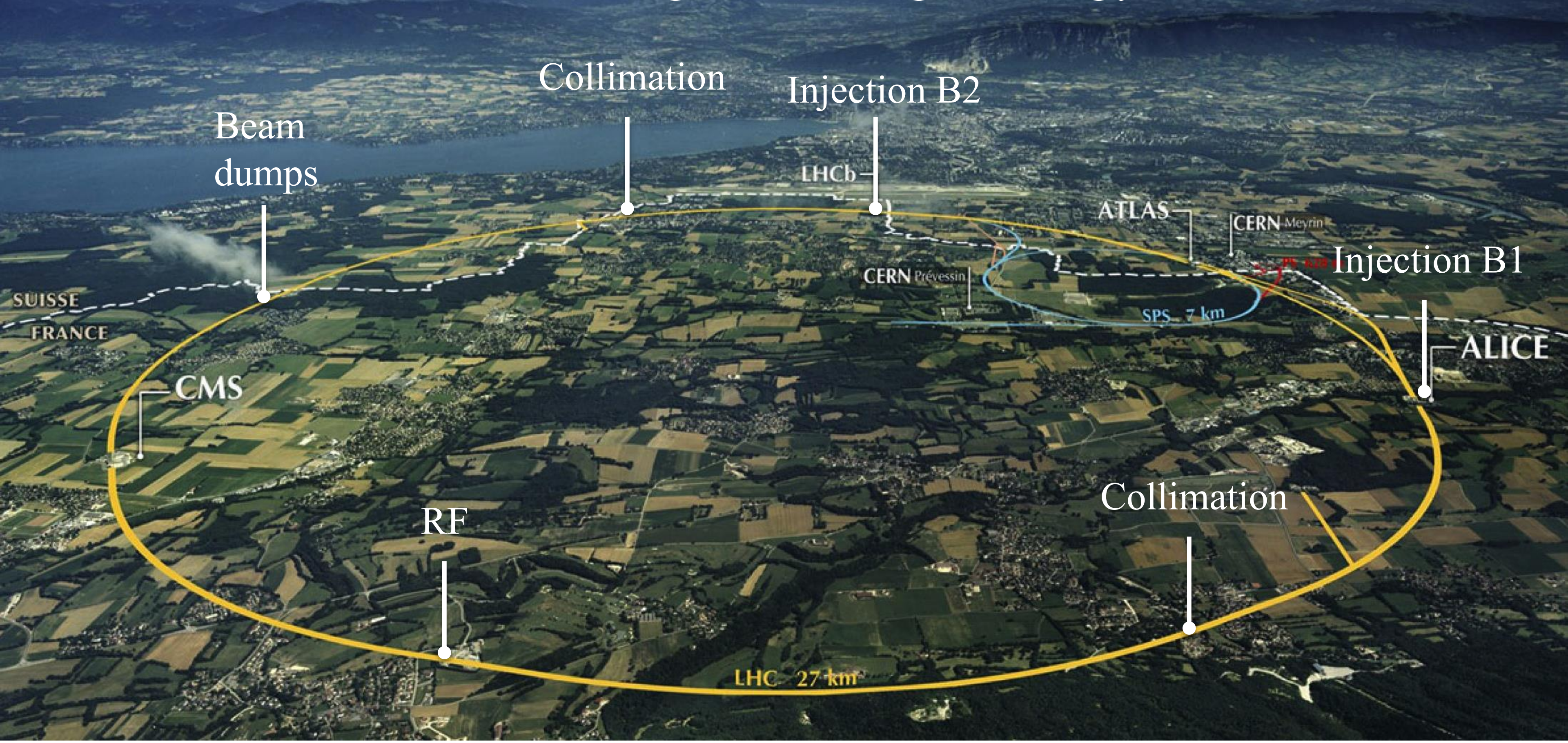
Overview

Summer student lectures 2016

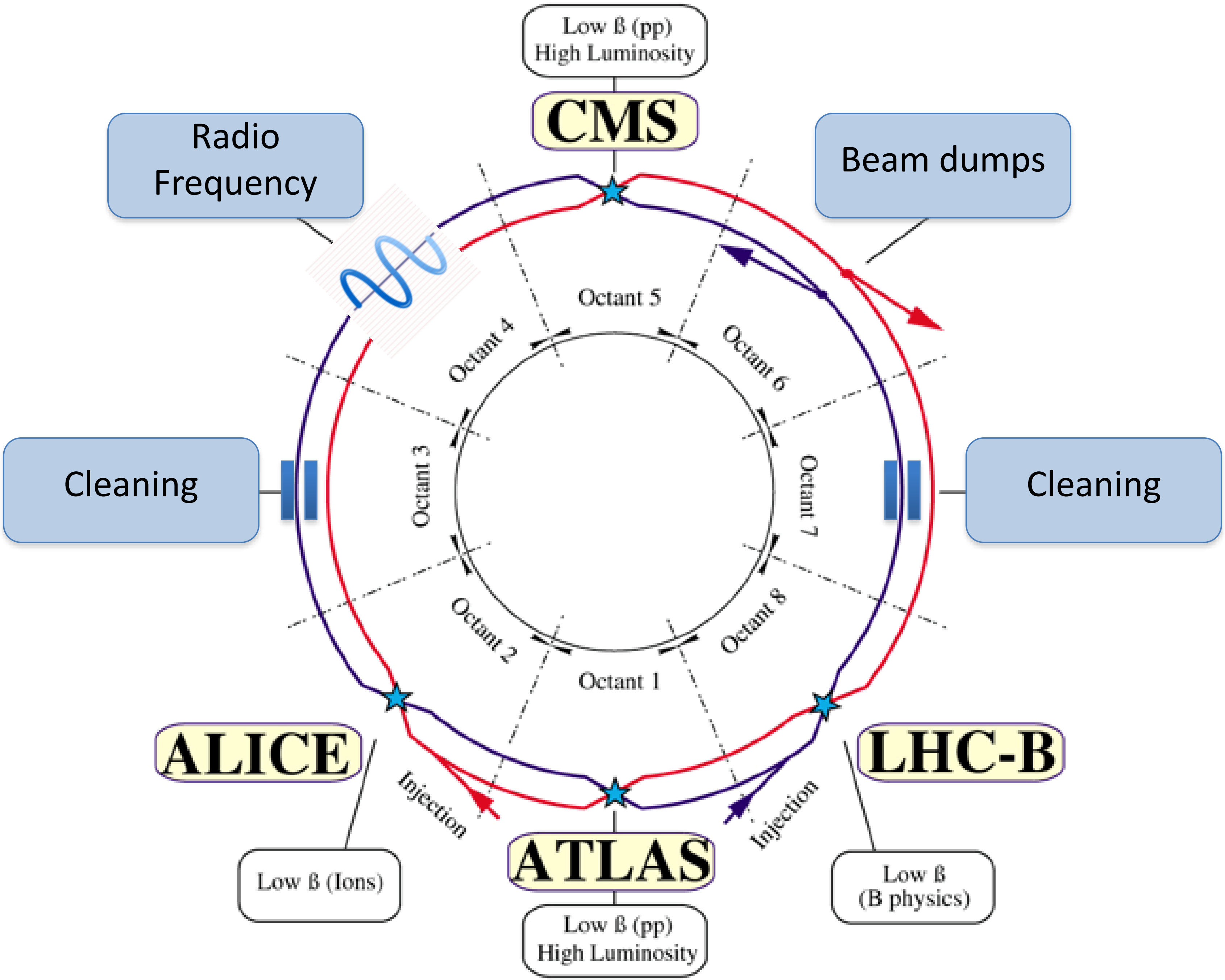
Mike Lamont with acknowledgements to Lucio Rossi and Oliver Bruning

