The LHC machine - present and future

Part 2

- Overview of the current machine, performance and limitations
- Upgrades towards ultimate luminosity
- Possibilities and challenges for higher energy

Mike Lamont
with acknowledgements to the people whose material I've used

FOLLOW-UP TO QUESTIONS

HTS current leads

- The LHC HTS current leads operate in a temperature range between room temperature and the saturated liquid helium bath.
- They consist of a resistive section, convection cooled by helium gas available in the LHC machine at a nominal temperature of about 20 K, and a superconducting section, self-cooled by the vapour generated by the lead itself at 4.5 K. The two circuits are hydraulically separated.
- The warm end of the superconducting section, T_{HTS}, is maintained at 70 K in stand-by operation and at 50 K in operation with current.

http://at-mel-cf.web.cern.ch/at-mel-cf/html/HTS_leads.htm

Right of ATLAS

TE-VSC Group

J.M. Jimenez

High field magnets

- The maximum field reached in an accelerator-type dipole is around 14 T at 4.5 K, using Nb_3Sn conductor, in an aperture similar to the HE-LHC requirements (40 mm).
- Due to the shape of the critical surface, the maximum field attainable with Nb_3Sn accelerator magnets is around 18 T.
- Superconducting cables based on HTS are able to withstand fields larger than 15 T: they have been successfully used in high-field solenoids but not in accelerator dipoles.

CONCEPTUAL DESIGN OF 20 T DIPOLES FOR HIGH-ENERGY LHC

L. Rossi, E. Todesco, CERN, Geneva, Switzerland 2011

PERFORMANCE THUS FAR

Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

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**

$$\sigma^* = \sqrt{\beta^*\varepsilon}$$

$$\varepsilon_N = 2.5 \times 10^{-6}\ \mathrm{m.rad}$$

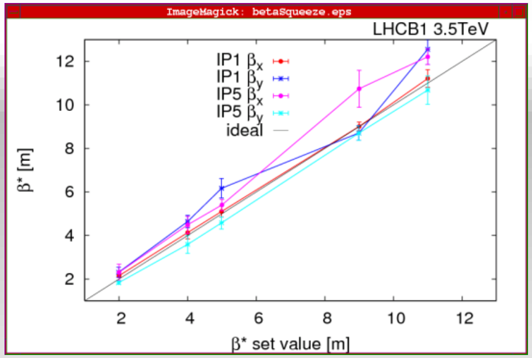
$$\varepsilon = 3.35 \times 10^{-10}\ \mathrm{m.rad}$$

$$\sigma^* = 11.6 \times 10^{-6}\ \mathrm{m}$$

$$\left(p = 7\ \mathrm{TeV},\ \beta^* = 0.4\ \mathrm{m}\right)$$

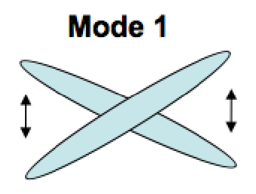
Feb 27
Beam back

March 30
First collisions
3.5 TeV



April
Commission
squeeze

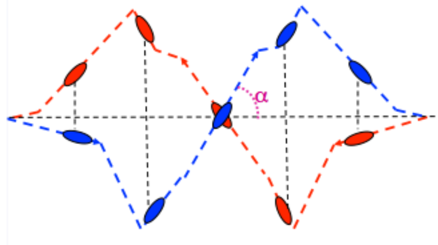
June
Commission
nominal bunch
intensity

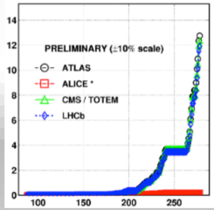


February | March | April | May | June | July | August | September | October | November

QUALIFICATION

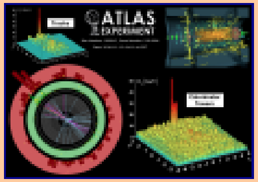
September
Crossing angles on





October 14 2010
1e32
248 bunches

November: jet
"quenching" in HI

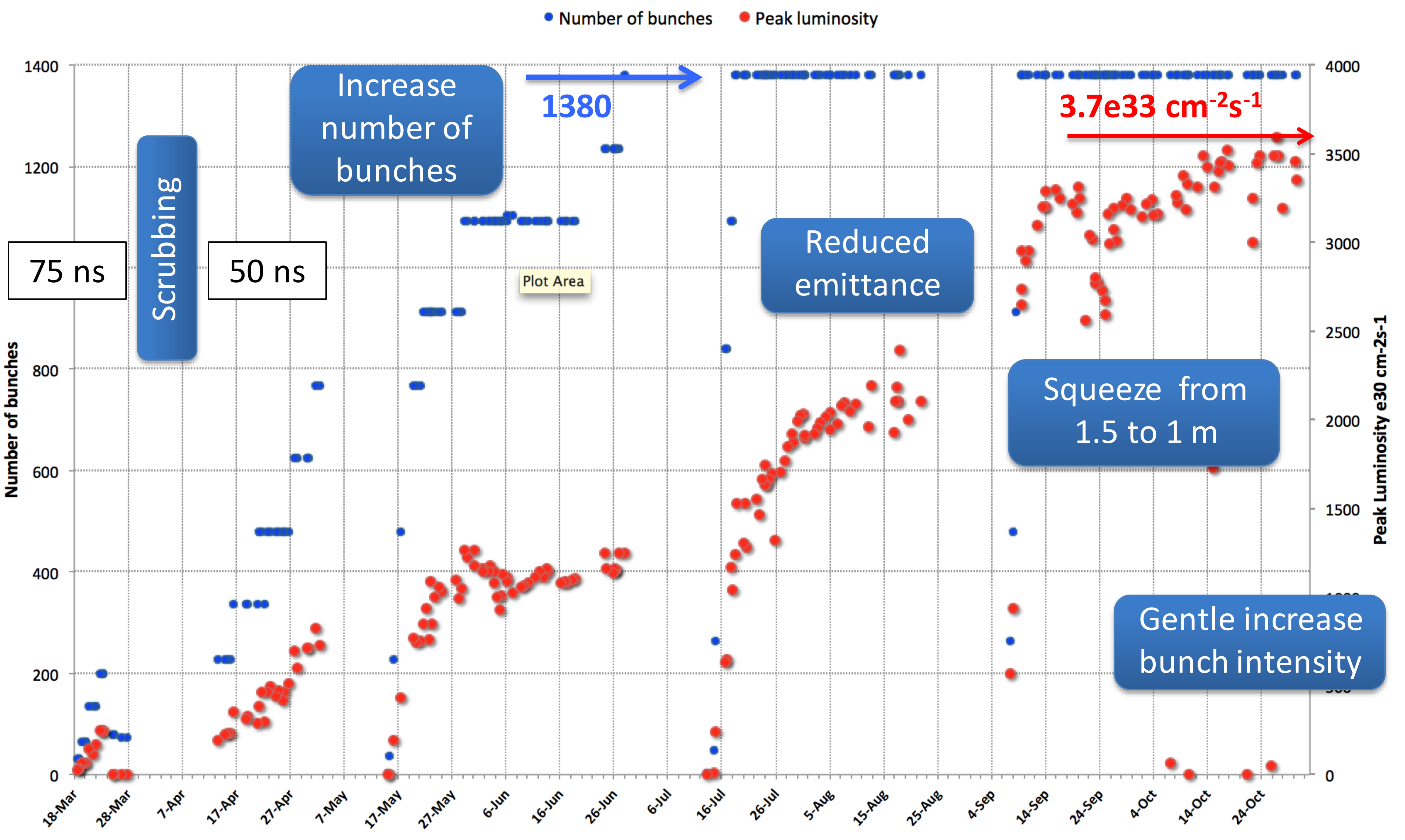


November 4
Switch to lead
ions

Total for year: 50 pb^{-1}

2011

3.5 TeV
Beta* = 1.5 m



75 ns

Scrubbing

50 ns

Increase number of bunches

1380

Reduced emittance

3.7e33 $cm^{-2}s^{-1}$

Squeeze from 1.5 to 1 m

Gentle increase bunch intensity

4 TeV
50 ns
Beta* = 60 cm
Tight collimator settings

March | April | May | June | July | August | September | October | November | December

March 15
Beam back

March 18
Squeezed to 60 cm

18 April
1380 bunches
5.5e33 $cm^{-2}s^{-1}$

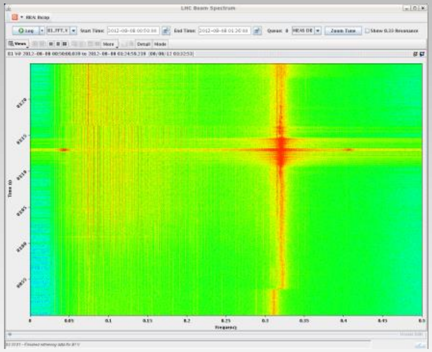
6 June
6.8e33 $cm^{-2}s^{-1}$

ICHEP2012
Melbourne

18 June: end running period ~6.7 fb^{-1} for summer conferences

4 July

7 August
Flip octupole polarity
Raise chromaticity

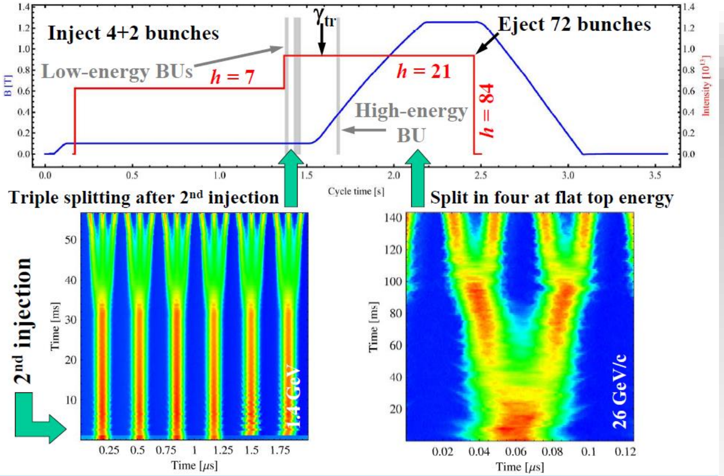


13-14 September
Proton-lead test

December
25 ns scrubbing run

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



→ Each bunch from the Booster divided by 6 → 6 × 3 × 2 × 2 = 72

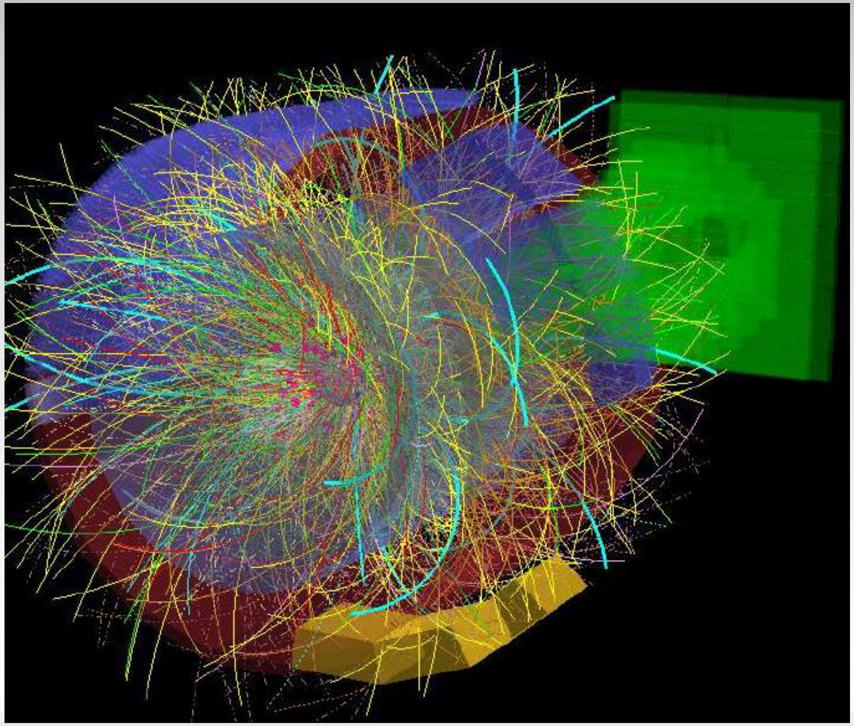
Chose to stay with 50 ns:

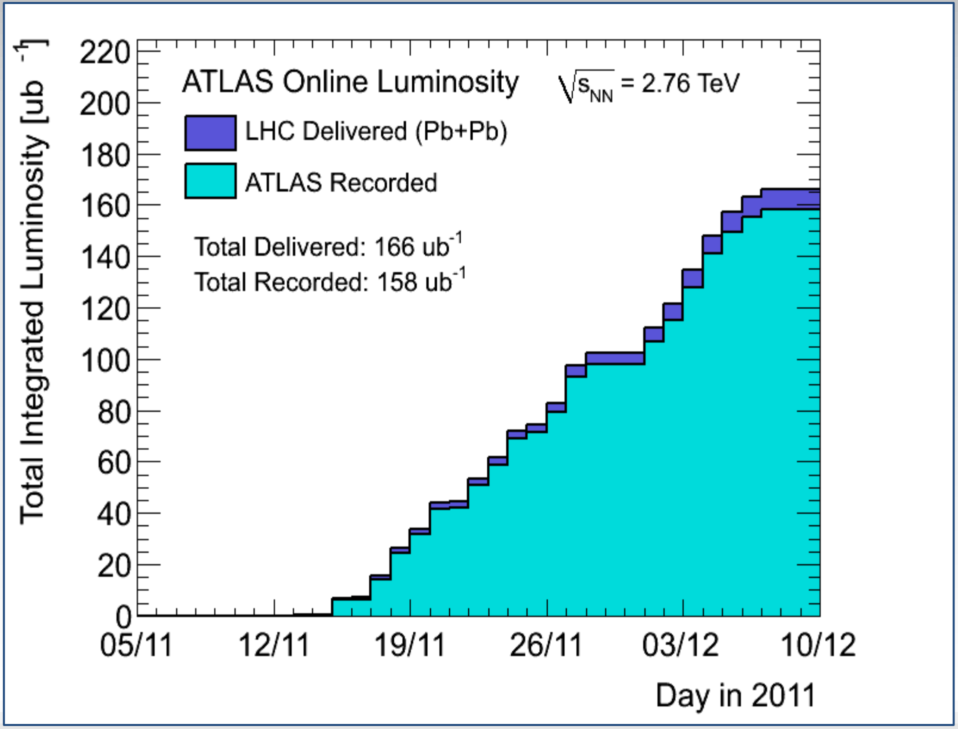
- I_b^2
- lower total intensity
- less of an electron cloud challenge

