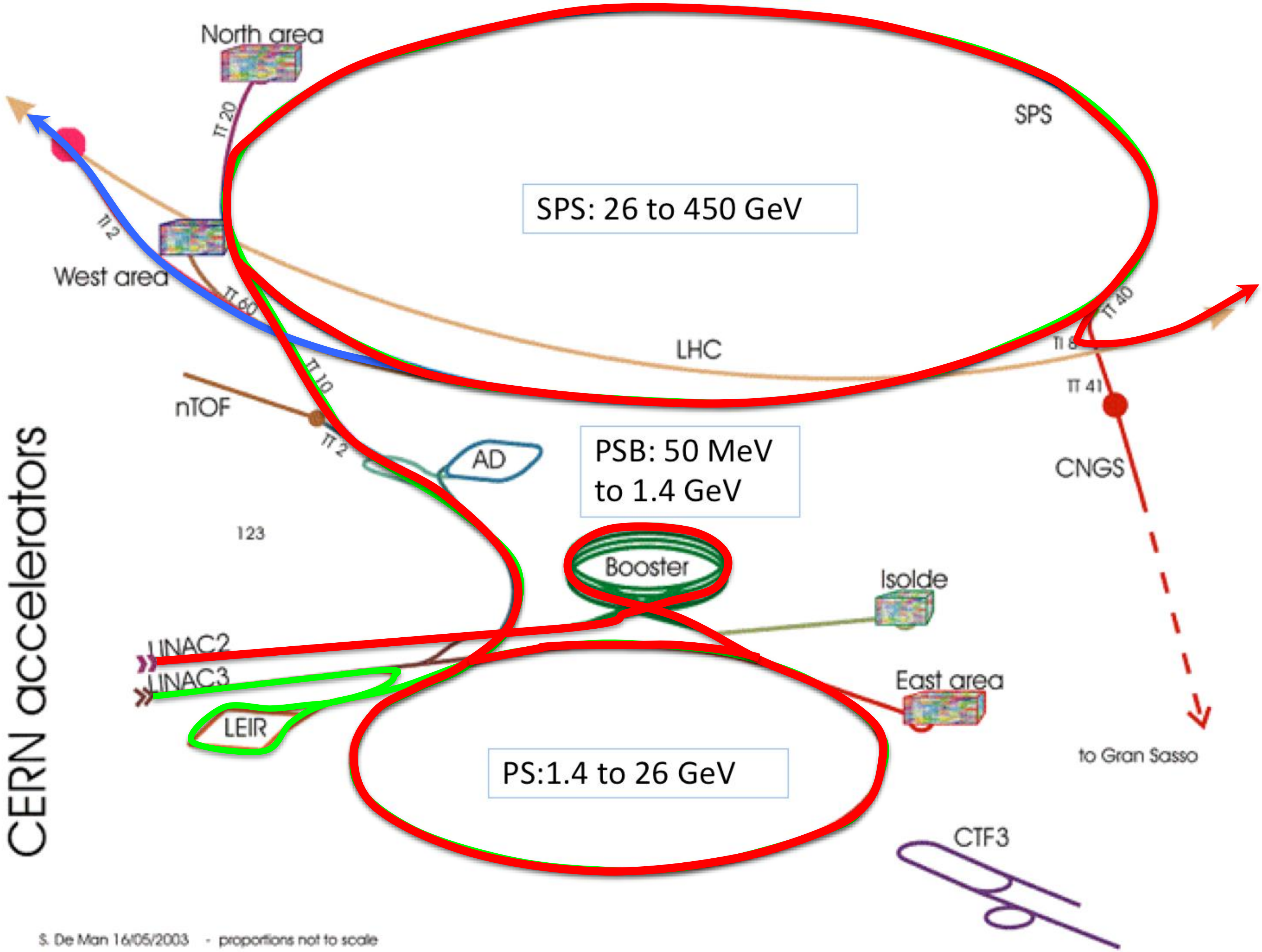
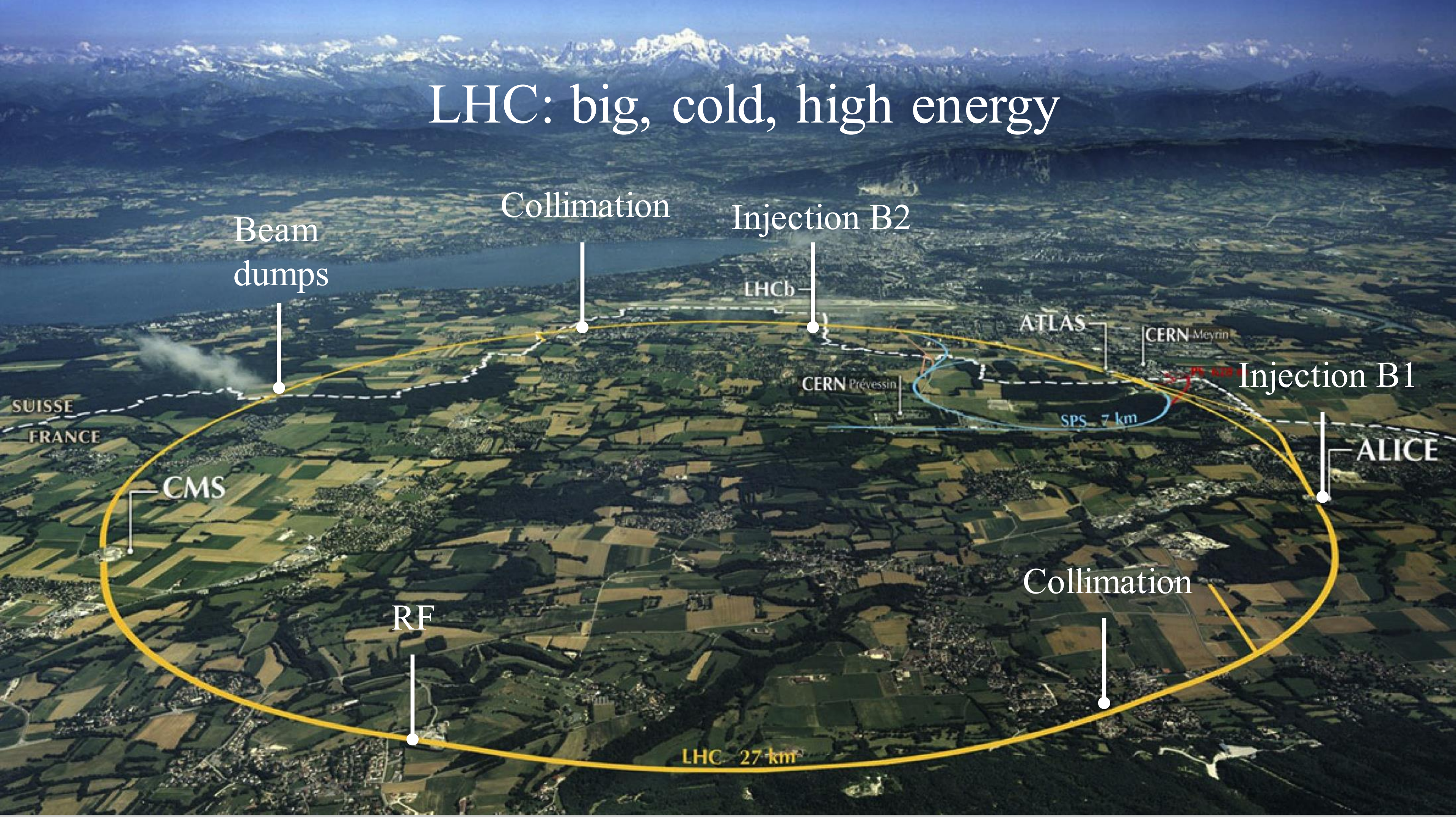
LHC, HL-LHC and beyond

Mike Lamont
for the LHC team

Acknowledgements: Frédérick Bordry, Steve Myers, Frank Zimmermann


CERN accelerators
North area
SPS
SPS: 26 to 450 GeV
TT 20
TI 2
West area
TT 60
LHC
TT 40
TI 8
TT 41
TT 10
nTOF
TT 2
AD
PSB: 50 MeV
to 1.4 GeV
CNGS
123
Booster
Isolde
LINAC2
LINAC3
East area
LEIR
PS:1.4 to 26 GeV
to Gran Sasso
CTF3
S. De Man 16/05/2003 - proportions not to scale

LHC: big, cold, high energy

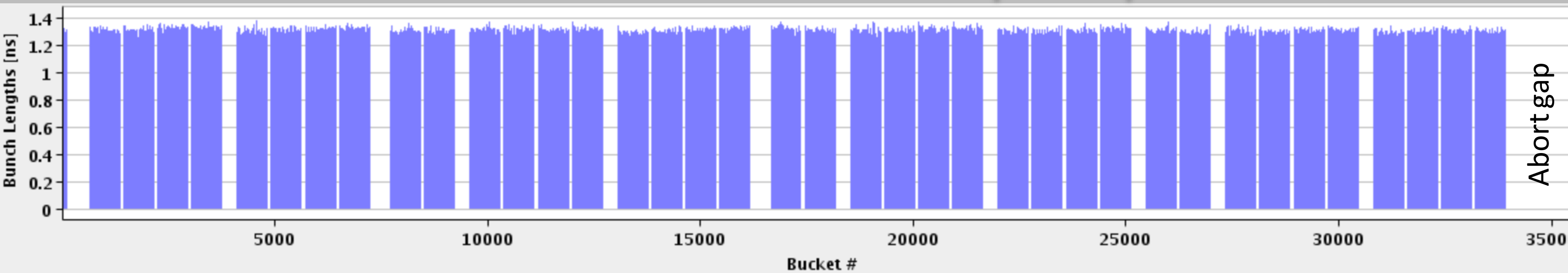


1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

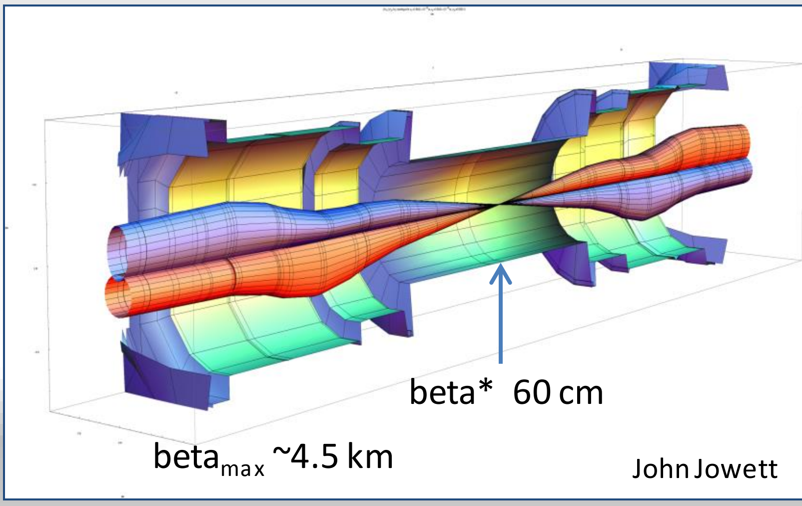
150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV

