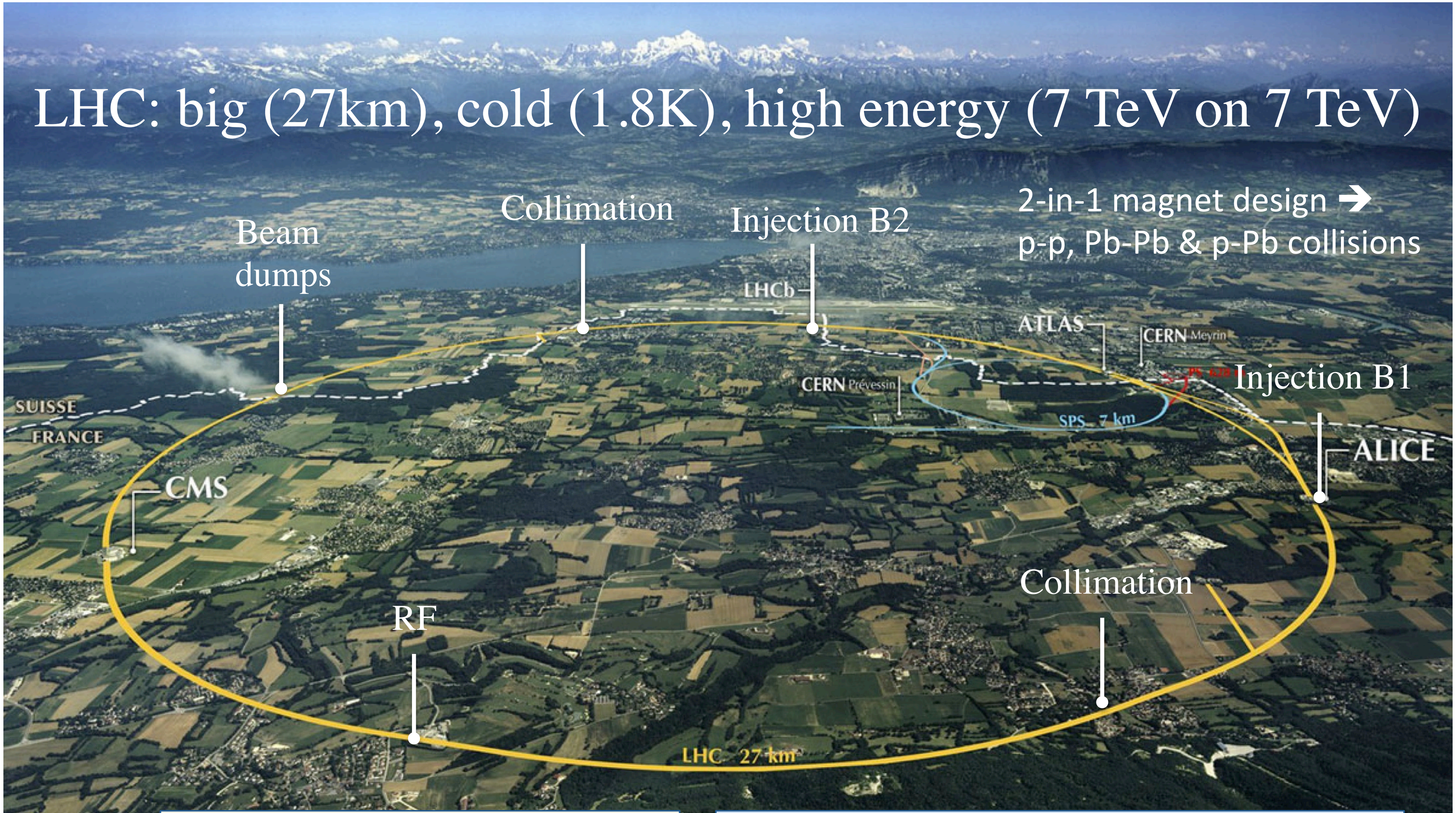
The LHC luminosity upgrade and HL-LHC-UK

(Or, which luminosity, why, how and what the UK will do about it)

Rob Appleby
University of Manchester/Cockcroft Institute
HL-LHC-UK Spokesperson
robert.appleby@cockcroft.ac.uk

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



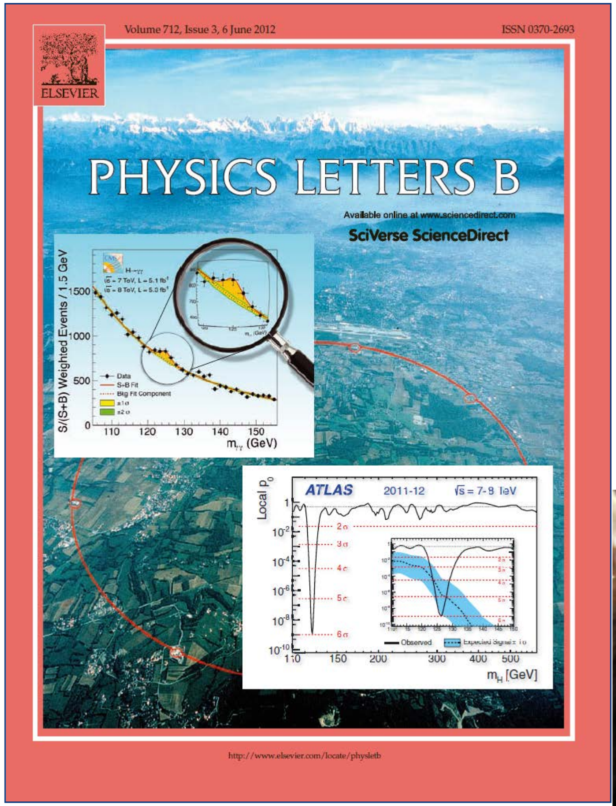
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

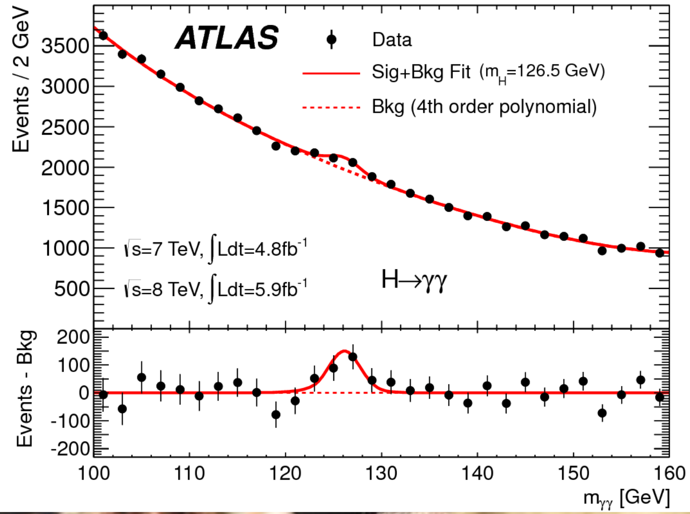
150 tonnes Helium
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
450 MJ magnetic energy per sector at 4 TeV
➔ ≈ 10 GJ total @ 7 TeV

The LHC!!!!

- In only three years of 7~8 TeV operation:

4 July 2012:
5σ observation of a Higgs-like boson

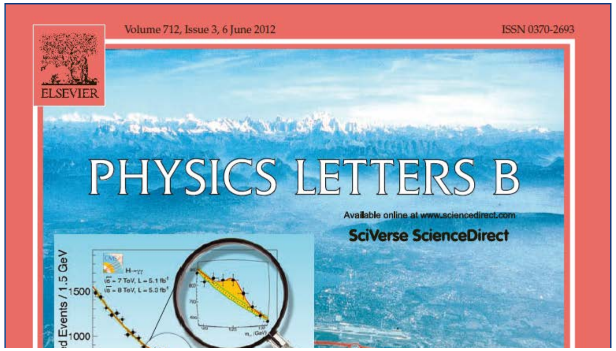


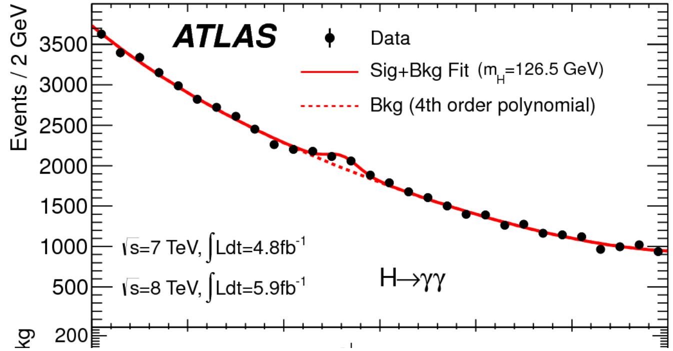


The LHC!!!!

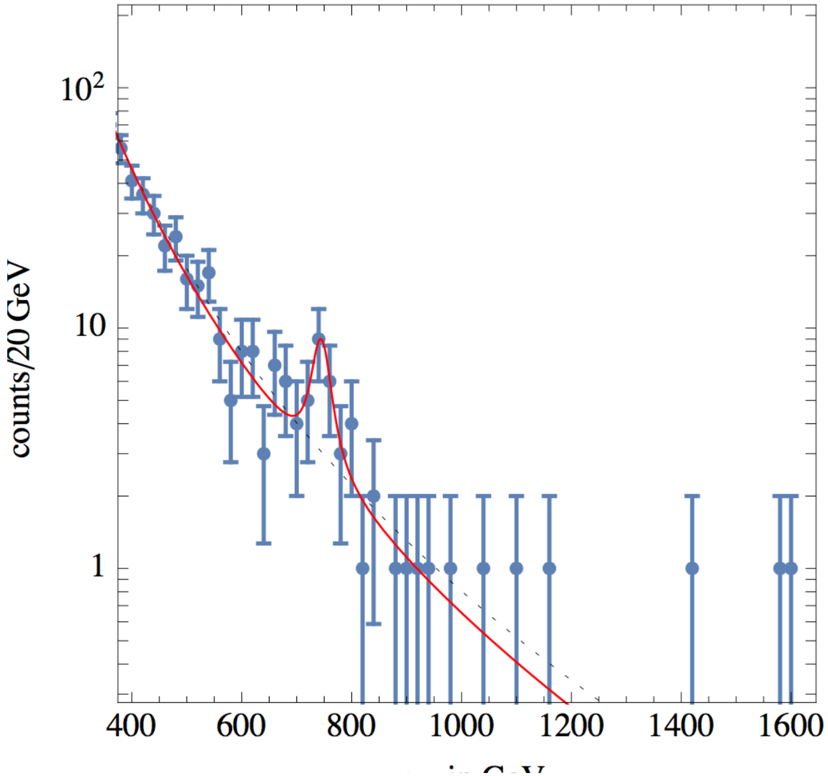
- In only three years of 7~8 TeV operation:

