HL-LHC Accelerator Status & Schedule

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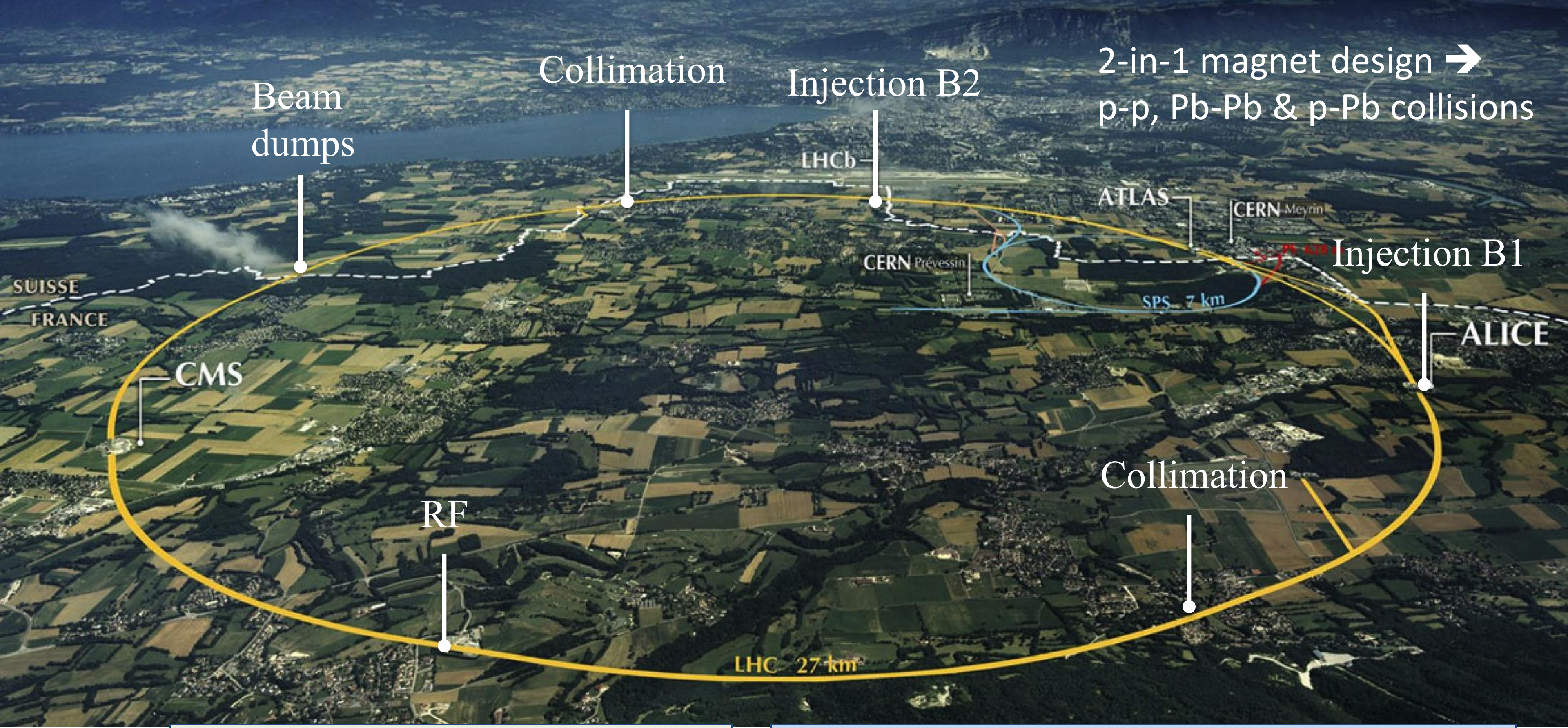
For the HL-LHC Project team

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

LHC: big (27km), cold (1.8K), high energy (7 TeV on 7 TeV)



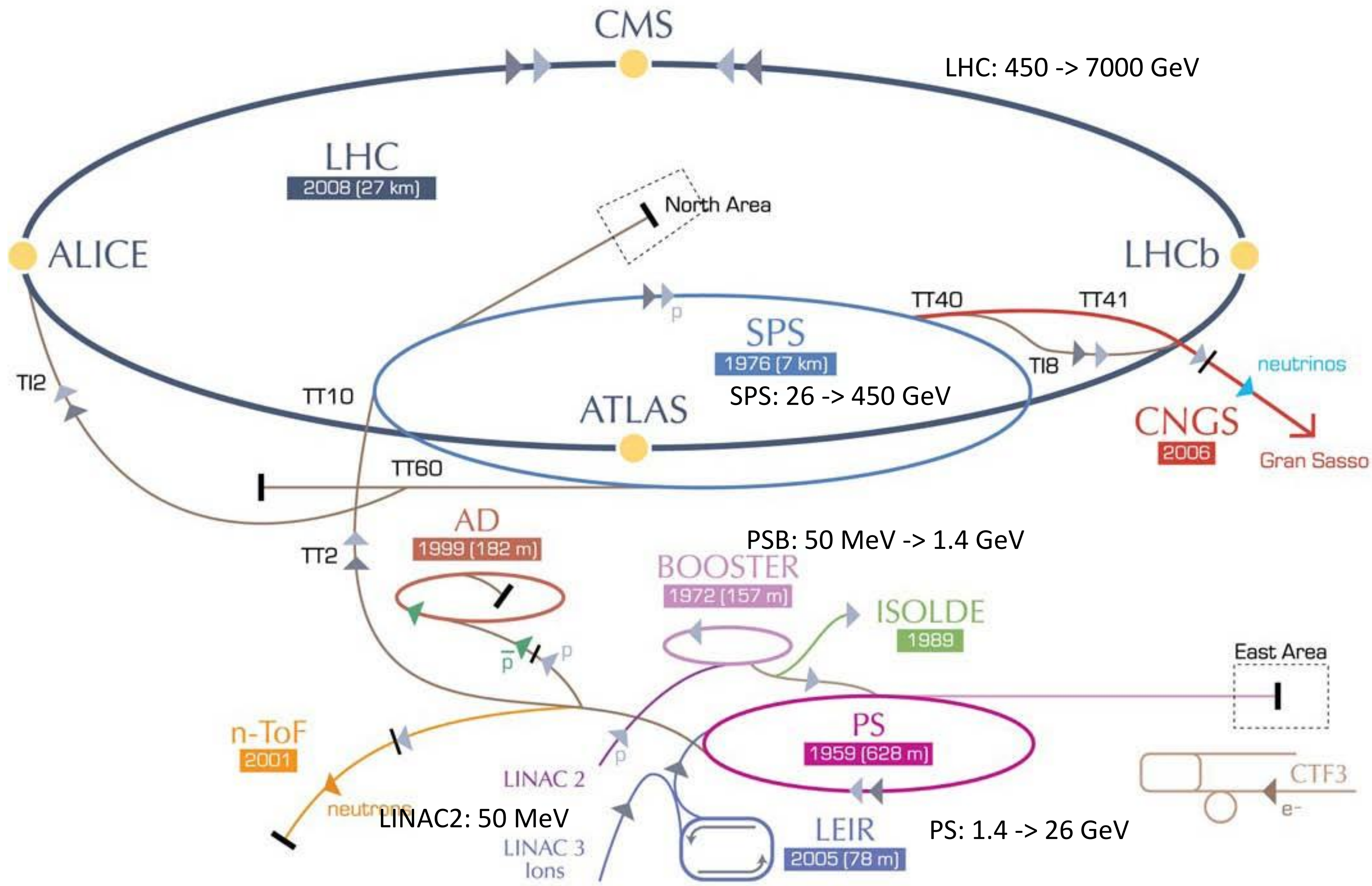
2-in-1 magnet design ➔
p-p, Pb-Pb & p-Pb collisions

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

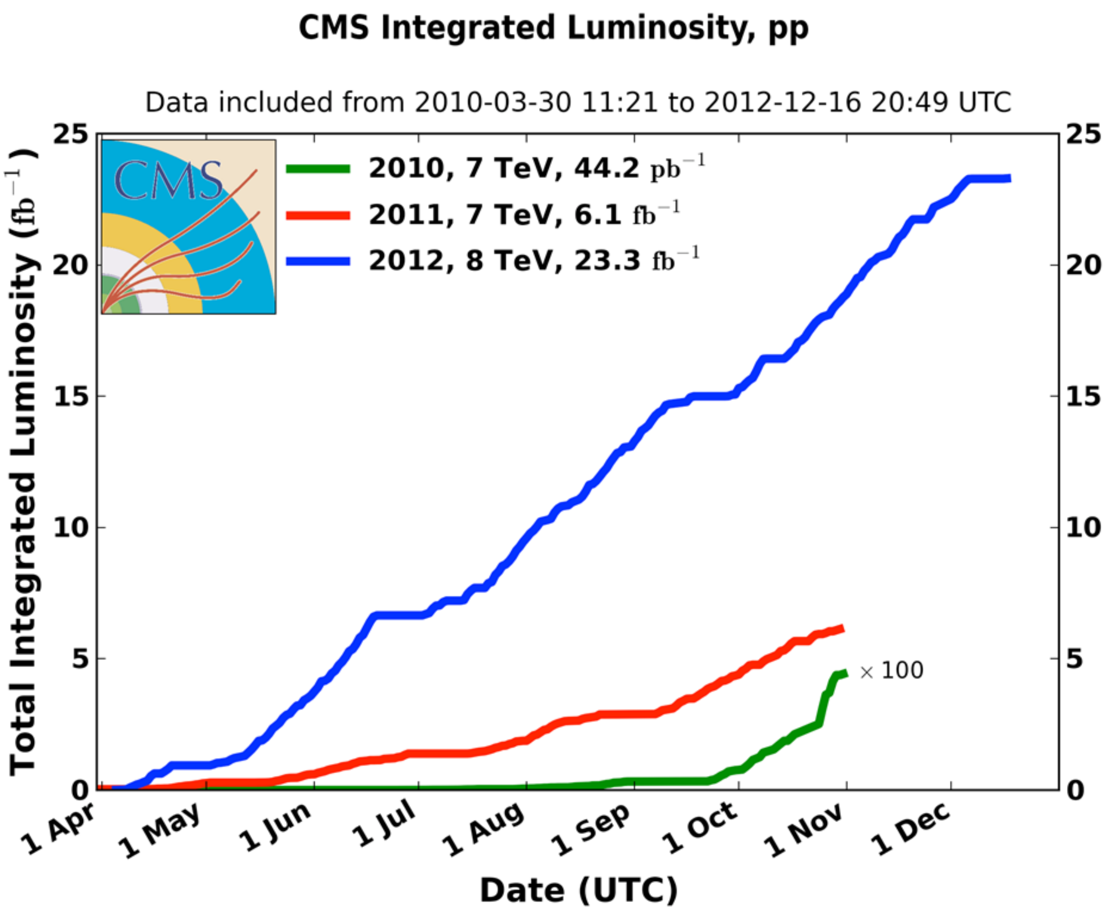
150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
450 MJ magnetic energy per sector at 4 TeV
➔ ≈ 10 GJ total @ 7 TeV

High Luminosity LHC

The LHC is NOT a Standalone Machine:



Integrated Luminosity 2010-2012

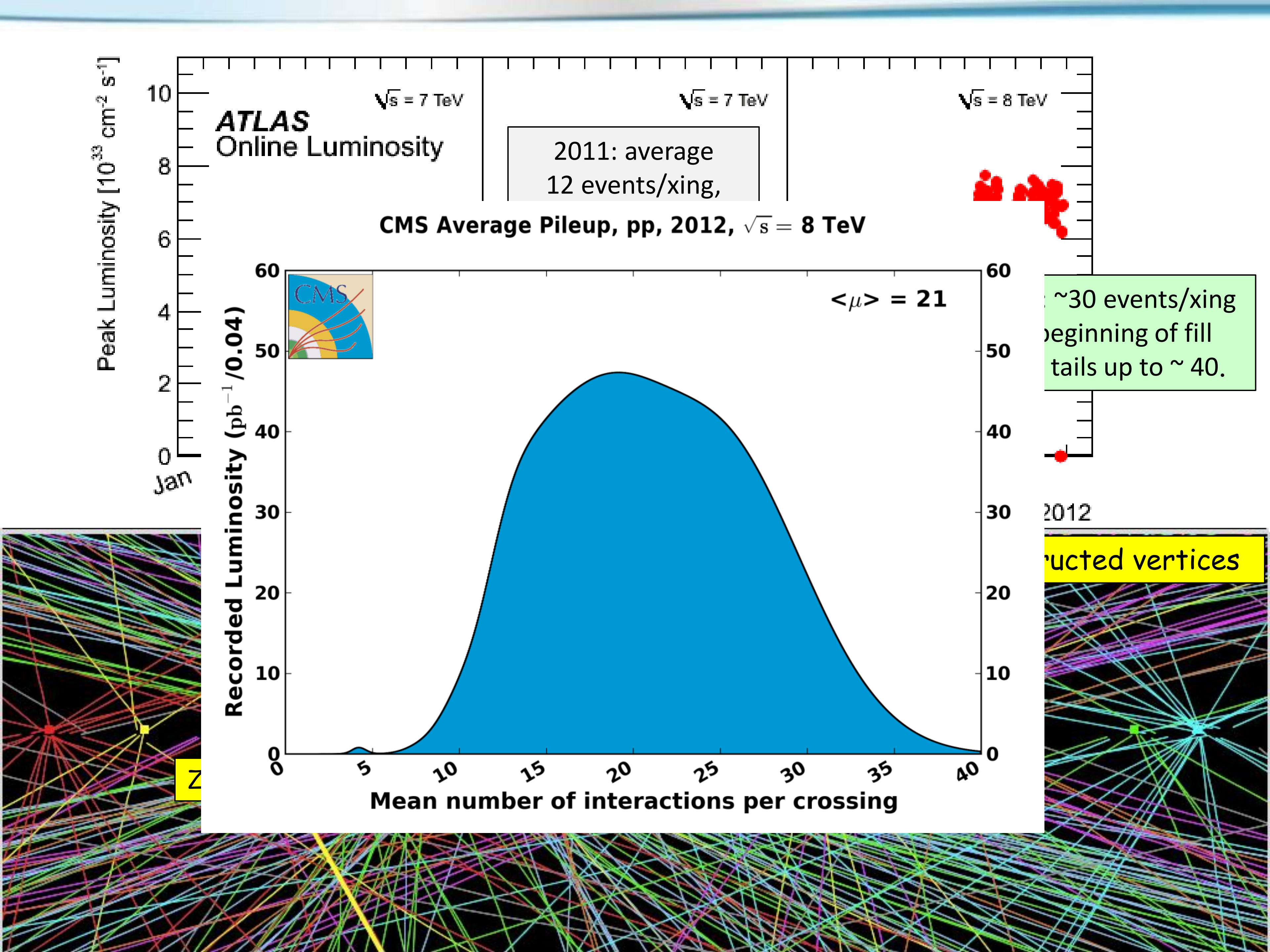


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

× 15

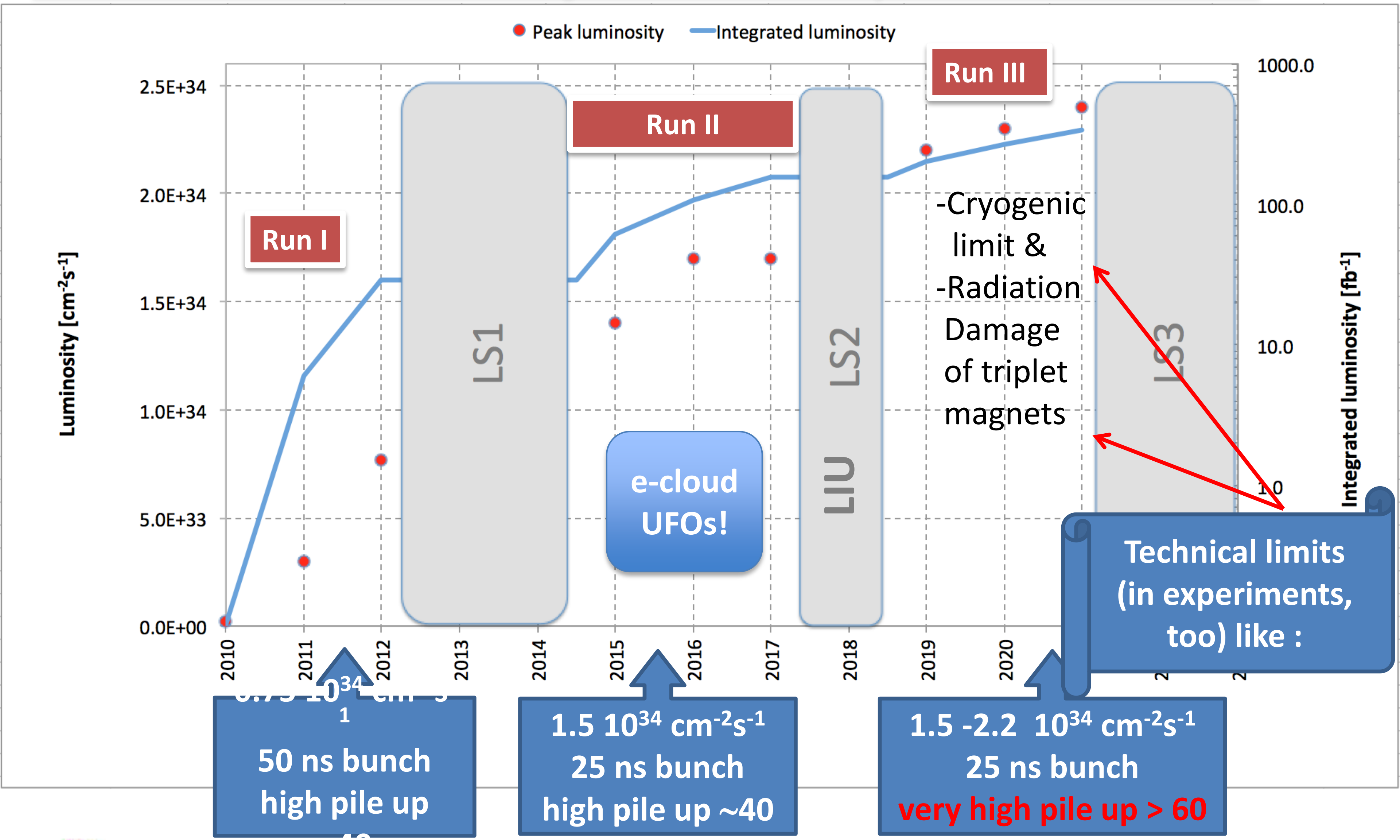
× 4

➔ x 60 in 2 years!



