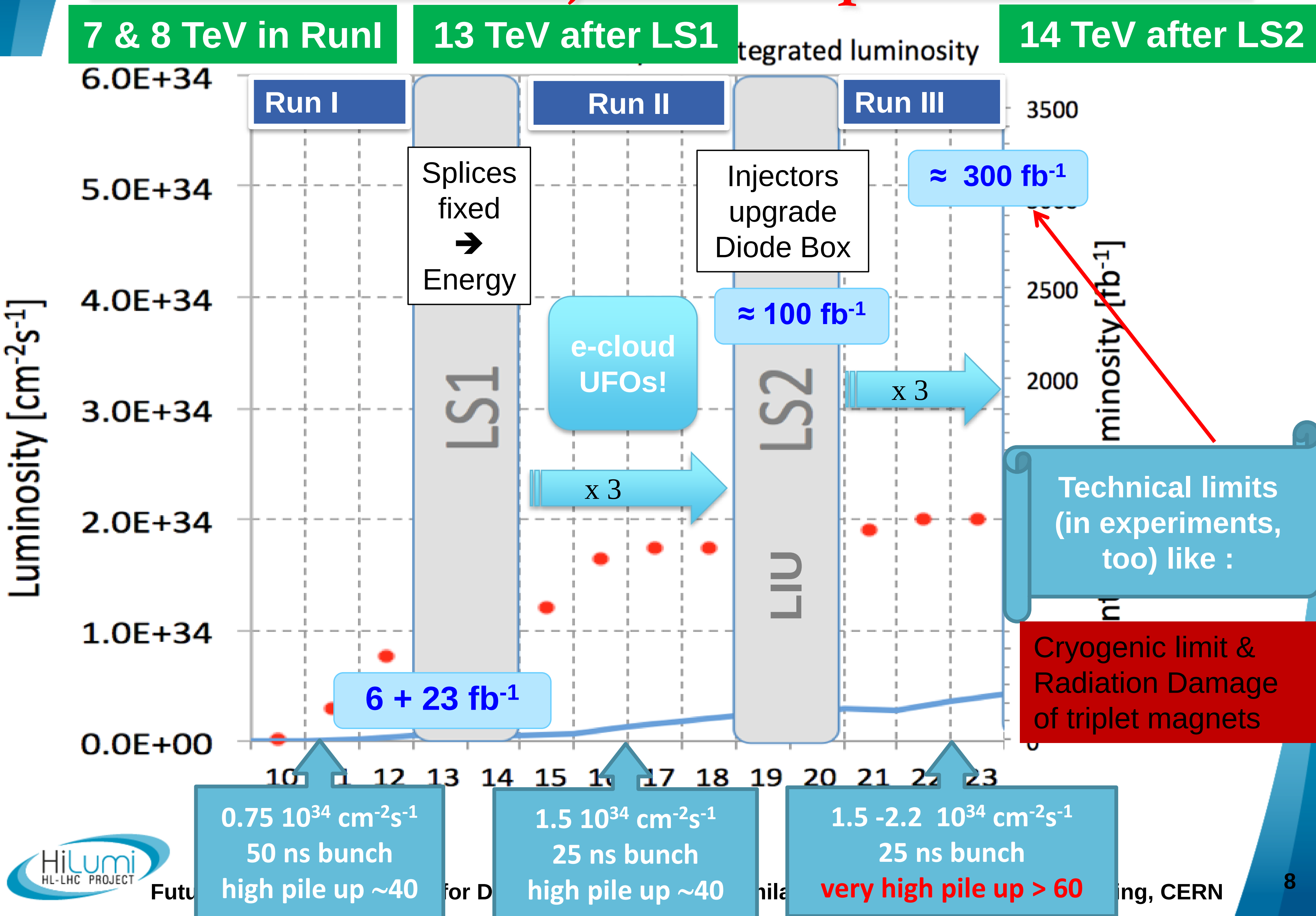
➔ ca. 500 to 600 quenches to reach 7 TeV