Peak performance through the years

	2010	2011	2012	Nominal
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}

Pb-Pb

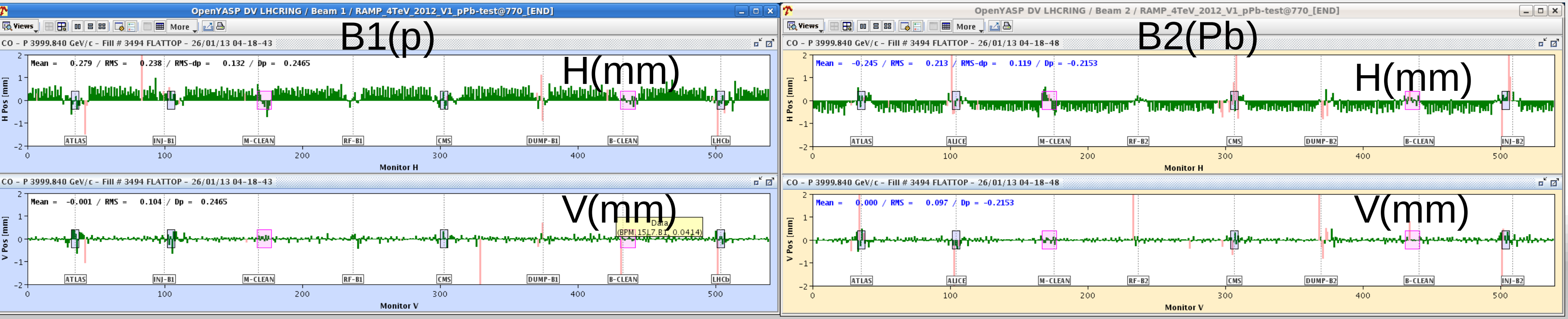




- Good performance from the injectors - bunch intensity and emittance
- Preparation, Lorentz's law: impressively quick switch from protons to ions
- Peak luminosity around 5 x 10^{26} cm^{-2}s^{-1} at 3.5Z TeV – nearly twice design when scaled to 6.5Z TeV

Proton-lead

- Beautiful result
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- Injectors: average number of ions per bunch was ~1.4x10^{8} at start of stable beams, i.e. around twice the nominal intensity



OpenYASP DV LHCRING / Beam 1 / RAMP_4TeV_2012_V1_pPb-test@770_[END]

CO - P 3999.840 GeV/c - Fill # 3494 FLATTOP - 26/01/13 04-18-43

Mean = 0.279 / RMS = 0.238 / RMS-dp = 0.132 / Dp = 0.2465

CO - P 3999.840 GeV/c - Fill # 3494 FLATTOP - 26/01/13 04-18-43

Mean = -0.001 / RMS = 0.104 / Dp = 0.2465

OpenYASP DV LHCRING / Beam 2 / RAMP_4TeV_2012_V1_pPb-test@770_[END]

CO - P 3999.840 GeV/c - Fill # 3494 FLATTOP - 26/01/13 04-18-48

Mean = -0.245 / RMS = 0.213 / RMS-dp = 0.119 / Dp = -0.2153

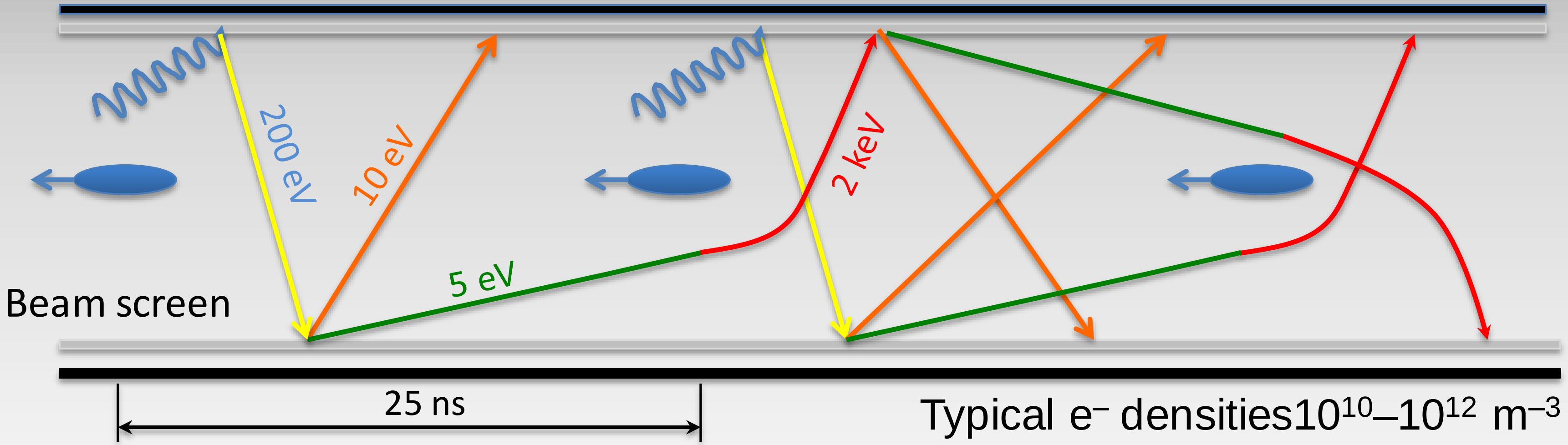
CO - P 3999.840 GeV/c - Fill # 3494 FLATTOP - 26/01/13 04-18-48

Mean = 0.000 / RMS = 0.097 / Dp = -0.2153

Beam orbits at top energy with RF frequencies locked to B1

LIMITATIONS

25 ns & electron cloud



Typical e$^-$ densities 10^{10}–10^{12} m^{-3}

Possible consequences:

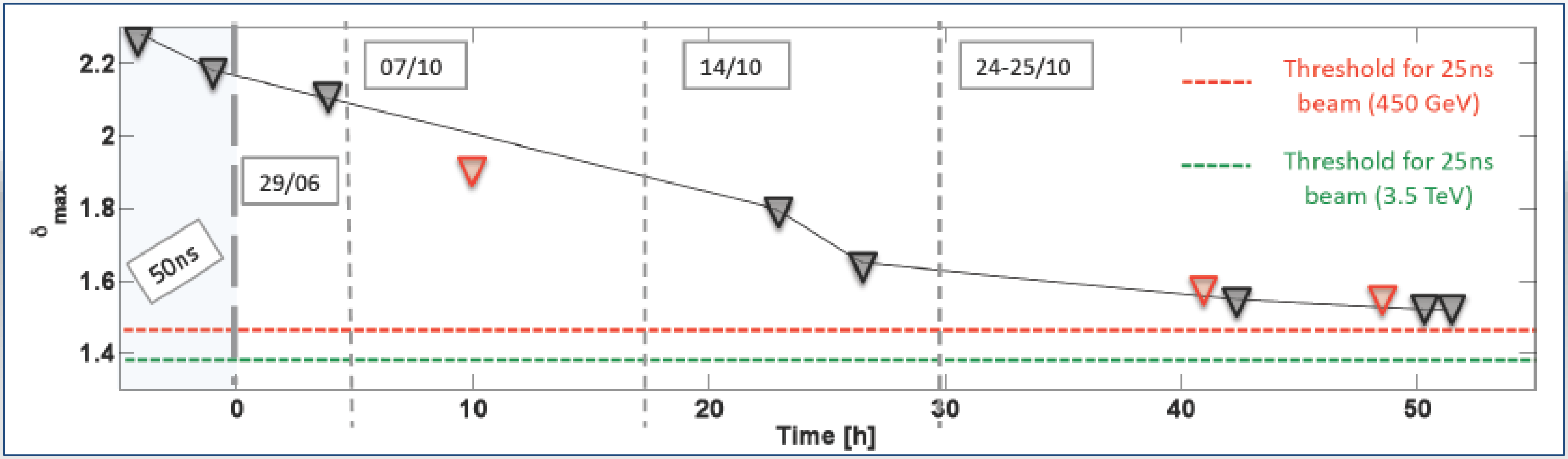
- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

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.

25 ns & electron cloud

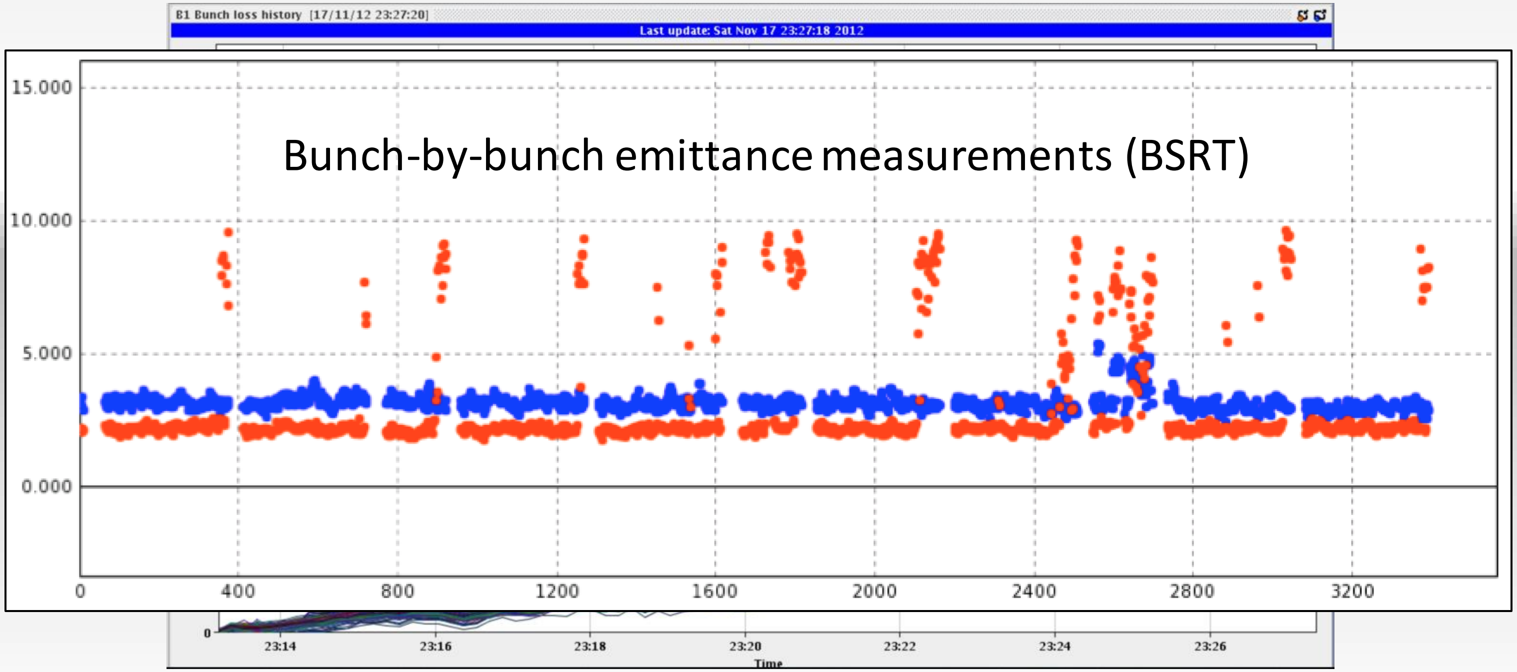
- During 25 ns scrubbing run last December the reduction in the secondary electron yield (SEY) flattened out
- A concentrated scrubbing run will probably be insufficient to fully suppress the EC from the arcs for 25 ns beams in future operation.



Evolution of δ_{max} on the the beam screen in the dipole magnets in 2011

Instabilities

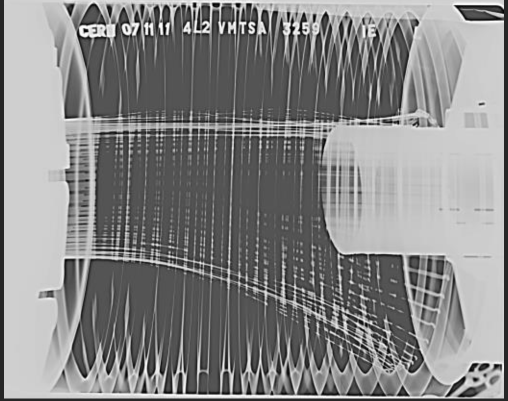
- Note: increased impedance from tight collimators in 2012 and near ultimate bunch intensity
- Instabilities have been observed:
  - on bunches with offset collisions in IP8 only
  - while going into collision
  - end of squeeze, few bunches: emittance blow-up and beam loss
- Defense mechanisms:
  - octupoles, high chromaticity, transverse damper, tune split, head-on collisions, understanding


Bunch-by-bunch emittance measurements (BSRT)

Some other issues…

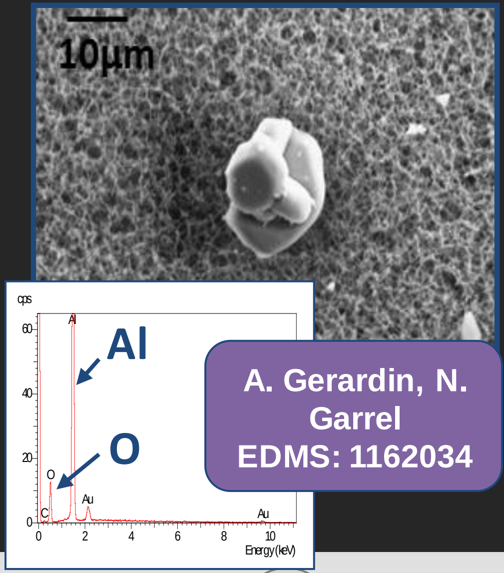
Beam induced heating

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



UFOs

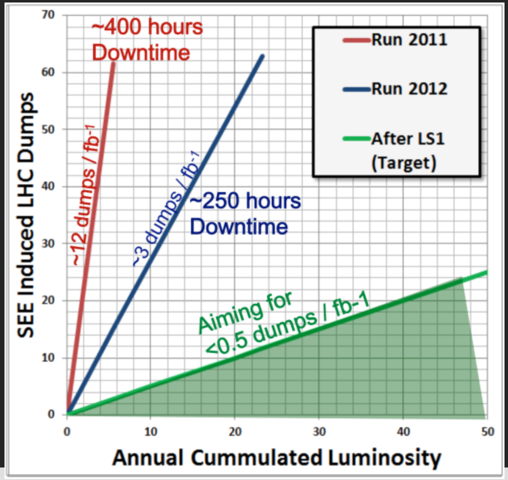
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV



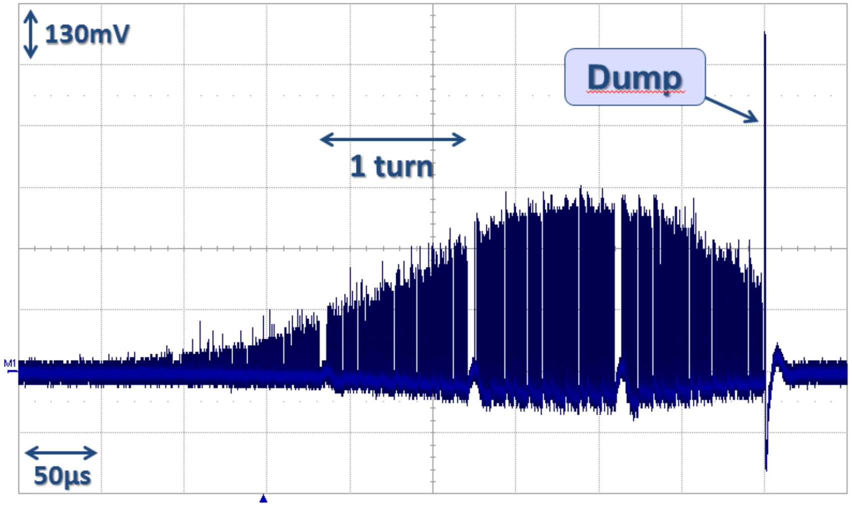
A. Gerardin, N. Garrel
EDMS: 1162034

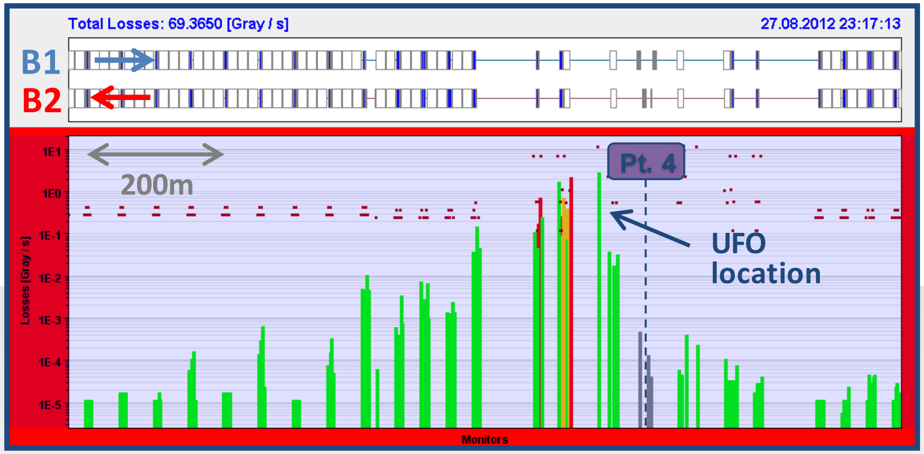
Radiation to electronics

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



UFO - introduction

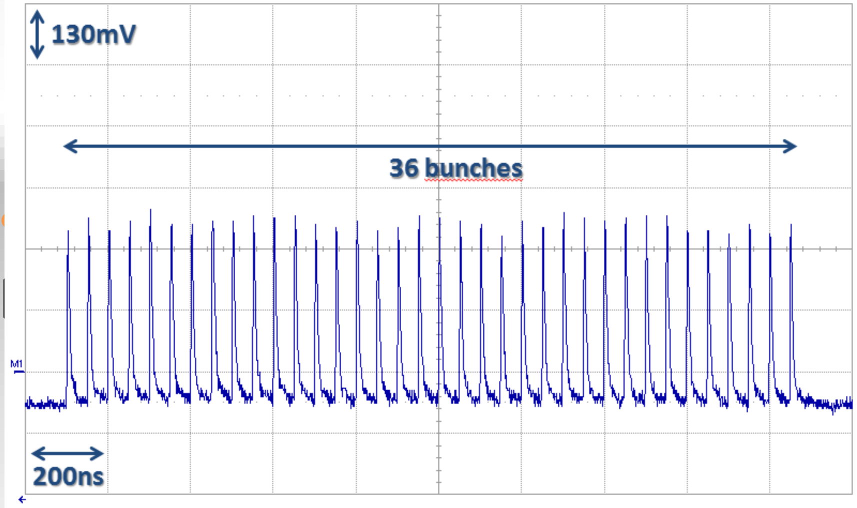


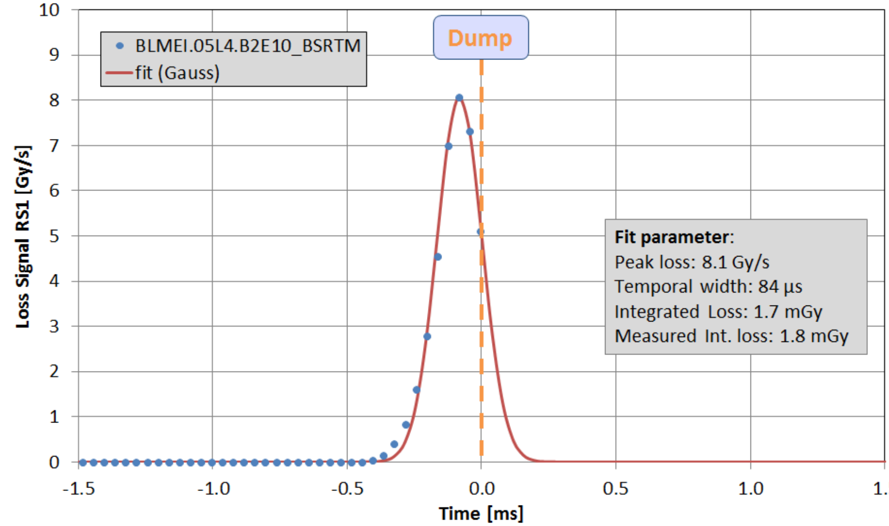


•8 dumps by UFOs,

Diamond BLM in IR7

4 by UFOs around collimators during





Spatial and temporal loss profile of UFO at BSRT.B2 on 27.08.2012 at 4TeV.

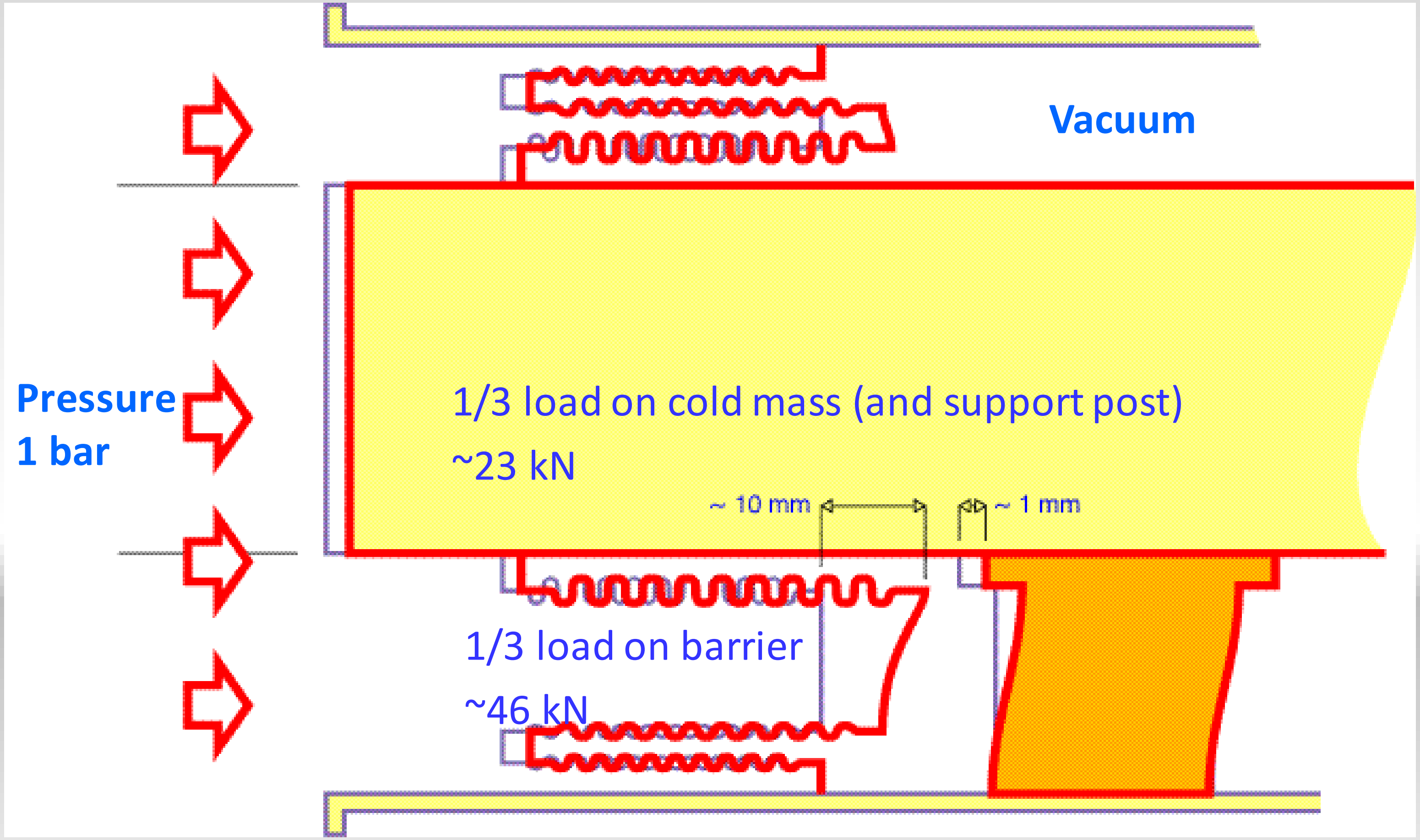
LS1

What happened on September 19th*

- Sector 3-4 was being ramped to 9.3 kA, the equivalent of 5.5 TeV
  - All other sectors had already been ramped to this level
  - Sector 3-4 had previously only been ramped to 7 kA (4.1 TeV)
- At 11:18AM, a quench developed in the splice between dipole C24 and quadrupole Q24
  - Not initially detected by quench protection circuit
  - Power supply tripped at .46 sec
  - Discharge switches activated at .86 sec
- Within the first second, an arc formed at the site of the quench
  - The heat of the arc caused Helium to boil.
  - The pressure rose beyond .13 MPa and ruptured into the insulation vacuum.
  - Vacuum also degraded in the beam pipe
- The pressure at the vacuum barrier reached ~10 bar (design value 1.5 bar). The force was transferred to the magnet stands, which broke.

*Official talk by Philippe LeBrun, Chamonix, Jan. 2009

Pressure forces on SSS vacuum barrier



1/3 load on cold mass (and support post)

