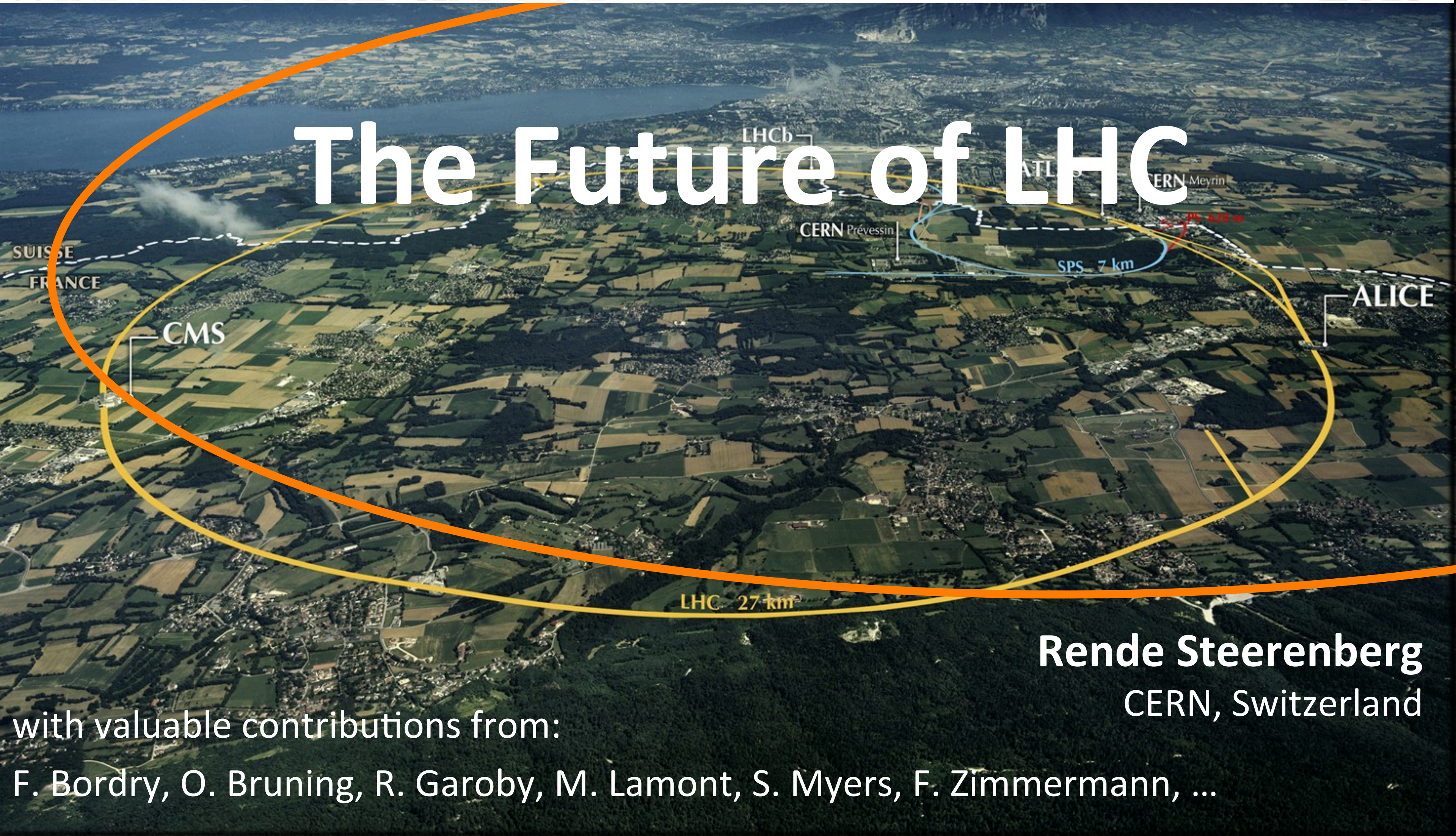
Rencontres du Vietnam — Aug 11 – 17

ICISE

INAUGURAL CONFERENCE

WINDOWS ON THE UNIVERSE 2013

The Future of LHC



Rende Steerenberg

CERN, Switzerland

with valuable contributions from:

F. Bordry, O. Bruning, R. Garoby, M. Lamont, S. Myers, F. Zimmermann, …

Contents

- **The LHC Yesterday and Tomorrow**
- **The Medium-Term Future**
- **The Possible Long-Term Future**
- **Summary**

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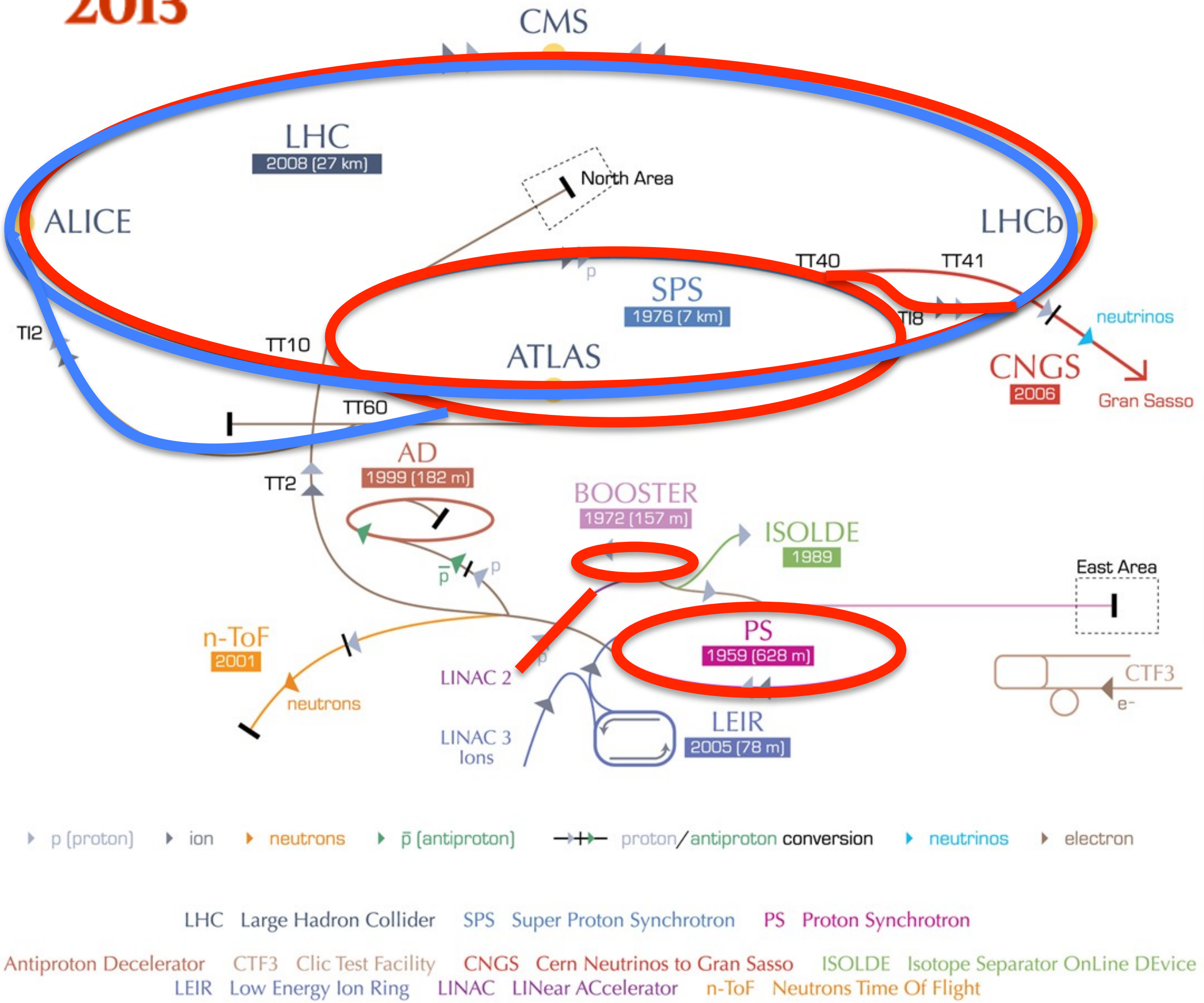
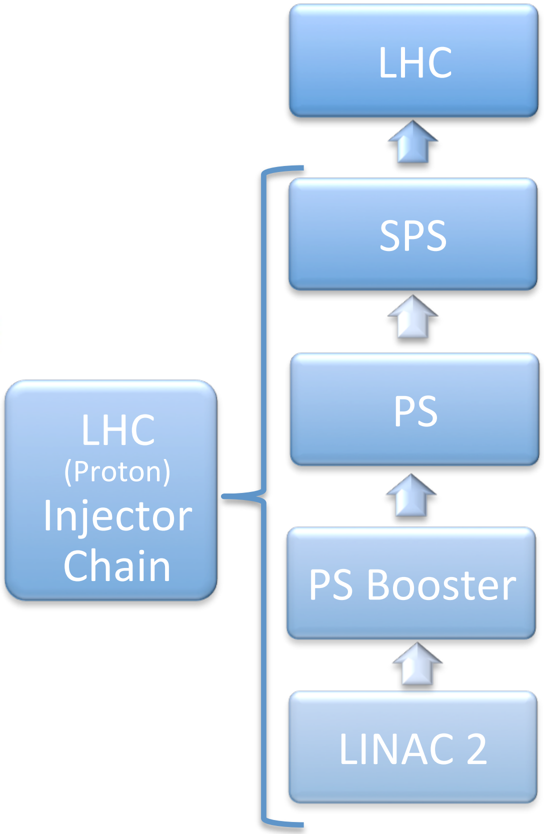
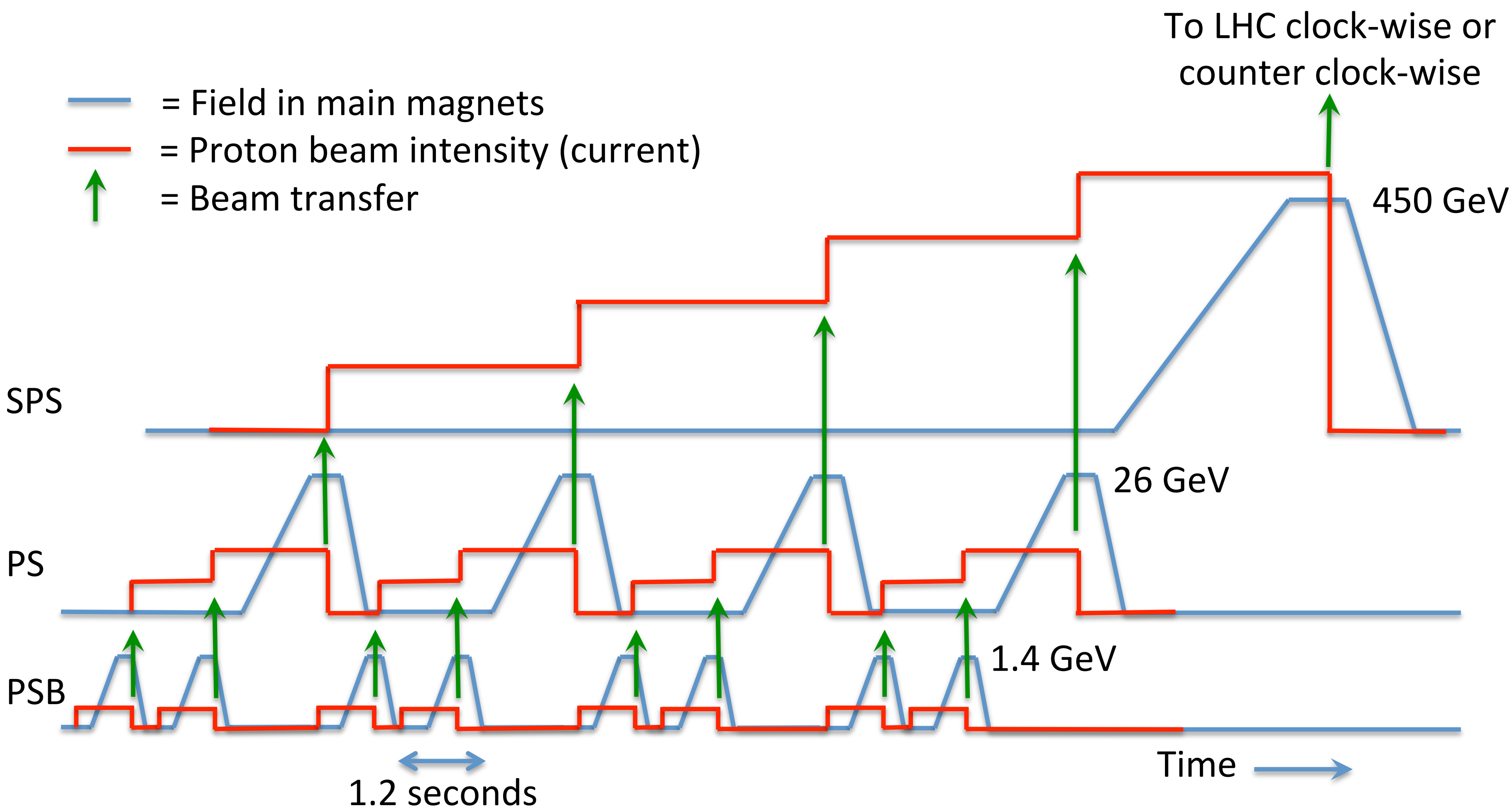
The CERN Accelerator Complex