ca. 2 quenches / day

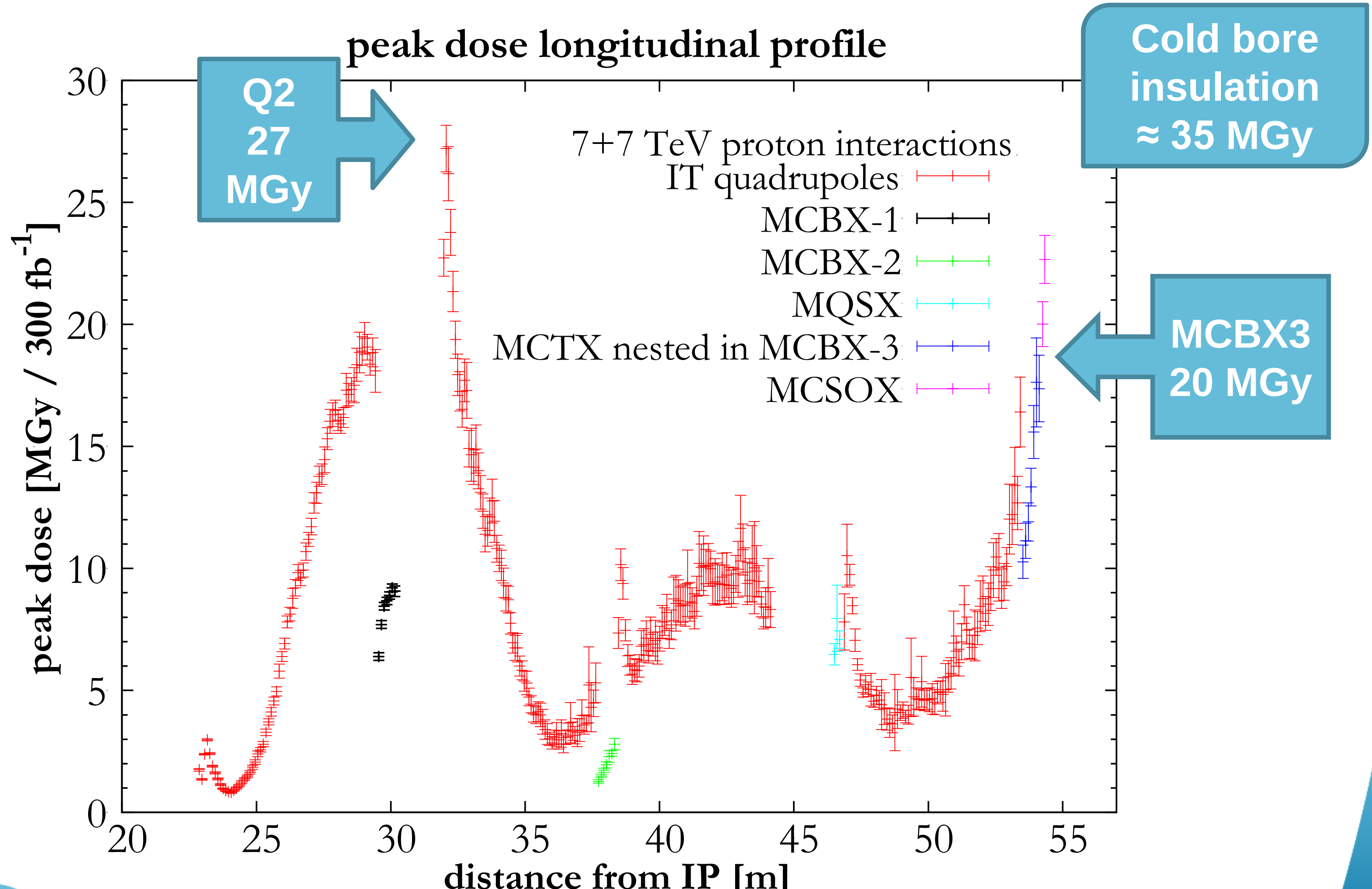
➔ Total of 1 month / sector



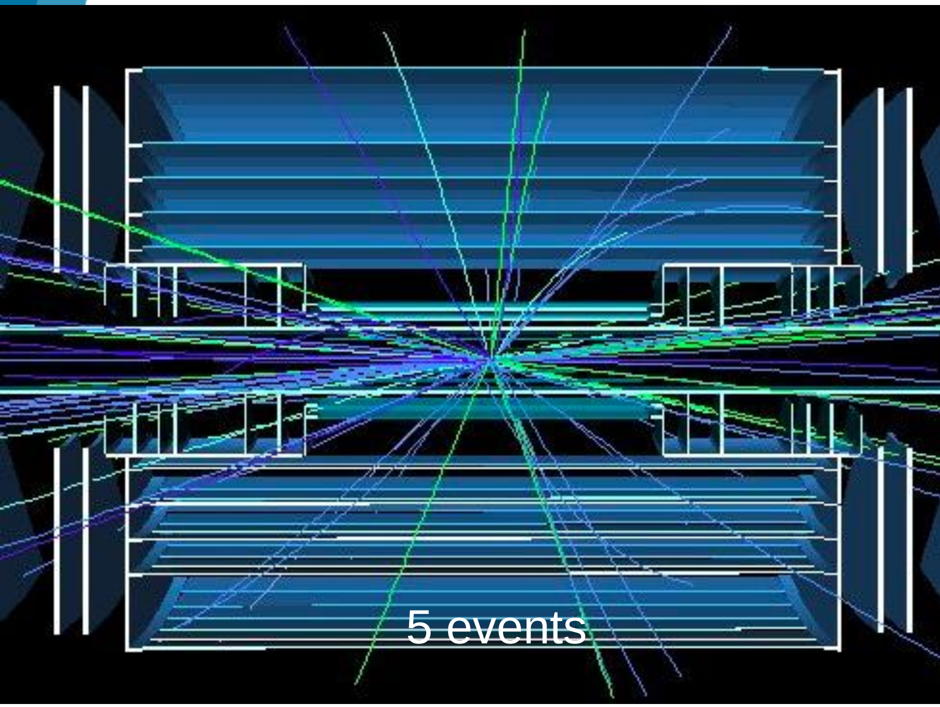
Performance Projections up to HL-LHC:

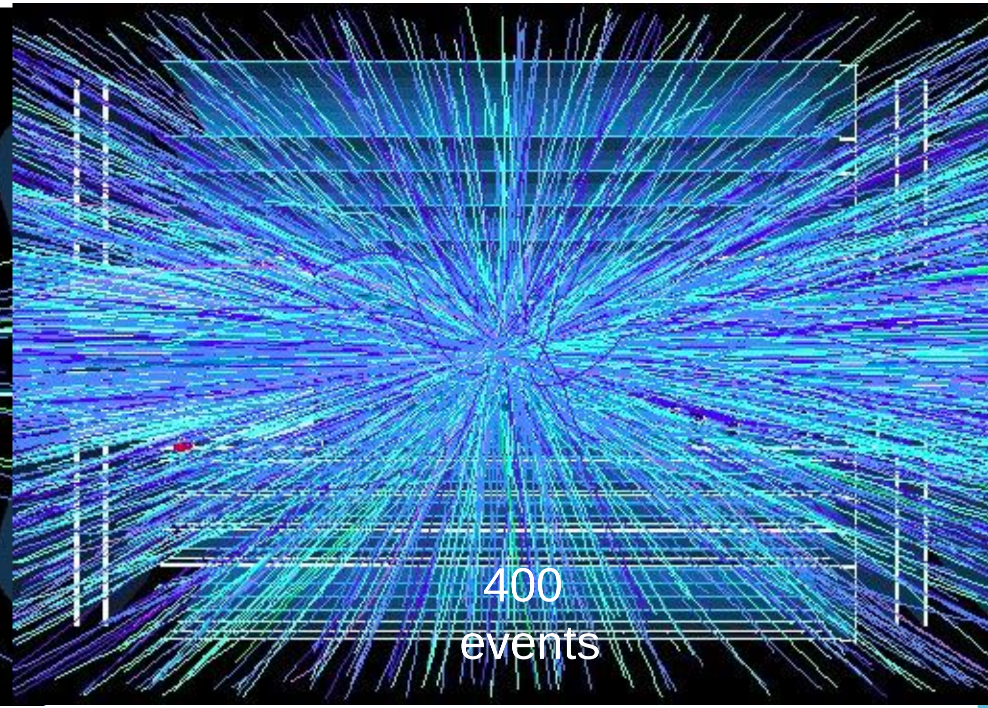


HL-LHC technical bottleneck:
Radiation damage to triplet magnets at 300 fb^{-1}



Goal of High Luminosity LHC (HL-LHC):





