HL-LHC Upgrade Project

Corfu Summer Institute 2021

Markus Zerlauth with acknowledgements to O.Brüning, M.Lamont, L.Rossi, J. Wenninger and many other CERN colleagues

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Outline

- LHC design performance and HL-LHC upgrade goals
- Key (technological) challenges of HL upgrade
  - Injector chain upgrade
  - R2E and collision debris
  - Final focusing magnets for lower beta*
  - Crab cavities for X-ing angle compensation
- HL-LHC as a truly international project
- Current Project planning
- Performance ramp-up

Introduction: LHC Performance Goals

- Collision energy: Higgs discovery requires $E_{CM} > 1$ TeV

  p collisions → $E_{beam} > 5$ TeV → LHC: E = 7 TeV [3.5TeV; 4TeV; 6.5TeV]

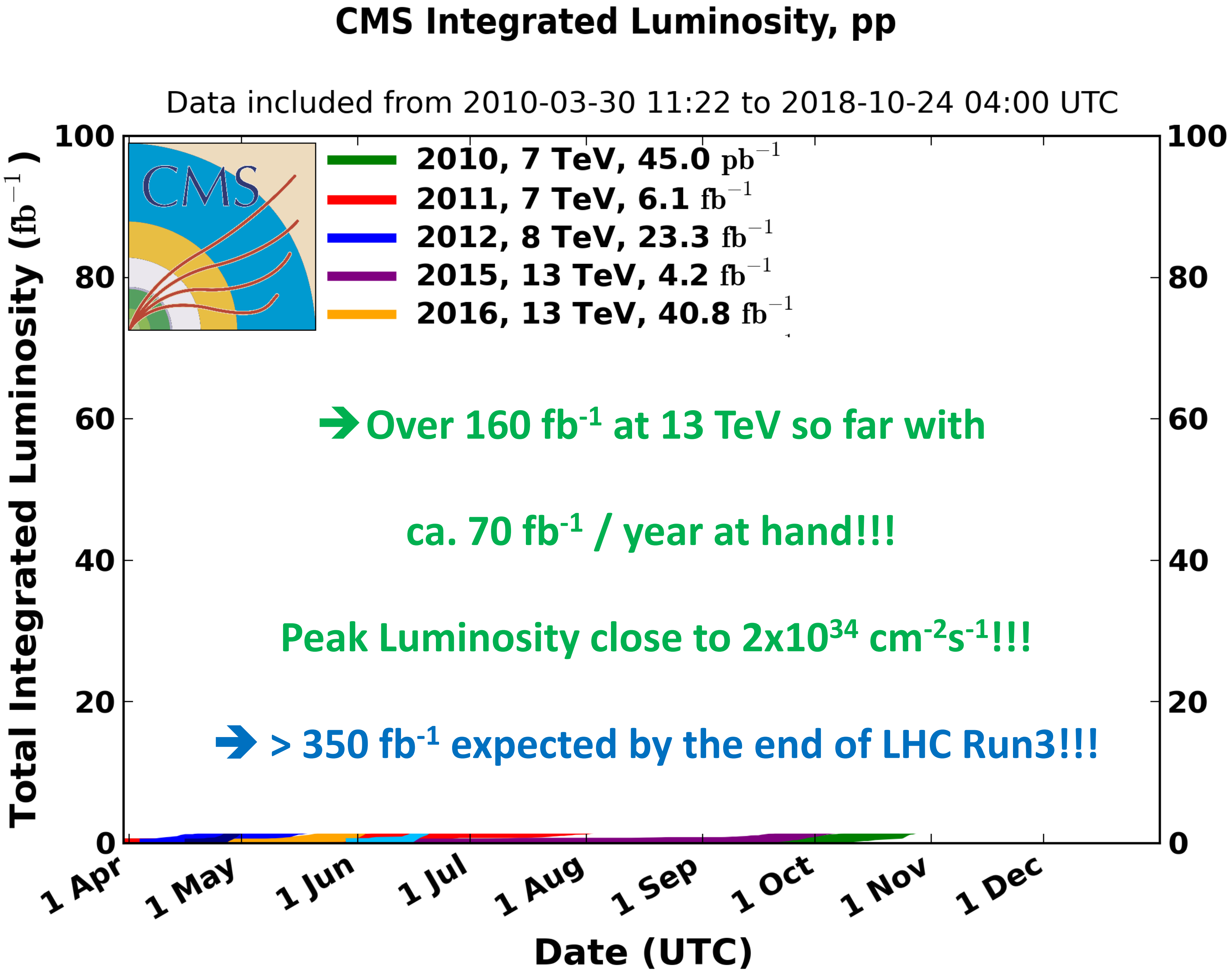
- Instantaneous luminosity: rate of events in detector $= L \times \sigma_{event}$

  rare events → $L > 10^{33} cm^{-2} sec^{-1}$ → $L = 10^{34} cm^{-2} sec^{-1}$ [$2\ 10^{34} cm^{-2} sec^{-1}$]

- 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} [193 fb^{-1}]

  depends on the beam lifetime, the LHC cycle and 'turn around' time and overall accelerator efficiency



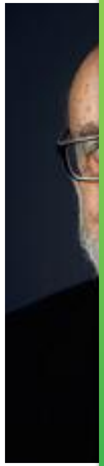
➔ Over 160 fb^{-1} at 13 TeV so far with

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

Peak Luminosity close to $2x10^{34}$ $cm^{-2}s^{-1}$!!!

➔ > 350 fb^{-1} expected by the end of LHC Run3!!!

Higgs Discovery in July 2012 and 2013 Nobel Price for the



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But many questions remain and the search continues!!!

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

➔Need more Data and Statistics!!
Doubling the present 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 cooling of triplet magnets & radiation damage in triplet magnets & machine efficiency!

➔ Need for an Upgrade!

Goal of High Luminosity LHC (HL-LHC):

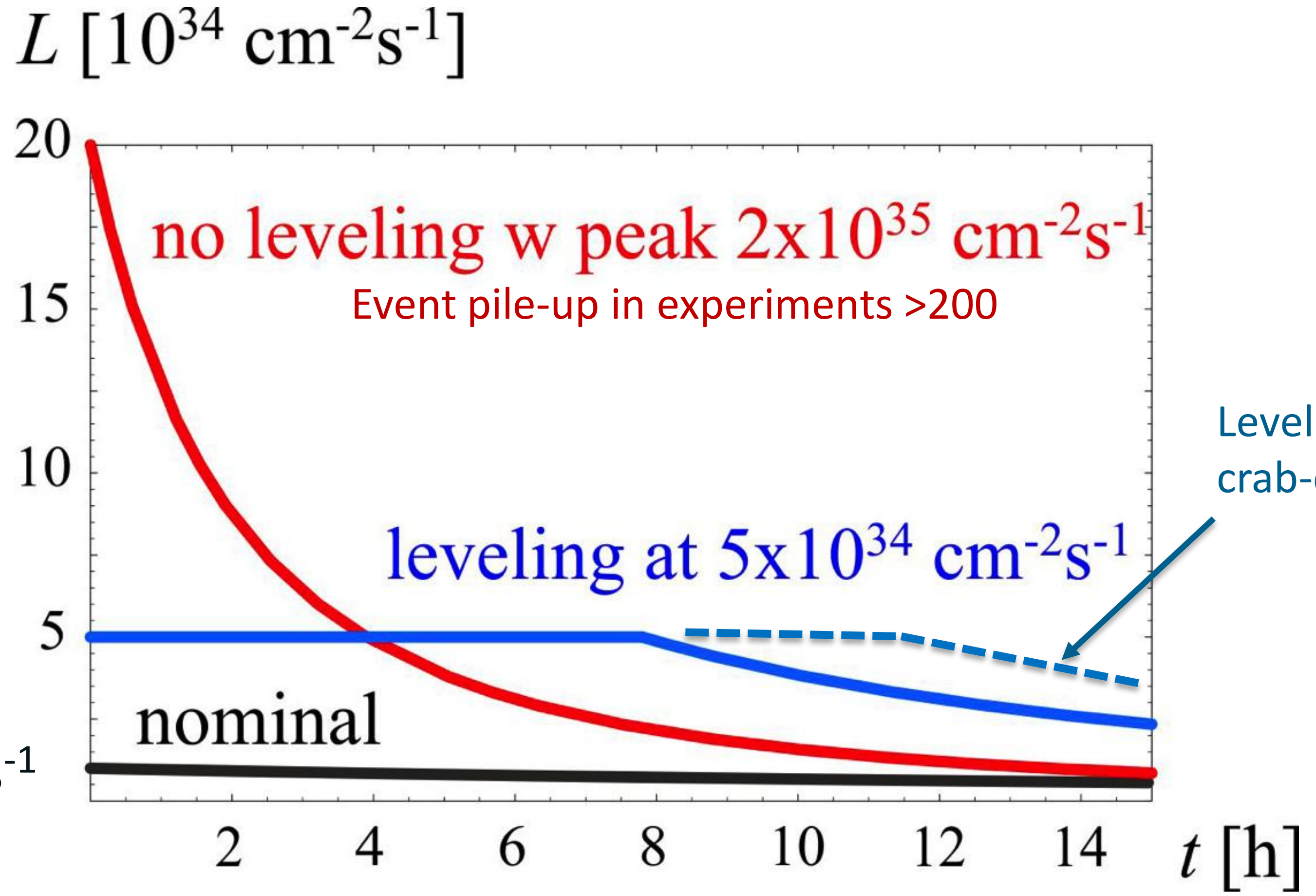
Now entering the phase of hardware production for most equipment!!!

Project approved by CERN Council in June 2016

➔ Operation with levelled luminosity!

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

Proposed Operational Scenario for HL-LHC



LHC: $1x10^{34}$ $cm^{-2}s^{-1}$

How to reach HL-LHC performance?

- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam
- **Dealing with the regime**
  - Collision debris, high radiation
- **Lower beta* (~15 cm)**
  - New inner triplet magnets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets and matching section quads
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation

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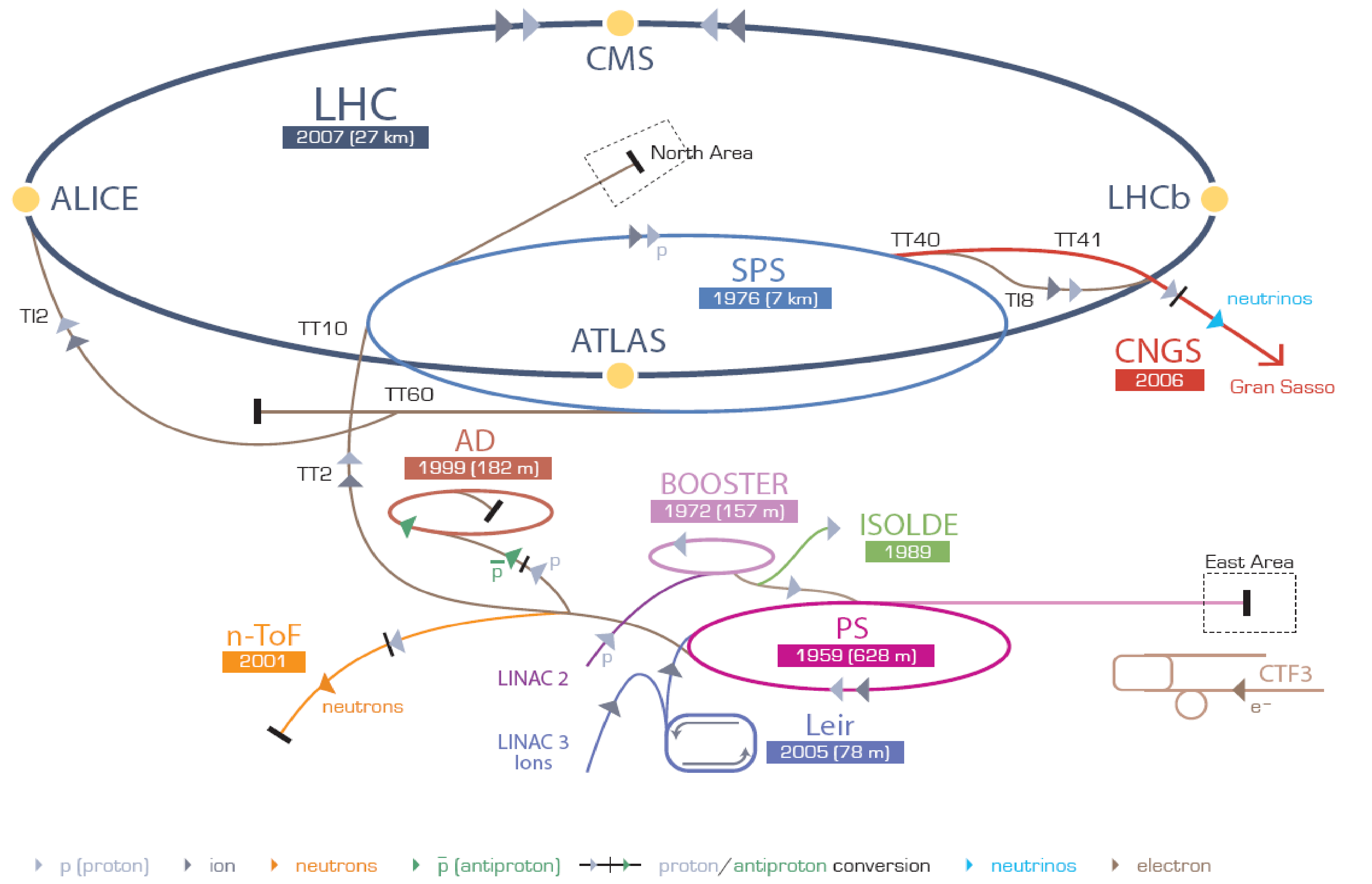
CERN accelerator complex



LHC Injector Upgrade Project (LIU)

- HL-LHC performance relies on more intense and brighter bunches from injector complex (2.2E11p / 2um at SPS extraction wrt to LHC nominal of 1.15E11p / 3.4um)
- 25ns beam limited by space charge in PS, PSB, SPS; SPS RF power and SPS longitudinal instabilities
- 50ns beam limited by PS longitudinal instabilities & SPS space charge and SPS TMCI

Linac4 in for Linac2	• H^- injection into PSB at 160 MeV • Expected double brightness for LHC beams out of the PSB
Booster	• Increase energy to 2 GeV • New RF system • New main power supply
PS	• Injection at 2 GeV • Beam production schemes • Feedback systems: new wide-band longitudinal feedback; transverse feedback against head-tail and e-cloud instabilities
SPS	• Power upgrade of the main 200 MHz RF system • Electron cloud mitigation through a-C coating (baseline) or beam induced scrubbing

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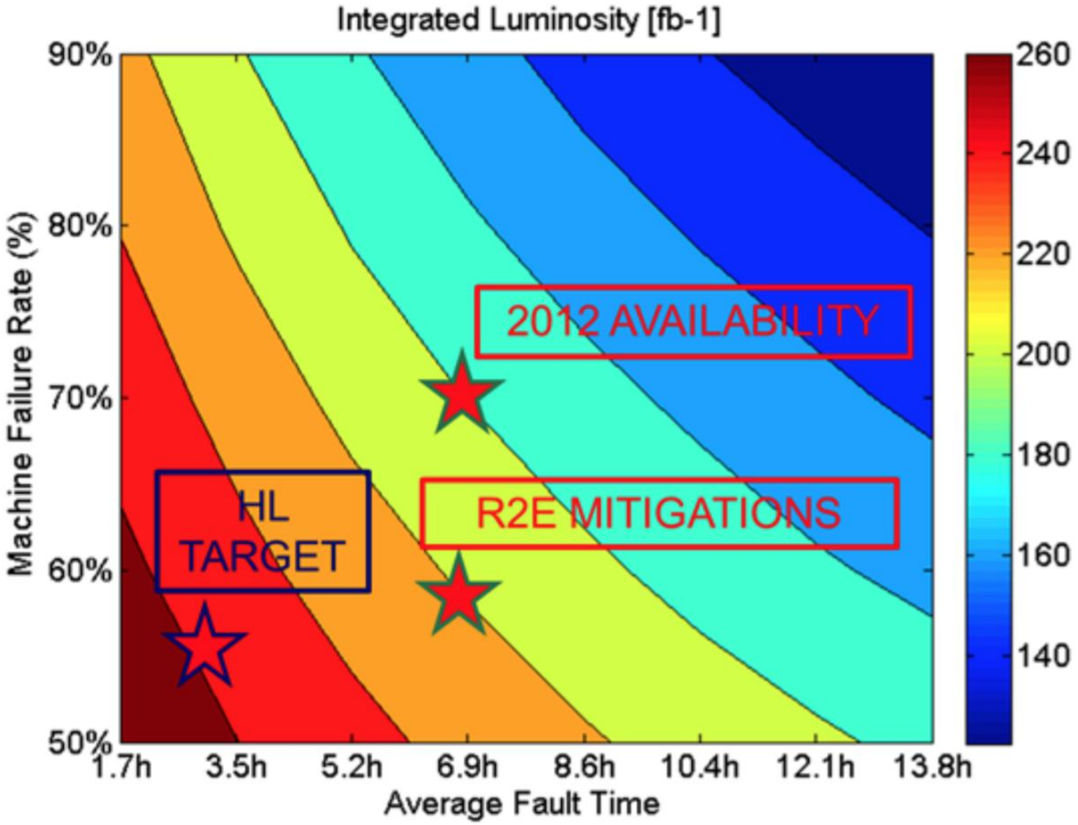
Dealing with the operation of a high energy high brightness machine

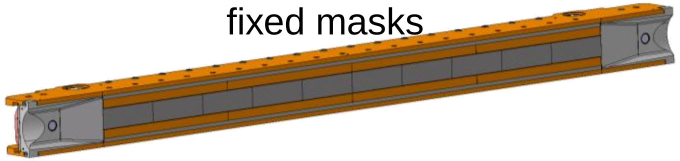
Very bright beams, very high bunch population, very high beam current

- Beam stability
  - New low impedance collimators
- Beam lifetime & loss spikes
  - Magnet quenches
- Machine protection
  - Failure scenarios - local beam impact - equipment damage
  - Quench protection
- Machine availability
  - Radiation to electronics (SEUs etc.)…



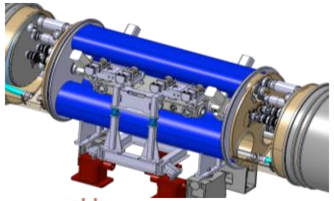
1) Shielding and Collimation upgrade:

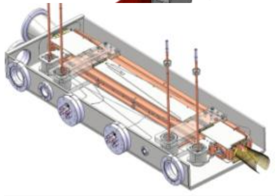
Completely new layouts
Novel materials.
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks



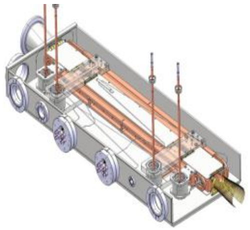
56 new collimators to be produced by LS3 in the present HL-LHC baseline!