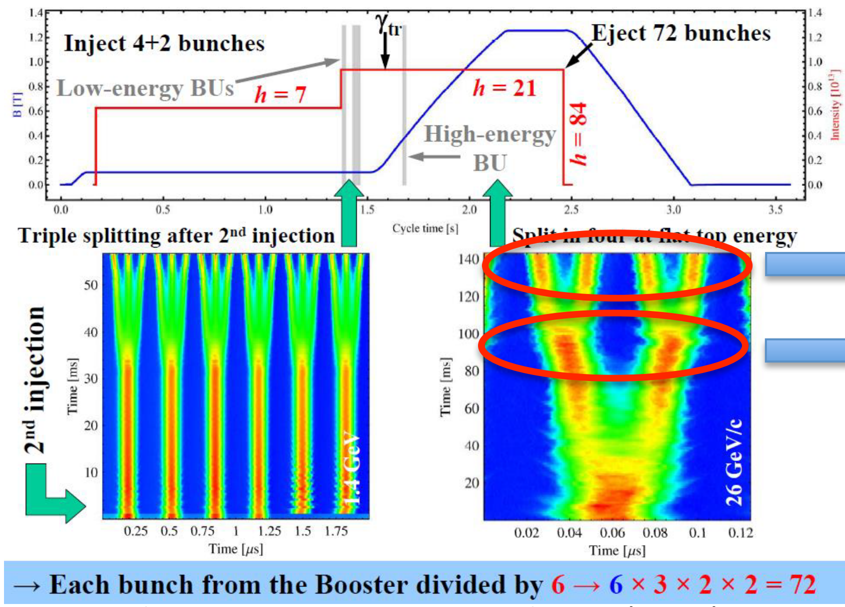




The LHC Injector Cycling



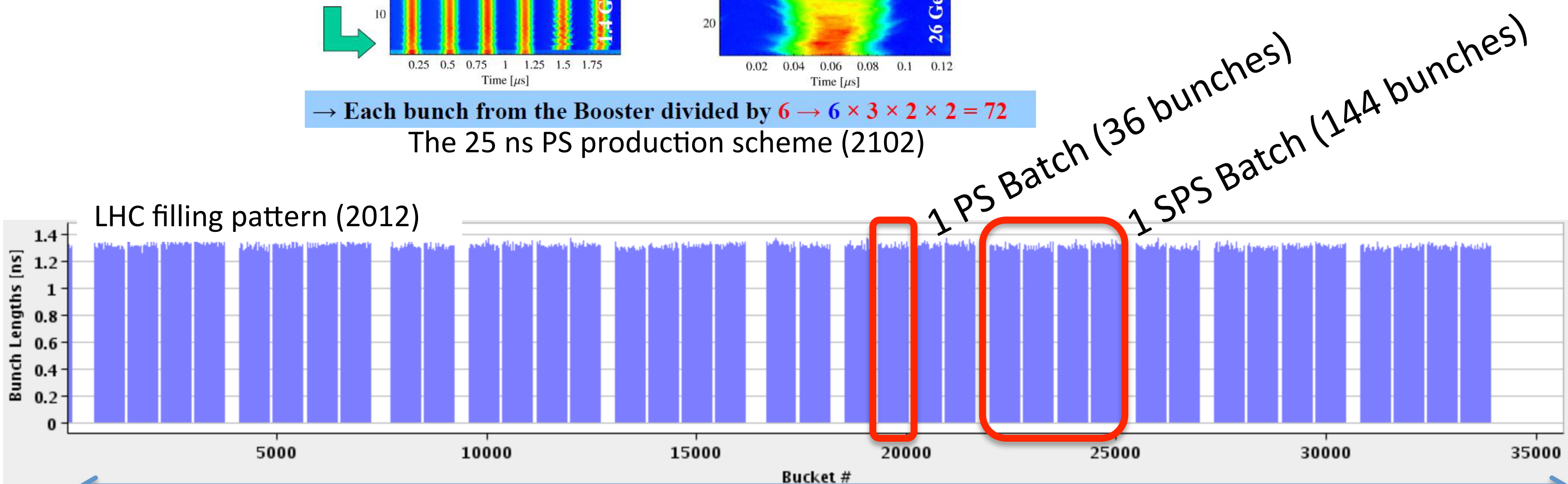
Beam Production and Filling Pattern



The 25 ns PS production scheme (2102)