LHC bunch structure

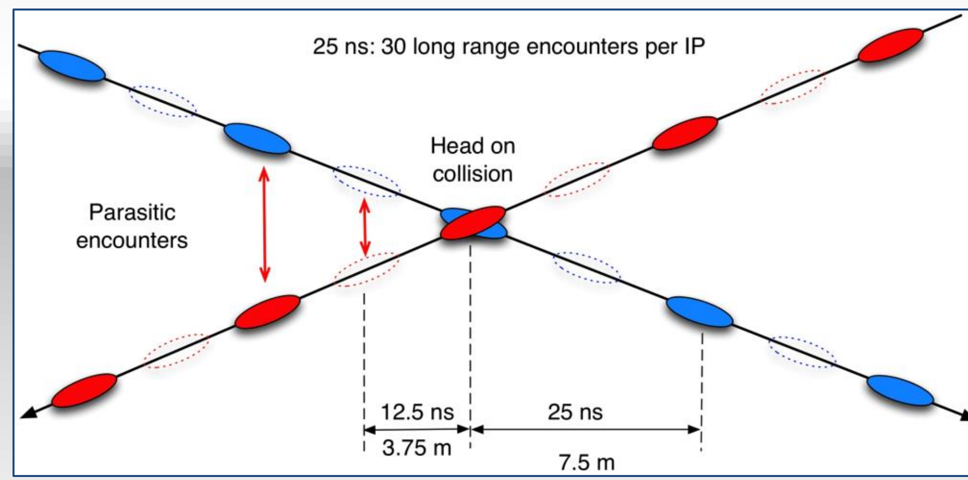
1 SPS injection



27 km 1380 bunches



$s^* \mu \sqrt{b^*}$

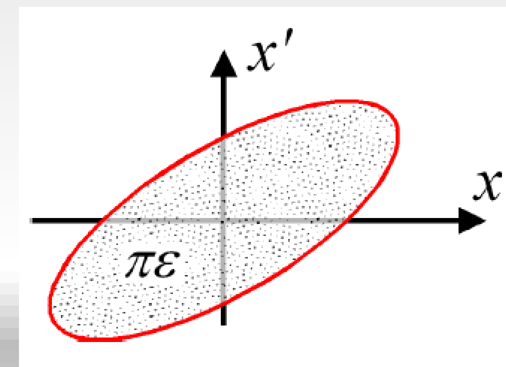


Luminosity

$$L = \frac{N^2 k_b f}{4 p s^*_x s^*_y} F = \frac{N^2 k_b f g}{4 p e_n b^*} F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
$ε_n$	**Normalized emittance**
β*	**Beta function at IP**

Round beams, beam 1 = beam 2

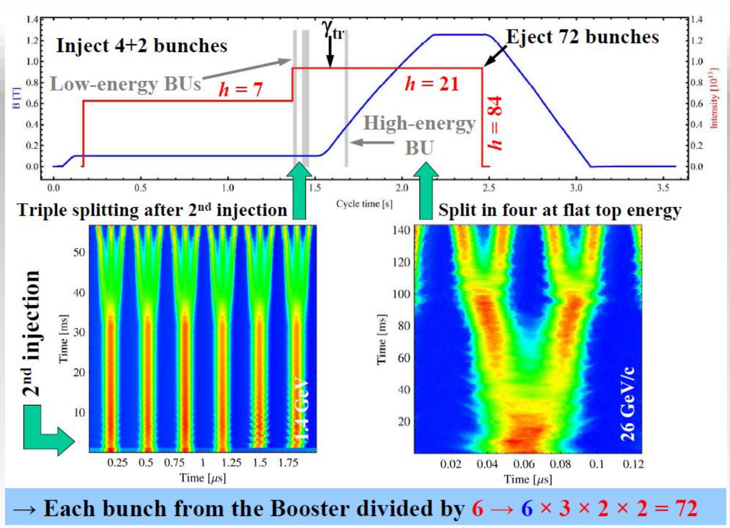


$$e_n = bge$$

$$s^* = \sqrt{b^* e}$$

Performance from injectors 2012

Bunch spacing [ns]	Protons per bunch [ppb]	Norm. emittance H&V [µm] Exit SPS
50	1.7×10^{11}	1.8
25	1.2×10^{11}	2.7
25 (design report)	1.15×10^{11}	3.75



Chose to stay with 50 ns:

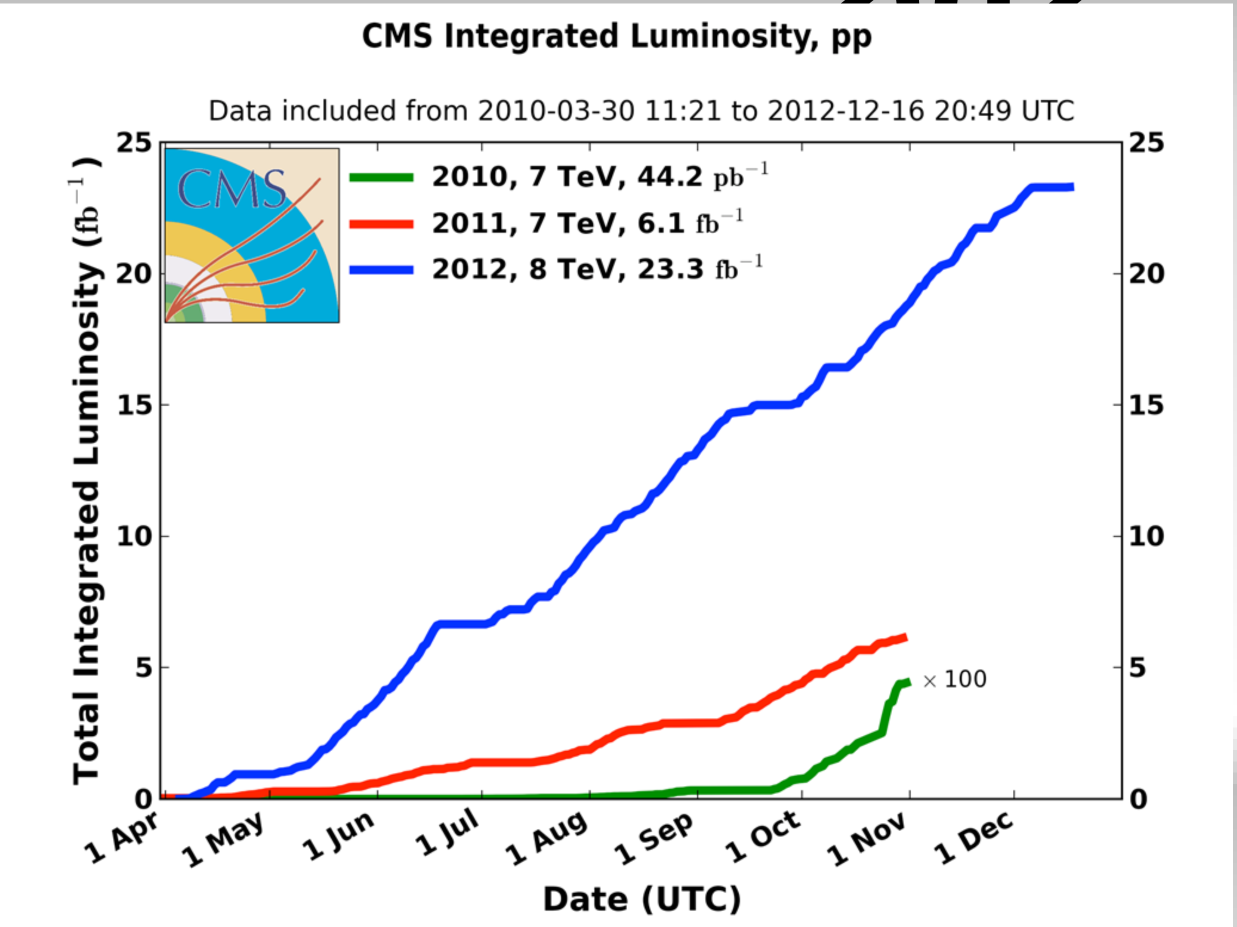
- I_b^2
- lower total intensity
- less of an electron cloud challenge

High pileup as a result

Peak performance through the years

	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	4	7
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

Integrated luminosity 2010-2012

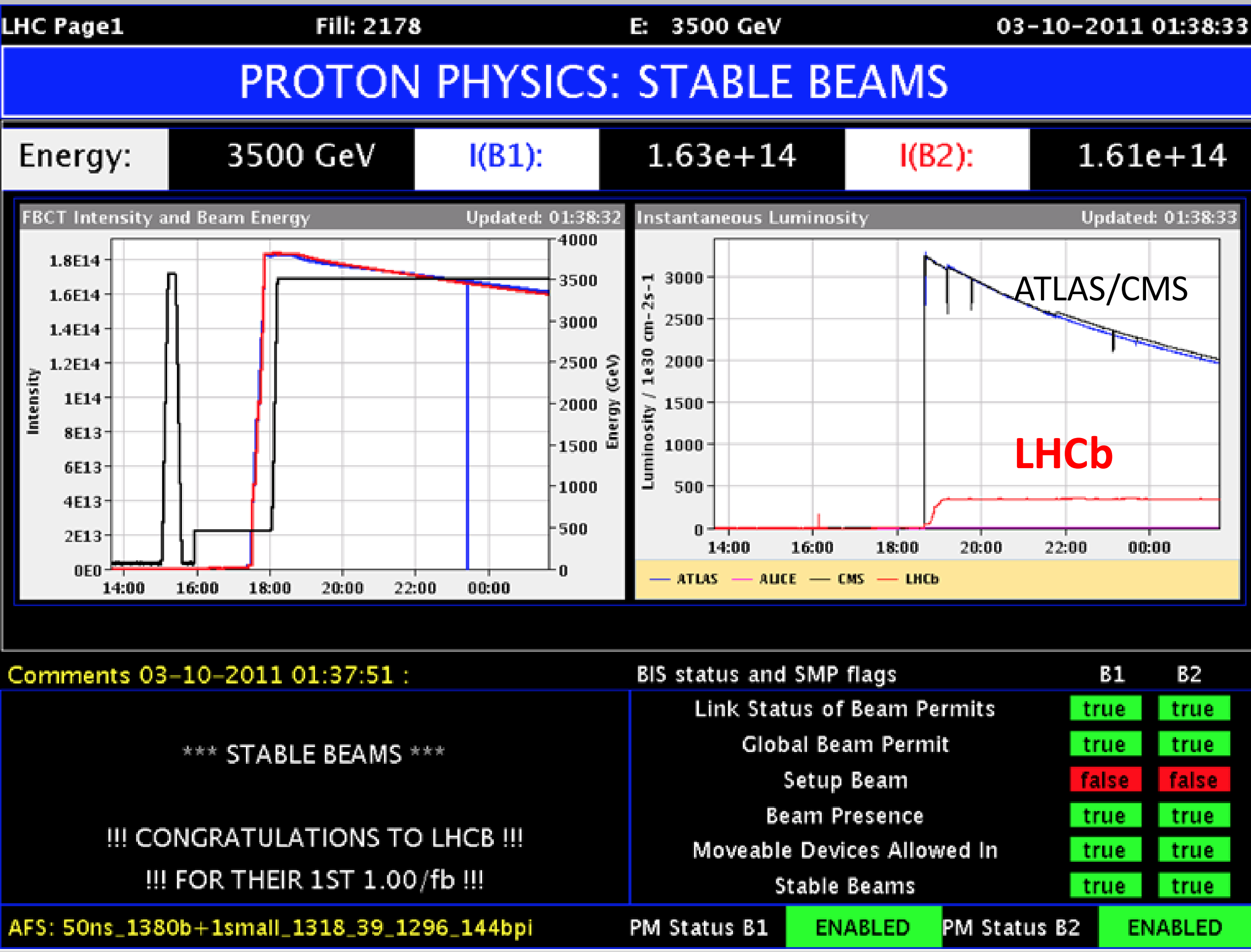


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

	2010	2011	2012
Max. luminosity delivered in 7 days [fb^{-1}]	0.025	0.58	1.35

We delivered 5.6 fb^{-1} to Atlas in 2011 and all we got was a blooming tee shirt