Peak Luminosity [10^{33} cm^{-2} s^{-1}]
10
8
6
4
2
0
Jan
√s = 7 TeV
√s = 7 TeV
√s = 8 TeV
ATLAS
Online Luminosity
2011: average
12 events/xing,
~30 events/xing
eginning of fill
tails up to ~ 40.
2012
ucted vertices
CMS Average Pileup, pp, 2012, $\sqrt{s}$ = 8 TeV
CMS
<μ> = 21
Recorded Luminosity (pb^{-1}/0.04)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
Mean number of interactions per crossing

Performance Projections up to HL-LHC:



The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation beyond 2025 and up to **2035**

Devise beam parameters and operation scenarios for:

enabling at total integrated luminosity of **3000 fb^{-1}**

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

design oper. for μ δ **140** (➔ peak luminosity of **5 10^{34} cm^{-2} s^{-1}**)

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

High Luminosity LHC

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

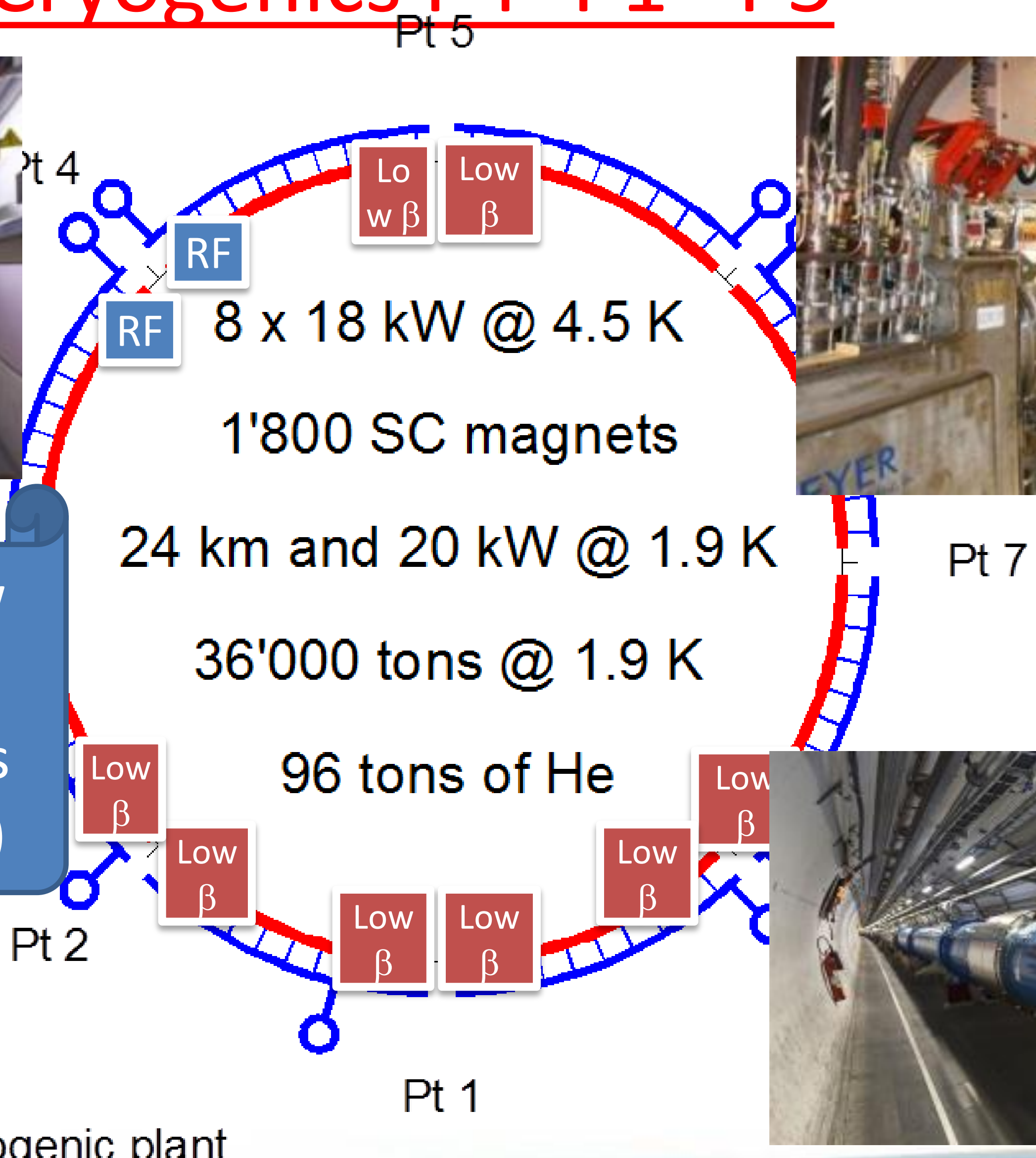
  ➔ devise parameters for virtual luminosity >> target luminosity
- Beam power & losses ➔ additional DS (cold region) collimators
- Machine effciency and availability:

  # R2E ➔ removal of all electronics from tunnel region

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

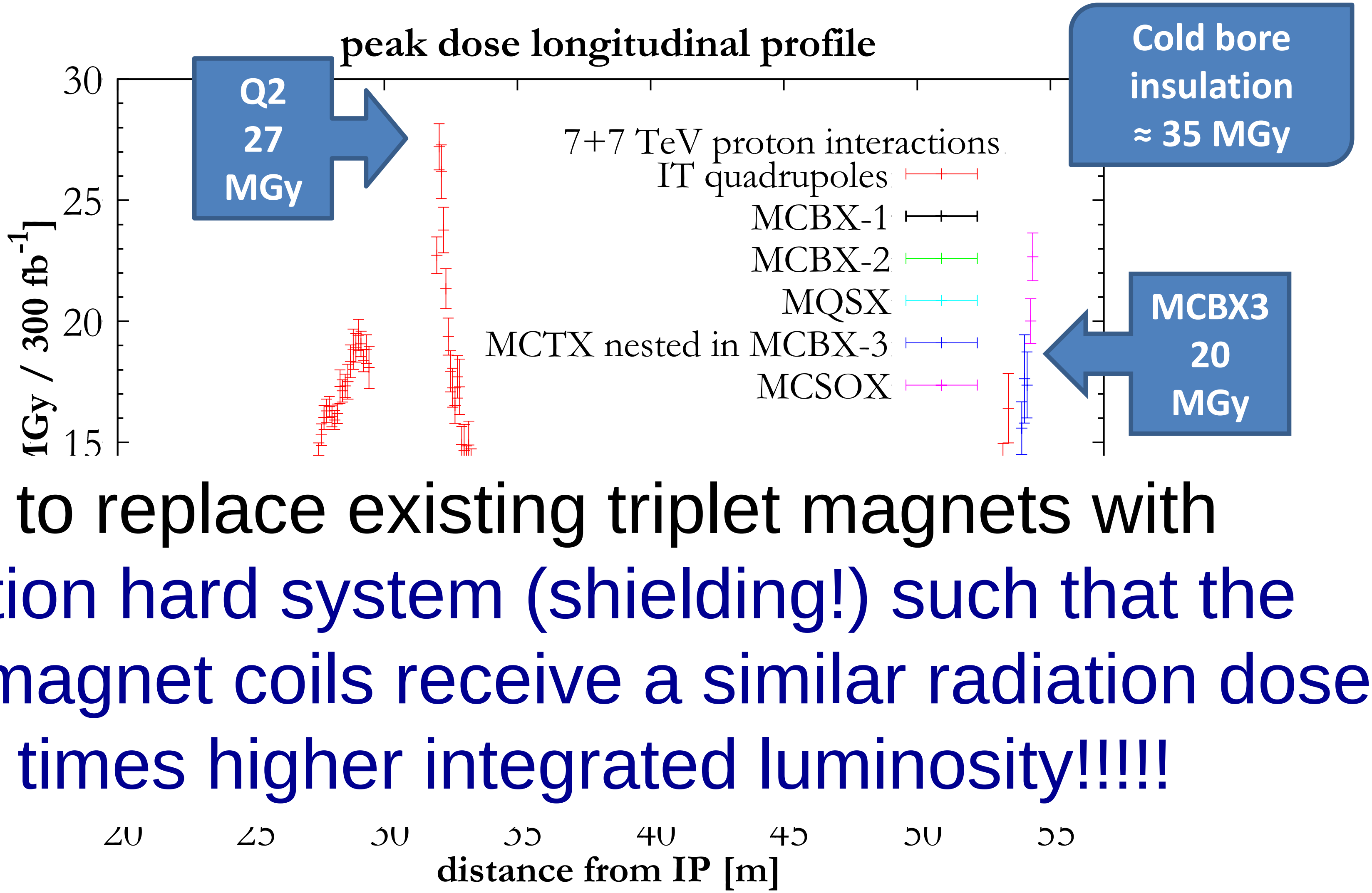
  # UFOs ➔ beam scrubbing (conditioning of surface)

Eliminating Technical Bottlenecks
Cryogenics P4- P1 –P5



New Plant ≥ 6 kW in P4 (LS2)
New 18 kW Plants in P1 and P5 (LS3)

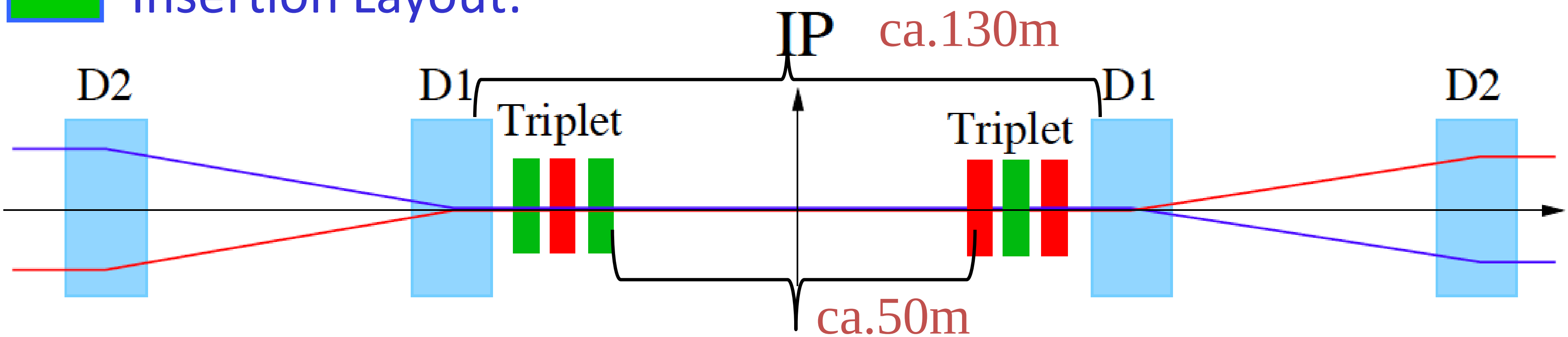
HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb^{-1}



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!!!!!

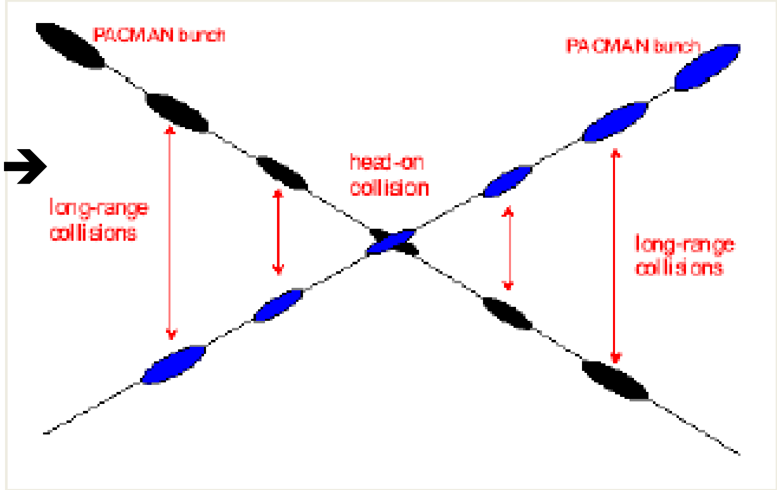
HL-LHC Challenges: Crossing Angle I

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!!

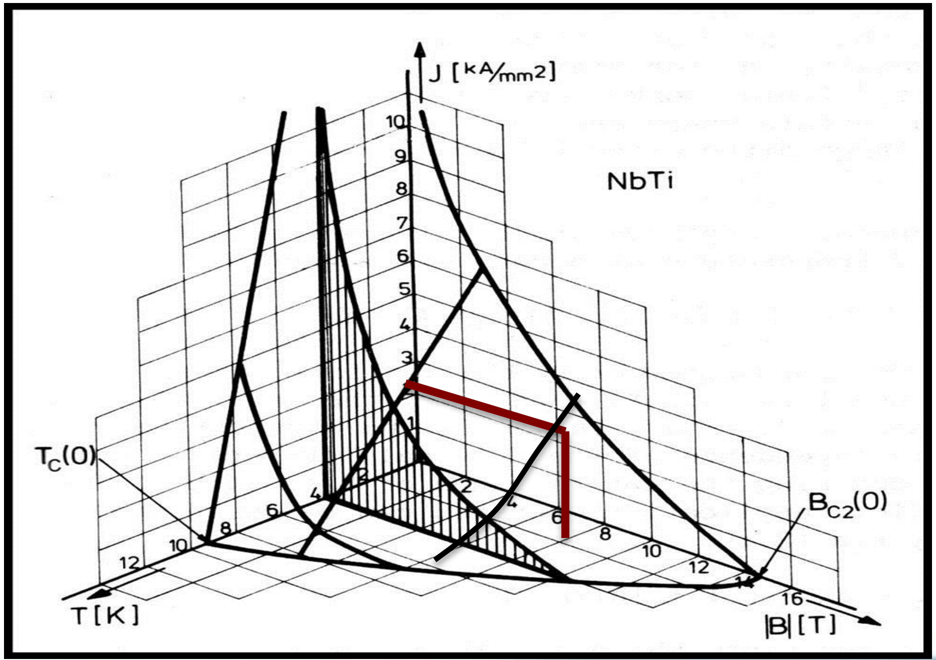
High Luminosity LHC

HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ➔ ca. 8 T @ coil
  - ➔ 1.8 K cooling with superfluid He (thermal conductivity)
  - ➔ current density of 2.75 kA / mm^2
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!!