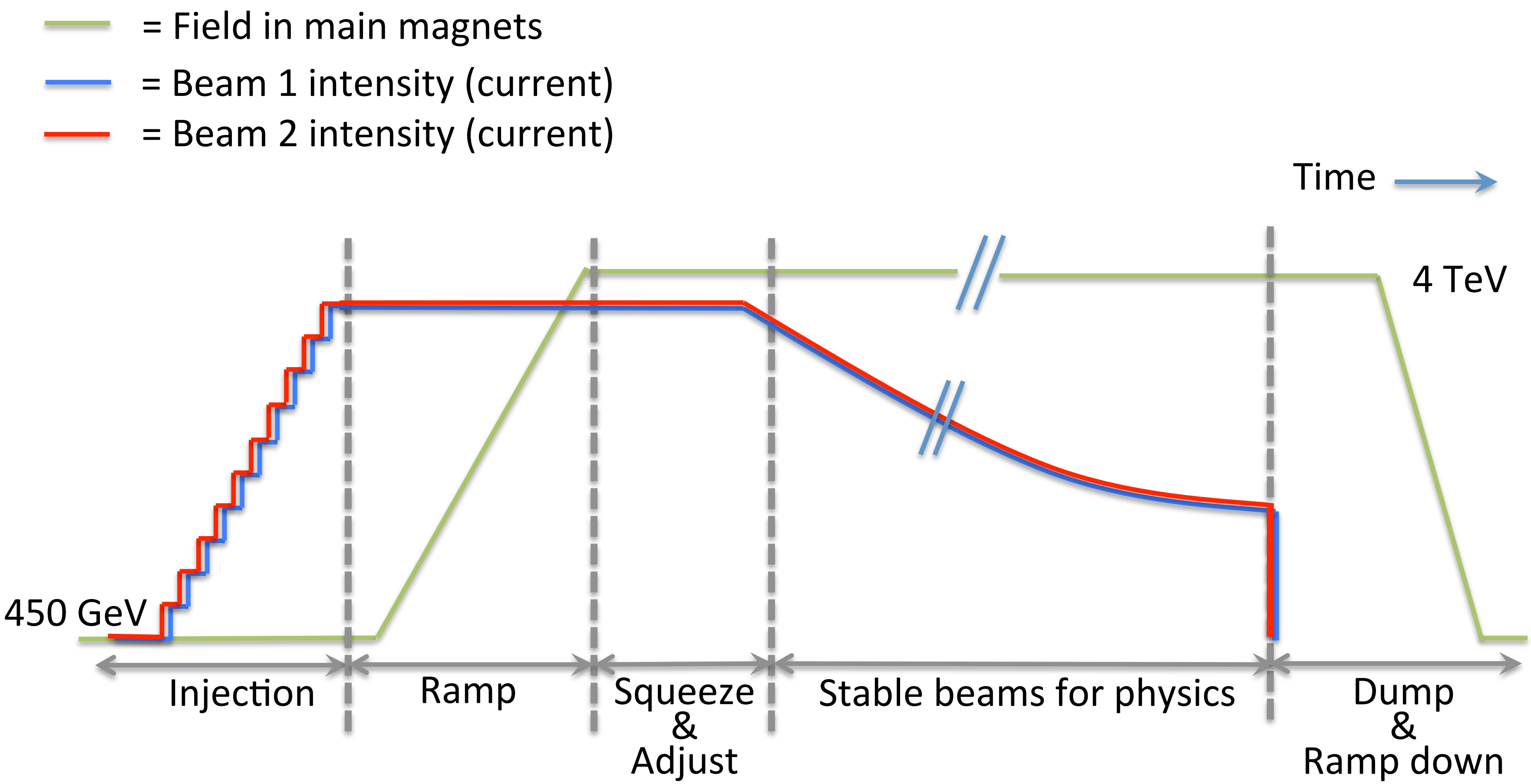
25 ns bunch spacing

50 ns bunch spacing



1380 bunches over 26.7 km (1 ring)

The LHC Cycle

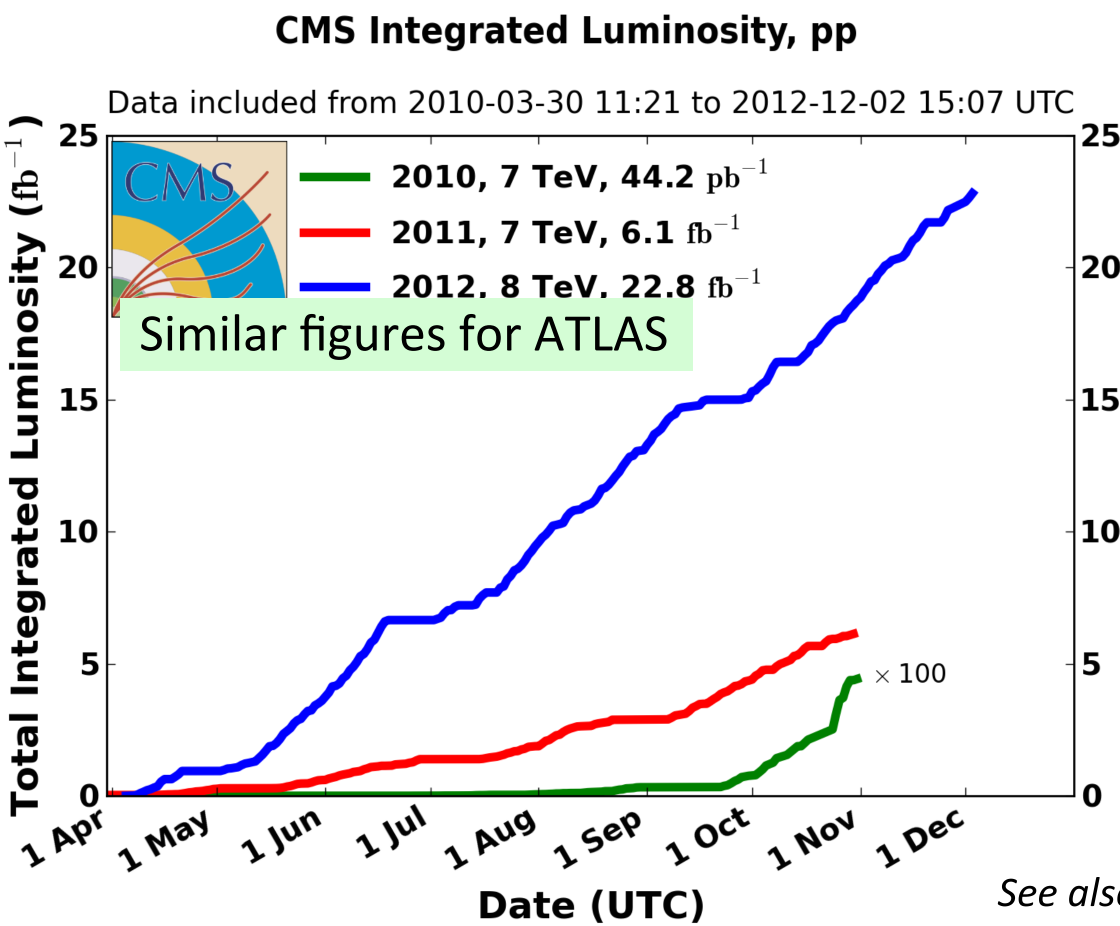


Some Main Beam Parameters

	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [x10^{11}]	1.15	**1.7**	1.2
Norm. Emittance H&V [µm]	3.75	**1.8**	2.7
Number of bunches	2808	**1380**	N.A. #
β* [m]	0.55	**0.6**	N.A. #
Peak luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	**7.7×10^{33}**	N.A. #

The 25 ns was only used for scrubbing and tests in 2012

Integrated Luminosity: 2010 - 2012



2010 - Commissioning:
- 7 TeV c.m.
- 0.04 fb^{-1}

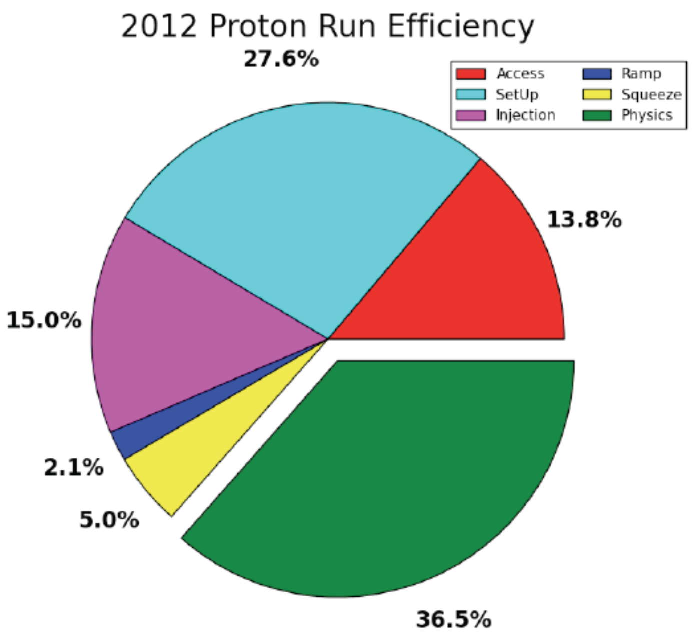
2011 - Exploring:
- 7 TeV c.m.
- 6.1 fb^{-1}

