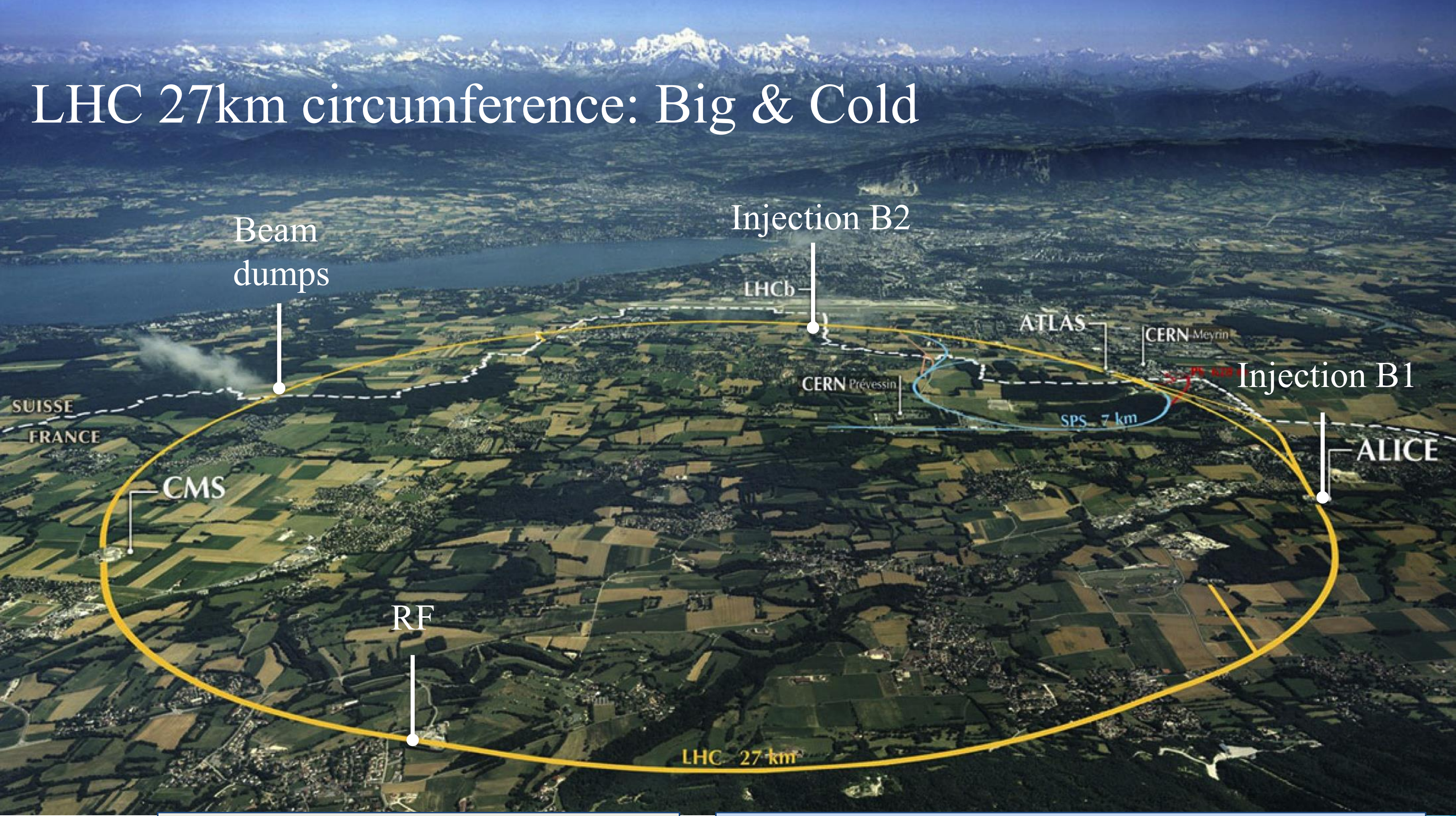
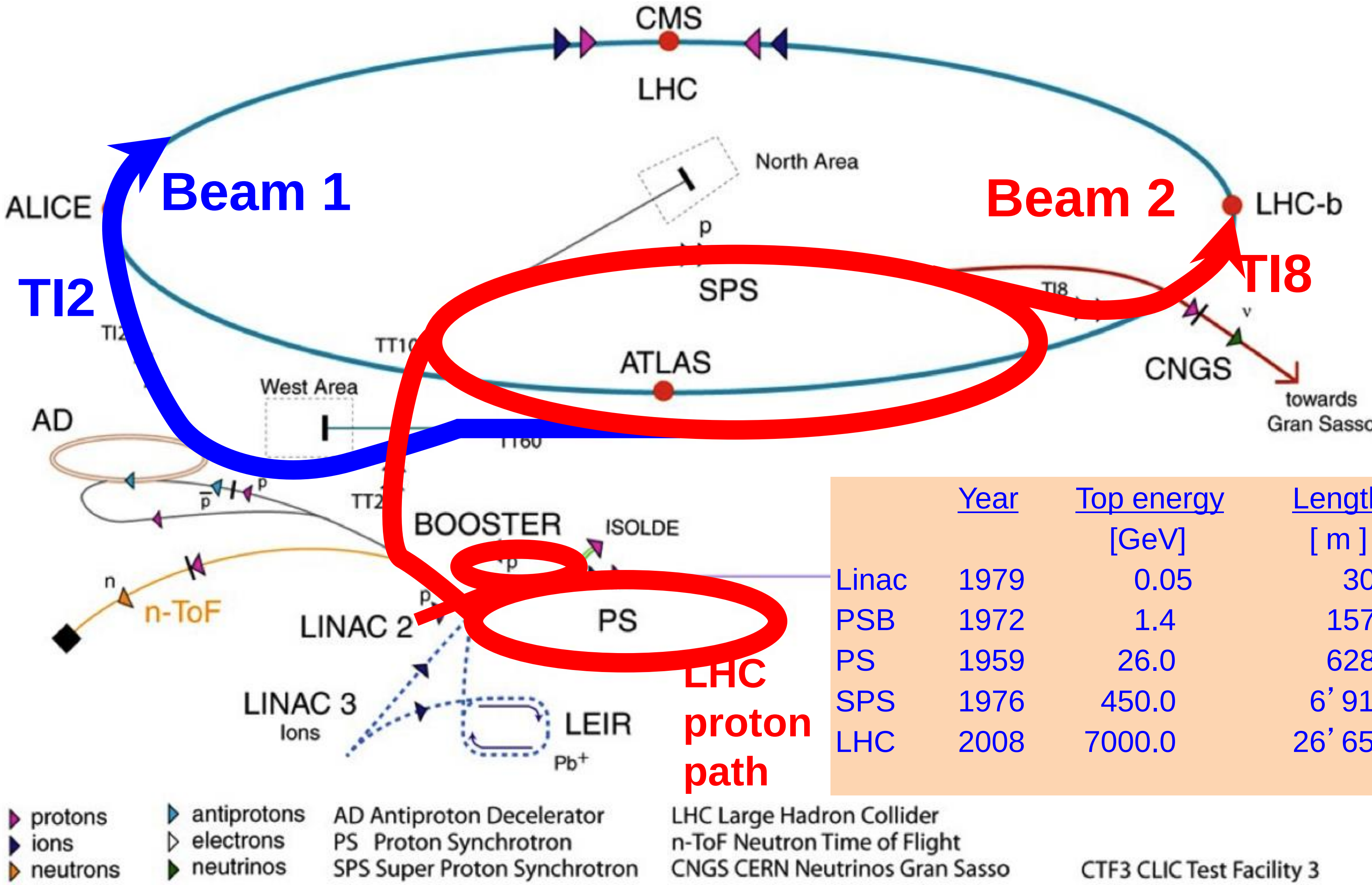
LHC 27km circumference: Big & Cold