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

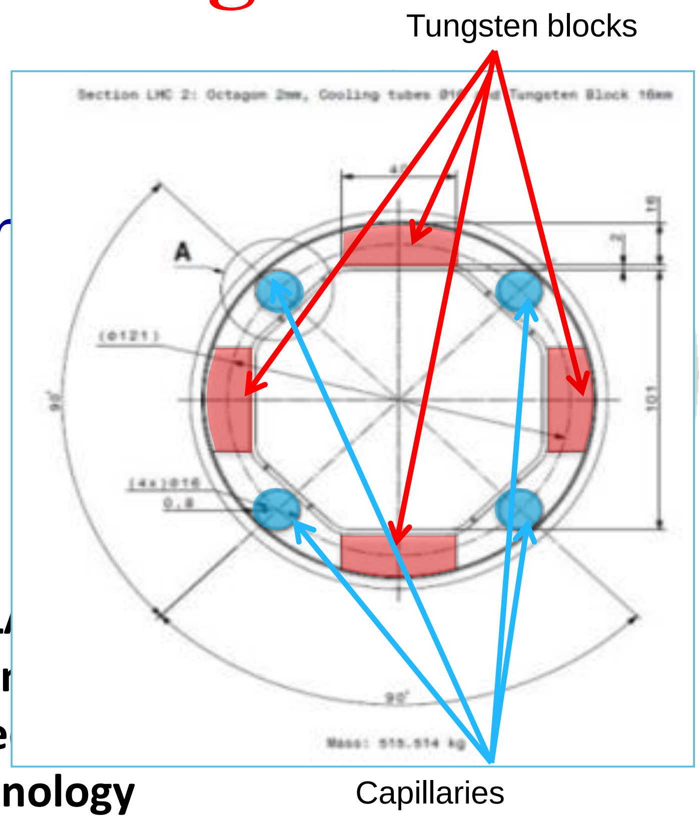
\# design oper. for μ δ **140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity!

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

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!!!!!



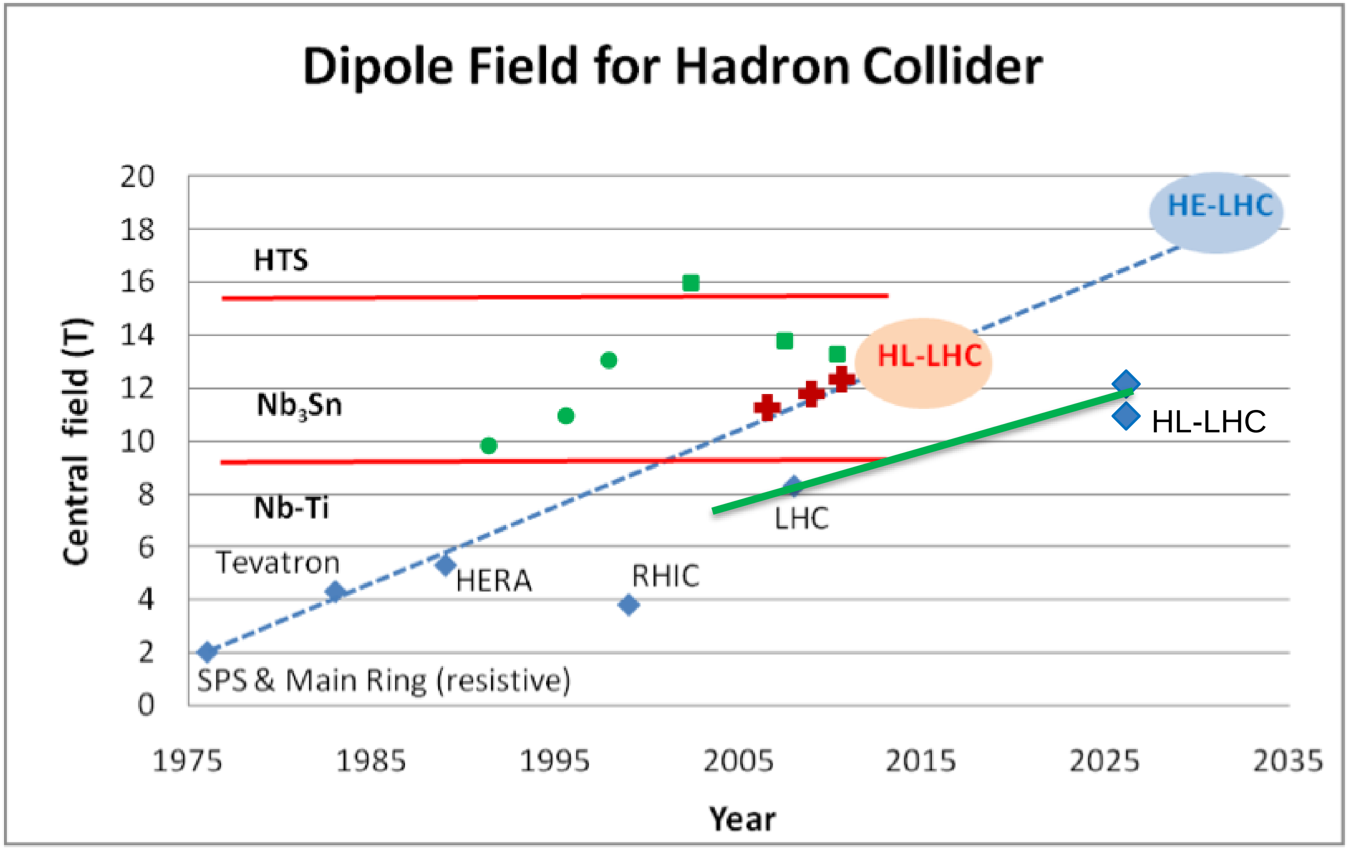
US-L magn Base technology

- ➔ 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:



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

Transition from $NbTi$ to Nb_3Sn:

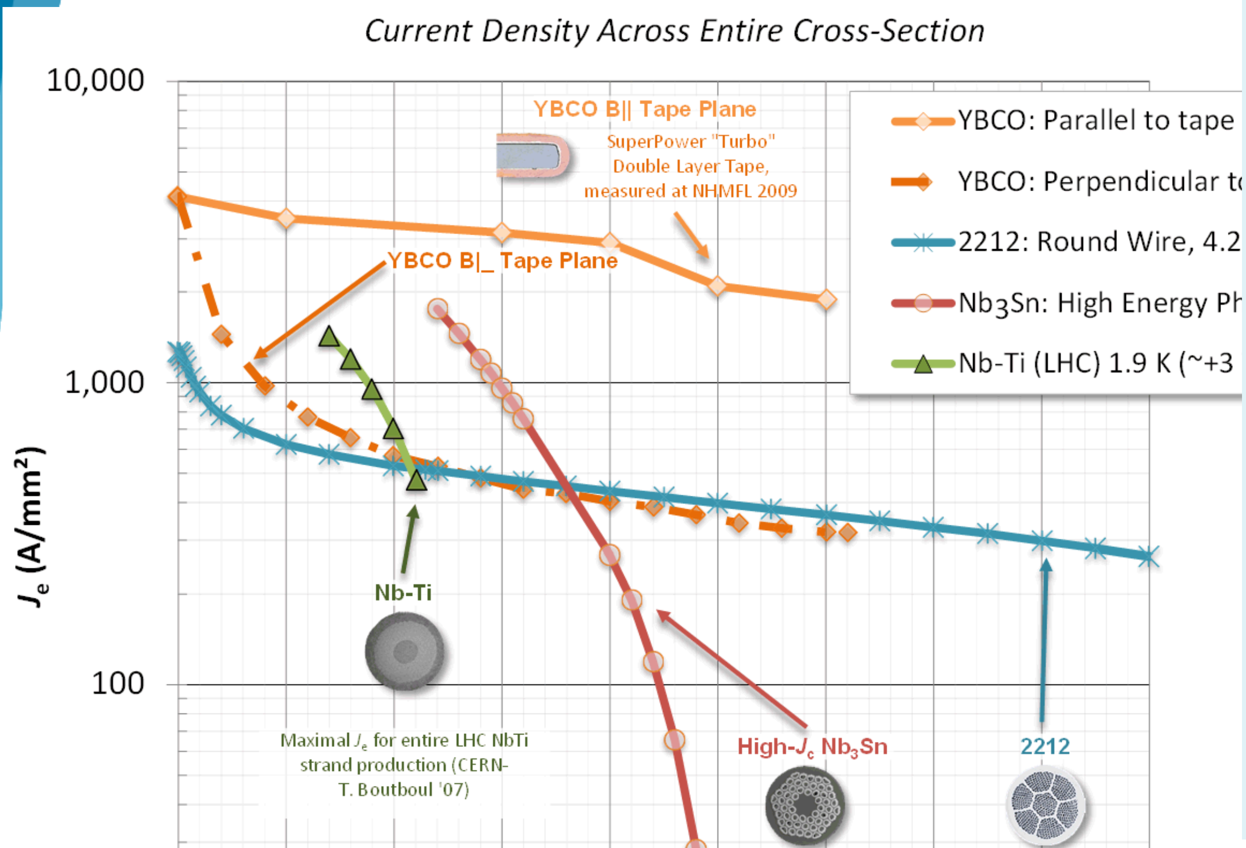
HL-LH lead the R&D for 11-12T magnets based on Nb_3Sn technology:

Started in earnest in 2004:

➔15-25 years R&D program

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

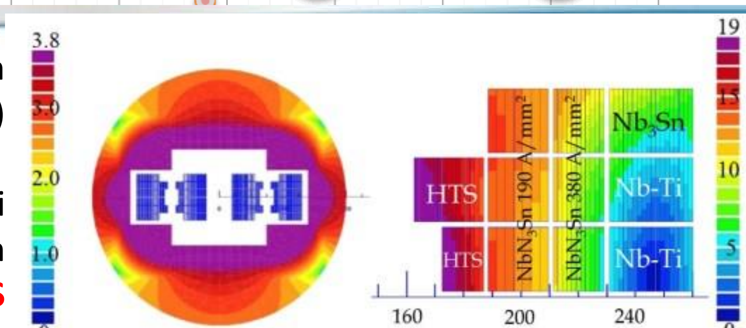
SC Magnet Technology



- 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
- HTS (needed → 20 T) ➔ on going R&D!
  - Bi-2212: cost today 2-5x Nb$_3$Sn
  - YBCO: cost today 10x Nb$_3$Sn

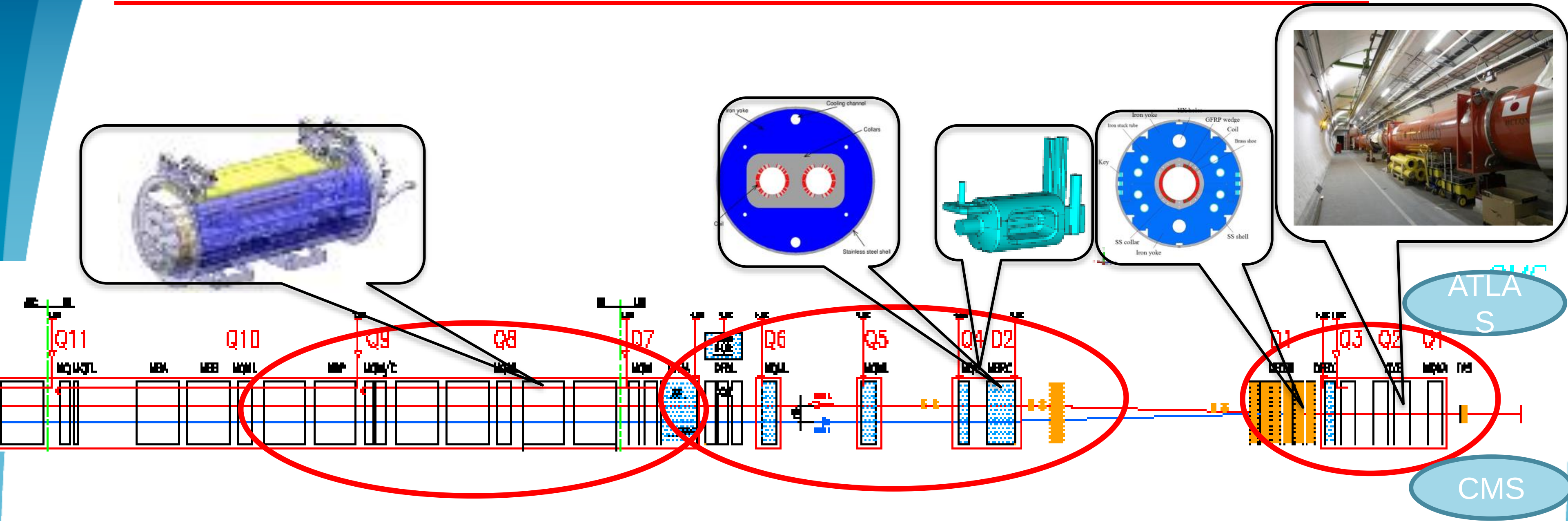
20 T "a l ta revised" design
3662 units (+ 120 spares)

1000 tons of LHC-grade Nb-Ti
3000 tons of HEP-grade Nb$_3$Sn
750 tons of HTS



source: L. Rossi
from 2011 - 2012

The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat in IR7: 11T Nb_3Sn dipole

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

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)!! and major Civil Engineering!!!

LHC Full Energy Exploitation:

- Operation at ultimate beam energy: E = 7.56TeV [9T]

All LHC and HL-LHC magnet systems are designed for operation at ‘ultimate’ field of 9T MB equivalent:

→ MB, MQ, PO, vacuum and cryogenics

→ but this operation mode implies strong reduction or removal of operation margins!

However, not all components are yet ready for operation at ‘ultimate beam energy’:

→ Beam Dump and Collimation systems among others.