2012 - Production:
- 8 TeV c.m.
- 23.3 fb^{-1}

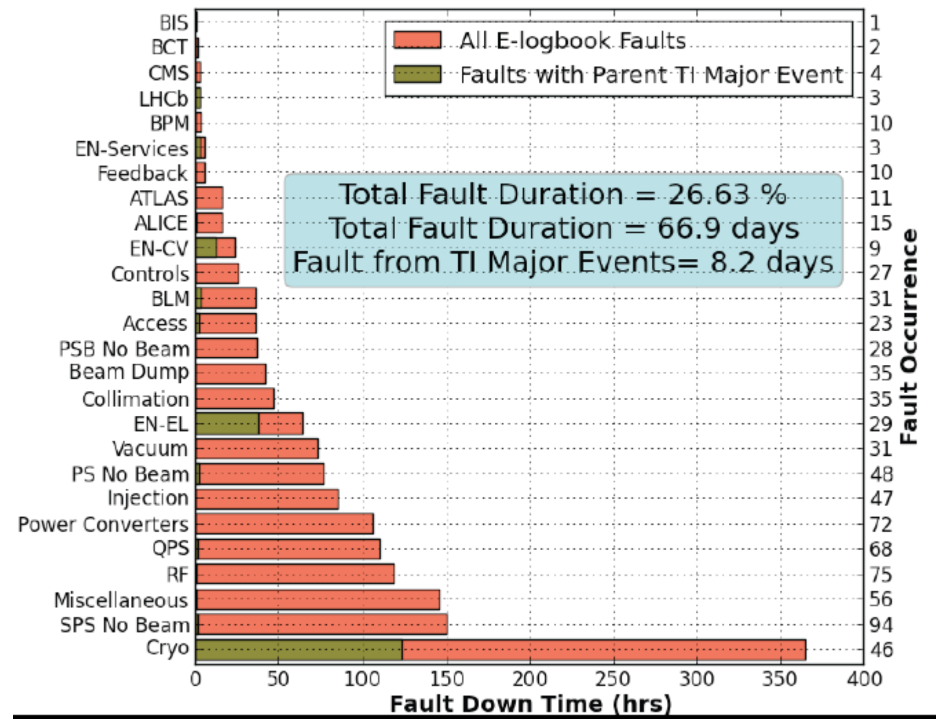
See also:
- *Highlights from CMS by Joe Incadela*
- *Highlights from ATLAS by David Charlton*

Machine and Beam Availability

- Rather good availability, considering the machine complexity and the principles of operation



SB Time: 73.2 days   Total Time: 200.5 days

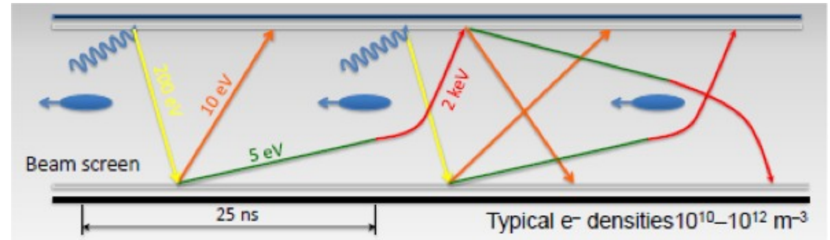


“There are a lot of things that can go wrong – It’s always a battle”

Mike Lamont, IPAC 2013

Some Limitations

- Electron cloud
  - Reason for running with 50 ns
  - Scrubbing to suppress electron cloud build up by reducing the secondary electron yield (SEY)
  - Remains still worrisome in the arcs for 25 ns bunch spacing
- Energy limitation of 8 TeV c.m.
  - Splice consolidation ongoing now
- UFOs
  - Several beam dumps due to UFOs generating beam losses & dumps
- Single Event Upset (SEU)
  - Presently, sensitive electronics is being put more remotely



CERN Mid-Term Plan 2014 – 2018

High Luminosity LHC → HL-LHC
LHC Injector Upgrade → LIU

Mid-term future

- Extract of the MTP:

The goals of the Management, already defined in the previous MTP and fully in line with the European Strategy for Particle Physics, are to:

1. exploit the full potential of the LHC and the high-luminosity upgrade project of the accelerator and experiments,
2. position and maintain CERN as the Laboratory at the energy frontier through accelerator design studies and a vigorous accelerator R&D programme,
3. prepare CERN to bid for a future large project in particle physics,

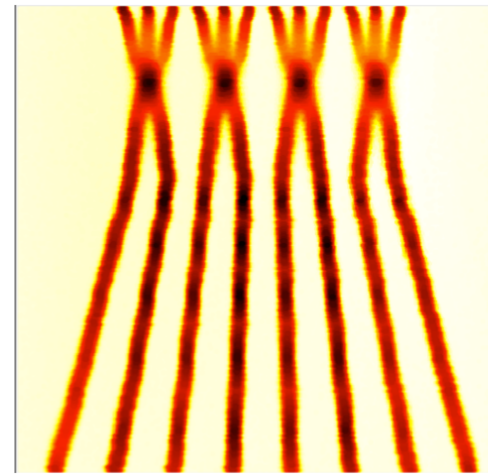
Long-term future

High Energy LHC → HE-LHC
Very High Energy LHC → VHE-LHC
(Circular e+ e- collider → TLEP)

Expectations after Long Shutdown 1 (2015)

- Collisions at least at **13 TeV** c.m.
- **25 ns** bunch spacing
  - Using new injector beam production scheme (BCMS), resulting in brighter beams.
- **β^* ≤ 0.5m** (was 0.6 m in 2012)
- Other conditions:
  - Similar turn around time
  - Similar machine availability
- Expected maximum luminosity: **1.7 x 10^{34} cm^{-2} s^{-1}** ± 20%
  - Limited by inner triplet heat load limit, due to collisions debris

Batch Compression and Merging and splitting (BCMS)



Courtesy of the LIU-PS project team

	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	2590	1.15 × 10^{11}	1.9 µm	1.7×10^{34} $cm^{-2}s^{-1}$	~49	~45 fb^{-1}

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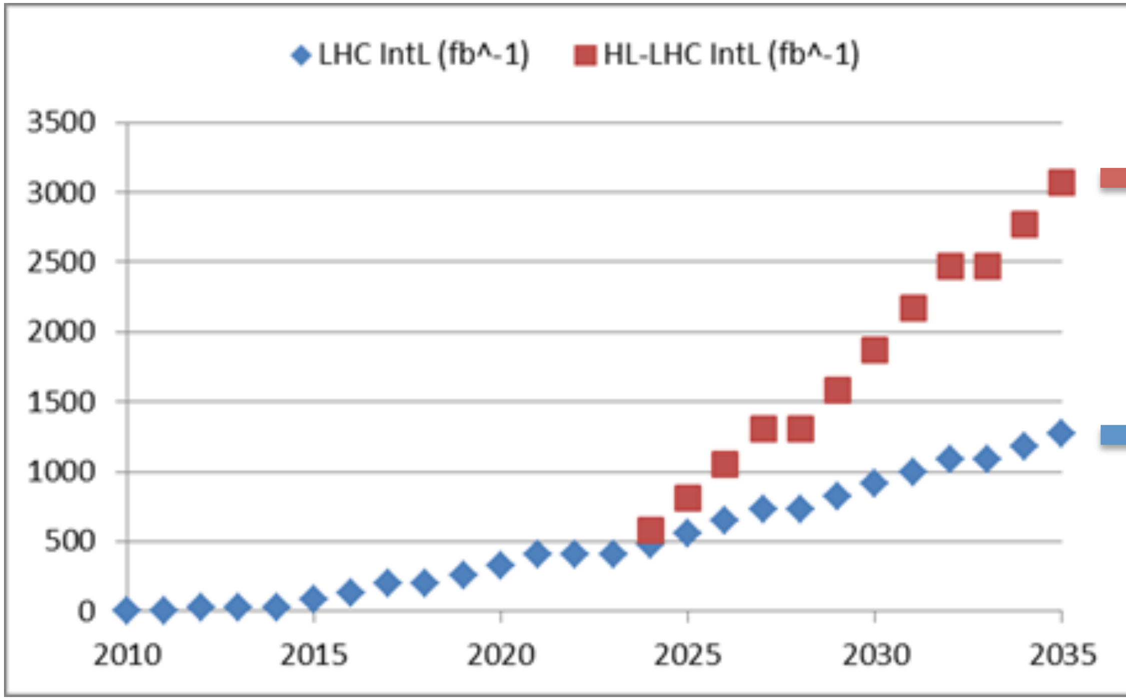
Why High-Luminosity LHC



By implementing HL-LHC

more than a factor 2

By continuous performance improvement and consolidation

- Goal of HL-LHC project:
  - 200 – 300 fb^{-1} per year
  - 3000 fb^{-1} in about 10 years

High Luminosity LHC

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Luminosity, the Figure of Merit

Intensity per bunch

Number of bunches

Correction factors

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

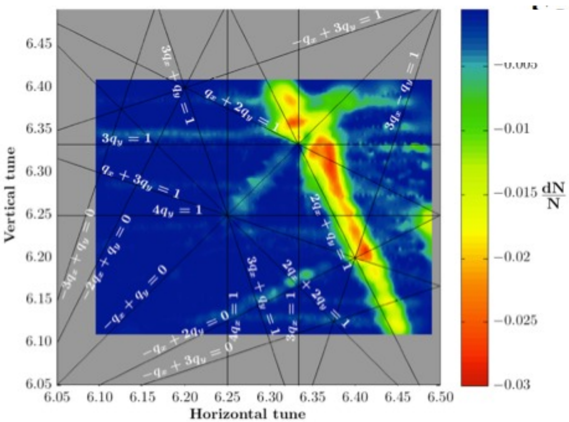
Beam dimensions

$$\sigma_{x,y} = \sqrt{\epsilon \cdot \beta^*_{x,y}}$$

- LHC Injectors:
  - Increase beam brightness, intensity and quality (*N and σ*)
- LHC (besides detector upgrades):
  - Use 25 ns bunch spacing, with 2.2×10^{11} ppb (*N*, n_b)
  - Reduce β* from 0.5 to 0.15 m (*σ*)
  - Use crab cavities to reduce crossing angle effect (*S*)
  - Apply luminosity levelling, to reduce pile-up at start of fill (*W*)