4 July 2012:

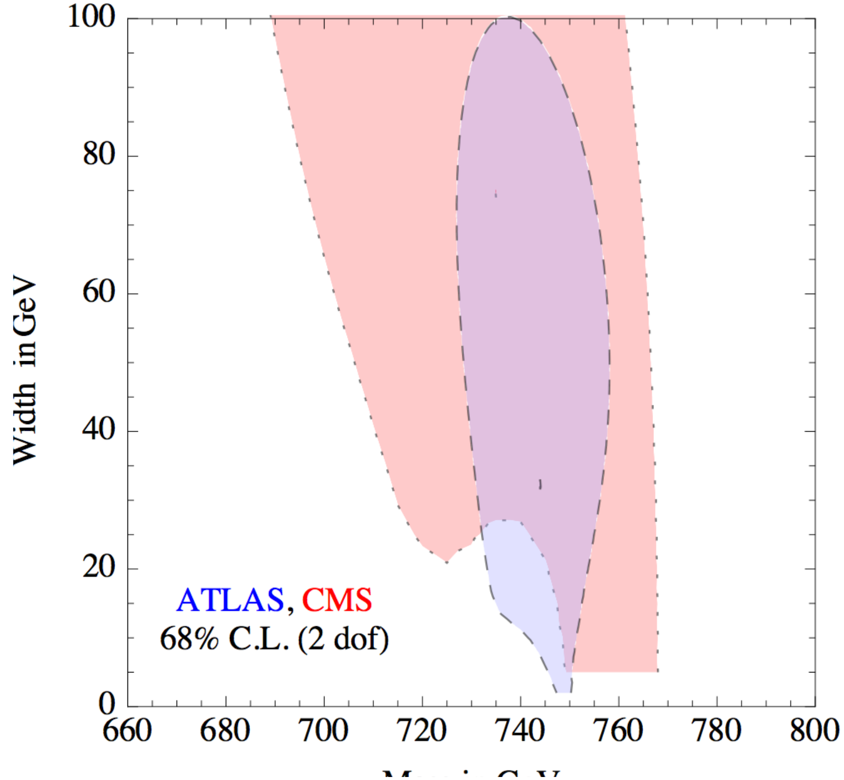




CMS + ATLAS, 13 TeV

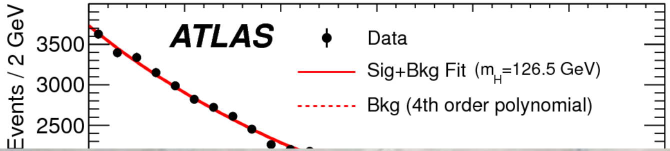


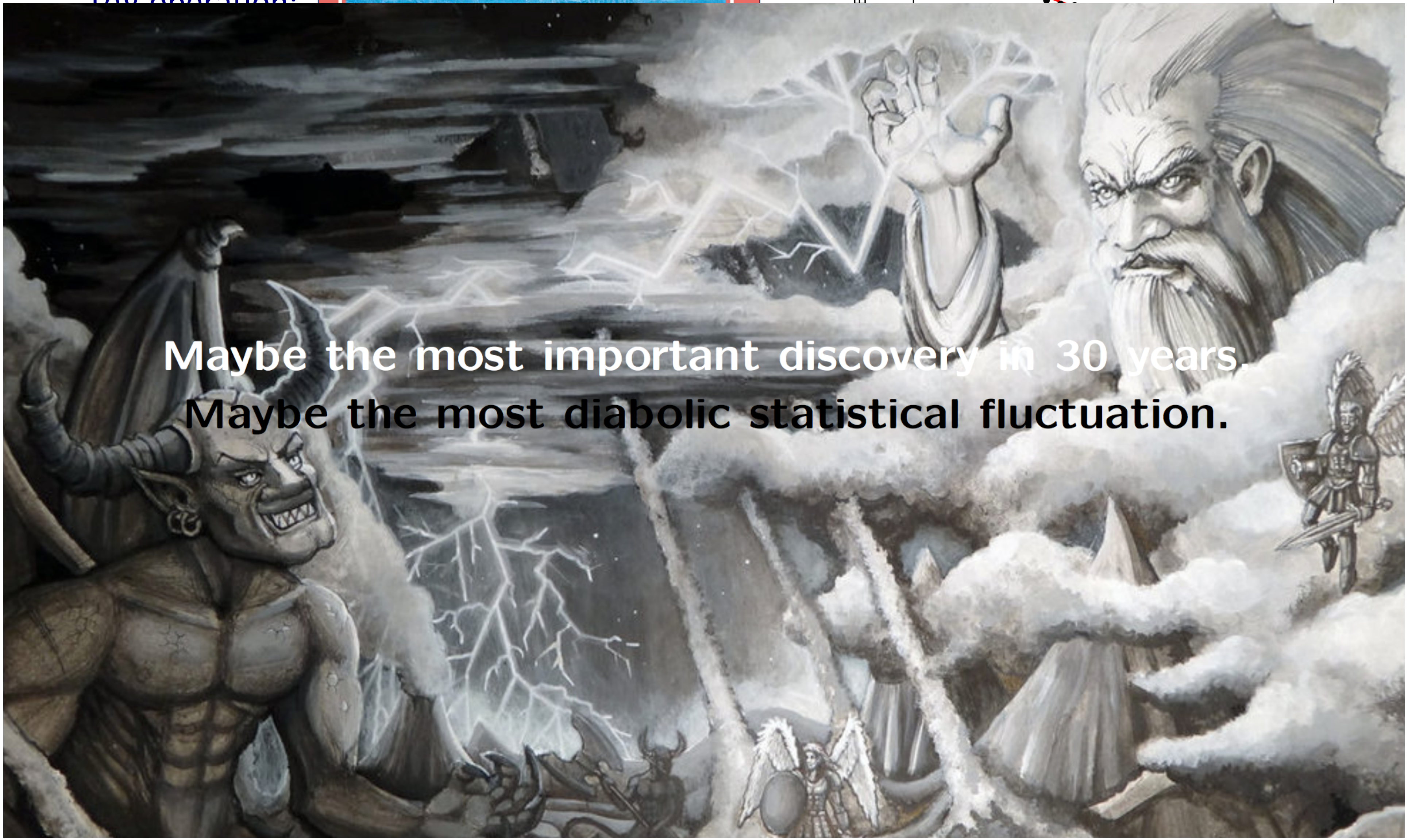
(M, Γ) fits



The LHC!!!!

- In only three years of 7~8 TeV operation:



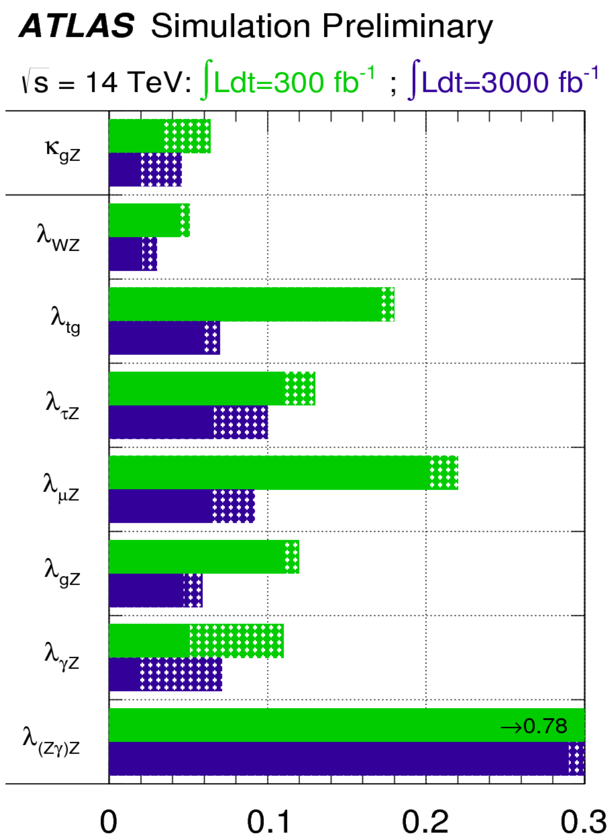


The goal of High Luminosity LHC (HL-LHC)

The HL-LHC physics programme has three broad goals

- **Precision measurements** of the strength and structure of the Higgs boson's interactions with other particles
- To perform more accurate measurements, with more luminosity and with reduced statistical uncertainty, on the **new particles** discovered so far in the LHC.
- Search for New Physics: SUSY, Dark Matter candidates, Extra dimensions & exotic physics, and **study rare processes**

These goals require a significant increase in luminosity over the existing machine



Higgs coupling precisions for 300 and 3000 fb^{-1}, with different systematic error assumptions ATLAS-PHYS-PUB-2013-014

$$\Delta\lambda_{XY}=\Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$$

The goal of High Luminosity LHC (HL-LHC)

European strategy for particle physics 2013 update "Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030"

STFC PPAN 2013 programmatic review "Continued involvement in this [LHC] exploration with higher energies and luminosities is the backbone of the UK programme" and "R11 - We recommend that the LHC experiments remain the highest priorities for the UK particle physics programme."

2014 UK STFC accelerator review, which recommended "R23: The UK HL-LHC accelerator community should prepare to seek funding for this project from STFC after the end of the EU funded HiLumi Design Study. These preparations should include the formal definition of a UK project with a nominated contact person and management structure".

Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

From FP7 HiLumi LHC Design Study application

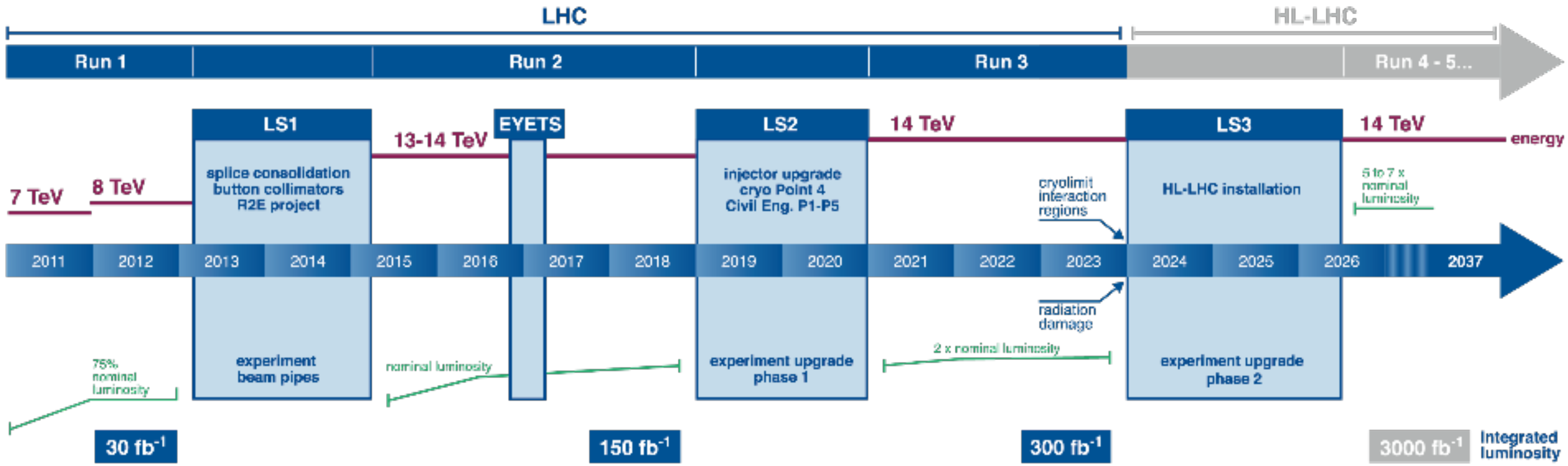
The main objective of HiLumi LHC design dtudy is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Concept of ultimate performance defined:
L_{ult} ≅ 7.5 10^{34} cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**
LHC should not be the limit, should Physics require more…

LHC / HL-LHC Plan



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

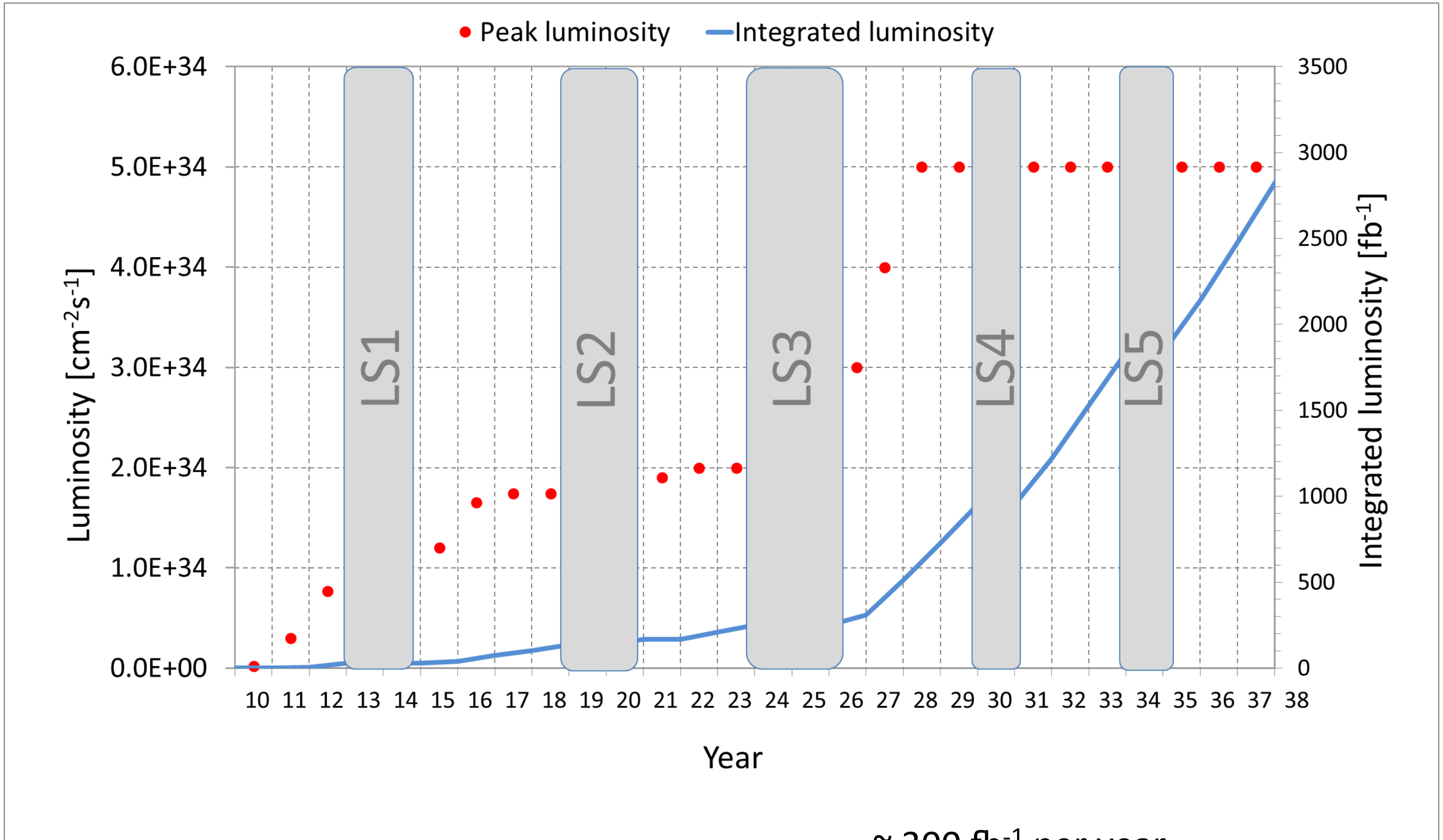
Technical limits to lumi increase (Machine & Experiments)

Note, some talk of delaying EYETS by 1 year, extending run 2 by 1 year

50 ⇒ 25 ns

Pile up 140-200

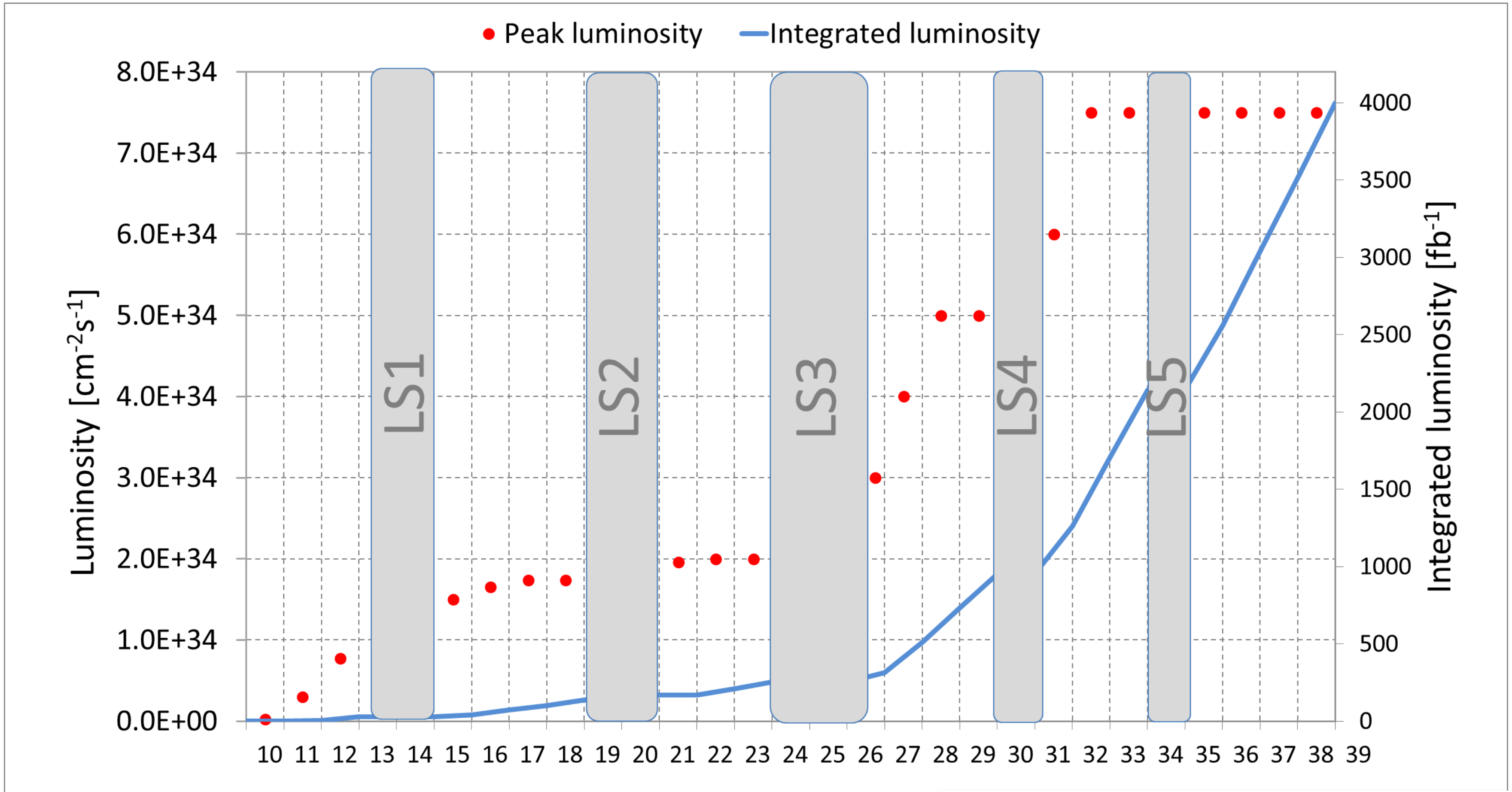
Nominal upgrade parameters
3000 fb^{-1} would be reached in 2037