→ This operation mode will require significant upgrades

→ Study still ongoing and results expected for Cham ’18

Could perhaps be envisaged for second half of HL-LHC exploitation, after LS4

LHC Full Energy Exploitation:

- Operation beyond ultimate beam energy: E > 7.56TeV

Proposal to replace 1/3 of all MB magnets with 11T Nb_3Sn magnets

- ➔ Major interventions [opening of all MB interconnects]
- ➔ Not clear other magnets can be scaled up in energy e.g. insertion quadrupoles and triplet magnets
- ➔ Not clear other systems [e.g. beam dump system] can be easily upgraded

Study ongoing and results expected for end 2018 / beginning 2019

Could perhaps be envisaged as a second LHC upgrade at the end of the HL-LHC exploitation period. But will require significant investment [time, resources and capital]!!!

pp colliders: Future Project Options

- HE-LHC: installation of new 16T magnets in LHC tunnel

➔ Requires Nb_3Sn magnet technology with 16T peak field:

Magnet technology not yet at accelerator grade level

Option for 'post LHC' ➔ 2040ies

Magnets will be more expensive than those of LHC (x 3-4?)

Detailed study conducted under the FCC umbrella

➔ results expected by 2018

Would imply ca. 5 years without HEP (LEP LHC took 10)!!

Would bring 'only' a factor two in CM collision energy!

Would be a technology demonstrator for FCC-hh

pp colliders – High Field SC Magnets

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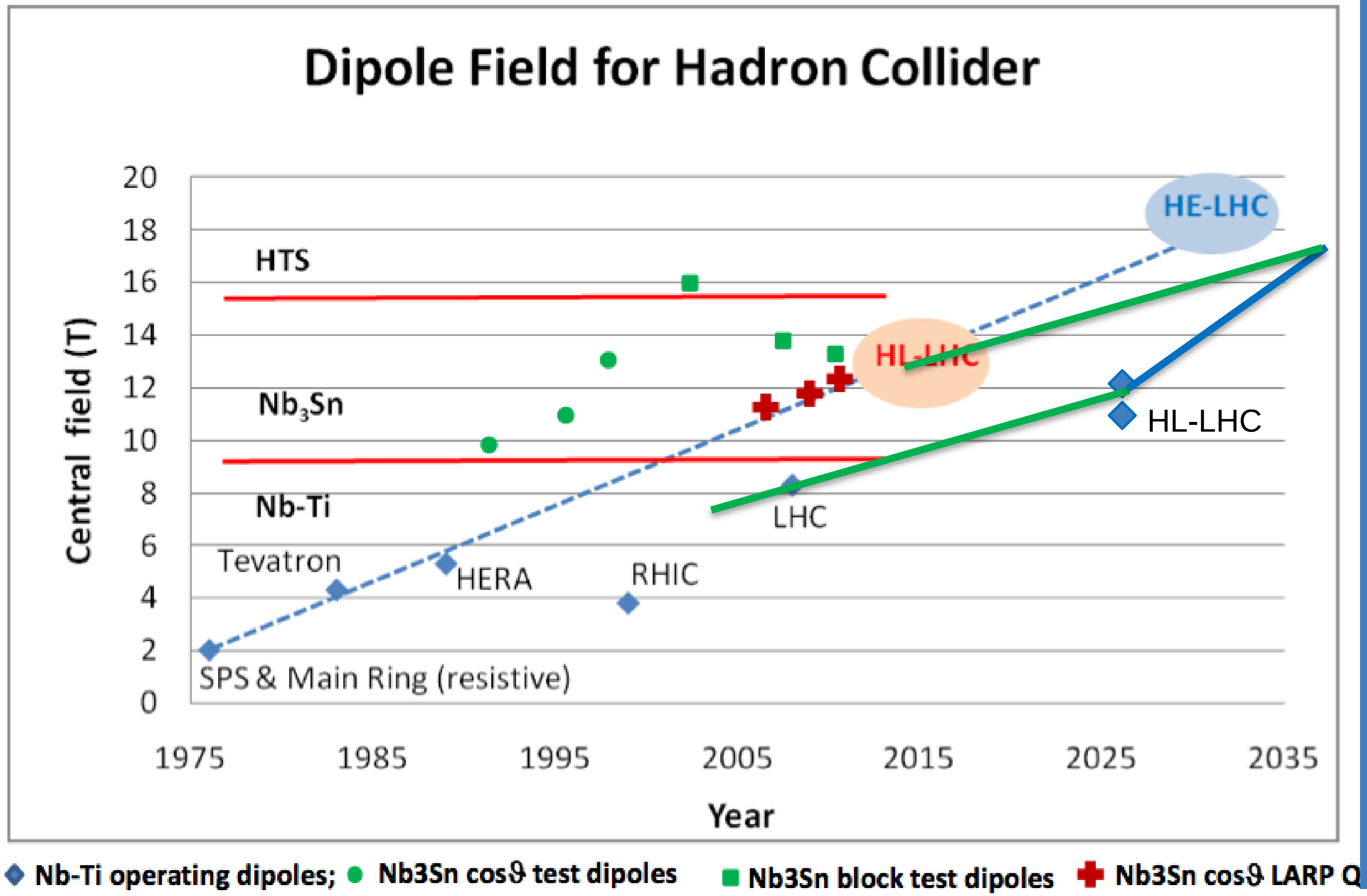


Transition from NbTi to Nb_3Sn:

HL-LH lead the R&D for 11-12T magnets based on Nb_3Sn technology:
➔15-25 years R&D program

Push Nb_3Sn and/or Transition to HTS:

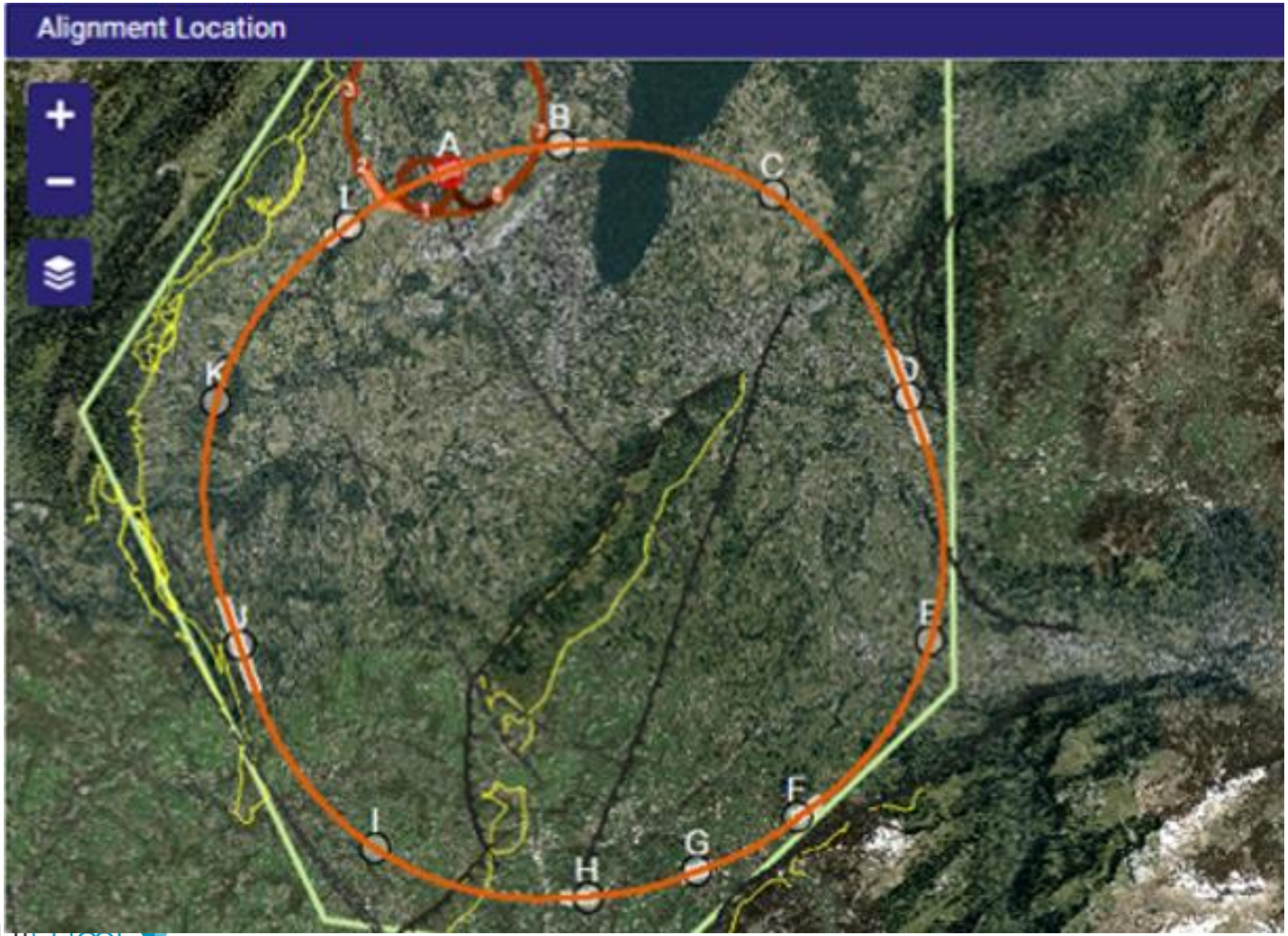
Assume R&D period of similar length ➔ 2035?

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

Future Circular p-p collider: Example FCC

Large new infrastructure development:

100 km circumference tunnel infrastructure, e.g. in CERN area



pp colliders: Future Project Options

- FCC-hh: International Study under CERN coordination

➔ Requires magnet technology with 16T peak field:

CDR planned for 2018 in time for next European Strategy

Based on 1 … ea (4 x LHC)

➔ a … /rt LHC

Main challenges will be:

-Magnet technology ➔ 16T ++

-Cost (installation and operation)

-Power consumption

-Operational efficiency for a facility of 100km size

- SppC: C …

➔ Similar design as FCC-hh:

PCDR published in 2015

Based on 54km (PCDR) circumference

➔ options for 78 and 100km considered in 2016

LHC Upgrade Goals: Performance optimization

- Luminosity recipe (round beams):

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

➔1) maximize bunch intensities ➔ Injector complex

➔2) minimize the beam emittance Upgrade LIU

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

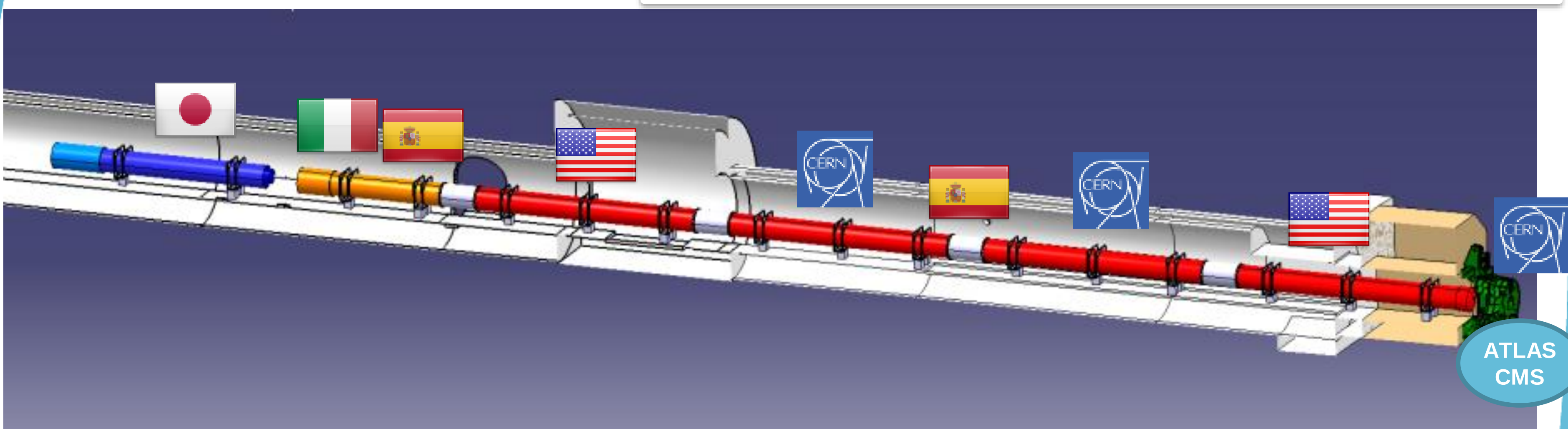
➔4) maximize number of bunches (beam power); ➔ 25ns