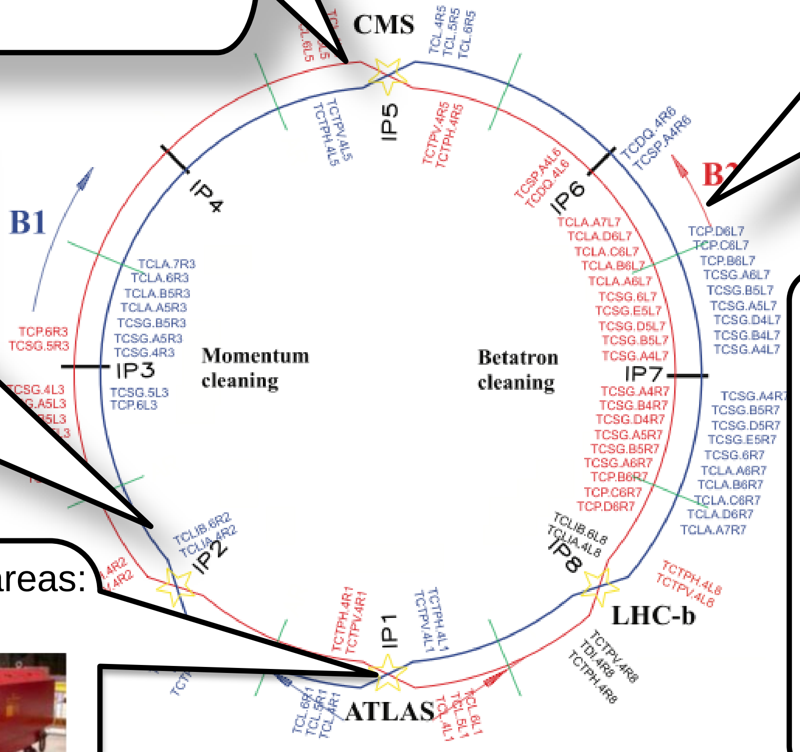
Cleaning of off-momentum particles: DS collimator + 11T dipoles per beam



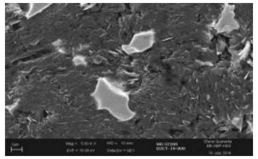


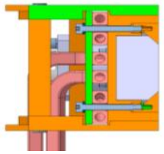
Ion physics debris:
DS collimation

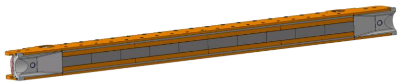




Low-impedance, high robustness secondary collimators

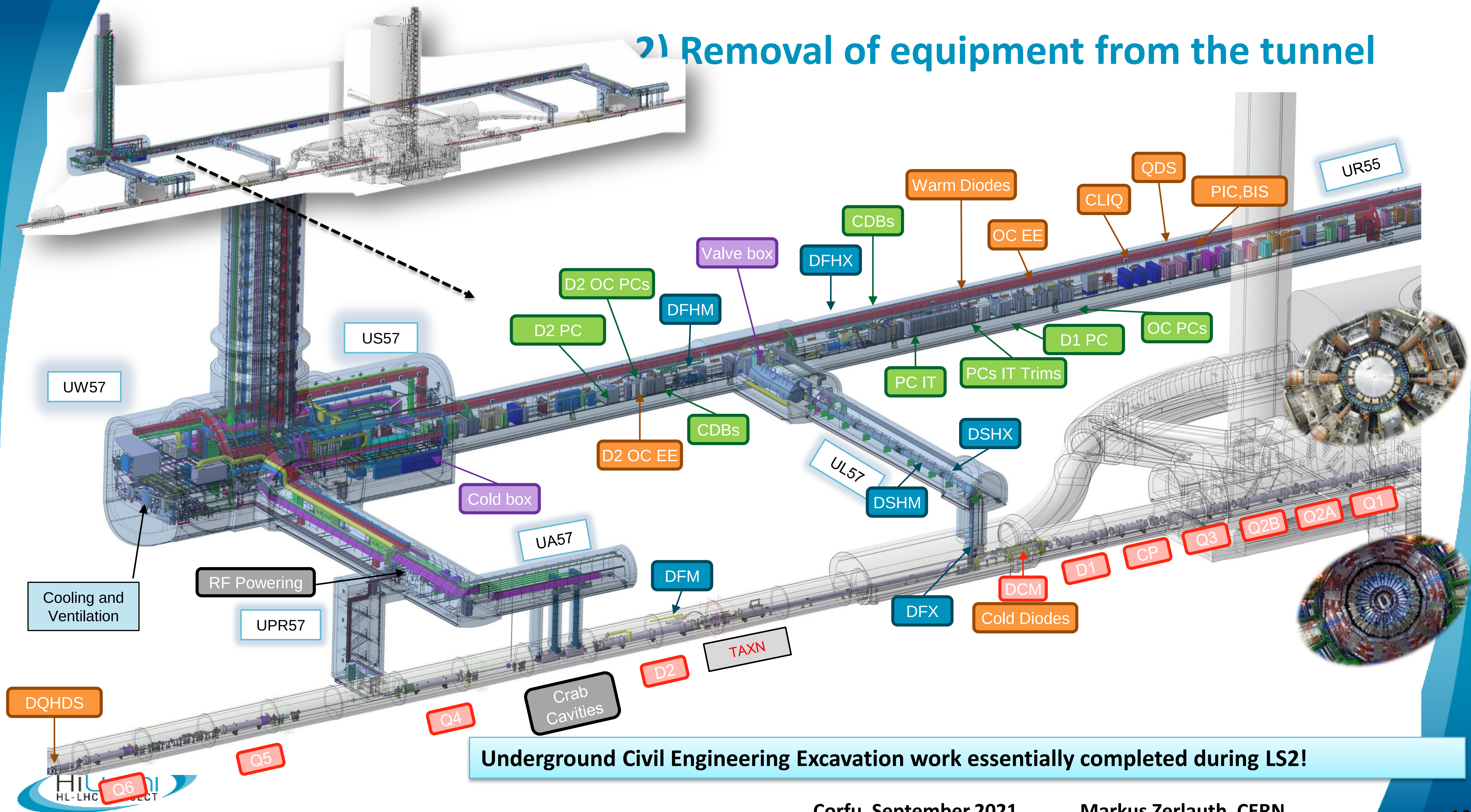






Shielding of the experimental areas:
New TAXS and TAXN

2) Removal of equipment from the tunnel

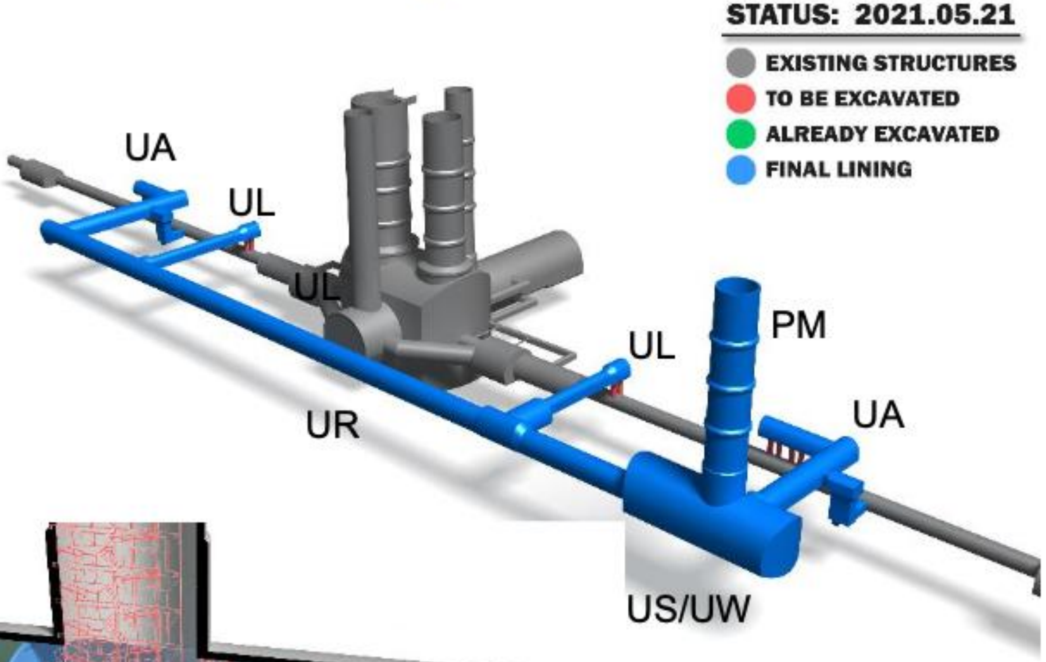


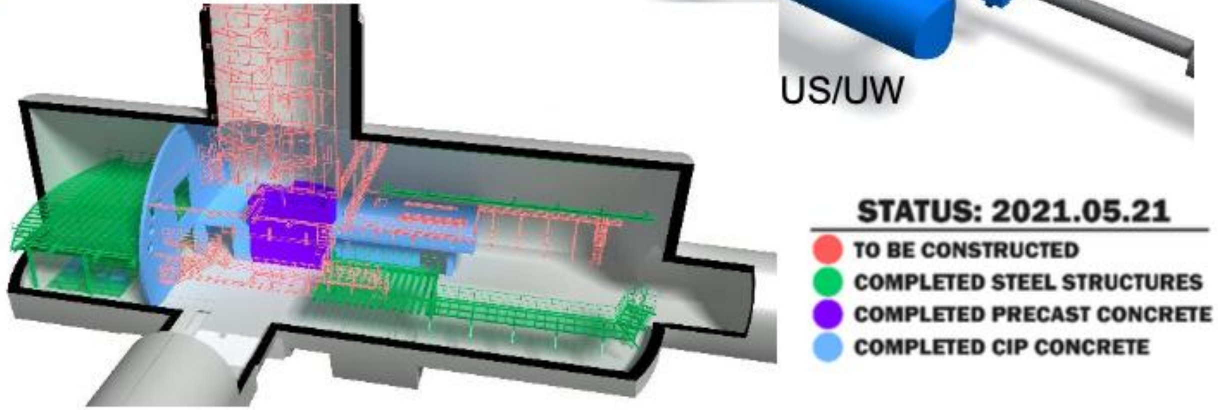
Underground Civil Engineering Excavation work essentially completed during LS2!

HL-LHC civil engineering status (Point 1)

Overall progress: 69%

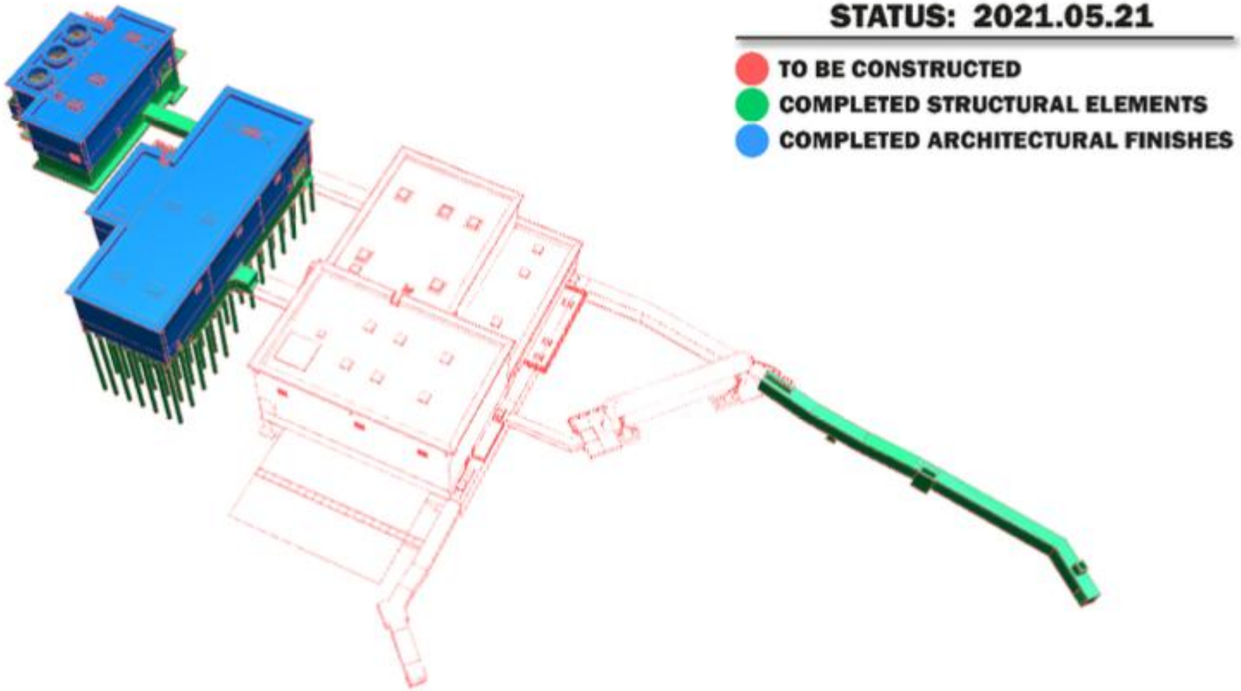
Underground





Expected completion by October 2021 (including + ~1 month due to Covid-19)

Surface



Expected completion by September 2022 (Including + ~1 month due to Covid-19)

HL-LHC civil engineering (early days)

HL-LHC civil engineering status (Point 1)

PM17 shaft
final lining

US/UW17 cavern

UA13/UR15 galleries

US17 cavern

IR1 & IR5 Surface Civil Engineering (early days)

SF57: Wall casting

SHM57: Ground slab casting

HiLumi HL-LHC PROJECT

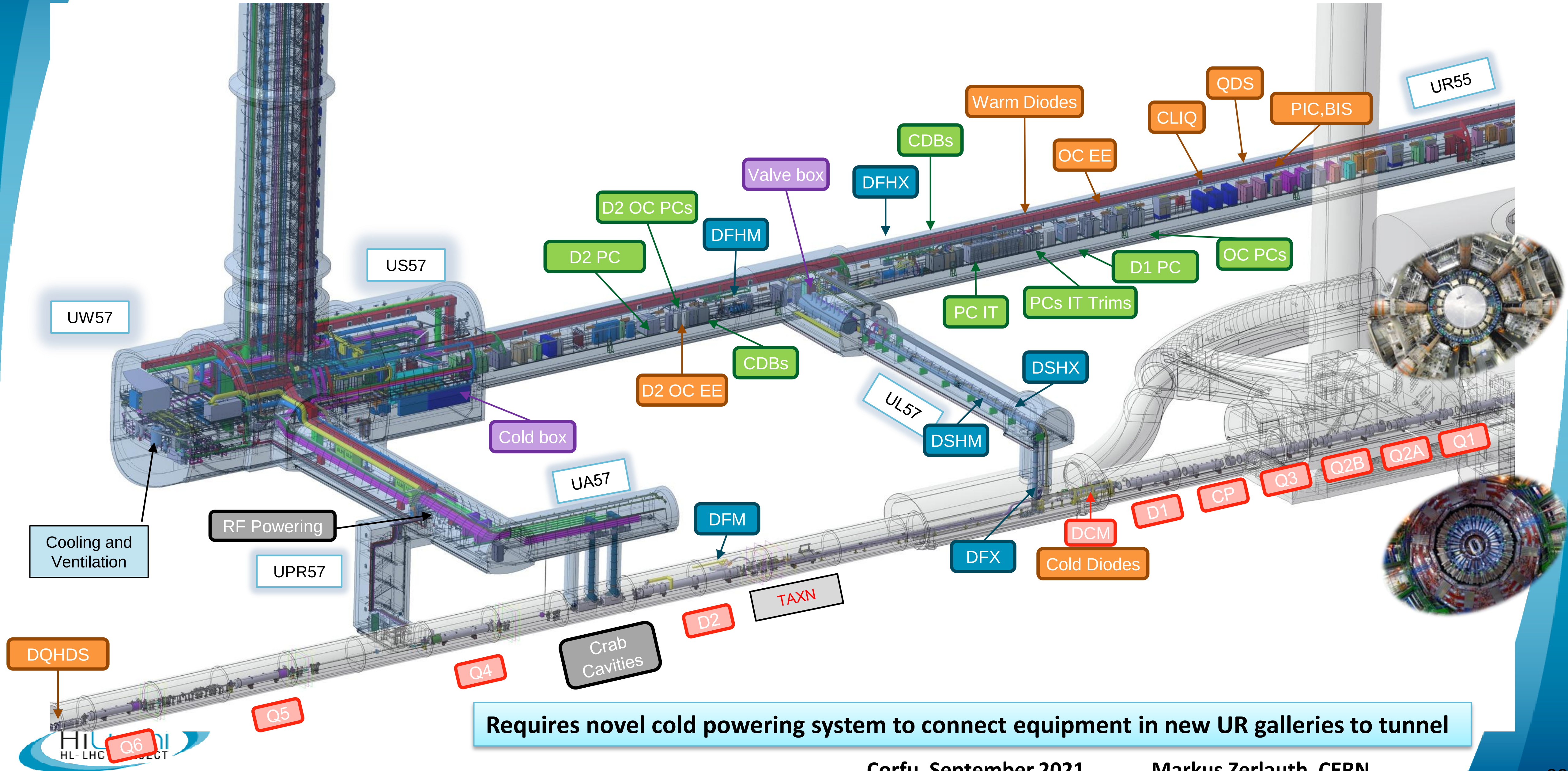
HL-LHC civil engineering status (Point 1)