LHCb



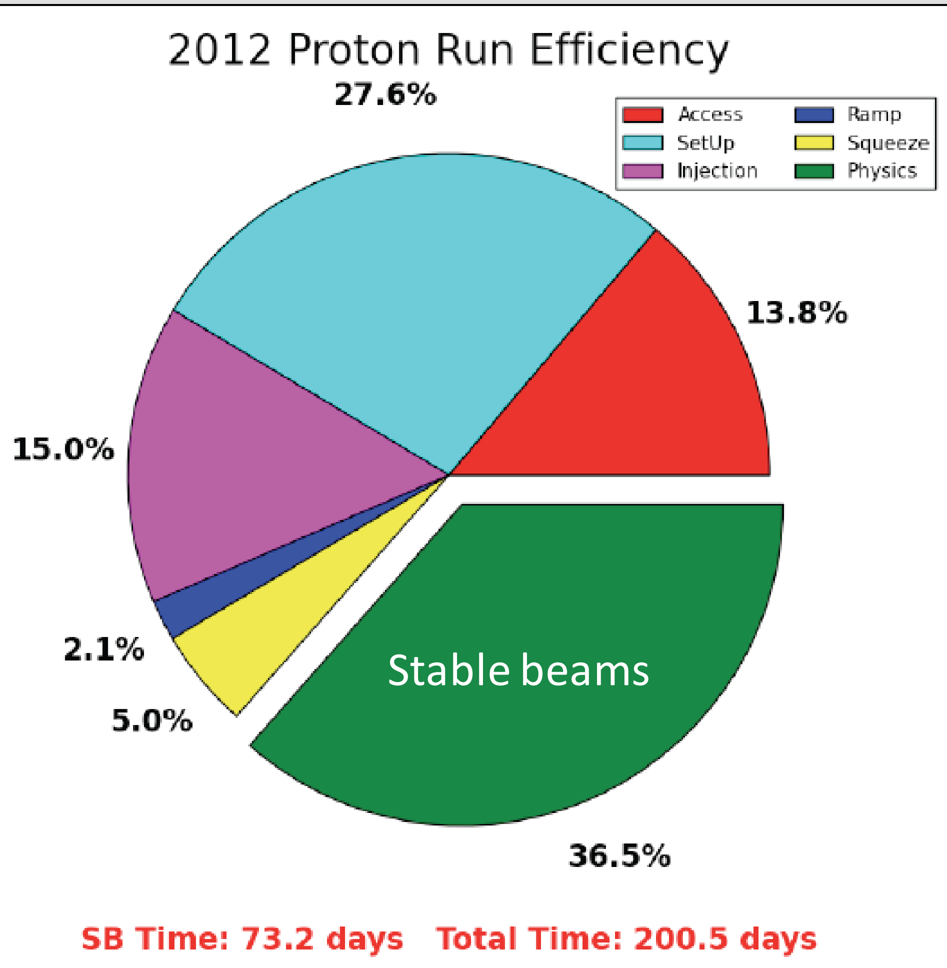
Luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation (with a tilted crossing angle)

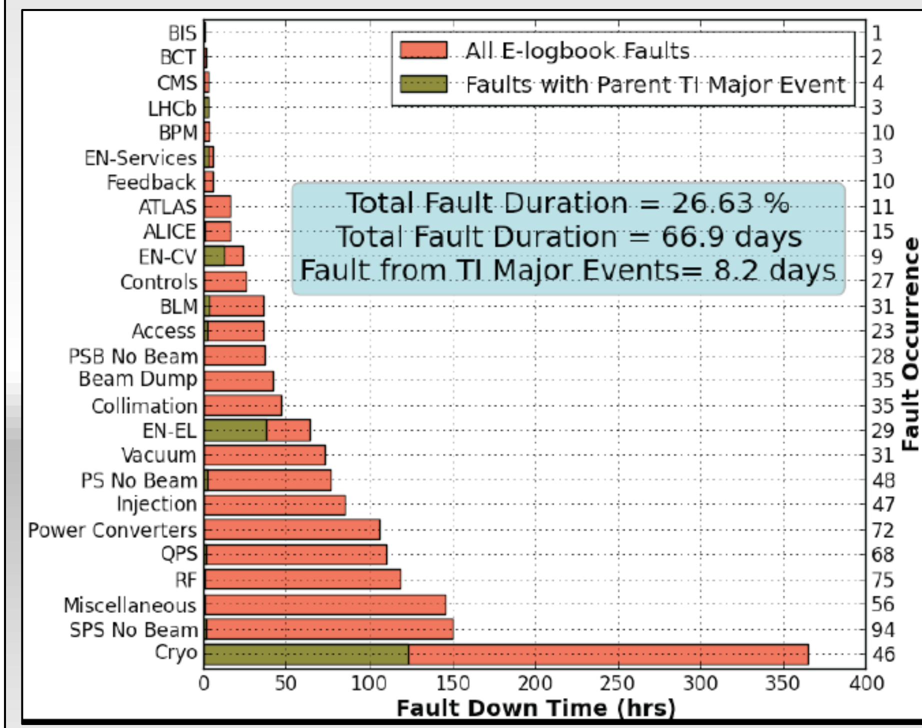
Not completely trivial!

Plus successful lead-lead (2010, 2011) and proton-lead (2013) runs

Availability

- There are a lot of things that can go wrong – it's always a battle
- Pretty good availability considering the complexity and principles of operation