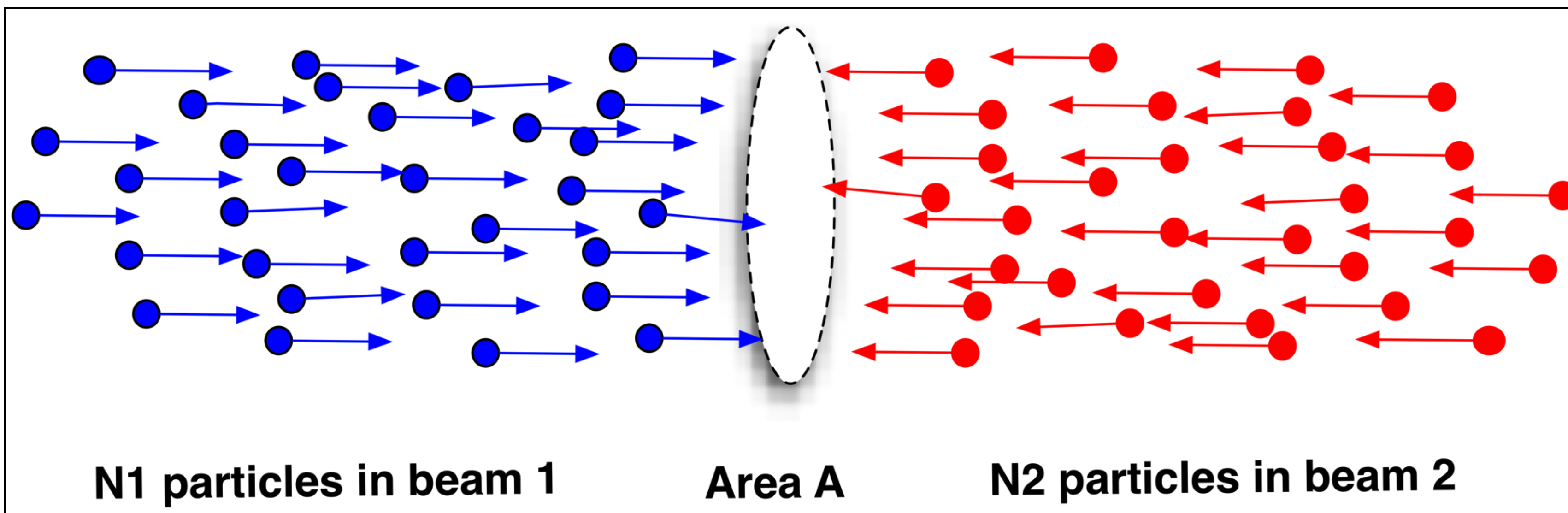
LHC: big, cold, high energy



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
350 MJ stored beam energy in 2015
1.2 GJ magnetic energy per sector at 6.5 TeV


Low ß (pp)
High Luminosity
CMS
Radio Frequency
Beam dumps
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS
Low ß (Ions)
Low ß
(B physics)
Low ß (pp)
High Luminosity



$$\text{Number of potential collisions per unit area} = \frac{N_1 N_2}{A}$$

Luminosity

$$L = \frac{N_1 N_2}{A}$$

Per bunch crossing

$$L = \frac{N_1 N_2}{A} \times f$$

Per bunch crossing f times a second

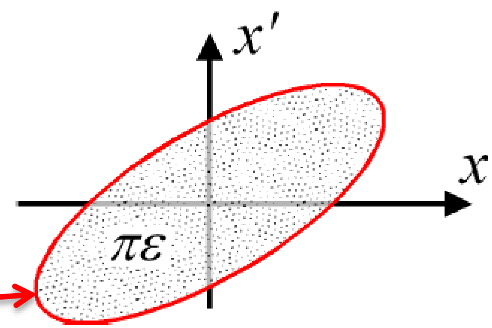
$$L = \frac{N_1 N_2}{A} \times f \times k_b$$

K_b bunches crossing f times a second

Luminosity

$$L = \frac{N_1 N_2 k_b f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{N_1 N_2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance** $\varepsilon_n = \beta\gamma\varepsilon$
β*	**Beta function at interaction point**