~ 300 fb^{-1} per year

Upgrades takes a long time…

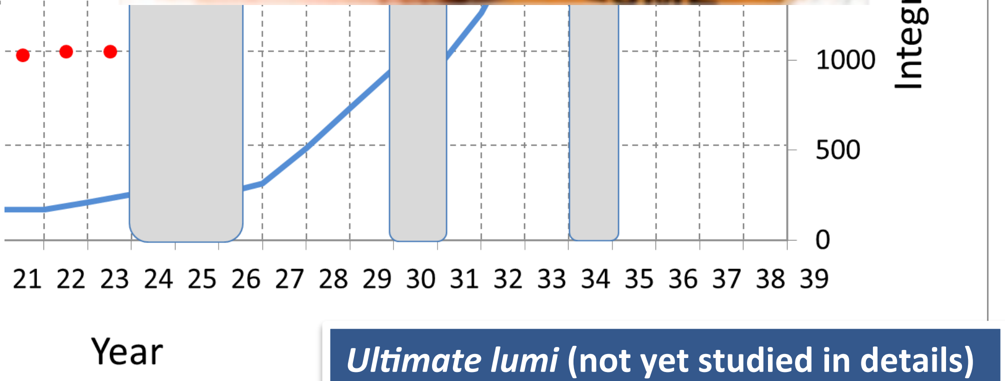
HL-LHC performance



Ultimate lumi **(not yet studied in details)**

- ***L = 5 → 7.5 10^{34} $cm^{-2}s^{-1}$***
- ***Int. L = 3000 → 4000 fb^{-1}***
- ***Pile up μ ~ 200 (was 140)***

HL-LHC performance



"You see, most blokes will be playing at 10. You're on 10, all the way up, all the way up...Where can you go from there? Nowhere. What we do, is if we need that extra push over the cliff...eleven. One louder."

Ultimate lumi (not yet studied in details)

- *L = 5 → 7.5 10^{34} $cm^{-2}s^{-1}$*
- *Int. L = 3000 → 4000 fb^{-1}*
- *Pile up $\mu \sim 200$ (was 140)*

Luminosity: the main ingredients

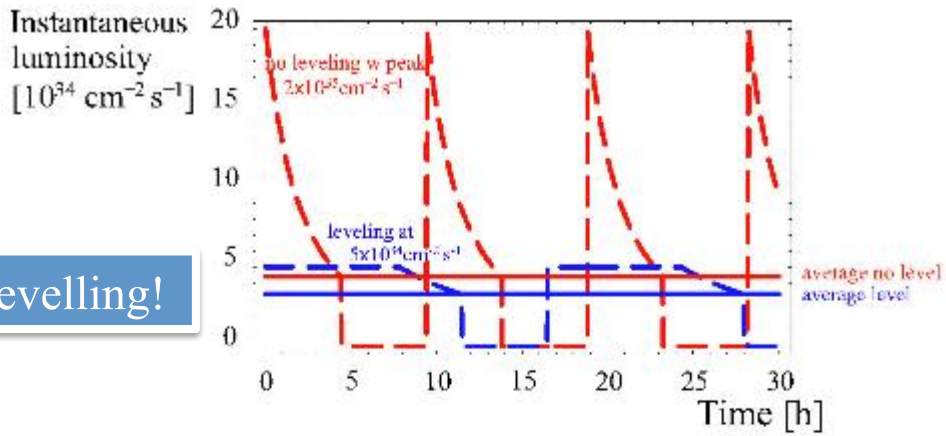
$$\dot{N}_{evt} = L \times \sigma_{evt} ; N_{evt} = \int L dt \times \sigma_{evt} \qquad L_{int}$$

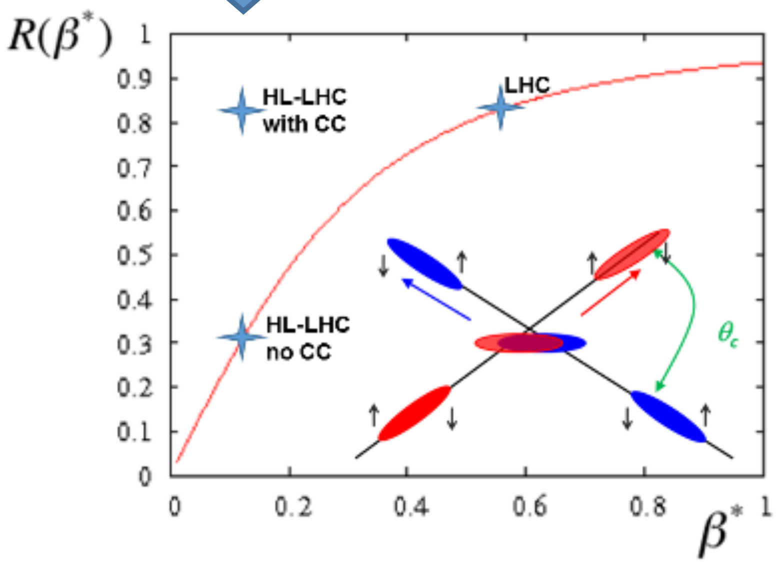
Beam current

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^2}{4\pi \varepsilon_n \beta^*} R \qquad R = \frac{1}{\sqrt{1 + (\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma)^2}}$$

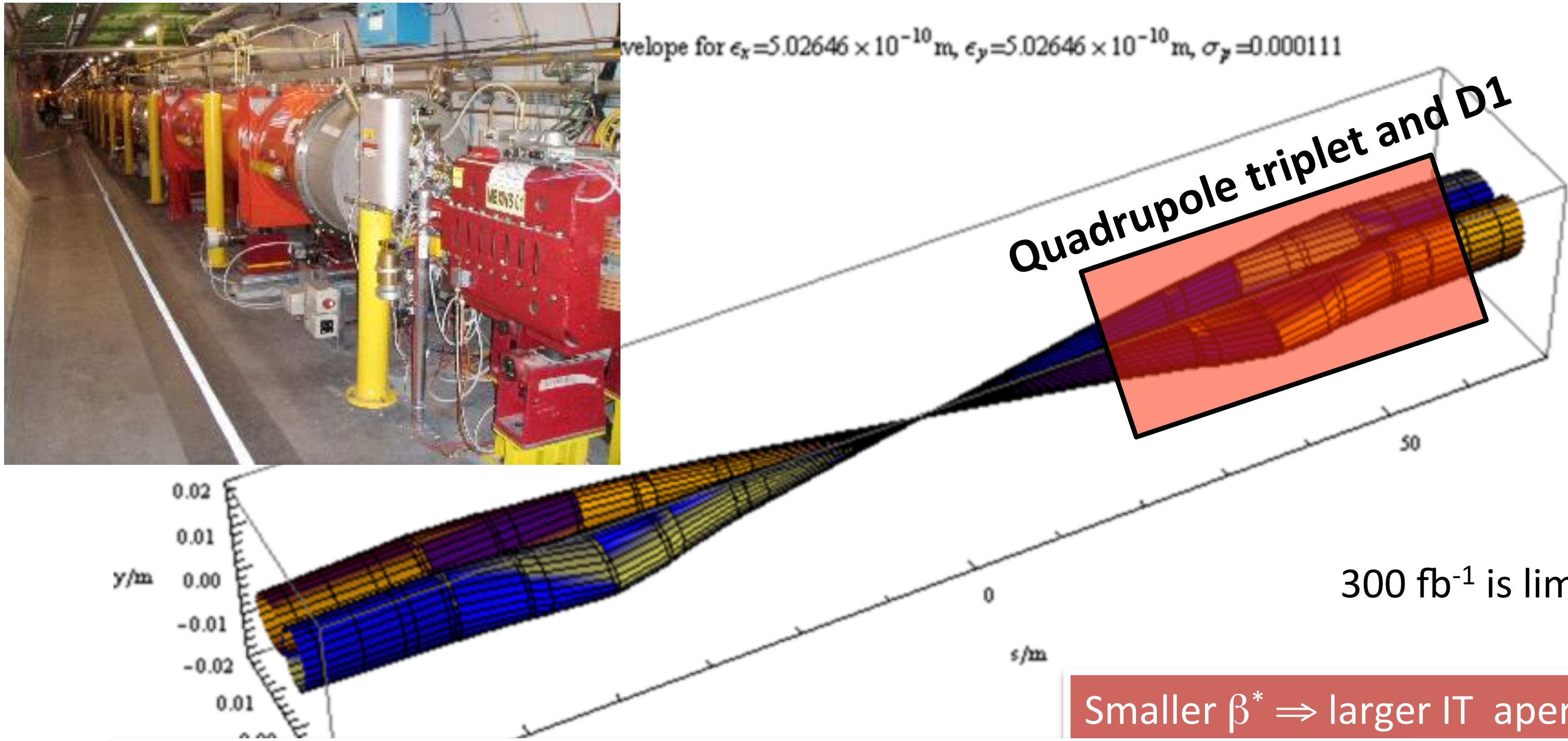
Beam size

Levelling!





The core: change of the inner triplet, triggered by rad-dam with leap in performance

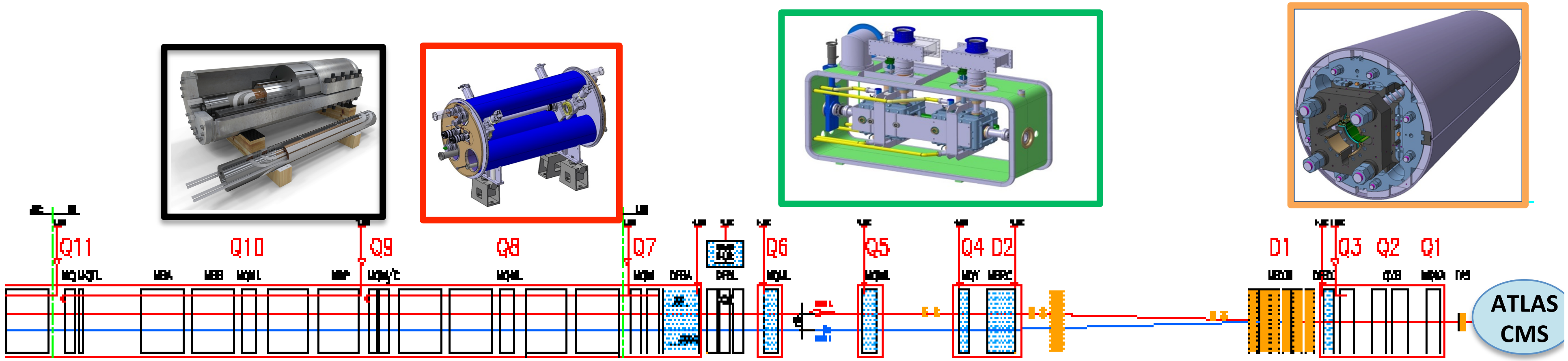


300 fb^{-1} is limit

Smaller β^* ⟹ larger IT aperture

LHC has better aperture than anticipated: now all margin is used; however seems very difficult to have β^* < 35-40 cm (55 cm being the nominal)

HiLumi: largest HEP accelerator in construction



Dispersion Suppressor (DS)	Matching Section (MS)	Interaction Region (ITR)

Dispersion Suppressor (DS)

Modifications

1. In IP2: new DS collimation.
2. In IP7 new DS collimation with 11 T

+ Cryogenics, Protection, SC Links, Interface, Vacuum, Diagnostics, Inj/Extr, new infrastruct.