LHC Production in collaboration with USA and KEK

Critical Surface for NbTi



HL-LHC Magnets:

- LHC triplet:

  210 T/m, 70 mm bore aperture

  ➔ 8 T @ coil (limit of NbTi tech.)
- **HL-LHC triplet:**

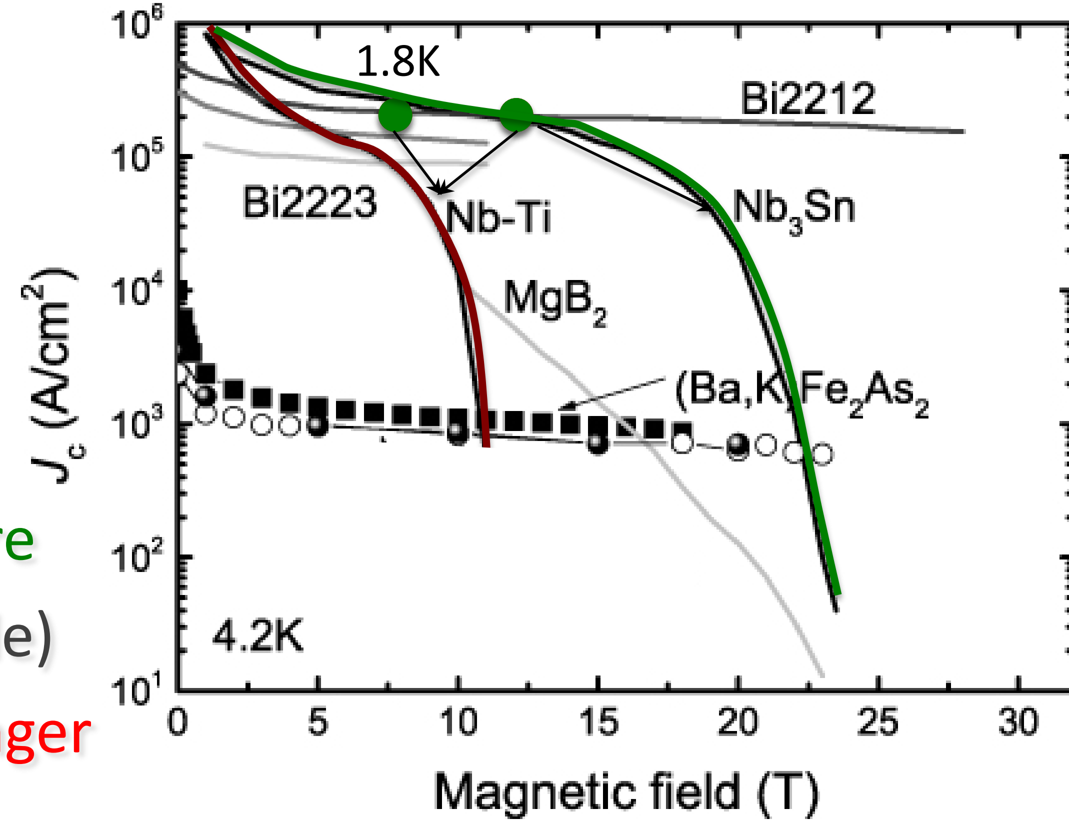
  140 T/m, 150 mm coil aperture

  (shielding, β^* and crossing angle)

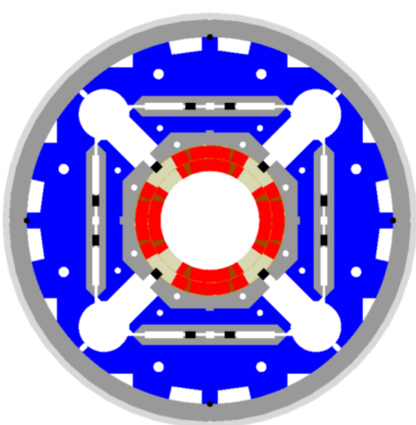
  ➔ ca. 12 T @ coil ➔ 30% longer
  - Requires Nb_3Sn technology

    ➔ ceramic type material (fragile)

    ➔ ca. 25 year development for this new magnet technology!
  - US-LARP – CERN collaboration

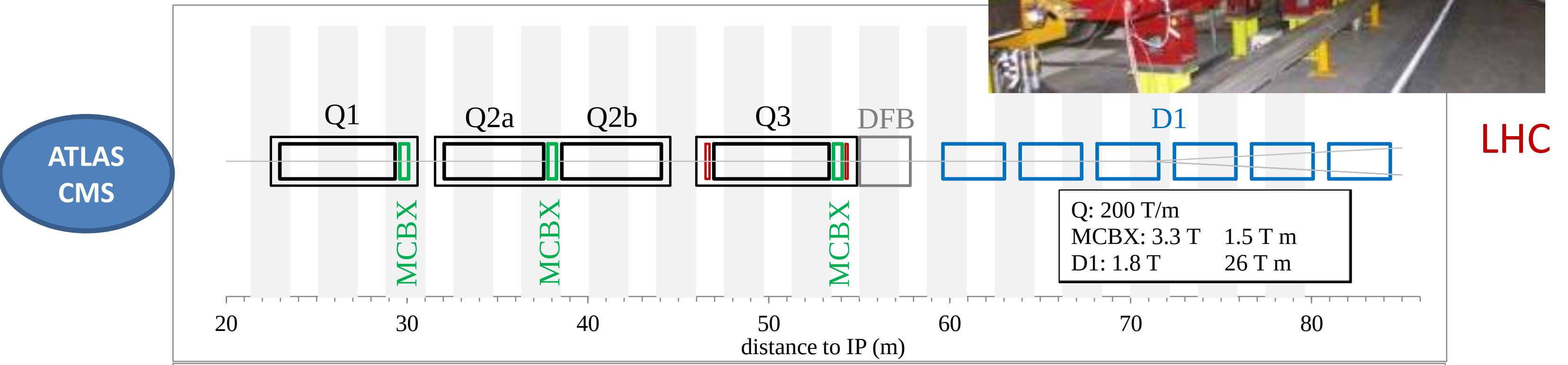


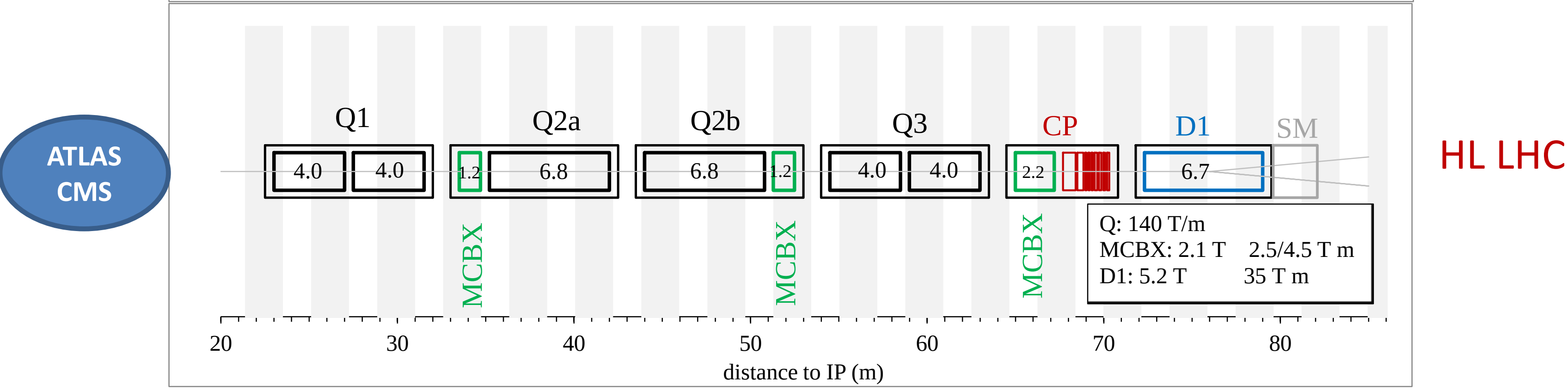
US-LARP MQXF magnet design Based on Nb_3Sn technology



New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)

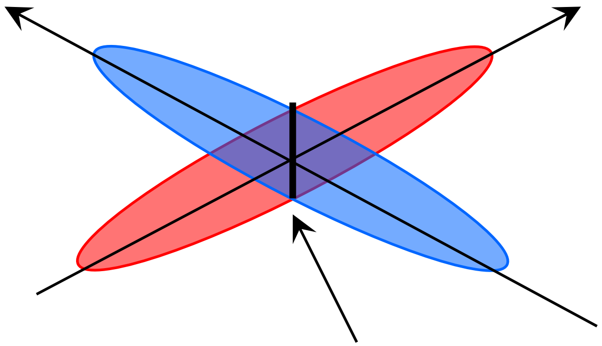




Thick boxes are magnetic lengths -- Thin boxes are cryostats

LHC Challenges: Crossing Angle II

geometric luminosity reduction factor:



large crossing angle:

- ➔ reduction of long range beam-beam interactions
- ➔ reduction of beam-beam tune spread and resonances
- ➔ reduction of the mechanical aperture
- ➔ increase of effective beam cross section at IP
- ➔ reduction of luminous region
  - ➔ reduction of instantaneous luminosity
  - ➔ inefficient use of beam current!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

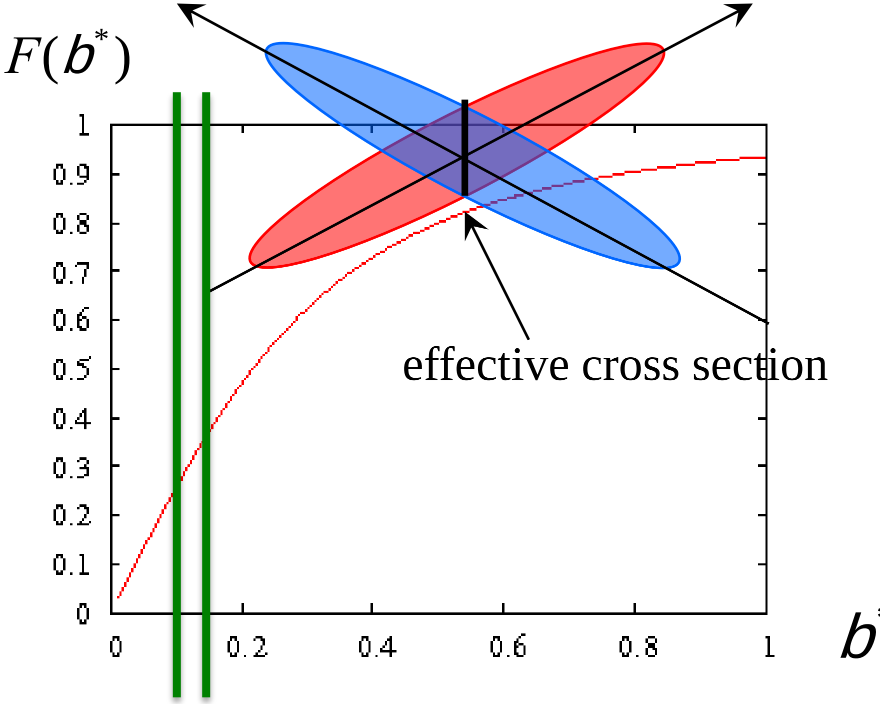
Crab Cavities:

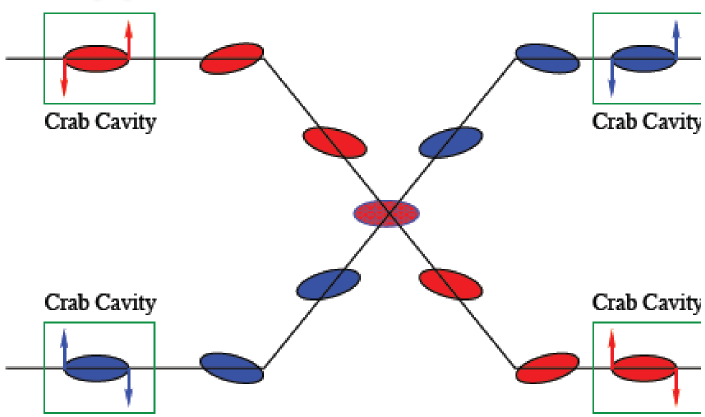
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

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

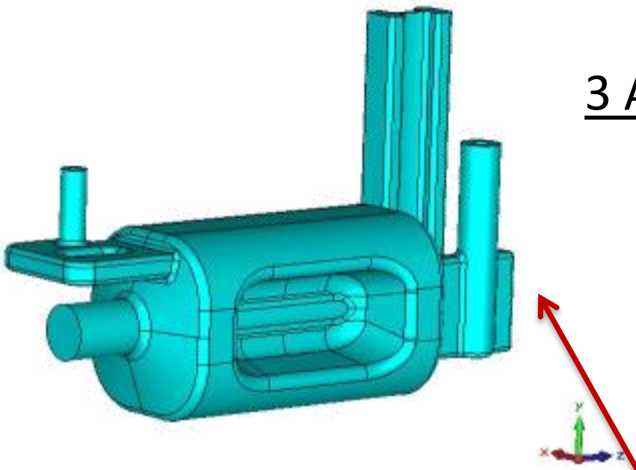
  ➔ requires novel compact cavity design



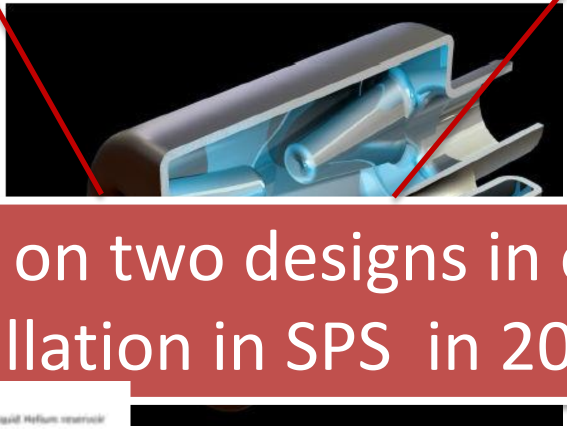


Latest cavity designs toward accelerator

3 Advanced Design Studies with Different Coupler concepts

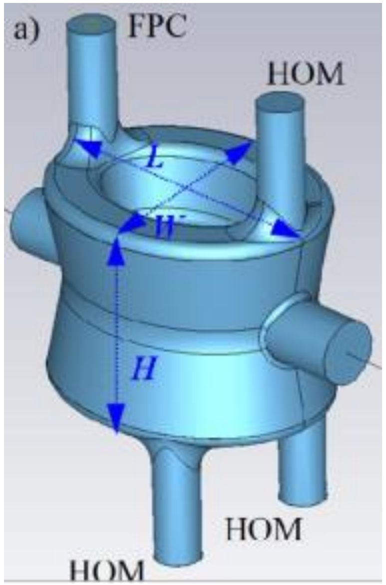


RF Dipole: Waveguide or waveguide-coax couplers



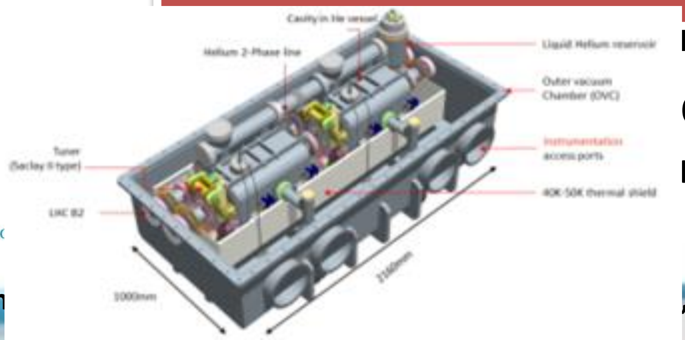
Coaxial couplers with

nt ar



Double ¼-wave:

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

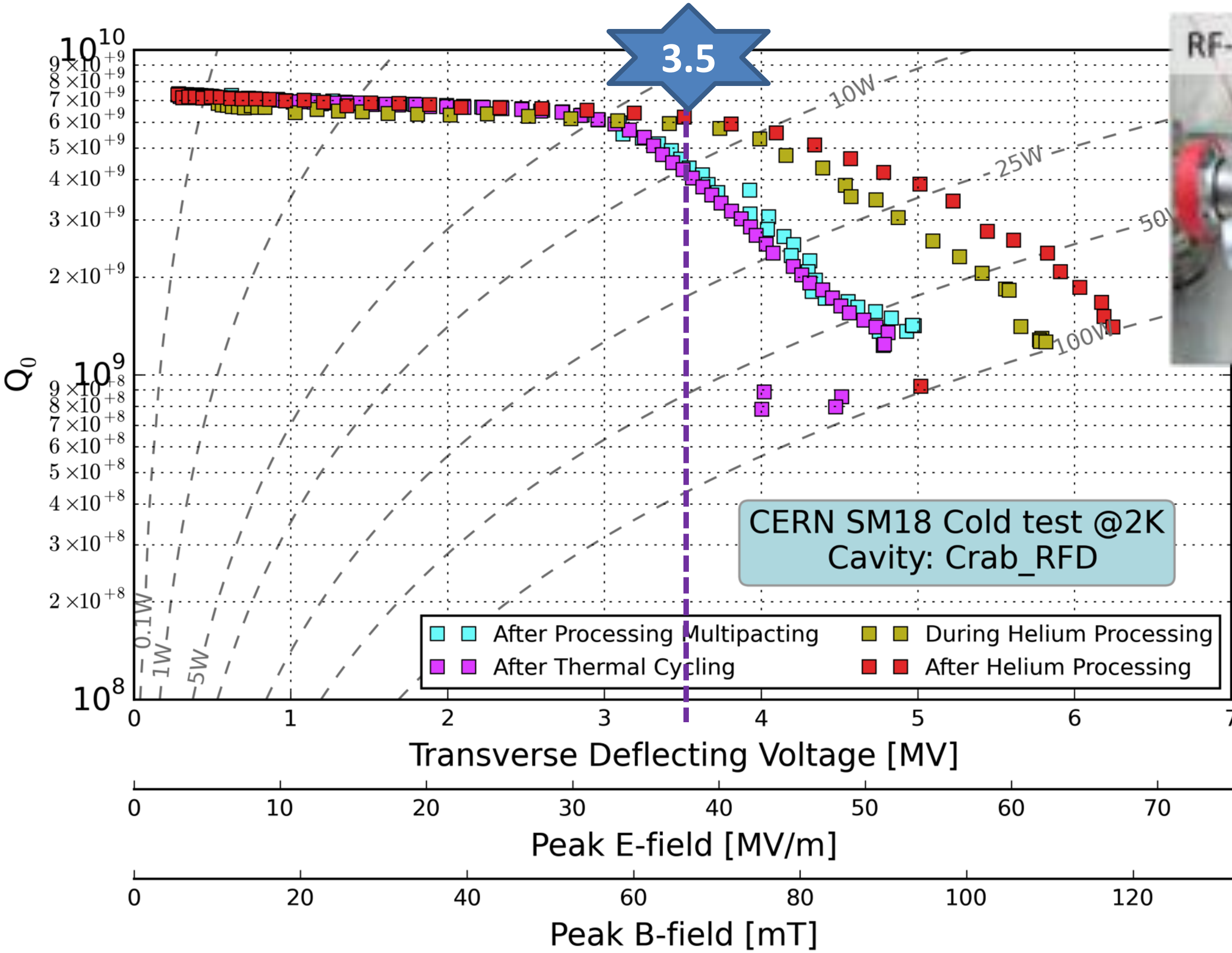


Present baseline: 4 cavity/cryomod

TEST in SPS under preparation for 2017

And excellent first results: RF Dipole

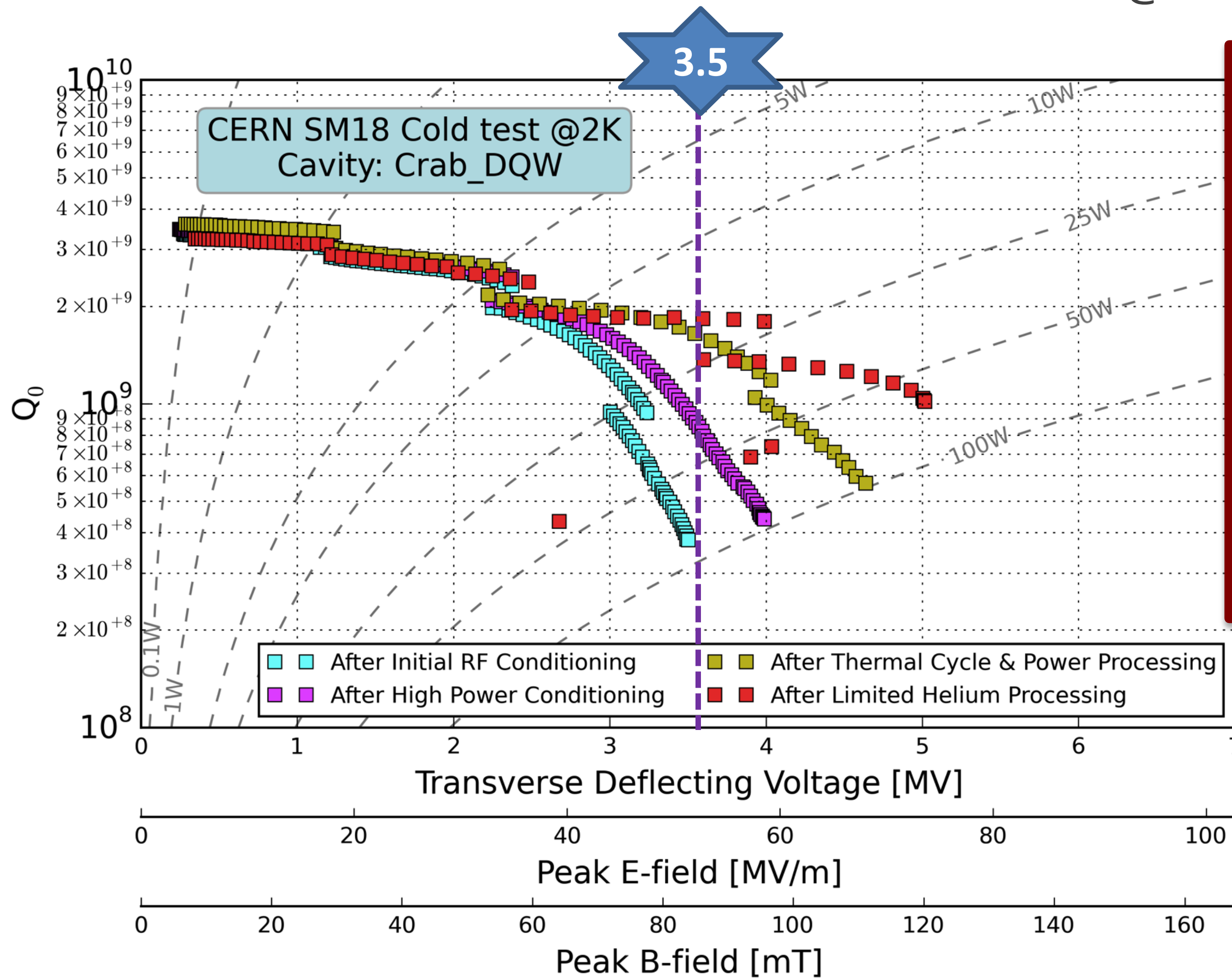
Recent results from Measurements @ CERN

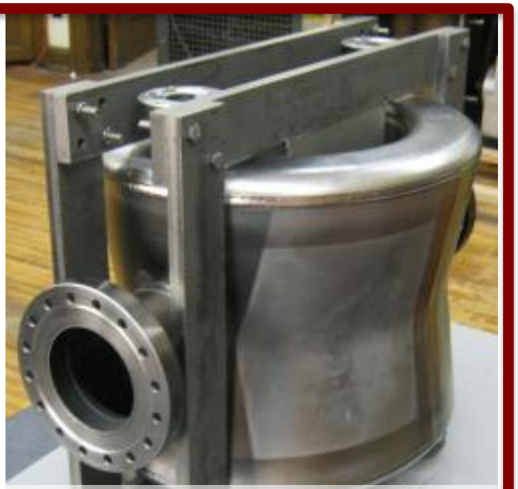


Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

And excellent first results: DQW

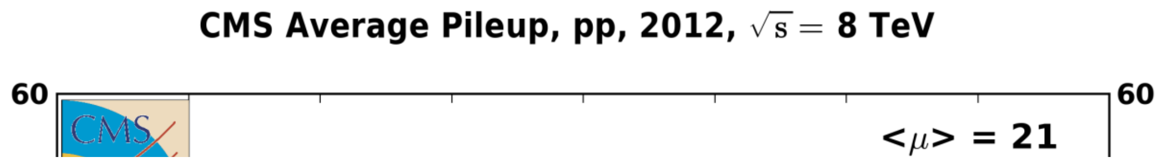
Recent results from Measurements @ CERN





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

HL-LHC Challenge: Event Pileup Density



Vertex Reconstru

HL-LHC Performance Optimization:

Use leveling techniques for keeping average

Pileup around 140 events per bunch crossing

➔ level luminosity at 5 10^{34} cm^{-2} s^{-1}

➔ $<\mu> = 140$; $\mu_{peak} = 280$ @ 25ns bunch spacing

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

→ Machine efficiency

LHC Challenges: Quench Protection

- Magnet Quench:

→ beam abort → several hours of recovery

- HL LHC beam intensity: I > 1 A => > 7 10^{14} p /beam

- Quench level: $N_{lost} < 7\ 10^{8}\ m^{-1}$ → $< 10^{-6}\ N_{beam}$!

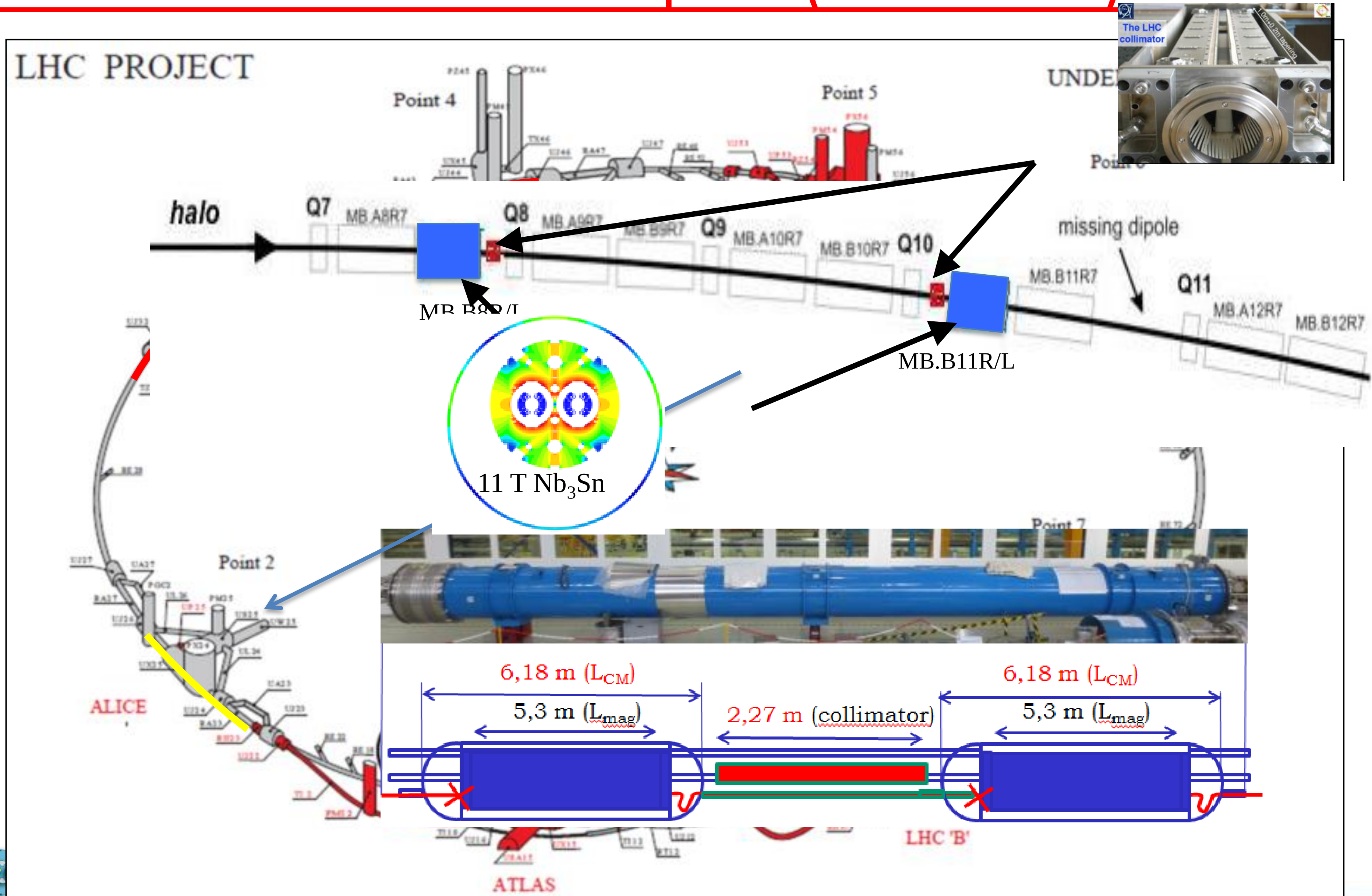
(compared to 20% to 30% in other superconducting rings)

→ requires collimation during all operation stages!

→ requires good optic and orbit control! → Which we have demonstrated during RunI

→ HL-LHC luminosity implies higher leakage from IP & requires additional collimators

DS collimators – 11 T Dipole (LS2 -2018)



Prototyping of cryogenics bypass @ CERN

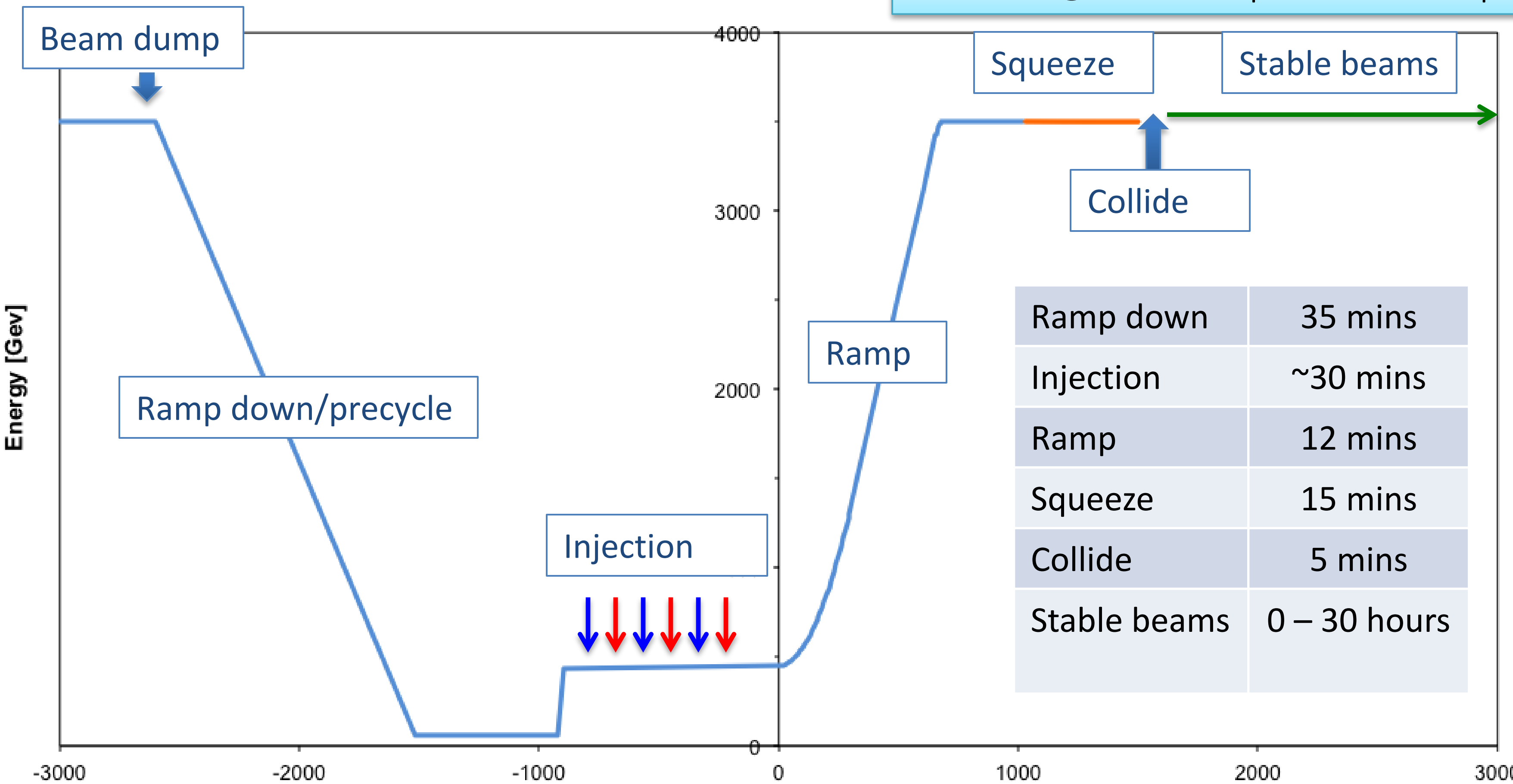
Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion suppressors.

Magnet: prototypes reached 11 T field in March 2013!

HL-LHC Challenge: Machine Efficiency

Nominal LHC Operation Cycle:

M. Lamont @ Evian LHC Operation workshop



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

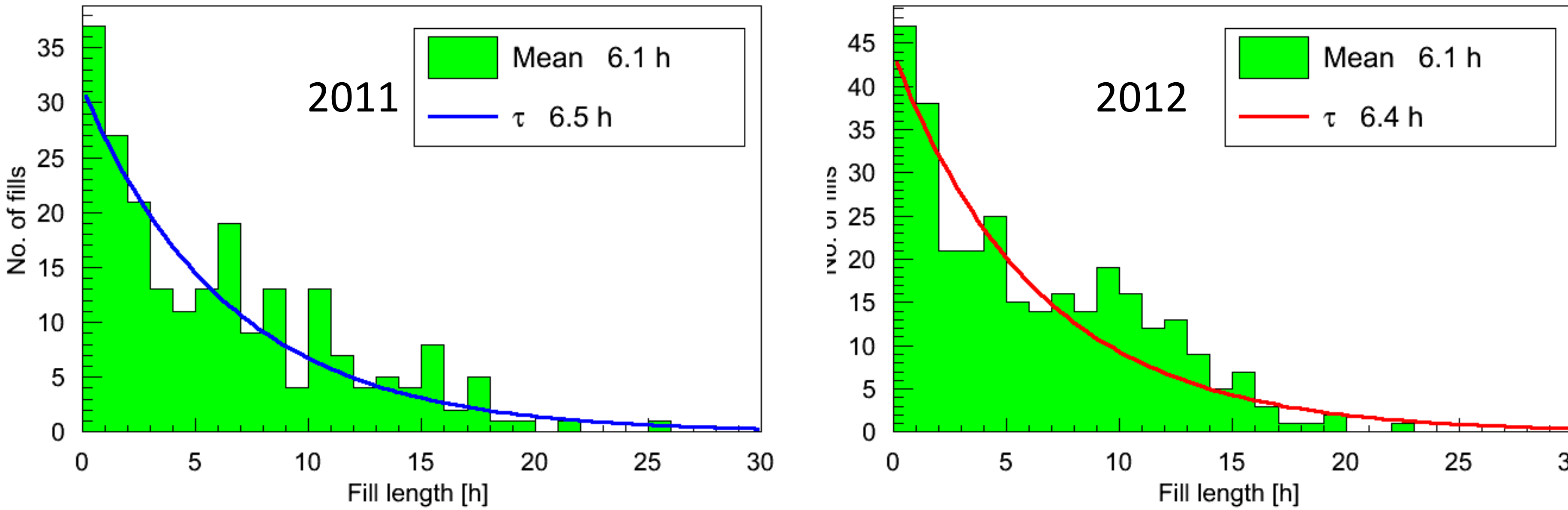
➔ Operational Turn around time of 2 - 3 hours ➔ Efficiency = time in physics / scheduled time

HL-LHC Challenge: Machine Efficiency ➔Integrated Luminosity

- Operation experience in 2011 and 2012:

J. Wenninger @ Evian LHC Operation workshop

- *Only ~30% of the fills are dumped by operation.*



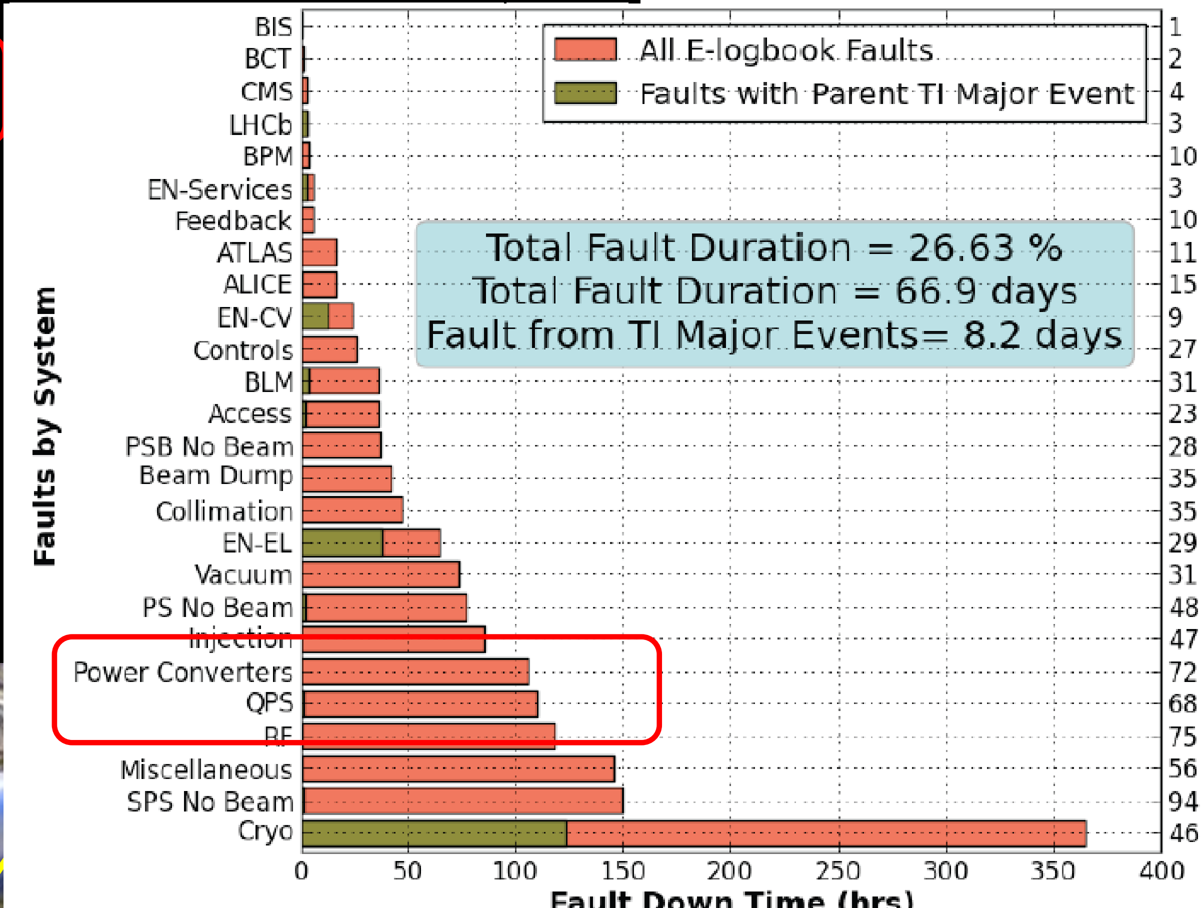
- ➔ corresponds to ca. 40% machine efficiency (time actually spend in physics divided by scheduled time for physics operation)
- ➔ 3000 fb-1 for HL-LHC will require significantly better machine efficiency!!!

  and average fill length above 6 hours (ca. 10 hours)!