~23 kN

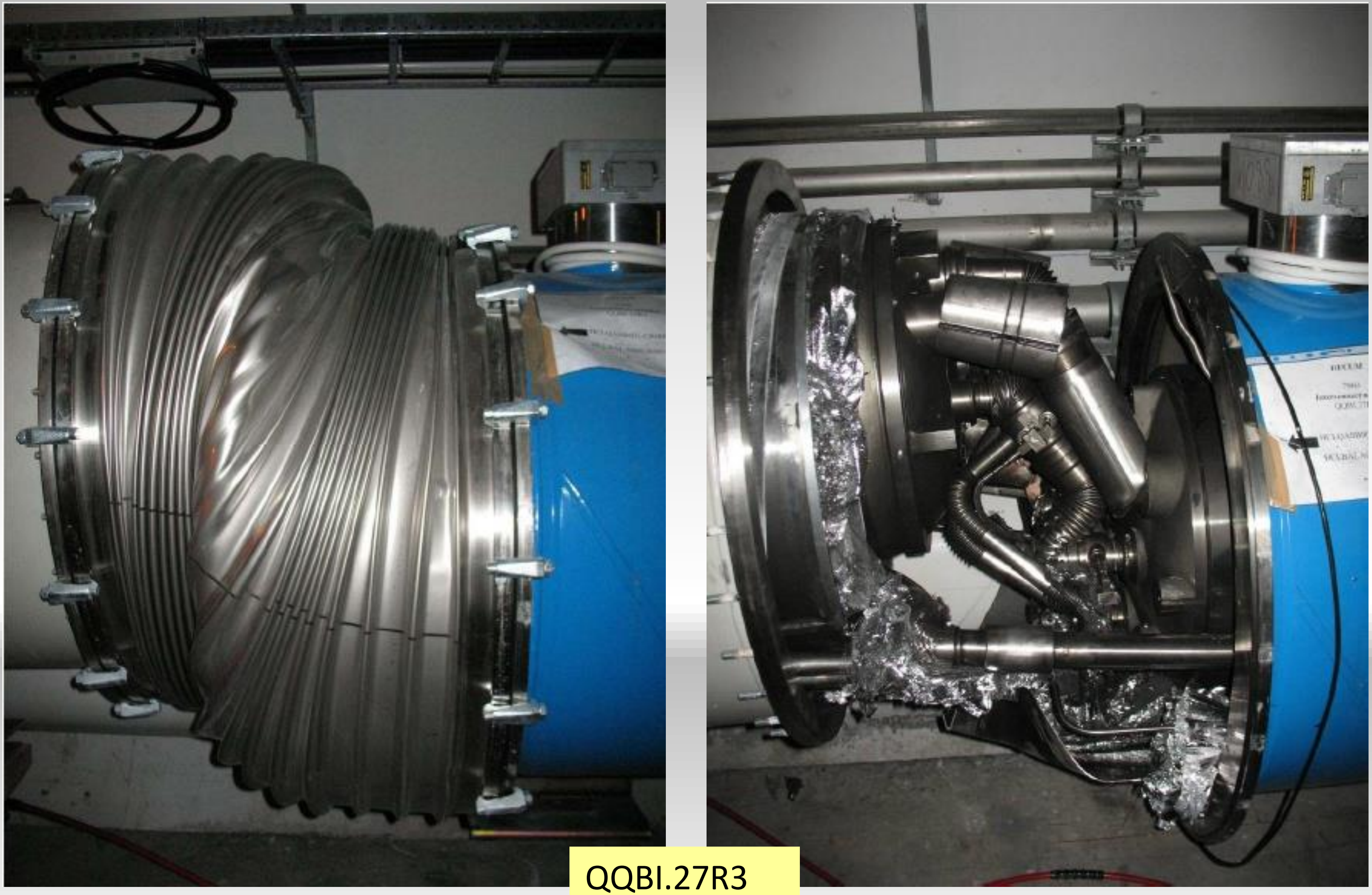
1/3 load on barrier

~46 kN

Total load on 1 jack ~70 kN

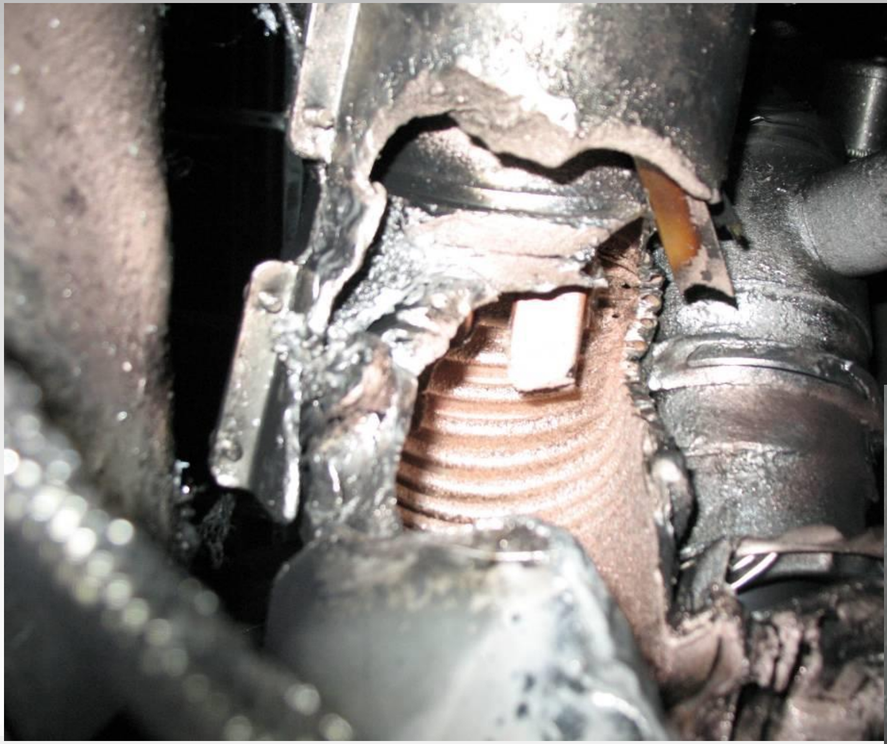
V. Parma

Collateral damage: magnet displacements



QQBI.27R3

Collateral damage: secondary arcs

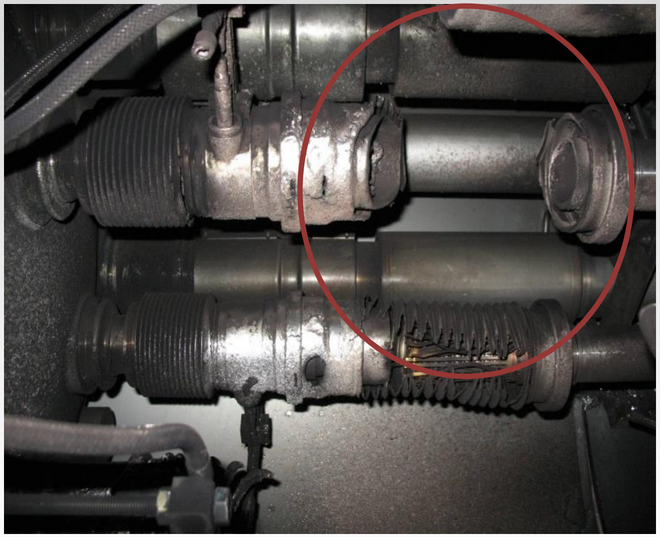


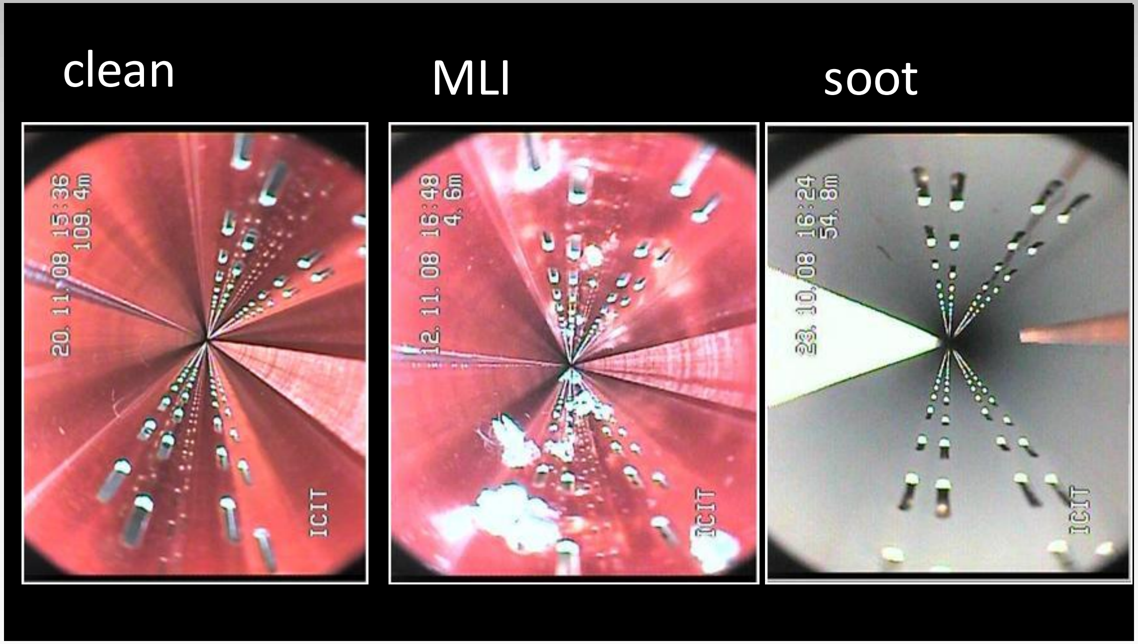
QQBI.27R3 M3 line

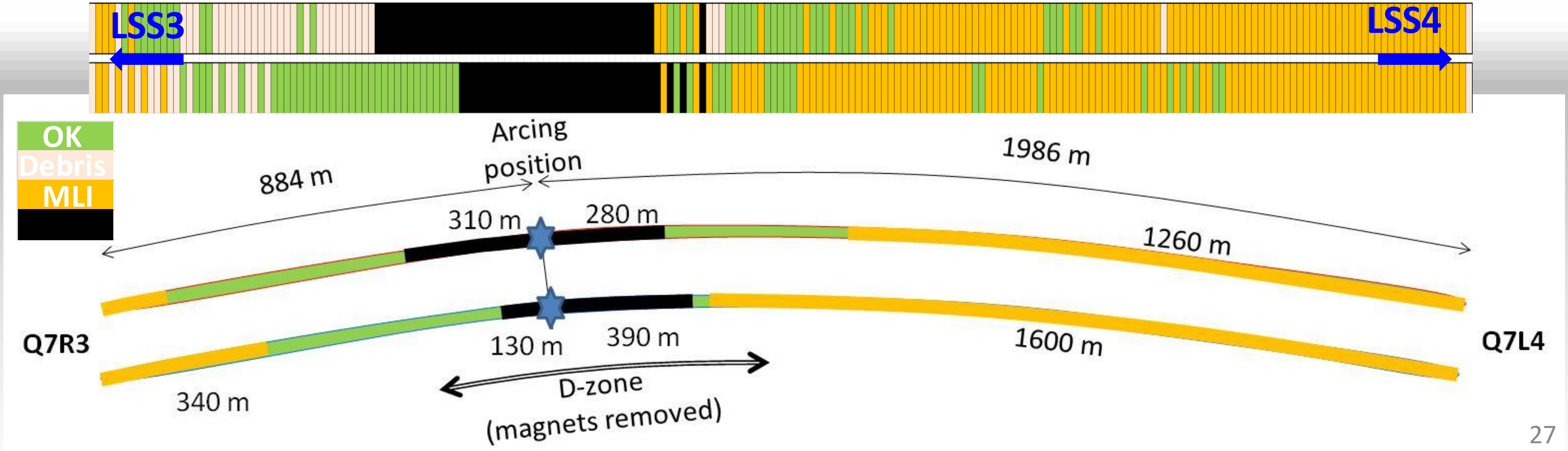
QBBI.B31R3 M3 line

Collateral damage: Beam Vacuum

Arc burned through
beam vacuum pipe

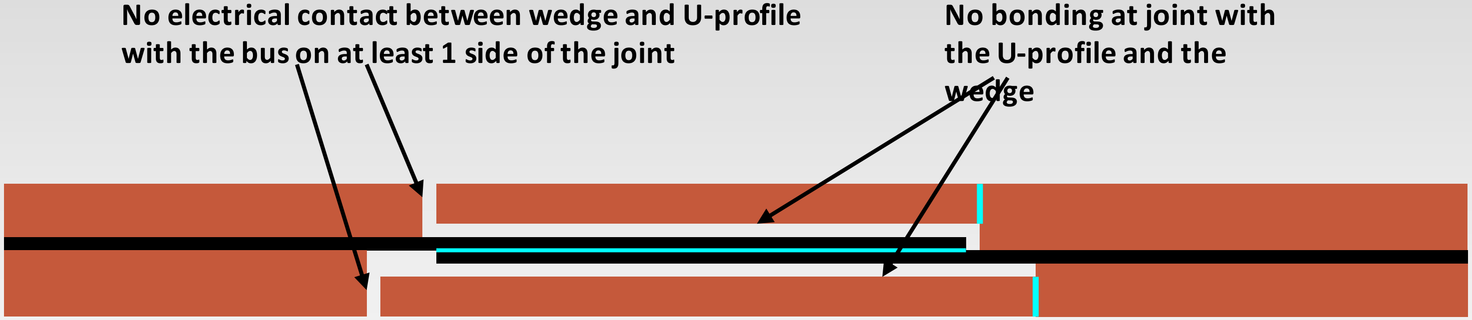




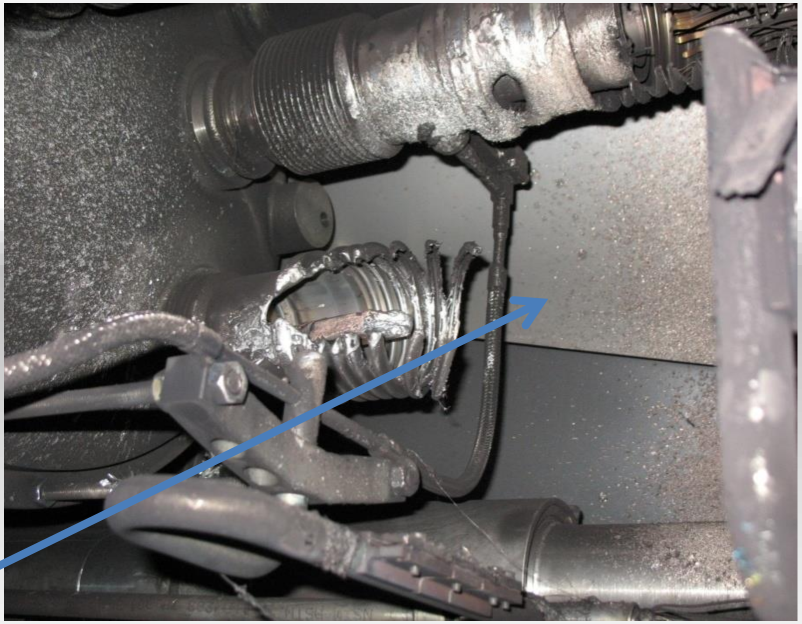


What happened?

Theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer



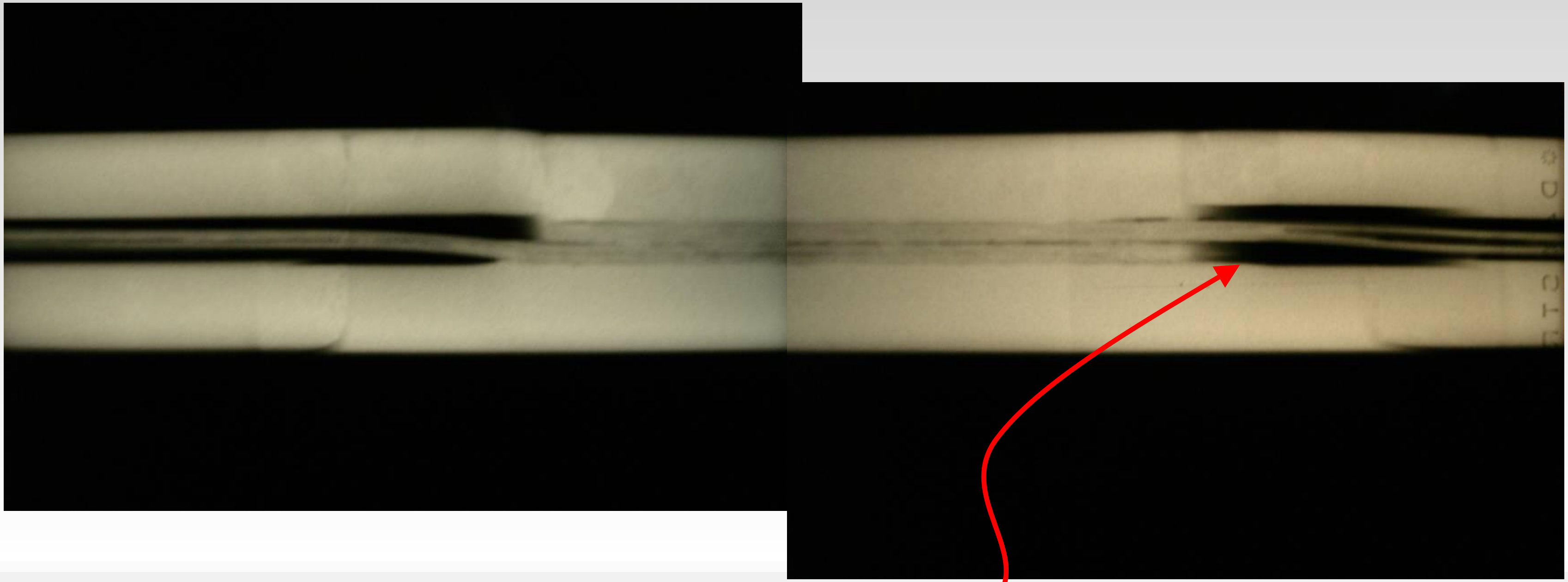
- Loss of clamping pressure on the joint, and between joint and stabilizer
- Degradation of transverse contact between superconducting cable and stabilizer
- Interruption of longitudinal electrical continuity in stabilizer