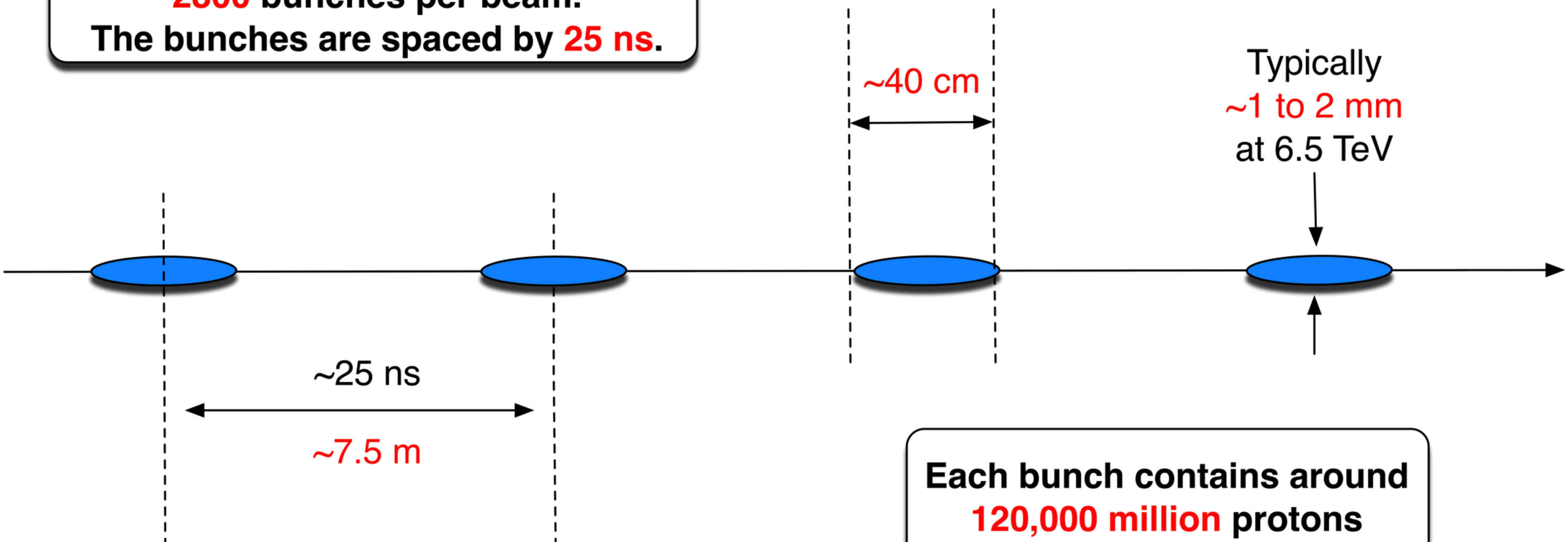


$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

Round beams, beam 1 = beam 2

Bunches

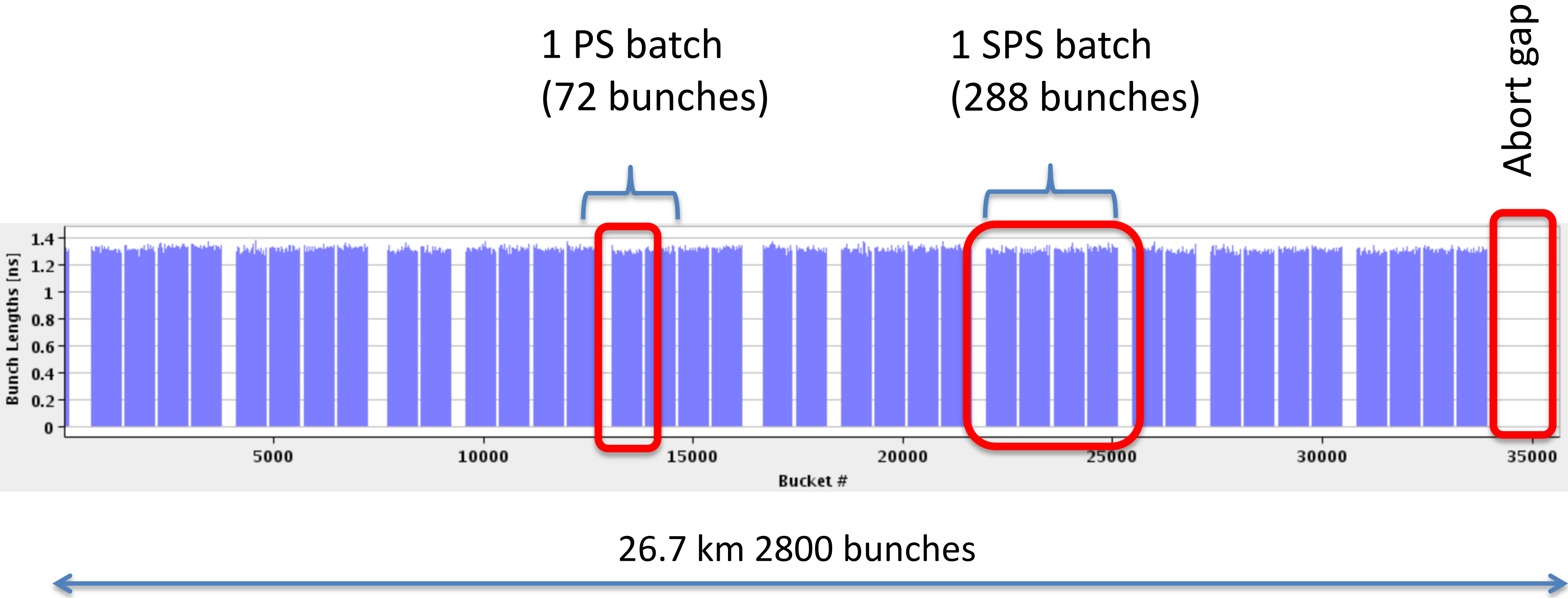
In 2016 the LHC should operate with 2800 bunches per beam. The bunches are spaced by 25 ns.