Matching Section (MS)

Complete change and new layout in IP1-IP5

1. TAN
2. D2
3. CC
4. Q4
5. All correctors
6. Q5
7. New MQ in Pt6
8. New collimators

Interaction Region (ITR)

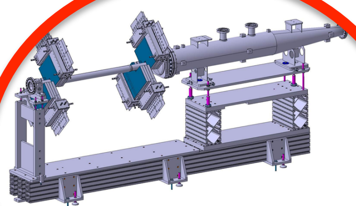
Complete change and new lay-out in IP1-IP5

1. TAS
2. Q1-Q2-Q3
3. D1
4. All correctors
5. Shielding

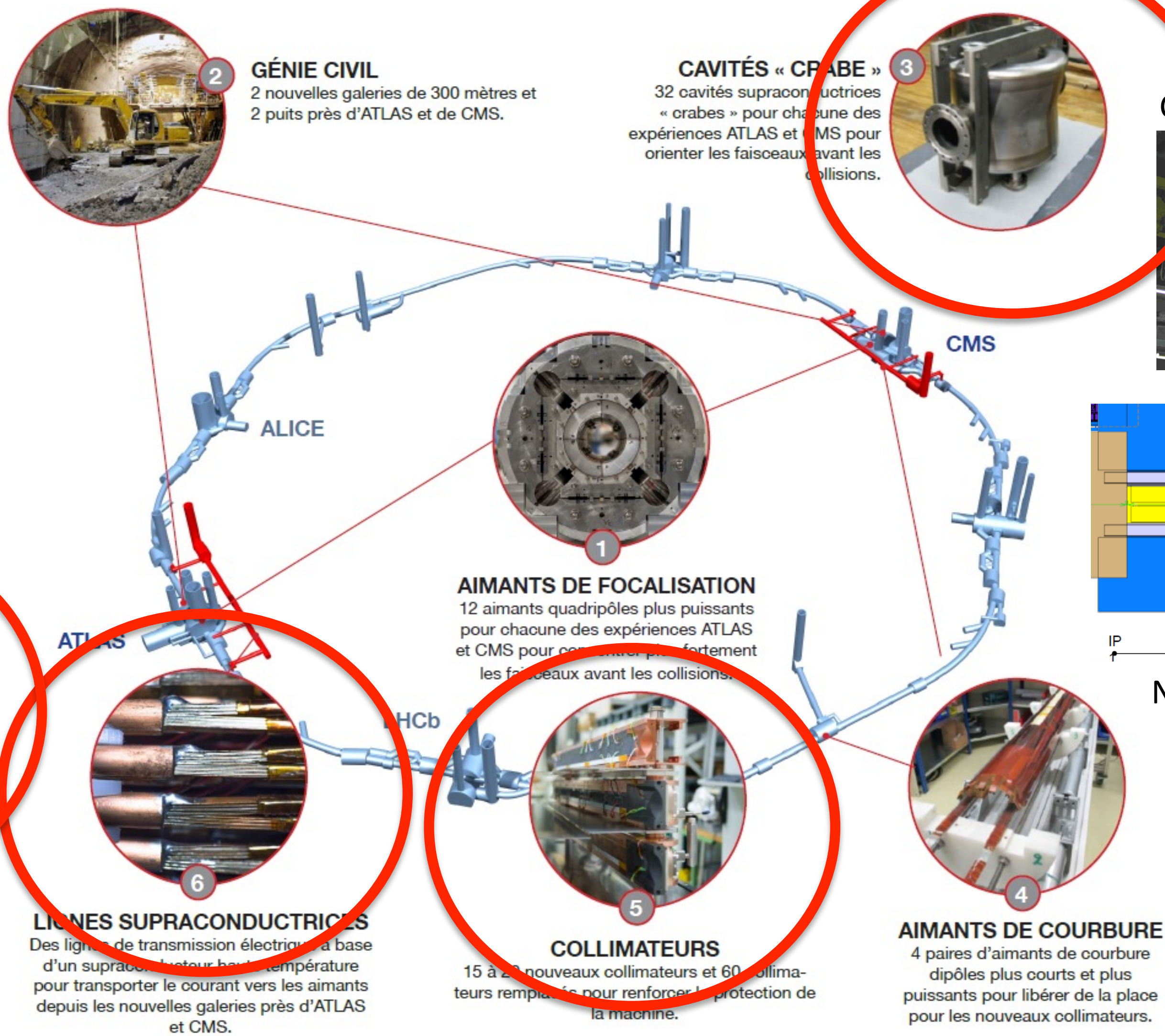
> 1.2 km of LHC !!

But work all around the ring!

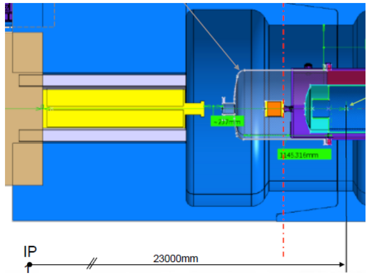
Cryo@P4



Beam diagnostics
BGV



Cryo@P1-P5



New TAS

Beam parameters in collision

Parameter	Nominal	25ns HL-LHC
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.09
Crossing angle [μrad]	285	590
Beam separation [σ]	9.9	12.5
Minimum β^* [m]	0.55	0.15
Normalized emittance ε_n [μm]	3.75	2.5
Virtual Luminosity [10^{34} cm^{-2}s^{-1}]	1.2	18.9
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.30
Levelled Pile-up/Pile-up density [evt. / evt./mm]	27/0.2	140/1.2
Integrated luminosity [fb^{-1}/year]	45	260

The UK in HiLumi-LHC (FP7, 2011-2015)

High Luminosity LHC Project

UK leadership

UK involvement

WP
Coordinator
Co-coordinator

PROJECT COORDINATION OFFICE

Project Coordinator: Lucio Rossi, CERN
Deputy Project Coordinator: Oliver Brüning, CERN
Technical Coordinator: Isabel Bejar Alonso, CERN
Project Safety Officer: Thomas Otto, CERN
Budget & Resource Management: Dorothée Duret, CERN
FP7 HiLumi LHC Administrative Manager: Svetlomir Stavrev, CERN
Dissemination & Outreach: Agnes Szeberenyi, CERN
Administrative Support: Cécile Noels & Julia Double, CERN

FP7 HiLumi Design Study

WP1 Project Management
Lucio Rossi, CERN
Oliver Brüning, CERN

WP2 Accelerator Physics
Gianluigi Arduini, CERN
Andy Wolski, UNILIV

WP3 Magnets
Ezio Todesco, CERN
GianLuca Sabbi, LBNL

WP4 CC and RF
Erk Jensen, CERN
Graeme Burt, ULANC

WP5 Collimation
Stefano Redaelli, CERN
Robert Appleby, UNIMAN

WP6 Cold Powering
Amalia Ballarino, CERN
Francesco Broggi, INFN

WP7 Machine Protection
Daniel Wollmann, CERN
Jorg Wenninger, CERN

WP8 LHC-Exp. Interface
H. Burkhardt, I. Efthymiopoulos, (
A. Ball (CMS), B. Di Girolamo, (ATLAS

WP9 Cryogenics
Serge Claudet, CERN
Rob Van Weelderen, CERN

WP10 Energy depo.
Francesco Cerutti, CERN
Nikolai Mokhov, FNAL

WP11 11T Dipole
Mikko Karppinen, CERN
Alexander Zlobin, FNAL

WP12 Vacuum
Roberto Kersevan, CERN
Mark-Antony Gallilee, CERN

WP13 Beam Diagnostics
Rhodri Jones, CERN
Hermann Schmickler, CERN

WP14 Beam Transfer
Jan Uythoven, CERN
Brennan Goddard, CERN

WP15 Integration
Sylvain Weisz, CERN
Paolo Fessia, CERN

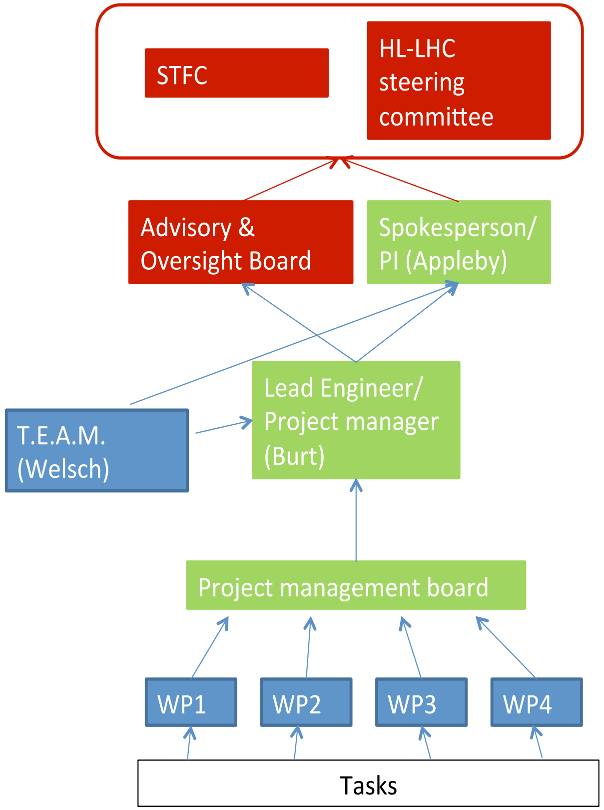
WP16 Hardware Commissioning
Mirko Pojer, CERN

WP18 High Field Magnets
Gijs de Rijk, CERN
François Kircher, CEA

R&D and Study

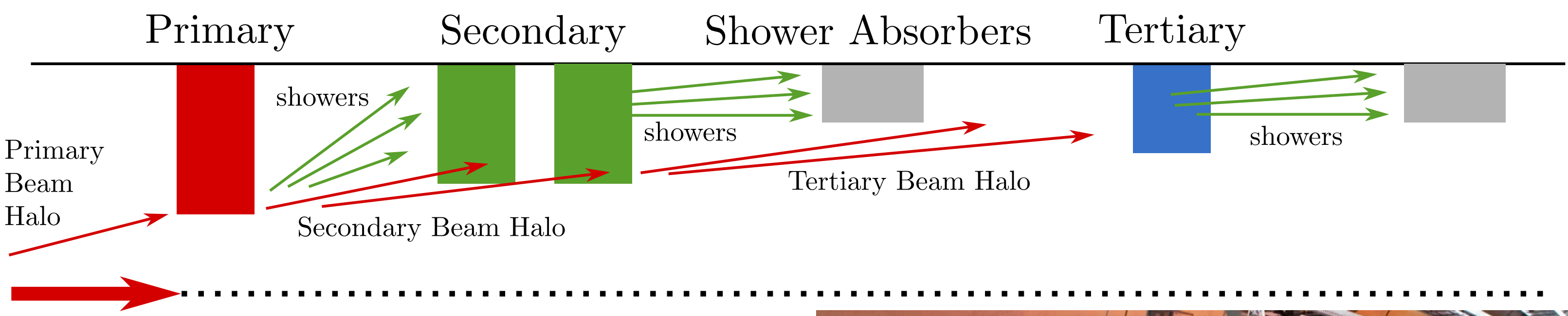
HL-LHC-UK

- ***HiLumi*-LHC** design study FP7 2011-2015 : UK success and leadership.
- The UK hosted the ***HL-LHC*** kick-off meeting at Cockcroft Institute in November 2013.
- Discussions with STFC for UK project followed, with early SoI for LHC-UK
- SoI (final one) submitted early 2015
- Proposal submitted in March 2016
- CERN finance approved October 2015
- STFC finance approved March 2016
- 7 UK institutes as members
  - £8M of UK and CERN funding over 4 years, with institute and university money combining with STFC
  - A reflection of efficient use of resources to leverage, and UK reputation
- Main UK activities:
  - *WP1 : Collimation*
  - *WP2 : Crab cavities*
  - *WP3 : Diagnostics*
  - *WP4 : Cold powering*



Challenge 1 : Collimation

Beam collimation has been considered one of the most critical aspects for the LHC
- Cleaning challenge vs quench (fundamental for this target luminosity)
- Small gaps challenge, <u>impedance</u>



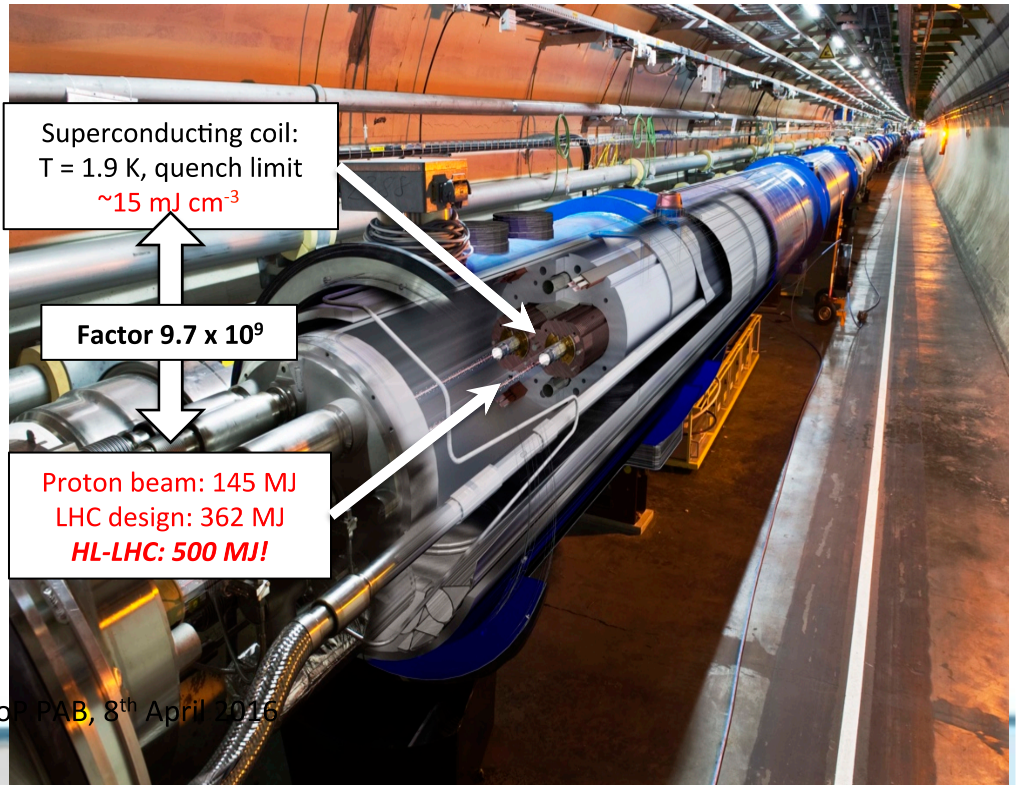
> 500 MJ of stored energy per beam

➔ requires collimation during all operation stages!