Intervention rate & time: QPS boxes

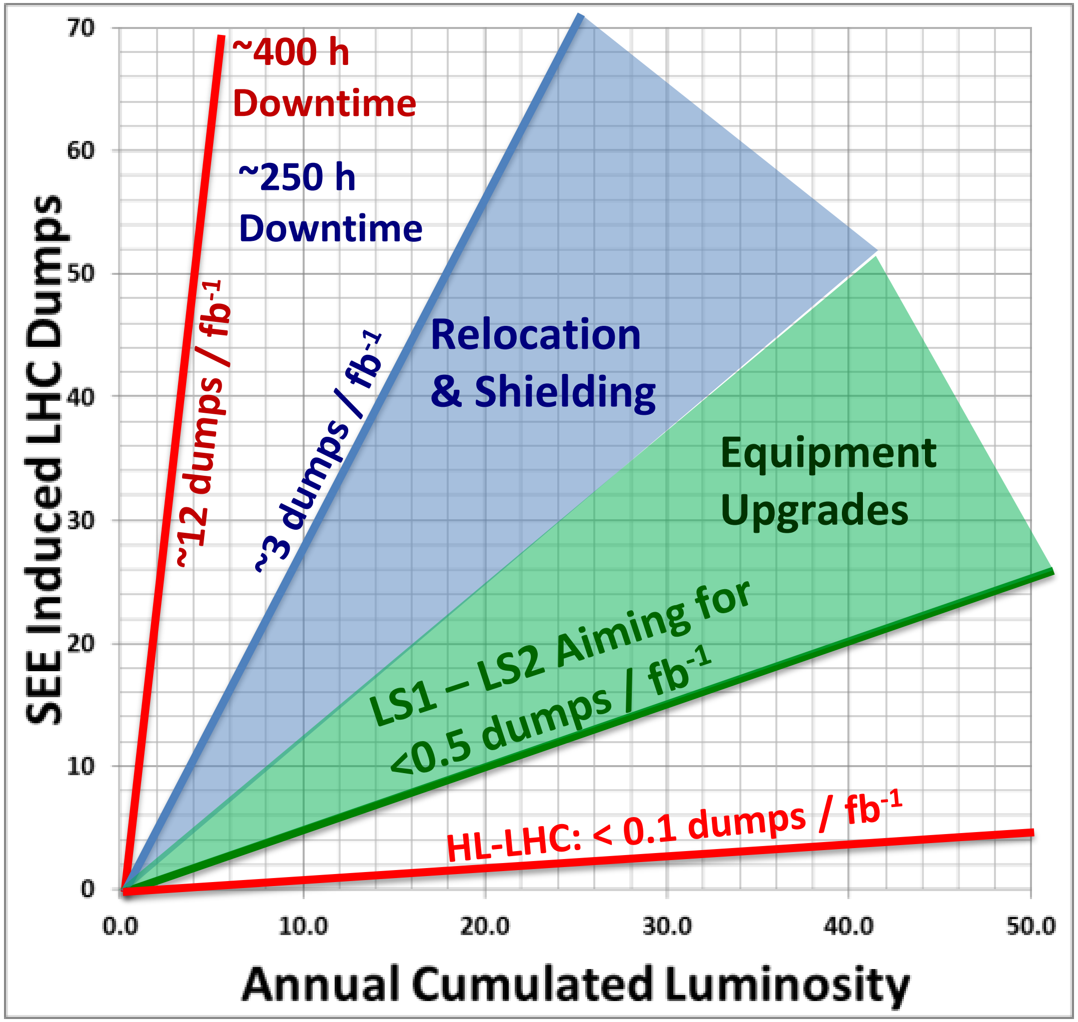
Dump Cause	#
Beam: Losses	58
Quench Protection	56
Power Converter	35
Electrical Supply	26
RF + Damper	23
Feedback	19
BLM	18
Vacuum	17
Beam: Losses (UFO)	15
Cryogenics	14
Collimation	12

Dump Cause	#



Consolidation of infrastructure !
But also new paradigme: remove as much as possible from the tunnel

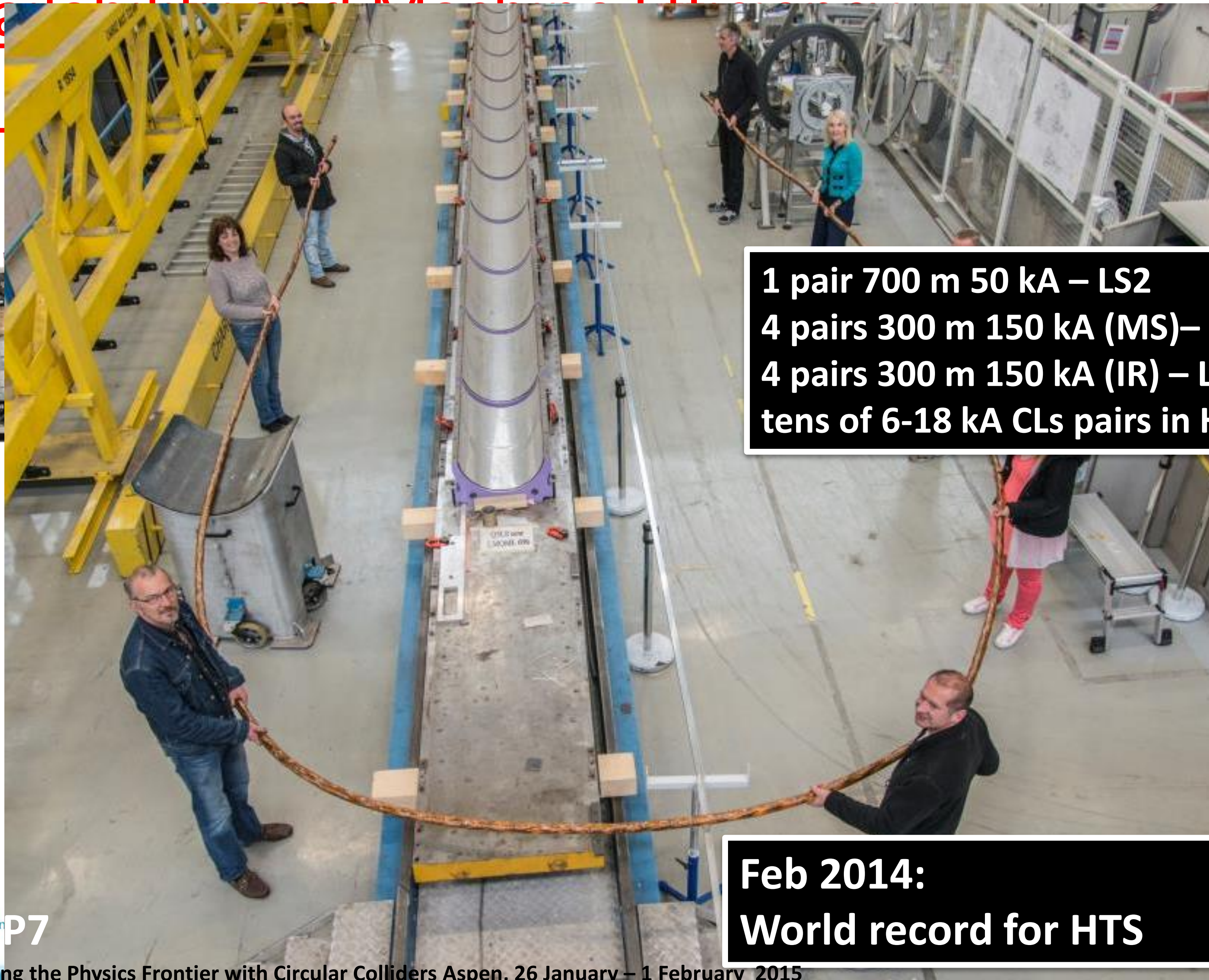
R2E SEU Failure Analysis - Actions



- **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

Ava

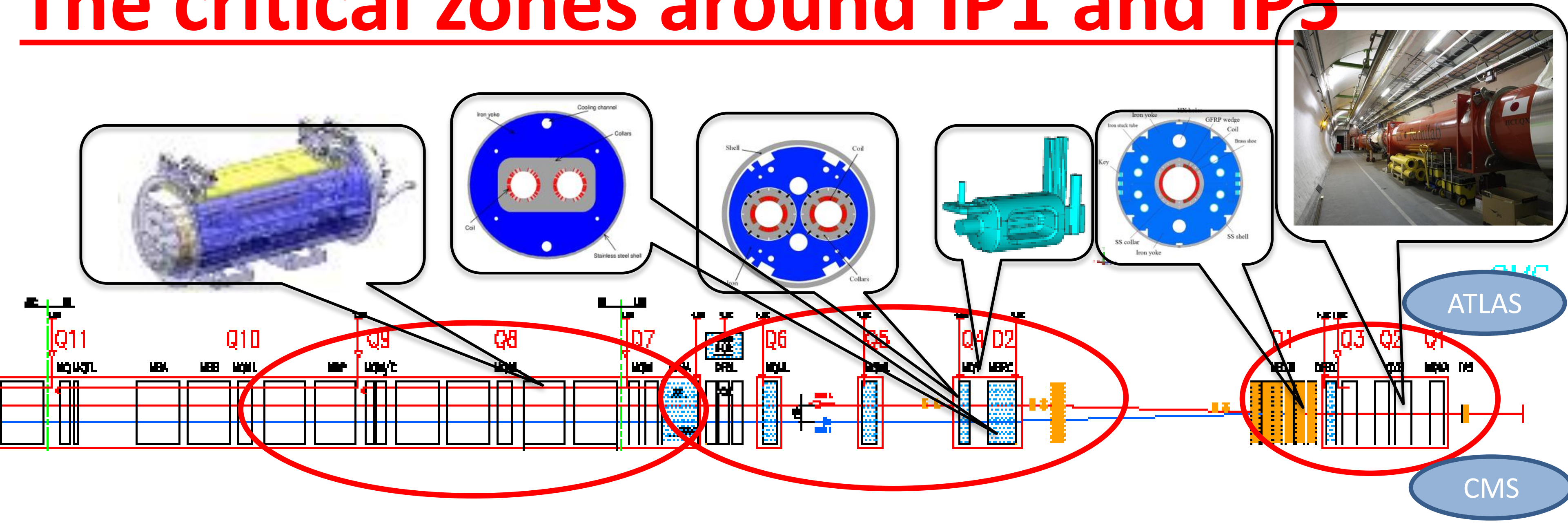
SC



1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS)– LS3
4 pairs 300 m 150 kA (IR) – LS3
tens of 6-18 kA CLs pairs in HTS

Feb 2014:
World record for HTS

The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in 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

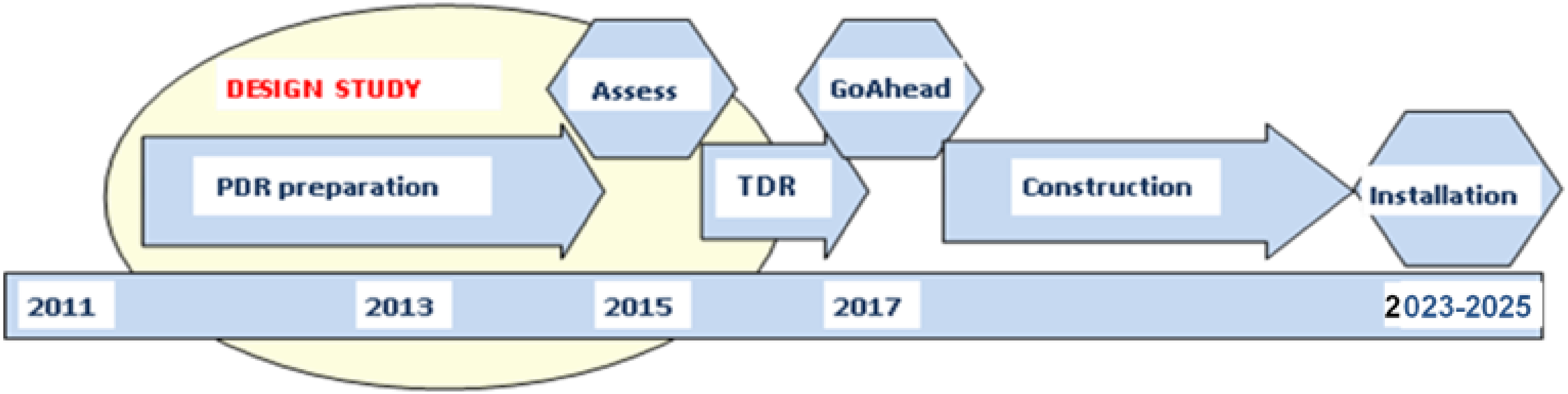
1. New triplet Nb_3Sn required due to:
   - -Radiation damage
   - -Need for more aperture

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)!!

Implementation plan:



- PDR: Oct 2014 ; Ext. Cost & Schedule Review in Jan-Feb 2015;
- TDR: OCT 2015; TDR_v2 : 2017
- 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 2023-25
- Though but – based on LHC experience – feasible

Reserve Transparencies

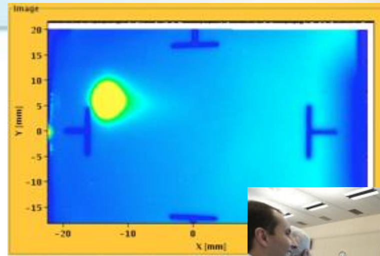
Project approval milestones:

- 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)

LHC Timeline

August 2008
First injection test

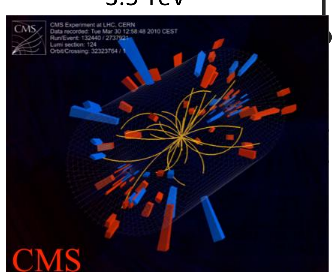


September 10, 2008
First beams around

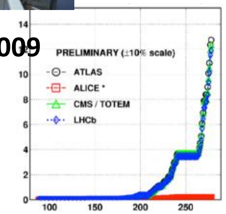
September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

March 30, 2010
First collisions at 3.5 TeV

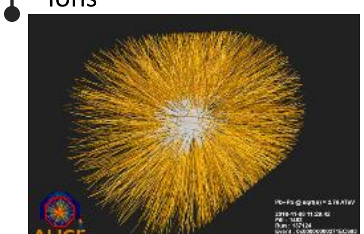


April 2010
Squeeze to 3.5 m



October 14 2010
1e32
248 bunches

November 2010
Ions



June 28 2011
1380 bunches (50ns)