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

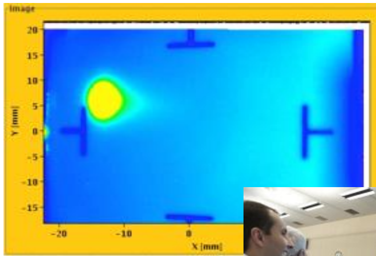
150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
830 MJ magnetic energy per sector at 6.5 TeV
➔ ≈ 10 GJ total @ 7 TeV

Introduction: LHC is NOT a Standalone Machine:

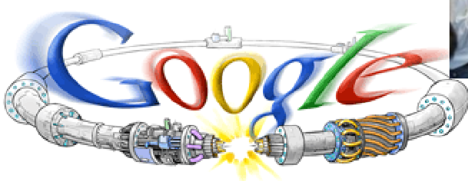


	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6’911
LHC	2008	7000.0	26’657

LHC RUN-I Timeline

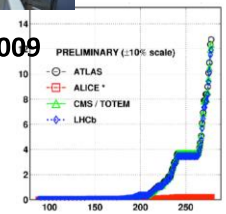


August 2008
First injection test



September 10, 2008
First beams around

November 29, 2009
Beam back



April 2010
Squeeze to 3.5 m

October 14 2010
1e32
248 bunches

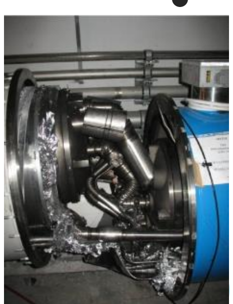
June 28 2011
1380 bunches (50ns)

1380

6 June, 2012
6.8e33

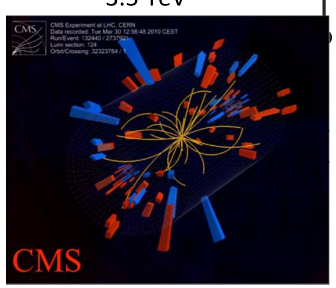
4 July, 2012
Higgs discovery

2008 | 2009 | 2010 | 2011 | 2012

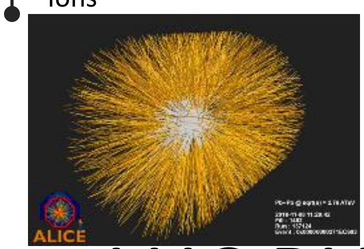


September 19, 2008
'Incident'
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at 3.5 TeV

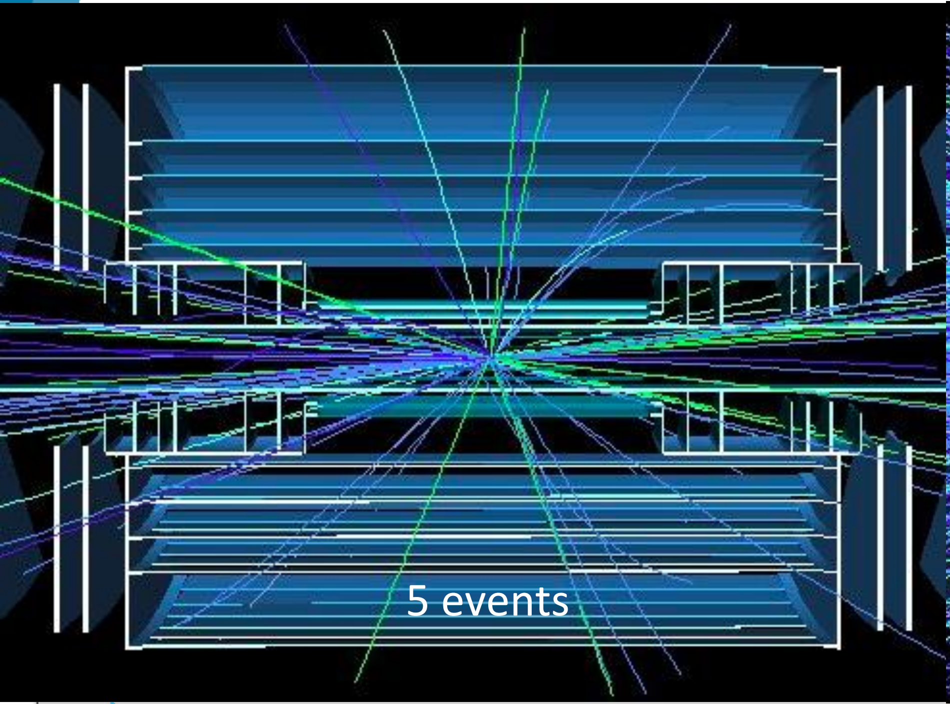


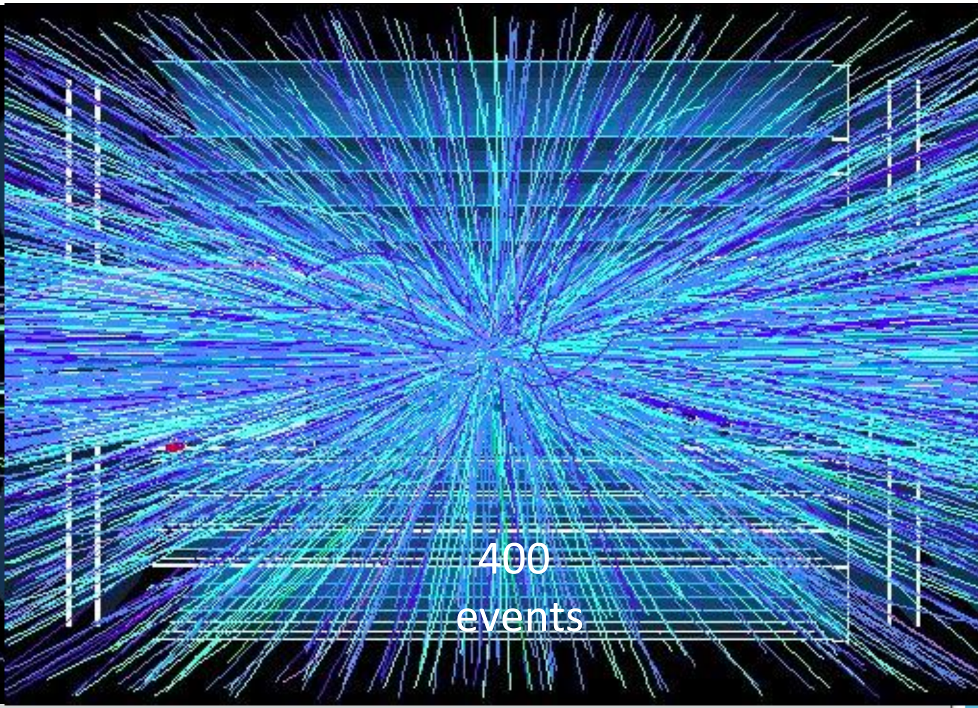
November 2010
Ions



18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

Goal of High Luminosity LHC (HL-LHC):





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

design oper. for $\mu\ \delta$ **140** (➔ peak luminosity of **5 10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity!

> Ten times the luminosity reach of first 10 years of LHC operation!!

LHC Upgrade Goals: Performance optimization

- Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

➔1) maximize bunch intensities ➔Injector complex Upgrade LIU

➔2) minimize the beam emittance

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

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

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

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

LHC Limitations and HL-LHC Challanges:

- Technical bottle necks (e.g. cryogenics) ➔ New addit. Equipment
- Insertion magnet lifetime and aperture:

  ➔ New insertion magnets and low-β with increased aperture

- Geometric Reduction Factor: ➔ SC Crab Cavities

  ➔ New technology and a first for a hadron storage ring!