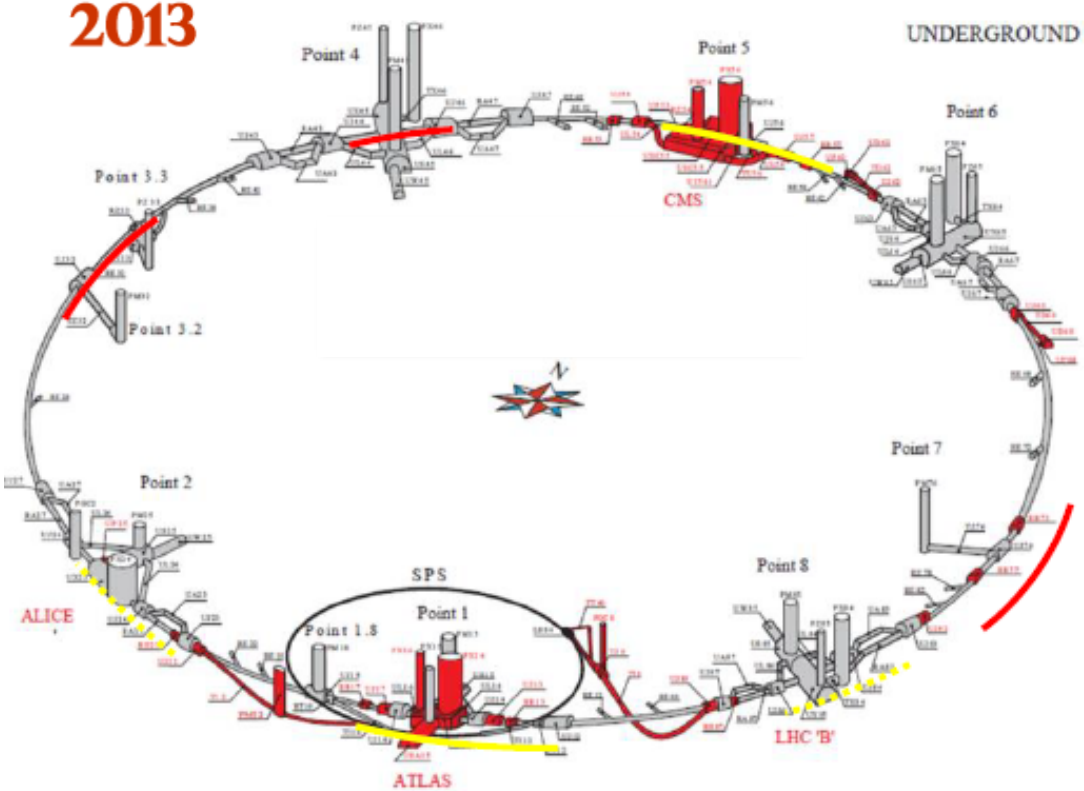
LHC Injector Upgrade Project LIU

- LINAC4 – PS Booster:
  - H⁻ injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
  - New Finemet® RF cavity system
  - Increase of extraction energy from 1.4 GeV to 2 GeV
- PS:
  - Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
  - Transverse resonance compensation
  - New Finemet® RF Longitudinal feedback system
  - New RF beam manipulation scheme to increase beam brightness
- SPS
  - Machine Impedance reduction (microwave instabilities)
    - 200 MHz RF cavities replacement
  - Vacuum chamber coating against e-cloud (?)
- These are only the main modifications and this list is far from exhaustive
- Project leadership: R. Garoby and M. Meddahi



Courtesy of A. Huschauer

The HL-LHC Project



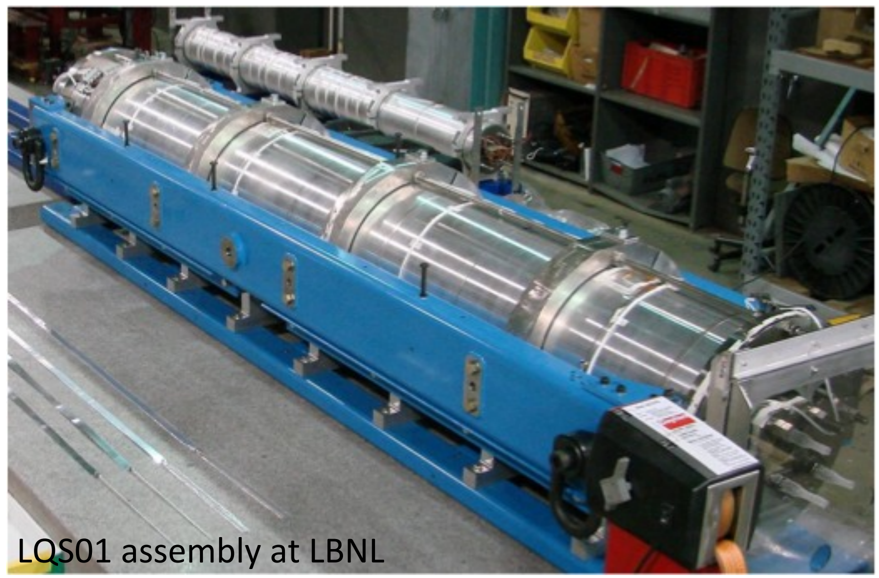
- New IR-quads (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

- Major intervention on more than 1.2 km of the LHC
- Project leadership: L. Rossi and O. Bruning

Interaction Region Quadrupoles (Inner Triplet)

- Aim: reduce β* from 0.5 m to 0.15 m or even lower.
- International R&D effort (USA & Europe)
- New material: Nb_3Sn instead of NbTi

- Main requirements:
  - **Aperture 120 mm**
  - Gradient 200 T/m
  - **Peak field ~ 13 T**
- Presently in LHC:
  - **Aperture 70 mm**
  - **Peak filed ~ 8 T**

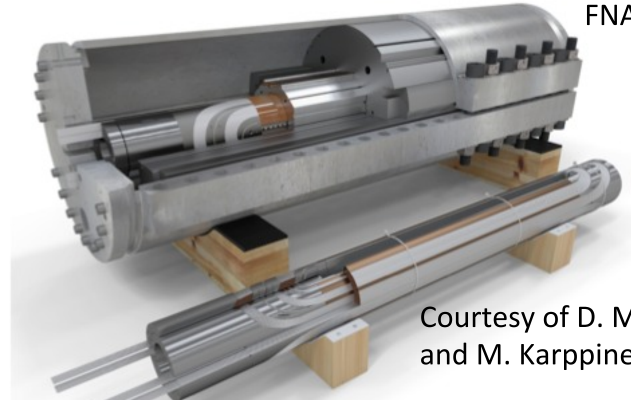

LQS01 assembly at LBNL


LQSD test at FNAL

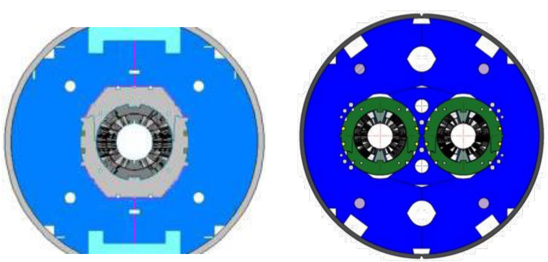
- The HL-LHC IR-Quadrupole design and R&D is a key stepping stone for future high-field applications

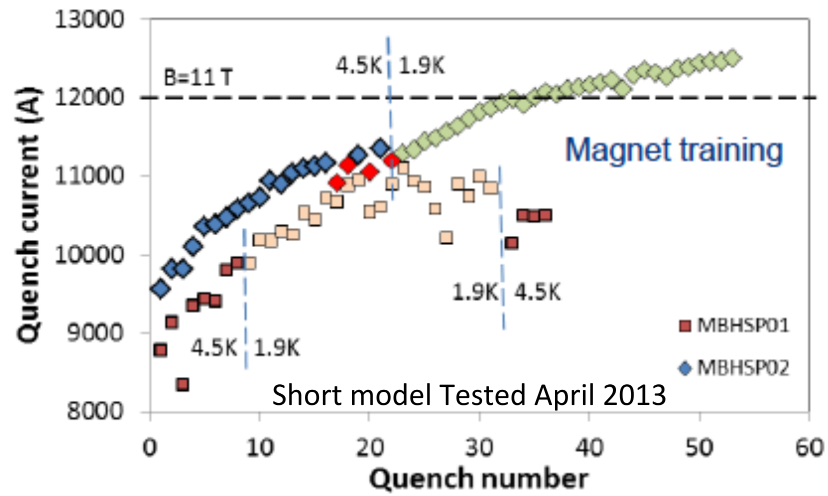
Dispersion Suppression Dipoles

- Aim: Create enough space to install additional collimators in order to cope with the increasing debris hitting the magnets when increasing the number of collisions
- International R&D (USA & Europe)
  - Nb_3Sn (instead of NbTi)
- Main requirements:
  - Length 11 m (3m shorter than today)
  - Single and twin aperture
  - Magnetic field 11 T (8 T today)