SF17: Cooling tower building

SHM17: Cryogenic compressor building

Delivery expected on time (Aug'21)

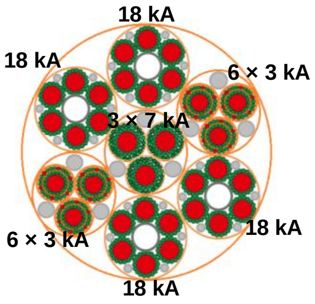
2) Removal of equipment from the tunnel



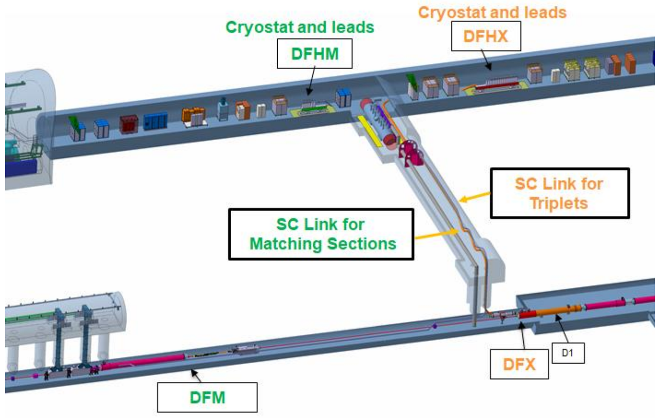
Requires novel cold powering system to connect equipment in new UR galleries to tunnel

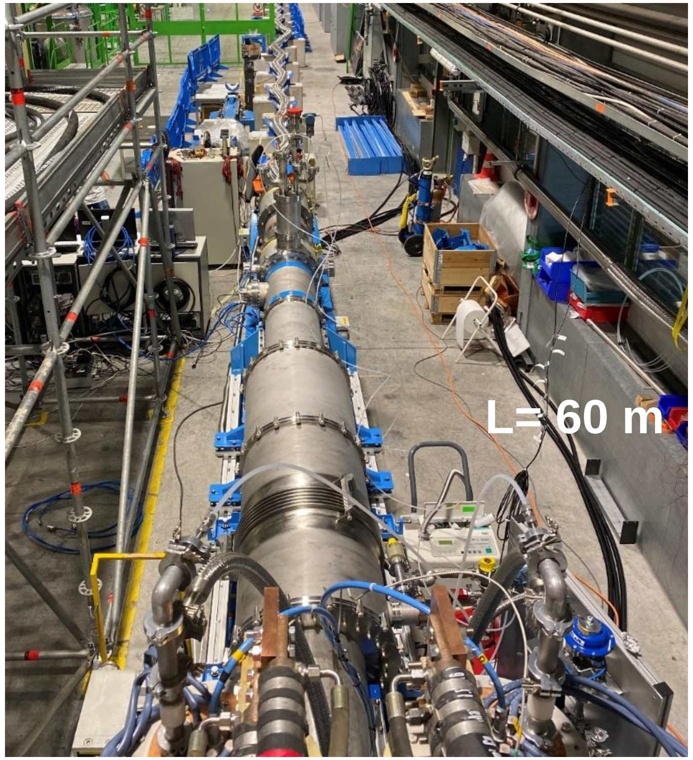
HL-LHC: Superconducting Link for HL-LHC Magnets

MgB_2 cable:
$\Phi \sim$ 90 mm
|Itot| > 100 kA @ 25 K



Φ~ 90 mm



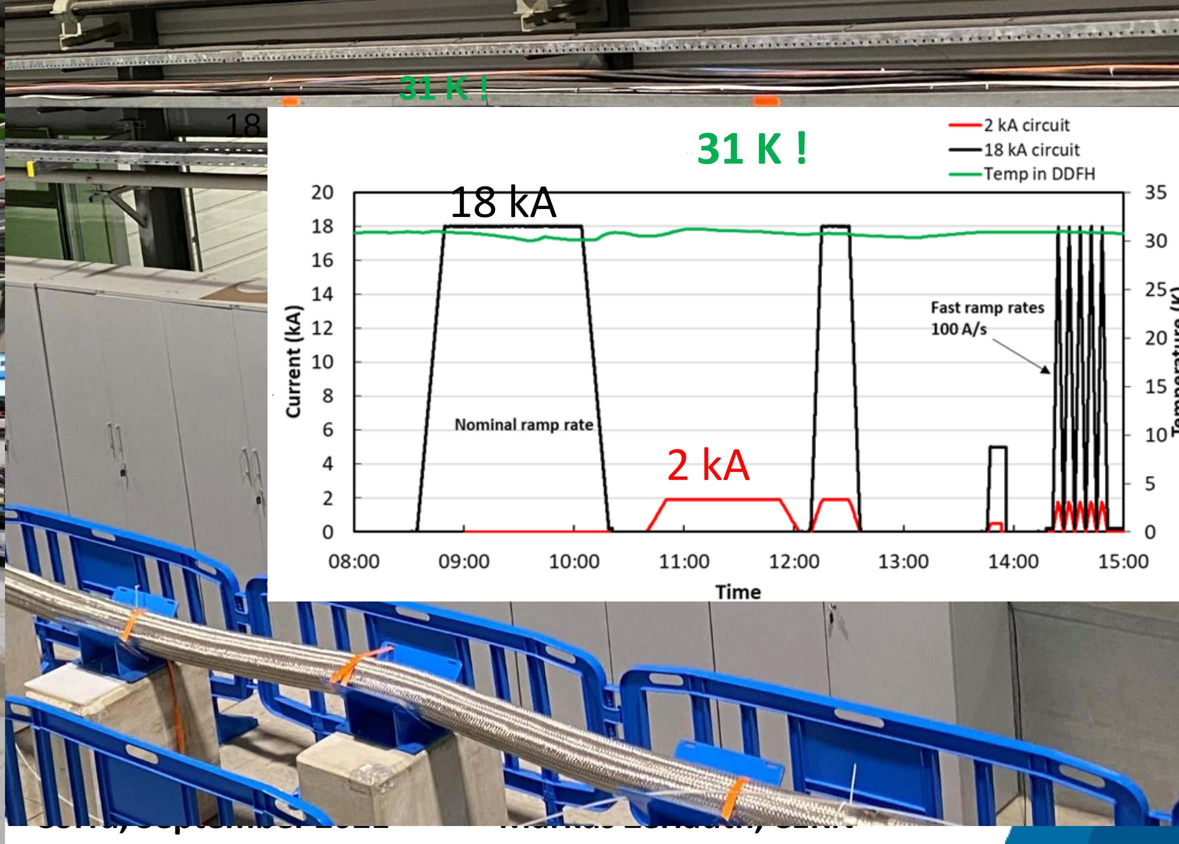


System demonstrator in SM 18
DEMO2
Demonstration of **2 x 20kA +**
2 x 7kA in June '20
in MgB_2 @ 30K
in flexible cryostat
over 60m [54kA total]

Courtesy of Amalia Ballarino

Superconducting Link: DEMO2 and DEMO3 completed!

- Successful qualification of SC Link for Triplets (Demo 2) – including EM compatibility 120 kA – Two cool-downs (June and September 2020). MgB_2 and HTS REBCO
- Assembled and successfully tested SC Link for Matching Section (Demo 3)
- Launching last large industrial procurement (long flexible cryostats for SC Links)



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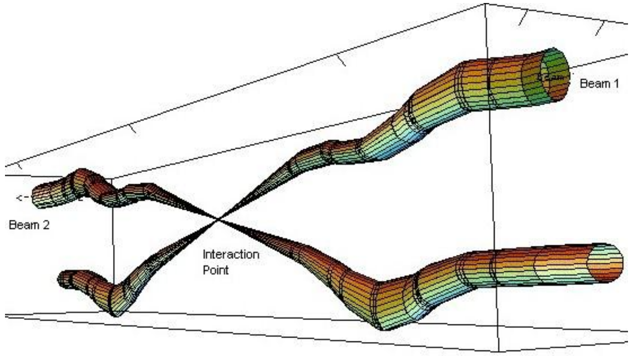
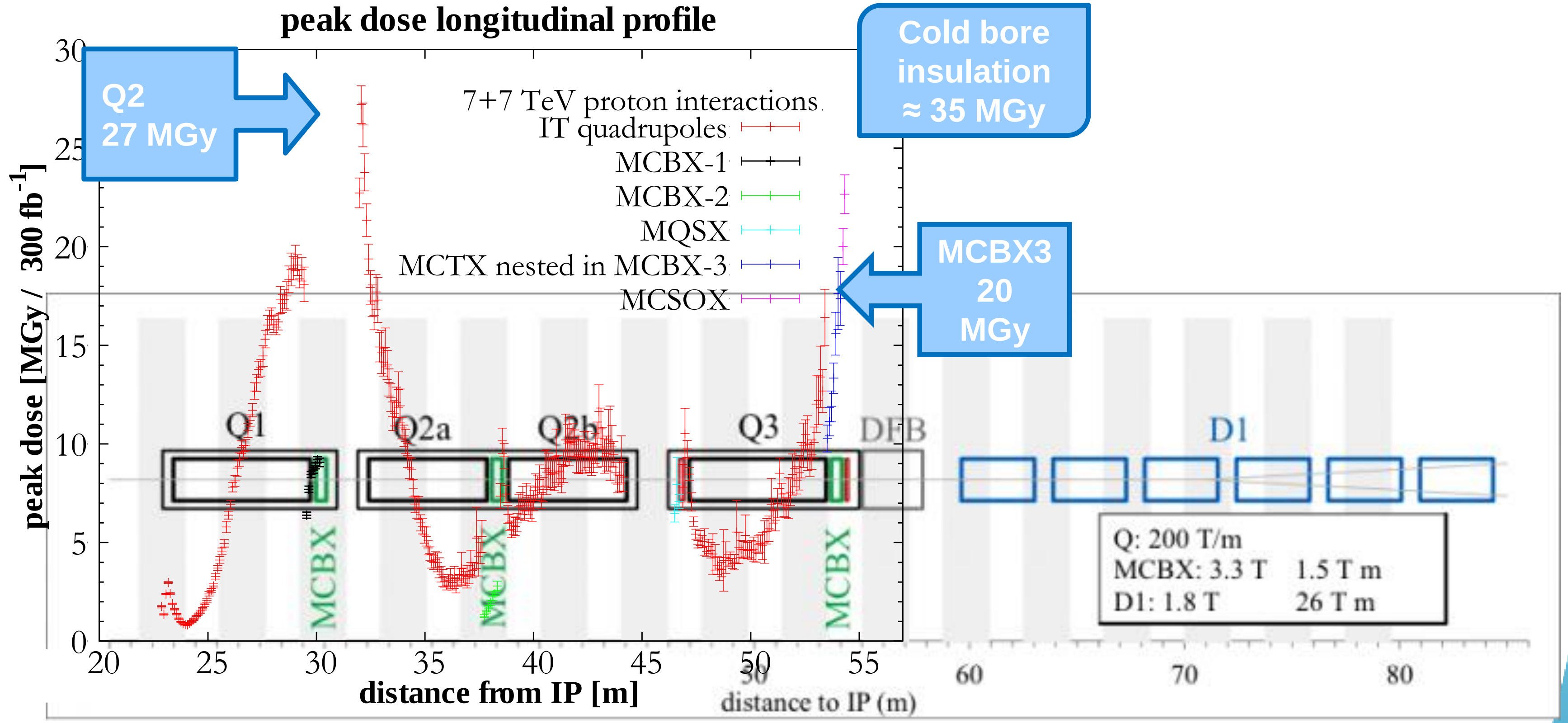
Luminosity Limitation: Debris from the IP
Radiation damage to magnets expected at 300 fb^{-1}





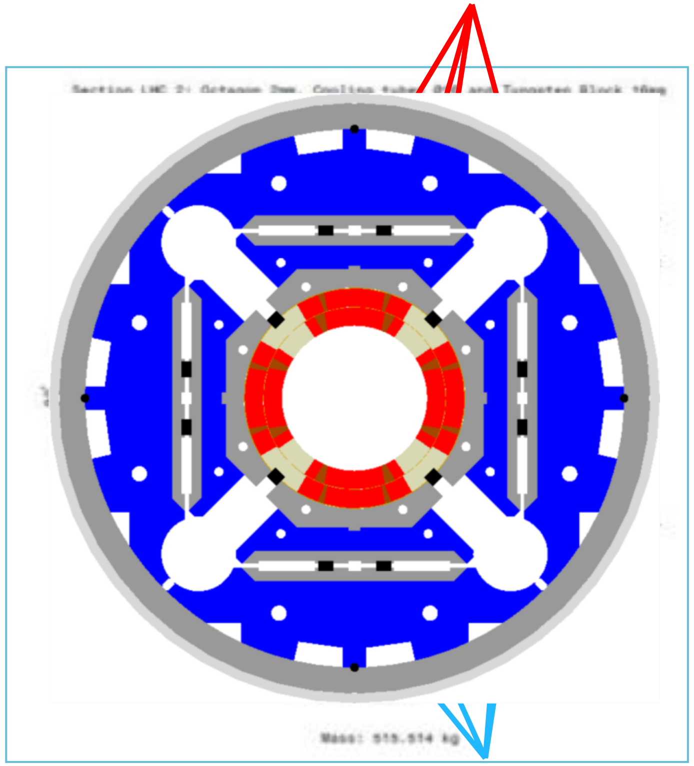
- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution and radiation concerns due to physics debris

HL-LHC technical bottleneck: Radiation damage to triplet magnets

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

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

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

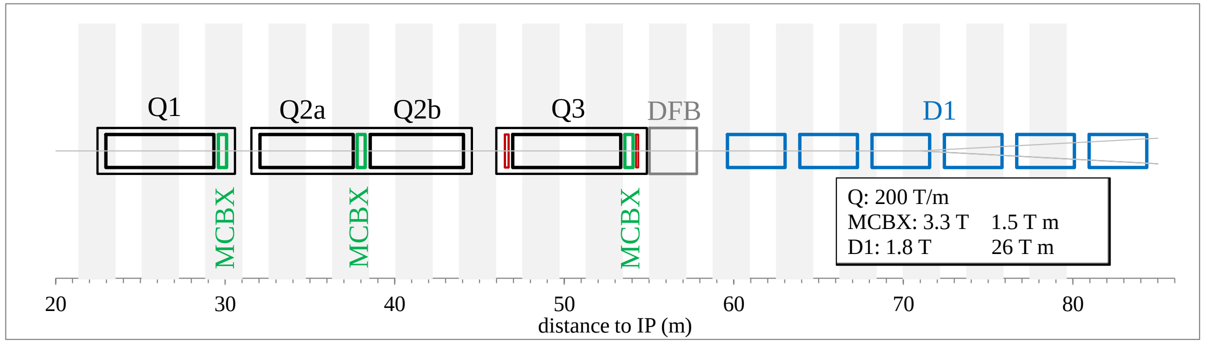


US-LARP MQXF magnet design Based on Nb_3Sn technology

New interaction region layout

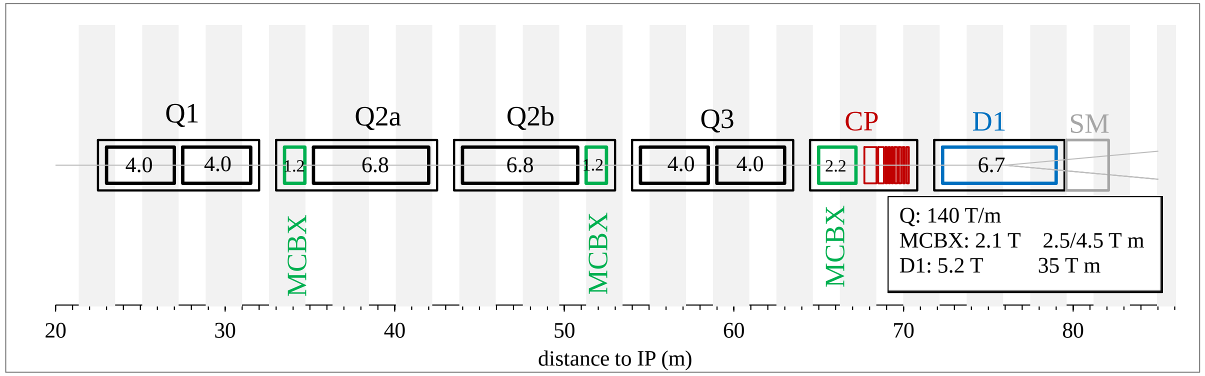
- New triplet magnets are not enough by themselves
  - Superconducting separation dipoles (D1)
  - Higher Order Corrector package (CP)
  - And beyond…