Each bunch contains around 120,000 million protons

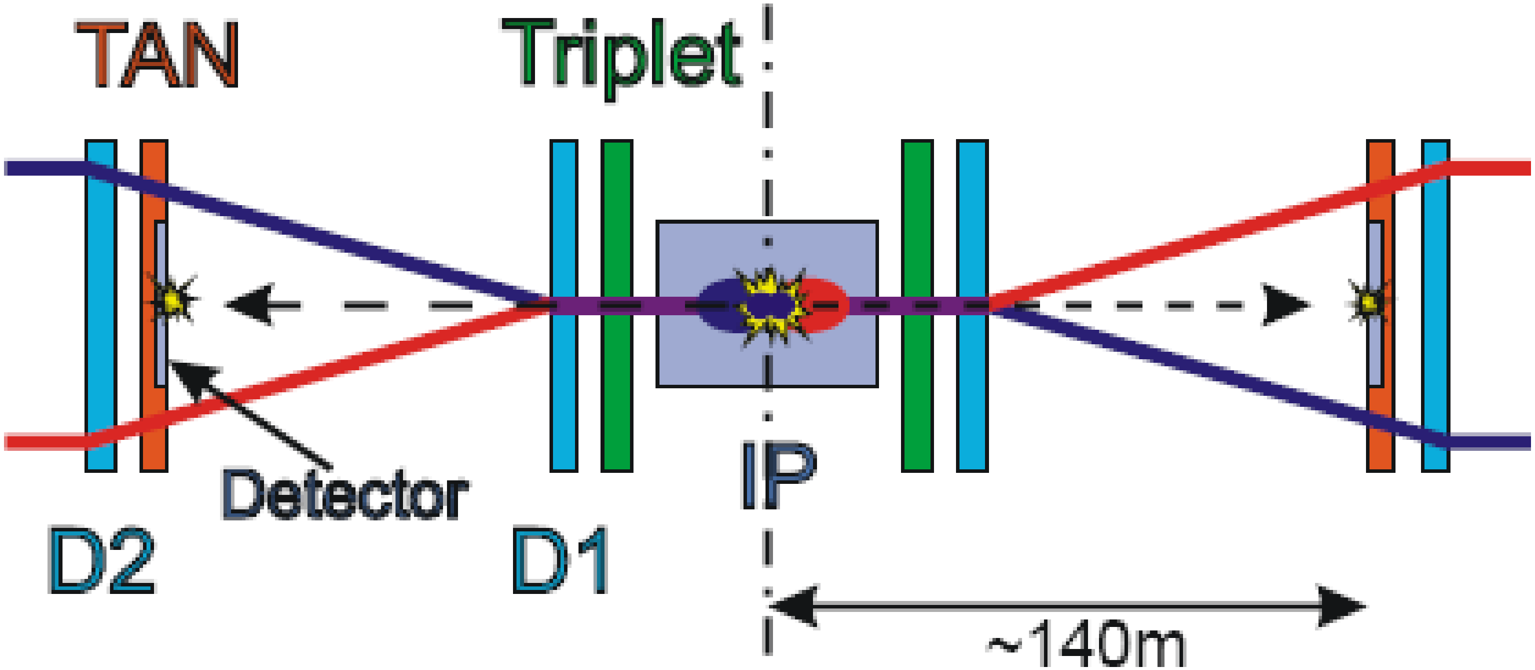
(Foreseen) LHC bunch structure - 2016

- 25 ns bunch spacing
- Nominal bunch intensity 1.15 x 10^{11} protons per bunch



We've had some problems with the SPS beam dump which is limiting us to 2076 bunches per beam for the moment.