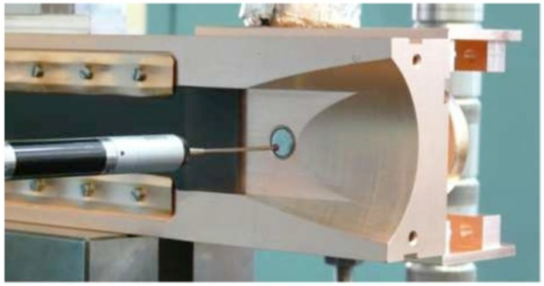
Courtesy of D. Mitchell, FNAL and M. Karppinen, CERN





IR Collimation Upgrade

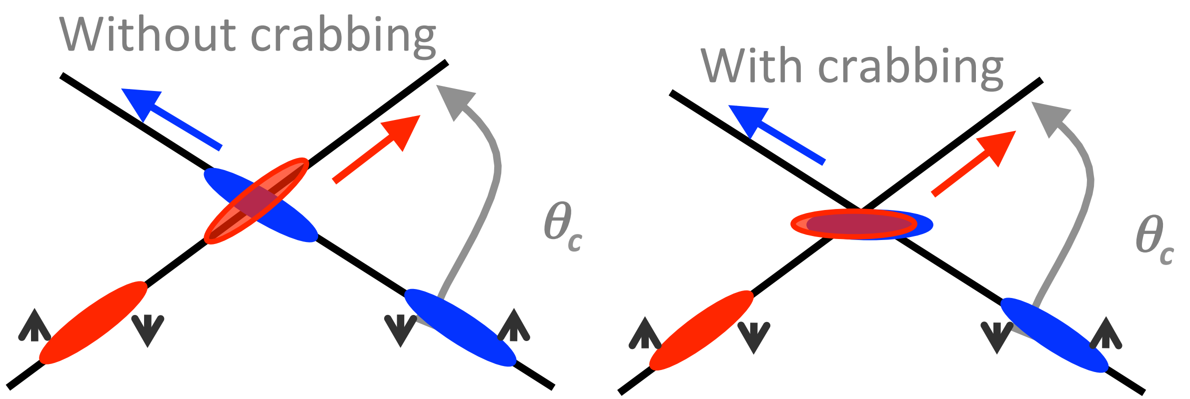
- Update of present collimation system during LS1:
  - Replace existing collimators
  - Reduce setup time (gain of factor ~100)
  - Improved monitoring



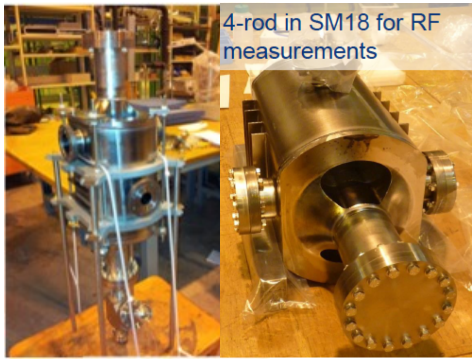
- For HL-LHC add dispersion suppressor collimation
  - Eliminate off-momentum particles in a region with high dispersion
  - Technology of choice for the DS collimators is warm with by-pass cryostat
  - Design completed with 4.5 m integration length.
  - Prototyping on-going
- Advanced collimation concepts being investigated for the future
  - Crystal collimation tests in SPS have been made and are being prepared in the LHC

Crab Cavities, Increase “Head on”

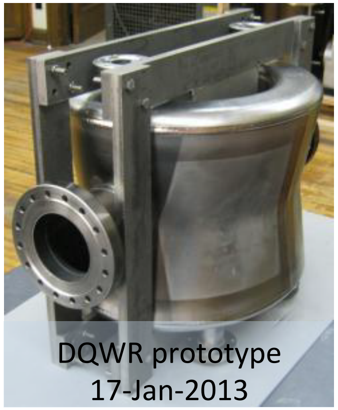
- Aim: reduce the effect of the crossing angle



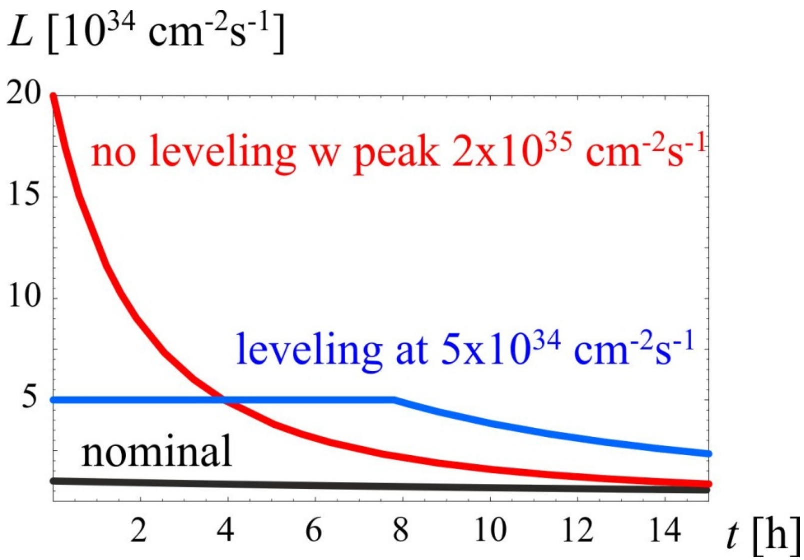

RF-Dipole Nb prototype



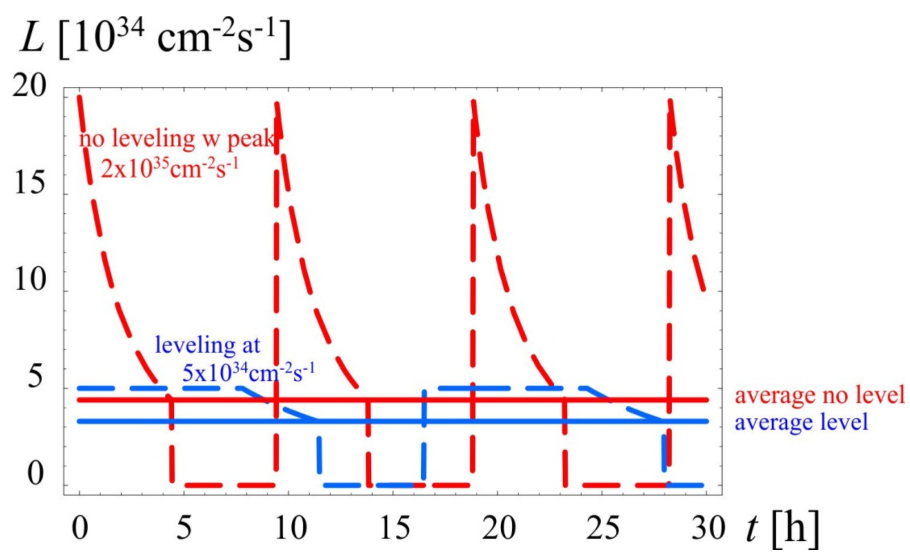
- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017


DQWR prototype
17-Jan-2013

Luminosity Levelling, a key to success



- High peak luminosity
- Minimize pile-up in experiments and provide "constant" luminosity



- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/yr

Present HL-LHC Time Line

2012	Run I	4 TeV, peak luminosity 7.7e33
2013	LS1	Splice consolidation, R2E, DN200…
2014		Experiments' consolidation and upgrades
2015	Run II	6.5 to 7 TeV, peak luminosity 1.7e34
2016		
2017		
2018	LS2	LHC phase 1 and **injector** upgrades Experiments' consolidation and upgrades
2019	Run III	7 TeV, peak luminosity 2.0e34
2020		
2021		
2022	LS3	HL-LHC upgrade (insertions, crab cavities…)
2023		Experiments' HL upgrades