ATLAS CMS

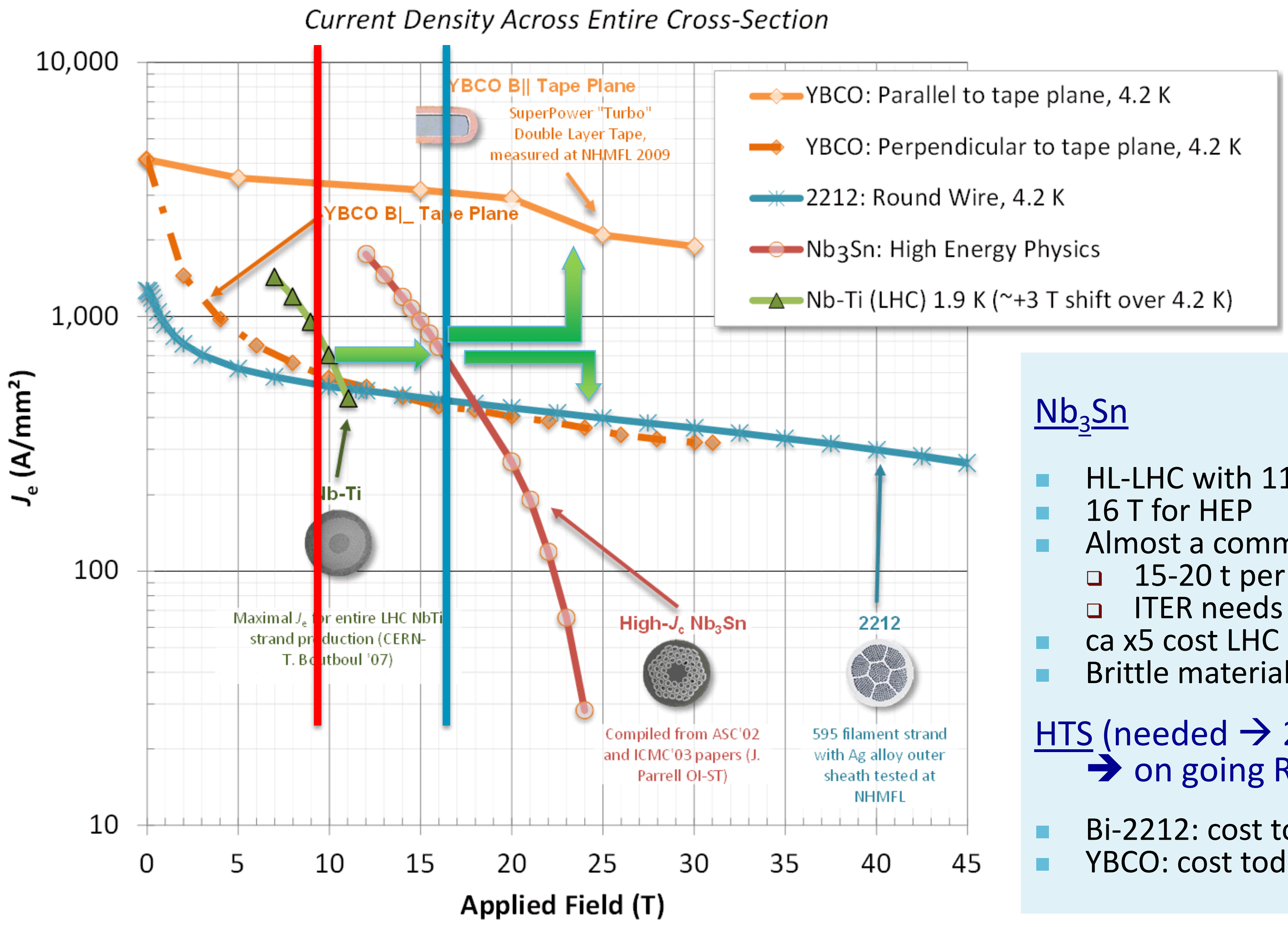


LHC

ATLAS CMS



HL-LHC



SC Magnet Technology

source: L. Rossi

Nb_3Sn

- 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

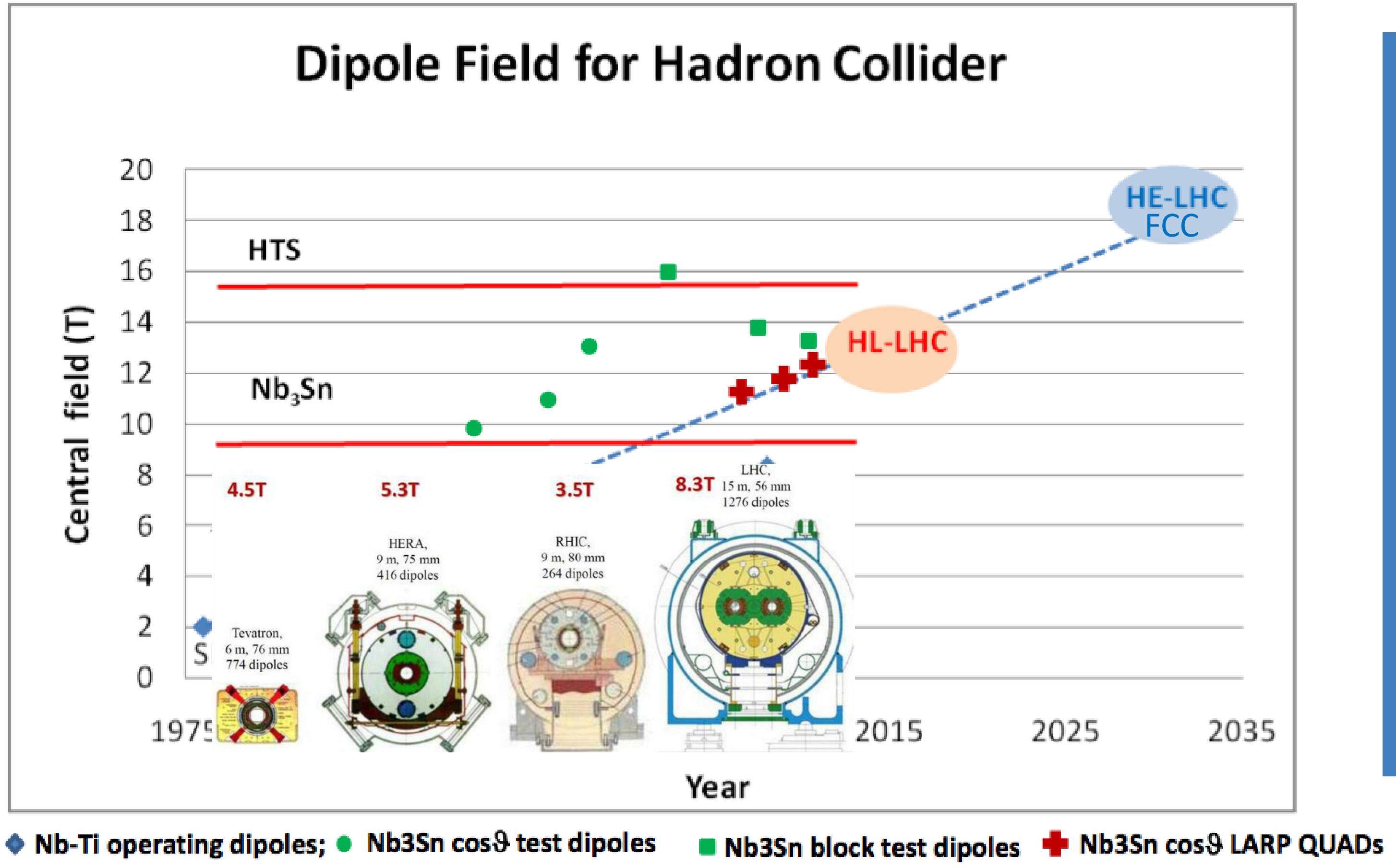
HTS (needed → 20 T)

➔ on going R&D!

- Bi-2212: cost today 2-5x Nb_3Sn
- YBCO: cost today 10x Nb_3Sn

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



Transition from NbTi to Nb_3Sn: requires similar length of R&D!

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

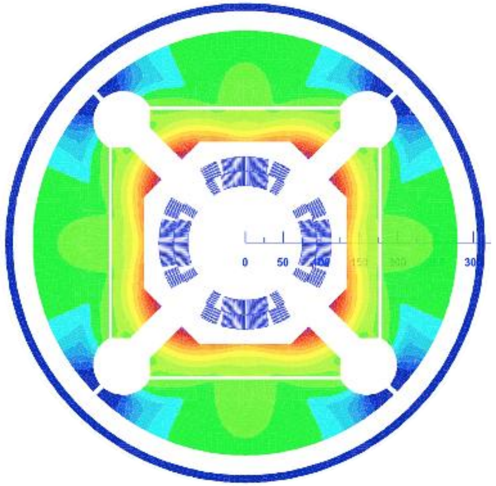
➔ Started in early 2000

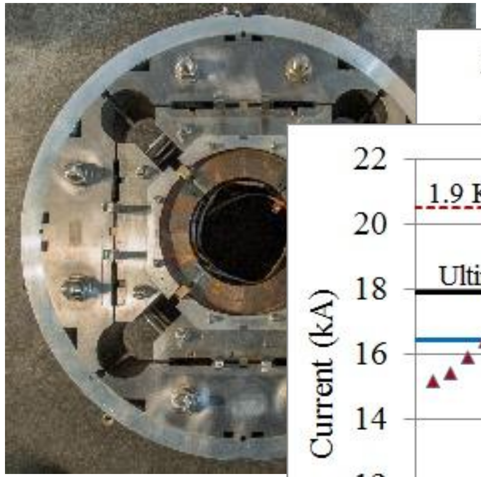
➔ 15-20 years R&D program

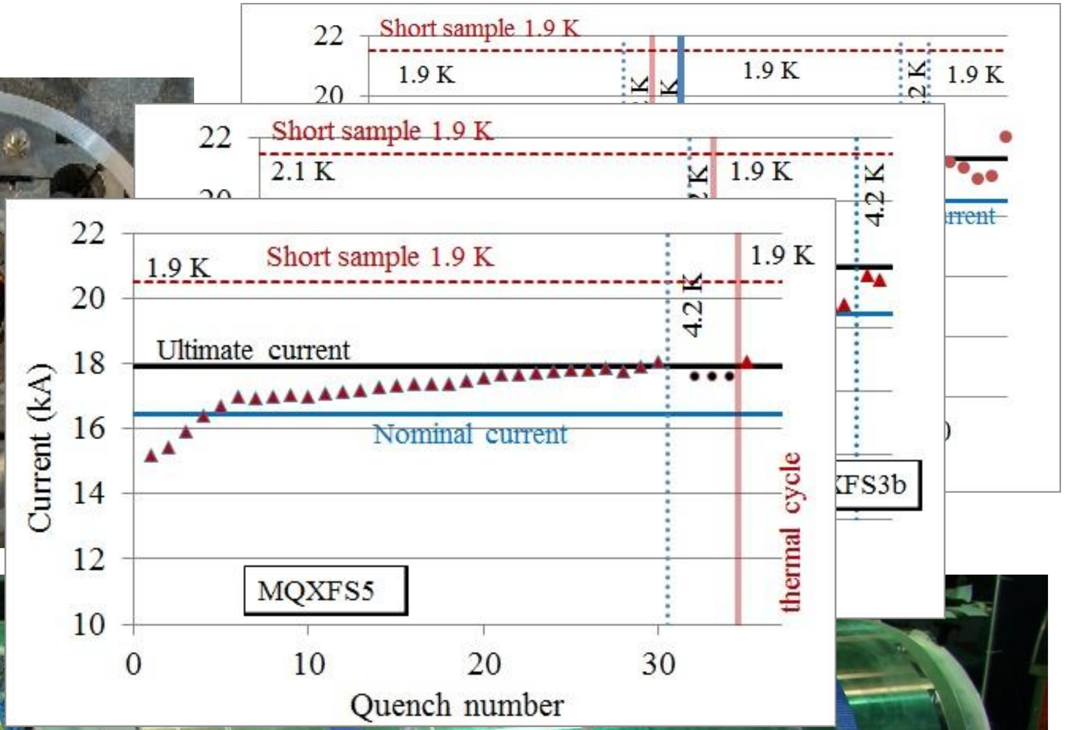
➔ Ready by 2025

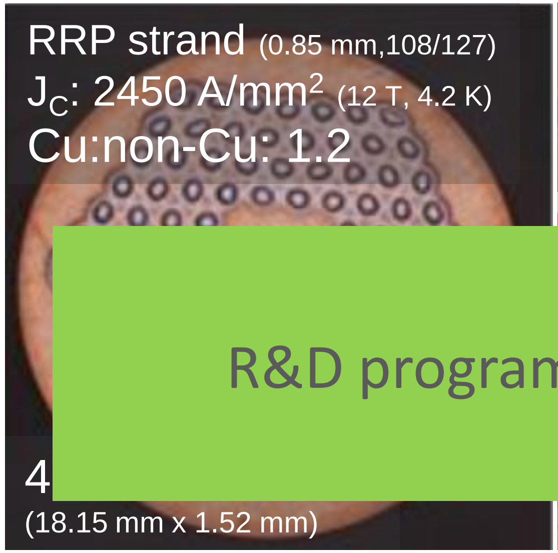
courtesy: L. Rossi (CERN)

HL-LHC quadrupole R&D









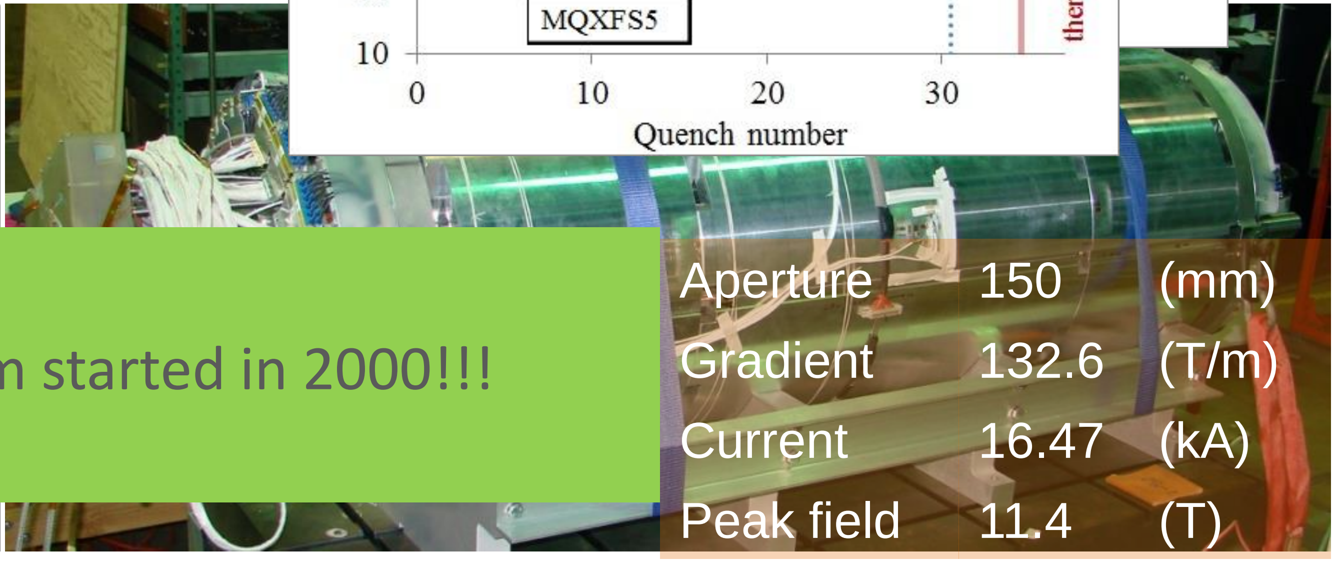
RRP strand (0.85 mm,108/127)

J_C: 2450 A/mm^2 (12 T, 4.2 K)

Cu:non-Cu: 1.2

4

(18.15 mm x 1.52 mm)



R&D program started in 2000!!!

