High Luminosity LHC

HL-LHC

Lucio Rossi and Oliver Brüning
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.

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}**

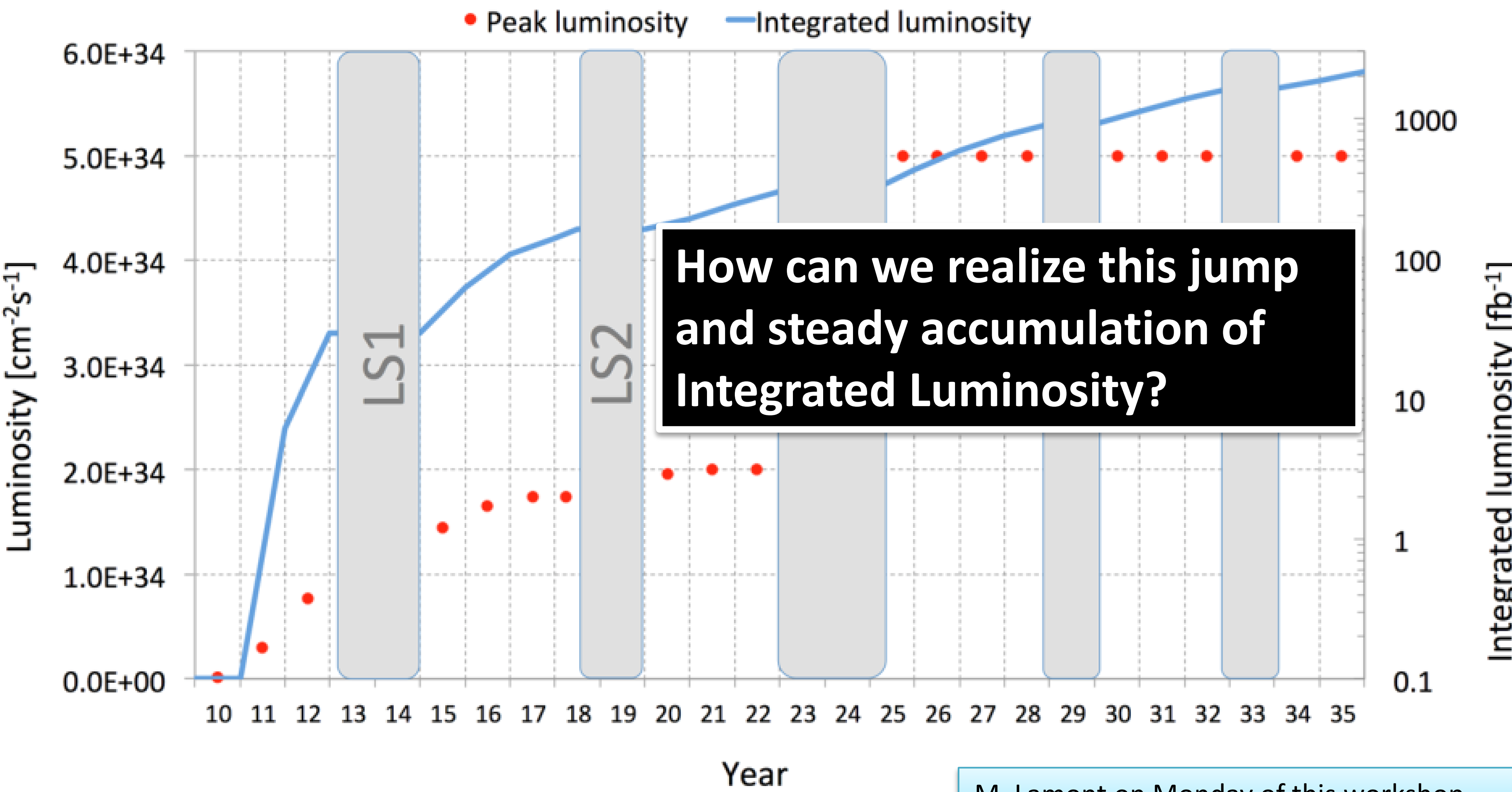
implying an integrated luminosity of **250 fb^{-1} per year**,

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

HL-LHC goal could be reached in 2036



M. Lamont on Monday of this workshop

LHC Upgrade Goals: Performance optimization

- Luminosity recipe (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

→ 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 Challanges:

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

  ➔ New insertion magnets and triplets 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:

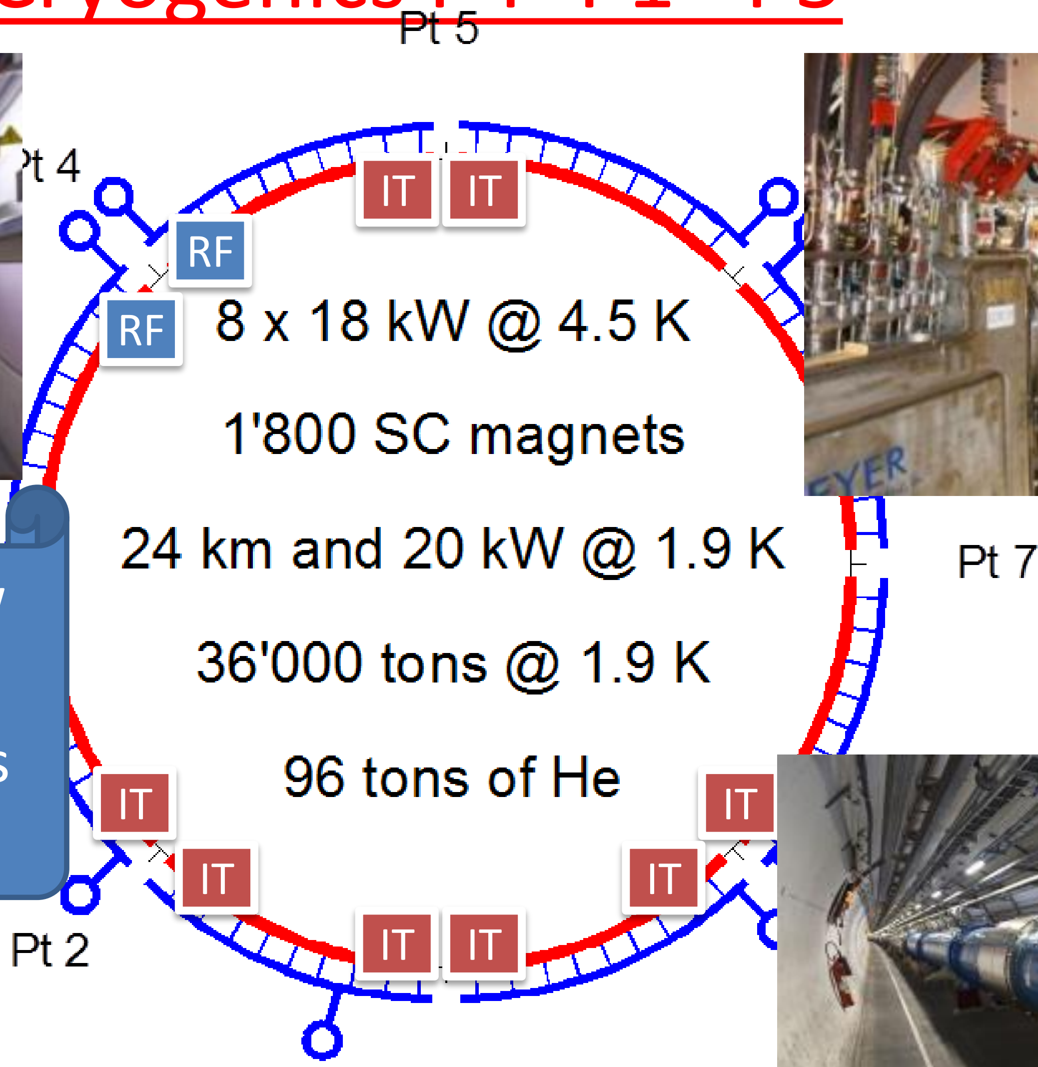
  # R2E ➔ removal of all electronics from tunnel region

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

  # UFOs ➔ beam scrubbing (conditioning of surface)

Eliminating Technical Bottlenecks

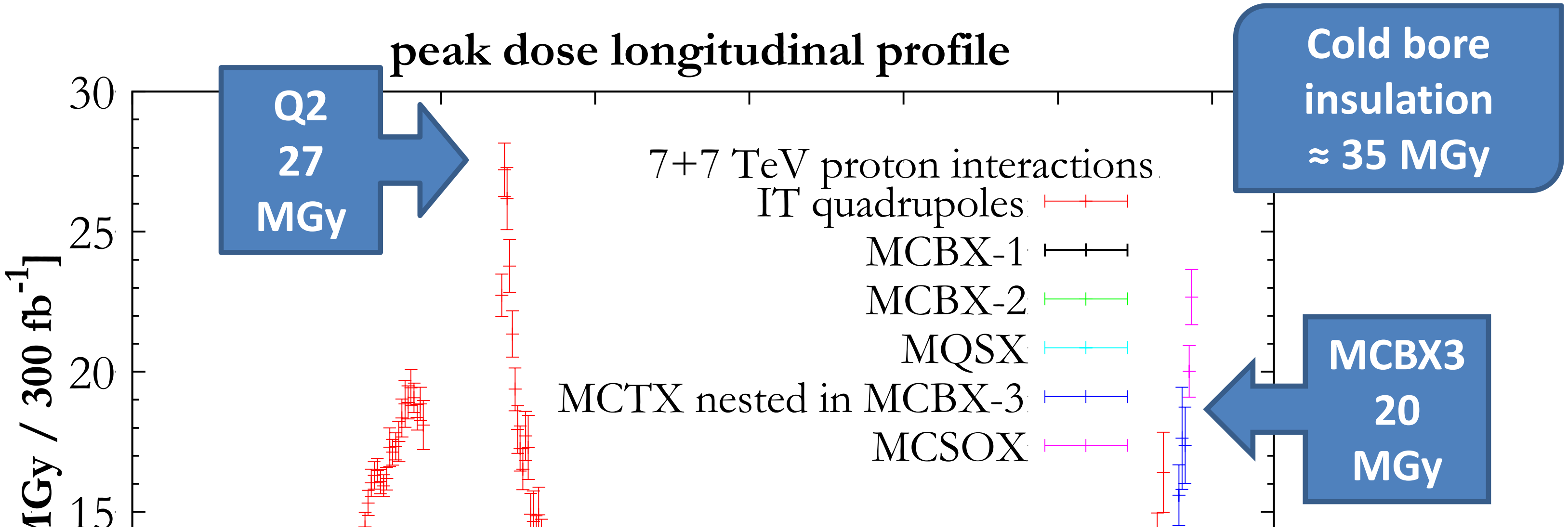
Cryogenics P4- P1 –P5



New Plant ≥ 6 kW in P4

New 18 kW Plants in P1 and P5

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



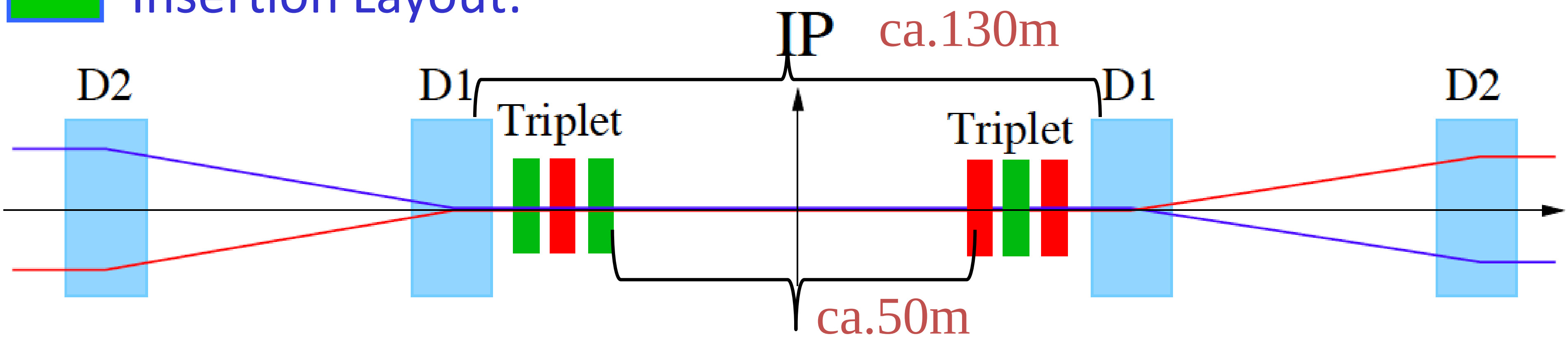
Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnets coils receive a similar radiation dose at 10 times higher integrated luminosity!!!!!