➔ requires careful design/study and exploitation of the run 2 beam

➔ requires novel collimation solutions

➔ HL-LHC luminosity implies higher leakage from IP & requires additional collimators and collimator diagnostics

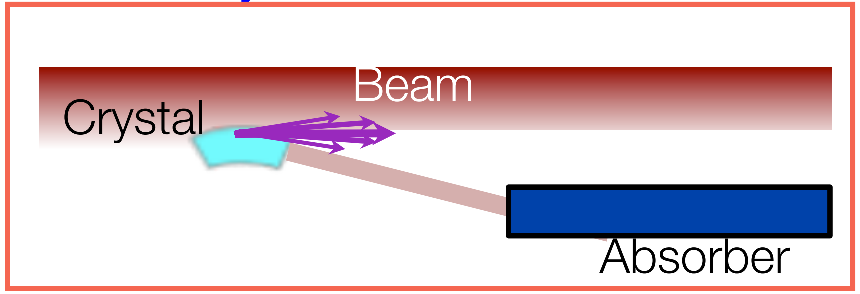


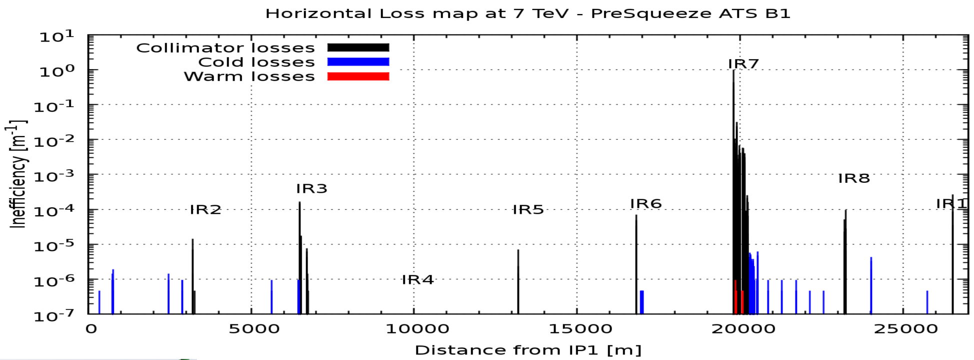
Collimation simulations and hardware

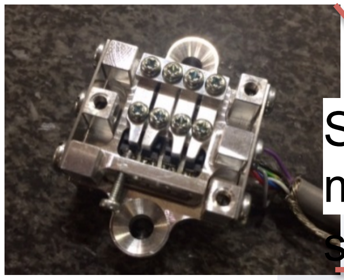
Key WP goals to

- Deliver metrology enabled active collimator
  - Improve and maintain jaw straightness
- Develop novel collimation schemes and tools
  - *SixTrack / FLUKA* developed by CERN
  - *MERLIN/FLUKA* – developed by Manchester / Huddersfield
  - *BDSIM* – developed by RHUL
- Increase our understanding of fundamental scattering

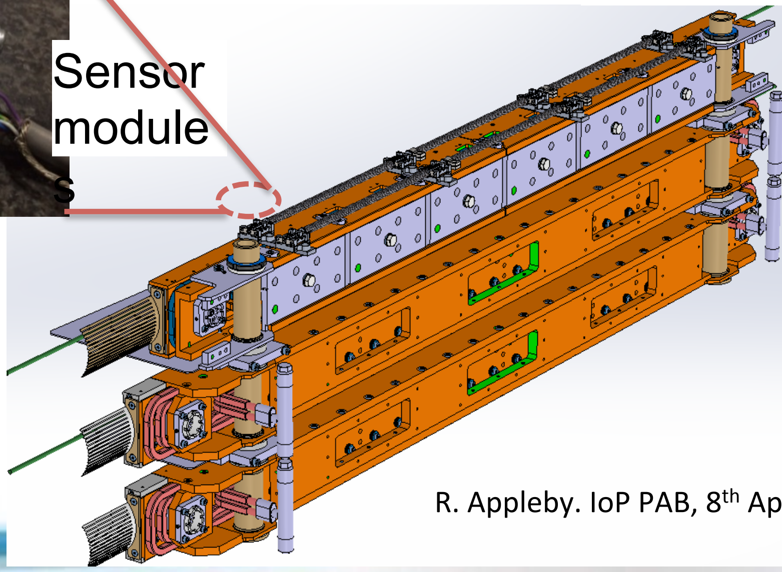
Crystal-based collimation



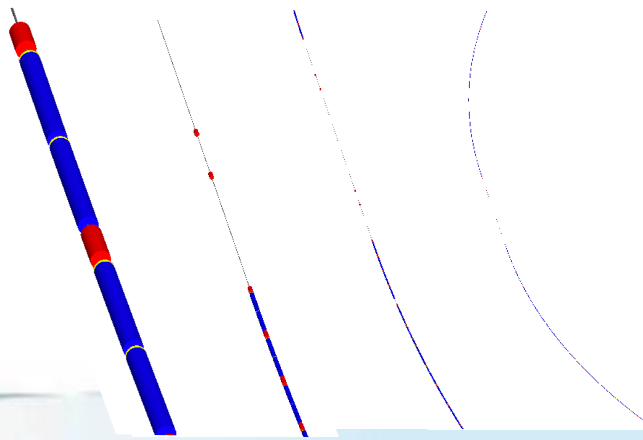




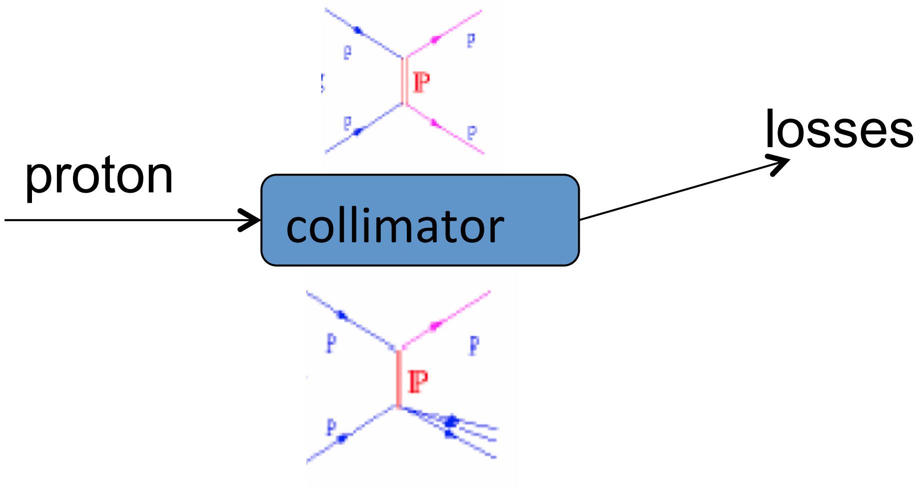
Sensor module s

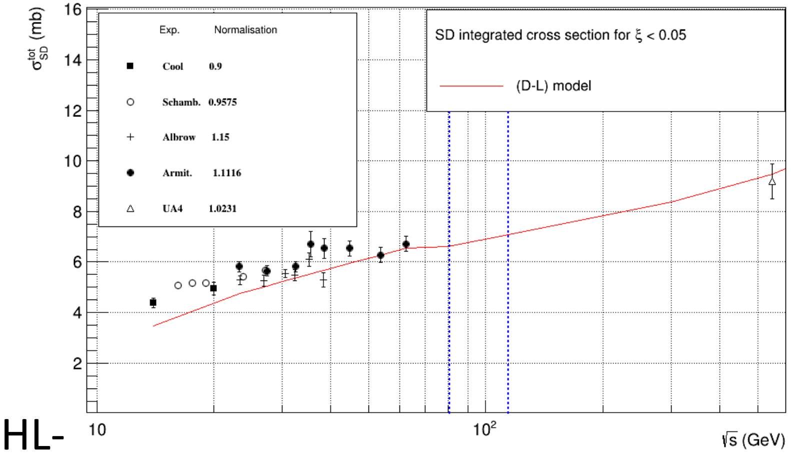


HiRadMat Beams



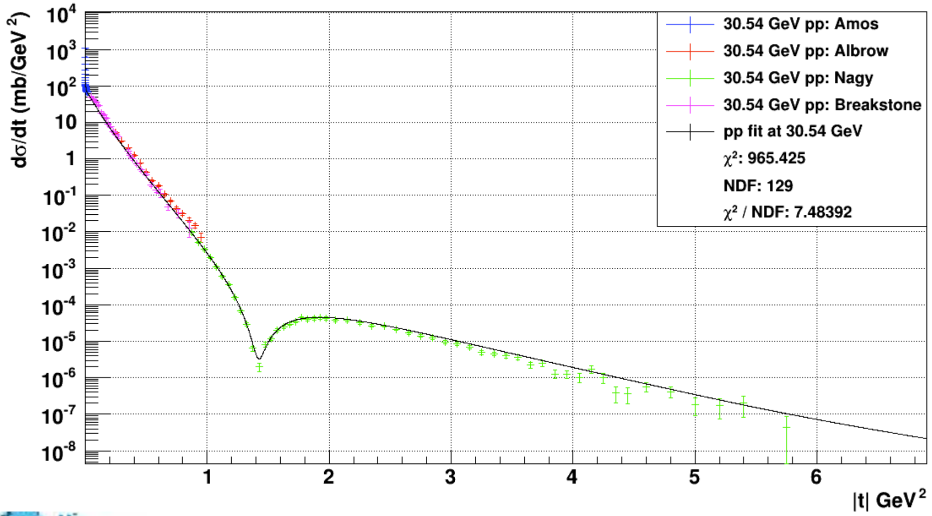
Advanced scattering theory



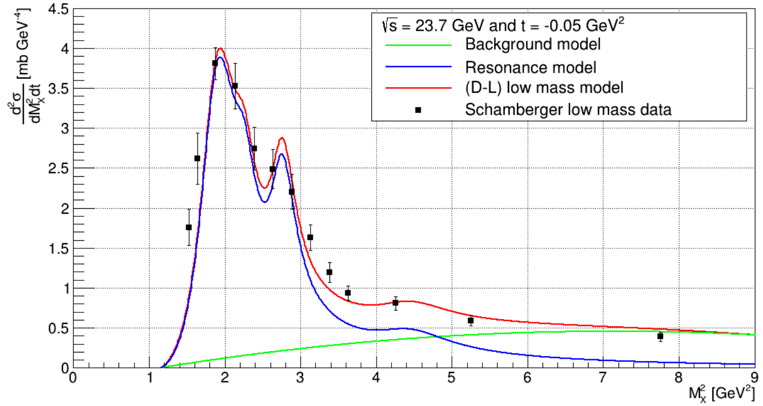


Now being used to predict loss patterns in HL-LHC, FCC-hh and being incorporated into Pythia

elastic



diffractive



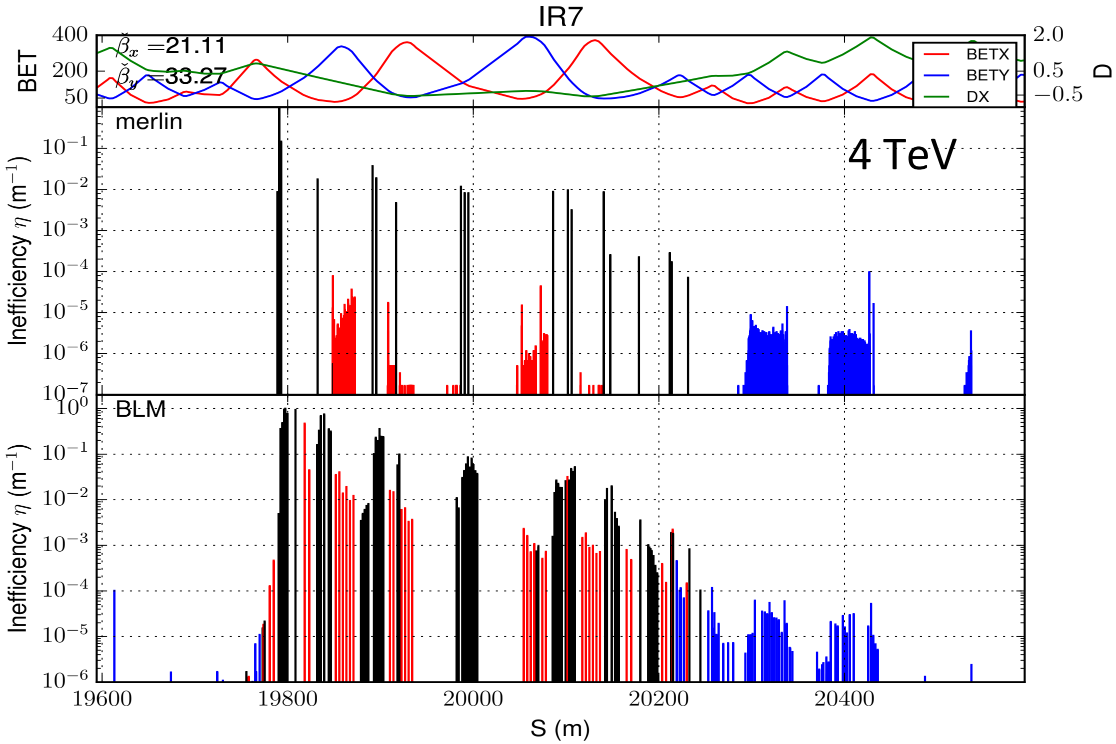
Collimation simulations : MERLIN

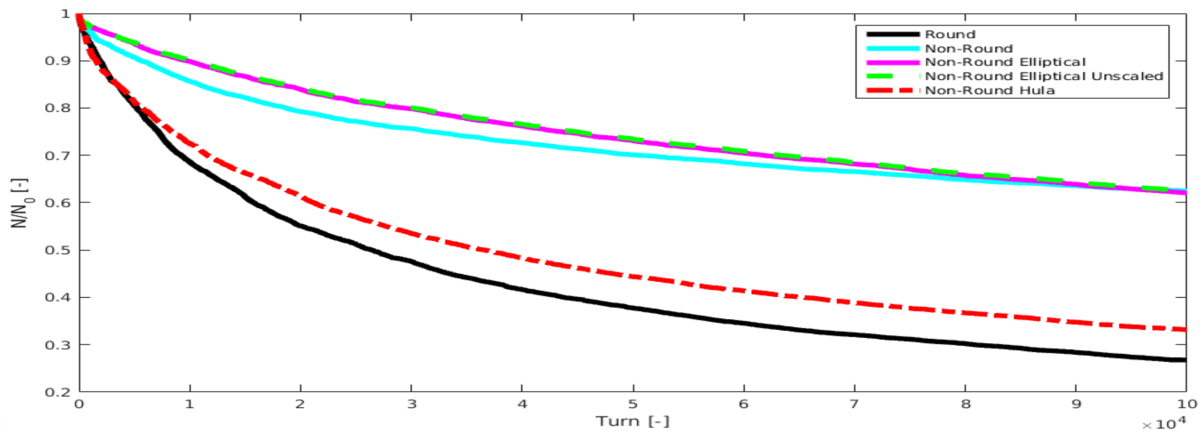
-> Now established alongside Sixtrack (CERN) for loss map production and collimation layout study (top-right).

-> Loss maps with new scattering physics now at 4 TeV and 6.5 TeV, with good prediction of BLM loss patterns.