Aperture	150	(mm)
Gradient	132.6	(T/m)
Current	16.47	(kA)
Peak field	11.4	(T)

Nb_3Sn quadrupole: Series production ongoing

Developments in 2020:

Q2: FIRST IT QUAD built and tested at CERN

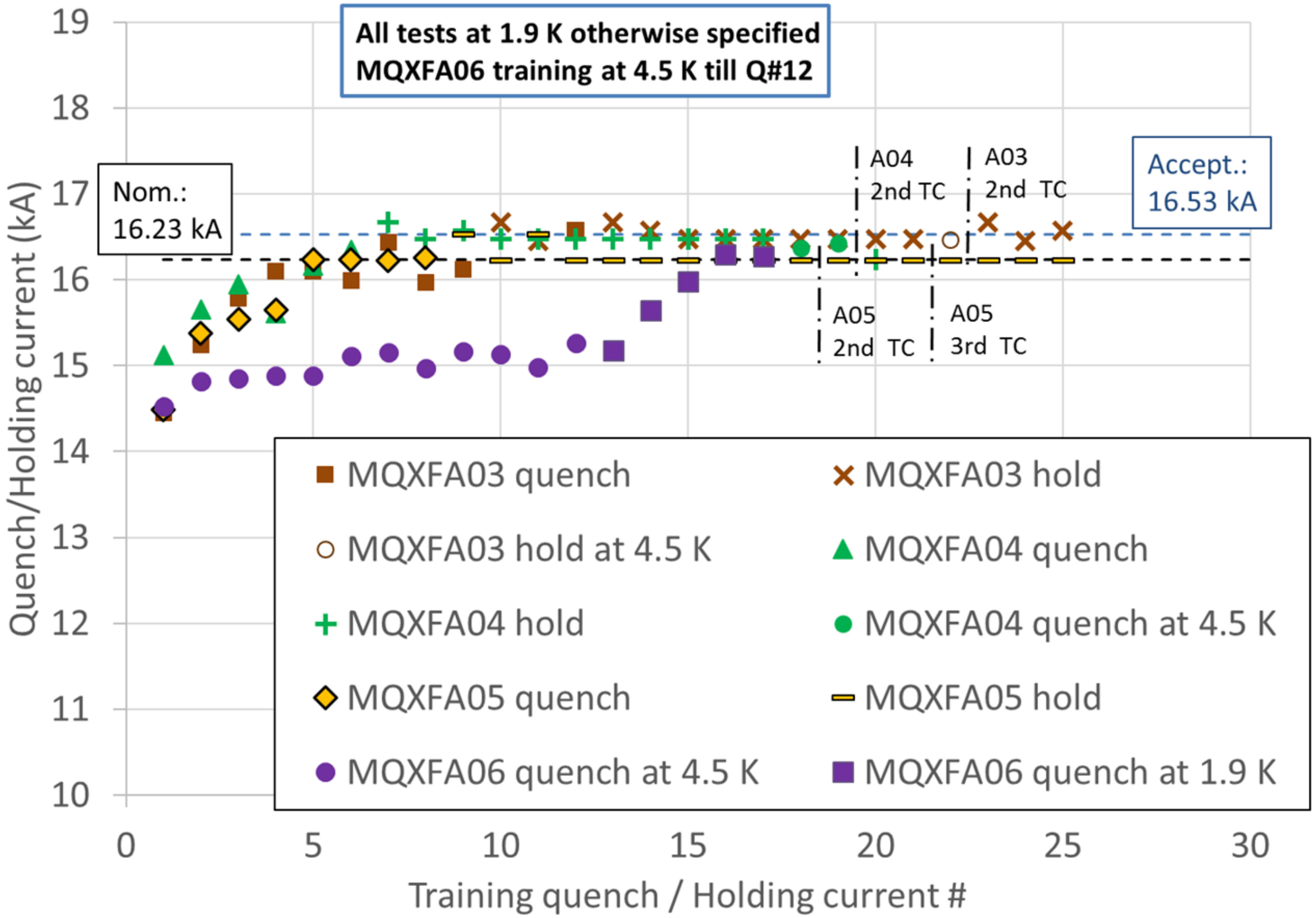
Q1/Q3: FIRST IT QUAD for HL-LHC
Successfully tested!

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

2 US [AUP] magnets passed successfully tests in 2020 and received CD3 approval from DOE in 2020, ever since 2 additional magnets validated

First CERN prototypes tested in 2020 and 2021, first series magnet finished and to be cold tested towards early 2022

Nb_3Sn quadrupole: 4th series magnet successfully tested at AUP



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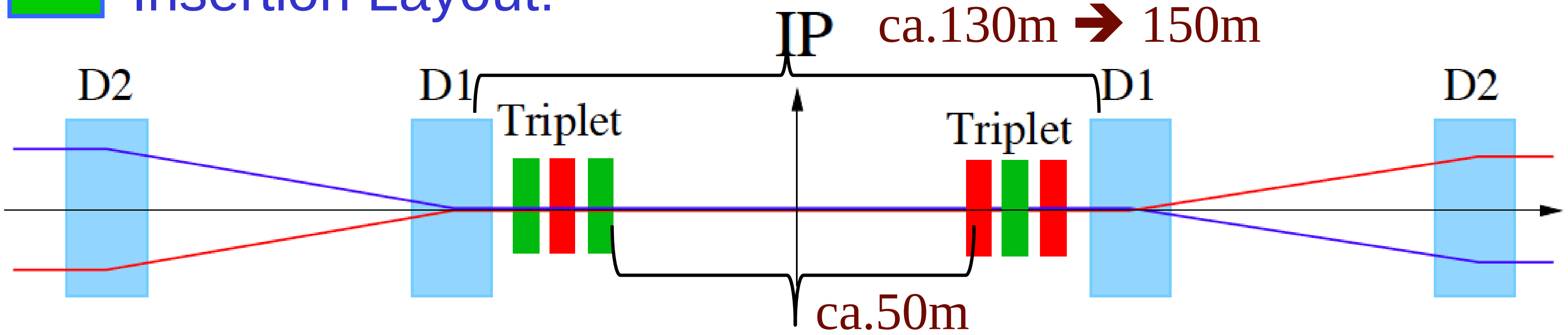
HL-LHC Challenges: Crossing Angle I

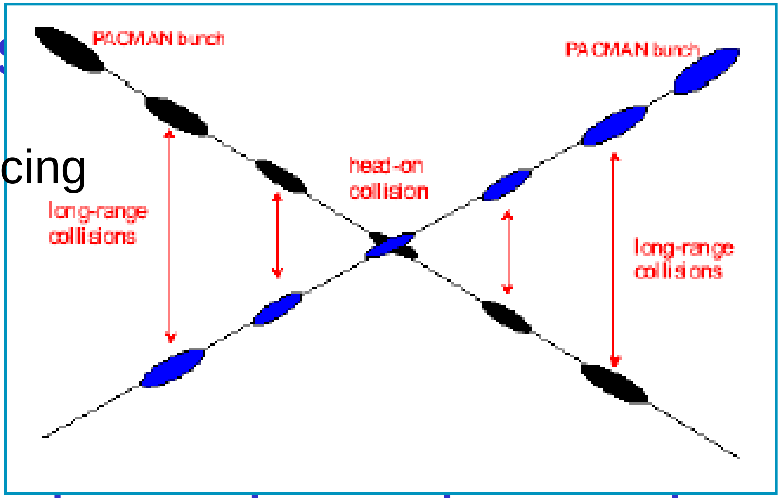
Insertion Layout:



Maximize the number of Protons

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

➔ Operation requires crossing angle



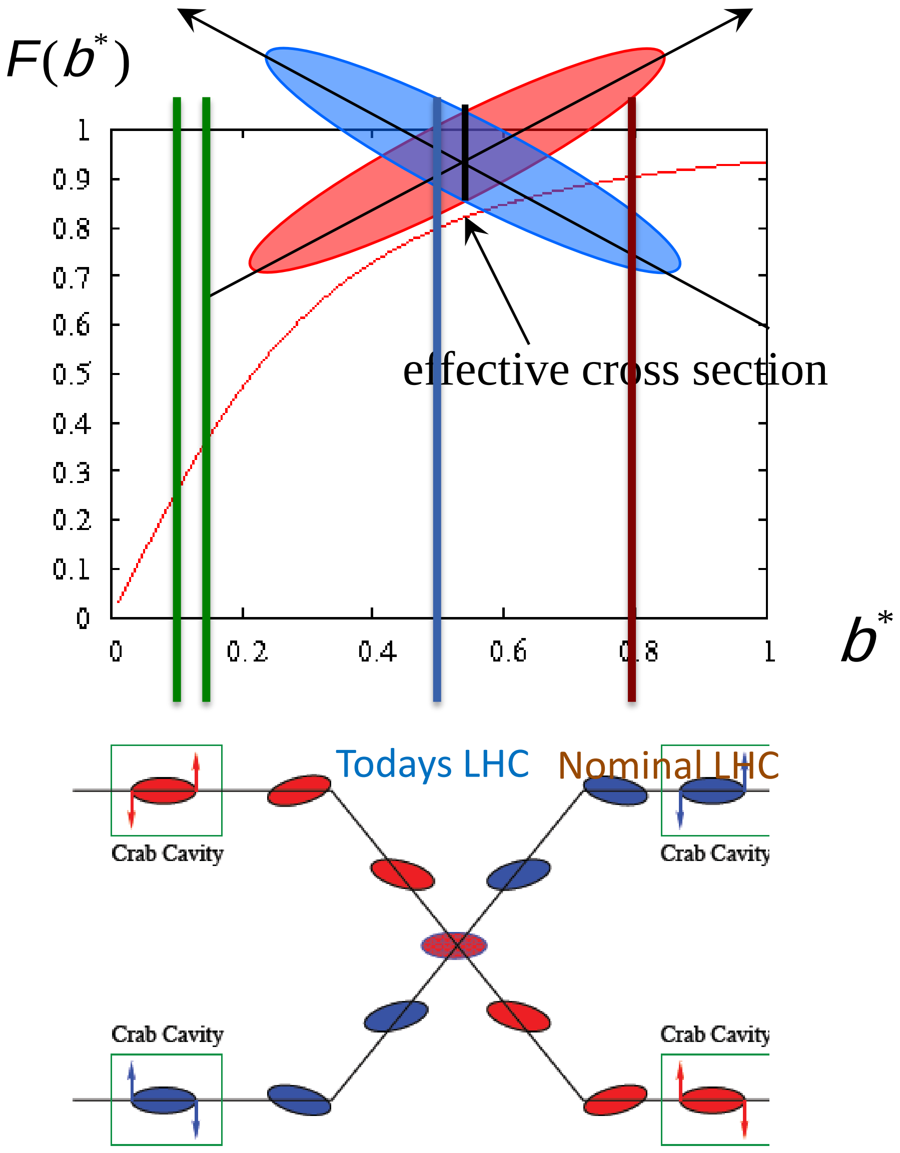
non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points ➔ Separation of 10 -12 σ ➔ large crossing angle at Interaction Point!

HL-LHC Upgrade Ingredients: Crab Cavities

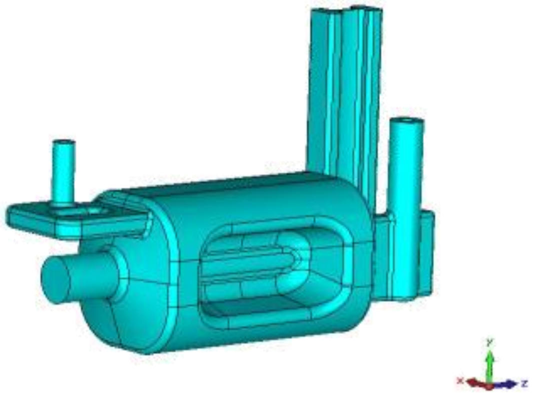
- Attempt to claw back the very significant reduction in luminosity from the large crossing angle
- Create an oscillating transverse electric field that kicks head and tail of the bunches in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP
- Challenging space constraints:

  ➔ requires novel compact cavity design



Crab cavity development

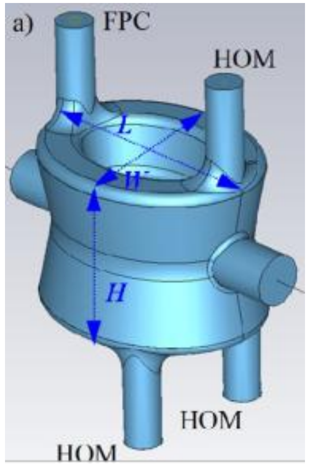
Major R&D program
Concentrating on two designs for test installation and beam validation in SPS

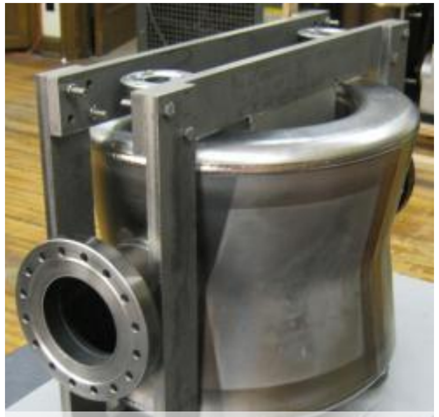


RF Dipole: waveguide or waveguide-coax couplers

RF-Dipole Nb prototype [ODU-SLAC]

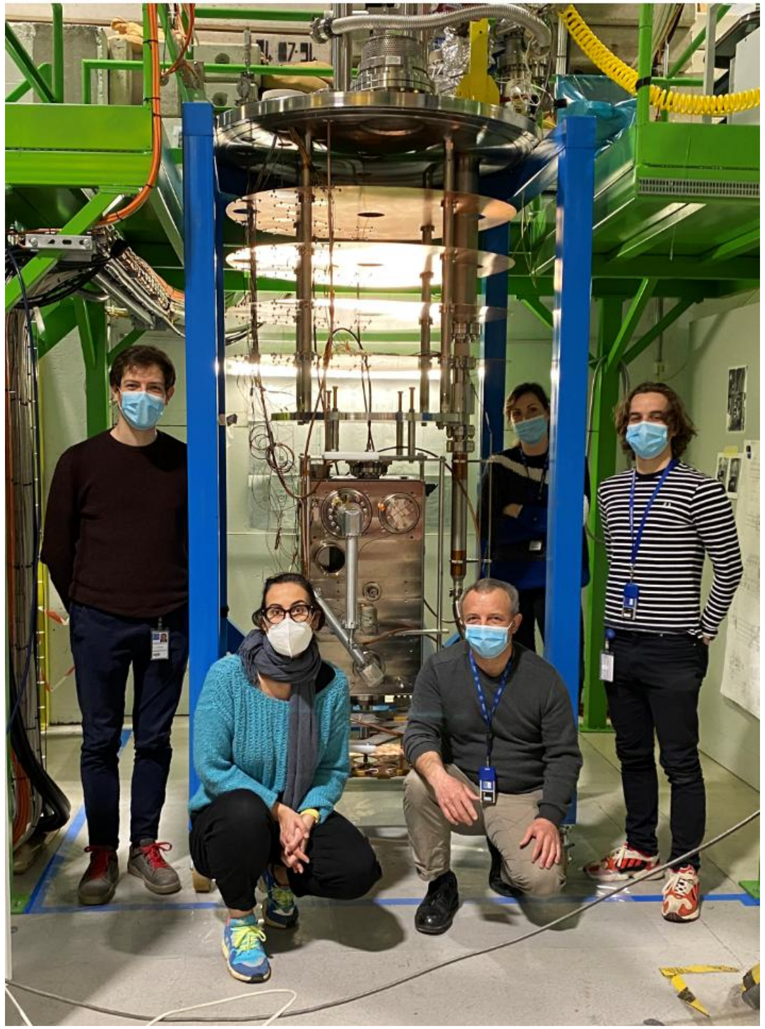
Double ¼-wave (DQW): coaxial couplers with hook-type antenna

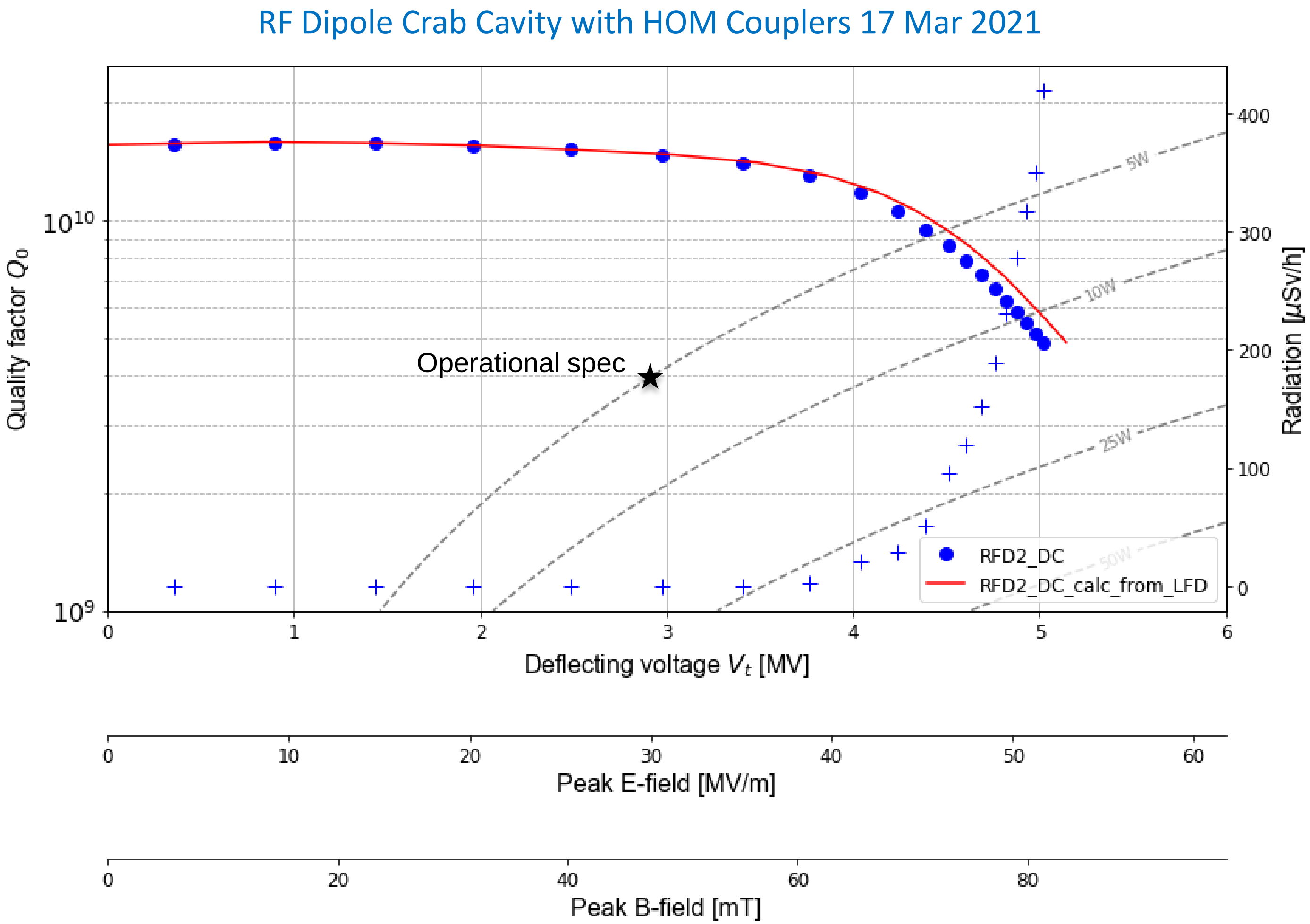




DQWR prototype (17-Jan-2013) [BNL]