Problem: this is where the evidence used to be

A. Verweij

Bad surprise



Solder used to solder joint had the same melting temperature as solder used to pot cable in stablizer

⇒**Solder wicked away from cable**

Copper stabilizer issue

- Despite correct splice resistance between SC cables, a 13 kA joint can burn-out **in case of a quench**, if there would be a bad bonding between the SC cable and the copper bus, coinciding with a discontinuity in the copper stabilizer

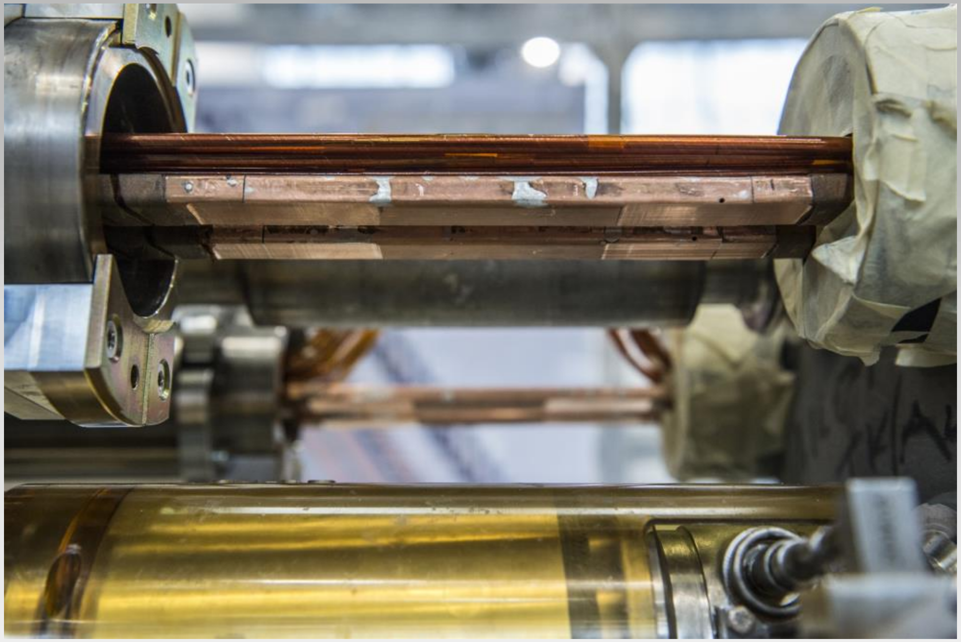
- Resistance measurements and ⍰-ray pictures have shown the presence of many of such defective joints in the machine, limiting the safe operating current

2013 – 2014: LS1

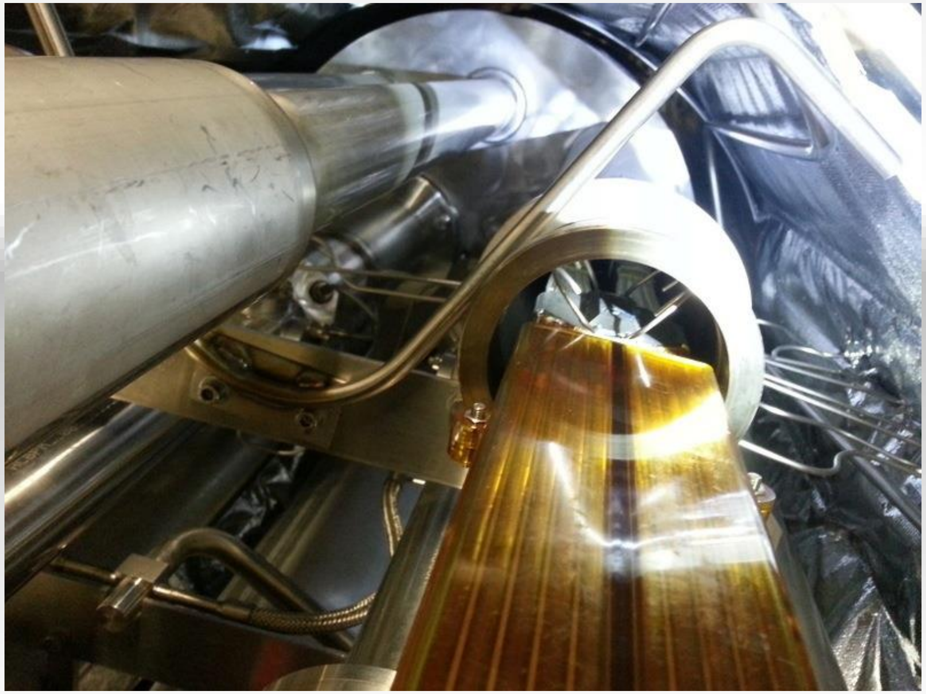
Primary aim: consolidation for 6.5 to 7 TeV

- Measure all splices and repair the defective ones
- Consolidate interconnects with new design (clamp, shunt)
- Finish installation of pressure release valves (DN200)
- Magnet consolidation - exchange of weak cryo-magnets
- Consolidation of the DFBAs
- Measures to further reduce SEE (R2E):
  - relocation, redesign, shielding…
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Experiments consolidation/upgrades

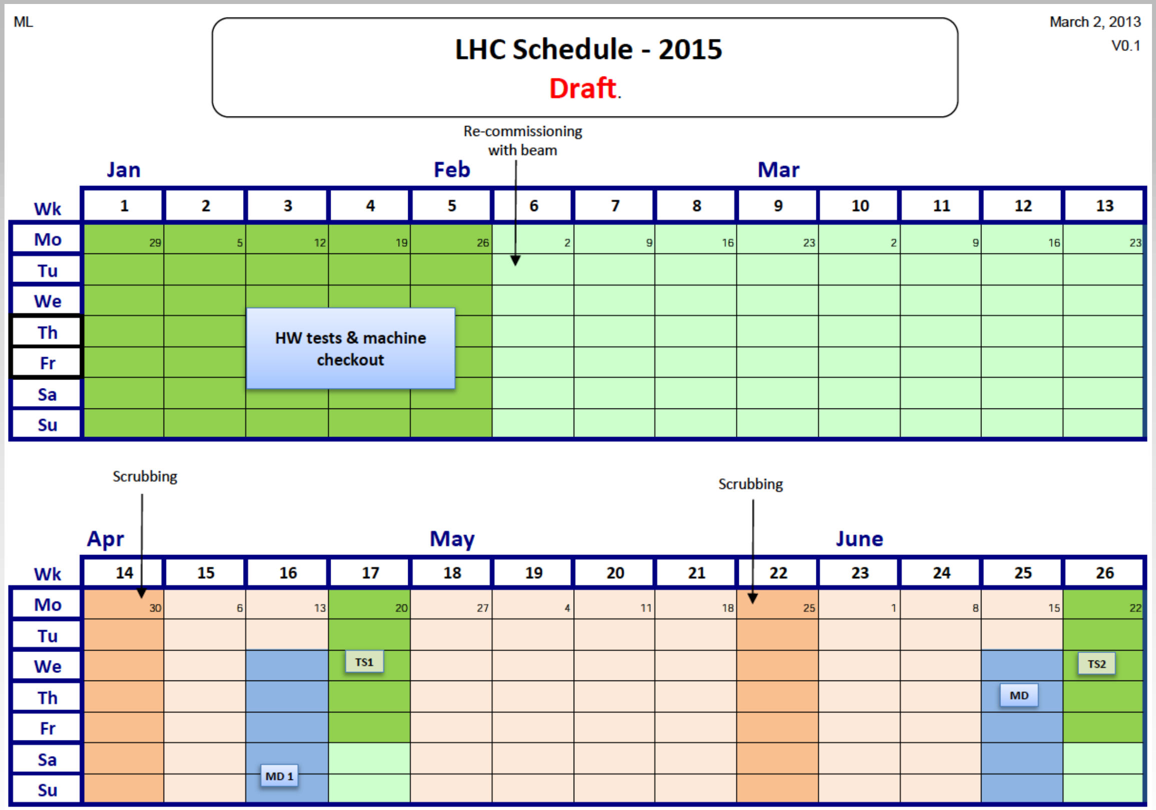

metabo
25R7 / 27R7



D NOT
VELD



Installing shunts



ML

March 2, 2013
V0.1

LHC Schedule - 2015
Draft.

Re-commissioning with beam

	Jan				Feb				Mar				
Wk	1	2	3	4	5	6	7	8	9	10	11	12	13
Mo	29	5	12	19	26	2	9	16	23	2	9	16	23
Tu													
We			HW tests & machine checkout										
Th													
Fr													
Sa													
Su													

Scrubbing

Scrubbing

	Apr				May				June				
Wk	14	15	16	17	18	19	20	21	22	23	24	25	26
Mo	30	6	13	20	27	4	11	18	25	1	8	15	22
Tu													
We				TS1									TS2
Th												MD	
Fr													
Sa			MD 1										
Su													

AFTER LS1

Post LS1 energy

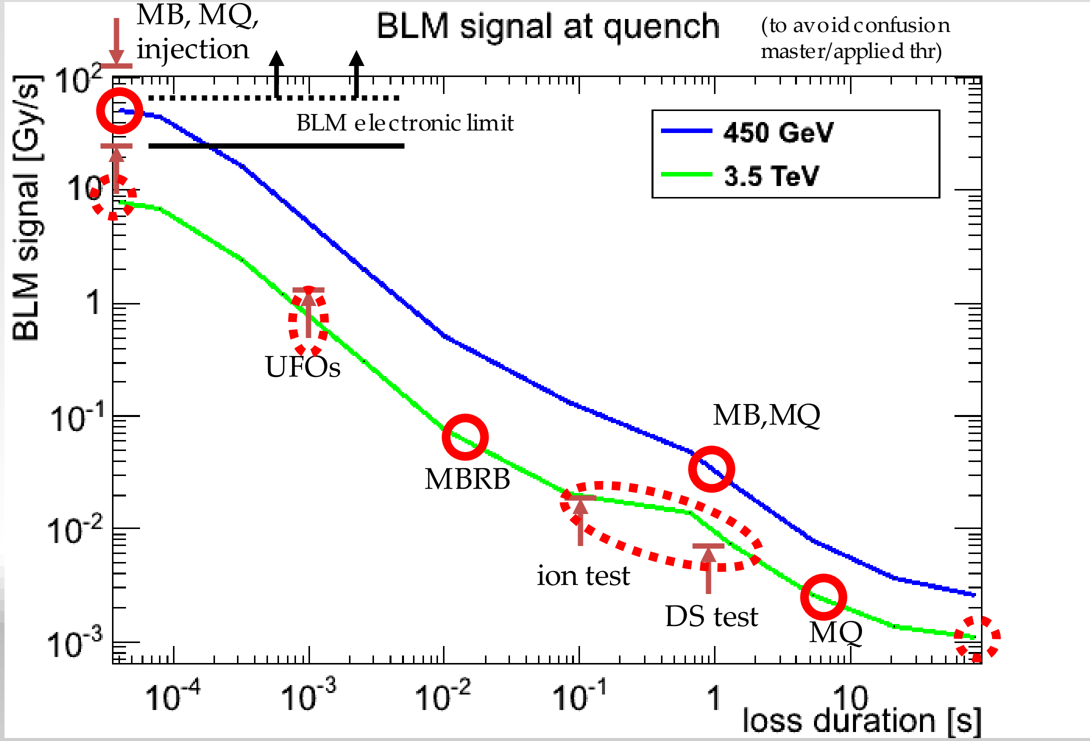
- Magnets coming from 3-4 do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV
- The plan
  - Try to reach 6.5 TeV in four sectors in **JULY to SEPTEMBER 2014** (NB updated after Aspen)
  - Based on that experience, we decide if to go at 6.5 TeV or step back to 6.25 TeV

Ezio Todesco – Chamonix 12

Challenges of high energy

- Quenches
  - Less margin to critical surface
- Protons have higher energy
  - acceptable loss level is reduced (losses in ramp, UFOs…)
  - set-up beam limit reduced
- Magnets run into saturation
  - field quality (although this is modelled)
- Hardware nearer limits
  - Power converters, beam dump (higher voltages), cryogenics (synchrotron radiation…)

BLM signal at quench



50 versus 25 ns

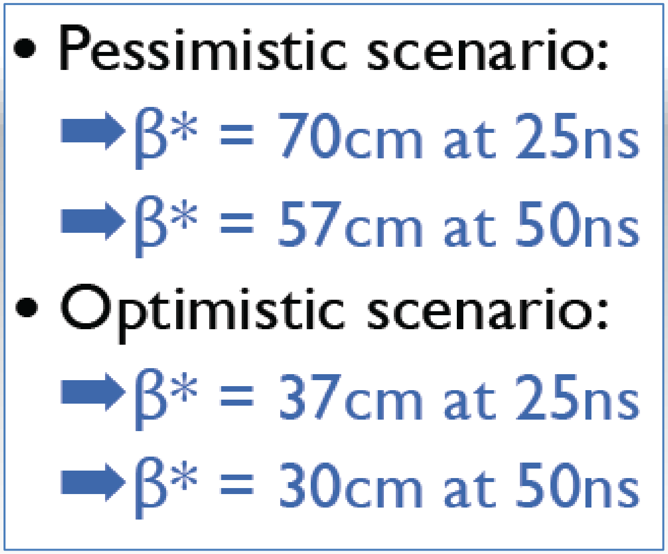
	50 ns	25 ns
GOOD	- Lower total beam current - Higher bunch intensity - Lower emittance	- **Lower pile-up**
BAD	- **High pile-up** - Need to level - Pile-up stays high - High bunch intensity – instabilities…	- More long range collisions: larger crossing angle; higher beta* - Higher emittance - Electron cloud: need for scrubbing; emittance blow-up; - Higher UFO rate - Higher injected bunch train intensity - Higher total beam current