-> Used for forward showers from TCLs

-> Now applied to transverse halo diffusion using hollow electron lenses (bottom-right)





Collimation simulations : BDSIM

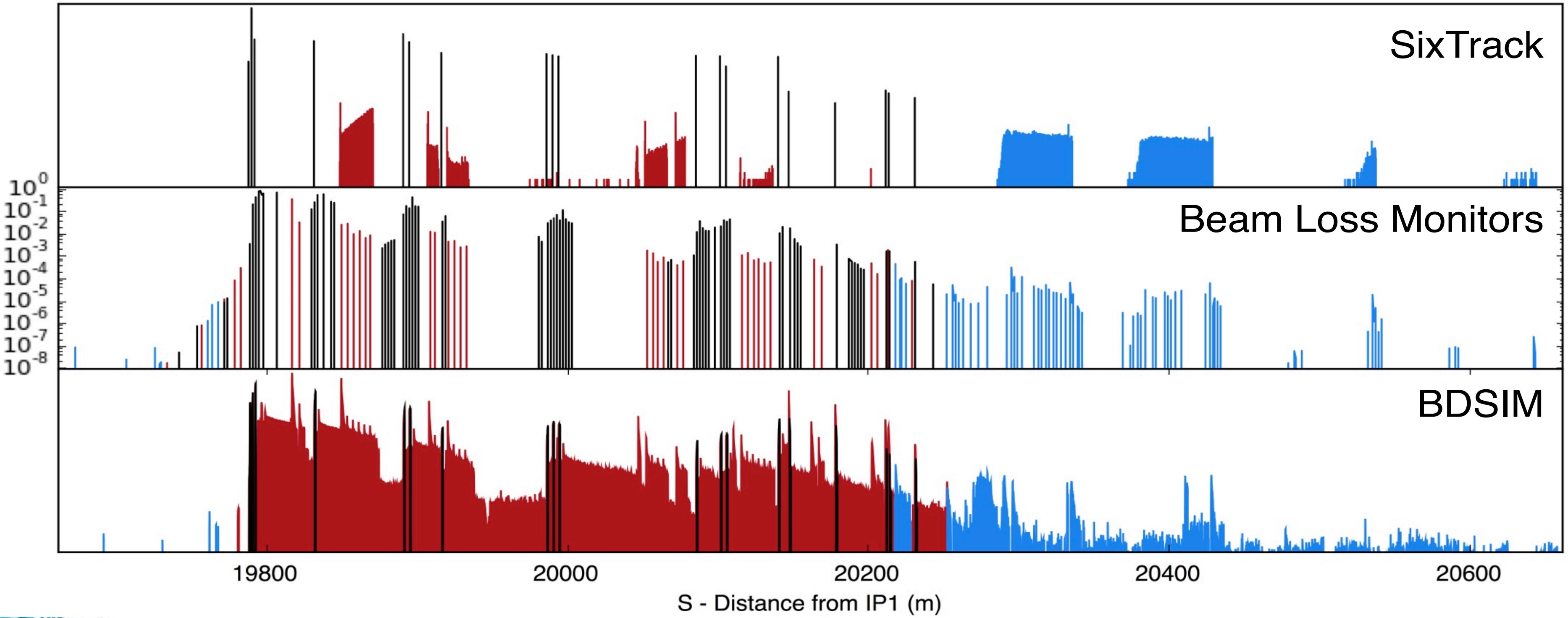
SixTrack / BDSIM

BDSIM -> Fast vacuum tracking with Geant4 for interactions with machine. Full energy loss from showers and secondaries tracked throughout the accelerator.

Though development of BDSIM is outside HL-LHC-UK scope, the plan is to use tool for loss-map and experimental background studies.

Comparison with BLM data in IR7 region:

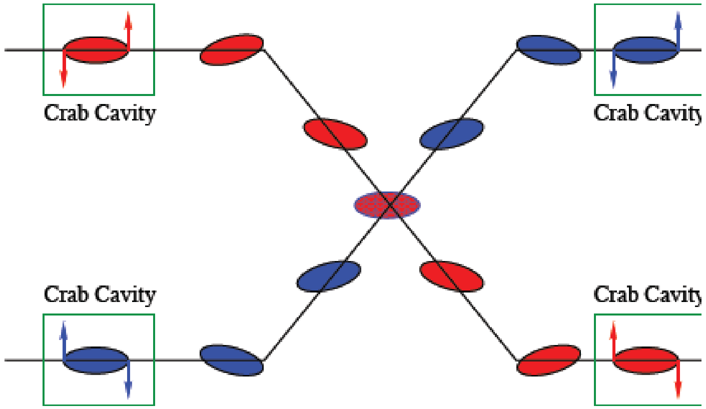
Data from R. Bruce et al, Phys. Rev. ST Accel. Beams 17, 081004 (2014)



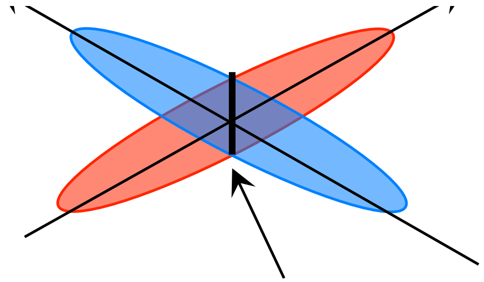
Challenge 2 : Crab Cavities

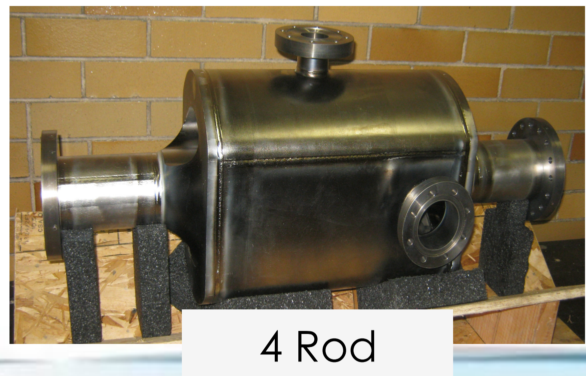
$F(\beta^*)$

- Crab cavities are proposed to provide bunch rotation to give a geometric overlap with the required crossing angle at HL-LHC
- Without crab cavities the beam would lose 50% of the luminosity and would have a greater pile-up density.
- They have not been tested on hadron beams.



- The SRF crab cavities need 3MV per cavity and 32 cavities are required.
- A proof of principle test is planned on the SPS beam at CERN before LS2. To understand cavity behaviour, beam dynamics, LLRF and machine protection issues.
  - UK will help test the SPS test cryomodule
- A pre-series cryomodule prototype will be designed and built to the LHC specification.

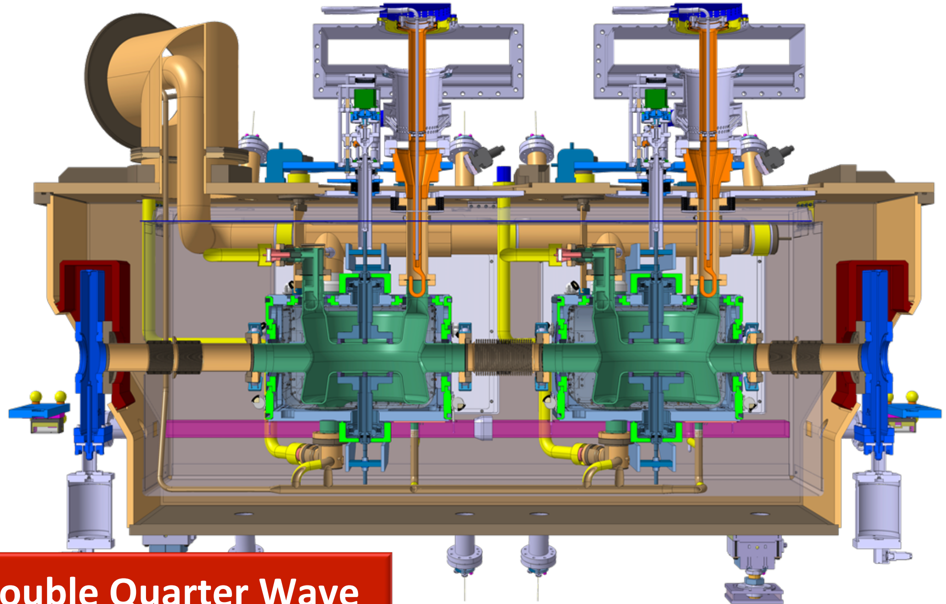




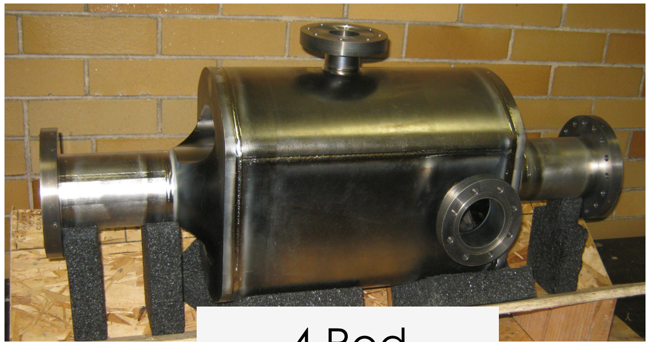
HL-LHC Crab Cryomodule and cavities

- Design of cryomodules well advanced
- Common effort between UK, CERN and US-LARP

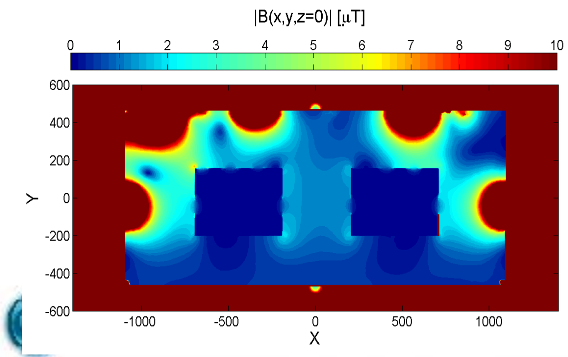
HL-LHC-UK is leading development of all magnetic and thermal shields plus the blade support structure.

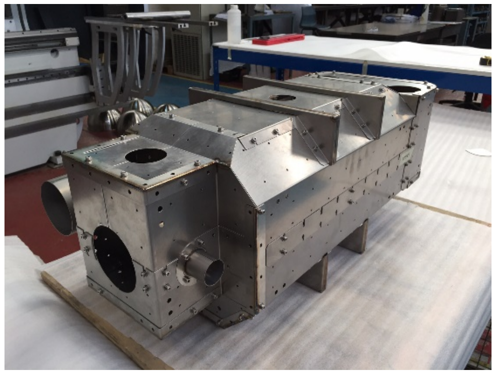


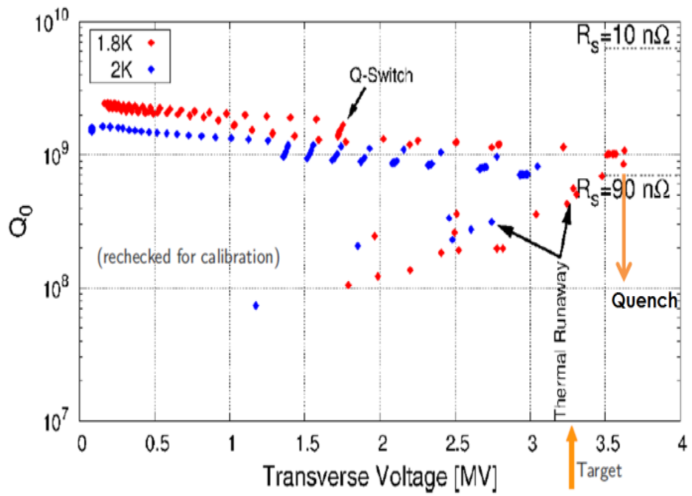
2 x double Quarter Wave



4 Rod







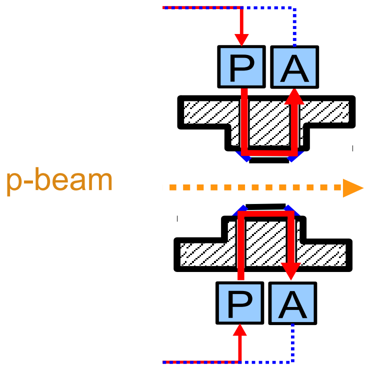
Cavity meets the goal of 3 MV/m without Q degradation

Challenge 3 : Diagnostics

Precise measurement of beam parameters is essential. The LHC is equipped with an extensive array of beam diagnostics that has played a major role in commissioning, rapid intensity ramp-up and safe and reliable operation of the accelerator. The HL-LHC presents new challenges:

Challenge 1:

- **Crab-cavities will rotate the bunches**
- ***A method to accurately measure the bunch rotation is required.***
- Conventional BPMs have insufficient bandwidth for single pass, intra-bunch measurements.
- *A new technology is needed:*



Electro-optic crystals as the BPM pickup

The electric field of the passing bunch induces a polarization change in the crystal that is readout with <50ps time resolution to derive the transverse position along the bunch. Measured with a polarised laser

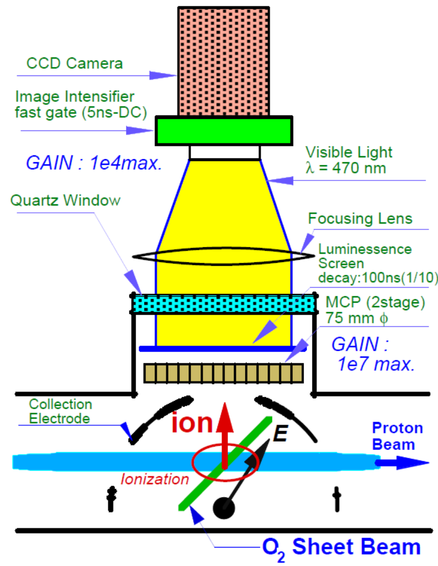
Challenge 2:

- **The unprecedented stored beam energy would damage conventional diagnostics and/or disrupt the particle beam.**
- *Non-invasive diagnostics are required to measure the beam profile and beam halo.*

Gas-jet based beam profile monitor

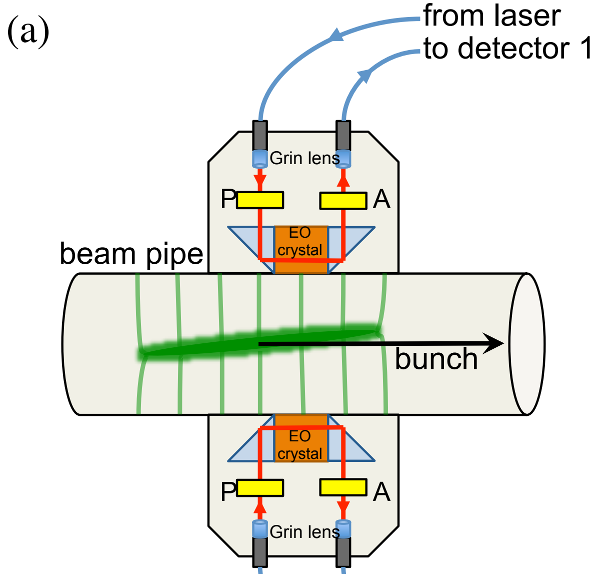
A supersonic jet of neutral gas is shaped into a thin sheet and injected with a 45° tilt across the particle beam.