RFD 2 Dressed Cavity with HOMs





Crab cavity cryo-module for installation in the SPS

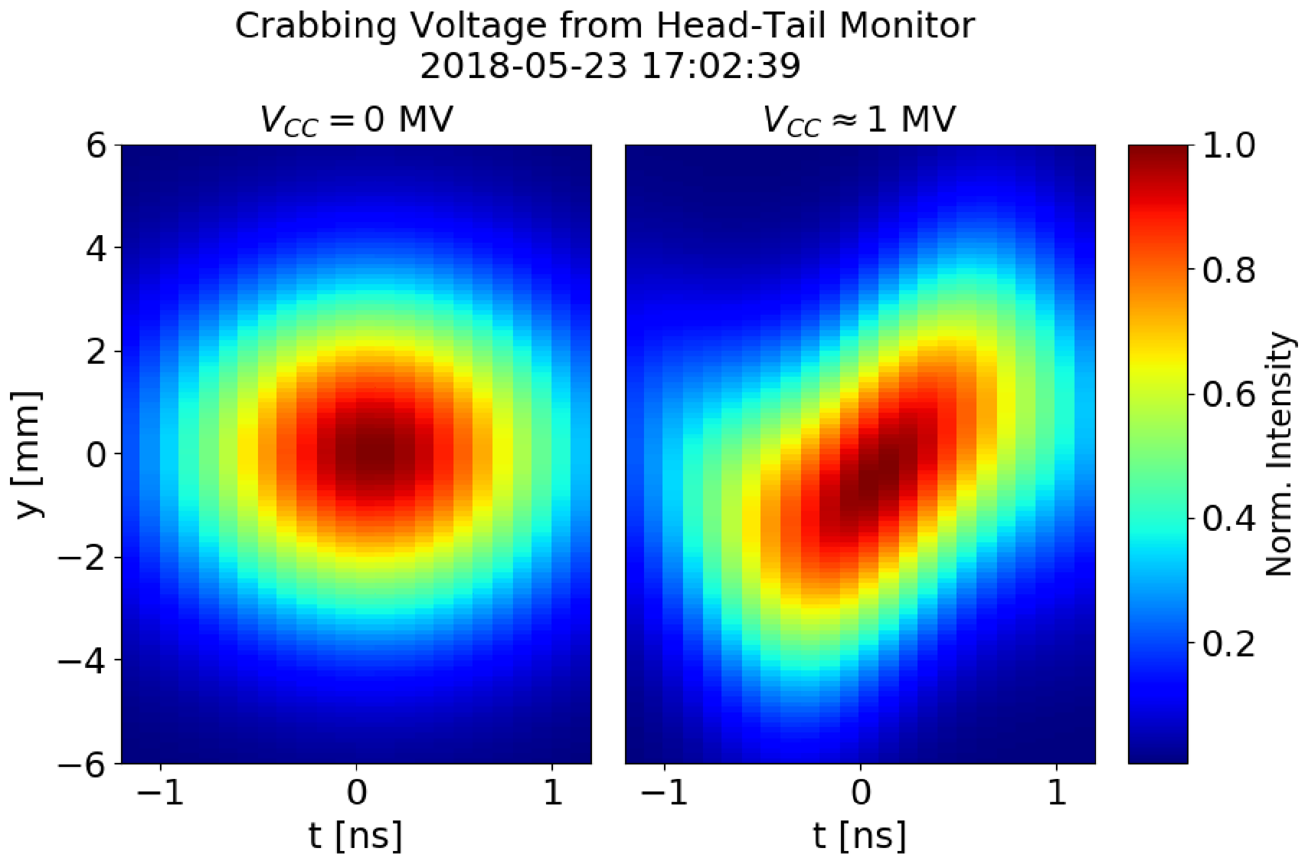
Compact Crab Cavity: SPS Installation

SRF test infrastructure operated with beam at end of Run 2 (2018) and planned to continue with DQW during Run 3 (as of 2022)

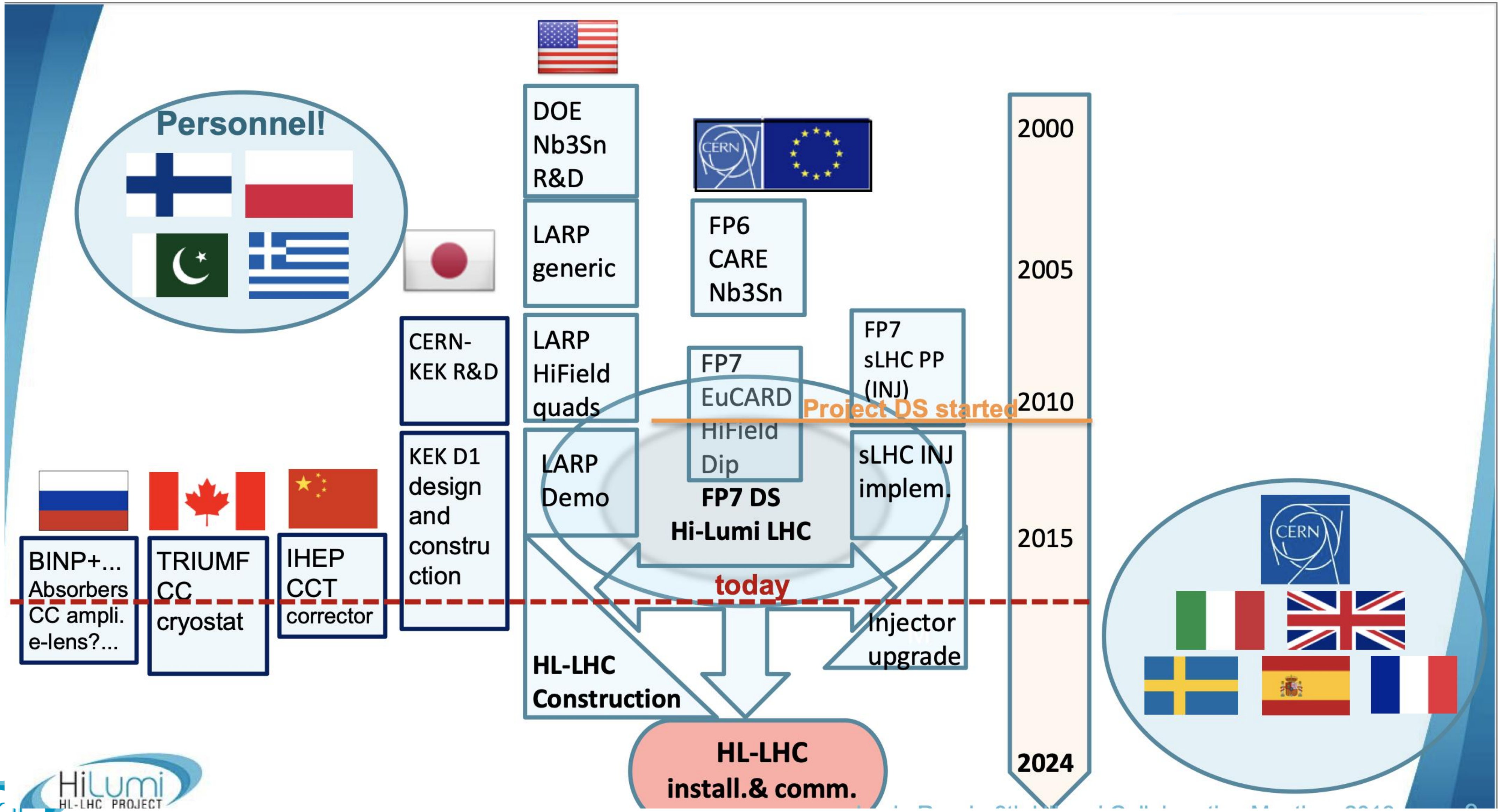
First proton crabbing ever!

Several Machine Development periods in SPS performed throughout 2018

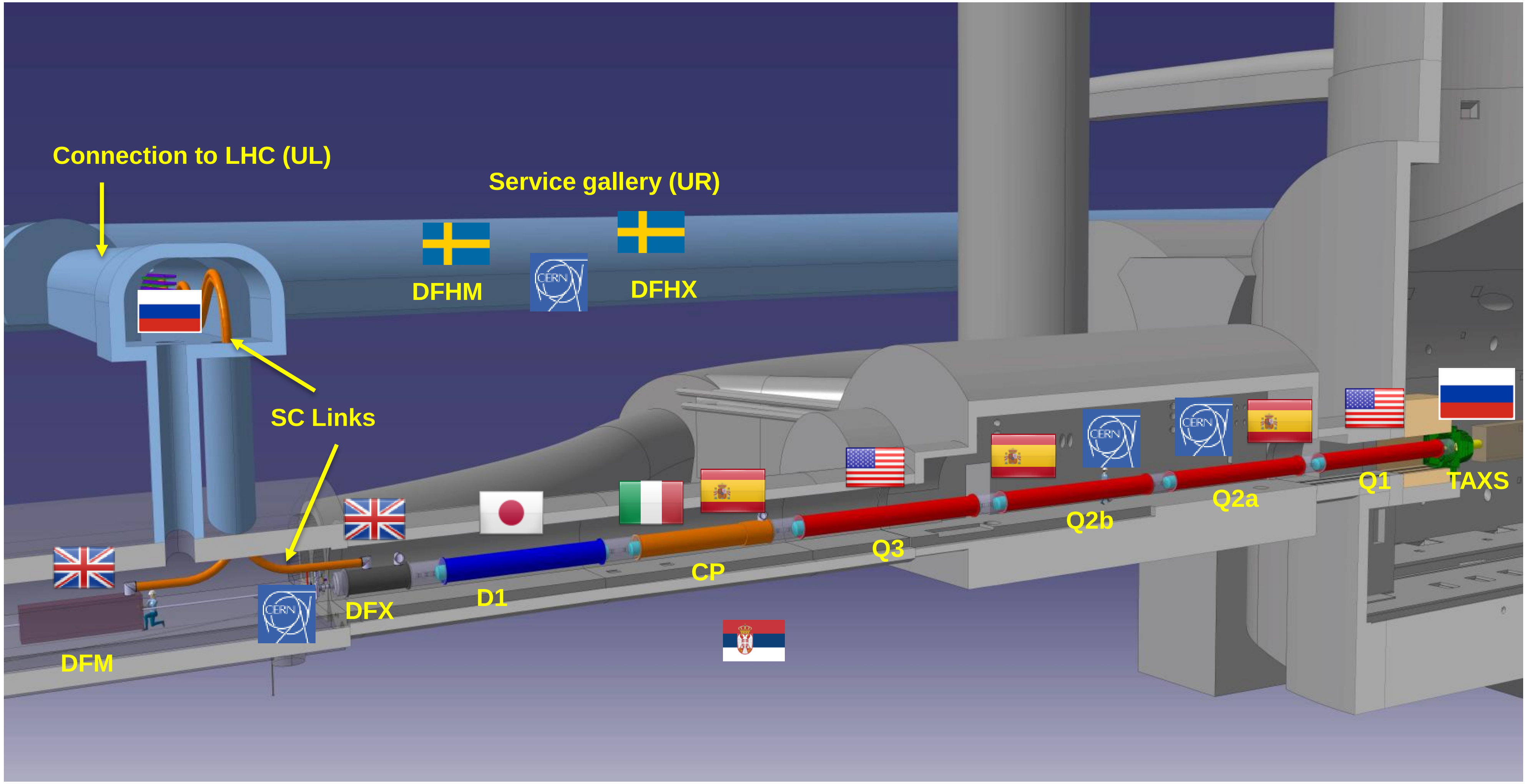
Intensive studies and R&D
have been instrumental to obtain this result



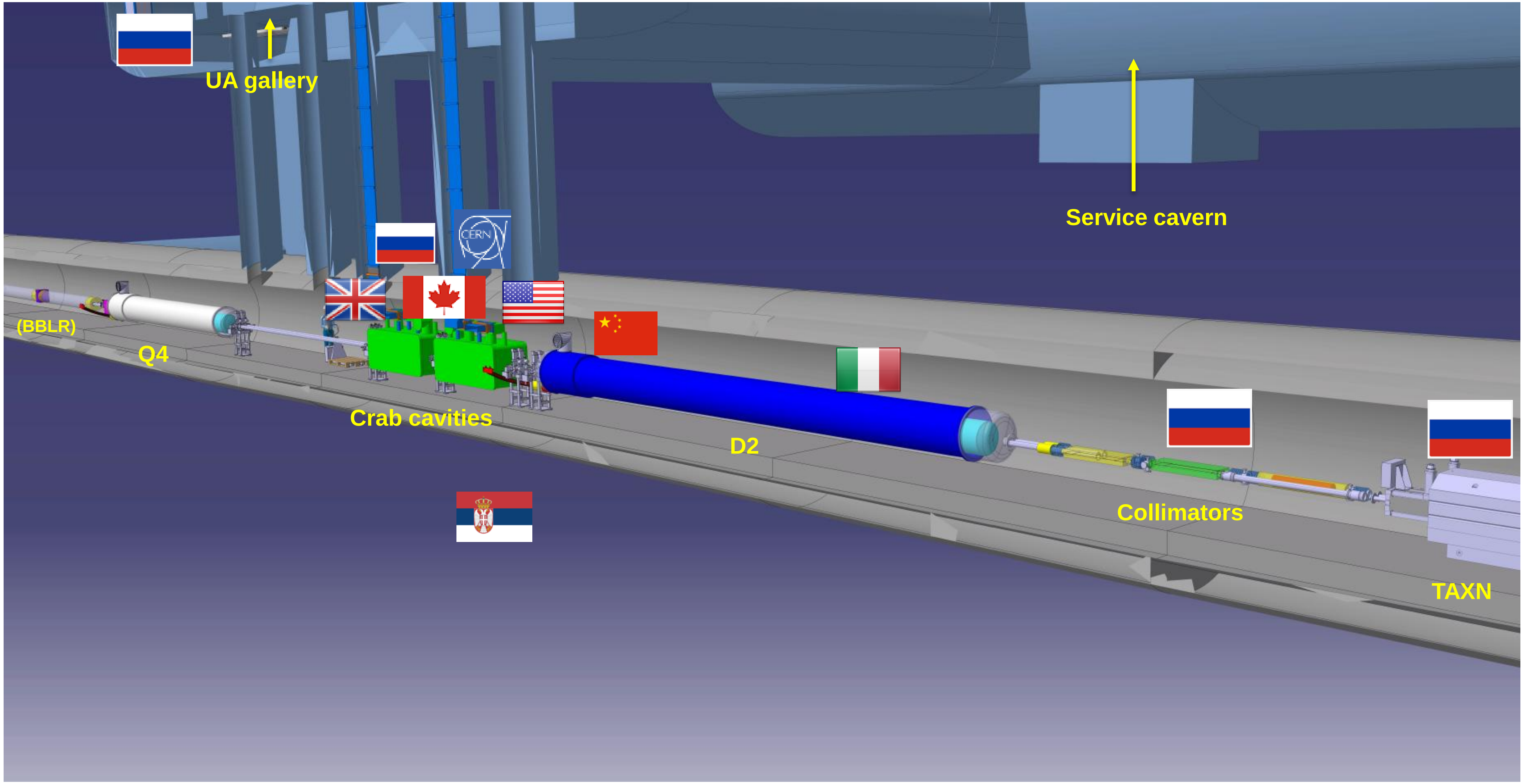
HL-LHC is a world-wide collaboration!



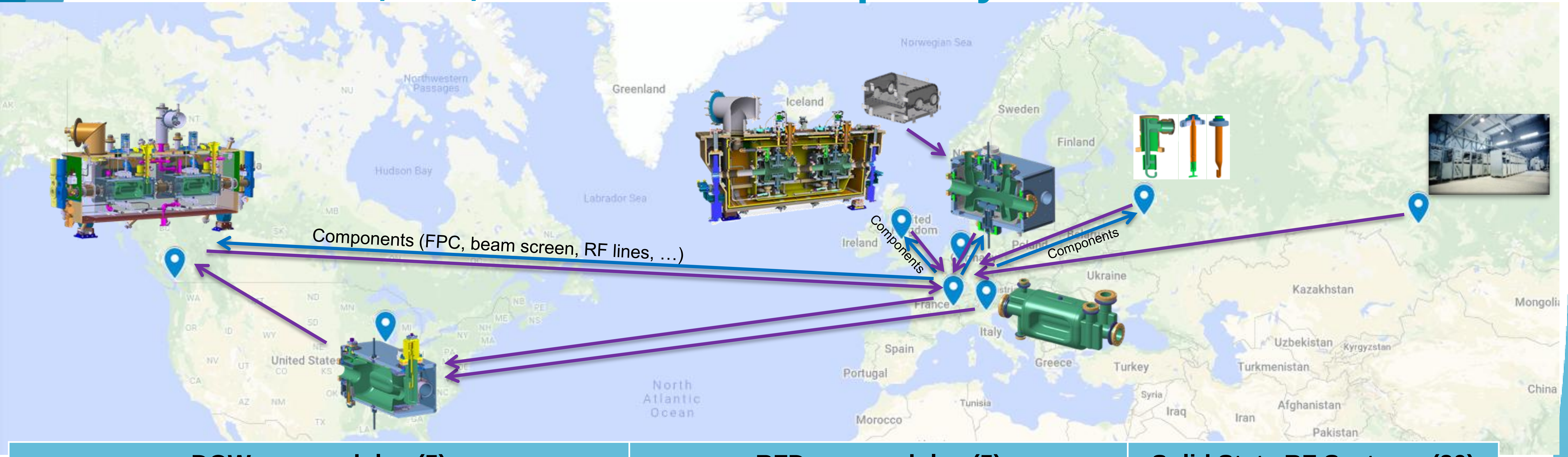
Truly International Collaboration offering exiting opportunities!