Expect to move to 25 ns because of pile up…

β* & crossing angle

- β* reach depends on:
  - – available aperture
  - – collimator settings, orbit stability
  - – required crossing angle which in turn depends on
    - emittance
    - bunch spacing

Beta* reach at 6.5 TeV



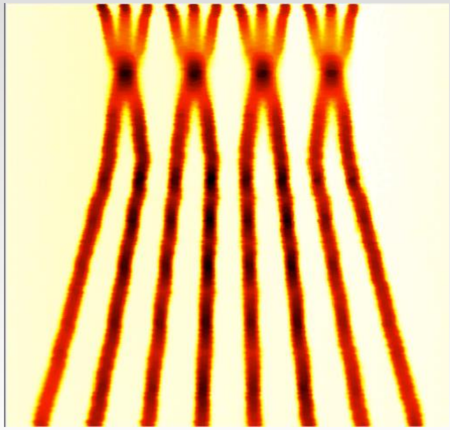
- Pessimistic scenario:
  - ➡β* = 70cm at 25ns
  - ➡β* = 57cm at 50ns
- Optimistic scenario:
  - ➡β* = 37cm at 25ns
  - ➡β* = 30cm at 50ns

Working hypothesis
β* = 40 cm

Run II – post LS1

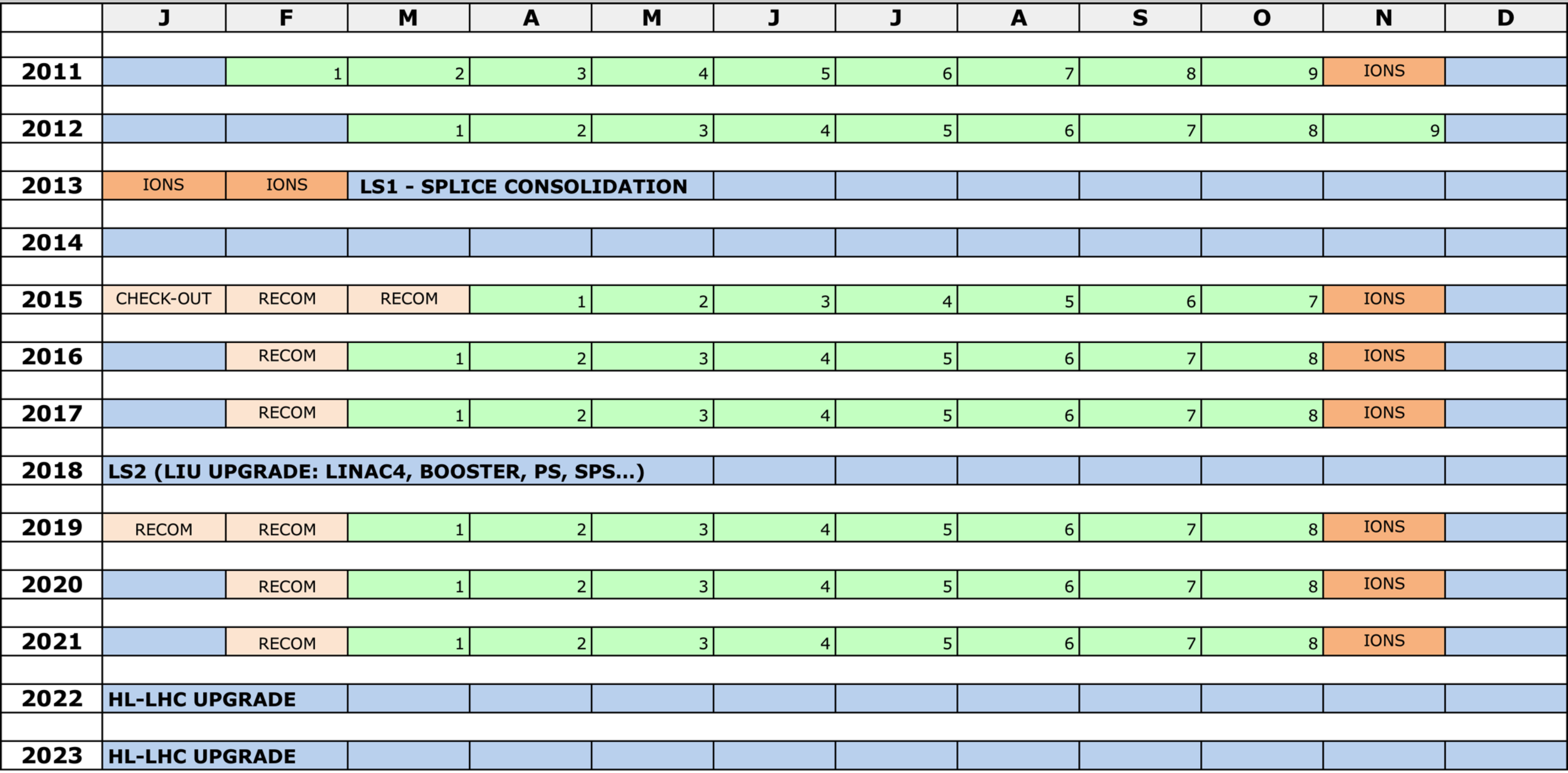
- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



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

Baseline



	J	F	M	A	M	J	J	A	S	O	N	D
2011	🟦	1	2	3	4	5	6	7	8	9	IONS	🟦
2012	🟦	🟦	1	2	3	4	5	6	7	8	9	🟦
2013	IONS	IONS	**LS1 - SPLICE CONSOLIDATION**			🟦	🟦	🟦	🟦	🟦	🟦	🟦
2014	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2015	CHECK-OUT	RECOM	RECOM	1	2	3	4	5	6	7	IONS	🟦
2016	🟦	RECOM	1	2	3	4	5	6	7	8	IONS	🟦
2017	🟦	RECOM	1	2	3	4	5	6	7	8	IONS	🟦
2018	**LS2 (LIU UPGRADE: LINAC4, BOOSTER, PS, SPS…)**					🟦	🟦	🟦	🟦	🟦	🟦	🟦
2019	RECOM	RECOM	1	2	3	4	5	6	7	8	IONS	🟦
2020	🟦	RECOM	1	2	3	4	5	6	7	8	IONS	🟦
2021	🟦	RECOM	1	2	3	4	5	6	7	8	IONS	🟦
2022	**HL-LHC UPGRADE**		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2023	**HL-LHC UPGRADE**		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

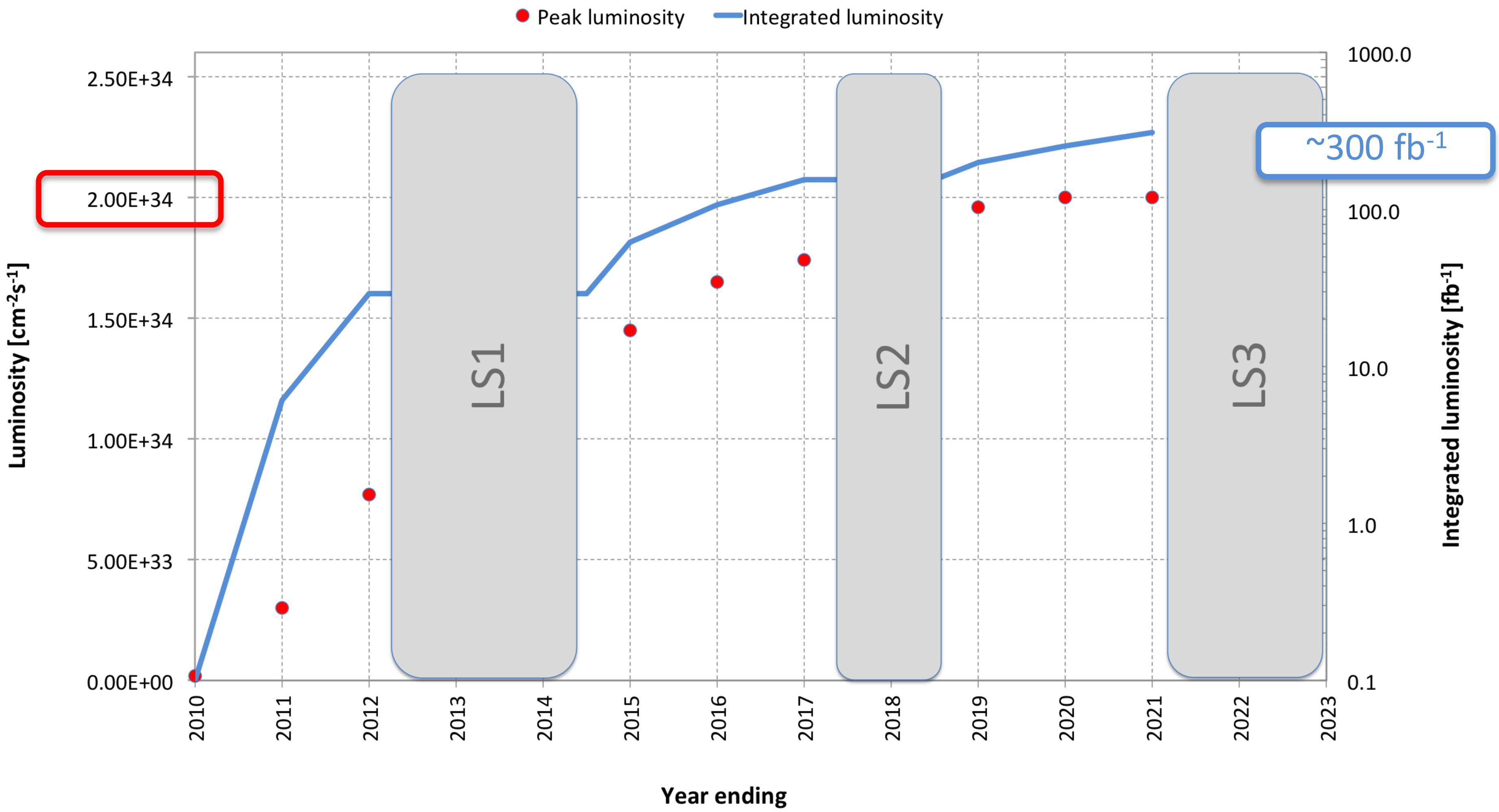
🟦	Technical stop or shutdown
🟩	Proton physics
🟥	Ion Physics
🟧	Recommissioning

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
this October – expect changes

"Baseline" luminosity evolution

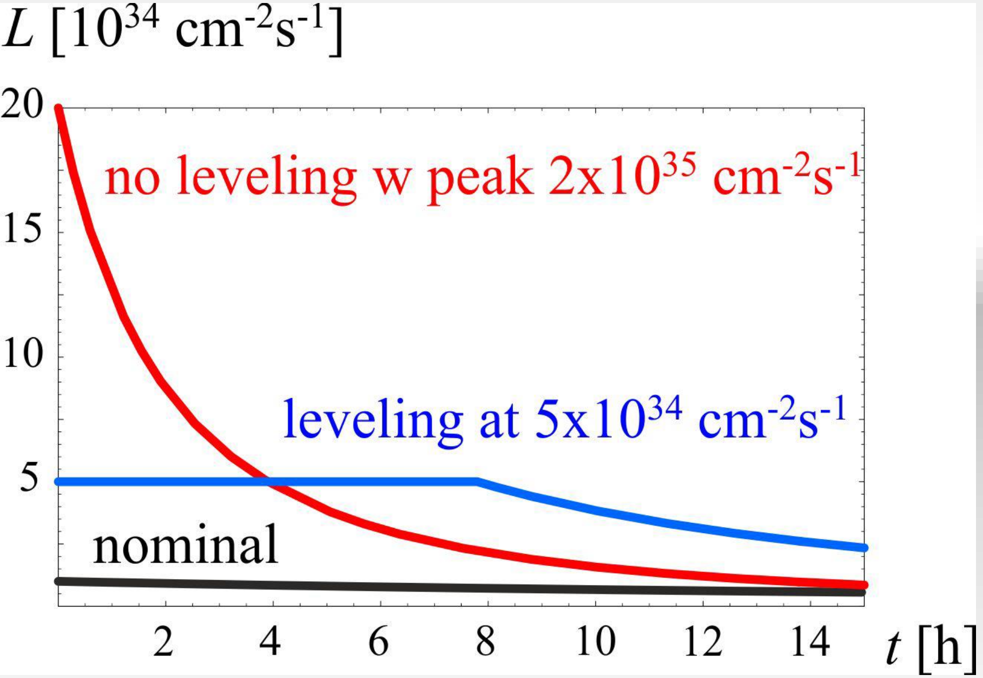


Usual caveats apply

~310 fb^{-1} by end 2021

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 2 GeV, PS and SPS)

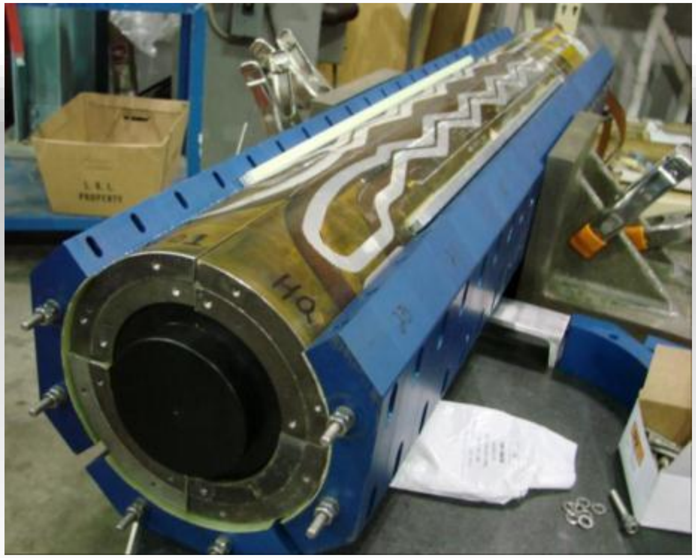


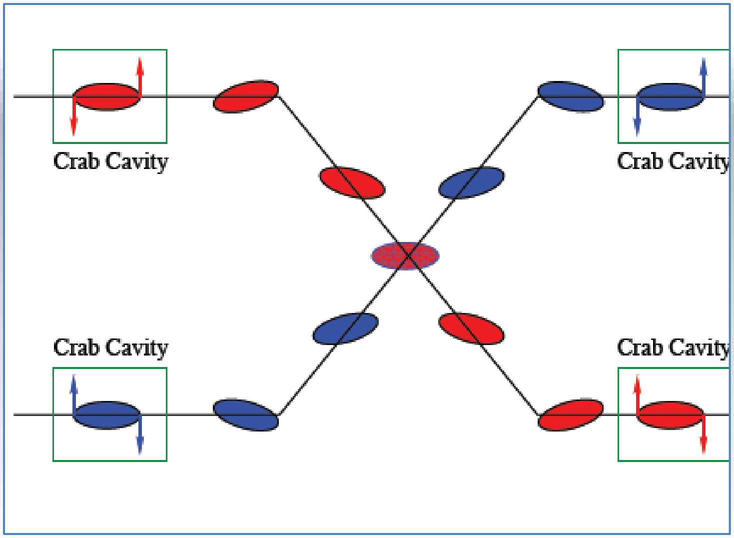
5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ levelled luminosity
3 fb^{-1} per day
~250 fb^{-1} /year