20 25 30 35 40 45 50 55
distance from IP [m]

High Luminosity LHC

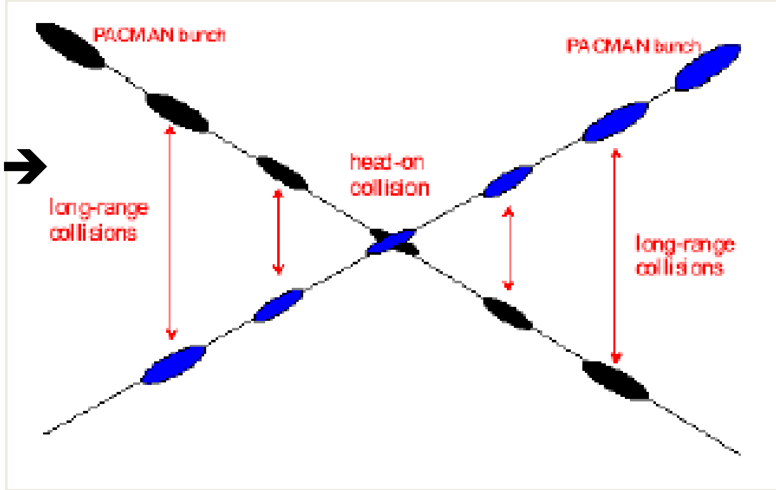
HL-LHC Challenges: Crossing Angle I

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

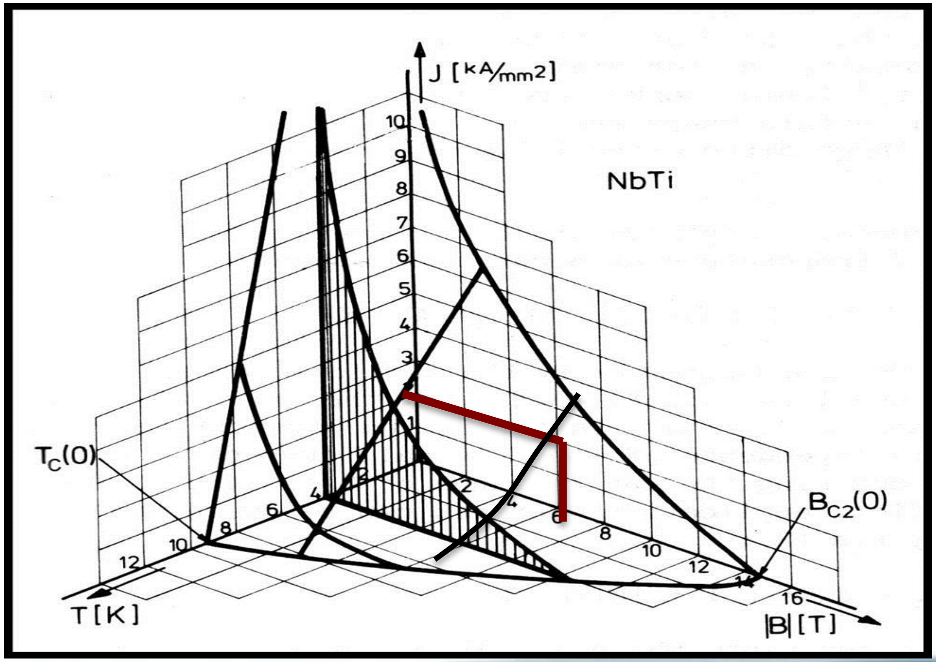
➔ Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC upgrade!!

HL-LHC Upgrade Ingredients: 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:**

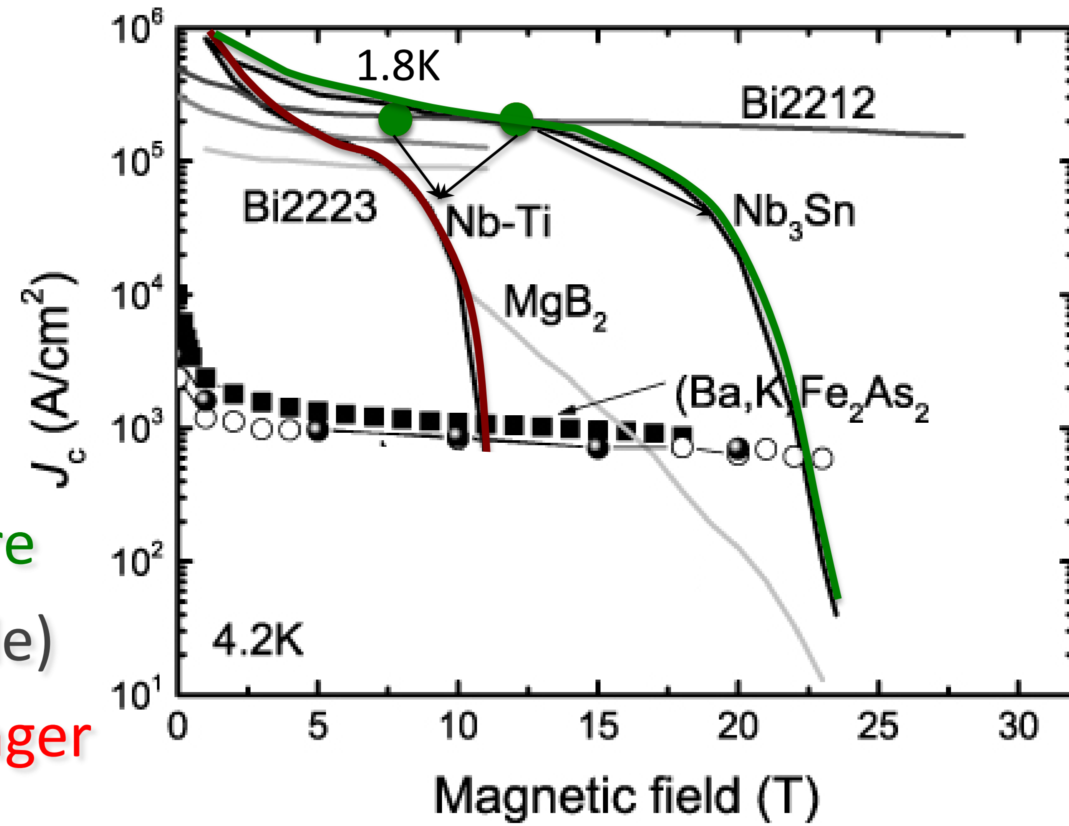
  140 T/m, 150 mm coil aperture

  (shielding, β* and crossing angle)

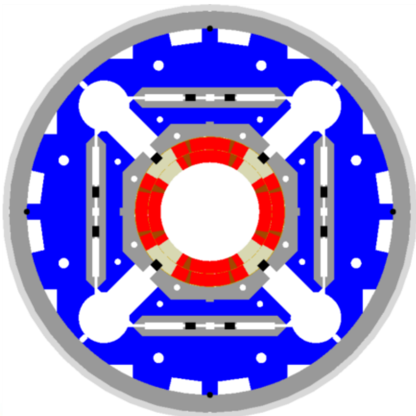
  ➔ ca. 12 T @ coil ➔ 30% longer
  - Requires Nb_3Sn technology

    ➔ ceramic type material (fragile)

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



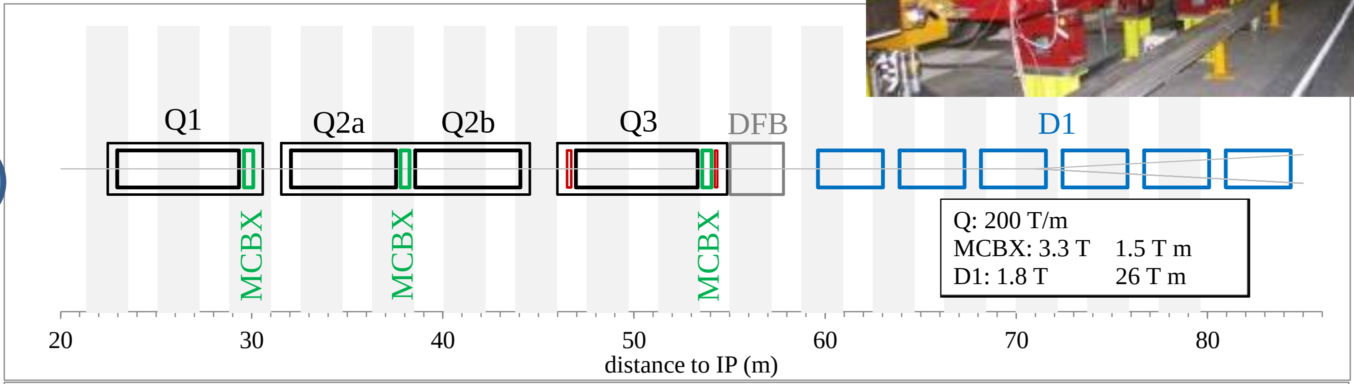
US-LARP MQXF magnet design Based on Nb_3Sn technology



New Interaction Region lay out

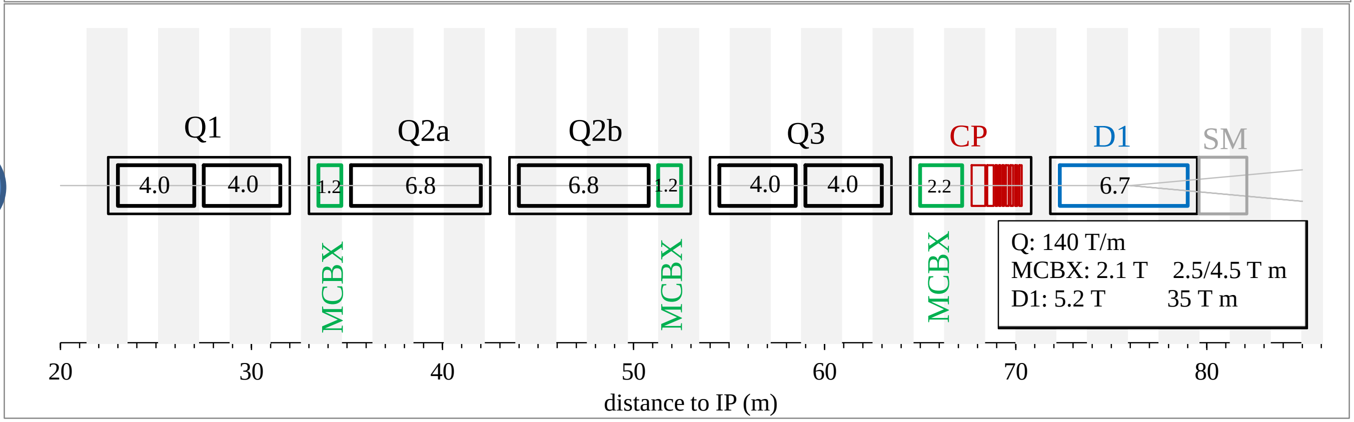
Longer Quads; Shorter D1 (thanks to SC)

ATLAS CMS



LHC

ATLAS CMS

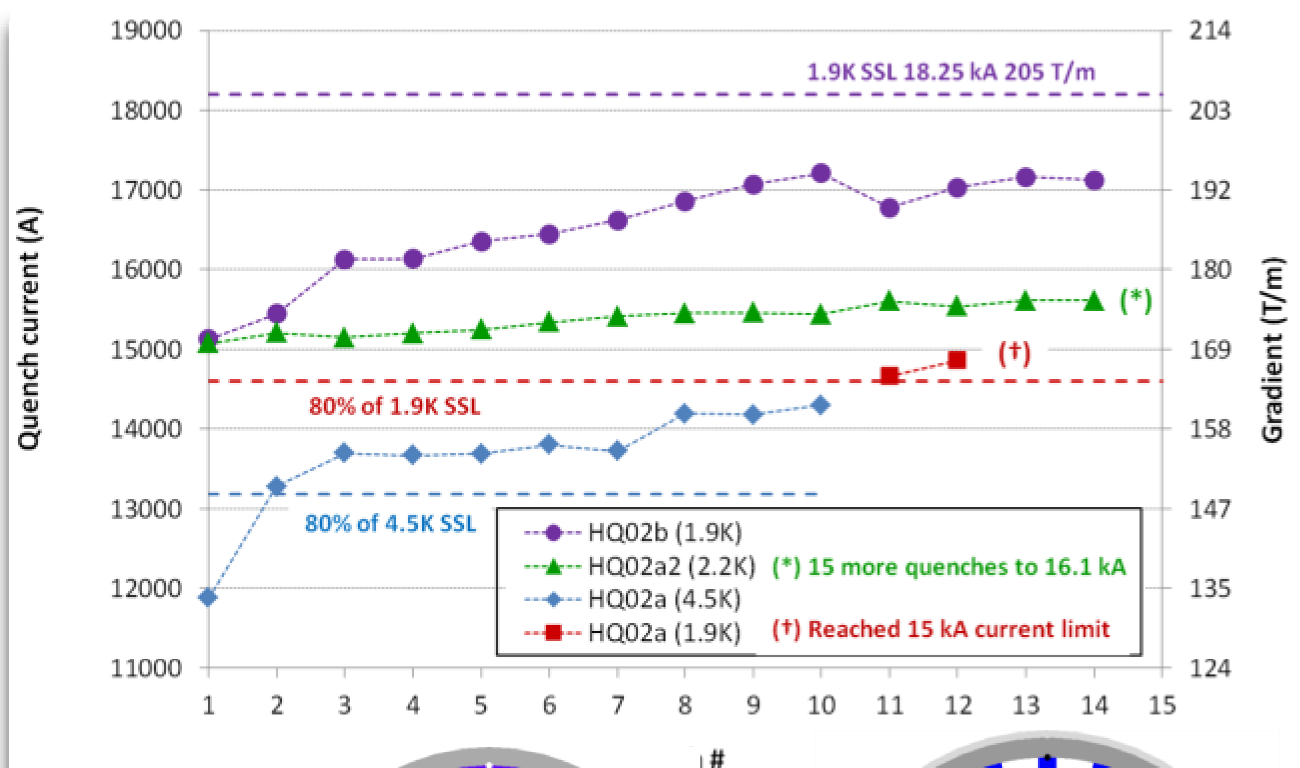


HL LHC

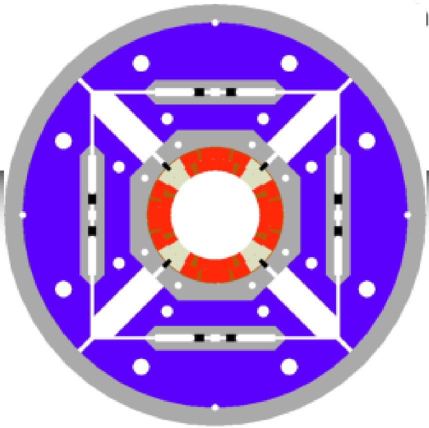
Thick boxes are magnetic lengths -- Thin boxes are cryostats

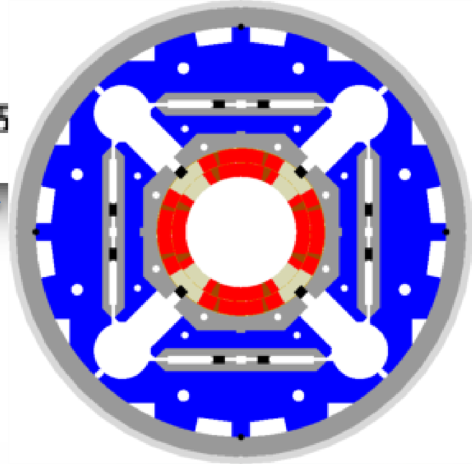
High Luminosity LHC

Progress with Triplet magnets:



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



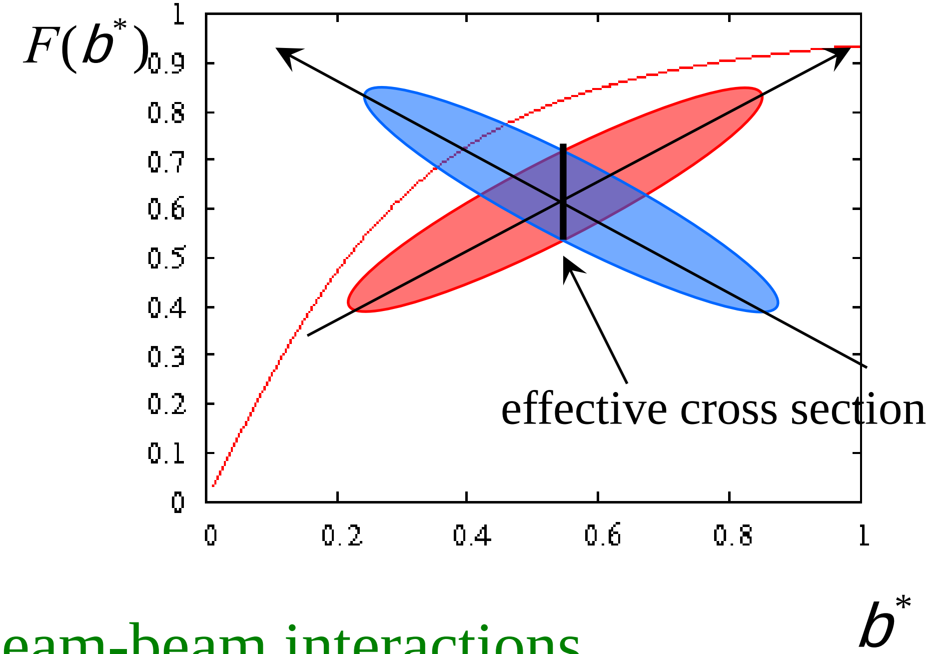


LARP & CERN MQXF
∅150 mm, B_{peak}~ 12.1 T
2013-2020

LHC Challenges: Crossing Angle II

- geometric luminosity reduction factor:

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



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

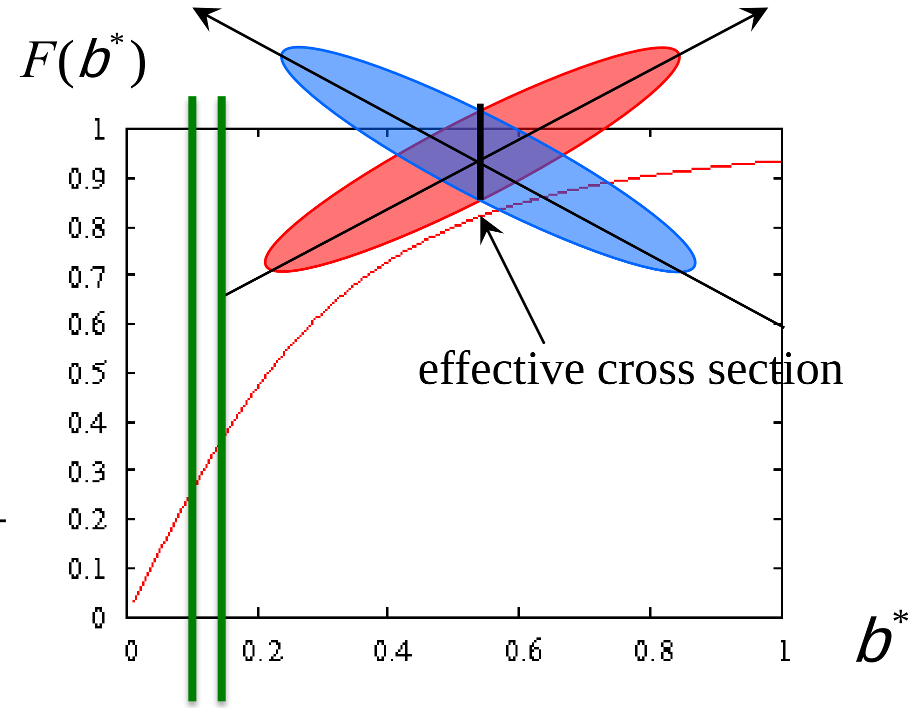
Geometric Luminosity Reduction Factor:

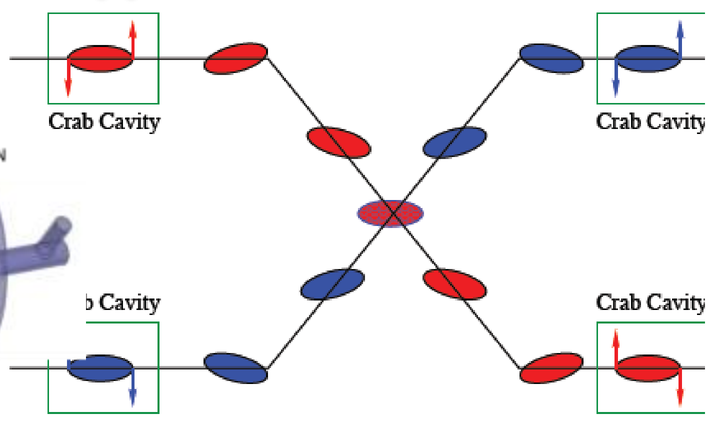
Crab Cavities:

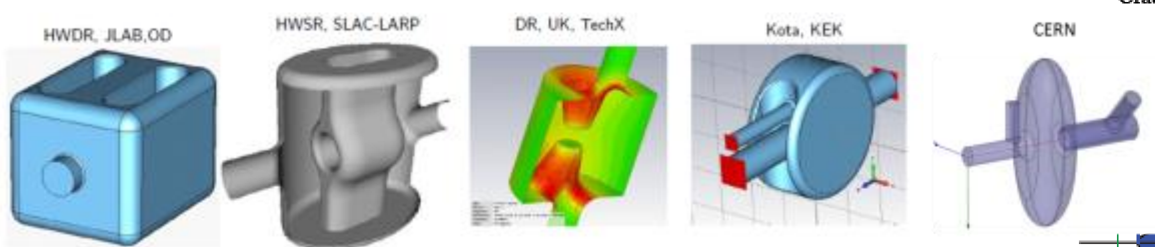
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

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







Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

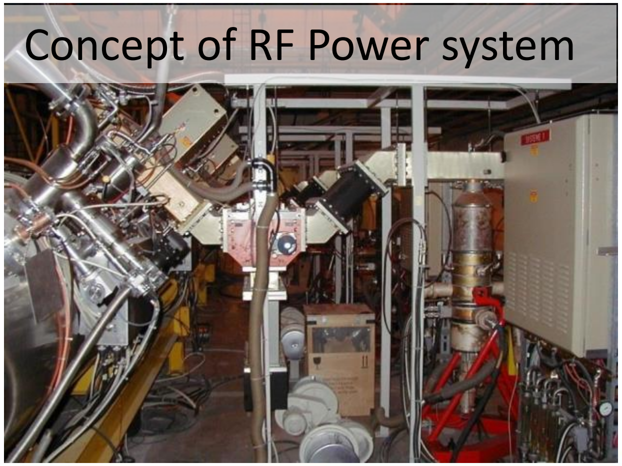
3 Crab Cavity prototypes:


RF-Dipole Nb prototype [ODU-SLAC]


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

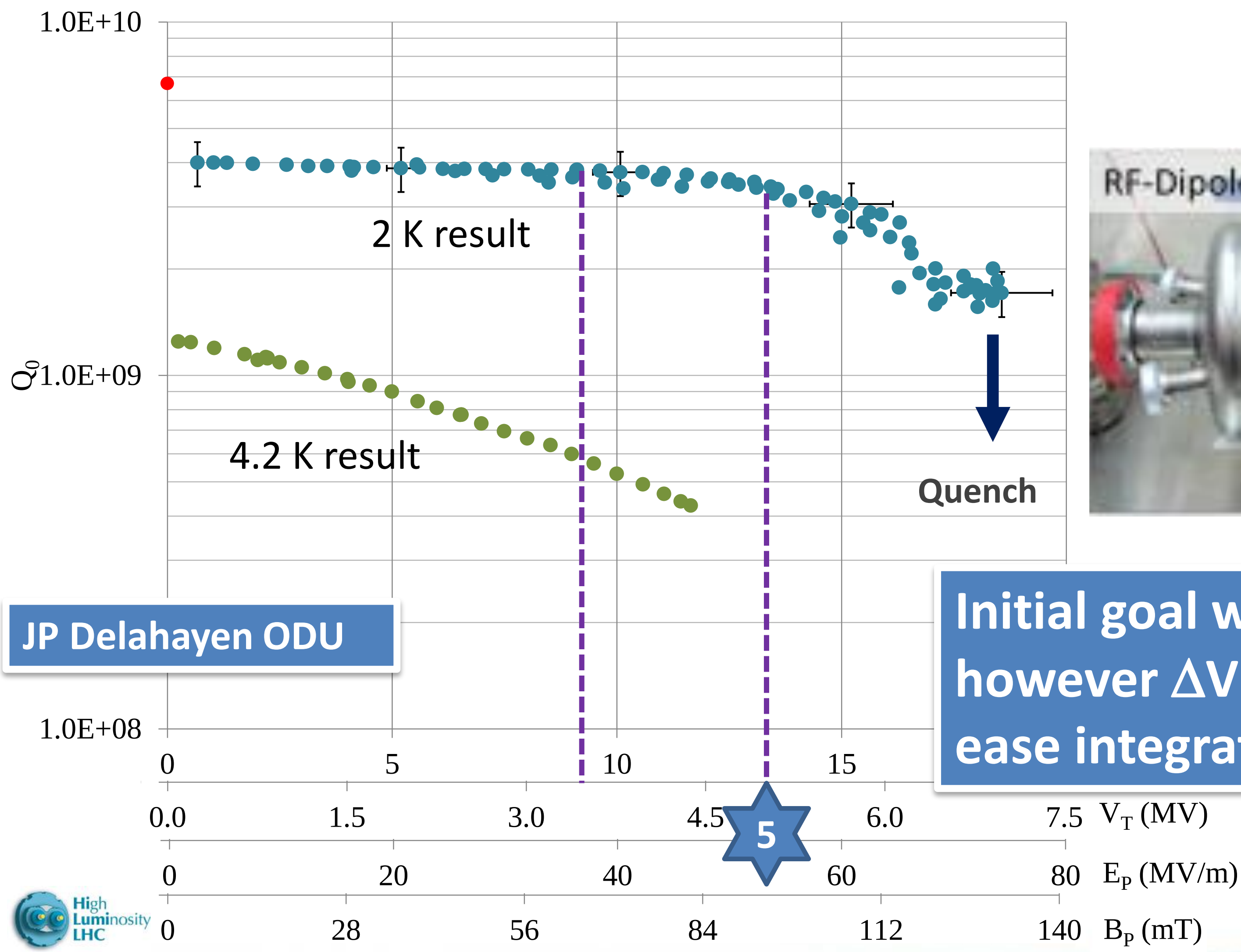

4-rod prepared for rinsing @ CERN


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


Concept of RF Power system

And excellent results: e.g. RF dipole > 5 MV

¼ w and 4-rods also tested (1.5 MV)

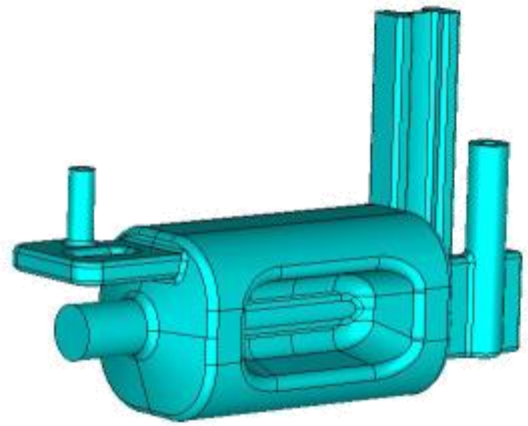


JP Delahayen ODU

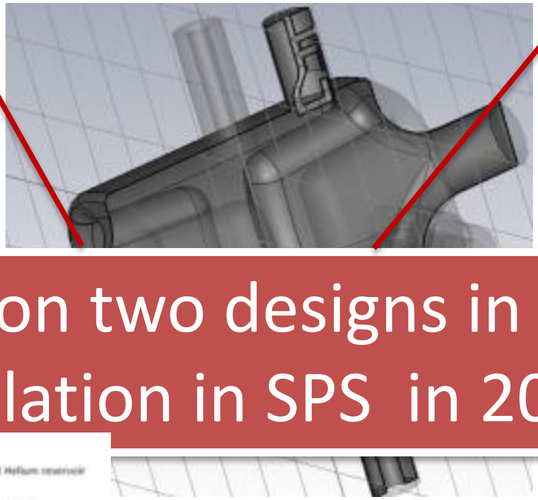
Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

Latest cavity designs toward accelerator

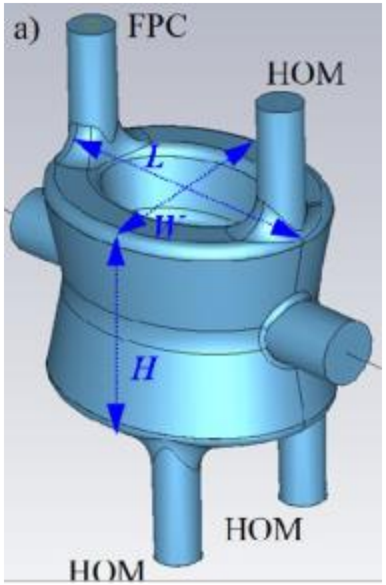
3 Advanced Design Studies with Different Coupler concepts



RF Dipole: Waveguide or waveguide-coax couplers

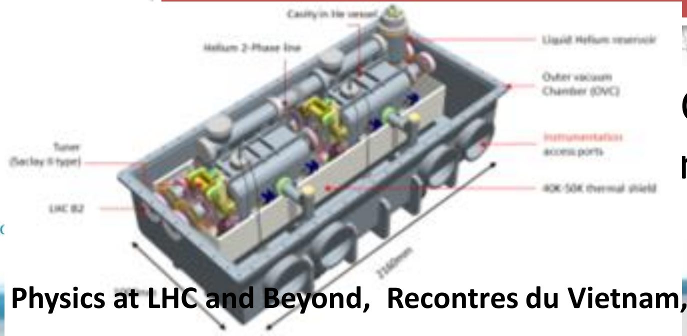


Coaxial couplers with nt ar



Double ¼-wave:

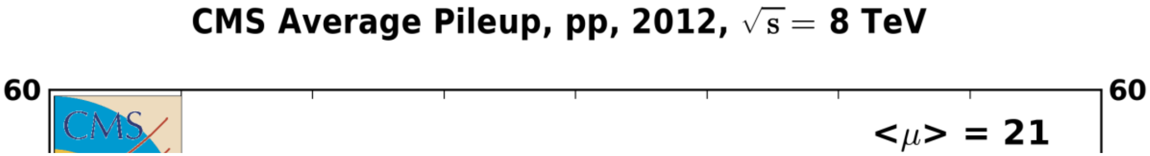
Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS



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

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)

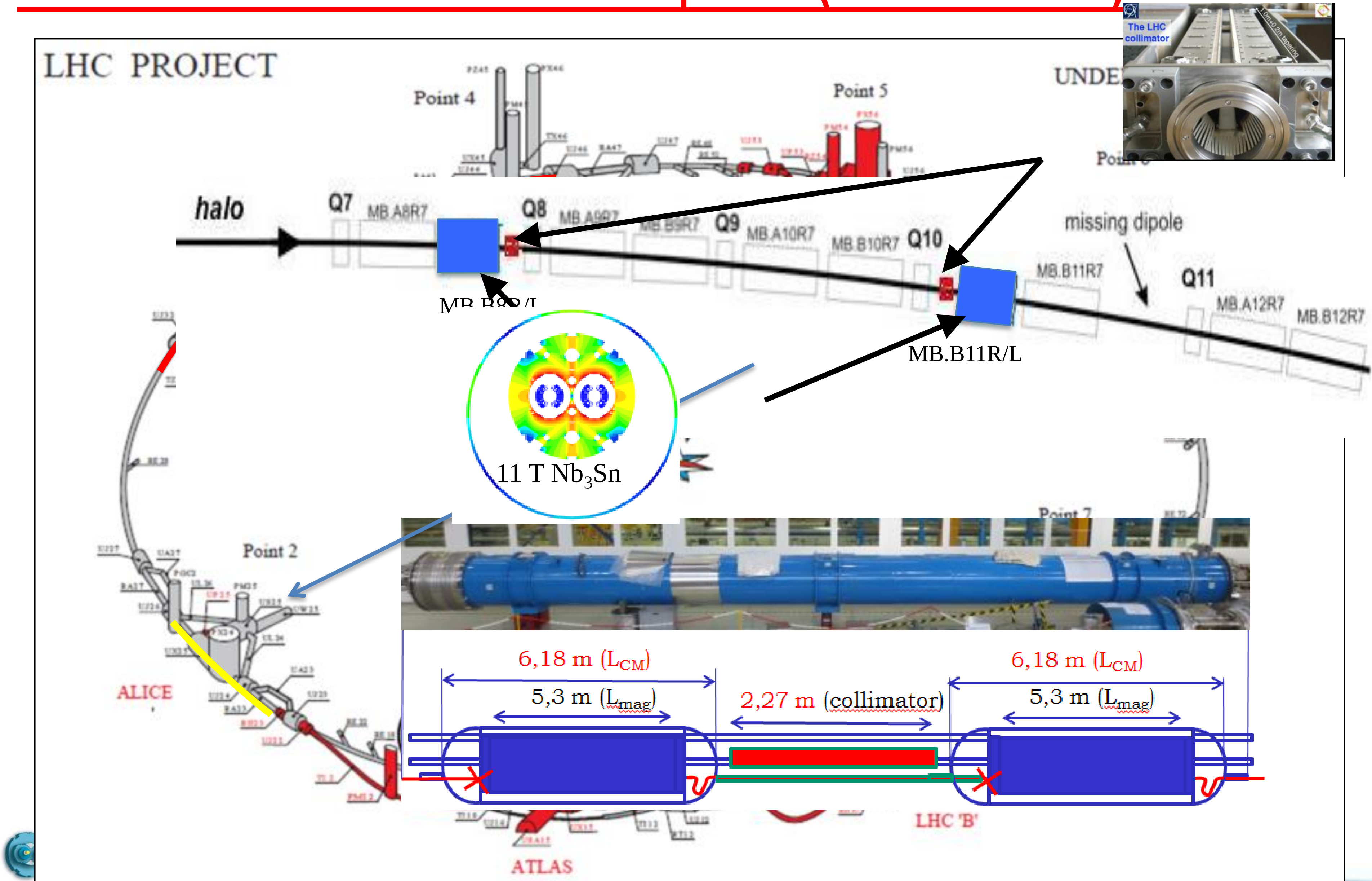
→ requires collimation during all operation stages!

→ requires good optic and orbit control!

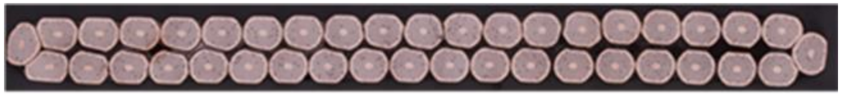
→ Which we have demonstrated during RunI

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

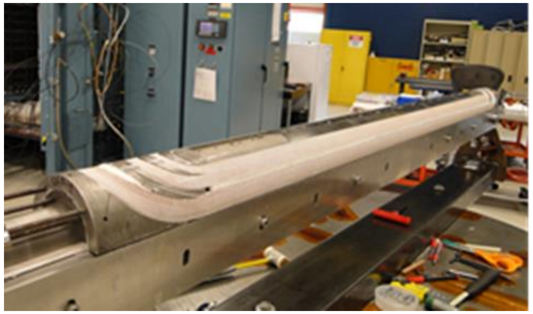
DS collimators – 11 T Dipole (LS2 -2018)



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

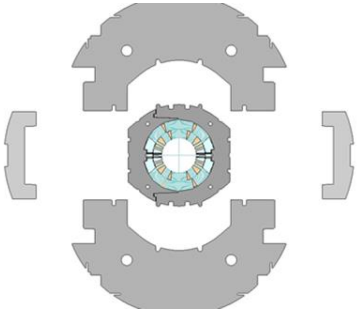


40-strand cable fabricated using FNAL cabling machine



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!

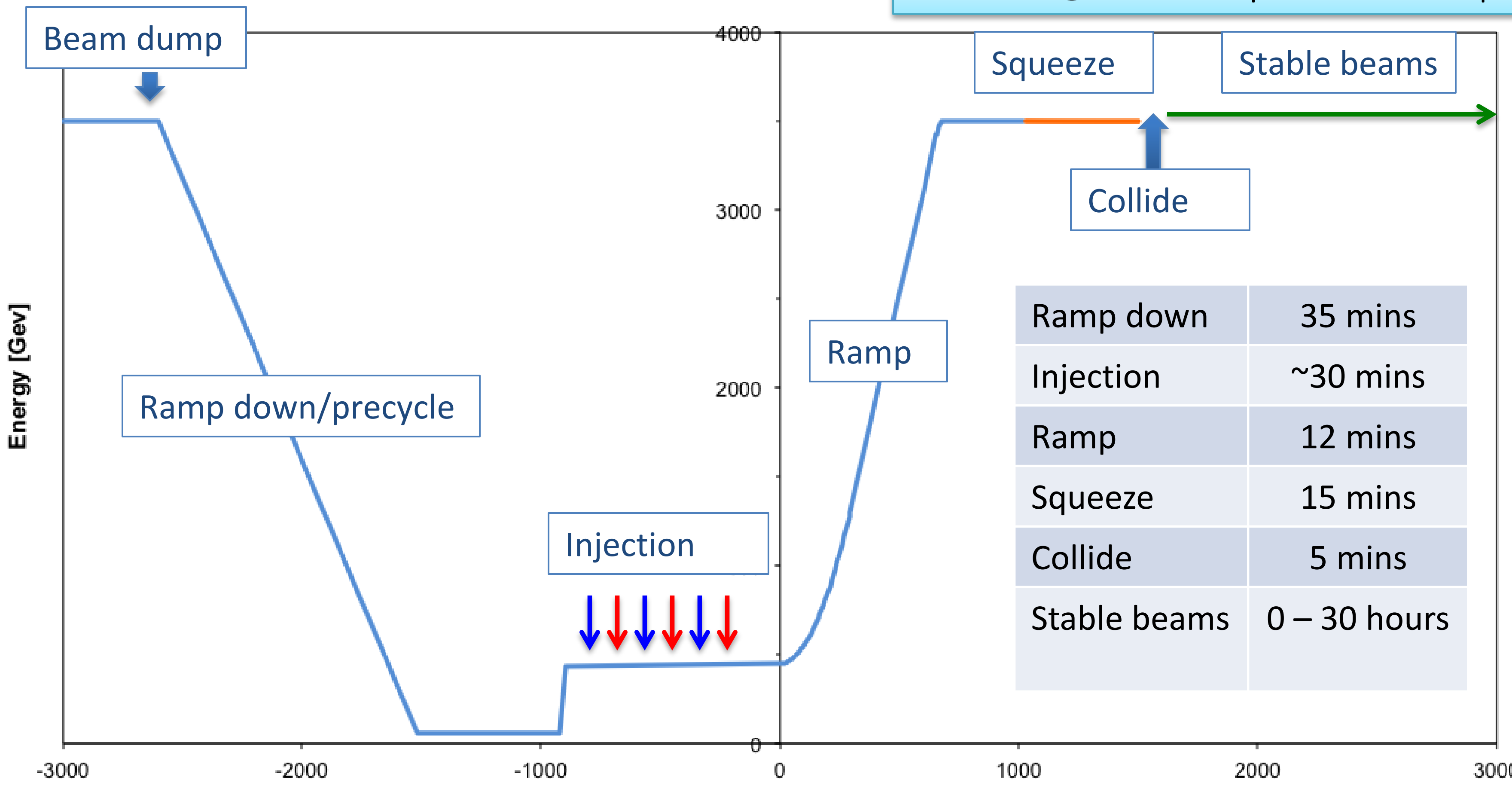
Prototyping of cryogenics bypass @ CERN

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

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

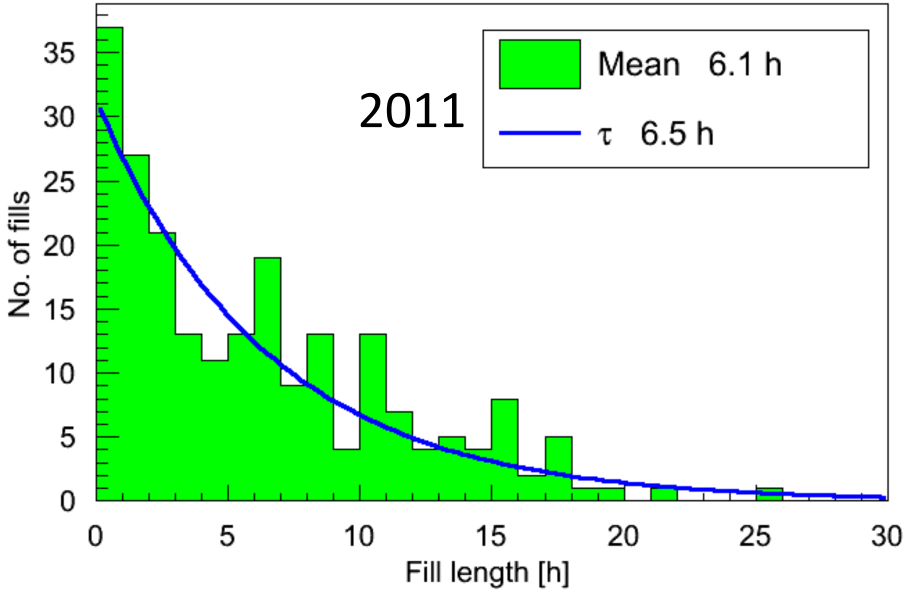
High Luminosity LHC

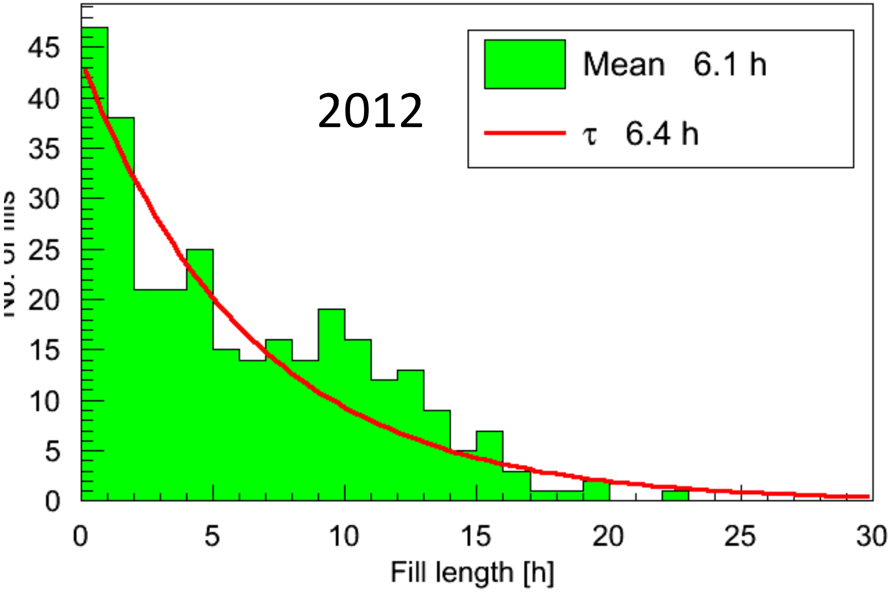
HL-LHC Challenge: Machine Efficiency
➔Integrated Luminosity

- Operation experience in 2011 and 2012:

J. Wenninger @ Evian LHC Operation workshop

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





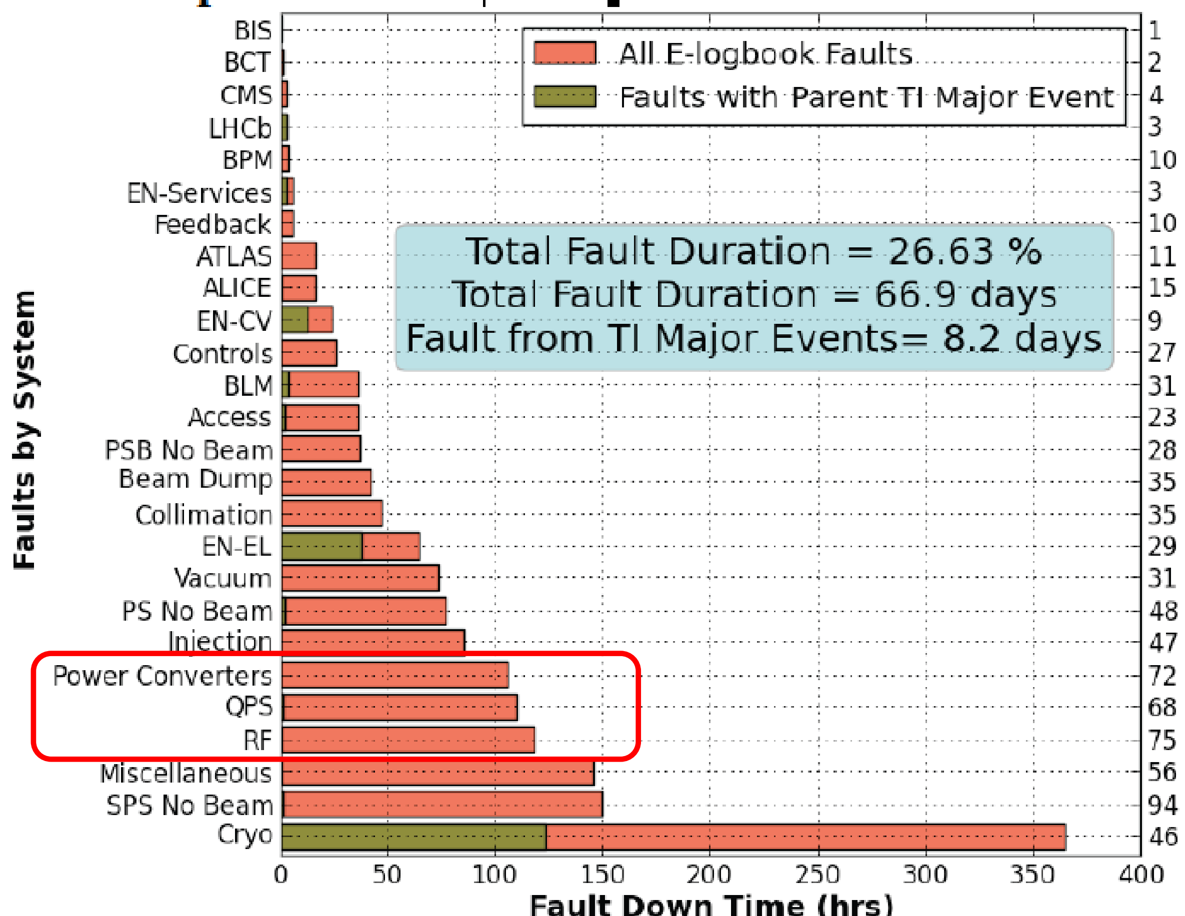
- ➔ corresponds to ca. 40% machine efficiency (time actually spend in physics divided by scheduled time for physics operation)
- ➔ 3000 fb-1 for HL-LHC will require significantly better machine efficiency!!!

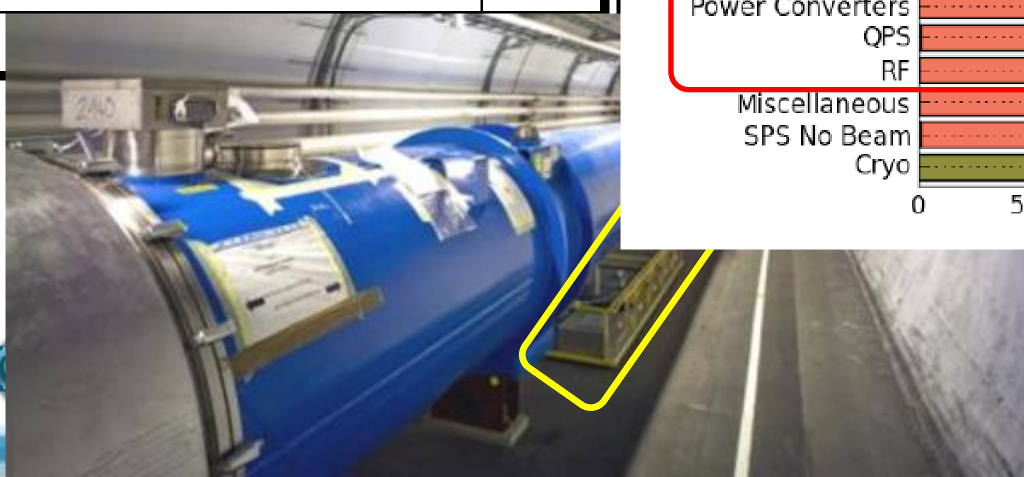
  and average fill length above 6 hours (ca. 10 hours)!