Ions produced accelerate toward a phosphor screen, to monitor profile



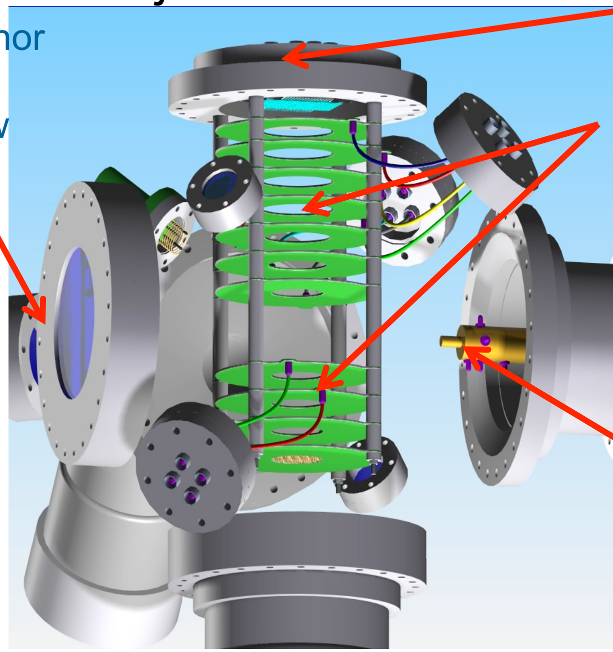
Diagnostics

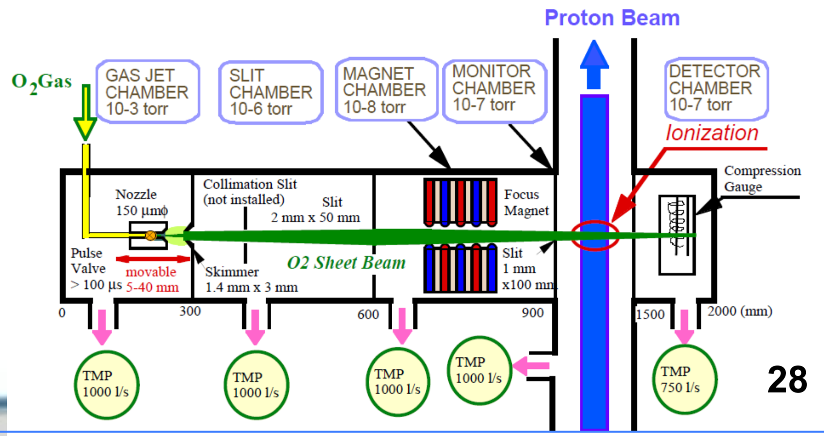
Task 1: Electro-Optic BPMs



Task 2: Gas-jet based beam monitor

Gas jet chamber at CI





Challenge 4 : Availability - SC links
$\Rightarrow$ removal of DFBs from tunnel to surface

Transport of unprecedented high-currents ($|I_{tot}|$ ~ 200 kA) via superconducting electrical transmission lines (SC-Links) consisting of HTS cables

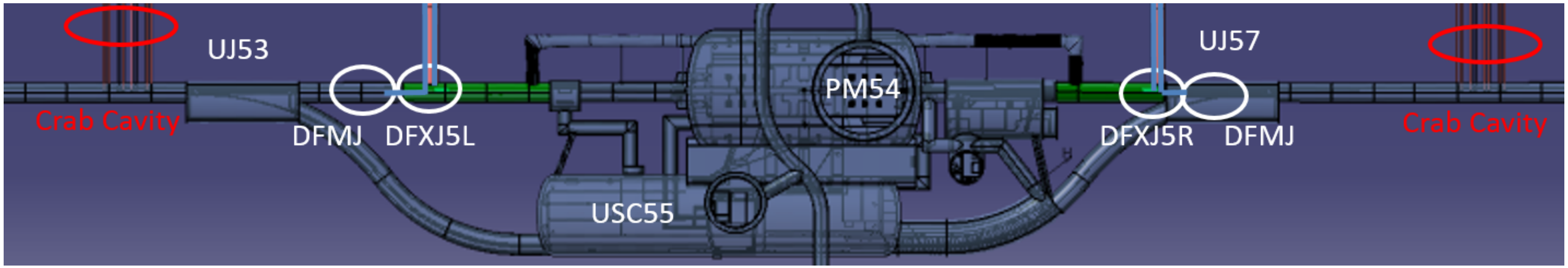
Developing a novel Cold Powering Systems relying on cooling with He gas (cheaper and much smaller heat transfer coefficient)

Required for powering the HL-LHC Triplets and the Matching Sections at P1/P5

- Four high power SC-Link (200kA-5 kV, total individual cables up to 20kA)
- Allows power converters to be located at surface or in the new underground cavern for Hi-Luminosity equipment

Long term and sustainable solution of R2E problems by remote powering

- Increasingly relevant to higher luminosity at higher energy
- Towards a full ALARA approach for radiation protection



Summary

- The HL-LHC-UK accelerator programme is focused, in order to create critical mass, on four key areas as part of the HL-LHC upgrade where the UK has existing expertise:
  - Development of the collimators
  - SCRF crab cavities
  - Diagnostics
  - Superconducting links for remote powering
- Each work package builds upon the design effort undertaken as part of the HiLumi-LHC project, and capitalises on UK strengths to develop the first prototypes for HL-LHC. So real hardware.

- CERN will provide considerable money – value for money for STFC

- The project will also allow leadership roles in HL-LHC, create collaborative links between the UK institutions, build a strong skill base and underpin the particle physics exploitation of the LHC.

- Our kick-off meeting is 21st April at CI – please come along if interested!

High Luminosity LHC: the (pre-)history

	Oct-98	US-DOE Institutes CDP (Nb_3Sn for accelerators and LHC up)
Jul-01	Dec-02	WG on LHC upgrades (F. Ruggiero)
	May-03	Start FP6-CARE-NED (Nb_3Sn) & HHH (study lumi upgrade)
Jun-03	Oct-04	LHC Upgrade goal defined - LARP proposal and LARP start
	Apr-05	Objective of long 90 mm Nb_3Sn Quad by 2009 fixed by LARP
Mar-05	Dec-06	LHC upgrade studies (FP6-CARE-HHH)
Jul-06	Oct-06	EU HEP strategy Lisbon and then Aymar White Paper approved
	Apr-07	Upgrade LHC Phase I - High Field Magnets (for Phase II)
	May-08	Start EuCARD (with HFM Fresca2 as WP7)
	Apr-09	Technology decision in LARP (bladder and keys) for Quads
	Sep-09	LQ01 (90mm, 3.6 m long) fulfill the LARP goal (200T/m @ 1.9 K)
	Jan-10	**Chamonix workshop: new strategy to maximize LHC output**
	Jun-10	**High Luminosity LHC: one project to coordinate all upgrades**
	Jul-10	Mandate to L. Rossi by D.A.T. to set up FP7-Design Study

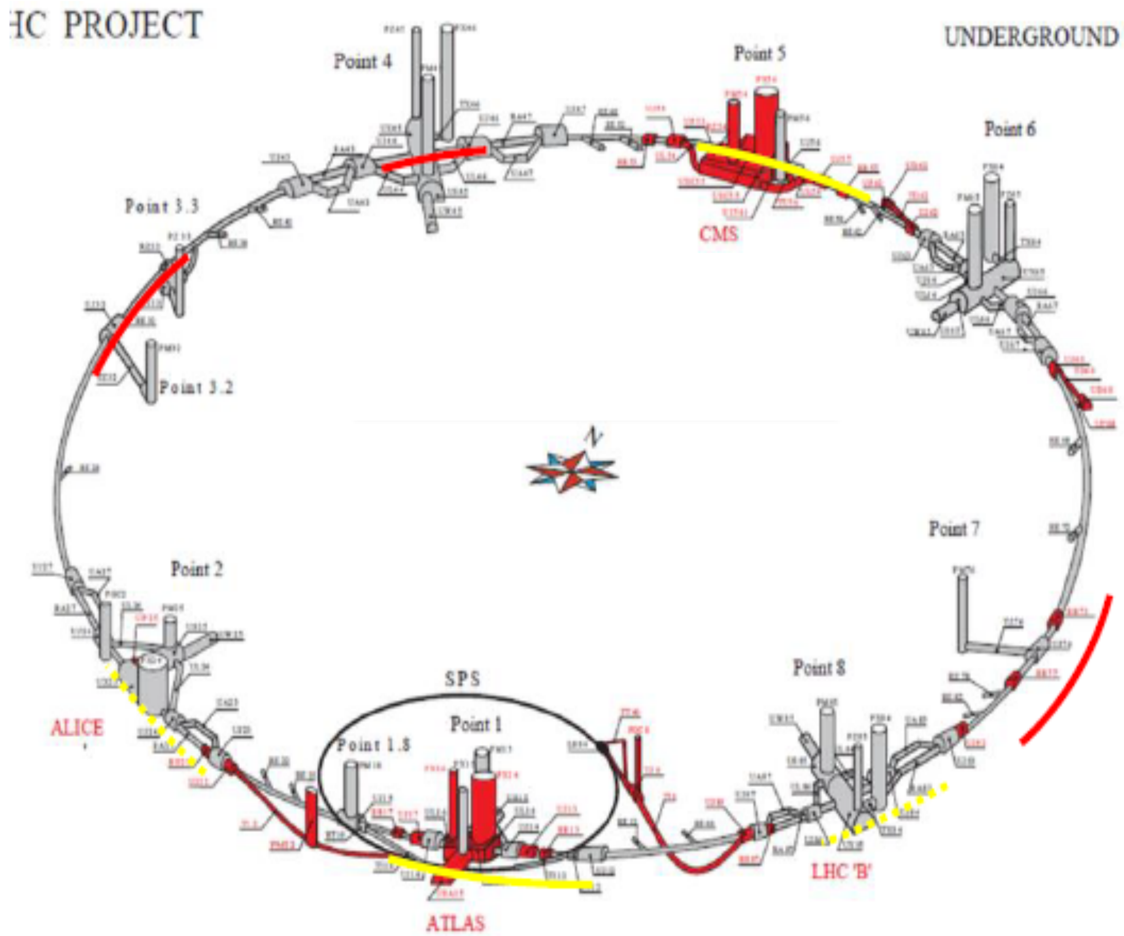
HiLumi LHC: project Milestones - 1

Jul-10	Mandate to L. Rossi by D.A.T. to set up FP7-Design Study
Nov-10	Application FP7-HiLumi LHC Design Study
Dec-10	Institution of the HL-LHC as a (design study) project by D.A.T.
Mar-11	**Approval FP7-HiLumi LHC Design Study**
Apr-11	CERN internal kick-off meeting of HiLumi
Nov-11	Start of FP7 DS and 1st General Meetign @ CERN
Jul-12	Document CERN-ATS-2012-236 describing HL-LHC for EU strategy
Jul-12	Decision MQXF (IT quad) aperture 150 mm
Nov-12	2nd General Meeting @ Frascati
May-13	**HL-LHC 1st Priority in EU strategy update(Council @ Brussels)**
May-13	International Review on Collimation
Jun-13	Partial insertion of HL-LHC budget in the MTP
Oct-13	RLIUP (Review of LHC and Inj Upgrade Plans by CMAC)
Oct-13	First HL-LHC detector ECFA workshop
Nov-13	**HL-LHC Project kick-off and 3rd General meeting @ Daresbury**

HiLumi LHC: project Milestones - 2

May-14	International Review on CC @BNL (w/LARP)
Jun-14	MTP CERN insert 90% HL-LHC budget
Oct-14	International Review on MQXF Nb_3Sn Conductor @ CERN (w/ LARP)
Nov-14	4th General Meeting @ KEK
Nov-14	Preliminary Design Report (PDR)
Dec-14	International Reviews on MQXF (w/LARP) and MBH design @ CERN
Mar-15	**Cost & Schedule Review @ CERN by CMAC (endorsing budget&time)**
Jun-15	Decision for C.E. "Underground" option Þ new schedule (Vibrations)
Sep-15	**MTP CERN incorporate revised HL-LHC in its budget (full CtC)**
Oct-15	5th General Meeting marking end FP7-HiLumi LHC DS – TDR_v0

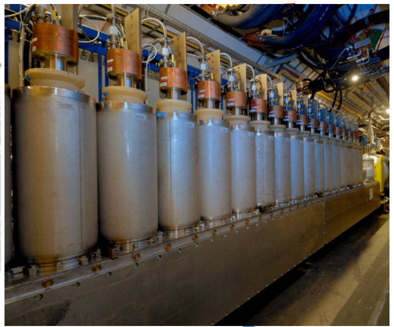
How to make this jump?