1380

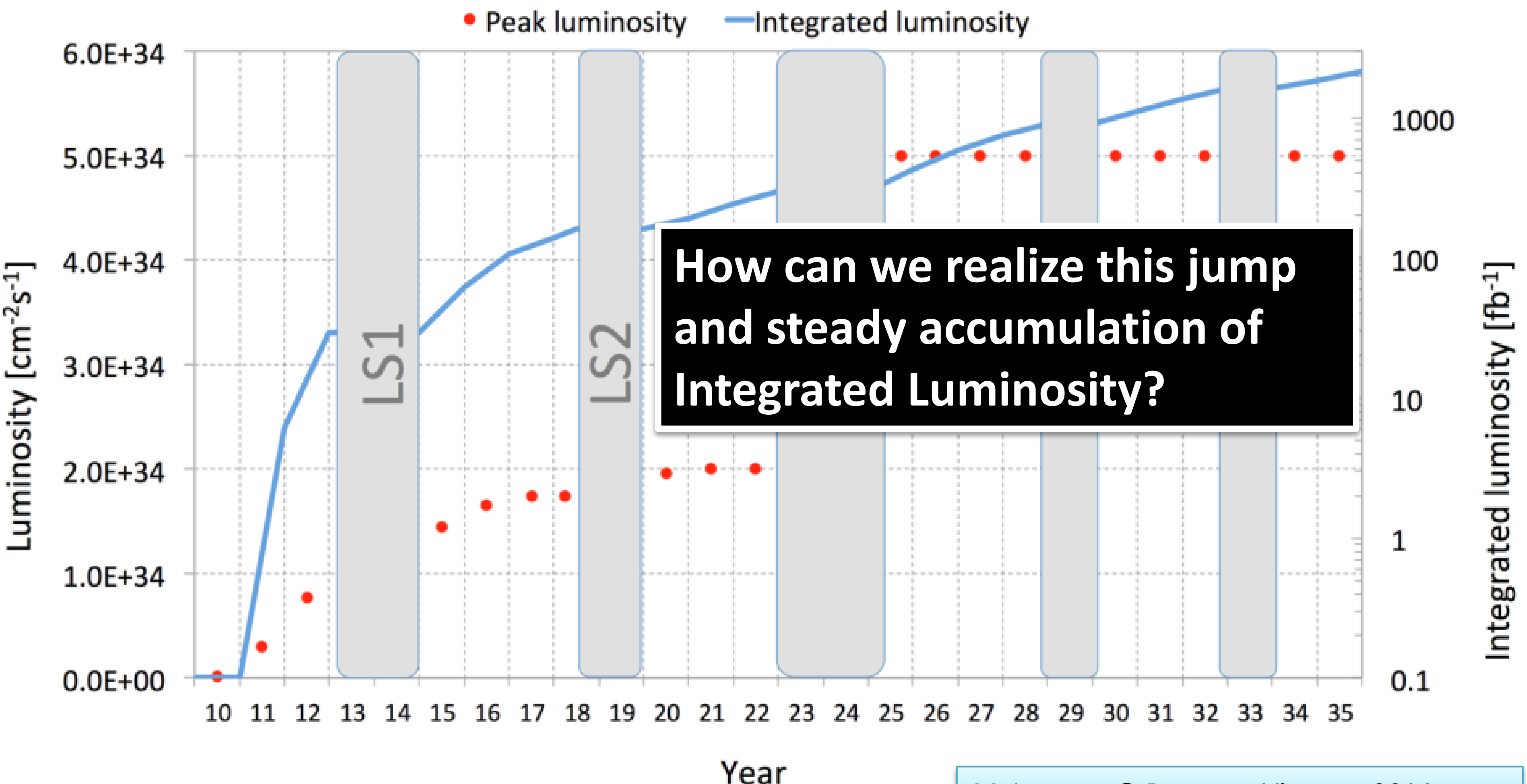
6 June, 2012
6.8e33

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

4 July, 2012
Higgs discovery

2008	2009	2010	2011	2012

HL-LHC goal could be reached in 2036



M. Lamont @ Recontre Vietnam 2014

LHC Upgrade Goals: Performance optimization

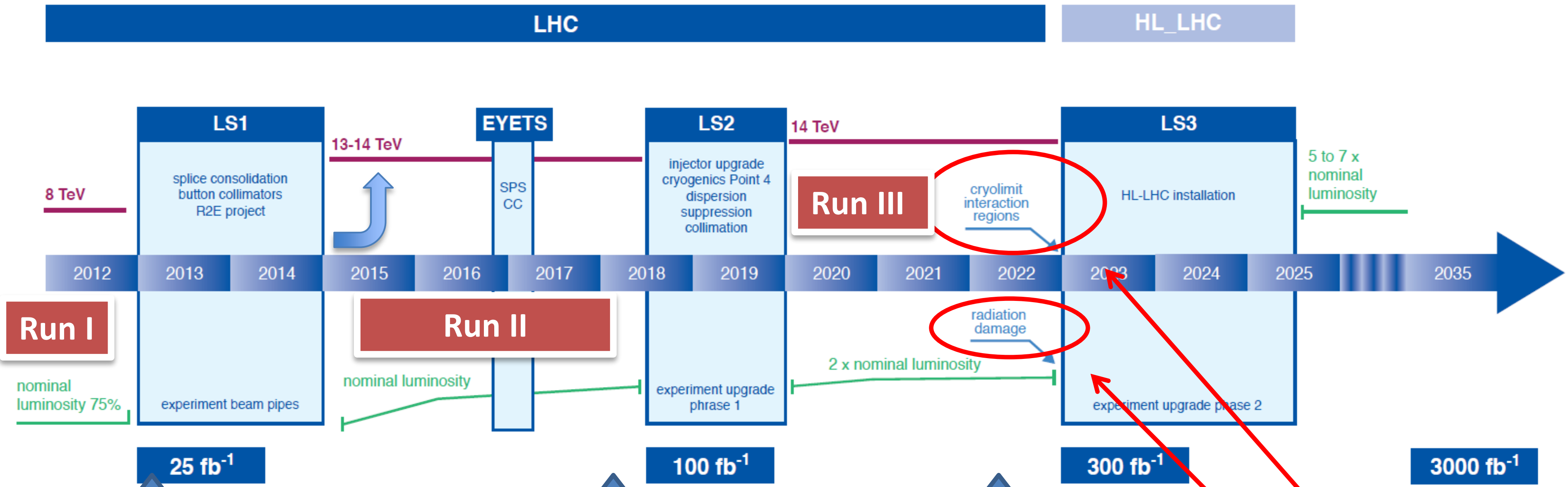
Luminosity recipe (round beams):

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

- ➔1) maximize bunch intensities ➔Injector complex
- ➔2) minimize the beam emittance Upgrade LIU
- ➔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

High Luminosity LHC

LHC to HL-LHC Transition



$0.75\ 10^{34}\ cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

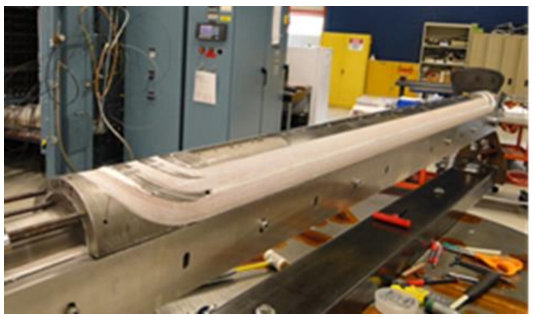
$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits (experiments, too) like :

50 ⇒ 25 ns

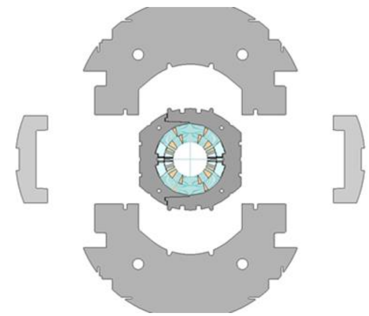
FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)

40-strand cable fabricated using FNAL cabling machine



Coil fabrication

Collared coil assembly



Cold mass assembly

MBHSP02 passed 11 T field during training at 1.9 K with I = 12080A on 5th March 2013!

HL-LHC Baseline Parameters:

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

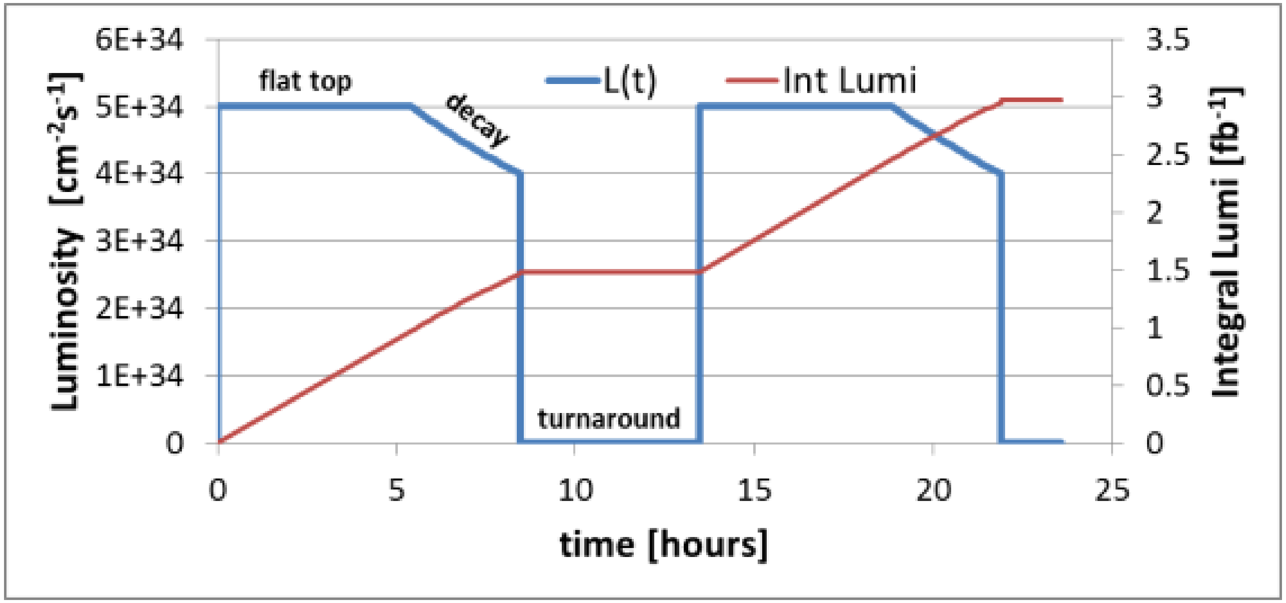
ATS required

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25 ns (BCMS)	HL-LHC 50ns
Beam energy in collision [TeV]	7	**7**	7	7
N_b	1.15E+11	**2.2E+11**	2.2E11	3.5E+11
n_b	2808	**2748**[1]	2604	1404
Number of collisions at IP1 and IP5	2808	**2736**	2592	1404
N_{tot}	3.2E+14	**6.0E+14**	5.7E+14	4.9E+14
beam current [A]	0.58	**1.09**	1.03	0.89
x-ing angle [μrad]	285	**590**	590	590
beam separation [σ]	9.4	**12.5**	12.5	11.4
β^* [m]	0.55	**0.15**	0.15	0.15
ε_n [μm]	3.75	**2.50**	2.50	3
ε_L [eVs]	2.50	**2.50**	2.50	2.50
r.m.s. energy spread	1.13E-04	**1.13E-04**	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	**7.55E-02**	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	**18.5**	18.5	17.2
IBS longitudinal [h]	61 -> 60	**20.4**	20.4	16.1
Piwinski angle	0.65	**3.14**	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	**0.305**	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	**0.829**	**0.829**	**0.838**
beam-beam / IP without Crab Cavity	3.1E-03	**3.3E-03**	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	**1.1E-02**	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [$cm^{-2}\,s^{-1}$]	1.00E+34	**7.18E+34**	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}\,s^{-1}$]	(1.18E+34)	**19.54E+34**	18.52E+34	21.38E+34
Events / crossing without levelling w/o crab-cavity	27	**198**	198	454
Levelled Luminosity [$cm^{-2}\,s^{-1}$]	-	**5.00E+34**	5.00E34	2.50E+34
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	**138**	146	135
Peak line density of pile up event [evt/mm] (max over stable beam)	0.21	**1.25**	1.31	1.20
Levelling time [h] (assuming no emittance growth)	-	**8.3**	7.6	18.0

Collision values

LHC Upgrade Goals: Performance optimization

- Levelling:



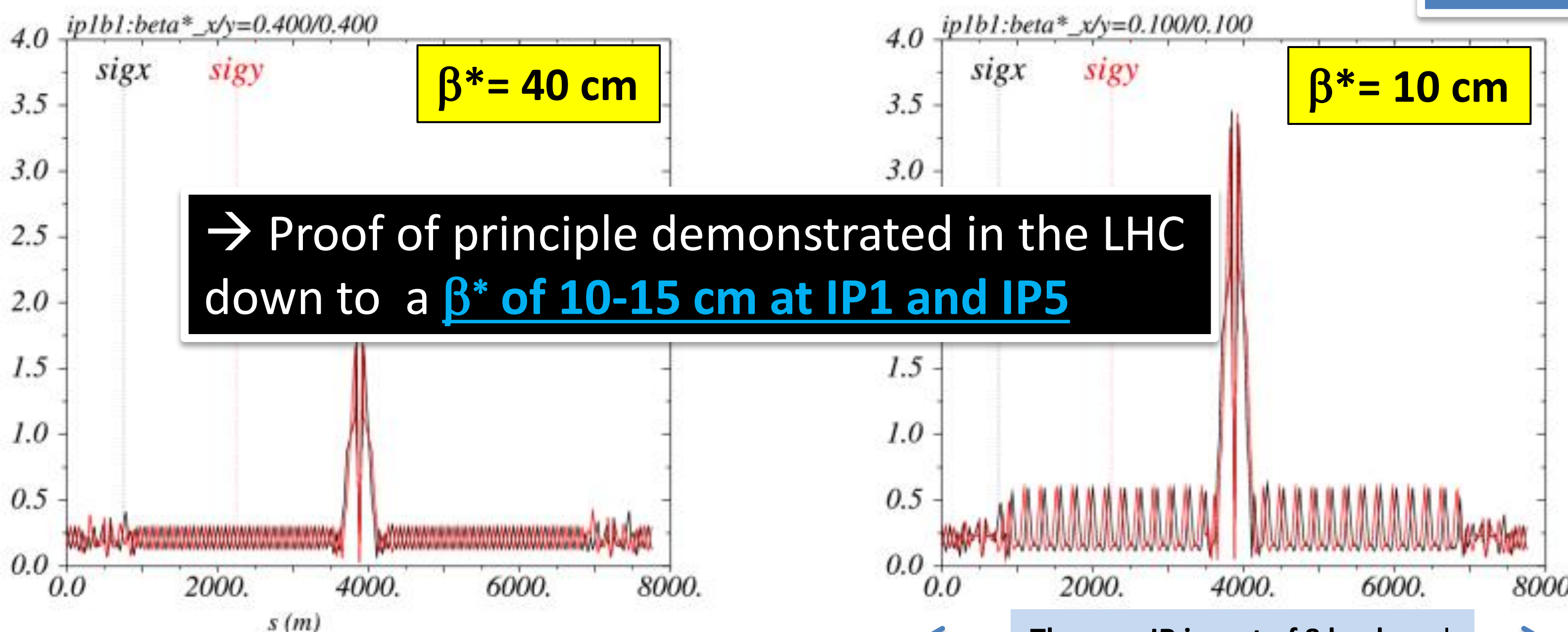
- Luminosity limitation(s):
  - Even Pileup in detectors
  - Debris leaving the experiments and impacting in the machine (magnet quench protection)
  - Triplet Heat Load

The ***Achromatic Telescopic Squeezing*** *(ATS) scheme*

Small β* is limited by aperture but not only: optics matching & flexibility (round and flat optics), chromatic effects (not only Q'), spurious dispersion from X-angle,..

A novel optics scheme was developed to reach un-precedent β^* w/o chromatic limit based on a kind of generalized squeeze involving 50% of the ring

(S. Fartoukh)



→ Proof of principle demonstrated in the LHC down to a β* of 10-15 cm at IP1 and IP5

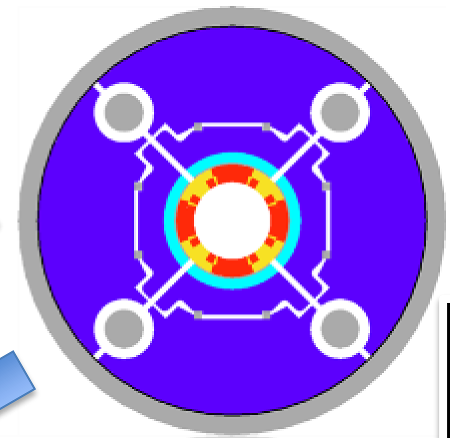
The new IR is sort of 8 km long !