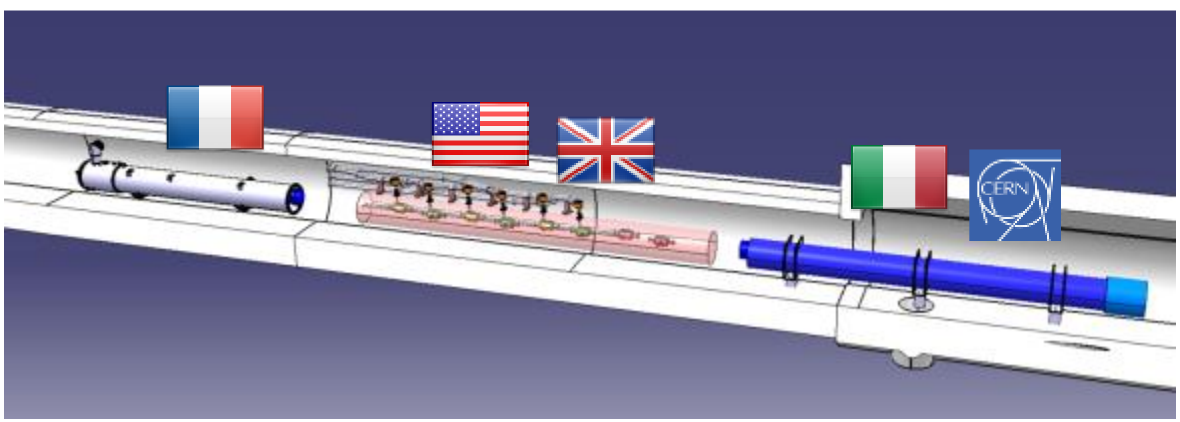
➔5) compensate for 'F'; ➔ Crab Cavities

➔6) Improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

In-kind contributions and collaborations for design and prototypes

First approval as construction Project: Sept. 2013



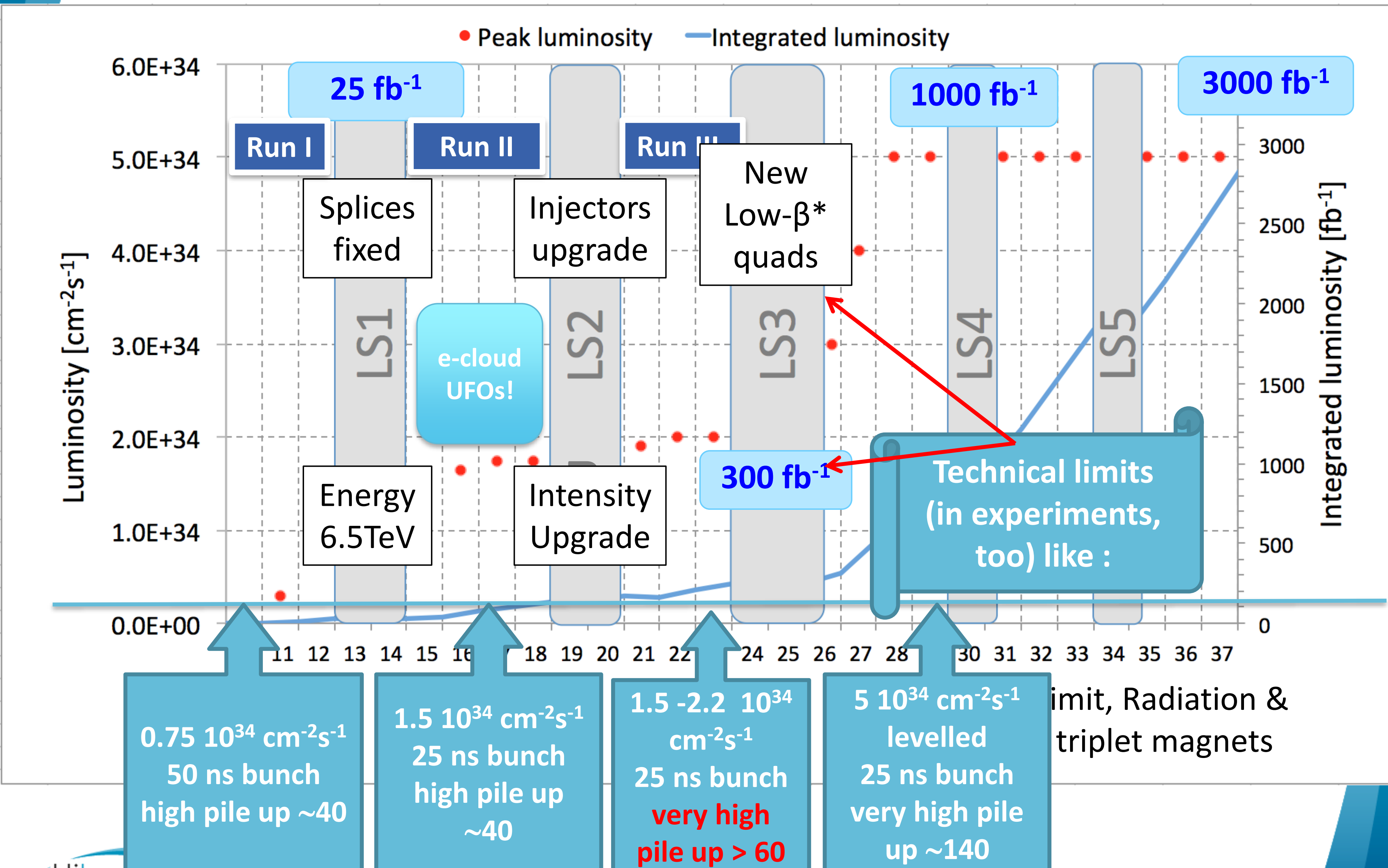


Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
D2: Design and Prototypes **IT**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