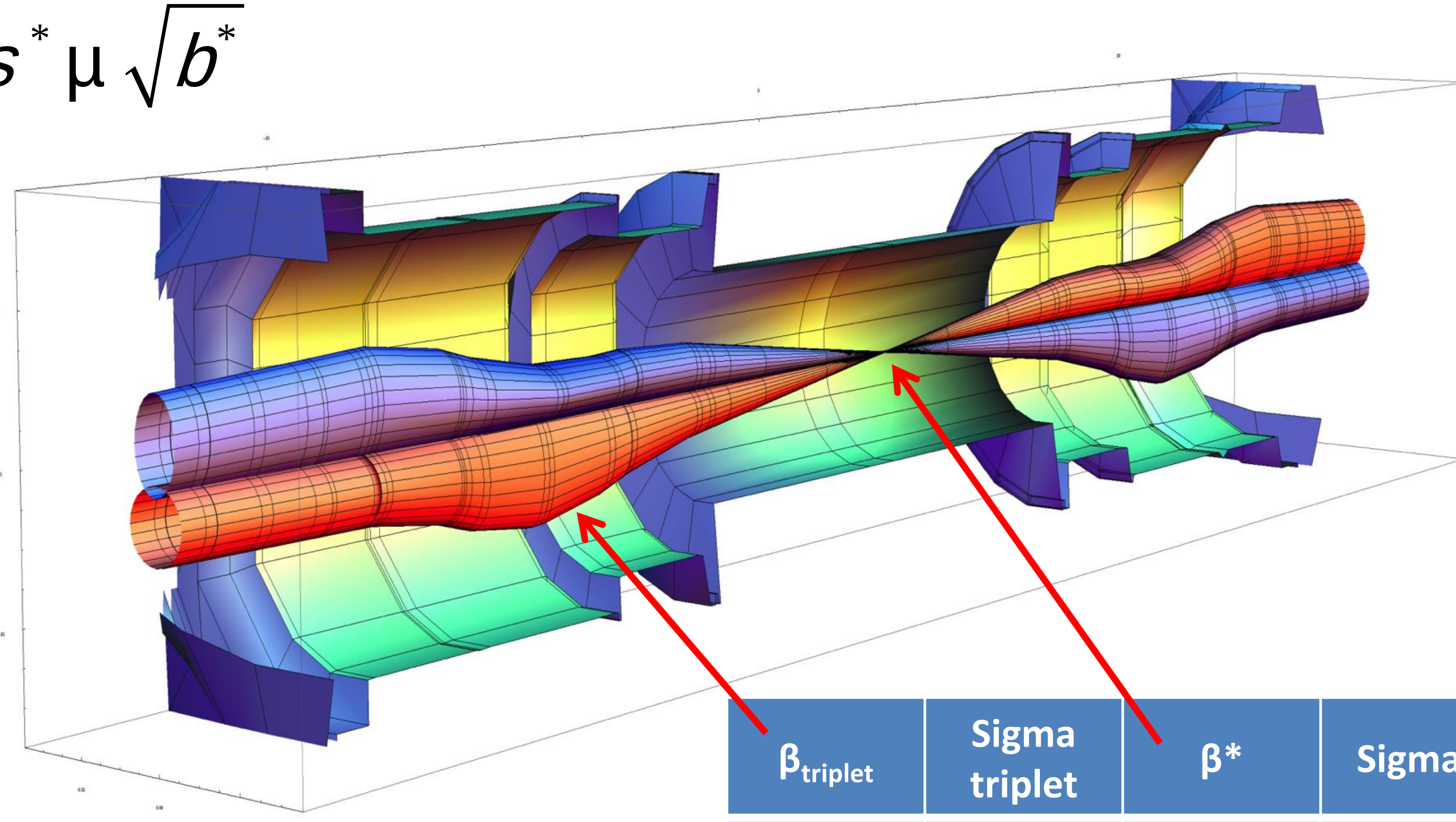
Interaction region



Squeeze in ATLAS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution

$$s^* \mu \sqrt{b^*}$$



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

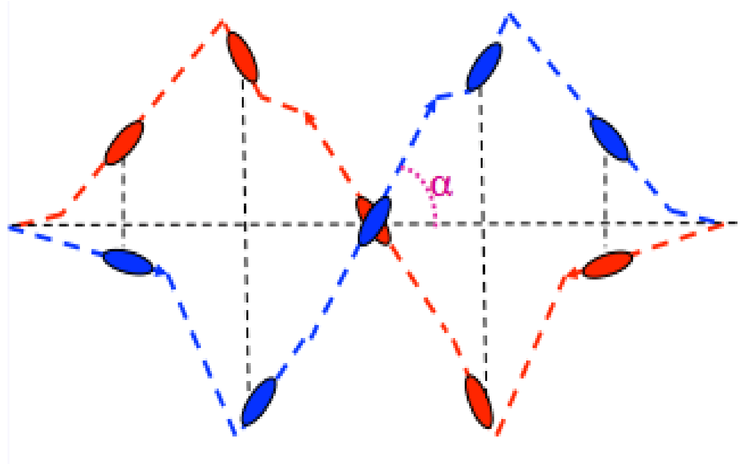