- Performance Optimization: Pileup density ➔ luminosity levelling

  ➔ devise parameters for virtual luminosity >> target luminosity

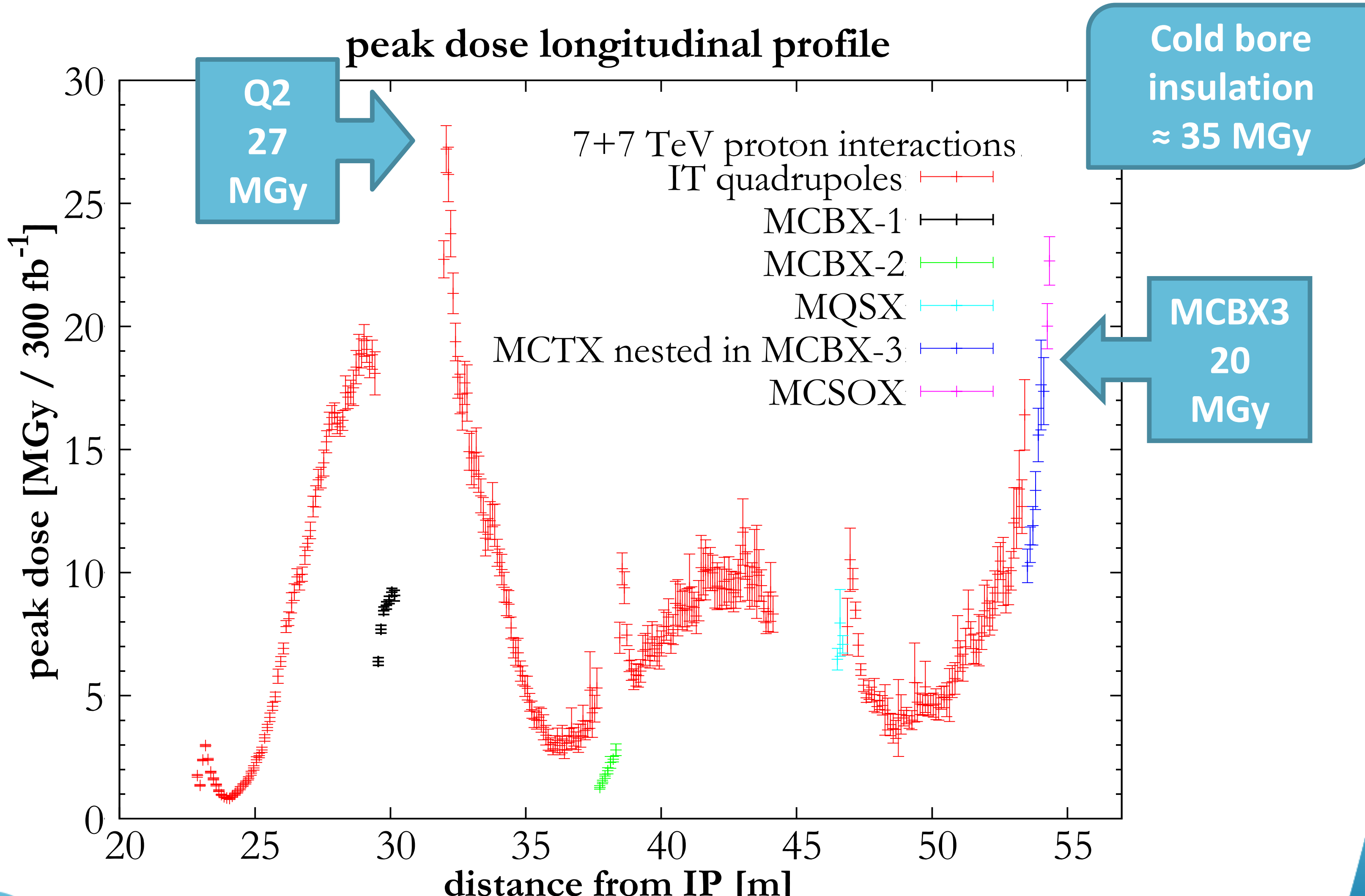
- Beam power & losses ➔ additional DS (cold region) collimators
- Machine effciency and availability:

  # R2E ➔ removal of all electronics from tunnel region

  # e-cloud ➔ beam scrubbing (conditioning of surface)

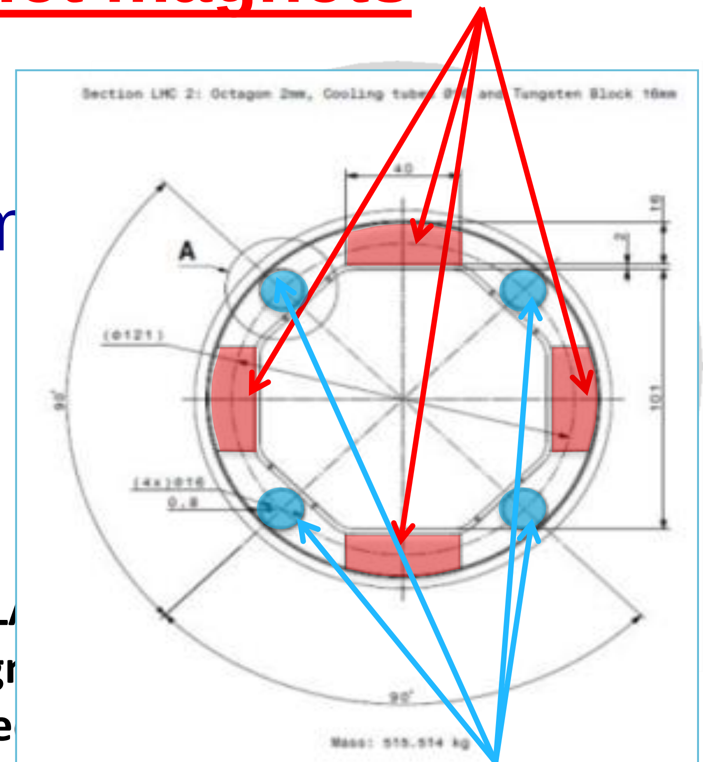
  # UFOs ➔ beam scrubbing (conditioning of surface)

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



HL-LHC technical bottleneck:
Radiation damage to triplet magnets

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



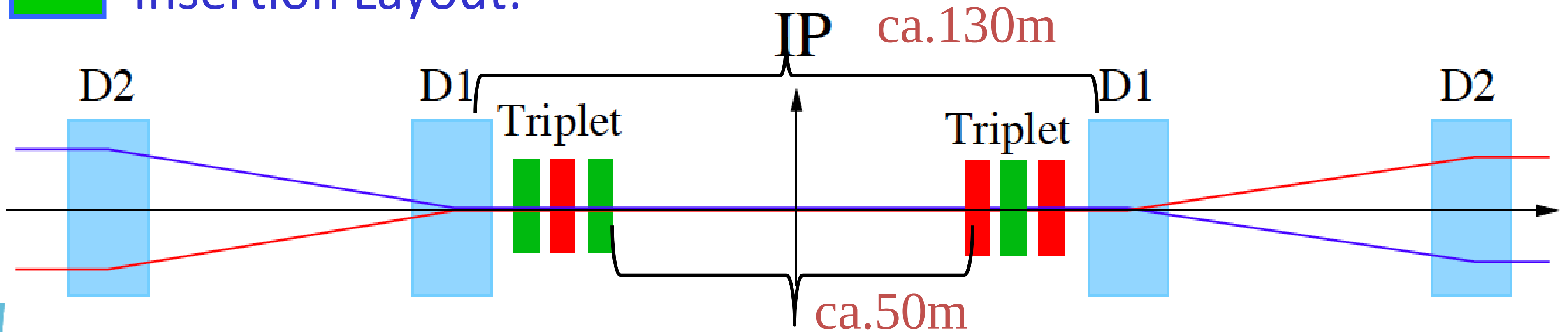
US-L
magr
Base
technology

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

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

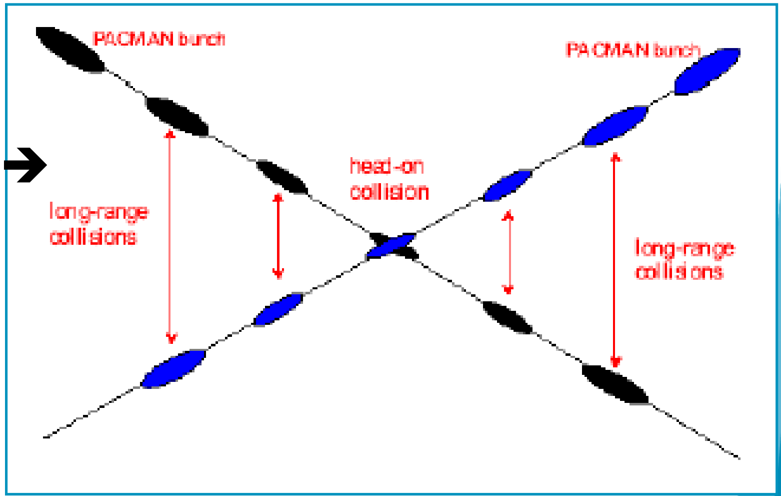
HL-LHC Challenges: Crossing Angle I

- Insertion Layout:



- Parasitic bunch encounters:

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 triplet apertures for HL-LHC upgrade!!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

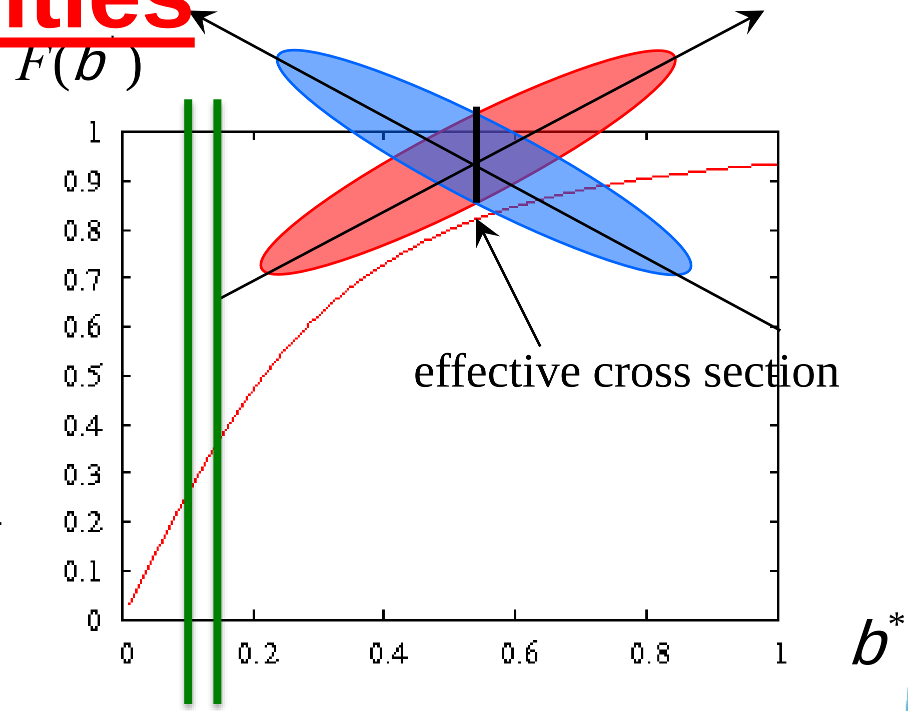
Crab Cavities:

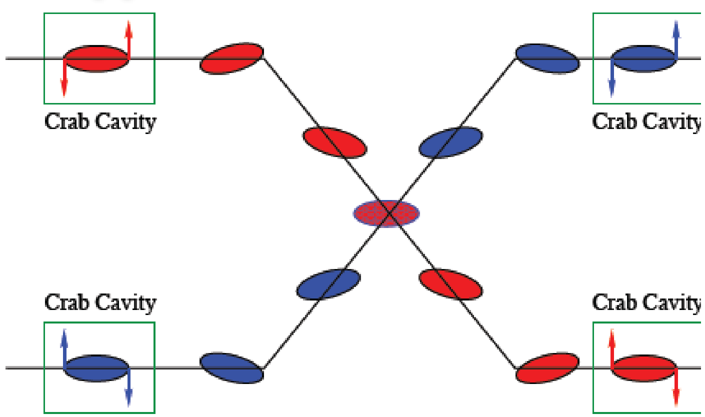
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+Q^2}}; \quad Q \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

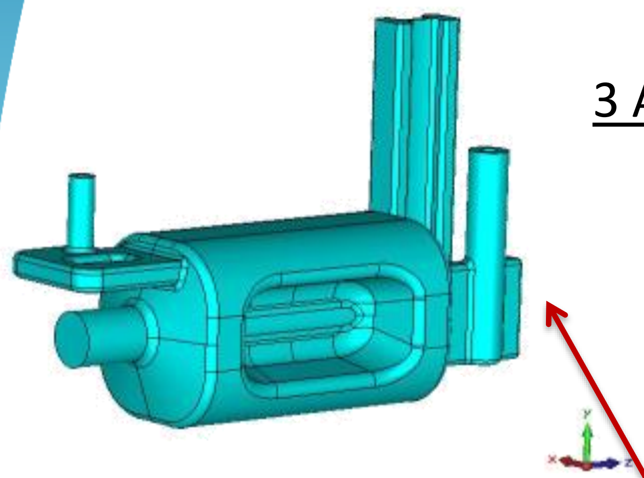
- Noise from cavities to beam?!?
- Challenging space constraints:

  ➔ requires novel compact cavity design

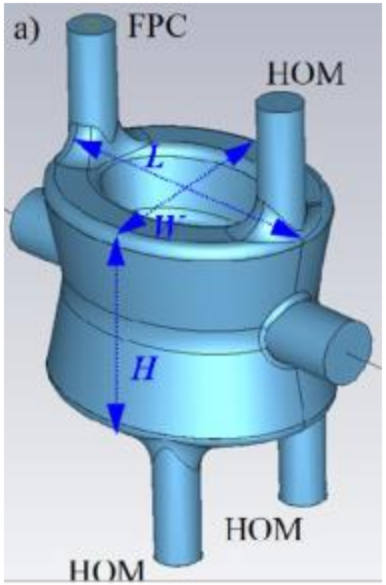




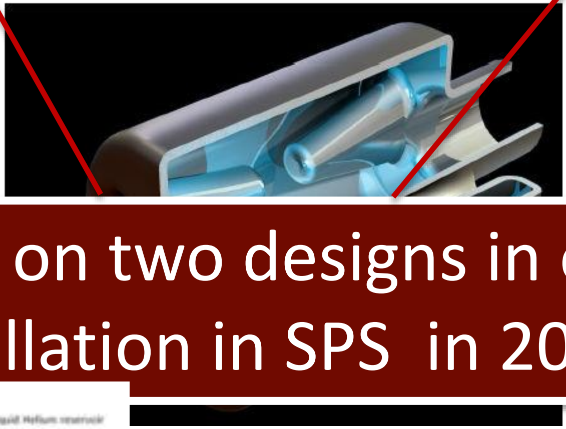
Latest cavity designs toward accelerator



3 Advanced Design Studies with
Different Coupler concepts

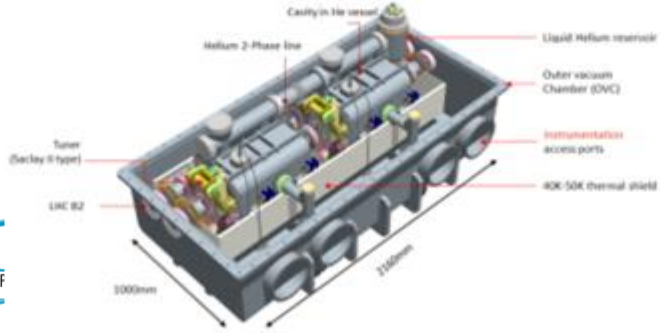


RF Dipole: Waveguide or waveguide-coax couplers



Double ¼-wave:

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

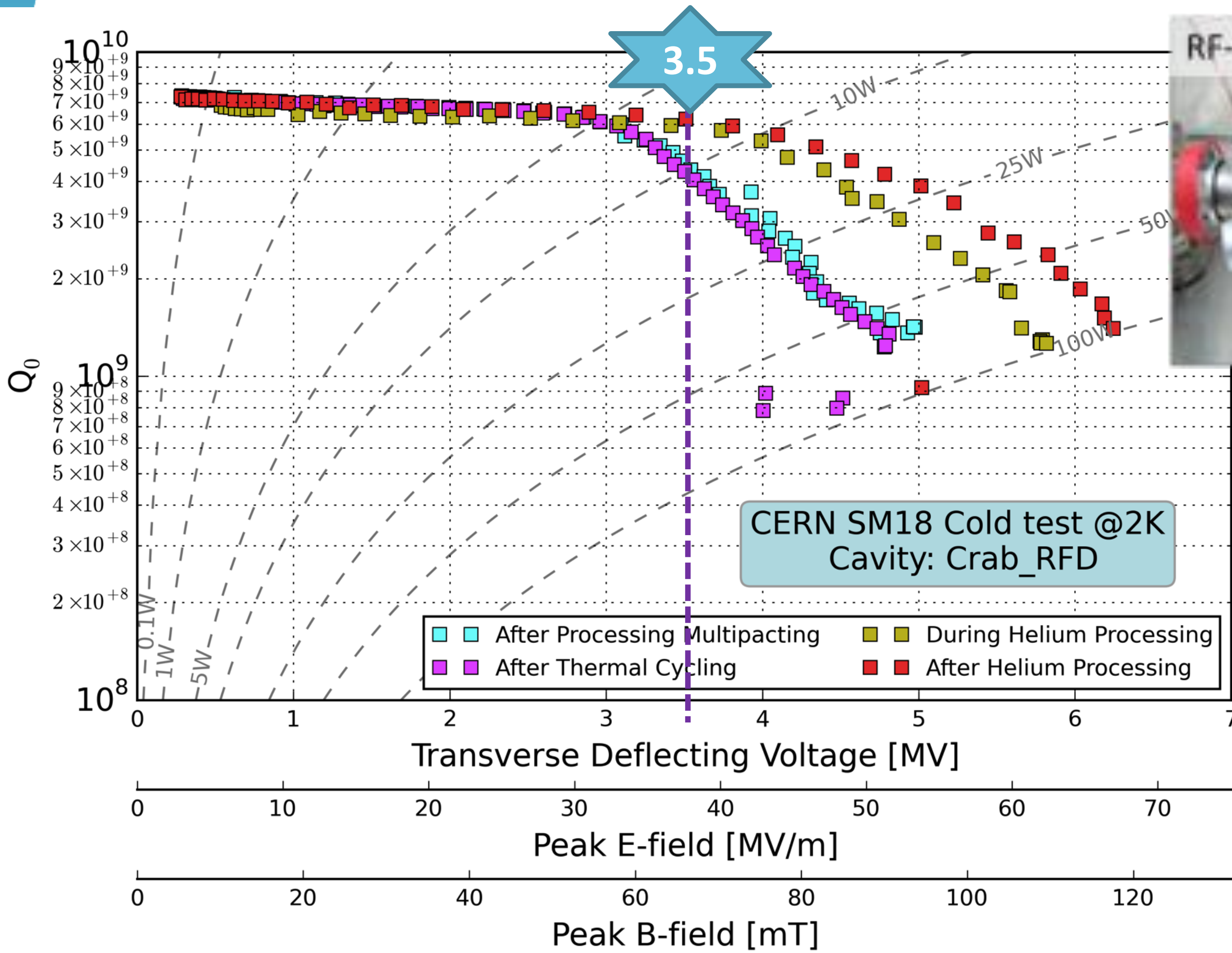


Coaxial couplers with
nt ar

Present baseline: 4 cavity/cryomod
TEST in SPS under preparation for 2017

And excellent first results: RF Dipole

Recent results from Measurements @ CERN



Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

LHC Challenges: Beam Power

- Unprecedented beam power:

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage

➔ Machine Protection

Lifetime & Loss Spikes ➔ Distributed losses

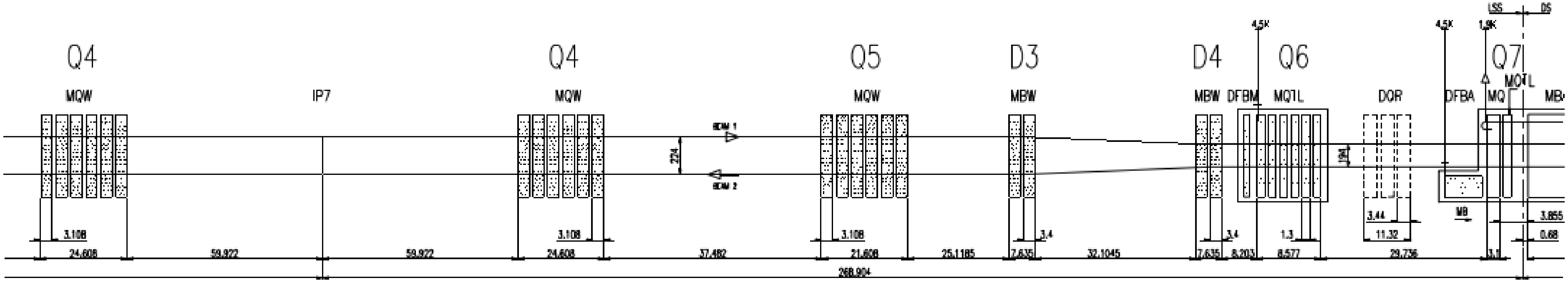
➔ Magnet Quench

➔ R2E and SEU and magnet lifetime (MQW!)

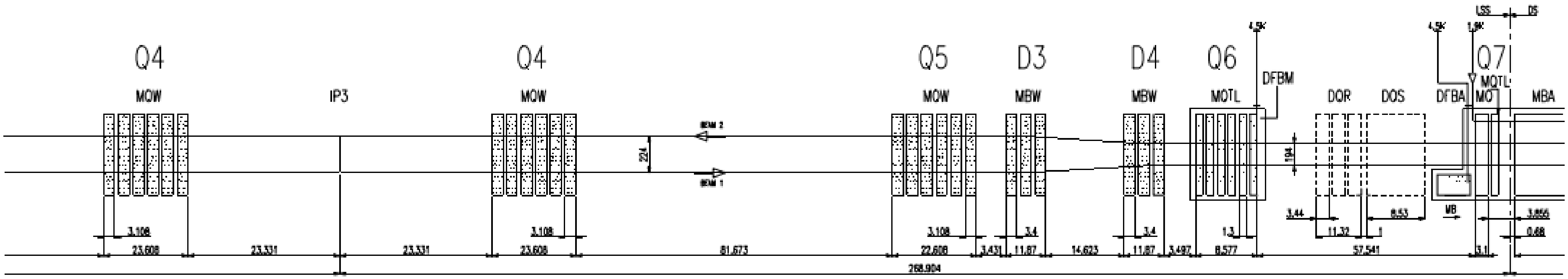
➔ Machine efficiency

Warm Magnets @ IR3 and IR7:

BETATRON CLEANING INSERTION



MOMENTUM CLEANING INSERTION



MQWA: apertures powered symmetrically [DF] ➔ gradients up to 35 T/m

MQWB: apertures powered anti-symmetrically [FF] ➔ gradients up to 29.6 T/m

Possible Failure modes

CERN-ACC-2014-0013

- Degradation of the insulation system due to radiation leading to inter turn short or shorts to ground
- Degradation of the mechanical shimming performed with ambient temperature cured resins

- Degradation of the insulation system due to radiation leading to inter turn short or shorts to ground
- Remark magnet build with no coil on the mid plane and therefore out from the expected zone of highest losses