HL-LHC: main thrusts

- Wide aperture Nb_3Sn triplet 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

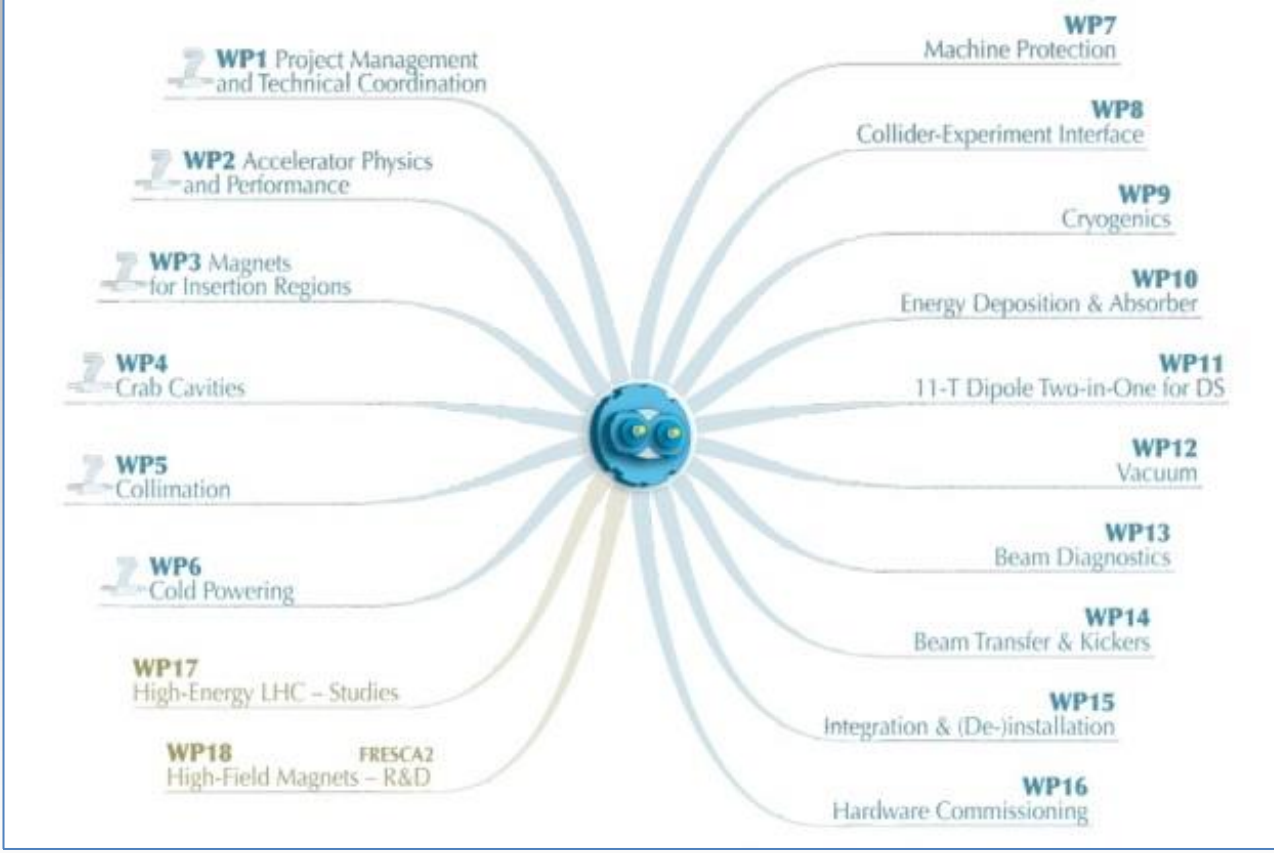


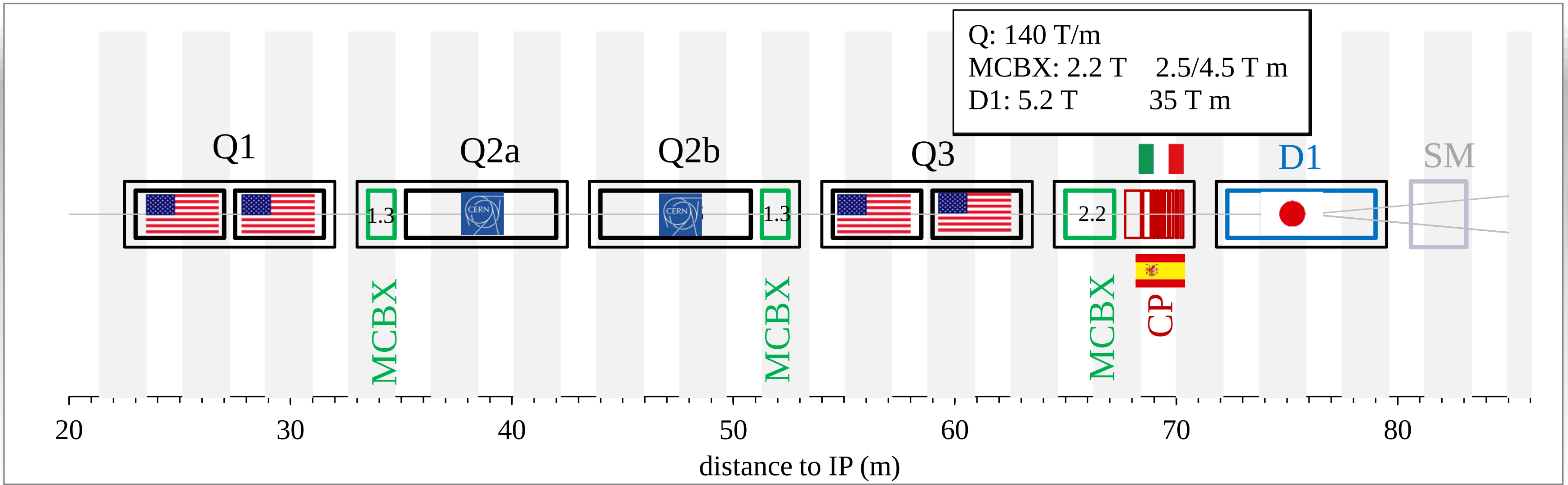


HL-LHC

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

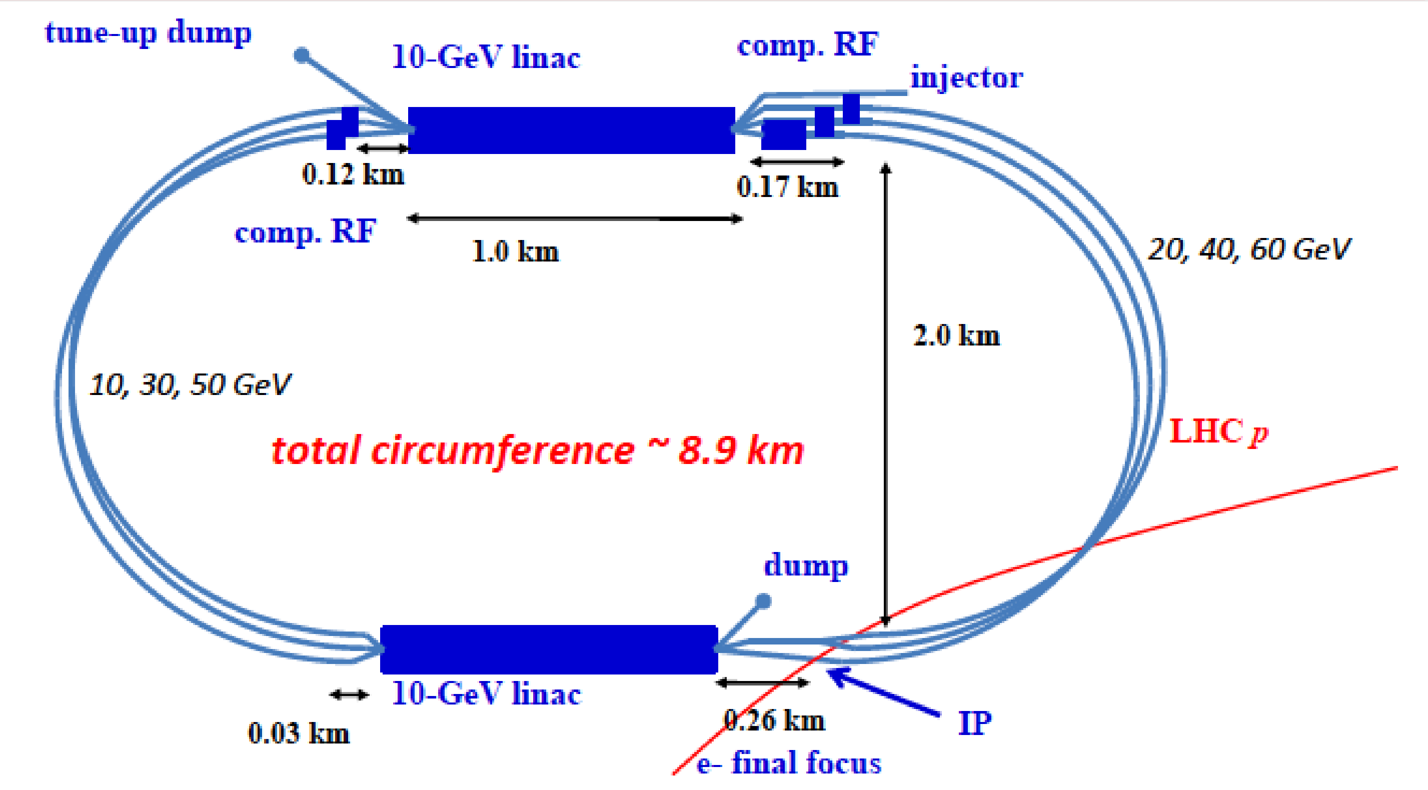
BEYOND

Options!

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)

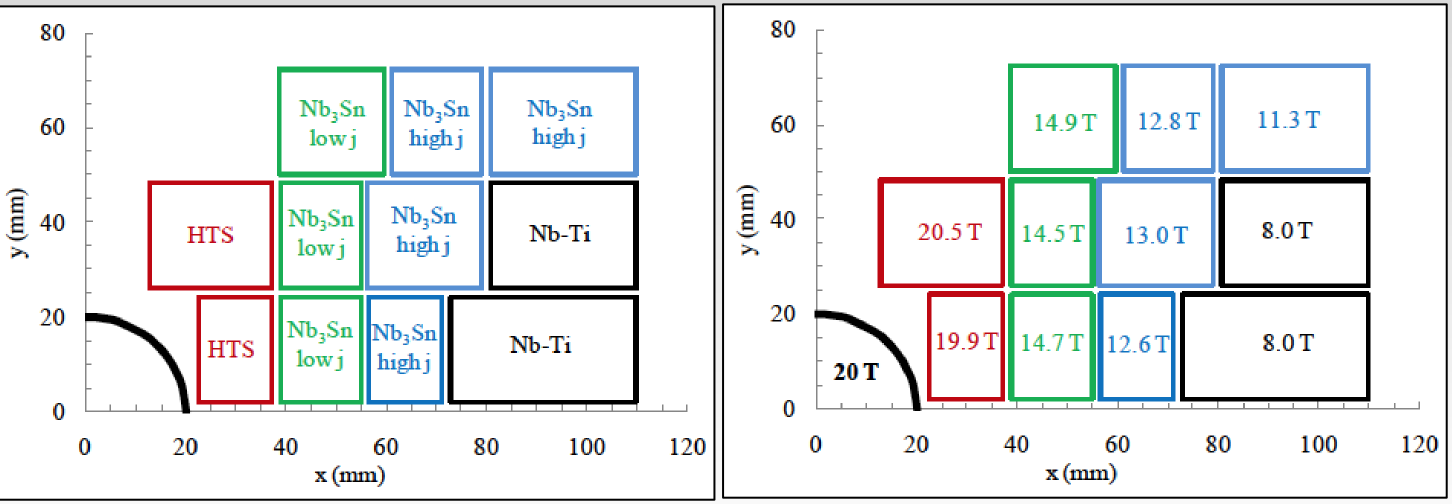
Linac-ring option: re-circulating linac with energy recovery



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)