Image courtesy John Jowett

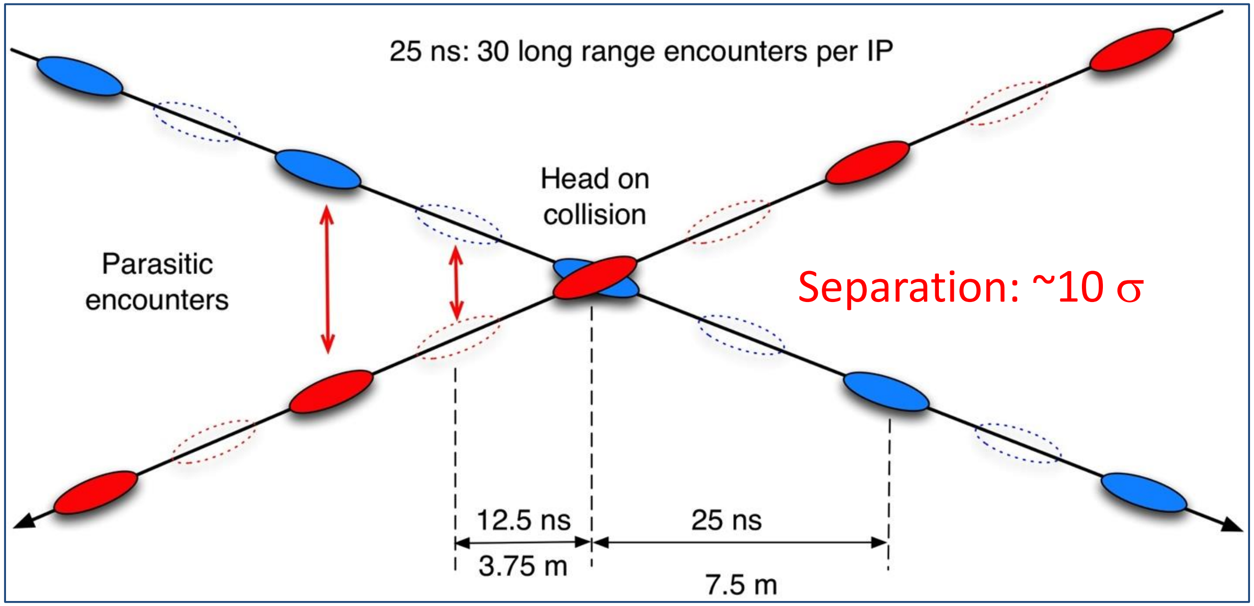
Video

Recombination/separation dipoles (D1) and inner triplet left of ATLAS

Crossing angle

work with a crossing angle to avoid parasitic collisions.