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

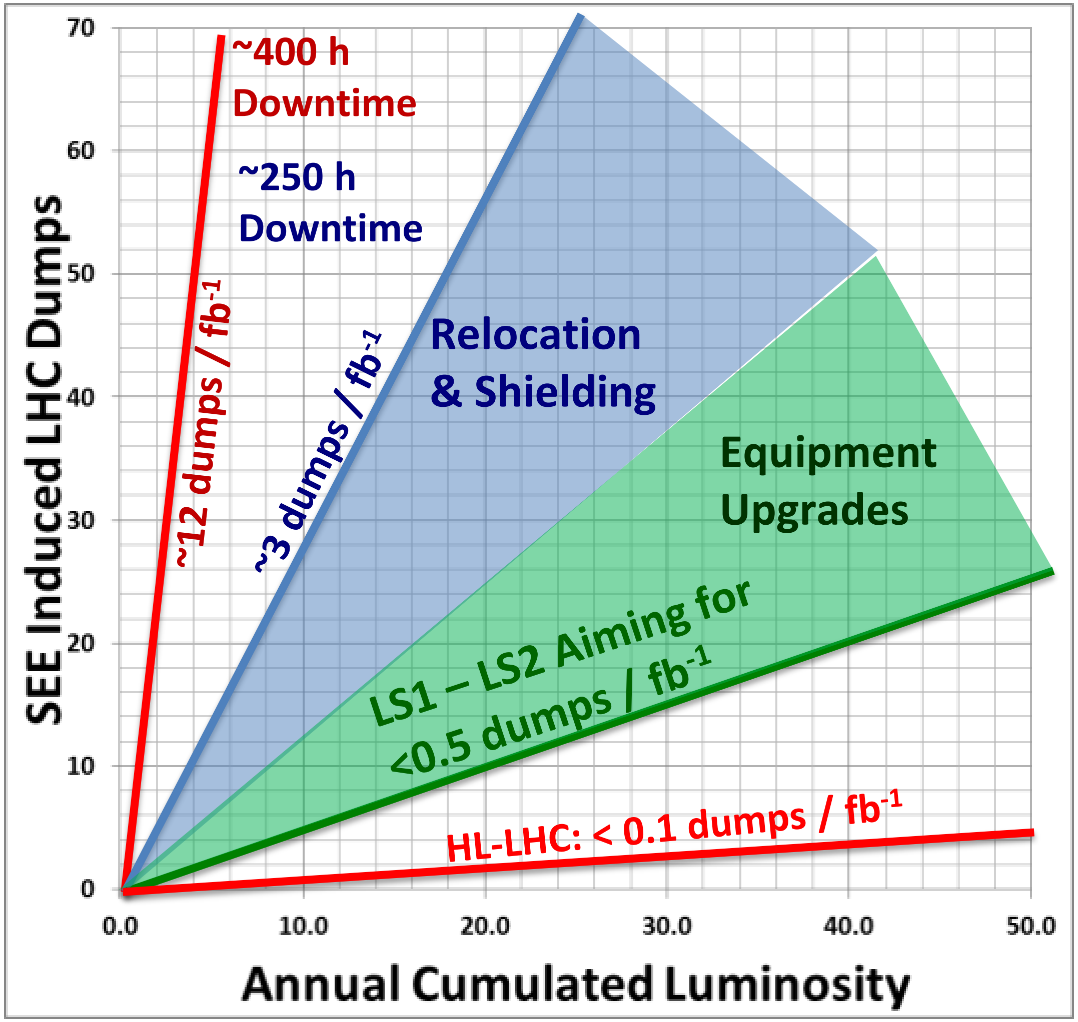
Dump Cause | #





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

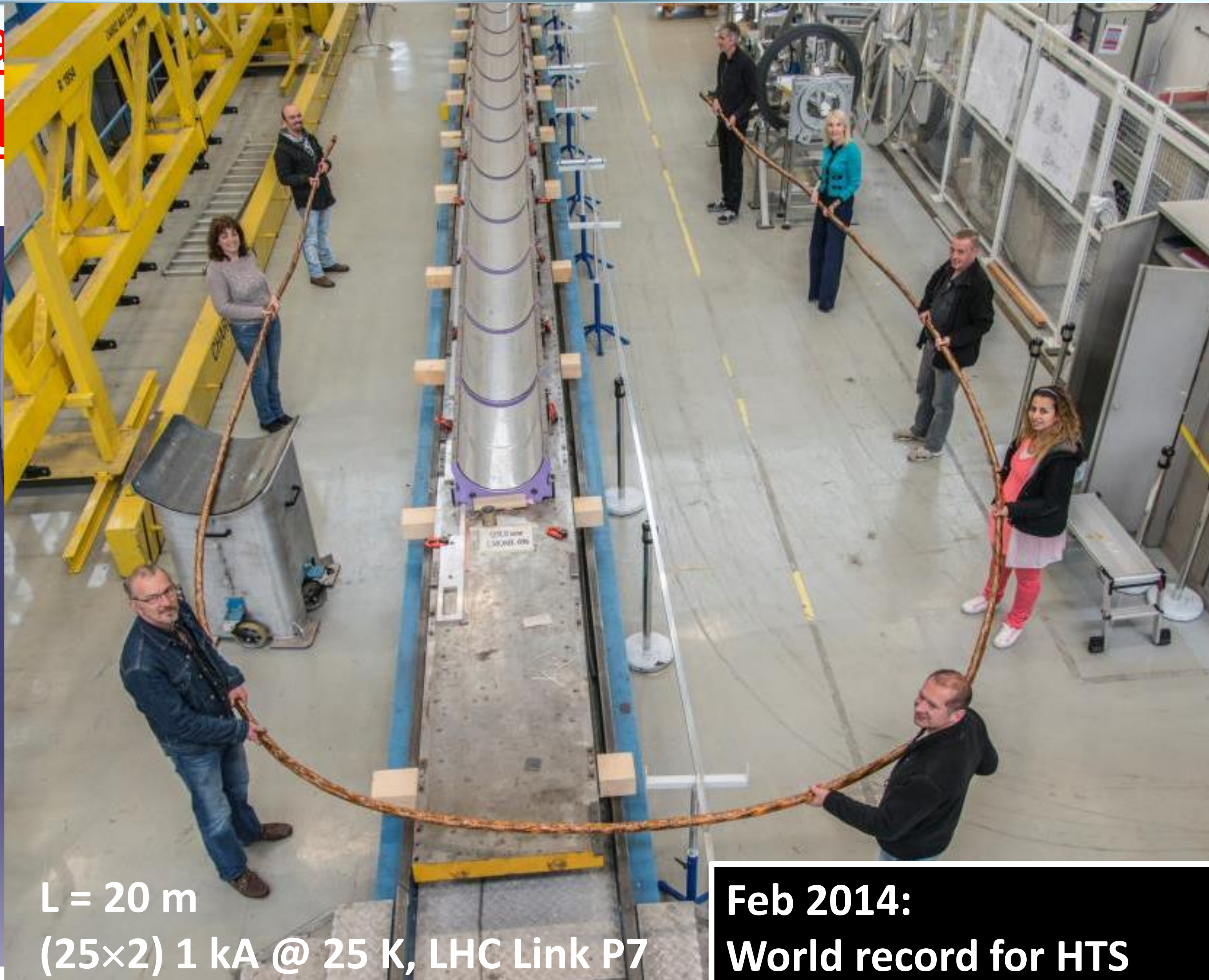
R2E SEU Failure Analysis - Actions



- **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

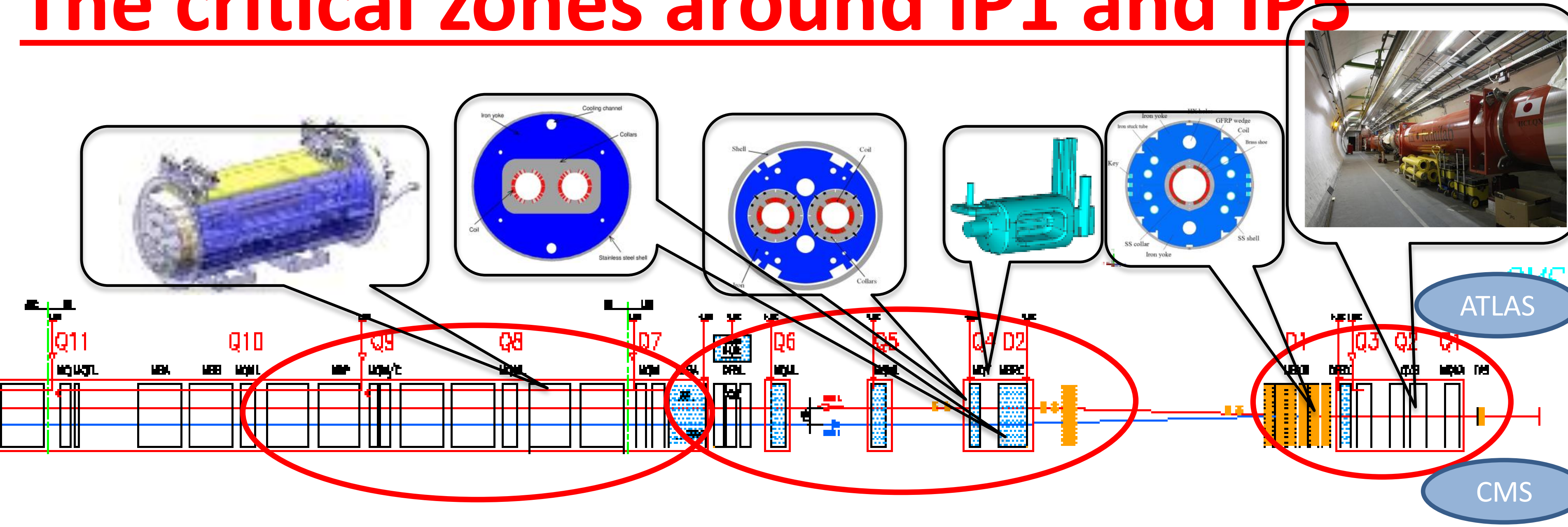
SC l



S3
3
S

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

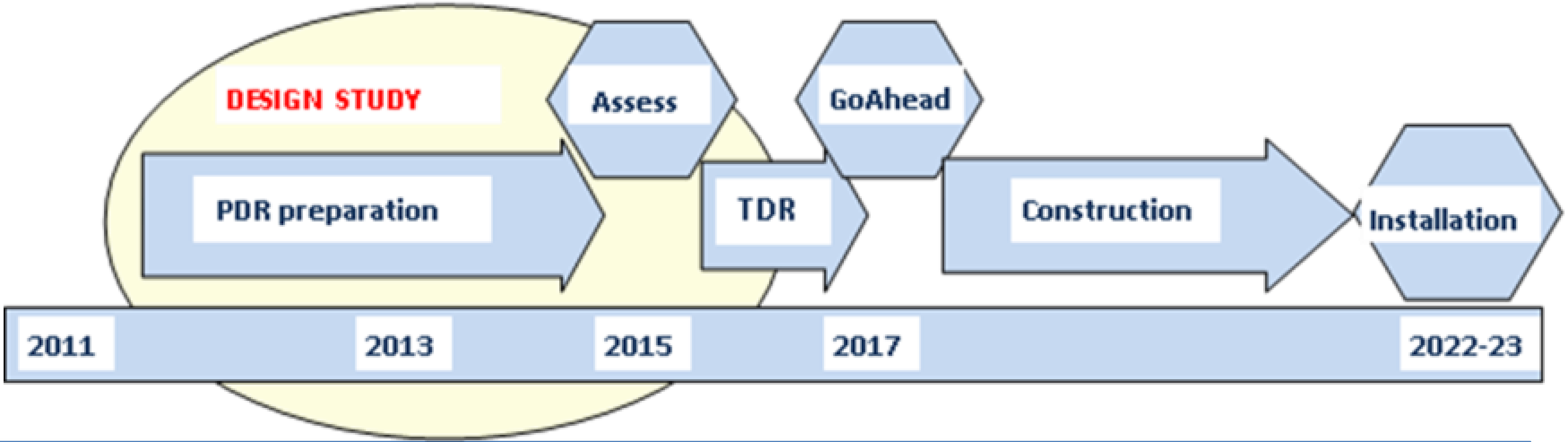
1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

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)!!

High Luminosity LHC

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 from IT, CC, other main hardware**
- **IT String test (integration) in 2019-20; Main Installation 2023-24**
- **Though but – based on LHC experience – feasible**

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)

Reserve Transparencies

HL-LHC Baseline Parameters:

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

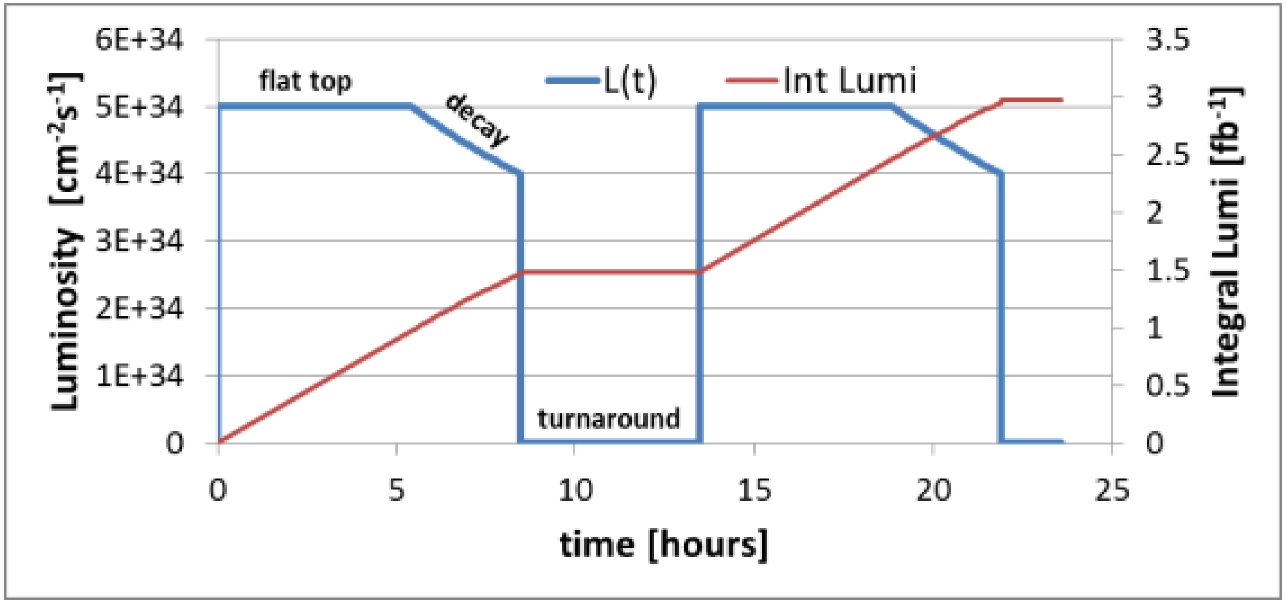
ATS required

Collision values

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

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

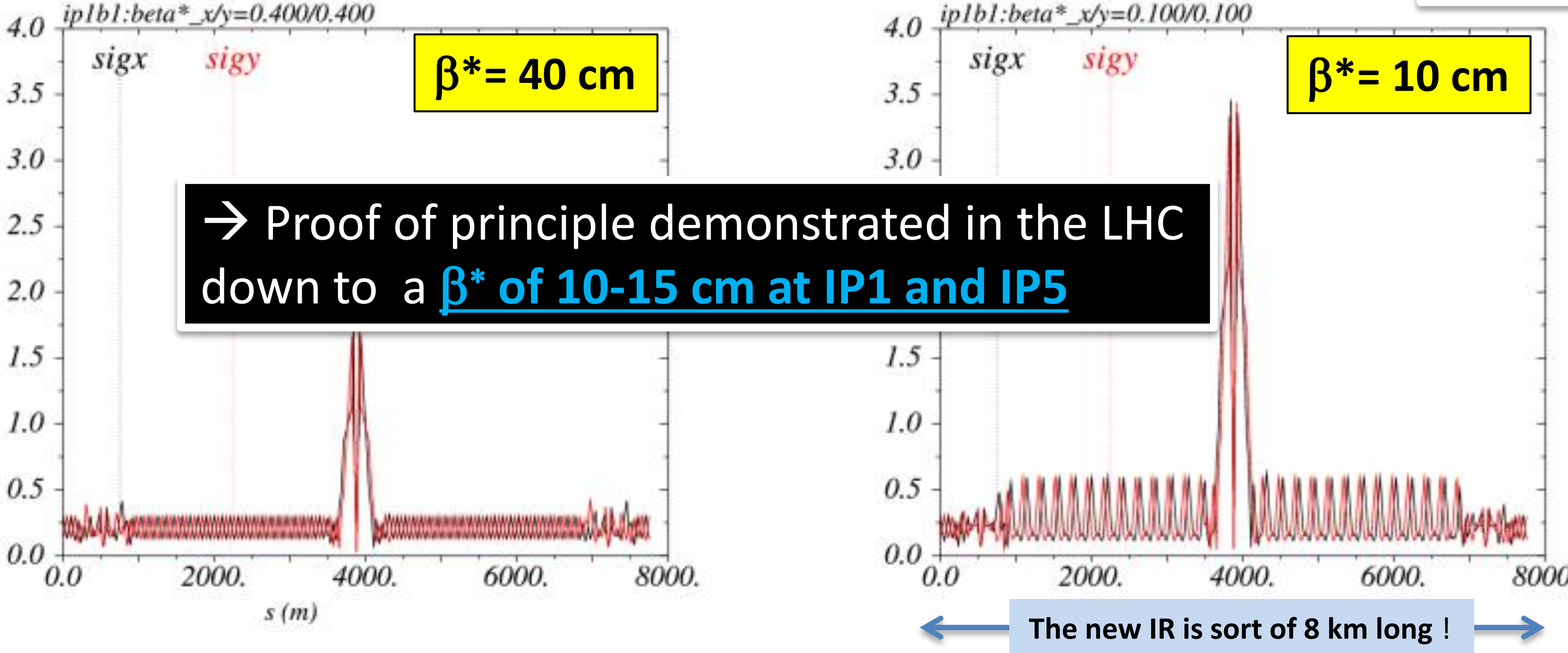
High Luminosity LHC

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**

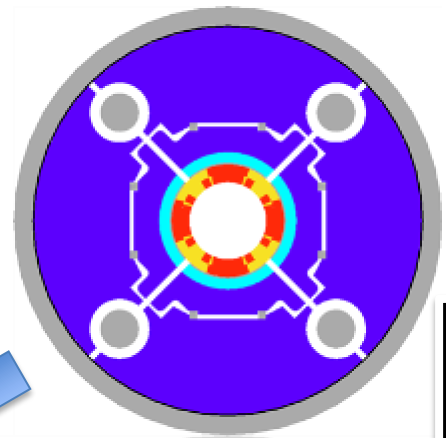
Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

High Luminosity LHC

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

Fermilab KEK

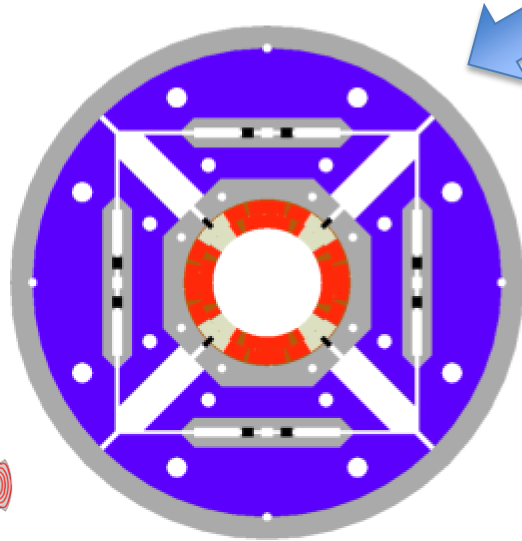
LHC (USA & JP, 5-6 m)
Ø70 mm, B_{peak}~ 8 T
1992-2005



LARP

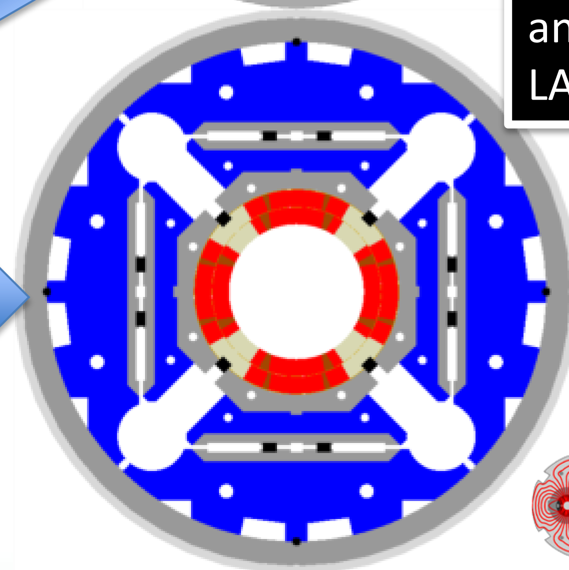
LARP TQS & LQ (4m)
Ø90 mm, B_{peak}~ 11 T
2004-2010

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



LARP HQ
Ø120 mm,
B_{peak}~ 12 T
2008-2014

LARP



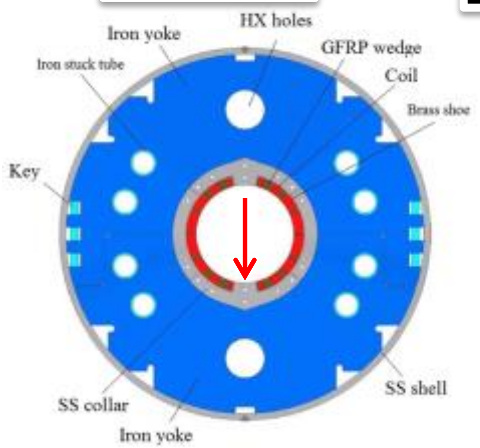
LARP & CERN MQXF
Ø150 mm,
B_{peak}~ 12.1 T
2013-2020

LARP CERN

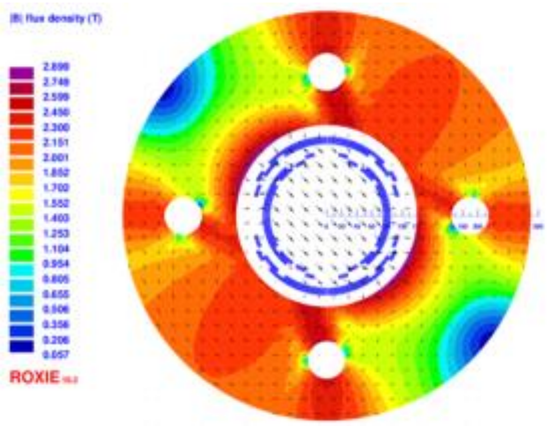
High Luminosity LHC

The HL-LHC Nb-T imagnet zoo…

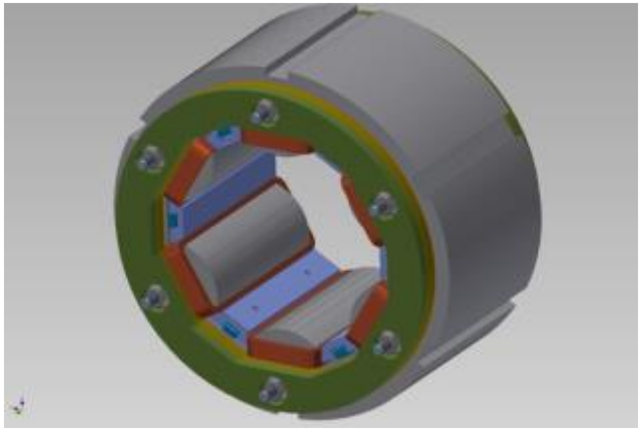
D1 (KEK)