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High Energy LHC

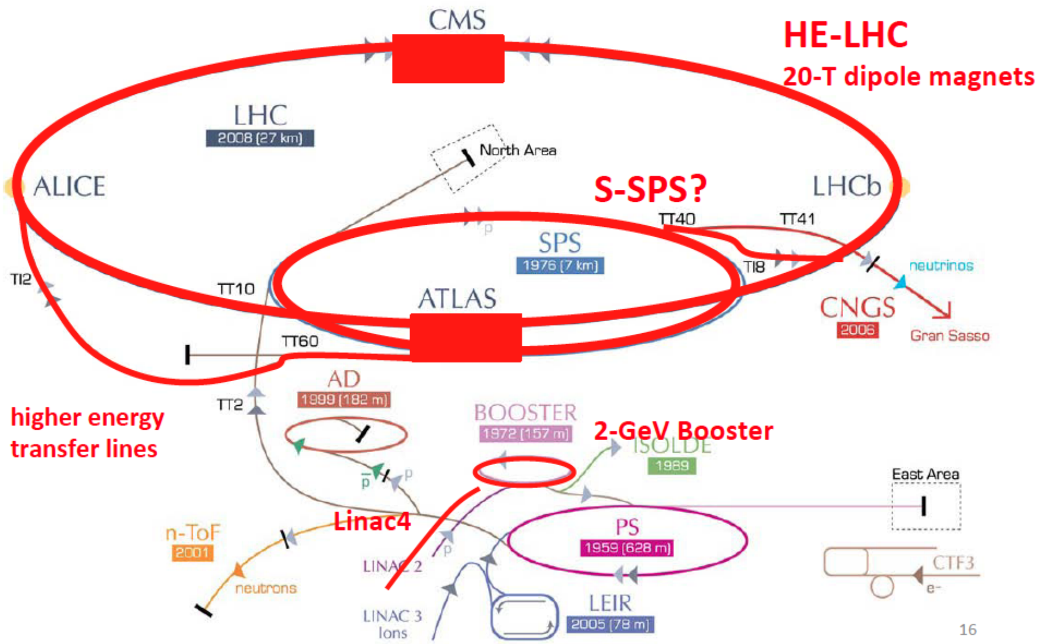
- Use the **existing LHC tunnel** and replace existing magnets with **high field superconducting magnets**
- Beam rigidity:

$$B\rho = 3.3356\ p$$

- **ρ = 2804 m** (fixed by tunnel geometry and filling factor)
- Vigorous international R&D for **20 T dipole magnets** on-going (Nb_3SN and HTS)

$$p = \frac{2804 \times 20}{3.3356} \Rightarrow \text{~16.5 TeV per beam} \Rightarrow \mathbf{33\ TeV_{cm}}$$

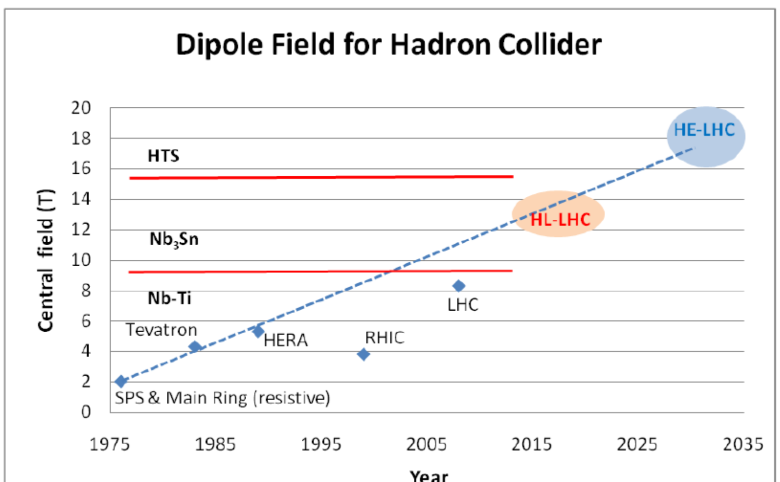
HE-LHC in the Present Complex

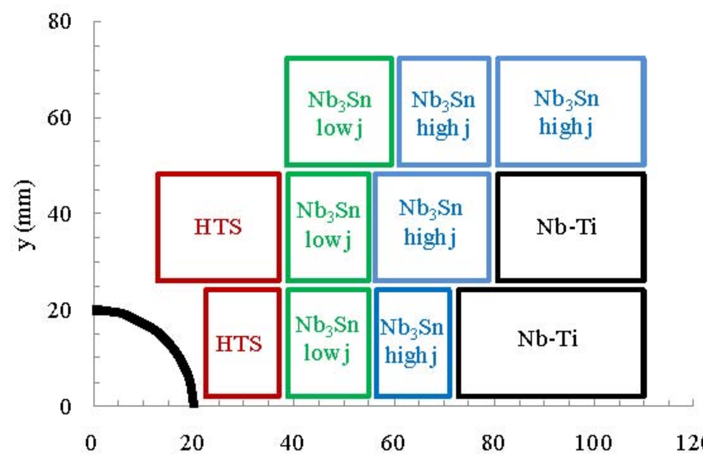


- 1 TeV injector (S-SPS) would require fast cycling SC magnets
- In the HE-LHC synchrotron radiation becomes more important:
  - Additional heat load to cryogenic system
  - Tool to control emittances (SR damping)
- Could deliver 5×10^{34} $cm^{-2}s^{-1}$ peak luminosity

HE-LHC the Main Parameters

Parameter	LHC	HL-LHC	HE-LHC
c.m. energy [TeV]	14	14	**33**
dipole field [T]	8.33	8.33	**20**
injection energy [TeV]	0.45	0.45	**> 1.0**
no. bunches n_b	2808	2808	2808
Bunch population N_b [$\times 10^{11}$]	1.15	2.2	0.94
init. transv. norm. emittance [μm]	3.75	2.5	**1.38**
stored beam energy [MJ]	362	694	701
arc SR heat load [W/m/aperture]	0.17	0.33	**4.35**
longit. SR emit. damping time [h]	12.9	12.9	1.9
Horiz. SR emit. damping time [h]	25.8	25.8	2.0
peak events per crossing	27	135 (lev.)	**147**
peak luminosity [$\times 10^{34}$ cm^{-2}s^{-1}]	1.0	5.0	**5.0**
optimum run time [h]	15.2	10.2	5.8
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	**1.4**



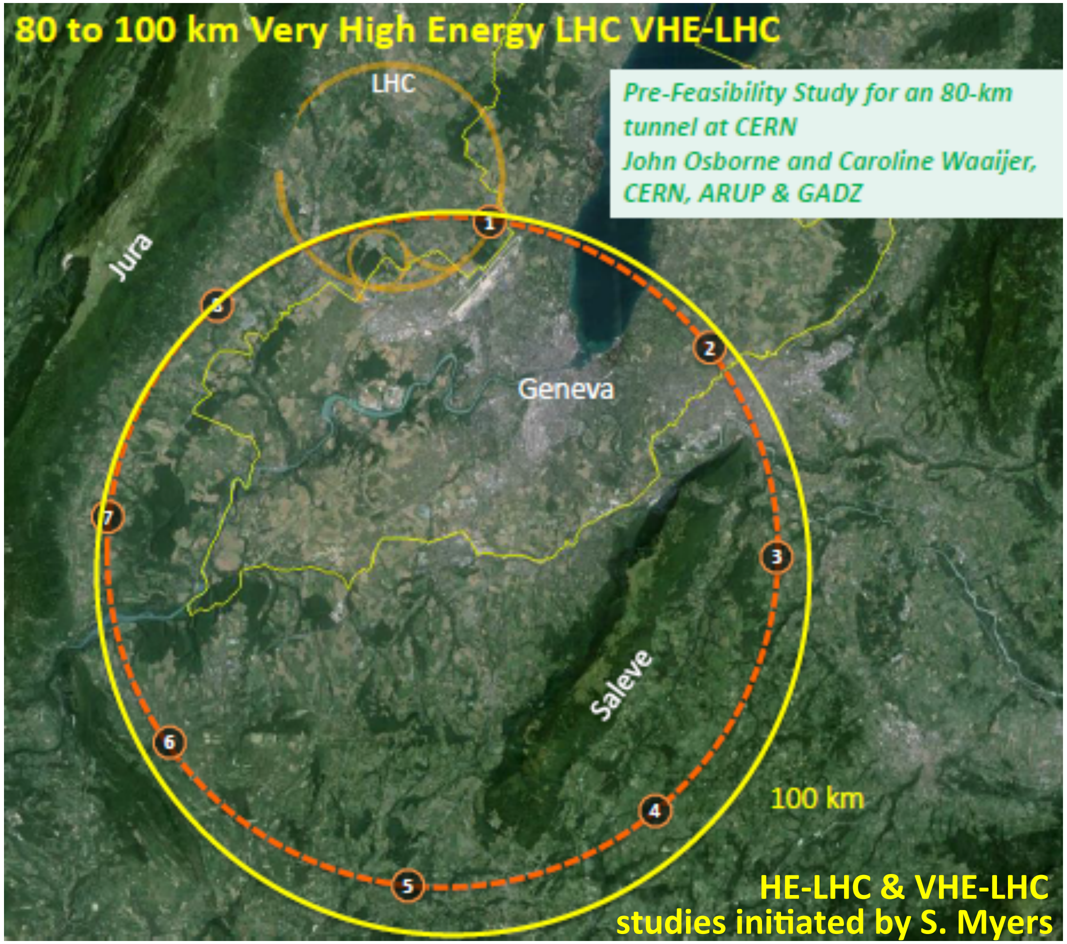


Courtesy of E. Todesco, L. Rosi, P. McIntyre

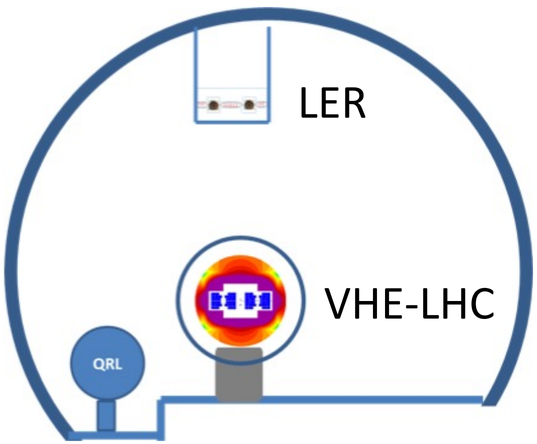
VHE-LHC, Location and Size

- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a e^+- e^- Higgs factory (TLEP)