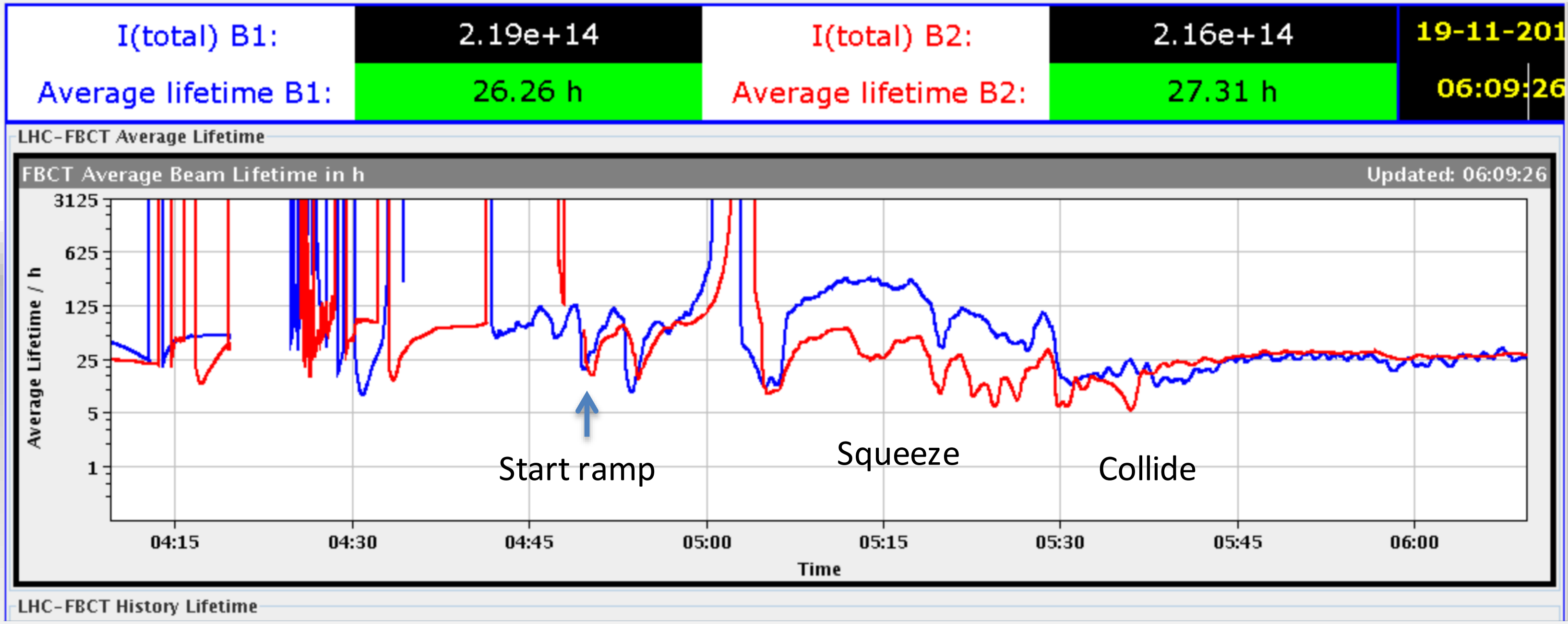




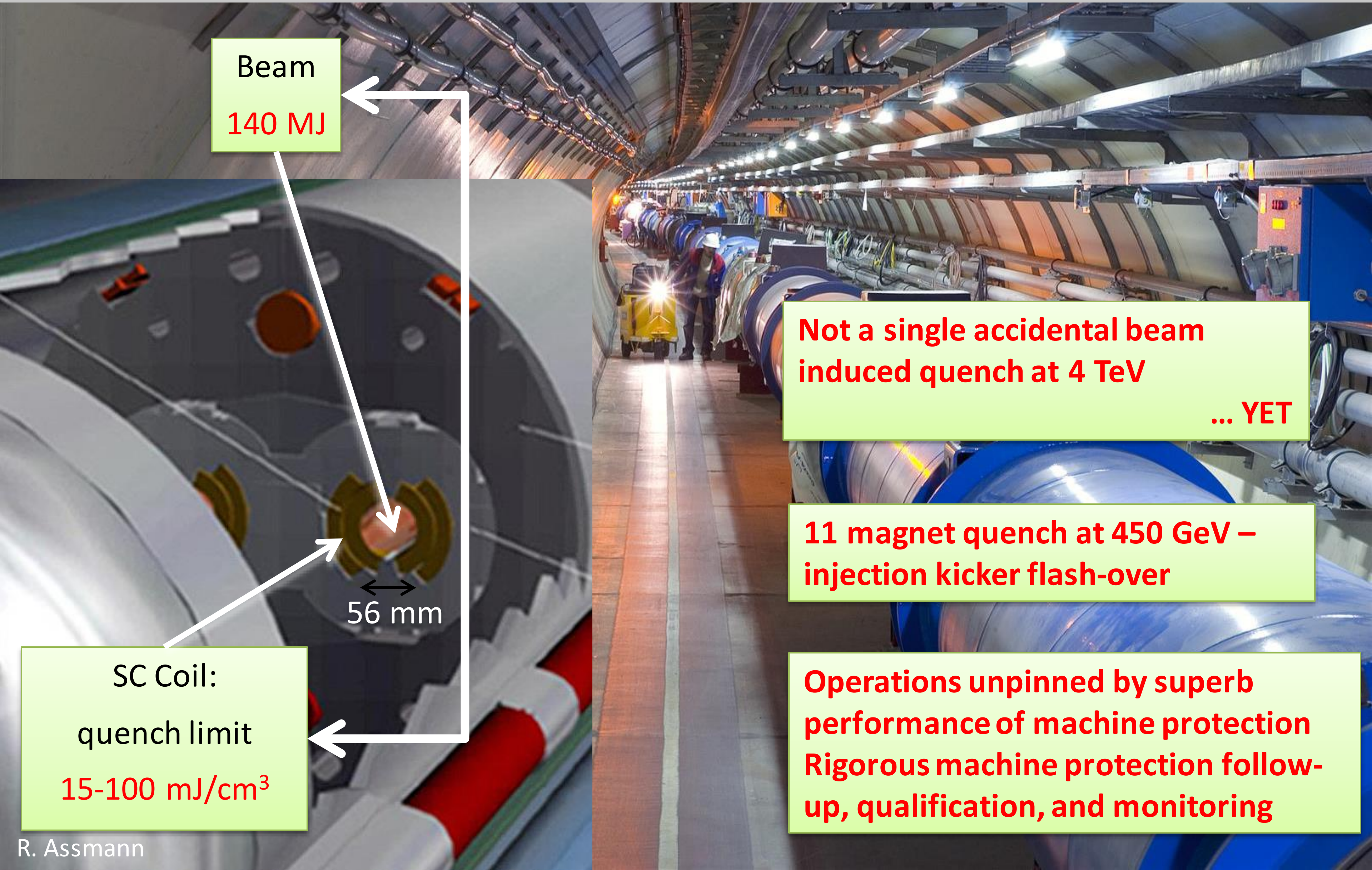
Cryogenics availability in 2012: 93.7%

Machine behaving well (in general)

- **Very good magnetic model, excellent field quality**
- **Linear optics**: close to model, corrected to excellent
- **Better than expected aperture**
- **Excellent single beam lifetime** – good vacuum conditions
- Low tune modulation, low power converter ripple, low RF noise



Machine protection



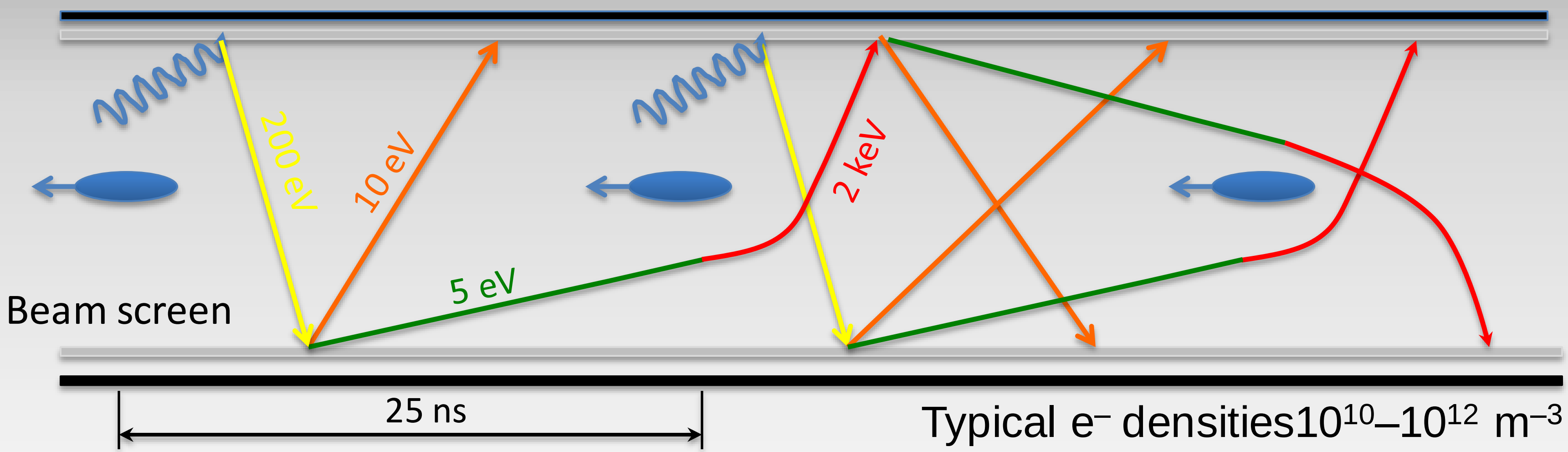
Not a single accidental beam induced quench at 4 TeV
… YET

11 magnet quench at 450 GeV – injection kicker flash-over

Operations unpinned by superb performance of machine protection
Rigorous machine protection follow-up, qualification, and monitoring

R. Assmann

25 ns & electron cloud



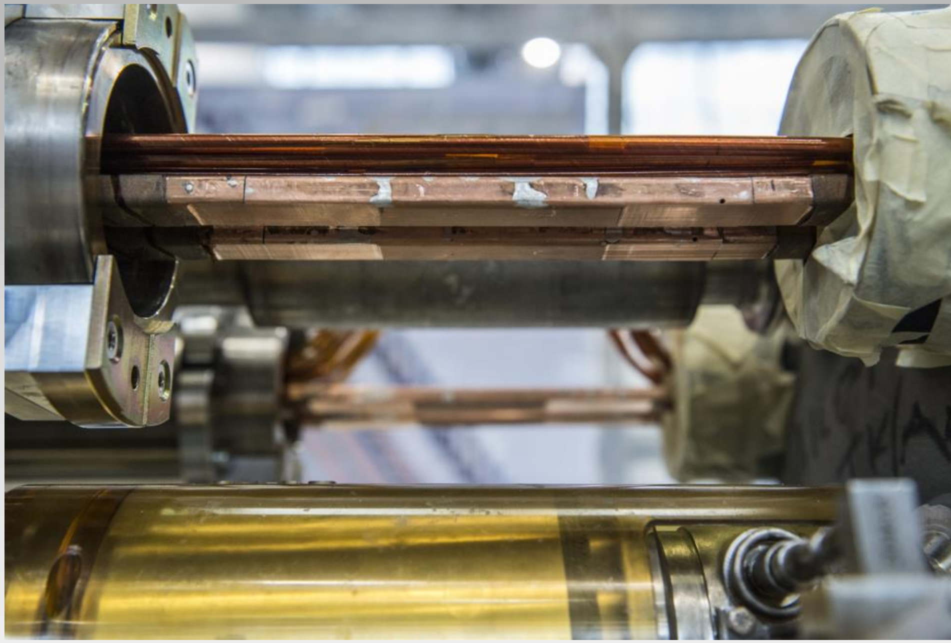
Possible consequences:

- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

Results from 2012 indicate that a scrubbing run will probably be insufficient to fully suppress electron cloud from the arcs for 25 ns beams.


25R7 / 27R7

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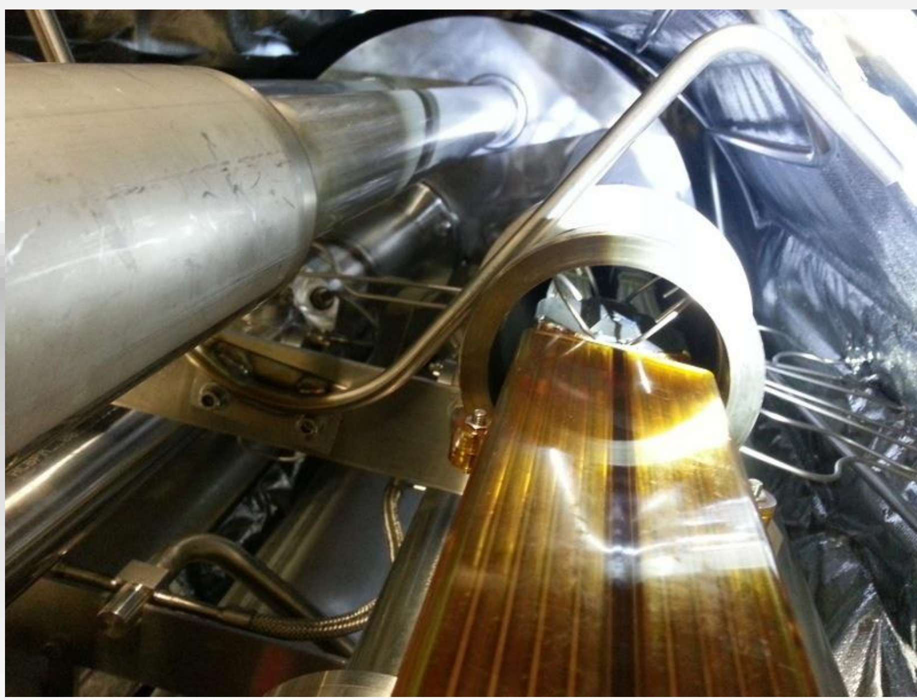
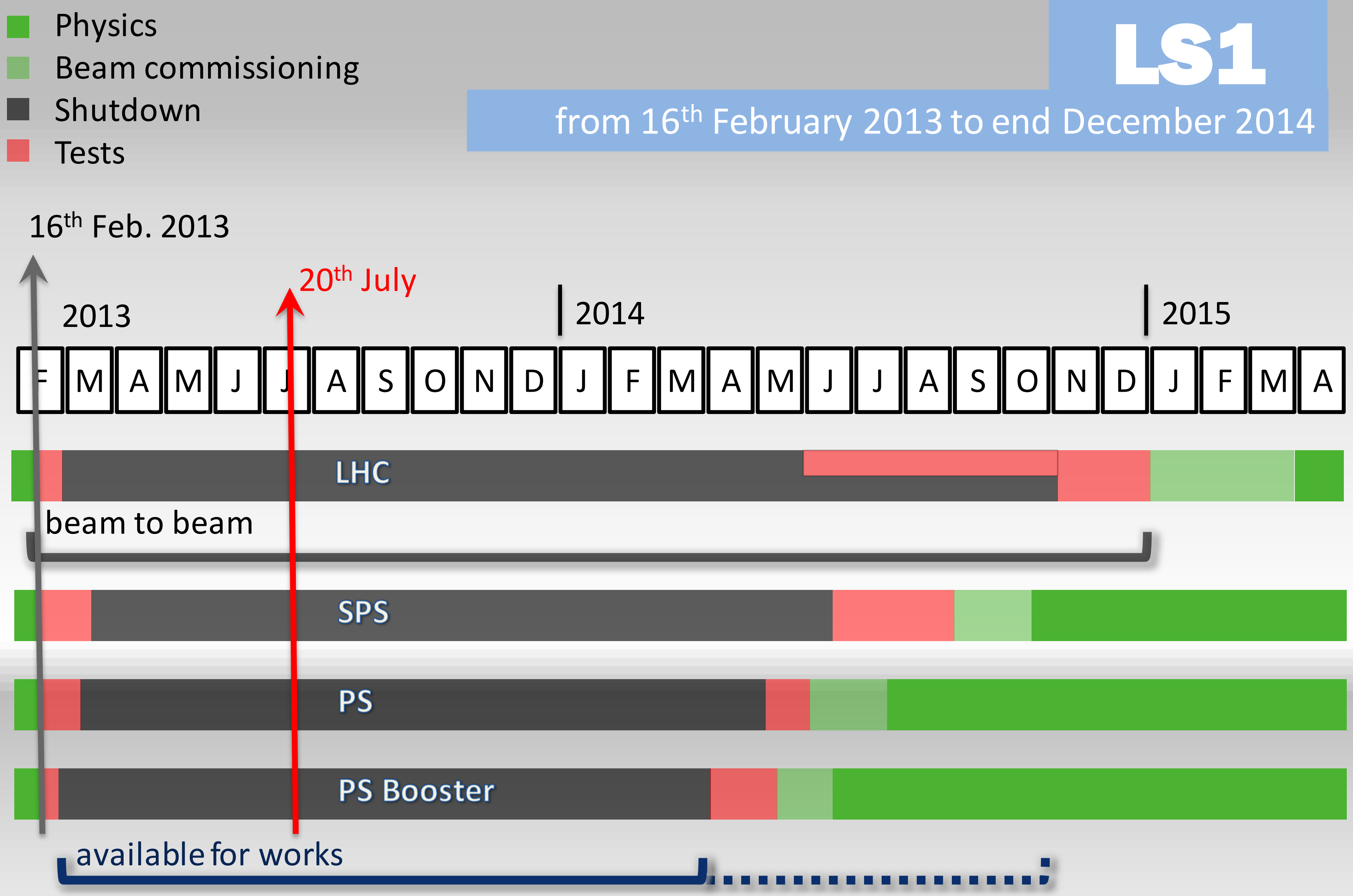