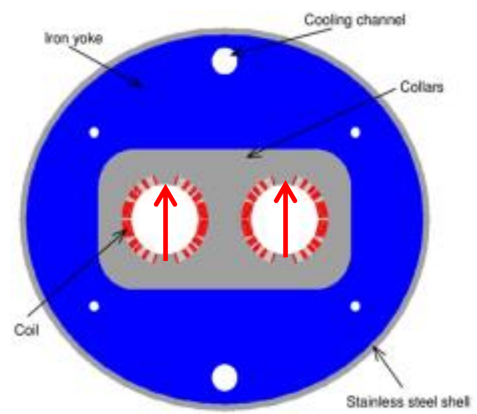


Nested Orbit corrector (CIEMAT)

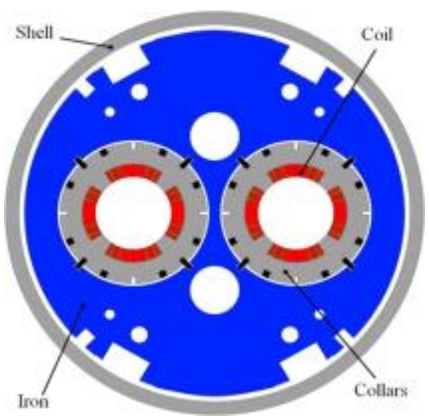


HO correctors: superferric (INFN)

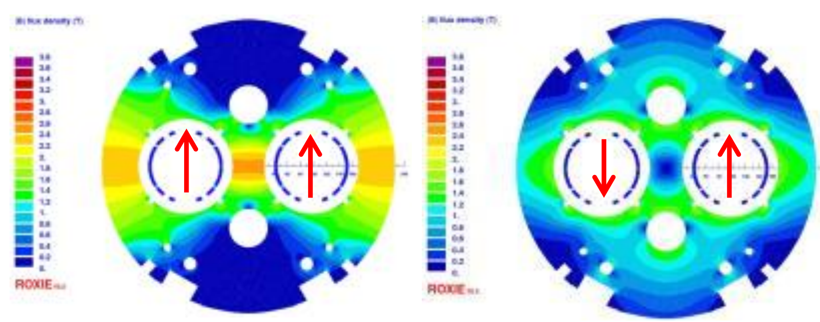




D2 (INFN)

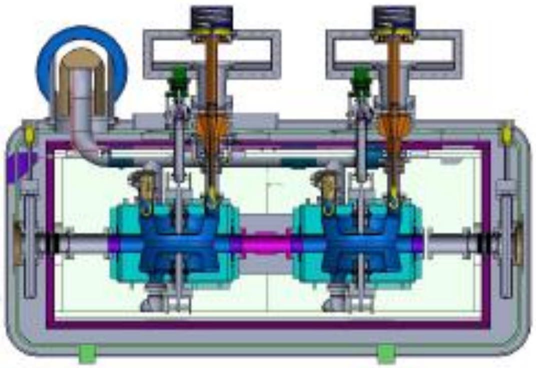


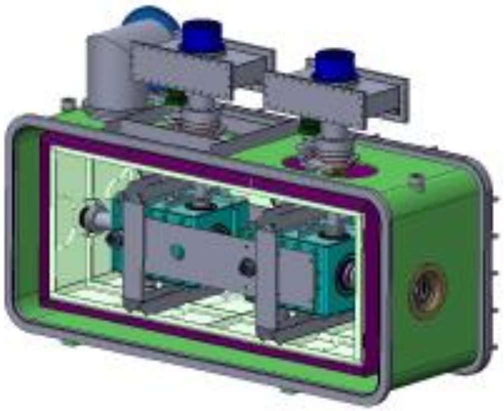
Q4 (CEA)

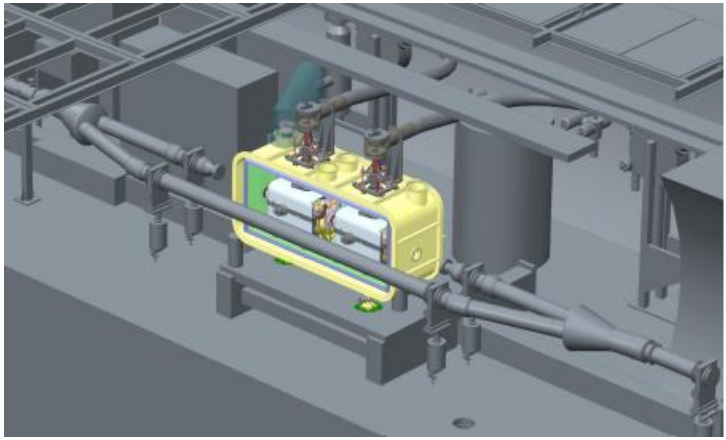


D2 corr

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







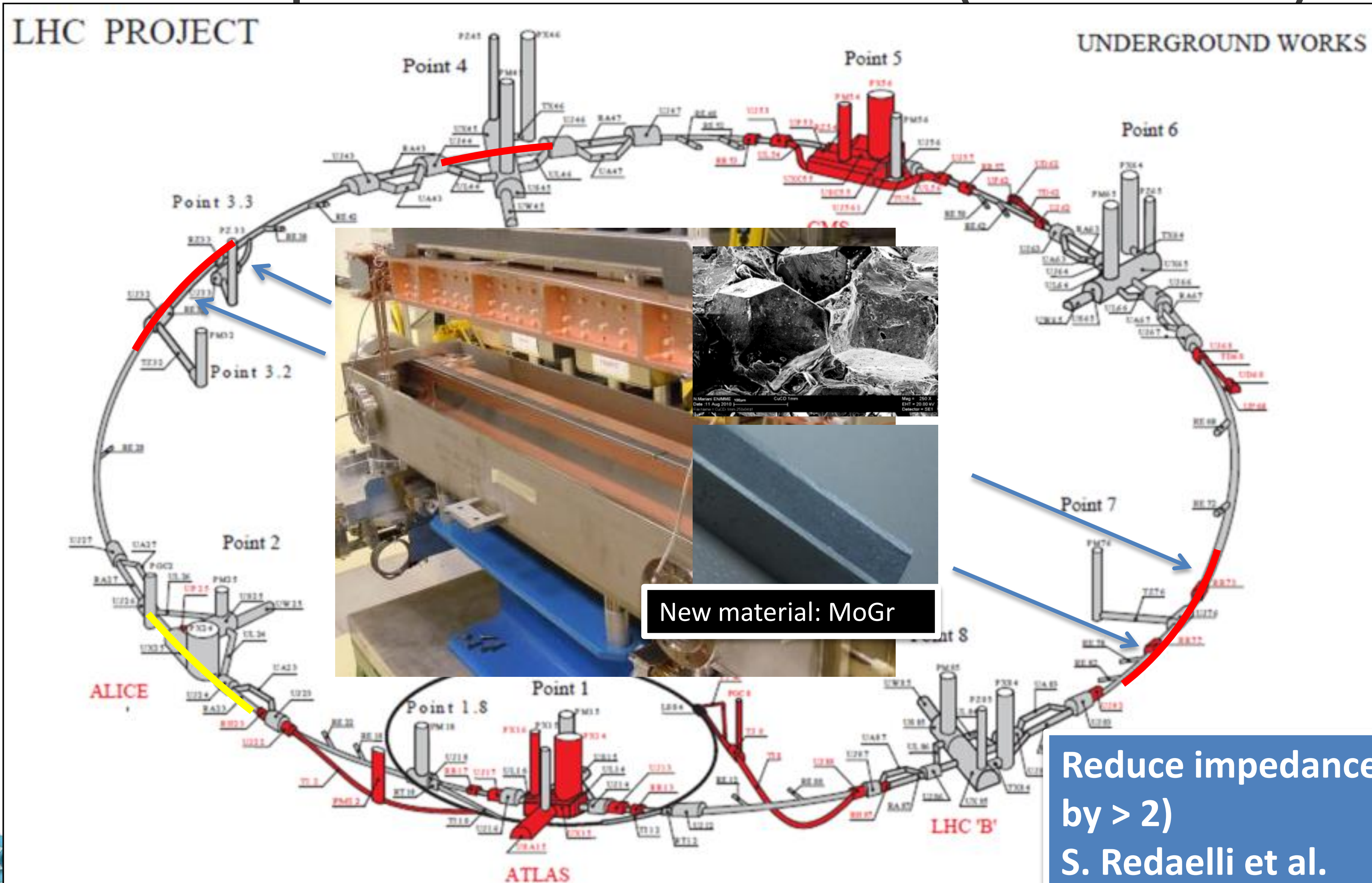
SPS test is critical: at least one cryomodule before LS2, possibly two, of different cavity type.

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

∅ = 90 mm. 2 K
11.6 MV required voltage ;
baseline is 4 cavites/beam-side, ⇒ 2.9MV/cavity

High Luminosity LHC

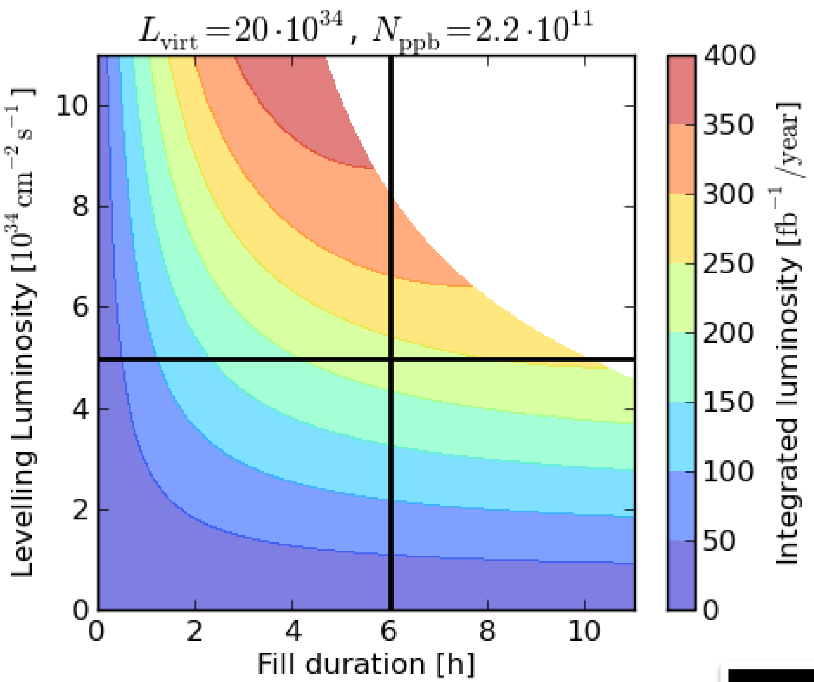
Low impedence collimators(LS2 & LS3)



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

Efficiency for ∫Ldt

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

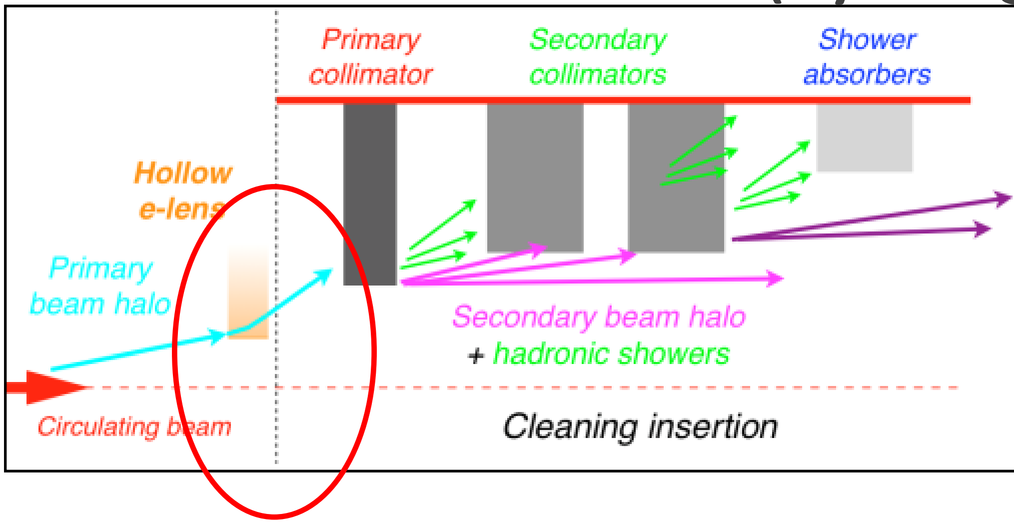


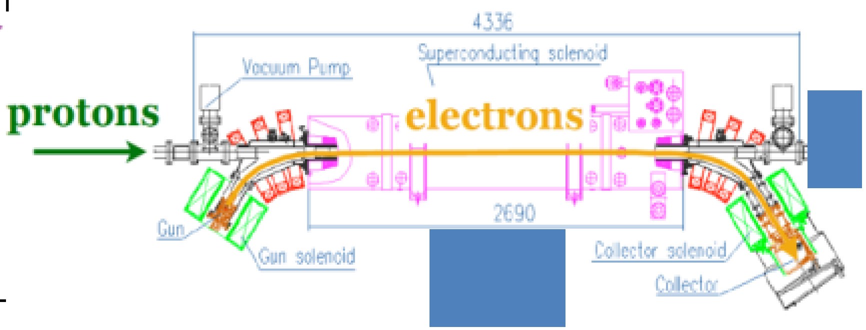
η ≥ 50%

High reliability and availbility are key goals

High Luminosity LHC

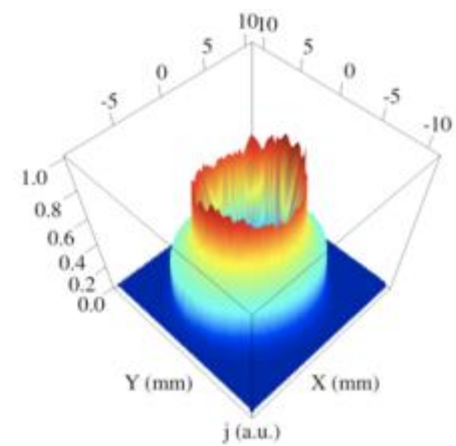
Controlling halo diffusion rate: hollow e-lens (synergy with LRBBCW)