CC : R&D, Design and in-kind **USA**

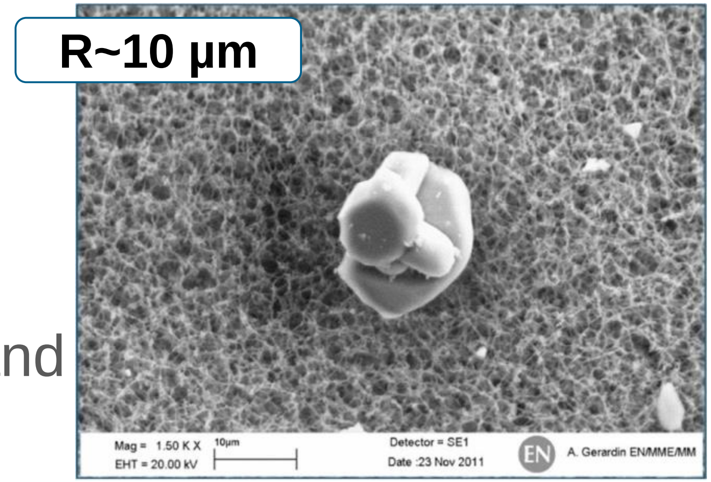
CC : R&D and Design **UK**

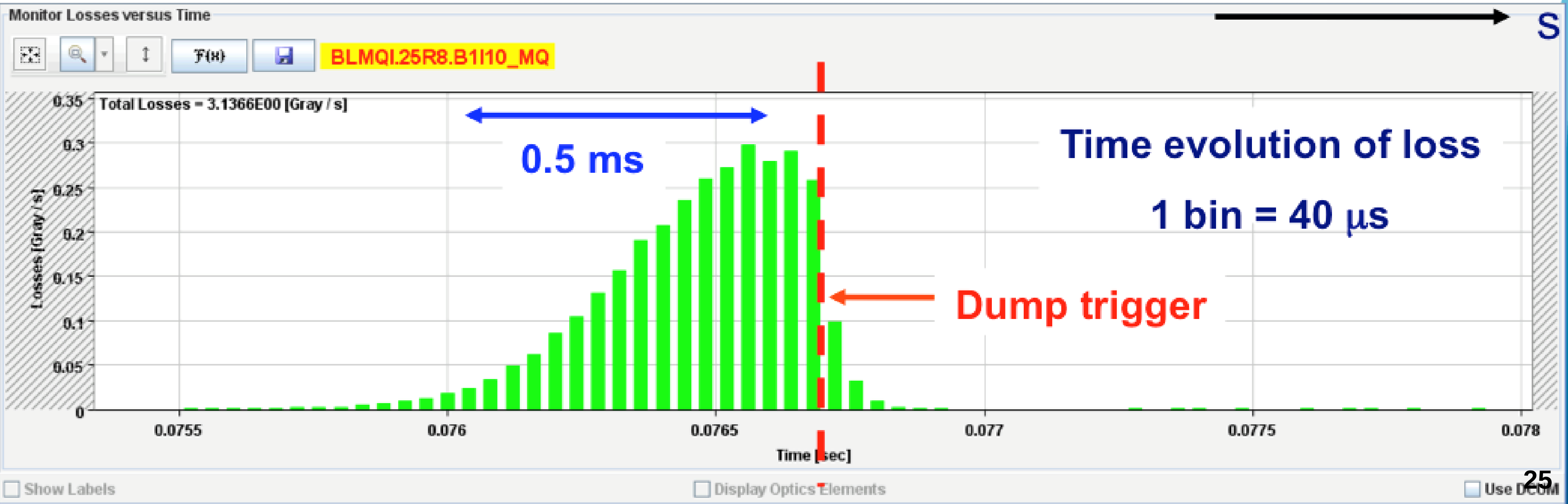
Performance Projections up to HL-LHC:



UFOs – Unidentified Falling Objects:

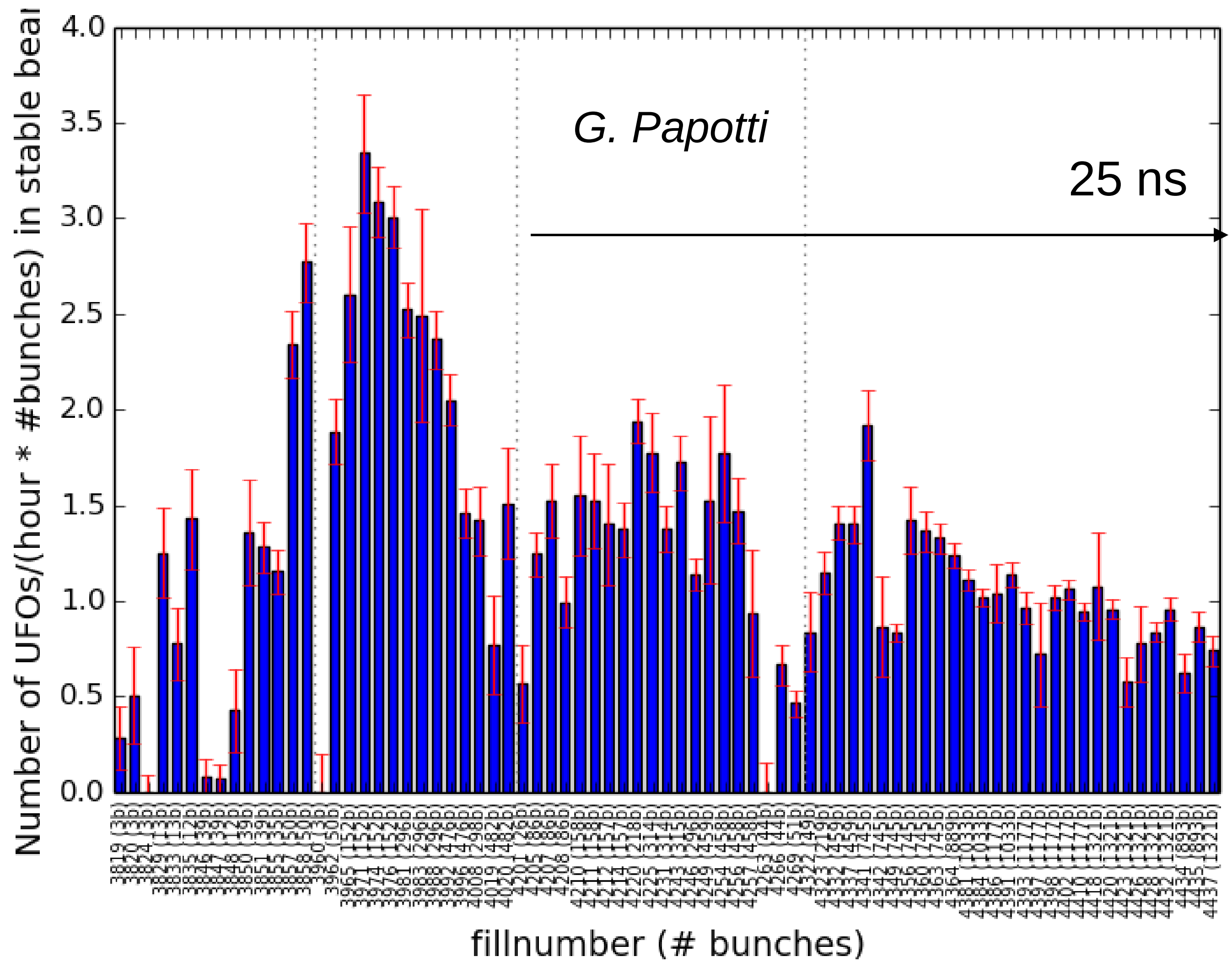
- Sudden local losses
- Rise time of the order of 1 ms.
- Potential explanation: dust particles falling into beam creating scatter losses and showers propagating downstream
- Distributed around the ring – arcs, inner triplets, IRs
- Even without quench, preventive dumps by QPS





RunII Startup: UFO rates (September 2015)

- 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



Extended Year End Technical Stop ‘16/’17:

- Requested by Experiments:

  CMS ➔ replacement of the pixel detector

- LHC machine:

  -De-cabling campaign in the PSB and SPS for LIU

  -New internal beam dump for SPS (vacuum leak in 2016)

  -Training campaign towards 7TeV of 2 sectors: S34 and S45

  -Magnet exchange in Sector 12

- Later startup for 2017 operation

  Luminosity production as of June (compared to May in ‘16)