LS1

from 16th February 2013 to end December 2014

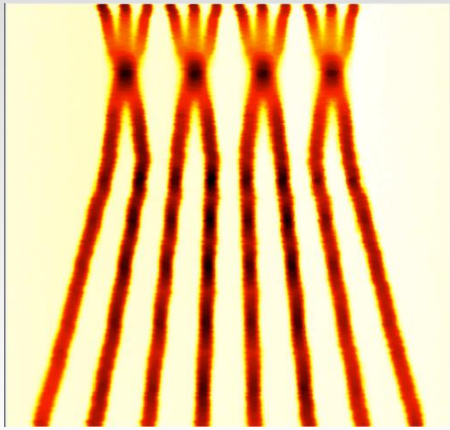


Frédérick Bordry

Run II – post LS1

- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



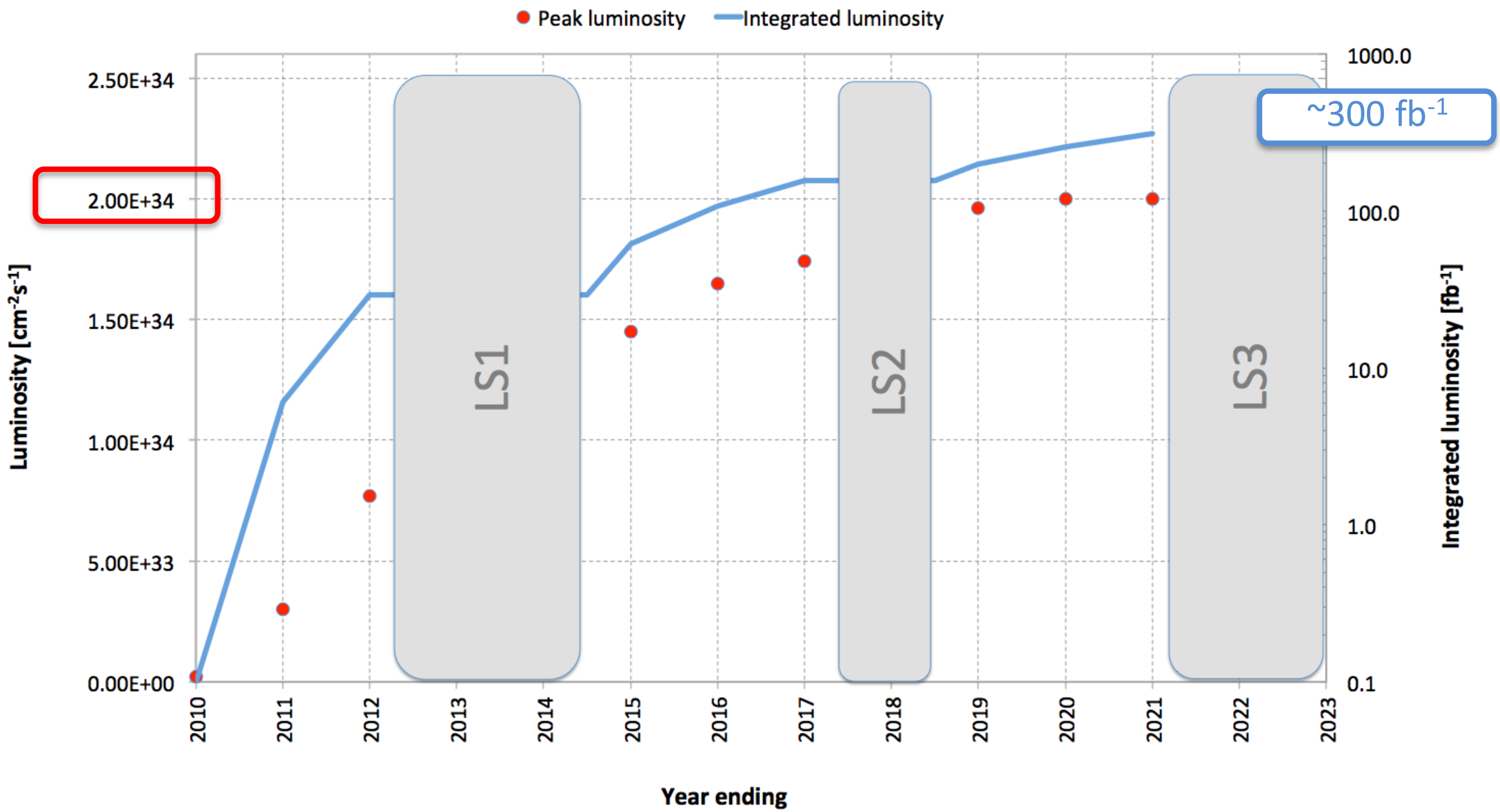
	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	**1.7e34**	49	~45

Next 10 years

2012	Run I	4 TeV, peak luminosity 7.7e33
2013	LS1	Splice consolidation, R2E, DN200... Experiments' consolidation and upgrades
2014		
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…) Experiments' HL upgrades
2023		

Review of LHC and Injectors Upgrade Plans
(RLIUP workshop) this October

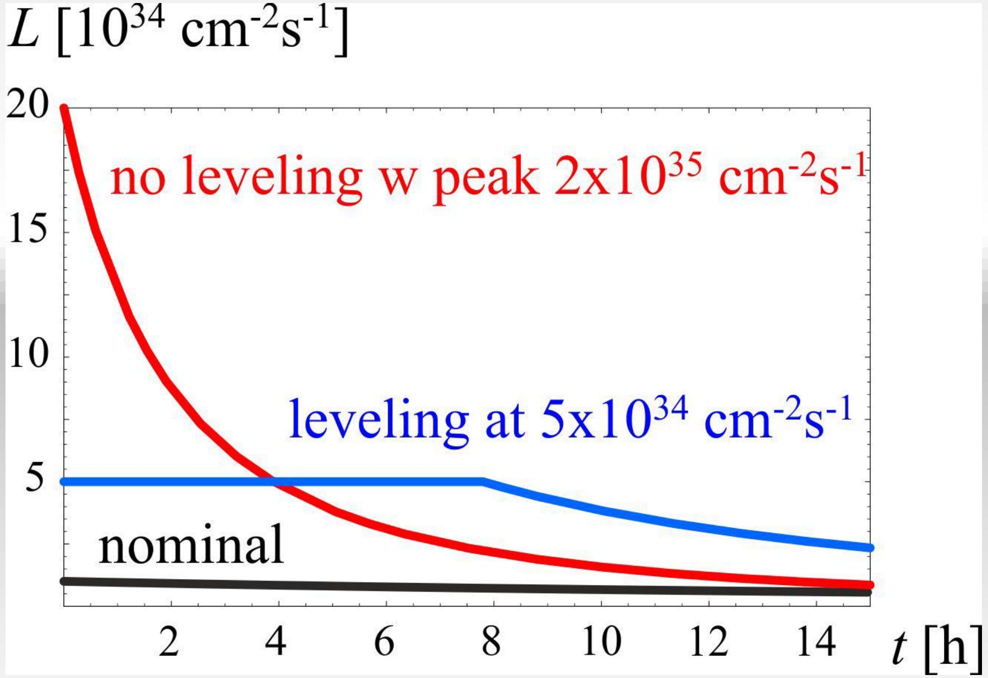
Luminosity evolution



Usual caveats apply

HL-LHC

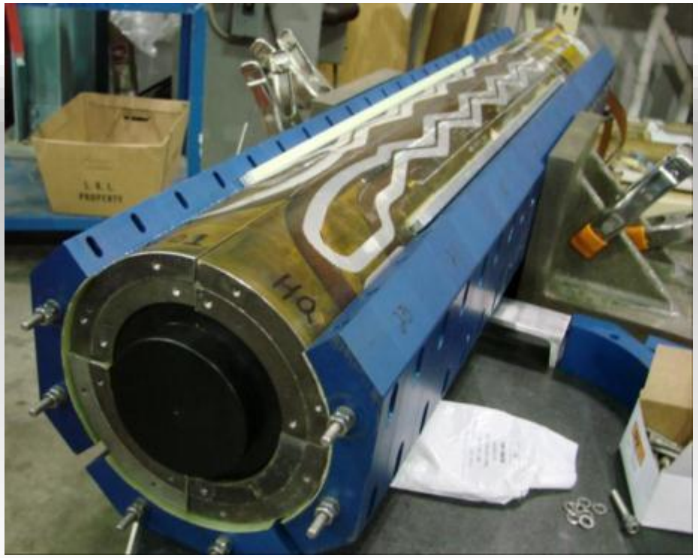
- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen (Linac 4, Booster 2GeV, PS and SPS)