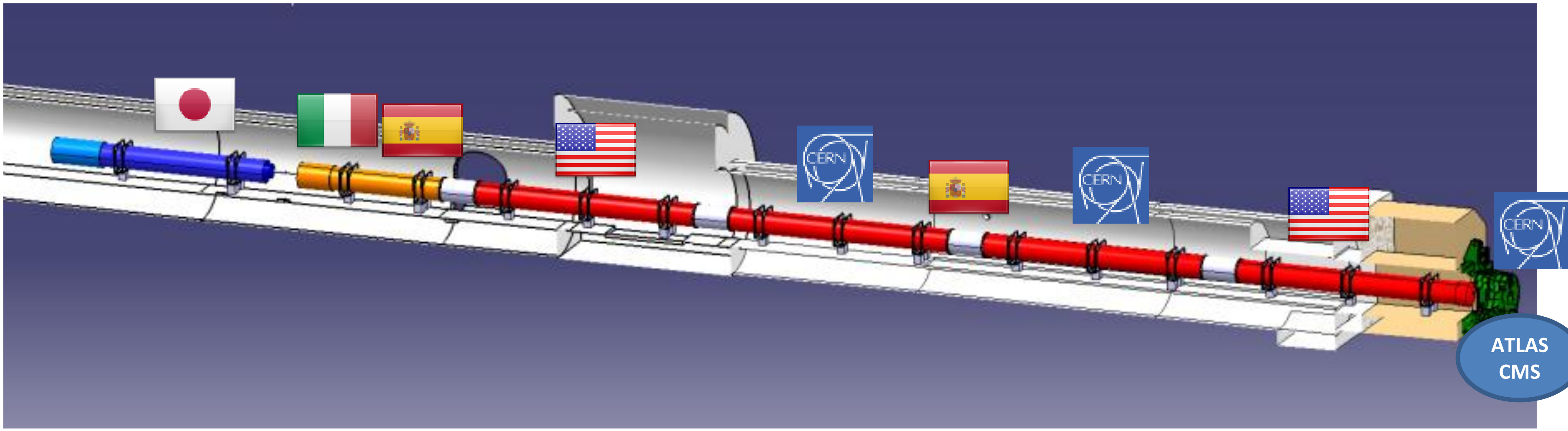


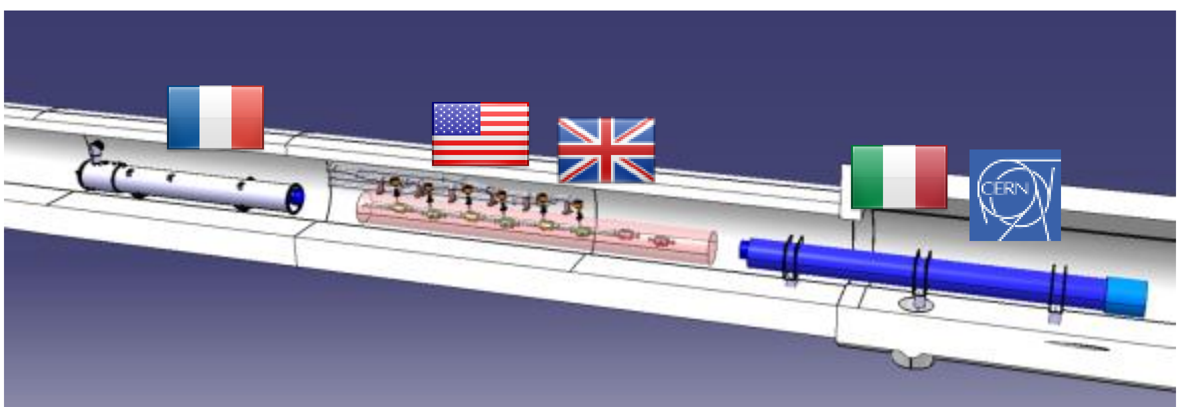
Promises of hollow e-lens:
1. Control the halo dynamics without affecting the beam core;
2. Control the time-profile of beam losses (avoid loss spikes);
3. Control the steady halo population (crucial in case of CC fast failures).

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





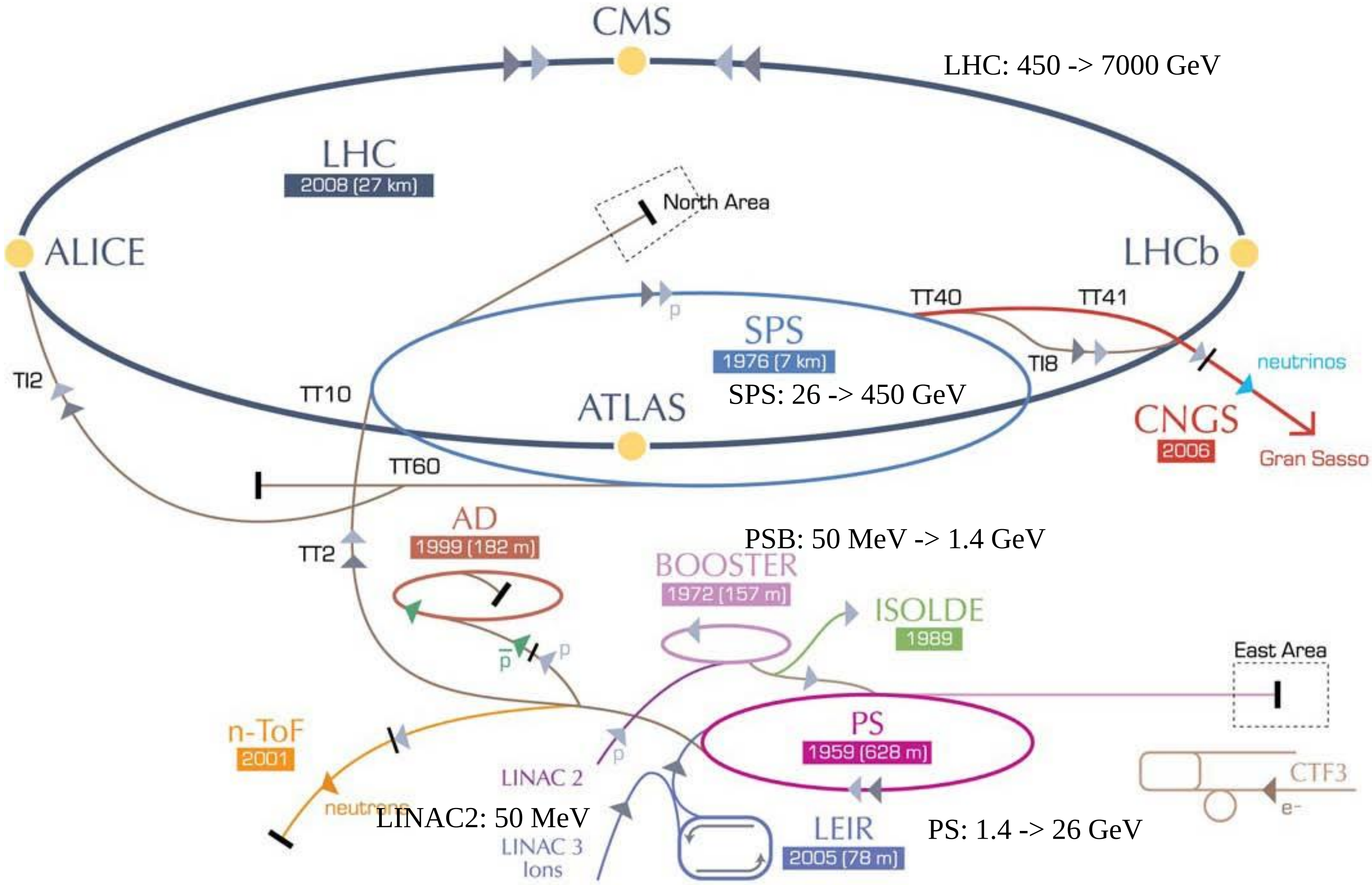
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

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

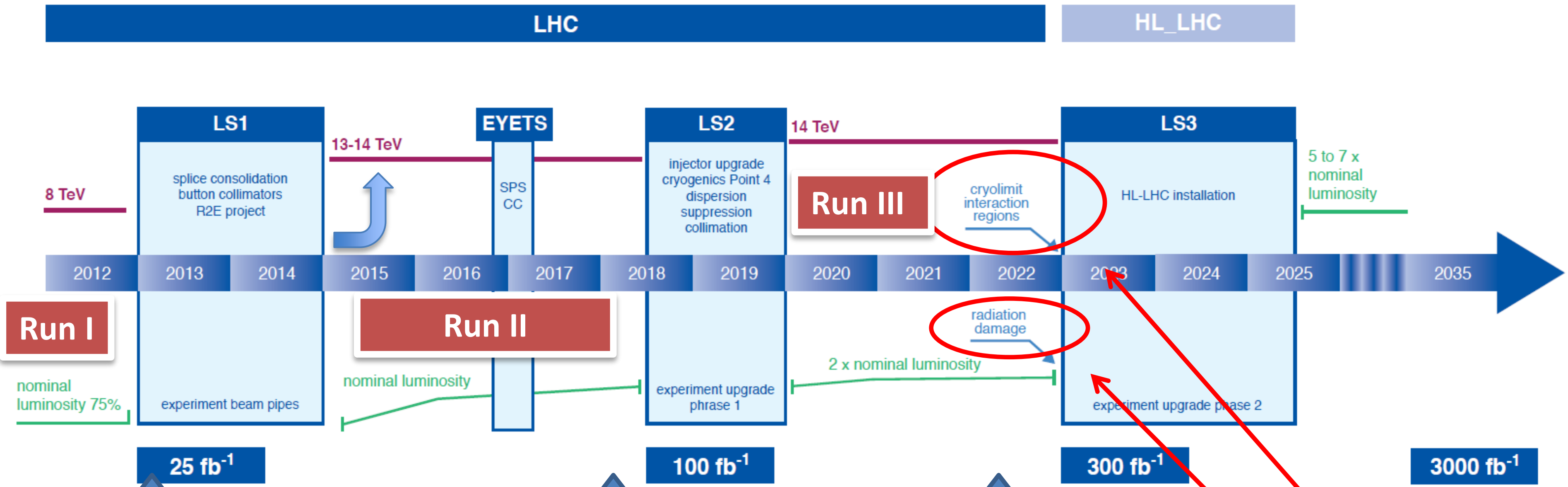
CC : R&D and Design **UK**

High Luminosity LHC Participants

The LHC and its Injector Complex:



LHC Performance Projection



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

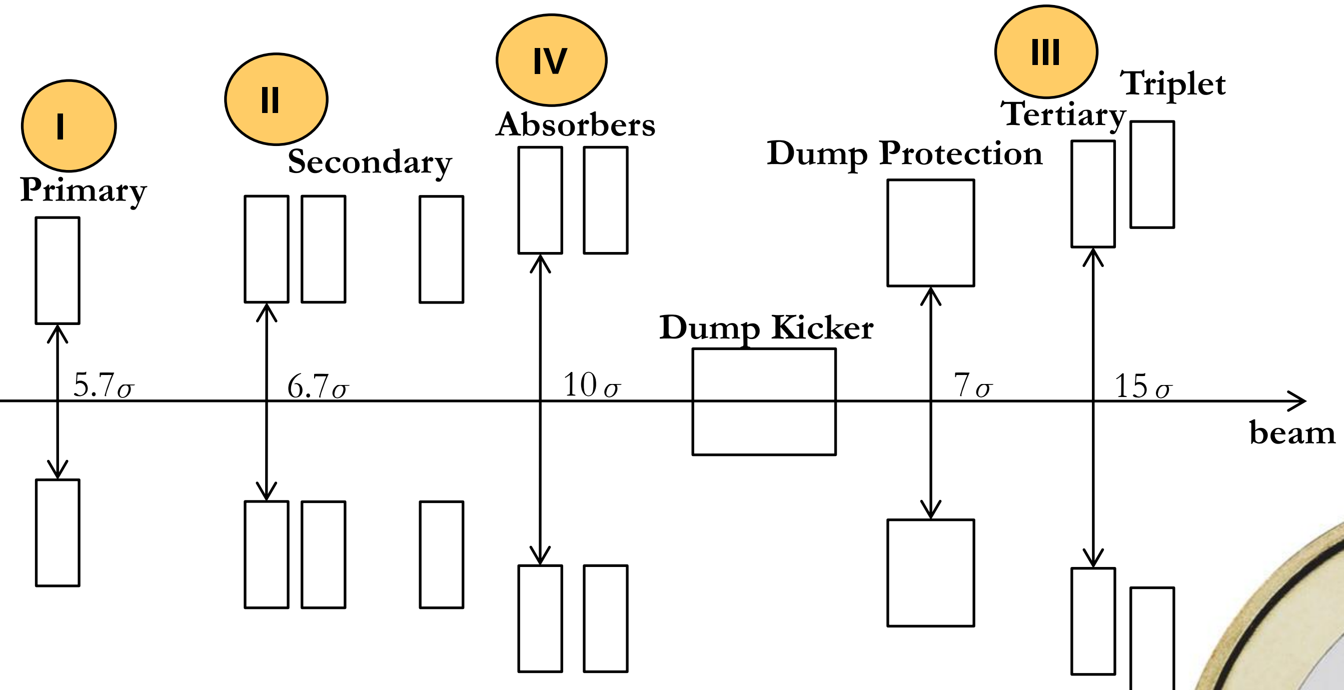
1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

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

Technical limits (experiments, too) like :

50 ⇒ 25 ns

HL-LHC Challenges: Collimation Efficiency



1 σ (450GeV) ≈ 1mm

1 σ (4TeV) ≈ 0.35mm

1 σ (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

High Luminosity LHC