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

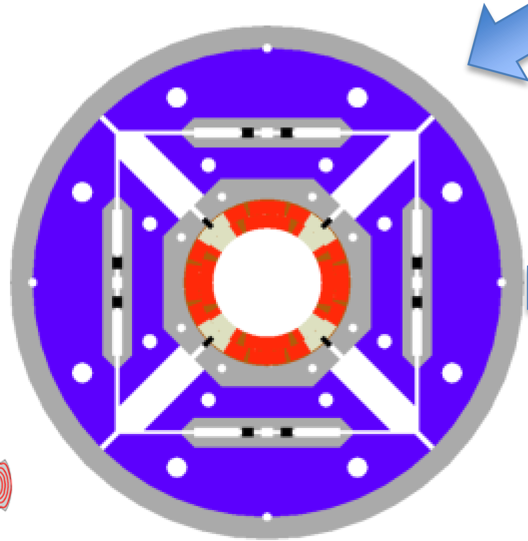
LHC (USA & JP, 5-6 m)
$\varnothing$70 mm, B_{peak}~ 8 T
1992-2005

LARP TQS & LQ (4m)
$\varnothing$90 mm, B_{peak}~ 11 T
2004-2010

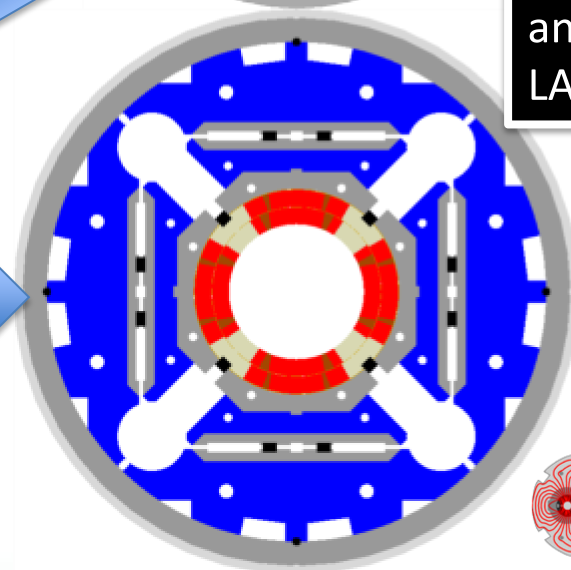


New structure based on bladders and keys (LBNL, LARP)

LARP HQ
$\varnothing$120 mm,
B_{peak}~ 12 T
2008-2014

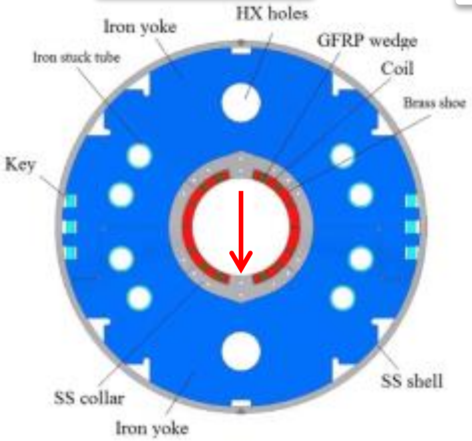


LARP & CERN MQXF
$\varnothing$150 mm,
B_{peak}~ 12.1 T
2013-2020

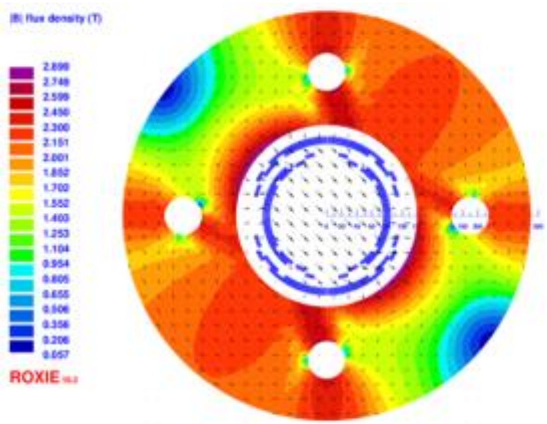


The HL-LHC Nb-Ti magnet zoo…

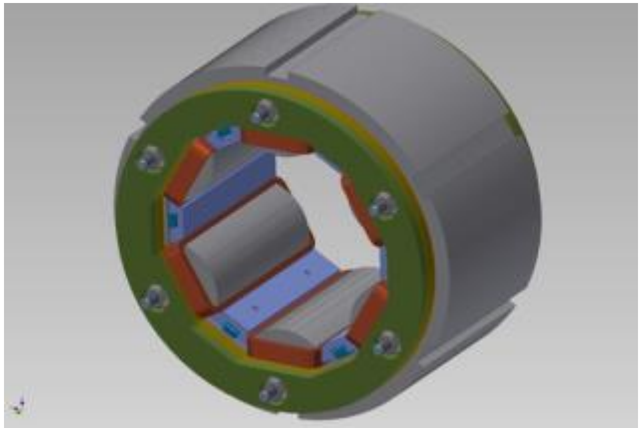
D1 (KEK)

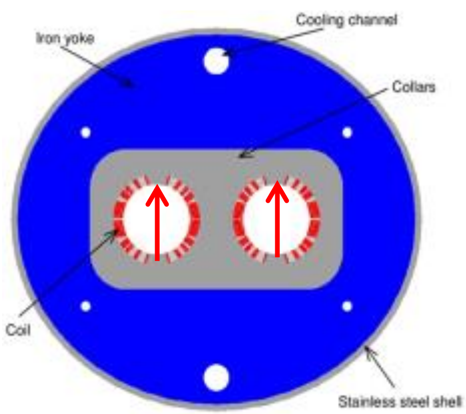


Nested Orbit corrector (CIEMAT)

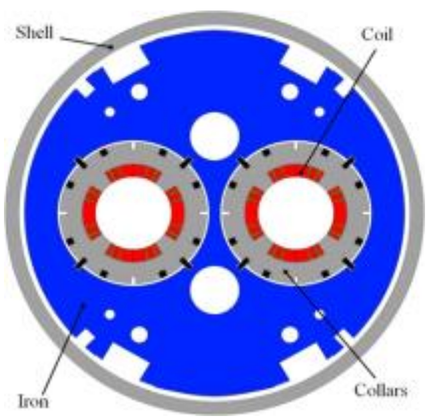


HO correctors: superferric (INFN)

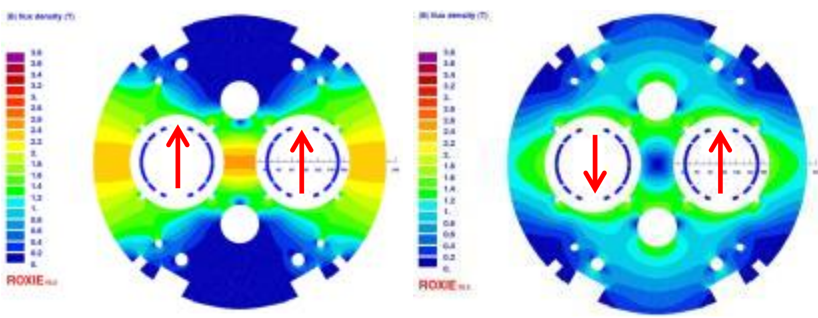




D2 (INFN)



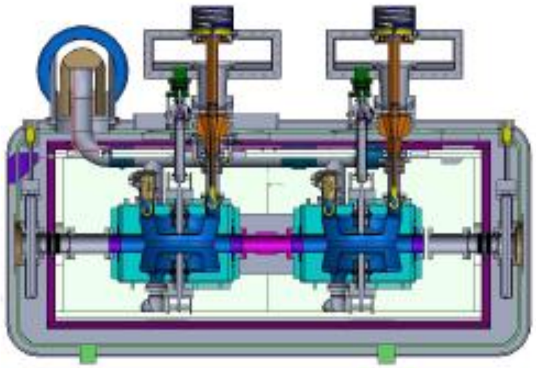
Q4 (CEA)

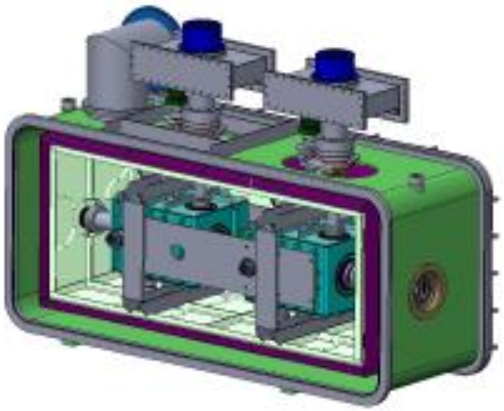


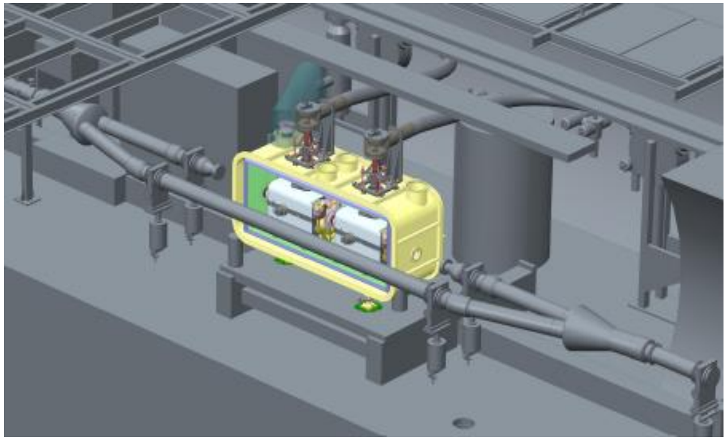
D2 corr

High Luminosity LHC

SPS beam test: a critical step for CC (profiting of the EYETS 2016- 2017)





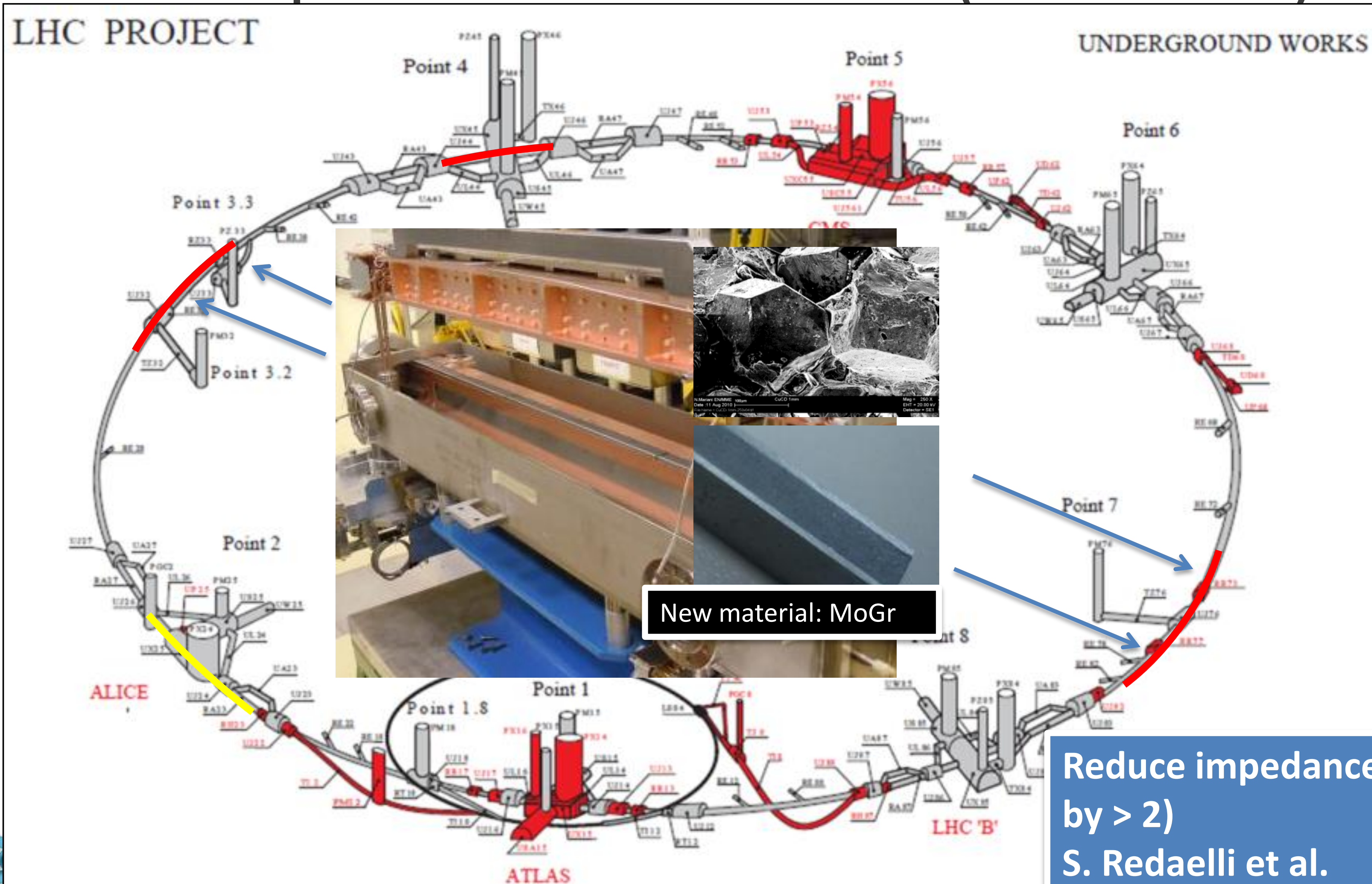


SPS test is critical: at least one cryomodule before LS2, possibly two, of different cavity type.

A test in LHC P4 is kept as a possibility but it is not in the baseline)

$\varnothing$ = 90 mm. 2 K
11.6 MV required voltage ;
baseline is 4 cavites/beam-side, $\Rightarrow$ 2.9MV/cavity

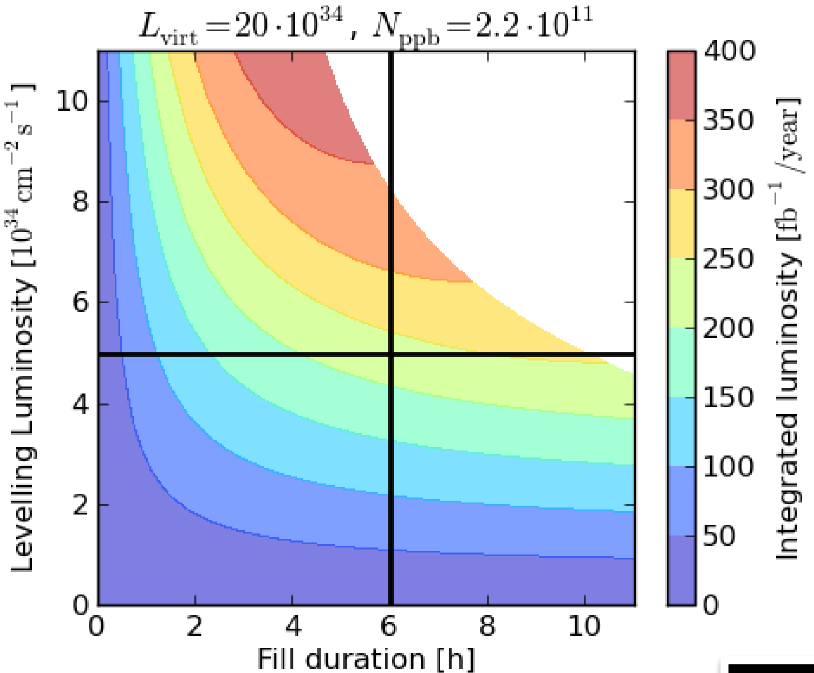
Low impedence collimators(LS2 & LS3)



Reduce impedance by > 2)
S. Redaelli et al.

Efficiency for ∫Ldt

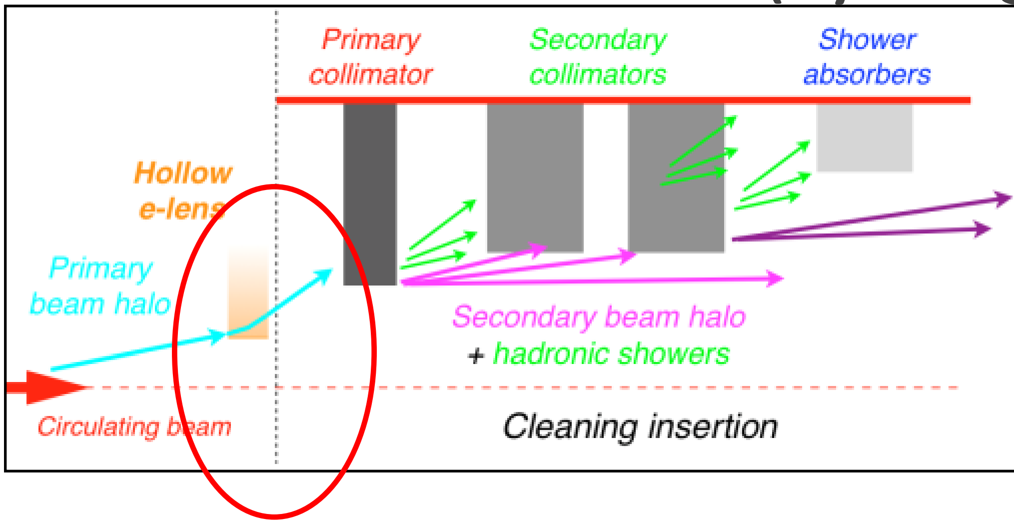
- All our assumptions are based on forecast for the operation cycle:

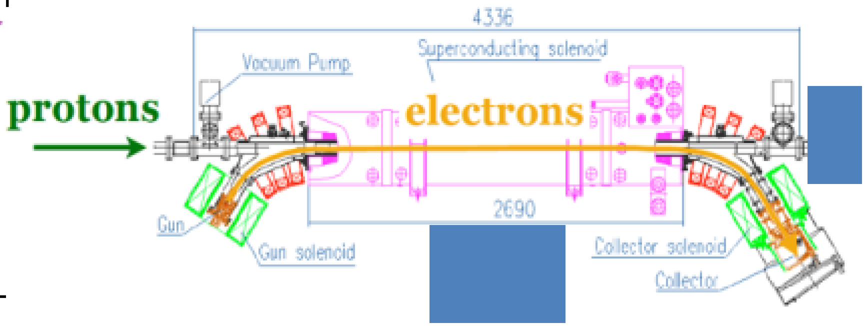


η ≥ 50%

High reliability and availbility are key goals

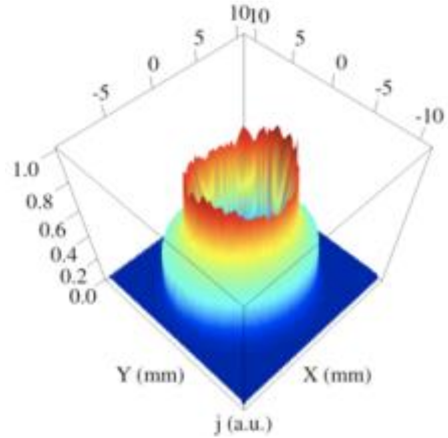
Controlling halo diffusion rate: hollow e-lens (synergy with LRBBCW)