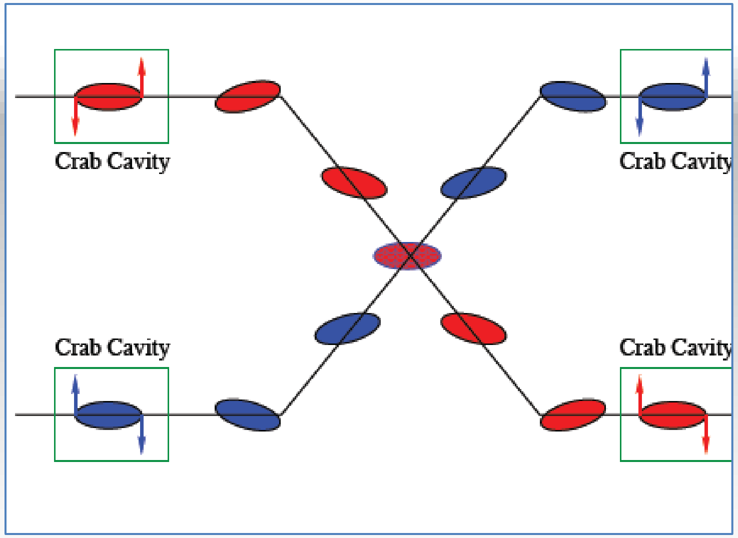
5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity
3 fb^{-1} per day
~250 fb^{-1} /year

HL-LHC: main thrusts

- Wide aperture Nb_3Sn quadrupoles
  - Optics and layout: beta* = 15 cm
- 11 T Nb_3Sn dipoles
  - Used to make room for collimation in dispersion suppression region
- Large Aperture NbTi separator magnets
  - First twin aperture magnets near interaction
- Crab cavities
  - Reduce the effect of the crossing angle
- Enhanced collimation for 500 MJ beams



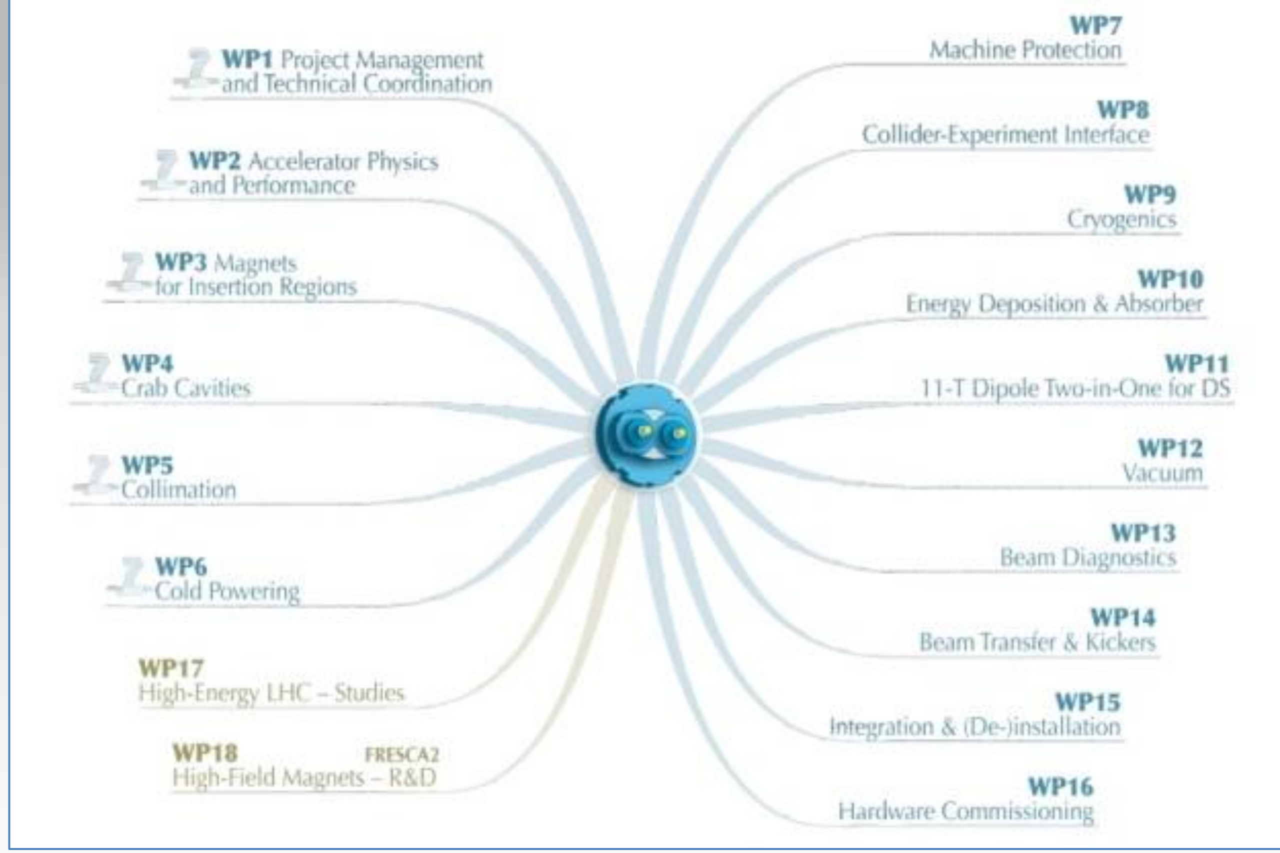
LARP: HQ02

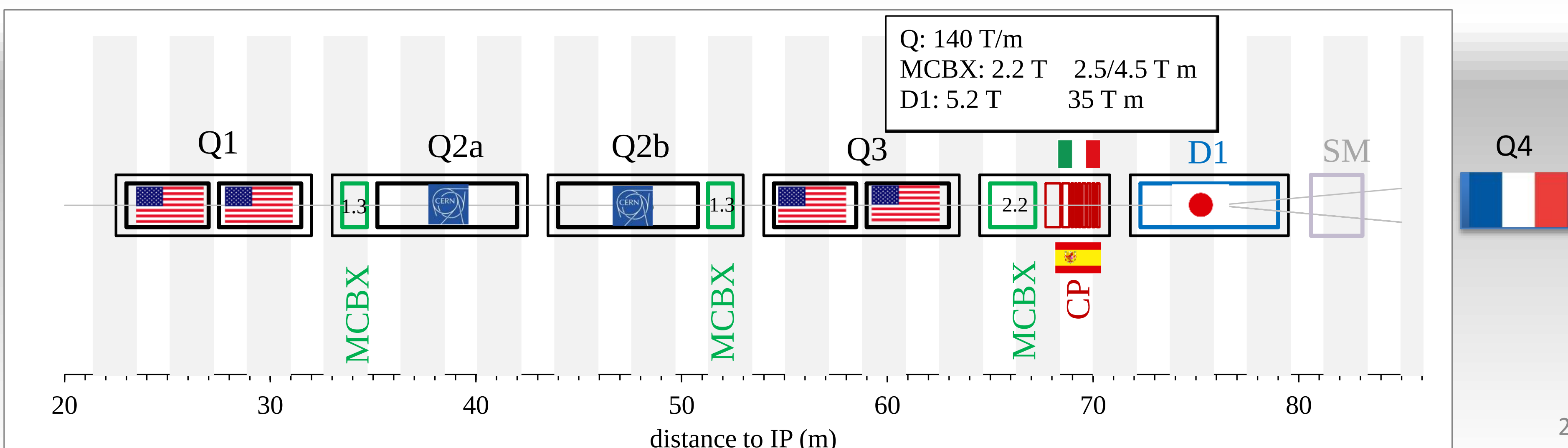


HL-LHC

Project firmly established under leadership of Lucio Rossi and Oliver Bruning

International collaboration with solid R&D program in place





HL-LHC: key 25 ns parameters

Protons per bunch	2.2×10^{11}
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	590 microrad
Geometric reduction factor	0.305
Peak luminosity	7.4×10^{34} $cm^{-2}s^{-1}$
Virtual luminosity	24×10^{34} $cm^{-2}s^{-1}$
Levelled luminosity	5×10^{34} $cm^{-2}s^{-1}$
Levelled <pile-up>	140

BEYOND

An invitation to further reading… e.g. last Saturday's accelerator session

The Circular Road to a Higgs Factory and Beyond Katsunobu OIDE *(KEK)*

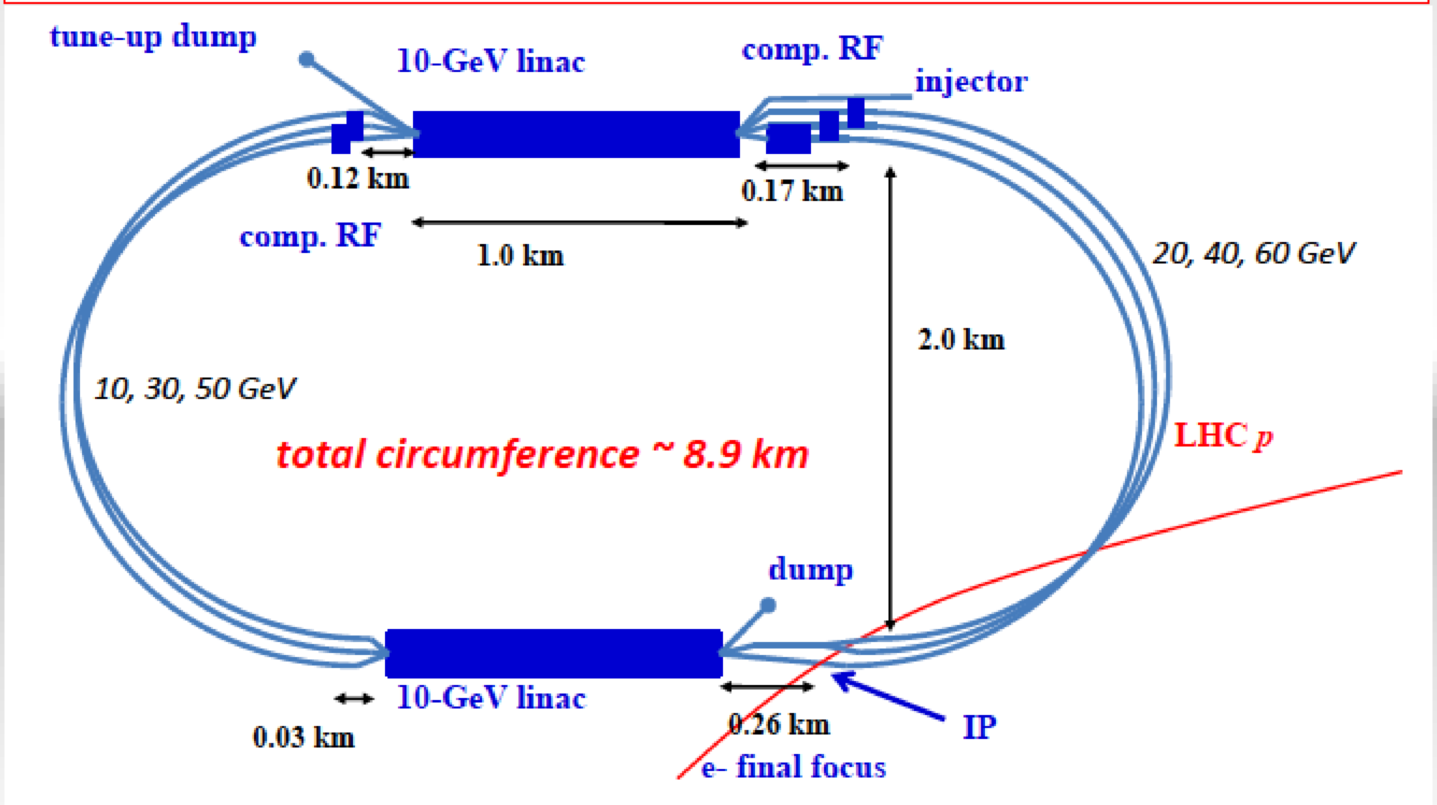
Research on high-field superconducting magnets and prospects for higher-energy hadron colliders Frederick BORDRY *(CERN)*