Truly International Collaboration offering exiting opportunities!



… and challenges…Crab Cavity Series: CERN, Canada, Russia, UK, US-AUP the complexity of in-kind chain

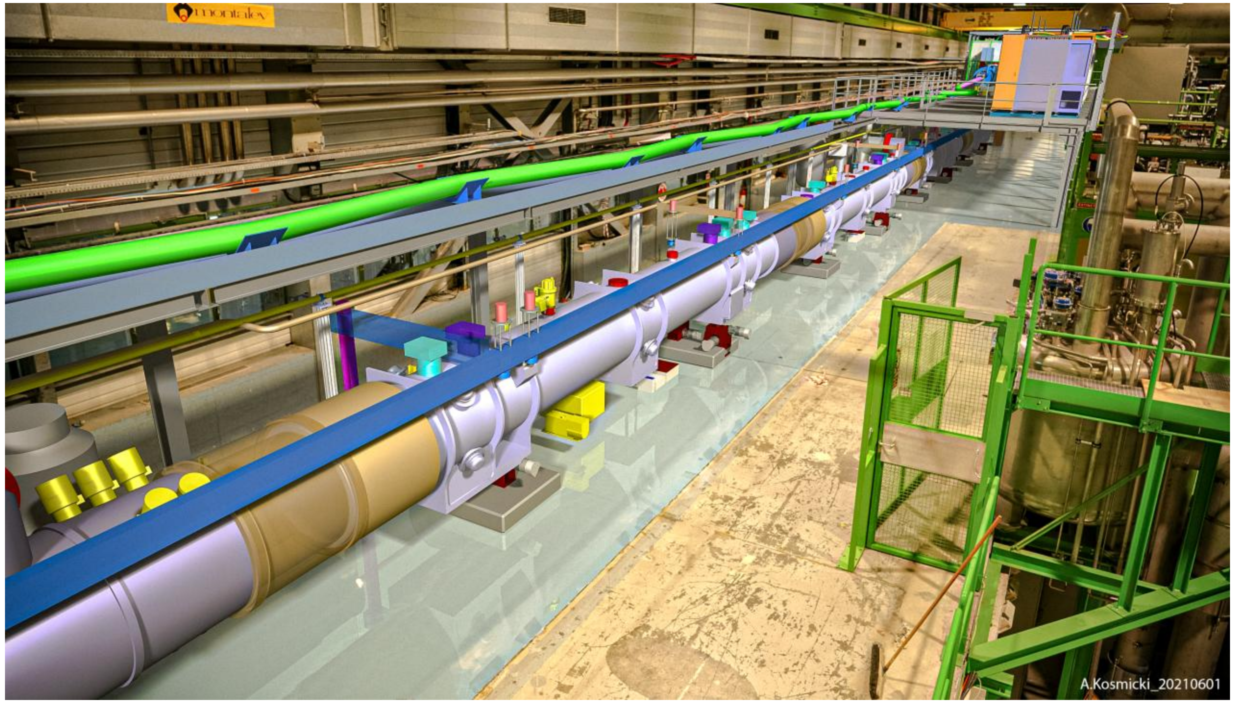


DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
• Cavities + processing + helium vessels by Research Instruments (**DE**) under **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **MEPHI-Russia & CERN** • 4 CM by **UK** (STFC) & 1 CM at CERN with some components by **CERN** • All cavities & CM cold validation tests at **CERN** (and a few at Uppsala-Sweden)	• Bare cavities by Zanon (**IT**) under **US-AUP** • Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by **US-AUP** • 5 CM by **TRIUMF-Canada** with some components by **CERN** • CM cold validation tests at **CERN**	• High power solid state amplifiers by **BINP-Russia** • First step, one amplifier prototype for qualification of SSPA technology

Next major milestone: IT String Installation in SM18

Important milestone for demonstrating before LS3:

- Overall interface compatibility
- Vacuum and cryogenic functionality
- Electrical system performance
- Magnet protection system and CLIQ
- Final validation of the cold powering system
- Power Converter integration
- Validation of installation and commissioning procedures etc…



Commissioning planned to start in 2023

After November 2019 retreat: CERN has decided, upon request of LHC Experiments Collaborations, to shift LS3 by 1 year, starting in 2025.

eYETS

13.6 TeV

HWC in full swing, beam test in October

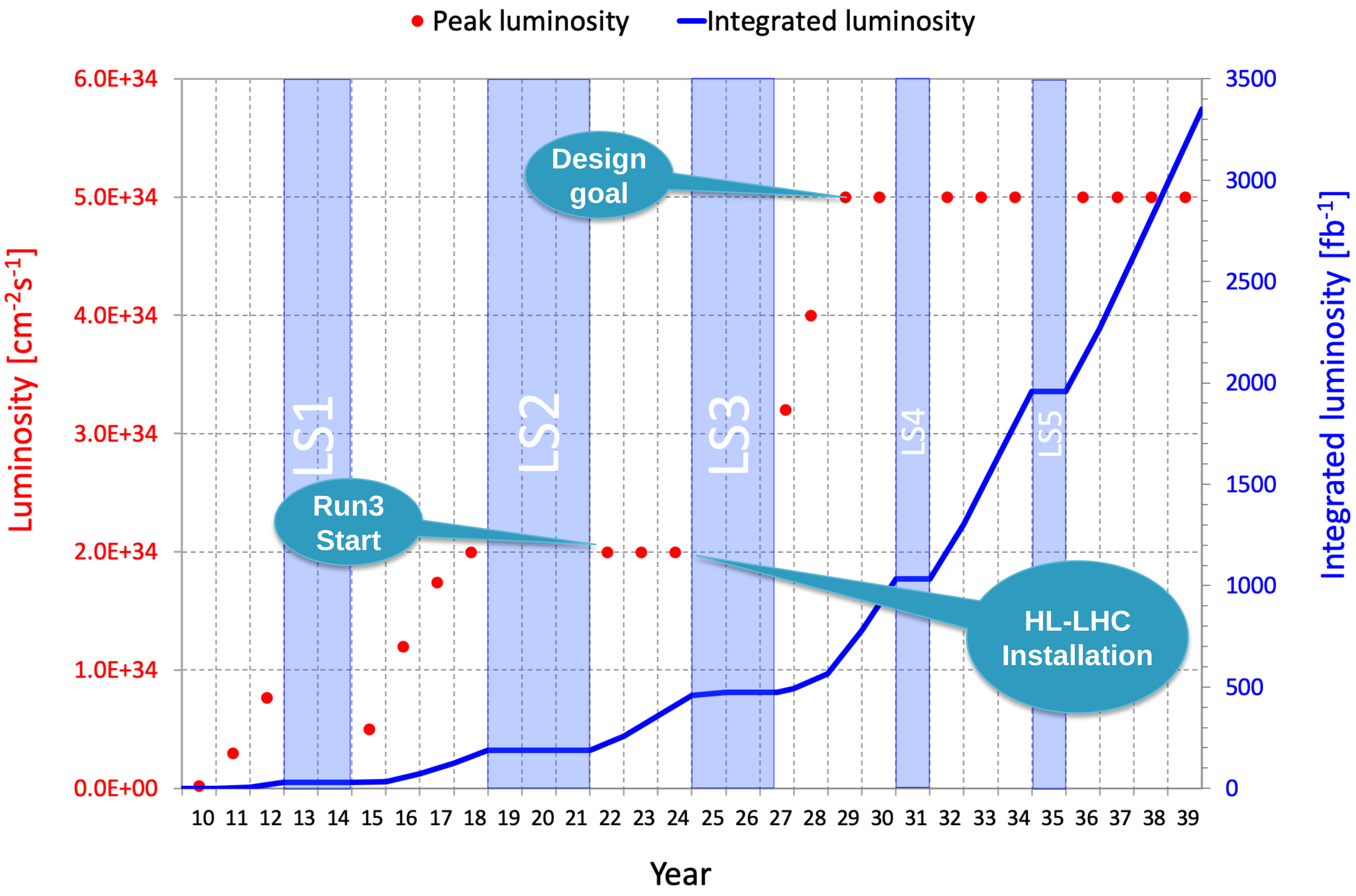
LS2 extended by 2 months; LS3 starts now in 2025
Meeting in June 2021 confirmed start of Run3 in Feb 2022 and need for eYETS 2023-24
However, HL-LHC keeps the construction schedule unchanged to keep the momentum!

HiLumi HL-LHC PROJECT

HL-LHC performance ramp-up after LS3

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]	HEL & crab cav.	$\overline{\rho}^{\dagger}$ $[\text{mm}^{-1}]$	Max. PU
2027	1.7	3.9	30	380	58	30	off	0.69	104
2028	1.7	3.9	120	380	58	30	off	0.69	104
2029	2.2	10.3	140	500	100	25	on	0.76	132
2030	2.2	13.5	160	500	100	20	on	0.78	132
2032	2.2	13.5	170	500	100	20	on	0.78	132
2033	2.2	16.9	200	500	100	15	on	0.80	132
2033	2.2	16.9	200	500	100	15	on	1.20	200

Expected HL-LHC performance

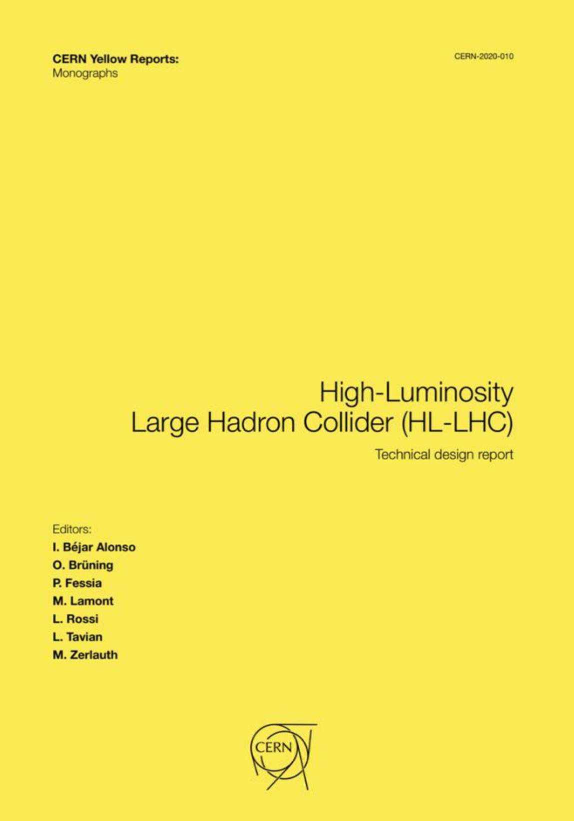


TDR V1.0 - The last version of the TDR including the added scope - 2020

V0.1 Published in electronic version for the October 2016 Cost & Schedule review

EDMS: 1723851

and as CERN Yellow Book in October 2017



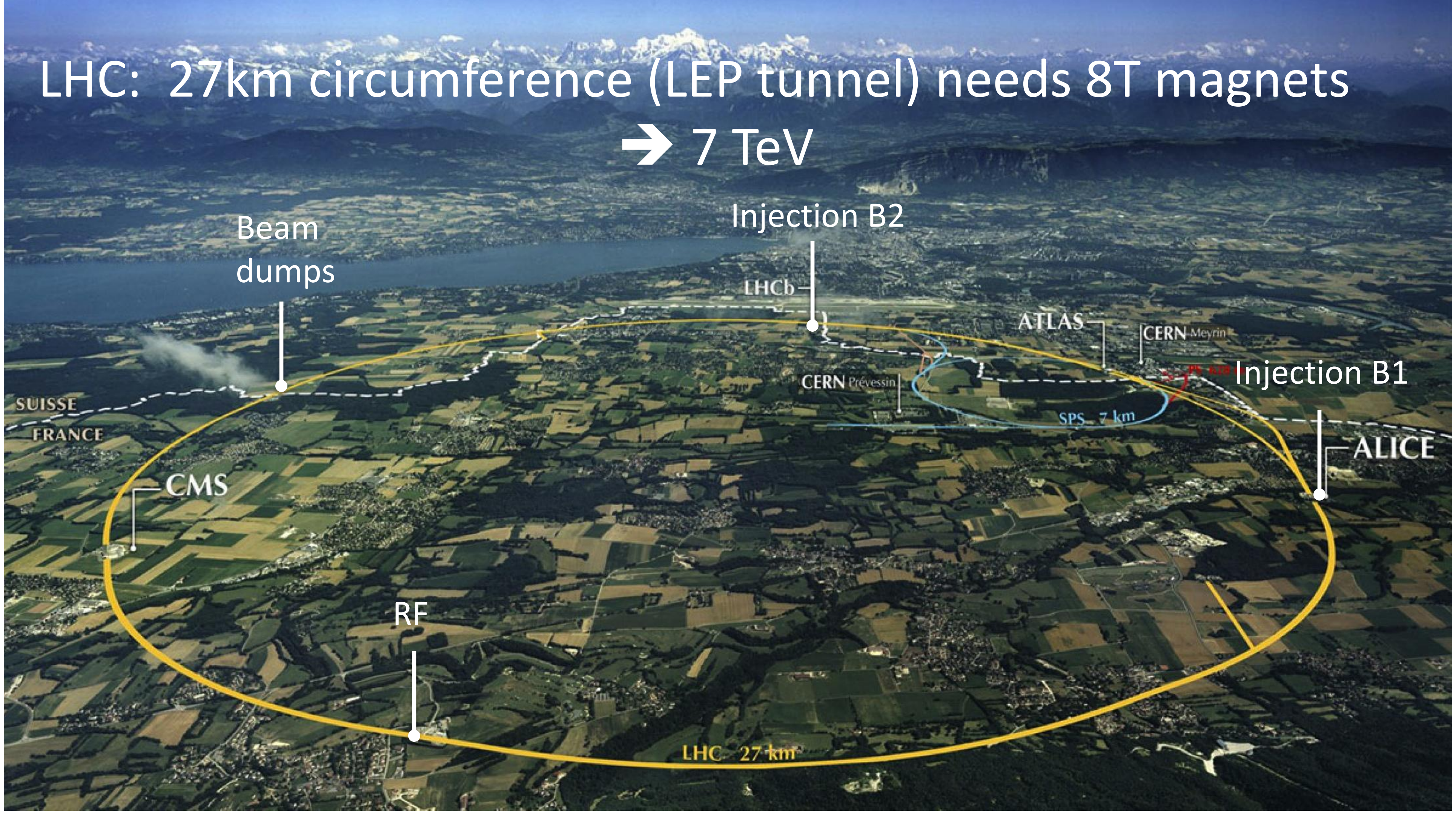
Updated Version V 1.0 published as

CERN Yellow Book in December 2020

https://e-publishing.cern.ch/index.php/CYRM/issue/view/127

Thank you for your attention!
Question?

LHC: 27km circumference (LEP tunnel) needs 8T magnets → 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 > 500 MJ for HL-LHC!
830 MJ magnetic energy per sector at 6.5 TeV
→ ≈ 10 GJ total @ 7 TeV

LHC (Large Hadron Collider)

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

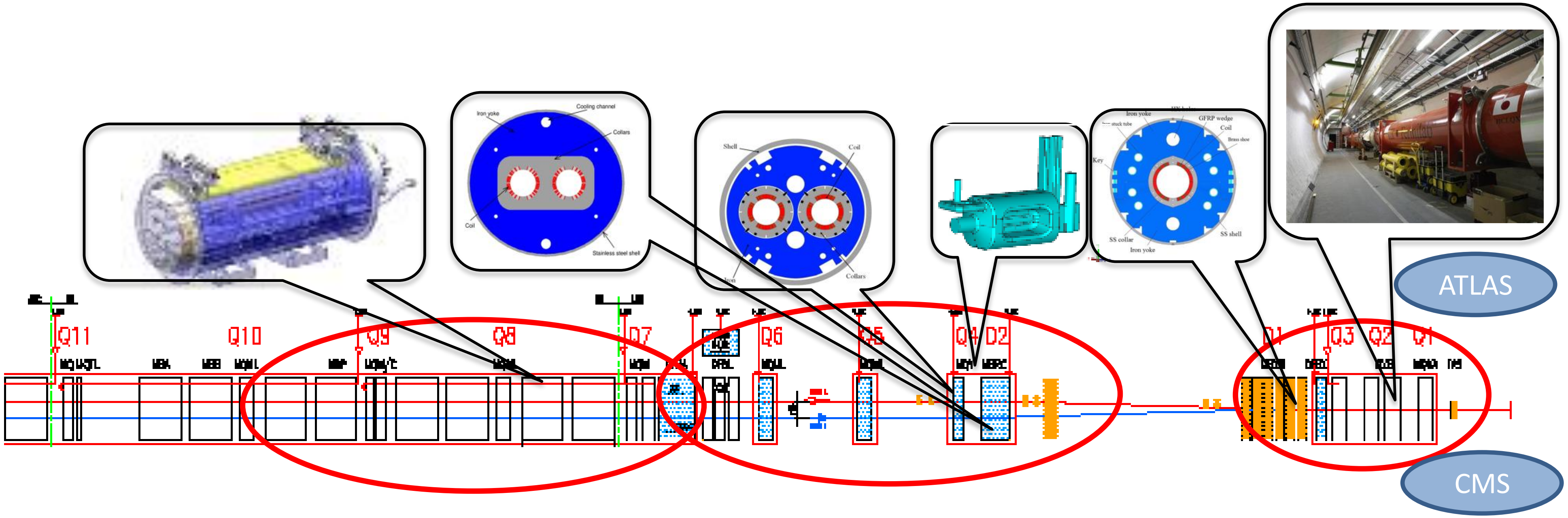
Lead-Lead (Lead-proton) collisions

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

2010-2025 : Physics exploitation

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

Major changes for insertion regions



3. Collision of off-momentum particles lost in the DS of 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

→ More than 1.2 km of LHC will be completely exchanged
→ Plus technical infrastructure (e.g. Cryo and Powering)…

Luminosity optimization:

Luminosity limitations: [for Hadron Collider]
- -Event rate and pileup
- -Debris from the IP [quench protection]
- -Heat load and radiation in magnets

Luminosity Levelling at the luminosity frontier:

Worry about beam losses!!!!