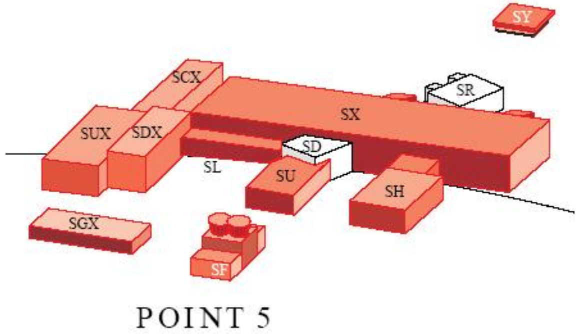


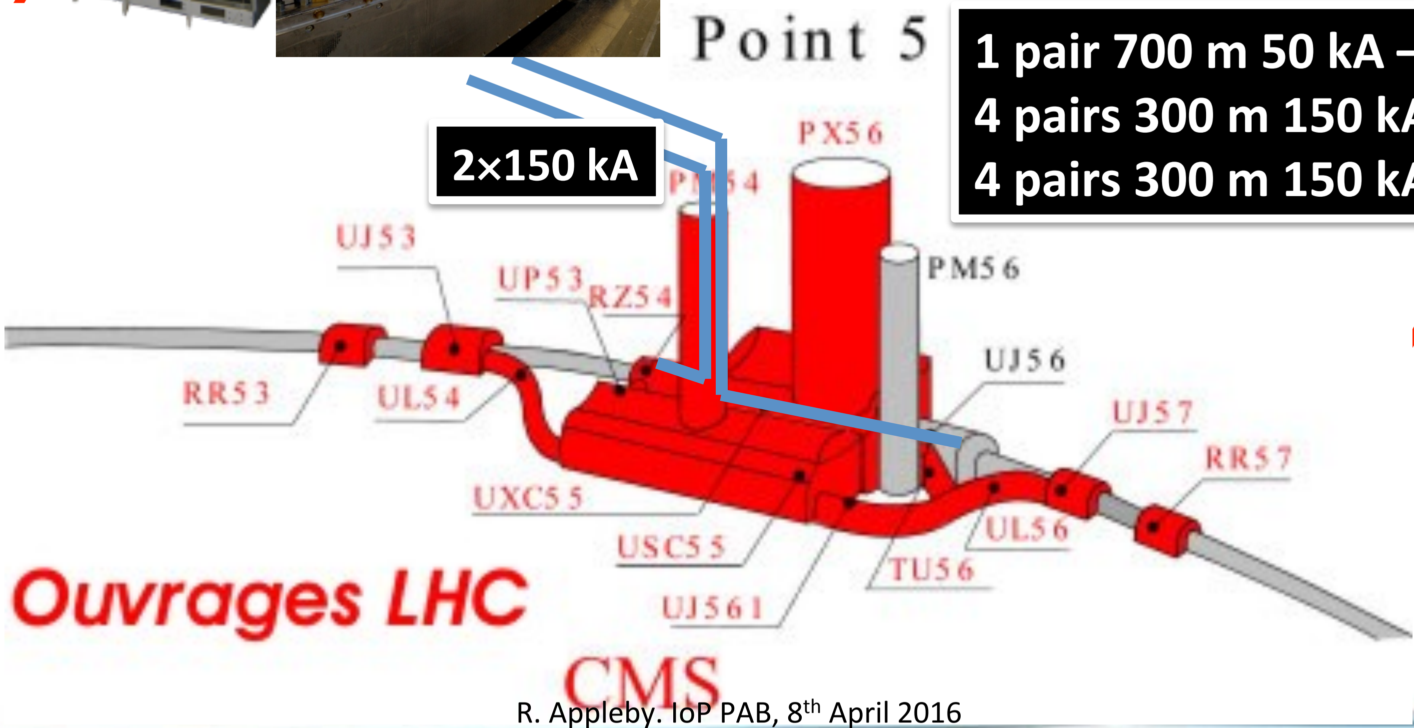
- Obtain about 3 - 4fb^{-1}/day (40% stable beams)
- ~250 to 300 fb^{-1} per year.

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- **Collimation upgrade**
- **Cryogenics upgrade**
- **Crab Cavities**
- Cold powering
- Machine protection
- **Enhanced diagnostics**

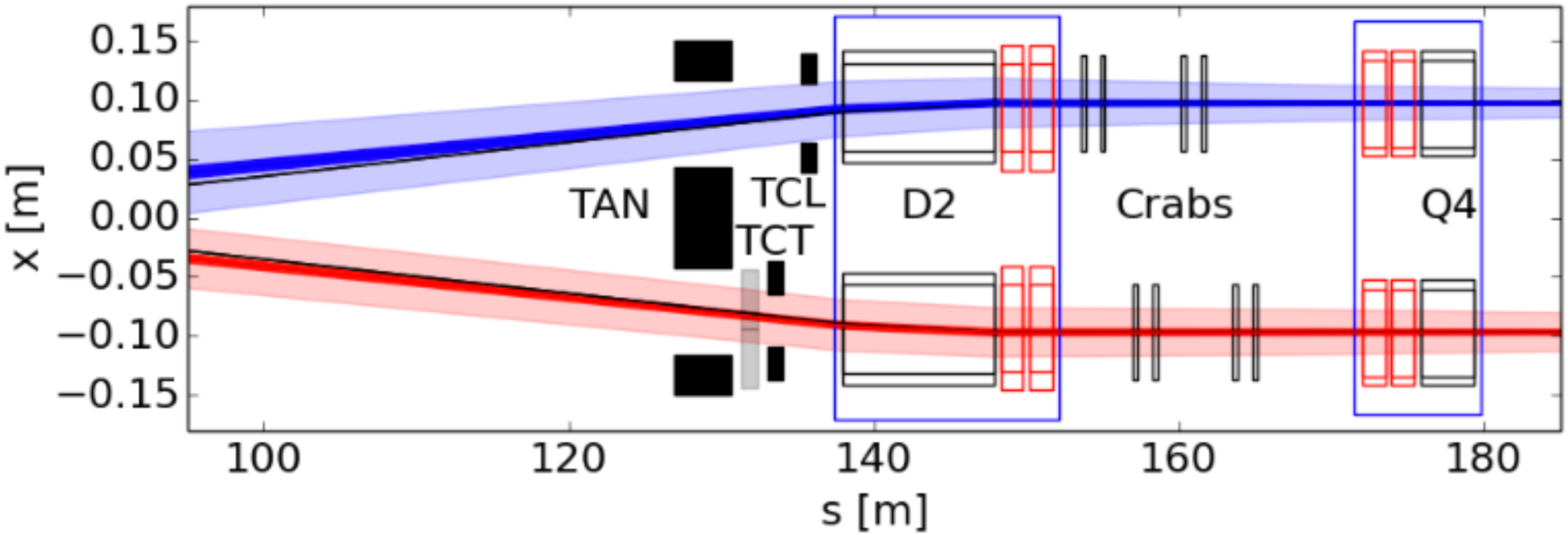
Challenge 4 : Availability - SC links
⇒ removal of DFBs from tunnel to surface

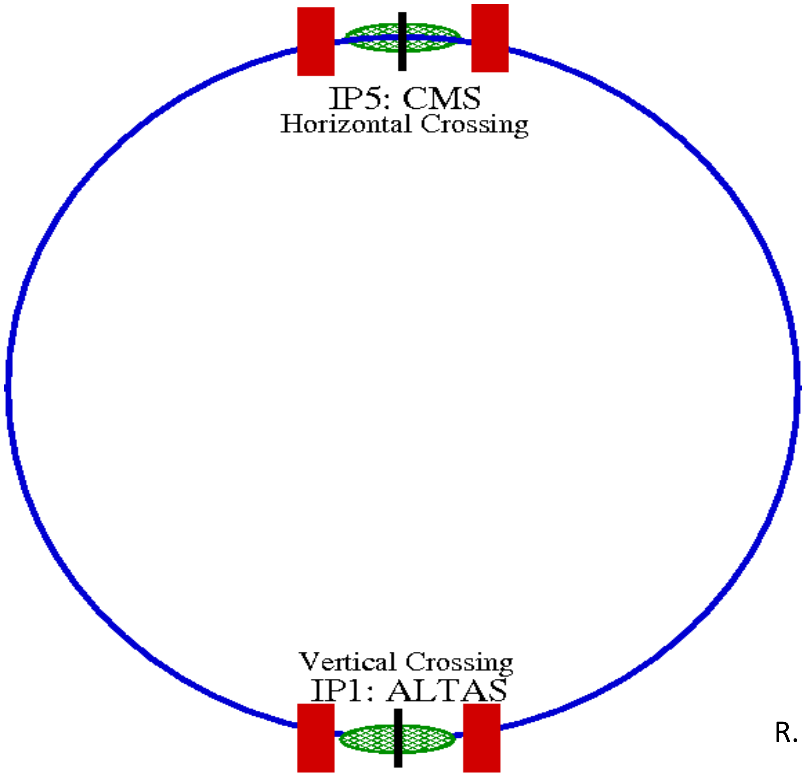


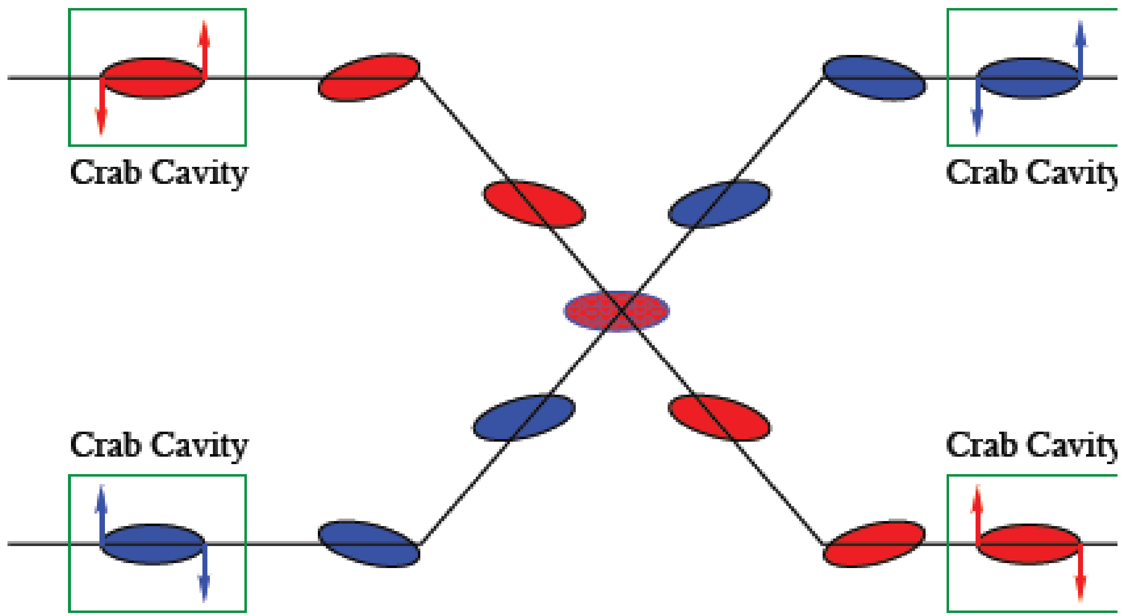




1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS)– LS3
4 pairs 300 m 150 kA (IR) – LS3







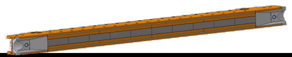
R. Appleby. IoP PAB, 8th April 2016

IR1+IR5, per beam:

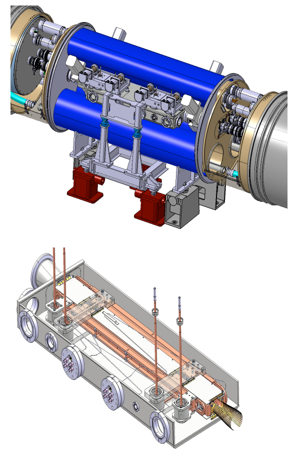
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

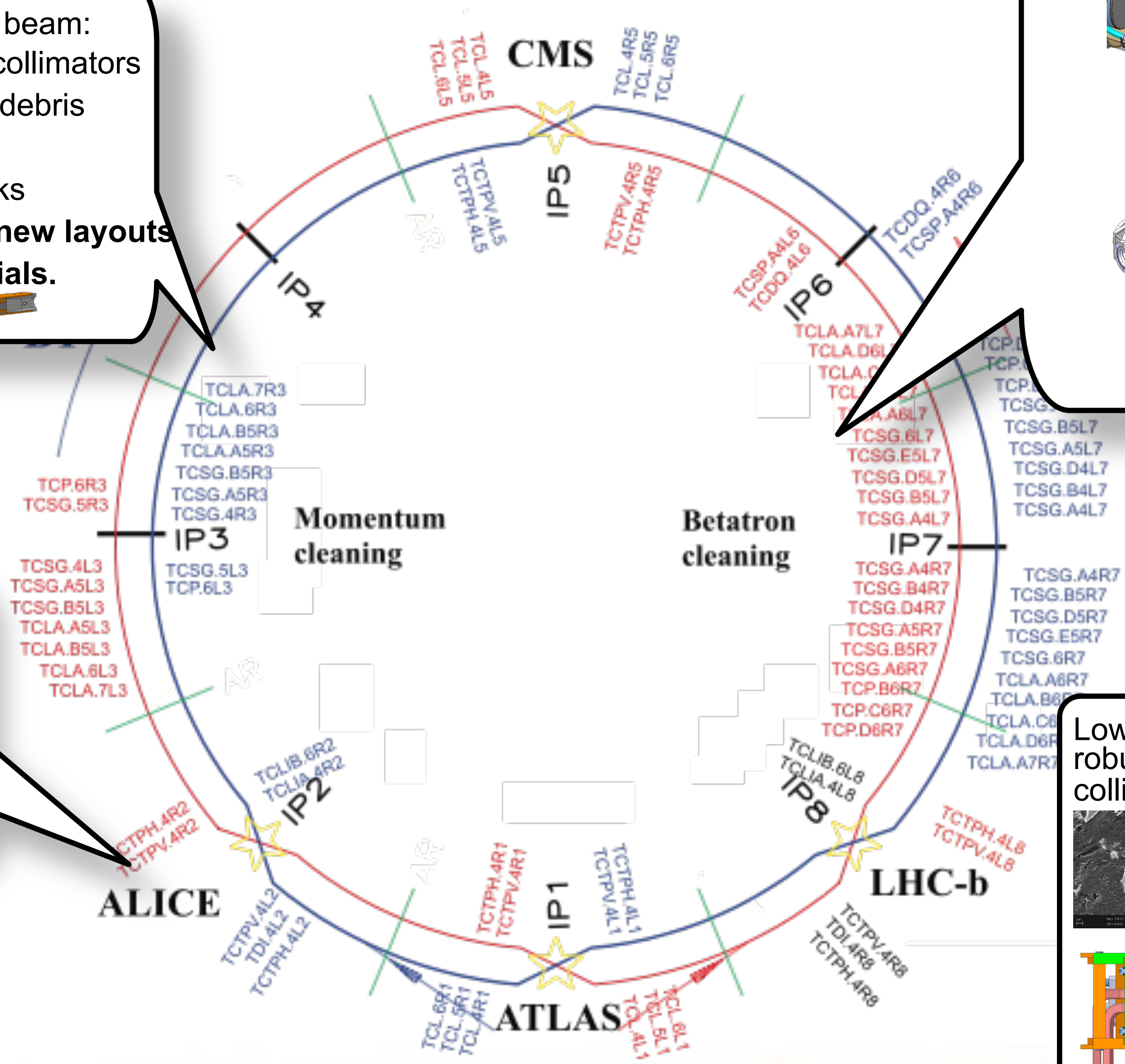
Completely new layouts

Novel materials.

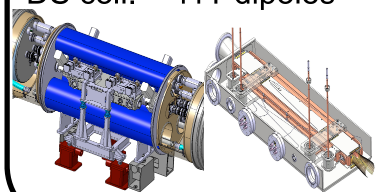


Cleaning: DS coll. + 11T dipoles, 2 units per beam





Ion physics debris:
DS coll. + 11T dipoles



Low-impedance, high robustness secondary collimators