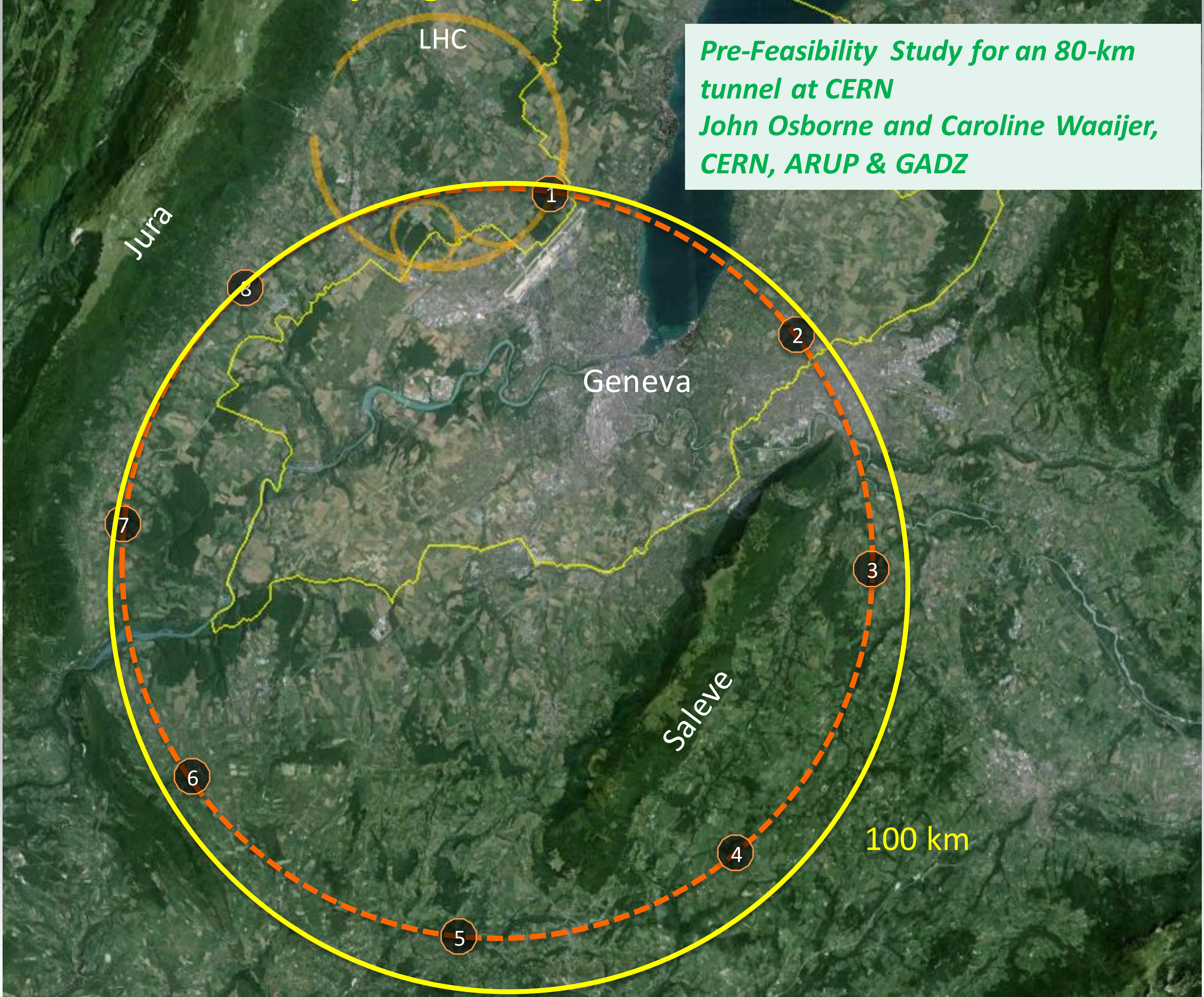
Intense R&D required

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



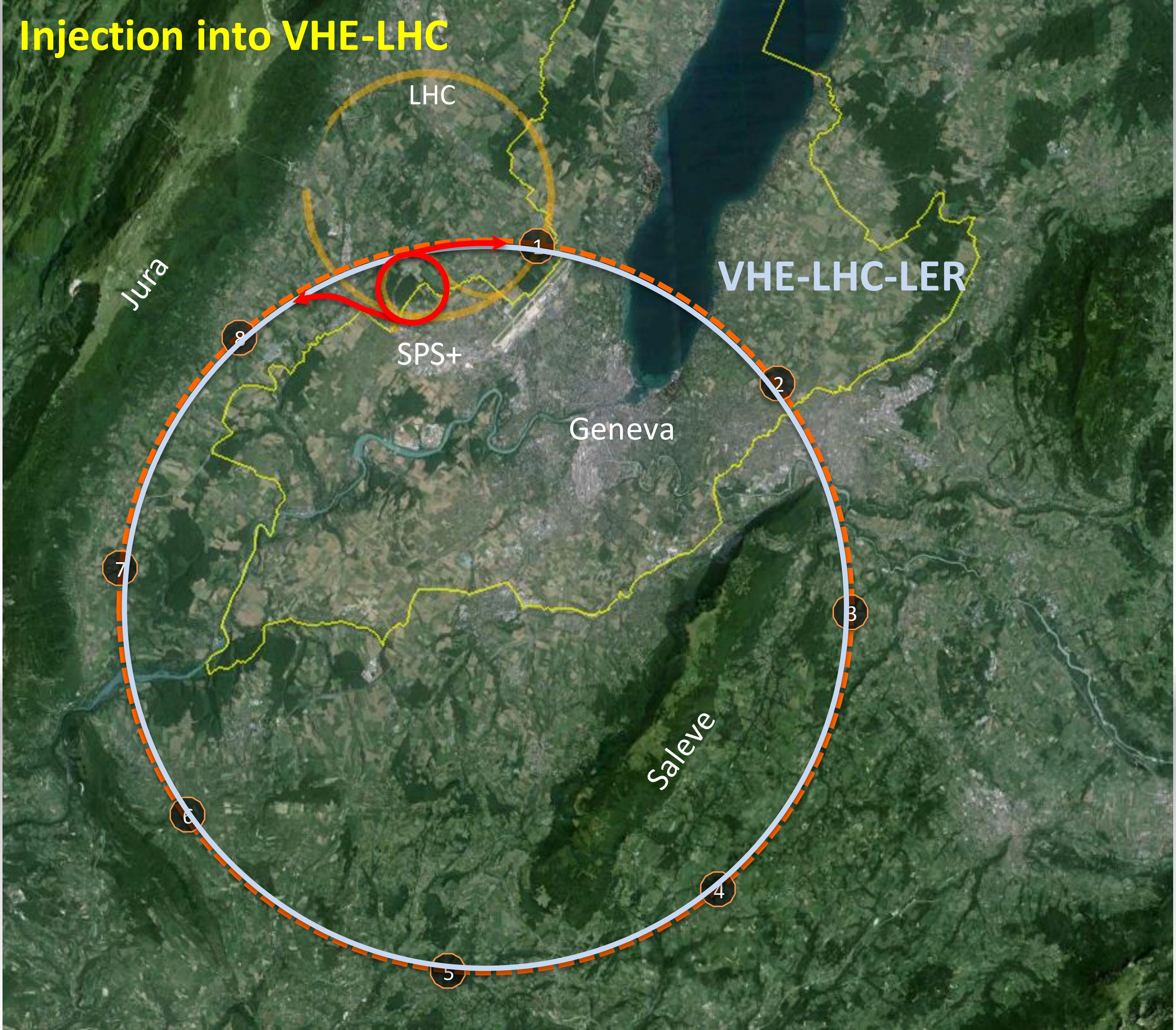
VHE-LHC

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

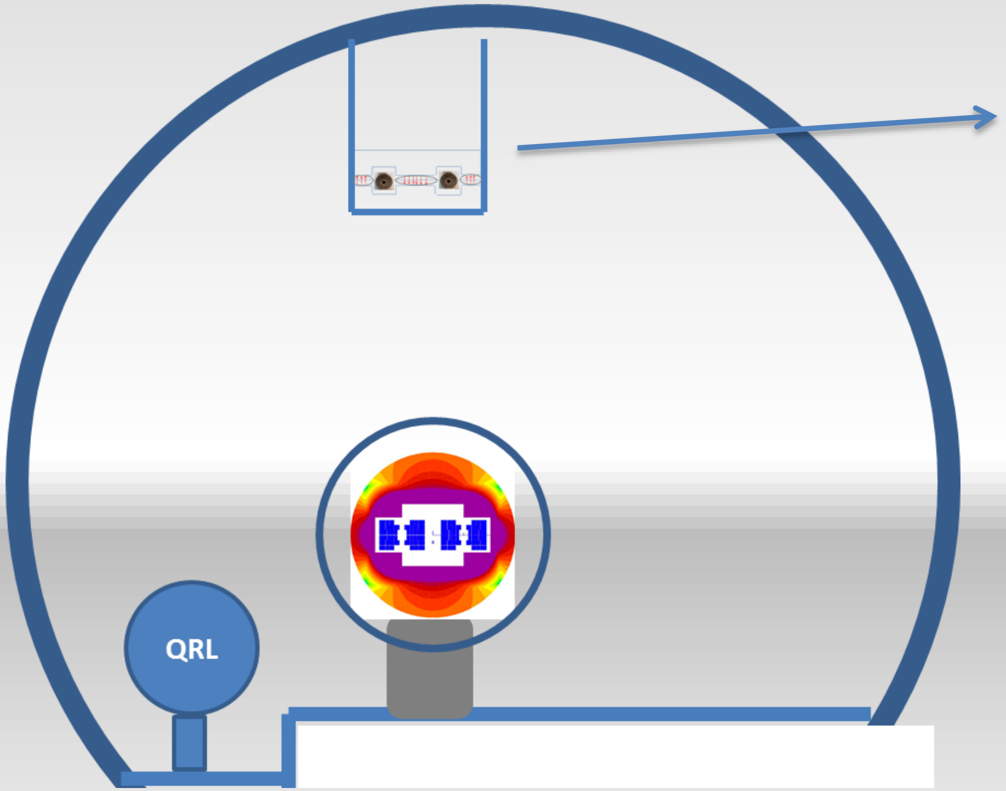
Among the many challenges:

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

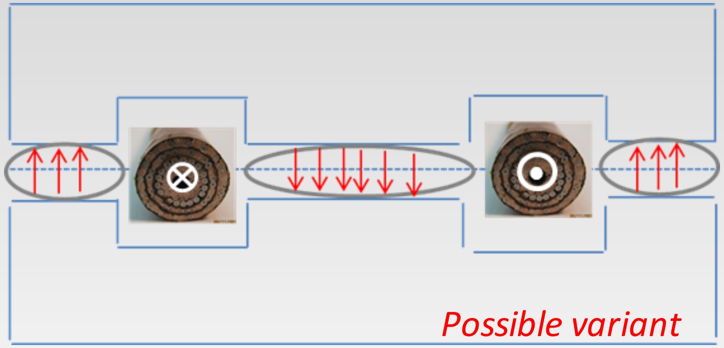
Injection into VHE-LHC



Possible VHE-LHC with LER



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



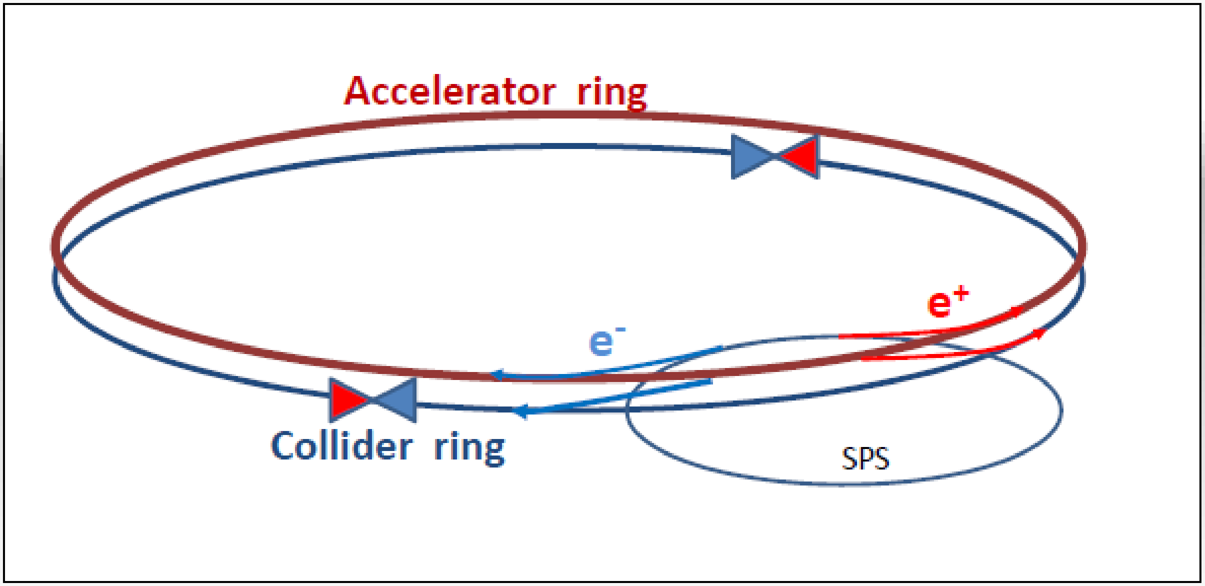
- Relatively cheap
- Limited cryogenic power – HTS

	energy [TeV]	field [T]
	0.026	0.117
SPS	↓	↓
	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

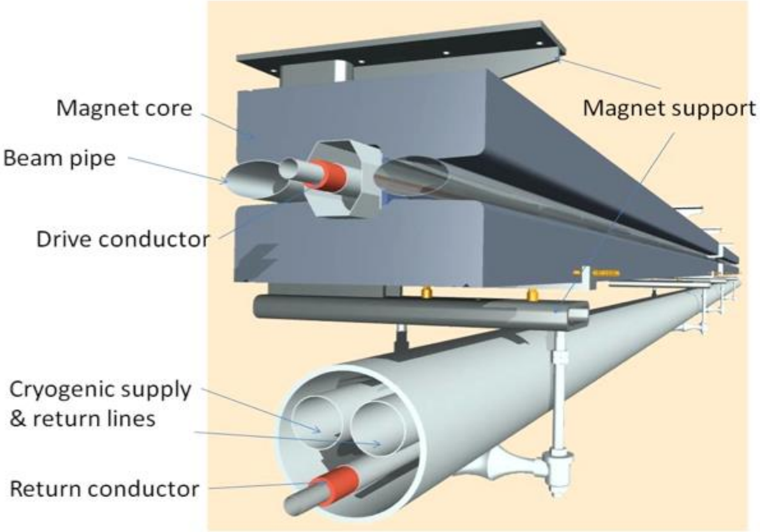
Beam lifetime dominated by Bhabha scattering and bremstrahlung

	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

Status of SC Transmission-Line Magnet



A 1.4 m long , 2 x 20 mm gap magnet was constructed at FNAL and successfully tested producing 2 T field with 88 kA current and 2.8 K temperature margin.

Conclusions

- Reasonably good performance from commissioning through run I
  - 2 years 3 months from first collisions to Higgs
- Foundations laid for run II and HL-LHC
- Some other interesting options under consideration

Acknowledgements

- LHC enjoying benefits of the decades long international design, construction, installation effort.
- Progress with beam represents phenomenal effort by all the teams involved, injectors included.
- On the accelerator physics side - huge amount of experience & understanding gained
  - impressive work by various teams (collective effects, beam-beam, optics, RF, beam transfer, beam loss, collimation…)
  - pushing diagnostics and instrumentation
  - backed by a vigorous MD program