Point 3 and 7 coil magnet damage estimation with shielding

green arrow shielding installed LS1

yellow arrow shielding foreseen for LS2

IP 3

	Dose [MGy] for integrated luminosity 150 fb^-1		Dose [MGy] for integrated luminosity 350 fb^-1		Dose [MGy] for integrated luminosity 3000 fb^-1	
	R	L	R	L	R	L
MQWA.A4	0	0	0	0	2	4
MQWA.B4	0	0	0	0	2	4
MQWB.4	0	0	0	1	2	4
MQWA.C4	0	0	0	1	3	6
MQWA.D4	0	1	1	2	7	14
MQWA.E4	[illegible]	3	2	5	13	24
MQWA.A5	[illegible]	2	2	3	8	15
MQWA.B5	[illegible]	3	2	4	10	19
MQWB.5	[illegible]	7	5	10	24	45
MQWA.C5	[illegible]	15	11	22	57	106
MQWA.D5	2	4	3	5	14	25
MQWA.E5	3	7	5	10	25	47
MBW.A6	2	4	3	6	15	27
MBW.B6	2	5	3	7	17	31
MBW.C6	3	7	5	9	24	44

MQW	MBW
From 10 to 20 MGy	From 40 to 60 MGy
From 20 to 50 MGy	From 60 to 80 Mgy
Larger than 50 MGy	Larger than 80 MGy

IP 7

R

	Dose [MGy] for integrated luminosity 150 fb^-1		Dose [MGy] for integrated luminosity 350 fb^-1		Dose [MGy] for integrated luminosity 3000 fb^-1	
	R	L	R	L	R	L
MQWA.A4	1	1	1	2	10	15
MQWA.B4	0	1	1	3	9	22
MQWB.4	1	2	1	3	6	14
MQWA.C4	6	6	9	9	41	41
MQWA.D4	2	2	4	4	24	24
MQWA.E4	1	2	2	5	19	39
MQWA.A5	3	3	4	4	20	20
MQWA.B5	4	4	6	6	29	29
MQWB.5	4	4	6	6	29	29
MQWA.C5	2	5	3	7	11	28
MQWA.D5	3	5	6	8	34	49
MQWA.E5	14	5	32	11	278	93
MBW.A6	7	5	16	12	138	99
MBW.B6	12	6	29	14	247	123

Point 3 and 7 coil magnet damage estimation with shielding

green arrow shielding installed LS1

yellow arrow shielding foreseen for LS2

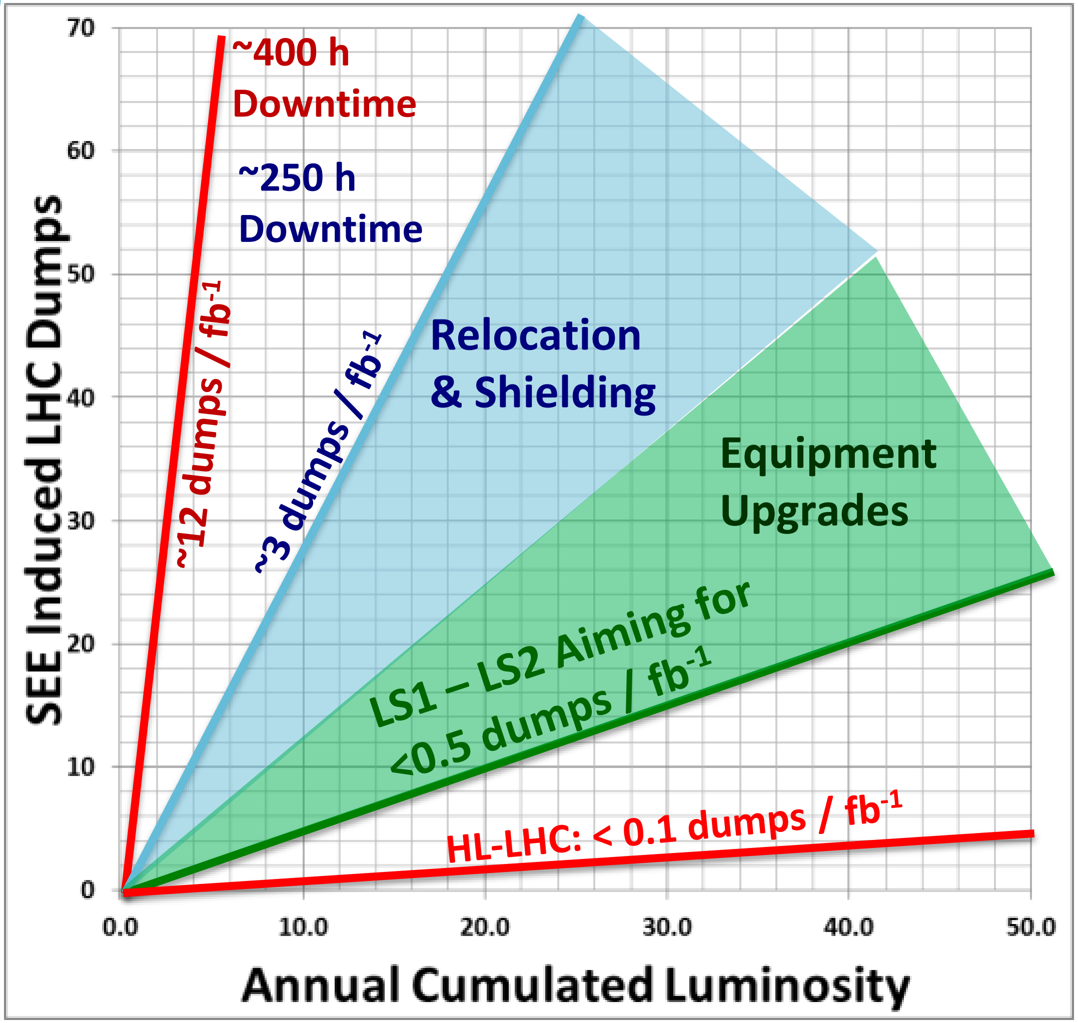
IP 3	Dose [MGy] for integrated luminosity 150 fb^-1		Dose [MGy] for integrated luminosity 350 fb^-1		Dose [MGy] for integrated luminosity 3000 fb^-1	
	R	L	R	L	R	L
MQWA.A4	0	0	0	0	2	4
MQWA.B4	0	0	0	0	2	4
MQWB.4	0	0	0	1	2	4
MQWA.C4	0	0	0	1	3	6
MQWA.D4	0	1	1	2	7	14
MQWA.E4	[illegible]	3	2	5	13	24
MQWA.A5	[illegible]	2	2	3	8	15
MQWA.B5	[illegible]	3	2	4	10	19
MQWB.5	[illegible]	7	5	10	24	45
MQWA.C5	[illegible]	15	11	22	57	106
MQWA.D5	2	4	3	5	14	25
MQWA.E5	3	7	5	10	25	47
MBW.A6	2	4	3	6	15	27
MBW.B6	2	5	3	7	17	31
MBW.C6	3	7	5	9	24	44

MQW	MBW
From 10 to 20 MGy	From 40 to 60 MGy
From 20 to 50 MGy	From 60 to 80 Mgy
Larger than 50 MGy	Larger than 80 MGy