An energy recovery electron accelerator for DIS at the LHC Daniel SCHULTE *(CERN)*

Large Hadron Electron Collider: LHeC

- Foresees 60 GeV electrons on 7 TeV protons
- Conceptual design report published in June 2012
- Two e^- options: linac-ring (LR) and ring-ring (RR)

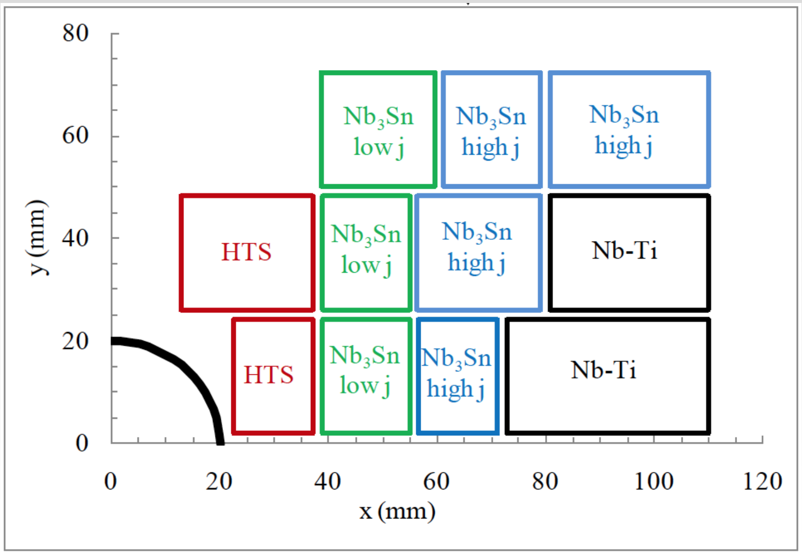
Linac-ring option: re-circulating linac with energy recovery



Oliver Bruning, Max Klein et al

High Energy LHC: HE-LHC

Re-equip existing LHC tunnel with high field magnets



Conceptual layout of 20 T dipole magnet (Nb_3Sn and HTS)

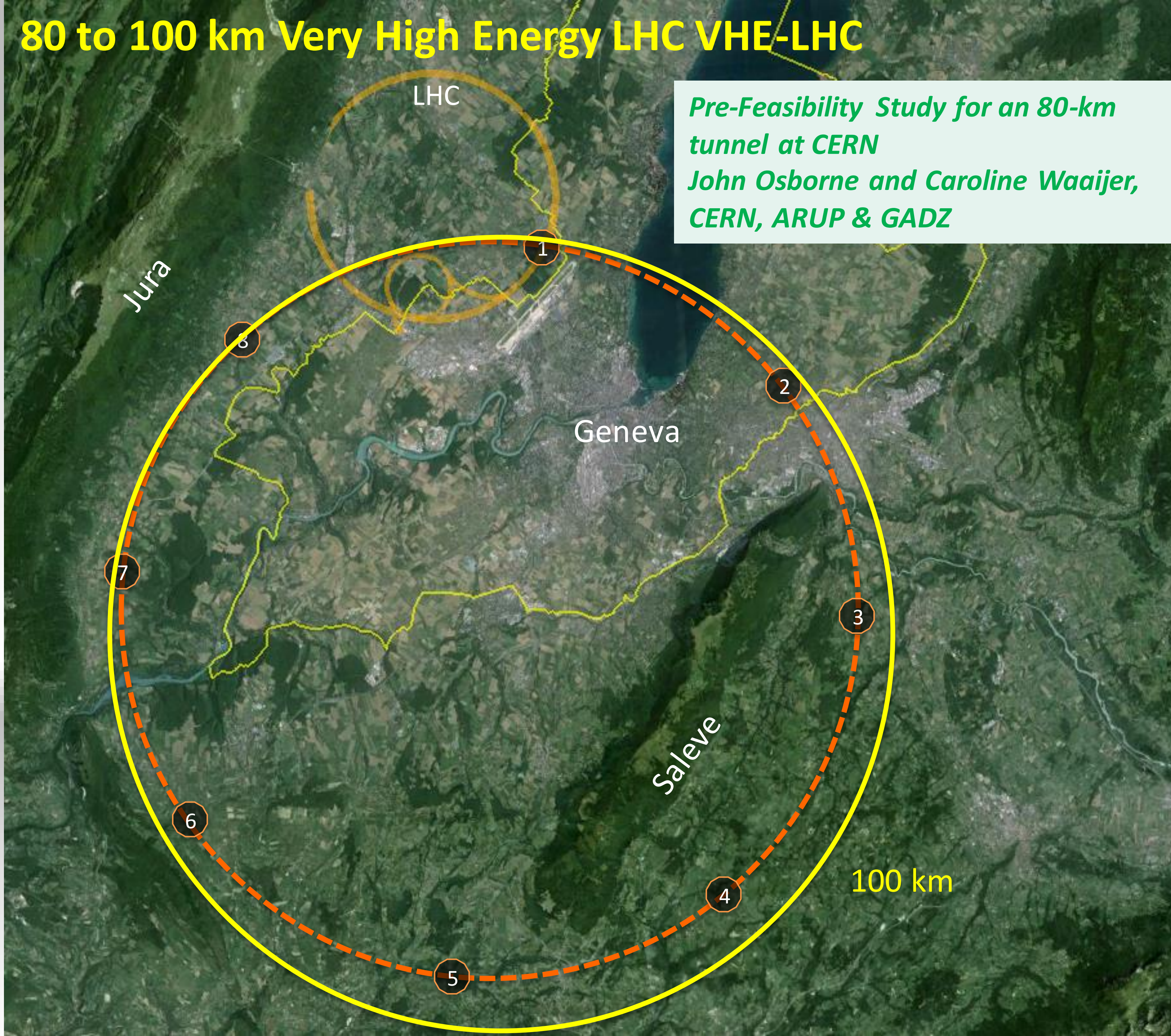
Intense R&D required

L. Rossi and E. Todesco

Circumference	26.7 km
Maximum dipole field	20 T
Injection energy from SC-SPS	1.3 TeV
Maximum c.o.m. energy	33 TeV
Peak luminosity	5×10^{34} $cm^{-2}s^{-1}$

80 to 100 km Very High Energy LHC VHE-LHC

Pre-Feasibility Study for an 80-km tunnel at CERN
John Osborne and Caroline Waaijer, CERN, ARUP & GADZ



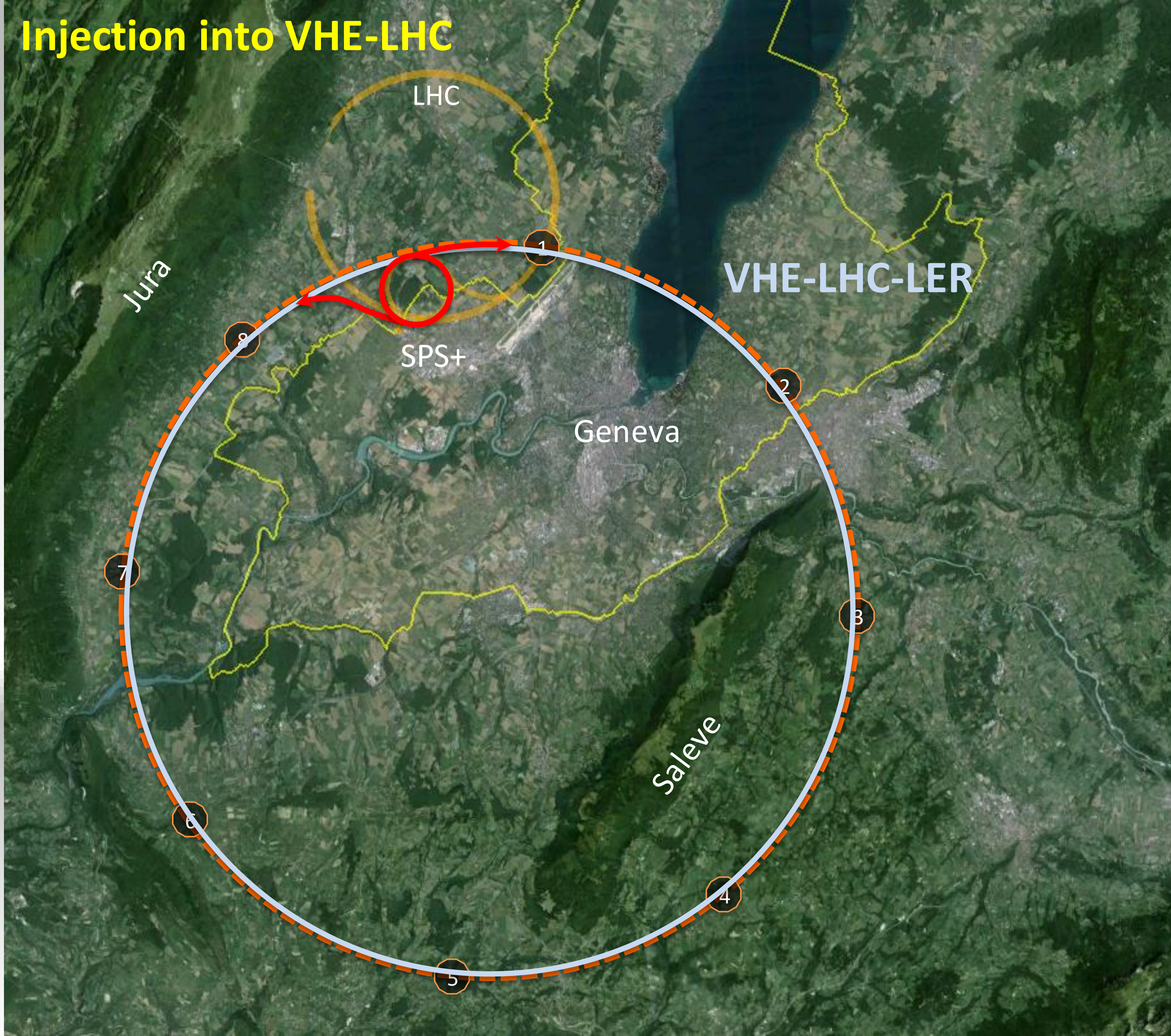
VHE-LHC

Circumference	80 or 100 km
Maximum dipole field	20 or 16 T
Injection energy	> 3.0 TeV
Maximum c.o.m. energy	100 TeV
Peak luminosity	5×10^{34} $cm^{-2}s^{-1}$
Stored beam energy	~5500 MJ