	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 240 GeV c.m.	4.8×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} $cm^{-2}s^{-1}$
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}$ $cm^{-2}s^{-1}$



VHE-LHC Parameters



Parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	**100**
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	**20**
injection energy [TeV]	0.45	0.45	**> 1.0**	**> 3.0**
no. bunches n_b	2808	2808	2808	8420
Bunch population N_b [$\times 10^{11}$]	1.15	2.2	0.94	0.97
init. transv. norm. emittance [μm]	3.75	2.5	1.38	**2.15**
stored beam energy [MJ]	362	694	701	**6610**
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	**43.3**
longit. SR emit. damping time [h]	12.9	12.9	1.9	**0.32**
Horiz. SR emit. damping time [h]	25.8	25.8	2.0	**0.64**
peak events per crossing	27	135 (lev.)	147	**171**
peak luminosity [$\times 10^{34}$ cm^{-2}s^{-1}]	1.0	5.0	5.0	**5.0**
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	**2.1**

- The tunnel can also be equipped with a Lepton ring to provide p – e^- collisions
- A circumference of 100 km is being considered for cost-benefit reasons

> 20T magnet in 80 km
> 16 T magnet in 100km } 100 TeV

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Comparing the Main Parameters

Parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference *C* [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
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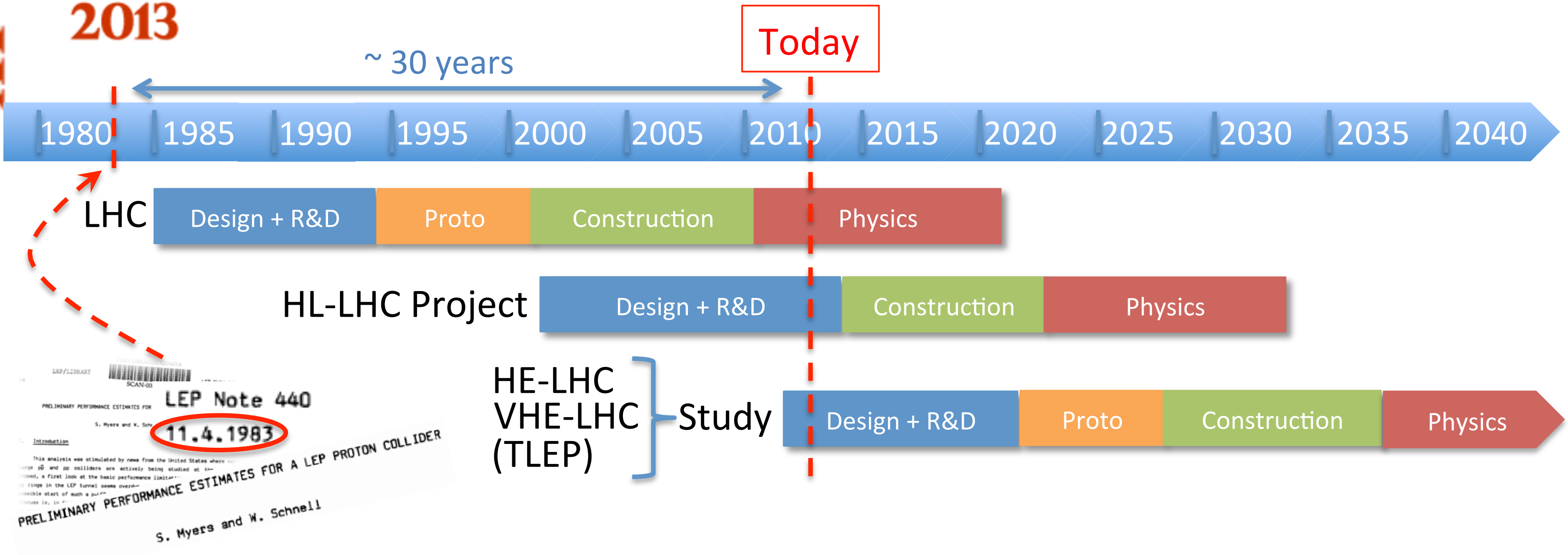
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	2.1

- CERN is clearly working at the energy frontier
- New high-field magnet technology development is well underway
- The LHC injectors need to provide high brightness and higher energy beams
- The stored beam energy becomes very high, requiring a very reliable machine protection system
- The synchrotron radiation heat load becomes important:
  - Puts extra strain on the cryogenic systems
  - Damping times become small and beneficial
- The number of events per crossing becomes important (levelling required)
- Luminosity with increasing energy remains high

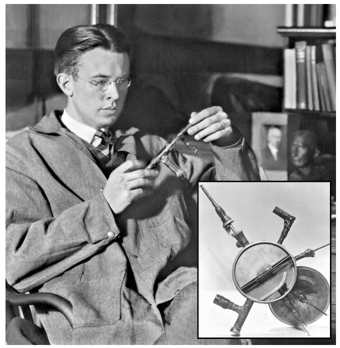
Possible Long Term Future



- We need to plan and decide the future soon
  - HL-LHC and LIU are approved projects
  - HE-LHC, VHE-LHC (TLEP) are studies
- Different technologies have different cost
  - The cost benefit ratio will play a major role in the decision making process

Final Remarks

- The European Strategy and the CERN Mid-term plan clearly position and maintain **CERN** as **the laboratory at the energy frontier**
- In order to fulfil this:
  - International (world-wide) collaboration is required and on-going
  - Vigorous R&D is on-going in many fields among which:
    - High field super conducting magnets
    - High gradient super conducting RF cavities
- Plans for the future High and Very High Energy colliders are being worked out in detail
- **In the meantime the potential of the present LHC will be fully exploited**



E. Lawrence who invented the cyclotron in 1929

The LHC March 2013

"We shall have no better conditions in the future if we are satisfied with all those which we have at present."

Thomas A. Edison
Inventor and businessman, 1874 – 1931

Spare Slides

European Strategy for Particle Physics Update 2013

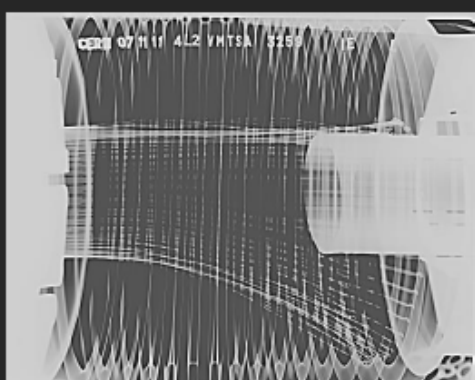
- **Extract of the LHC related High-priority large-scale scientific activities:**
  - *"Europe's top priority should be the* ***exploitation of the full potential of the LHC, including the high-luminosity upgrade*** *of the machine and detectors with a view to* ***collecting ten times more data than in the initial design, by around 2030****. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma."*
  - *"CERN should* ***undertake design studies for accelerator projects in a global context****, with emphasis on proton-proton and electron-positron* ***high-energy frontier machines****. These design studies should be coupled to a* ***vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures****, in collaboration with national institutes, laboratories and universities worldwide."*

Aug 11 - 17
ICISE
2013

More details on some issues

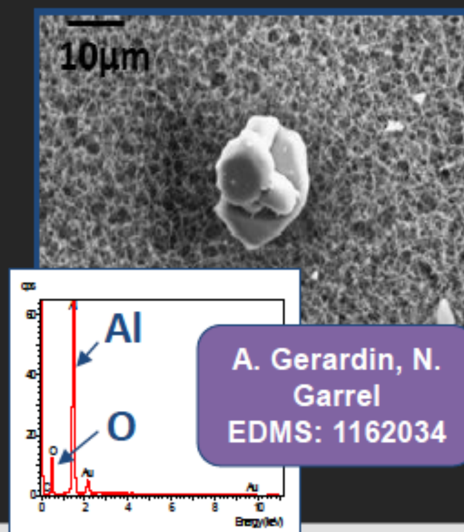
Beam induced heating

- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. Light mirrors
  - Vacuum assemblies



UFOs

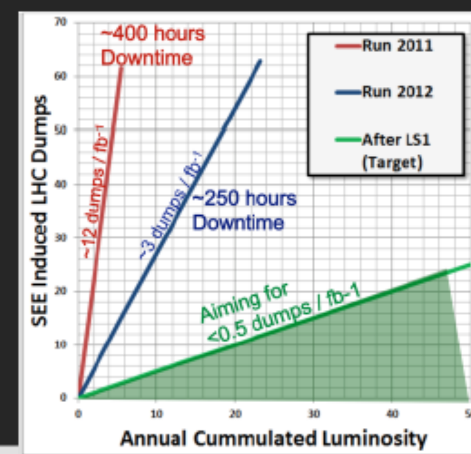
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV



A. Gerardin, N. Garrel
EDMS: 1162034

Radiation to electronics

- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from $12/fb^{-1}$ in 2011 to $3/fb^{-1}$ in 2012



WINDOWS ON THE UNIVERSE