Connected in series with the other in new Q5 configuration

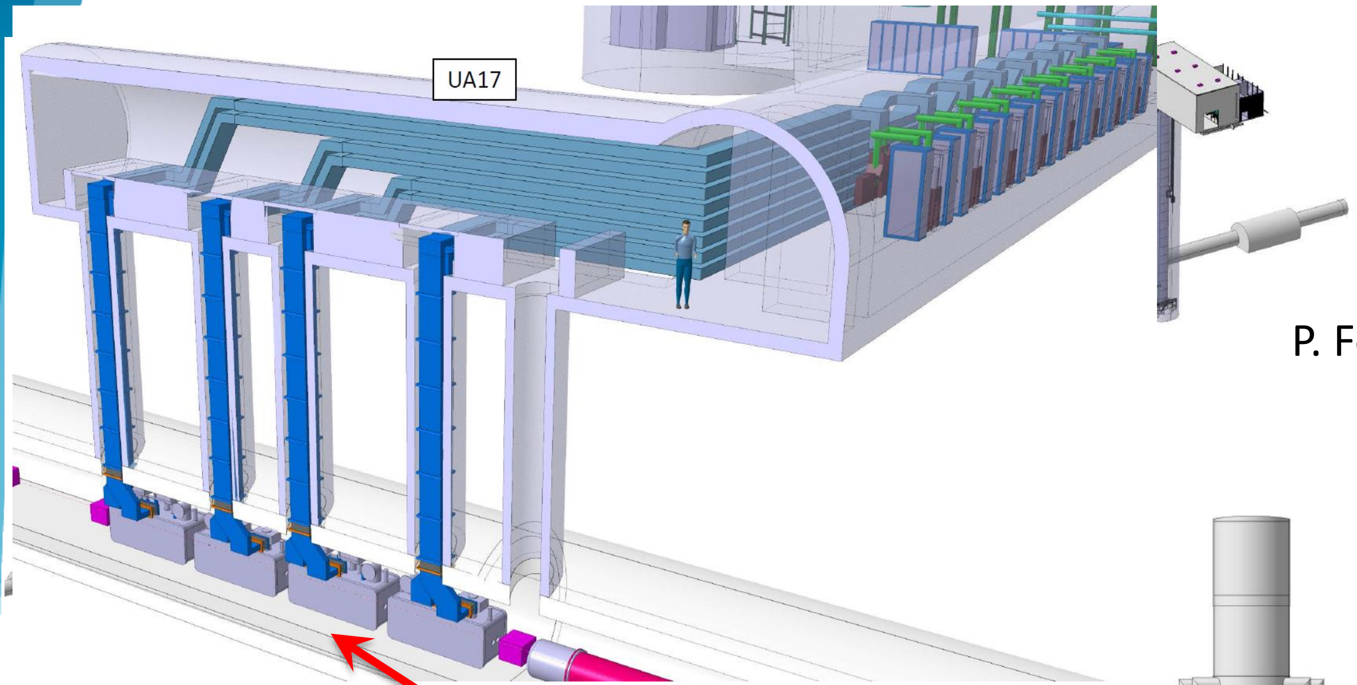
IP 7	Dose [MGy] for integrated luminosity 150 fb^-1		Dose [MGy] for integrated luminosity 350 fb^-1		Dose [MGy] for integrated luminosity 3000 fb^-1	
	R	L	R	L	R	L
MQWA.A4	1	1	1	2	10	15
MQWA.B4	0	1	1	3	9	22
MQWB.4	1	2	1	3	6	14
MQWA.C4	6	6	9	9	41	41
MQWA.D4	2	2	4	4	24	24
MQWA.E4	1	2	2	5	19	39
MQWA.A5	3	3	4	4	20	20
MQWA.B5	4	4	6	6	29	29
MQWB.5	4	4	6	6	29	29
MQWA.C5	2	5	3	7	11	28
MQWA.D5	3	5	6	8	34	49
Replaced by absorber						
MBW.A6	7	5	16	12	138	99
MBW.B6	12	6	29	14	247	123

R2E SEU Failure Analysis - Actions

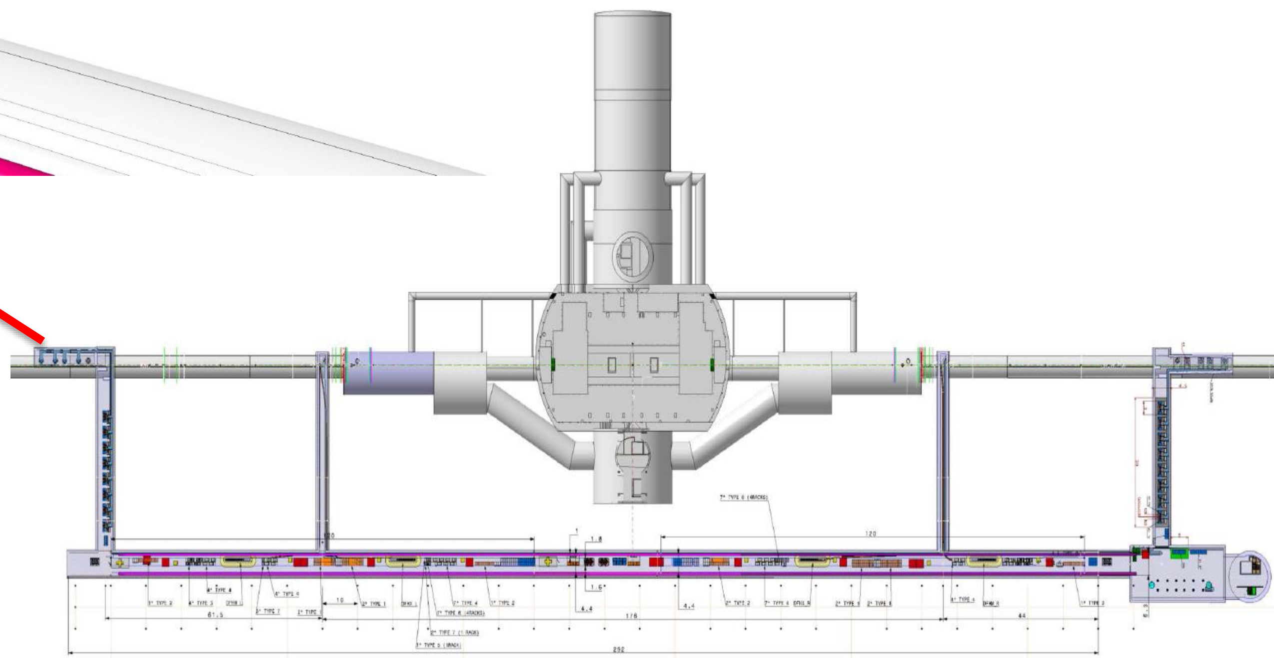


- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

IR1 & IR5 Underground Civil Engineering:

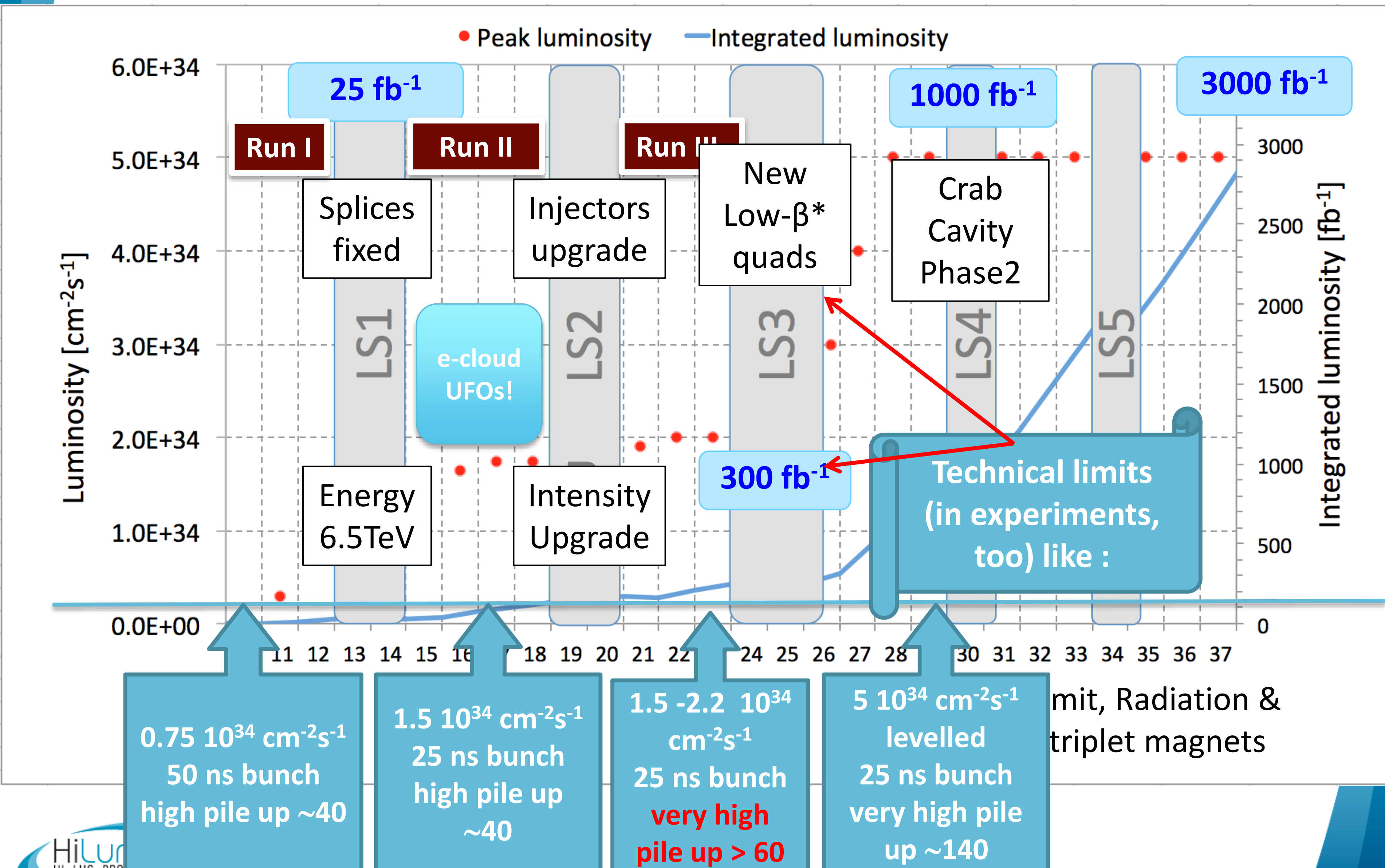


P. Fessia, HL-LHC TDR

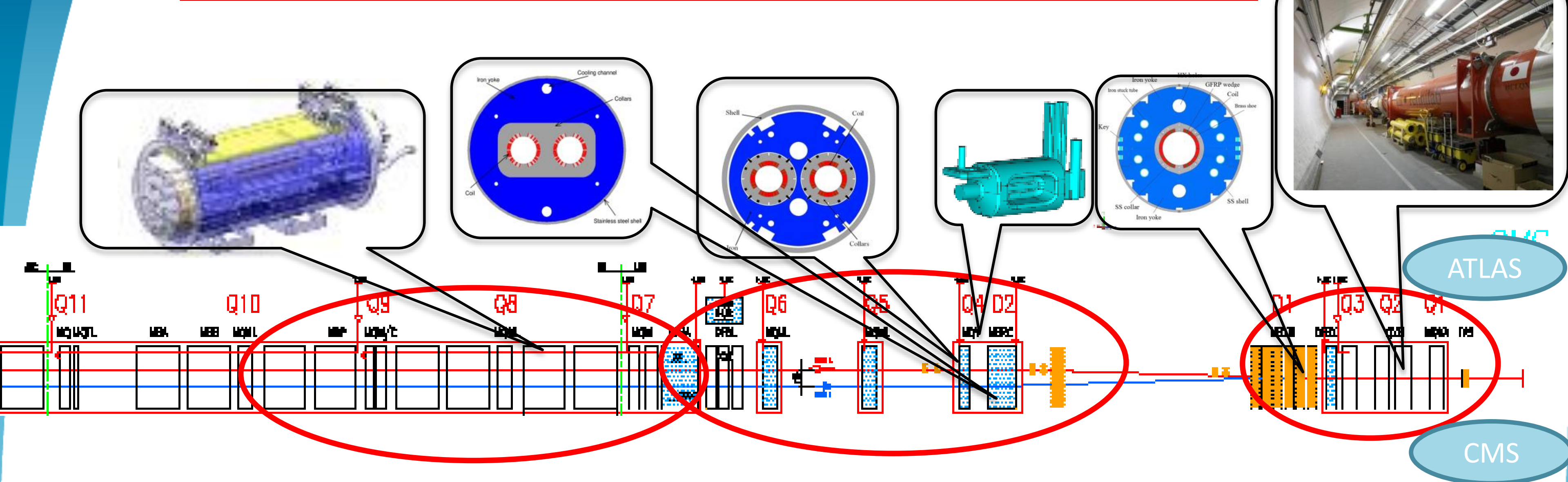


New Schedule: ➔ HL-LHC CE during LS2

Performance Projections up to HL-LHC:



The critical zones around IP1 and IP5



1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

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

Changing the triplet region is not enough for reaching the HL-LHC goal!

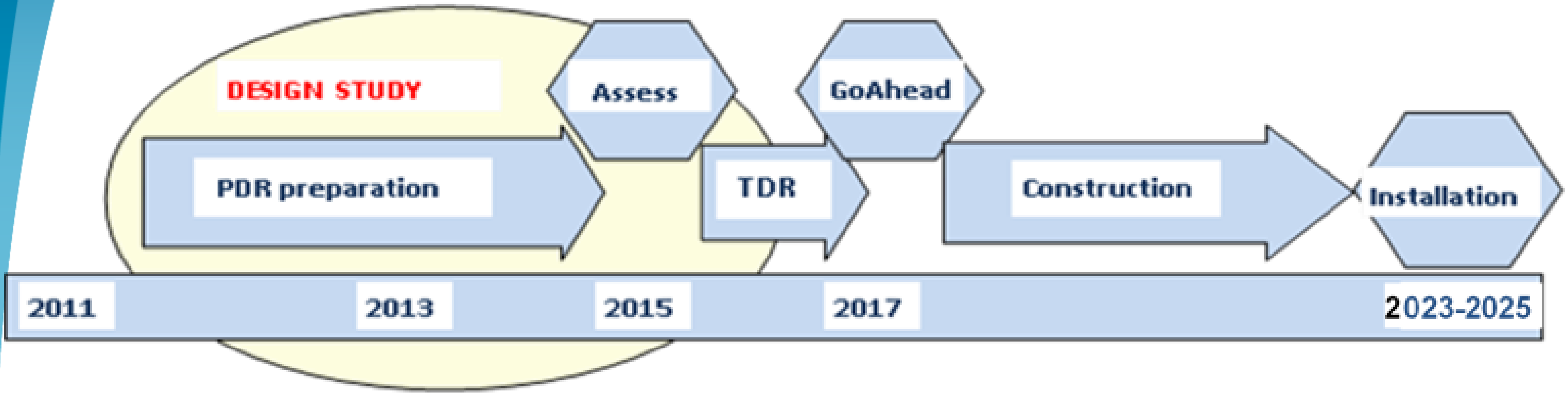
→ More than 1.2 km of LHC !!
→ Plus technical infrastructure (e.g. Cryo and Powering)!!

Project approval milestones:

- June 2010: launch of High Luminosity LHC
- November 2010 : HiLumi DS application to FP7
- November 2011: start FP7-HiLumi DS
- May 2013: approval of HL-LHC as 1st priority of EU-HEP strategy by CERN Council in Brussels
- May 2014: US P5 ranks HL-LHC as priority for DOE

  (Particle Physics Project Prioritization Panel)
- June 2014: CERN Council approves the financial plan of HL-LHC till 2025 (with an overall 10% budget cut)

Implementation plan:



- PDR: Oct 2014 ; Ext. Cost & Schedule Review in Jan-Feb 2015;
- TDR: OCT 2015; TDR_v2 : 2017
- Start Civil Engineering work prior to LS2 with planned completion by end of LS2
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Start construction 2018 for IT, CC & other main hardware
- IT String test (integration) in 2019-20; Main Installation 2024-26