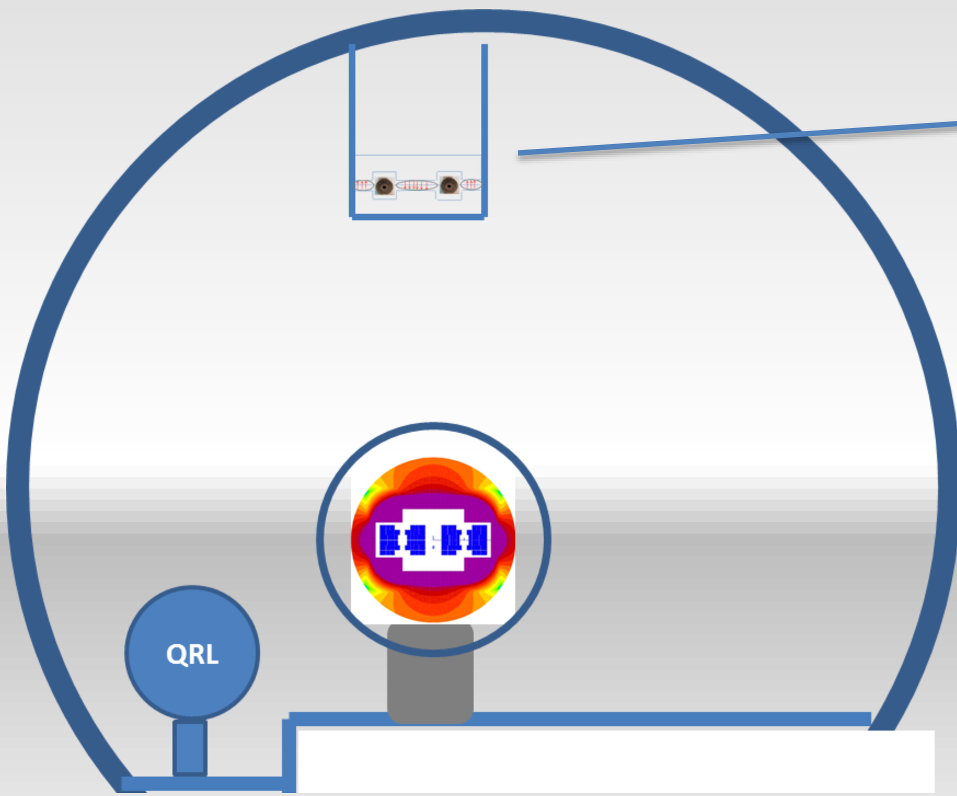
Among the many challenges:

- Synchrotron radiation heat load 33 W/m
- Collimation!
- IR quadrupoles
- Arc quadrupoles (naïve scaling gives 1593 T/m at 50 TeV beam energy)

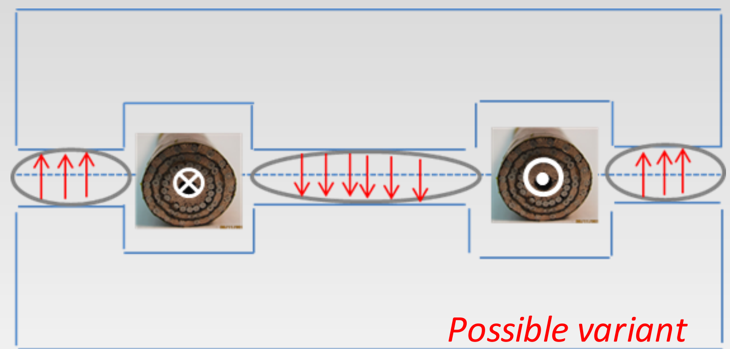
Injection into VHE-LHC



Possible VHE-LHC with LER



"Pipetron" using transmission line magnets (W. Foster, H. Piekarz)



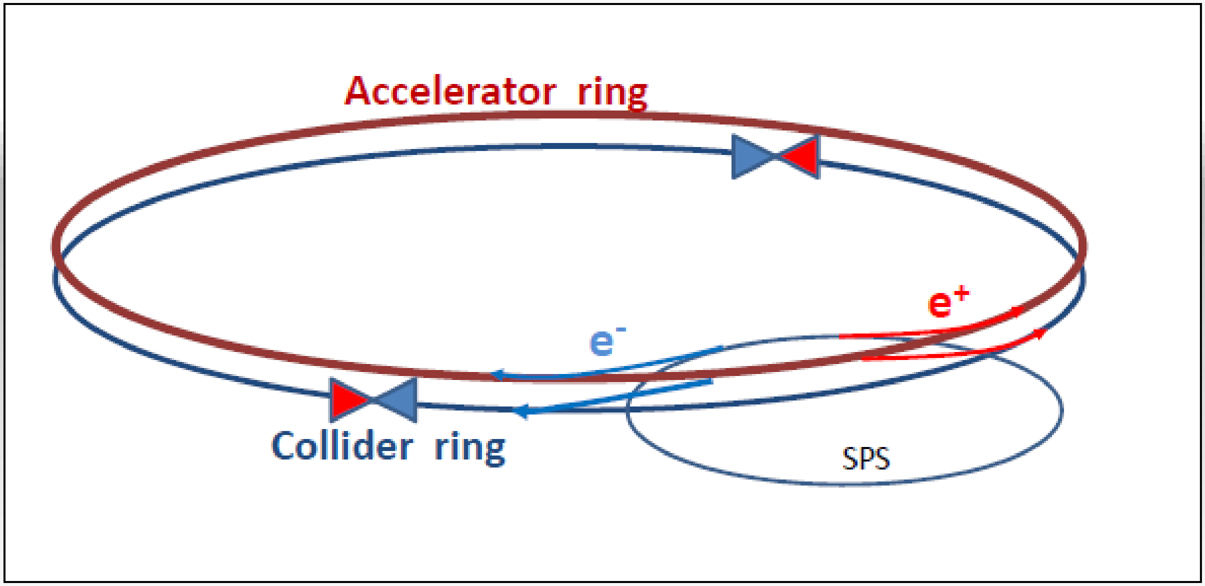
- Relatively cheap
- Limited cryogenic power – HTS

	energy [TeV]	field [T]
SPS	0.026	0.117
	↓	↓
	0.450	2.03
injector	0.450	0.167
80 km tunnel	↓	↓
ρ = 9.0 km	4.1	1.5

LER also suitable for e^+/e^- …

TLEP

- Circular electron-positron collider in new 80 – 100 km tunnel
  - Storage ring has separate beam pipes for e^+ and e^- for multi-bunch operation up to 350 GeV c.m.
  - top-up injection with an ancillary accelerator
  - Very high luminosity at Z pole and above WW threshold with operation up to tt threshold
- Using the tunnel before installation of the VHE-LHC



TLEP: parameters

Beam lifetime dominated by Bhabha scattering and bremstrahlung

	TLEP Z	TLEP W	TLEP H	TLEP t
E c.m. [GeV]	91	160	240	350
#bunches/beam	7500	3200	167	160
Peak luminosity [x 10^{34} $cm^{-2}s^{-1}$]	59	16	5	1.3
Beam lifetime to Bhabha [min.]	99	38	24	21
Beam lifetime to bremstrahlung [min.]	> 1025	>106	38	14

	TLHeC		VHE-TLHeC	
species	$e^{\pm}$	p	$e^{\pm}$	p
beam energy [GeV]	**60/120**	**7000**	**60/120**	**50000**

Frank Zimmermann et al

Conclusions 1/2 (LHC)

- Reasonably good performance from commissioning through run I
  - 2 years 3 months from first collisions to Higgs
- Foundations firmly laid for run II

Conclusions 2/2

From CERN's Medium Term Plan 2013

- A design study team will be set up during 2013 with the launch of the design study proposal.
  - Pre-studies have been launched for hadron colliders (VHE-LHC/HE-LHC), lepton colliders (TLEP) and hadron-lepton colliders (VHE-LHeC).

- Studies and R&D for high field magnets as well as high-gradient and high beam power superconducting RF cavities for the HL-LHC, HE-LHC, VHE- LHC (and TLEP) will enhance common efforts and exploit synergies.

Acknowledgements

The LHC is enjoying benefits of the decades long international design, construction, installation effort.

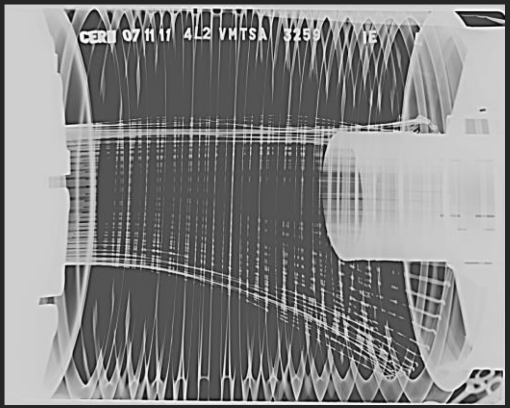
Progress with beam represents phenomenal effort by all the teams involved, injectors included.

RESERVE

Some issues…

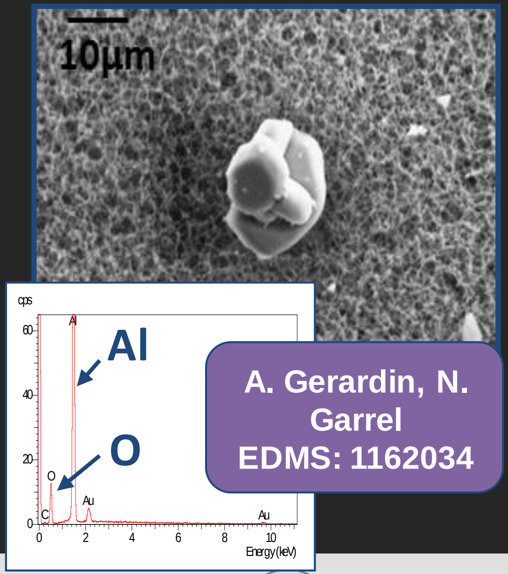
Beam induced heating

- 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



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