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

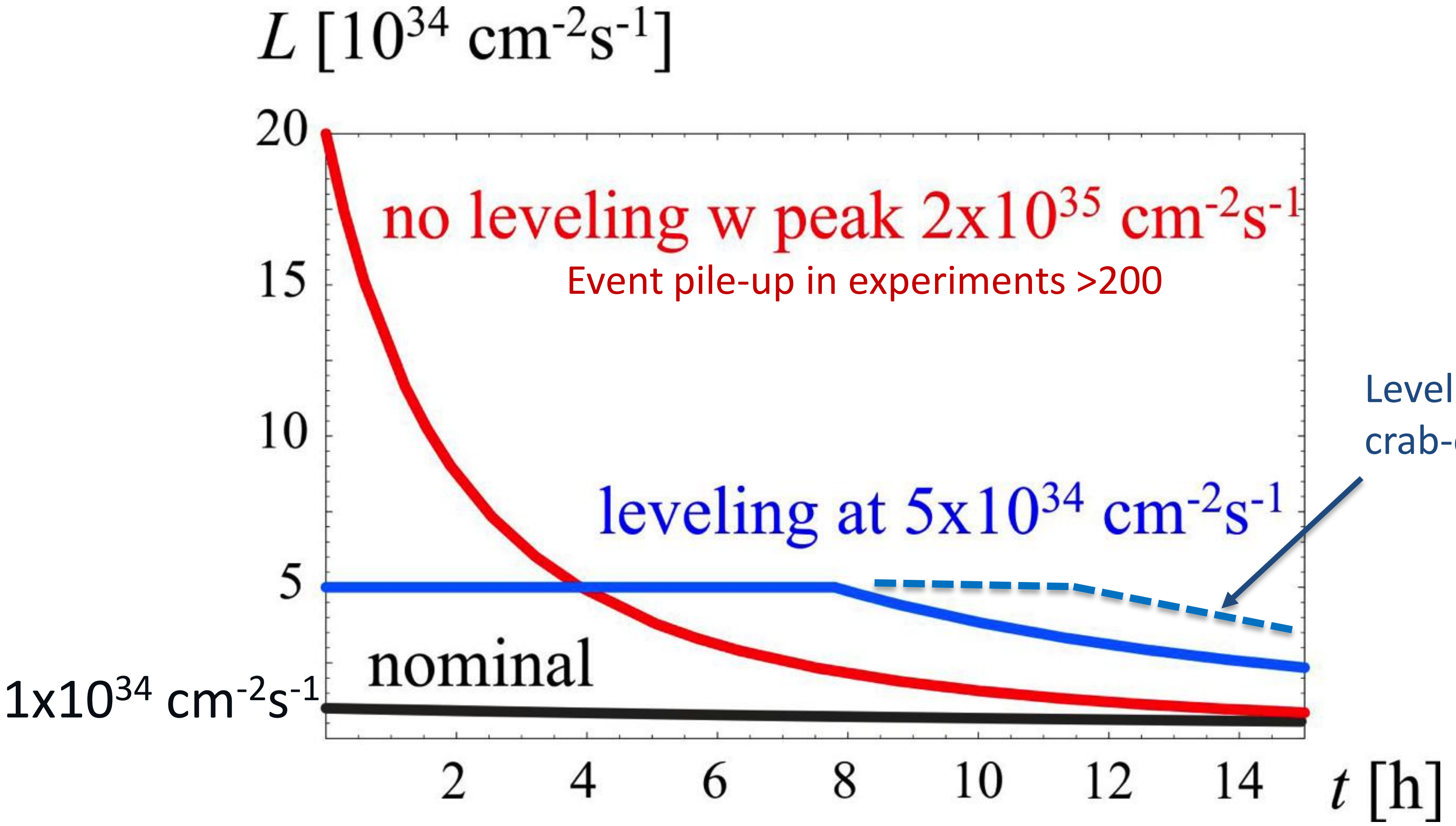
➔ Loss in integrated luminosity!

have been
strated in
the LHC!!!

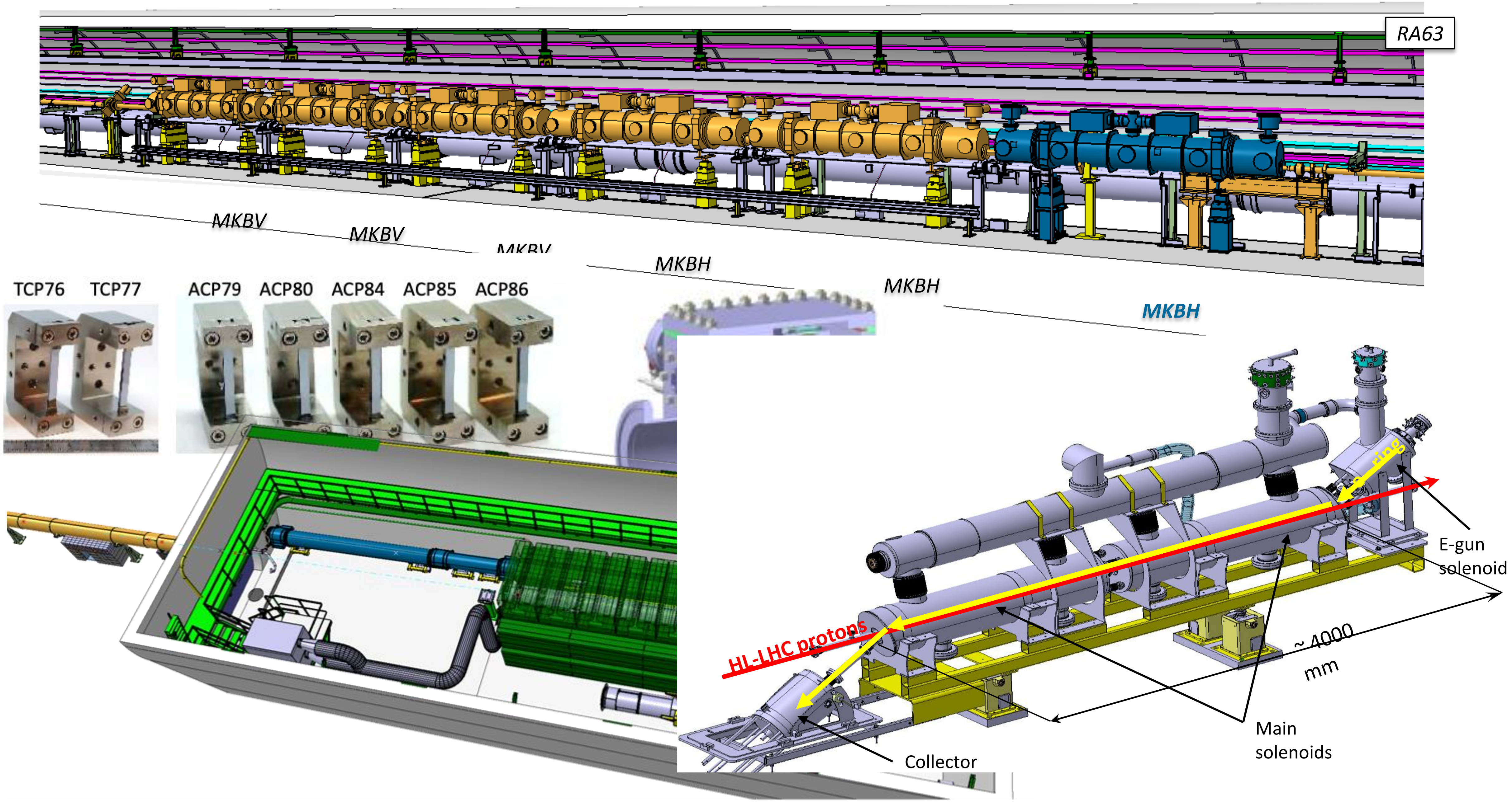
➔ Shielding, Additional Cooling and Removal of all active elements from the tunnel!!!

➔ Maximize the number of particles in the storage ring! ➔ Stored Beam Power!

Operational Scenario for HL-LHC



Added Scope since 2019



Timeline: Main Milestones in 2020

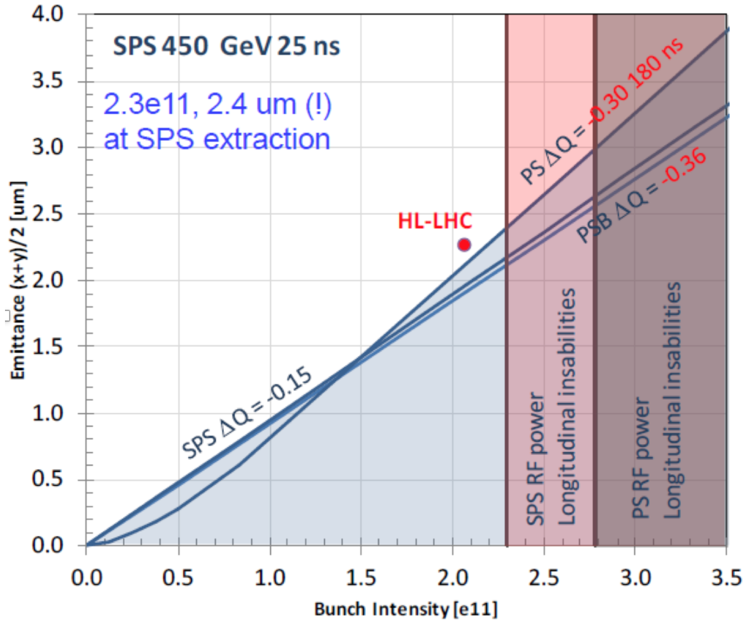
- March to May: CERN in Safe Mode ➔ fully back to full access as of 1st September
- **June: DEMO2-PhaseI successfully completed [Phase II completed last week]** ✓
- **July: Superferric decapole & skew quad corr [INFN Milan] powered to ultimate @ LASA**
- July: Inner triplet prototype MXQFBP1 tested @ SM18 ✓
- July: 2nd TCLD i
- **July: RFD2 was**
- May to August: M
- August: successfu
- August: Segment
- **August: Successf**
- August: successful completion of the contract for the MoGr production ✓
- **August: D2 short model was tested in SM18, CERN** ✓
- **August: RFD1 was tested - 4MV@ $5\ 10^9$** ✓
- September: four TSCPM collimators (with coated MoGr) successfully installed in P7 ✓
- **September: Test of nested orbit corrector [CIEMAT] MCBXFB2 @ CERN** ✓

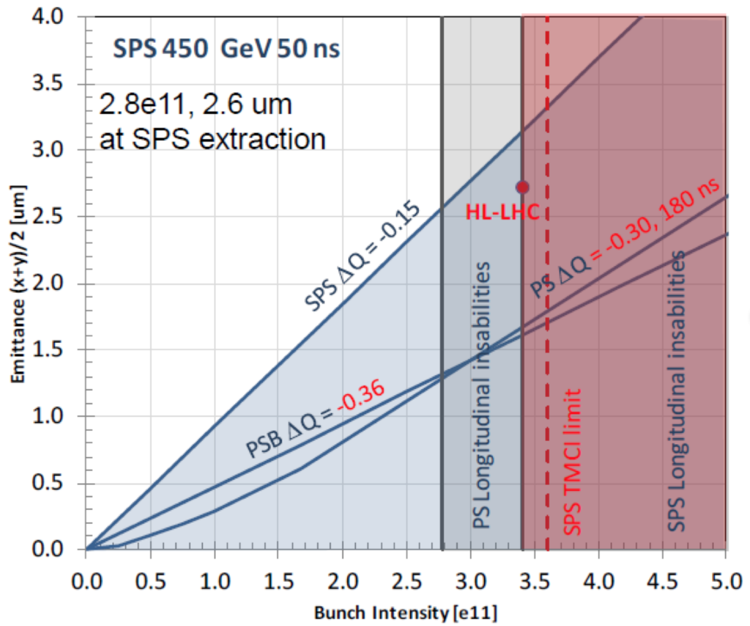
Now entering the phase of hardware production for most equipment!!!

2 US [AUP] magnets passed successfully tests in 2020; CD3 approval in 2020

First CERN prototype tested in 2020, second prototype being tested in February 2021

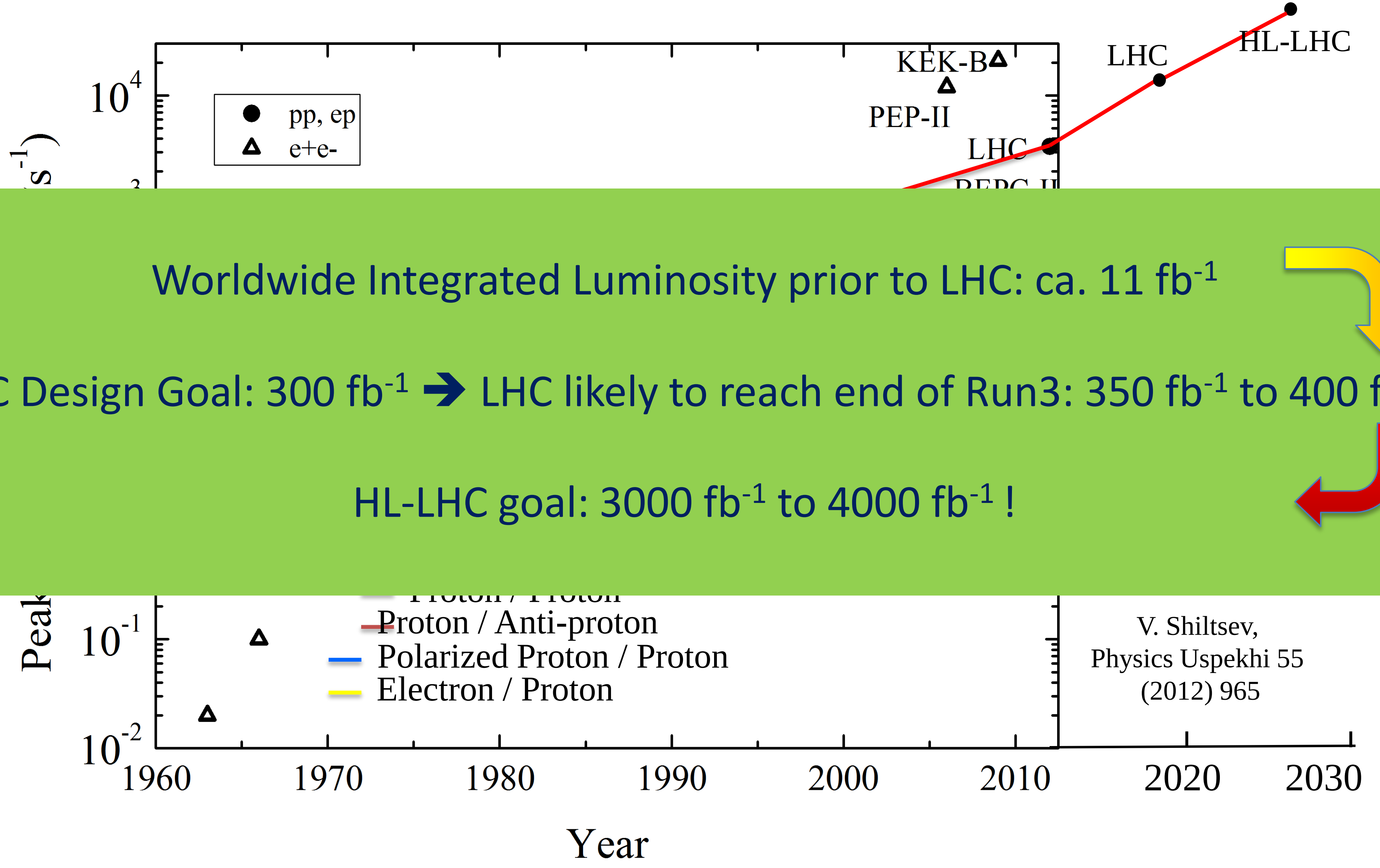
LHC Injector Upgra





- HL-LHC performance relies on more intense and brighter bunches from injector complex (2.2E11p / 2um at SPS extraction wrt to LHC nominal of 1.15E11p / 3.4um)
- 25ns beam limited by space charge in PS, PSB, SPS; SPS RF power and SPS longitudinal instabilities
- 50ns beam limited by PS longitudinal instabilities & SPS space charge and SPS TMCI

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 Run3: 350 fb^{-1} to 400 fb^{-1}

x 10

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