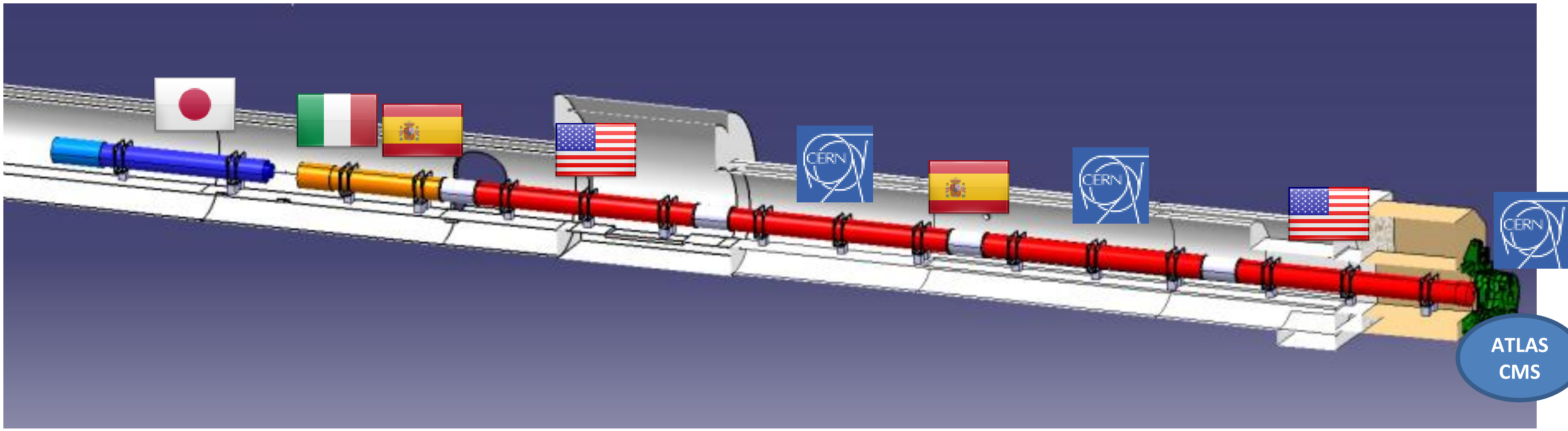


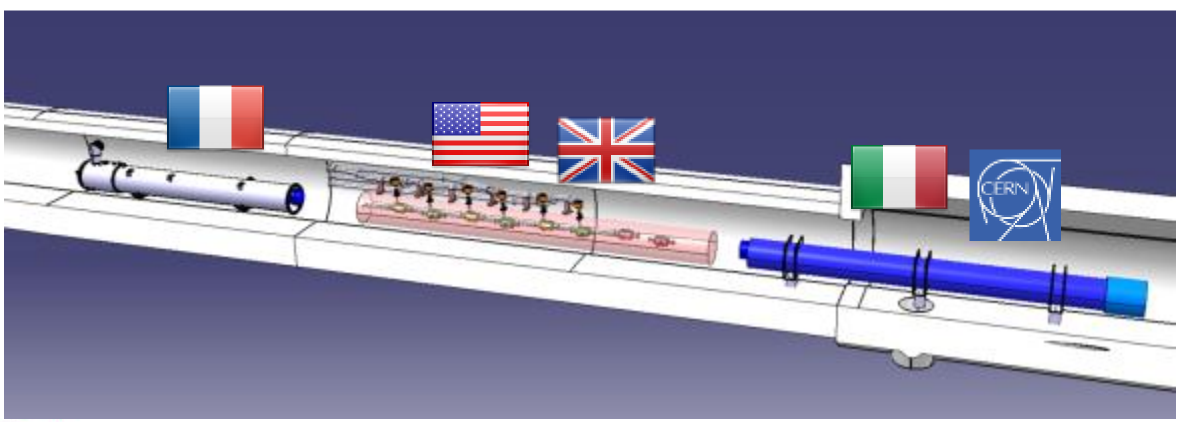
Promises of hollow e-lens:
1. Control the halo dynamics without affecting the beam core;
2. Control the time-profile of beam losses (avoid loss spikes);
3. Control the steady halo population (crucial in case of CC fast failures).

Remarks:
- very convincing experimental experience in other machines!
- full potential can be exploited if appropriate halo monitoring is available.



In-kind contribution and Collaboration for HW design and prototypes





Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

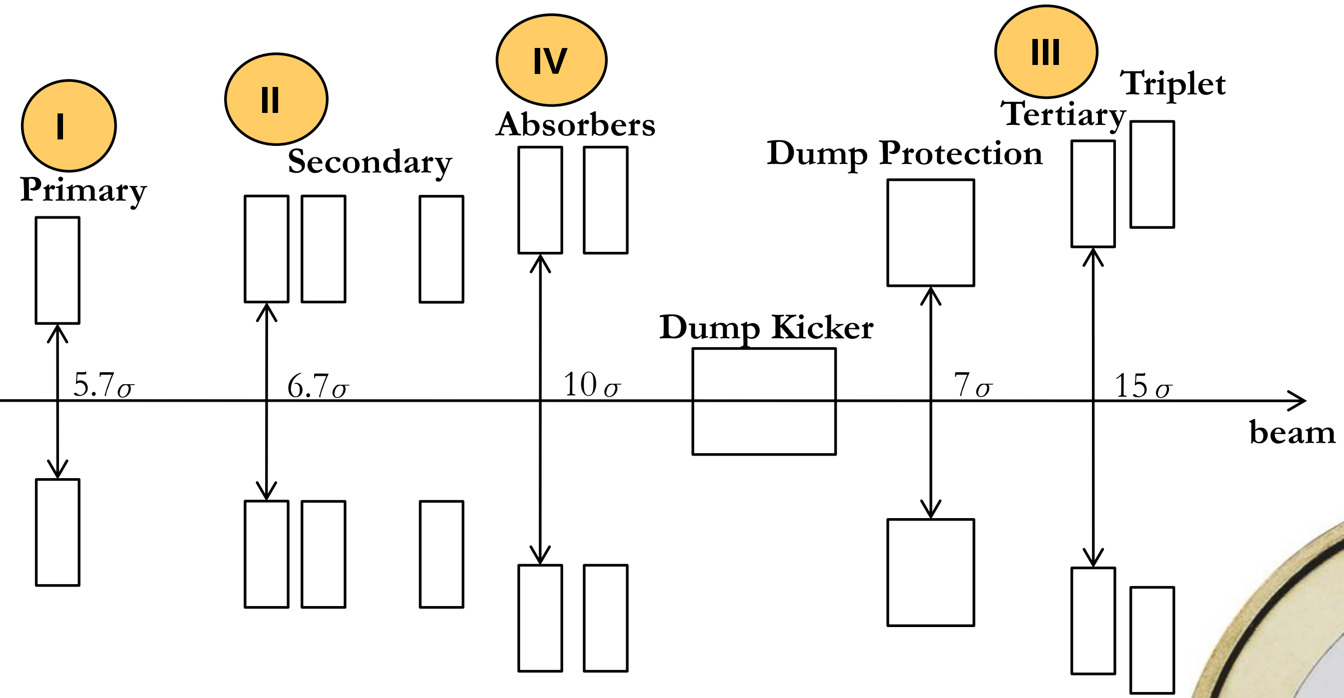
CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

High Luminosity LHC

High Luminosity LHC Participants

HL-LHC Challenges: Collimation Efficiency



$1\ \sigma$ (450GeV) ≈ 1mm

$1\ \sigma$ (4TeV) ≈ 0.35mm

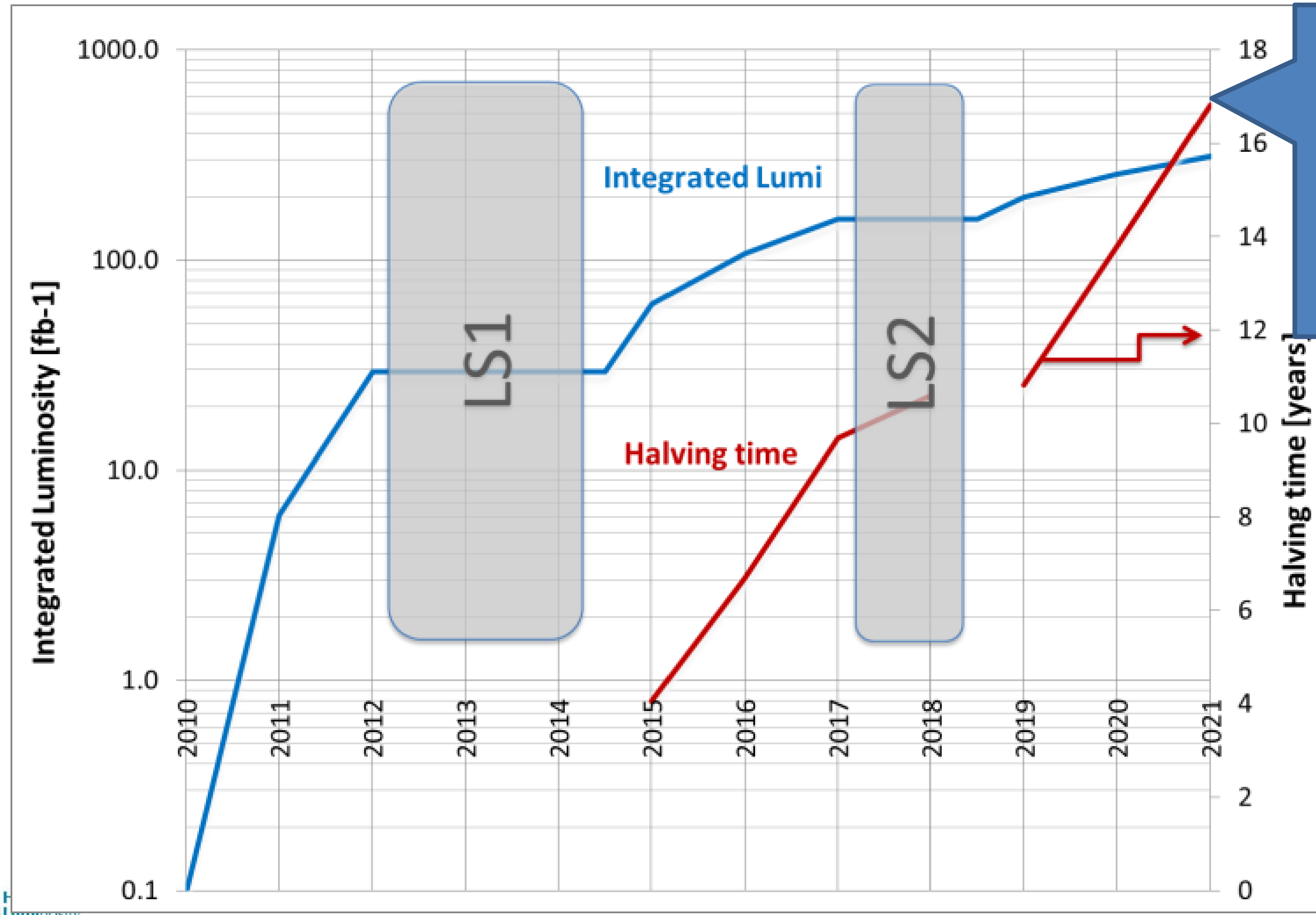
$1\ \sigma$ (6.5TeV) ≈ 0.25mm

Collimator type	N_i	Collimator type	N_i
TCP IR3	8 σ	TCDQ IR6	8 σ
TCSG IR3	9.3 σ	TCSG IR6	7 σ
TCLA IR3	10 σ	TCLI IR2/IR8	6.8 σ
TCP IR7	5.7 σ	TCT IR2/IR8	25 σ
TCSG IR7	6.7σ	TCT IR1/IR5	15 σ
TCLA IR7	10 σ	TCL IR1	20 σ

2011 'Interm.' Norway = 3.1mm

2012 'Tight' = Iberian Peninsula 2.2mm

HL-LHC: Mantain and increase physics reach!!!



Necessity of a jump in luminosity (useful luminosty ⇒ data quality)

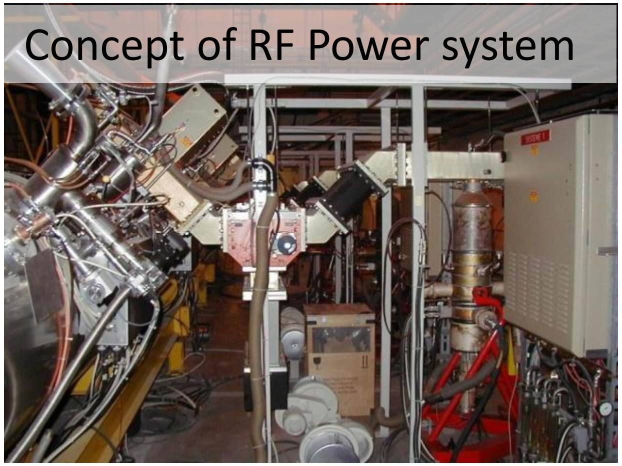
3 Crab Cavity prototypes:

RF-Dipole Nb prototype [ODU-SLAC]

4-rod in SM18 for RF measurements [Lancaster UK]

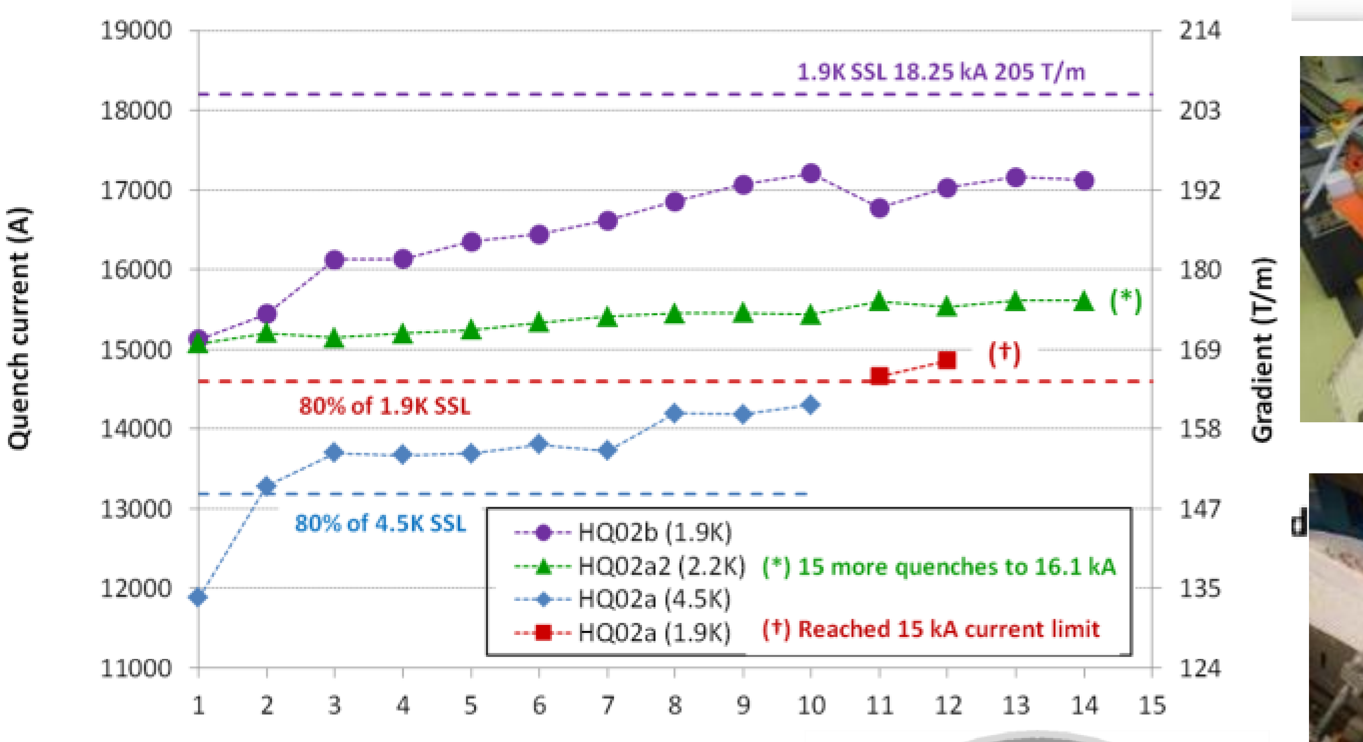
4-rod prepared for rinsing @ CERN

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

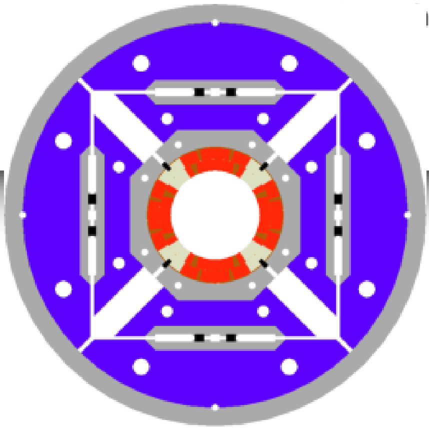


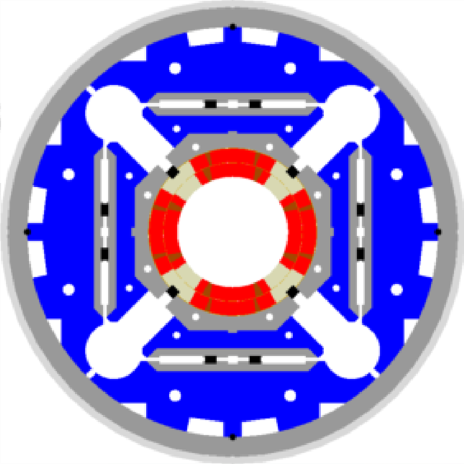
Concept of RF Power system

Progress with Triplet magnets:



LARP HQ
∅120 mm,
B_{peak}~ 12 T
2008-2014
Short → 4m





LARP & CERN MQXF
∅150 mm, B_{peak}~ 12.1 T
2013-2020