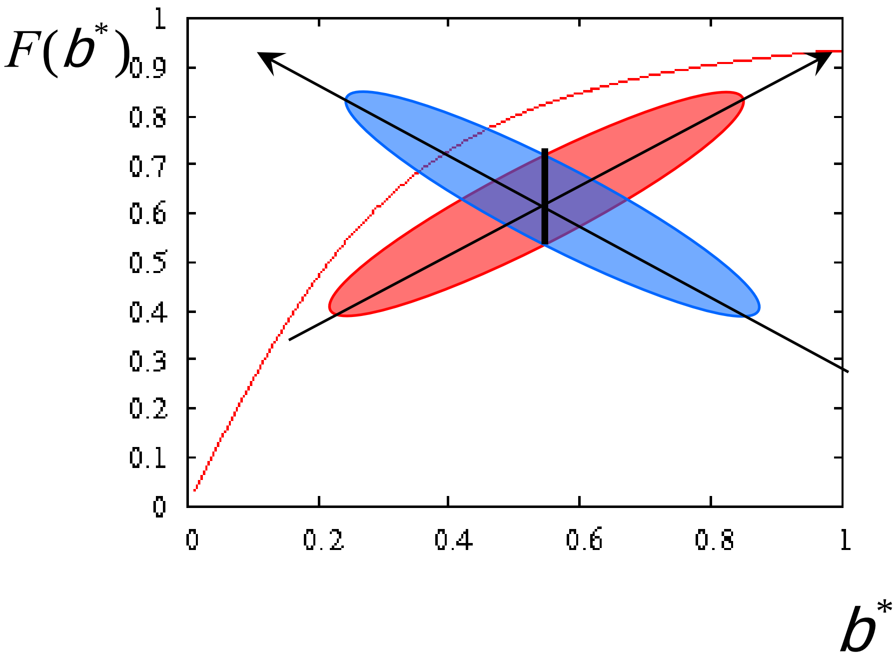




Crossing angle

Large crossing angle:

- ➔ reduction of long range beam-beam interactions
- ➔ reduction of beam-beam tune spread and resonances
- ➔ reduction of the mechanical aperture
- ➔ reduction of luminous region
- ➔ reduction of overlap & instantaneous luminosity



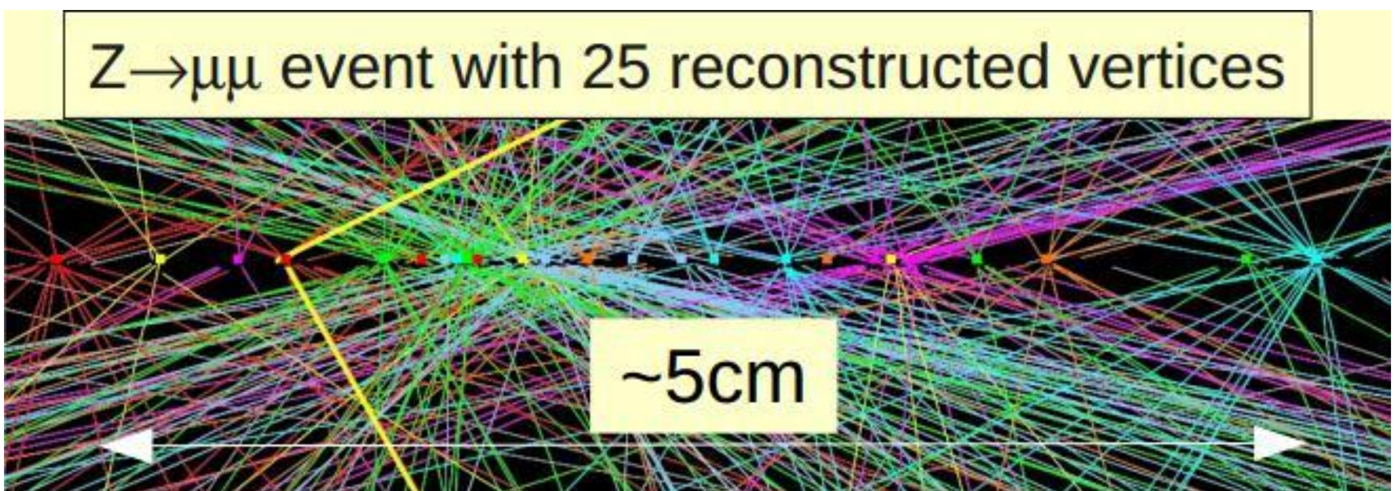
geometric luminosity reduction factor:

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

Pile-up

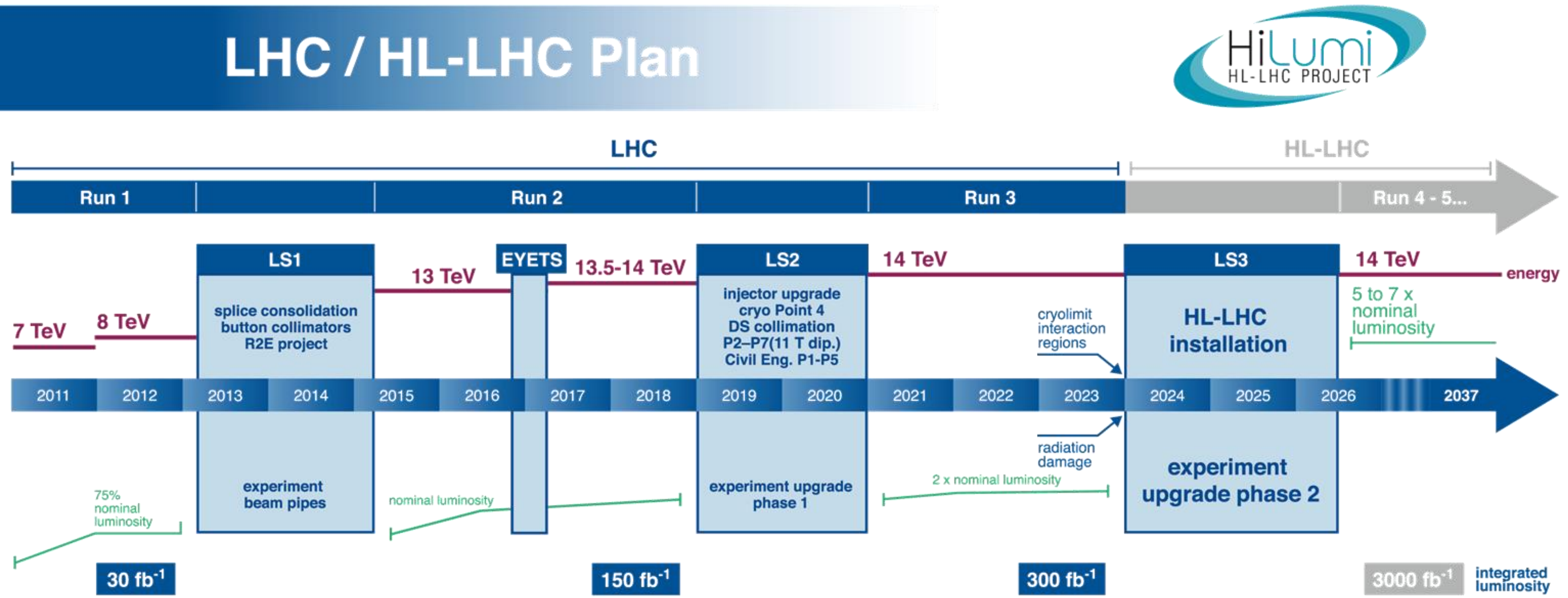
$$N_{coll} = L ´ s$$

Process	X-section	Luminosity	Events
Inelastic at 6.5 TeV	~80 mb	1×10^{34} cm^{-2}s^{-1}	8×10^{8} s^{-1}
		1×10^{34} cm^{-2}s^{-1}/($k_b f_{rev}$)	26
		5×10^{34} cm^{-2}s^{-1}	4×10^{9} s^{-1}
		5×10^{34} cm^{-2}s^{-1}/($k_b f_{rev}$)	130



HL-LHC - goals

- Prepare machine for operation beyond 2025 and up to ~2035
- Operation scenarios for:
  - total integrated luminosity of 3000 fb^{-1} in around 10-12 years
  - an integrated luminosity of ~250 fb^{-1} per year
  - mu ≤ 140 (peak luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$)



HL-LHC: key 25 ns parameters

Protons per bunch	2.2 x 10^{11}
Number of bunches	2750
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	590 microrad
Geometric reduction factor	0.305
Virtual luminosity	2.4 x 10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	5 x 10^{34} $cm^{-2}s^{-1}$
Levelled <pile-up>	140

HL-LHC How?

- **Lower beta* (~15 cm)**
  - New inner triplet magnets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - High bunch population, low emittance, 25 ns beam

Higher intensity

Increase bunch intensity

$$\mathcal{L} = \frac{N_1 N_2 f_{\text{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Increase F: shorter bunches, smaller crossing angle, crabs

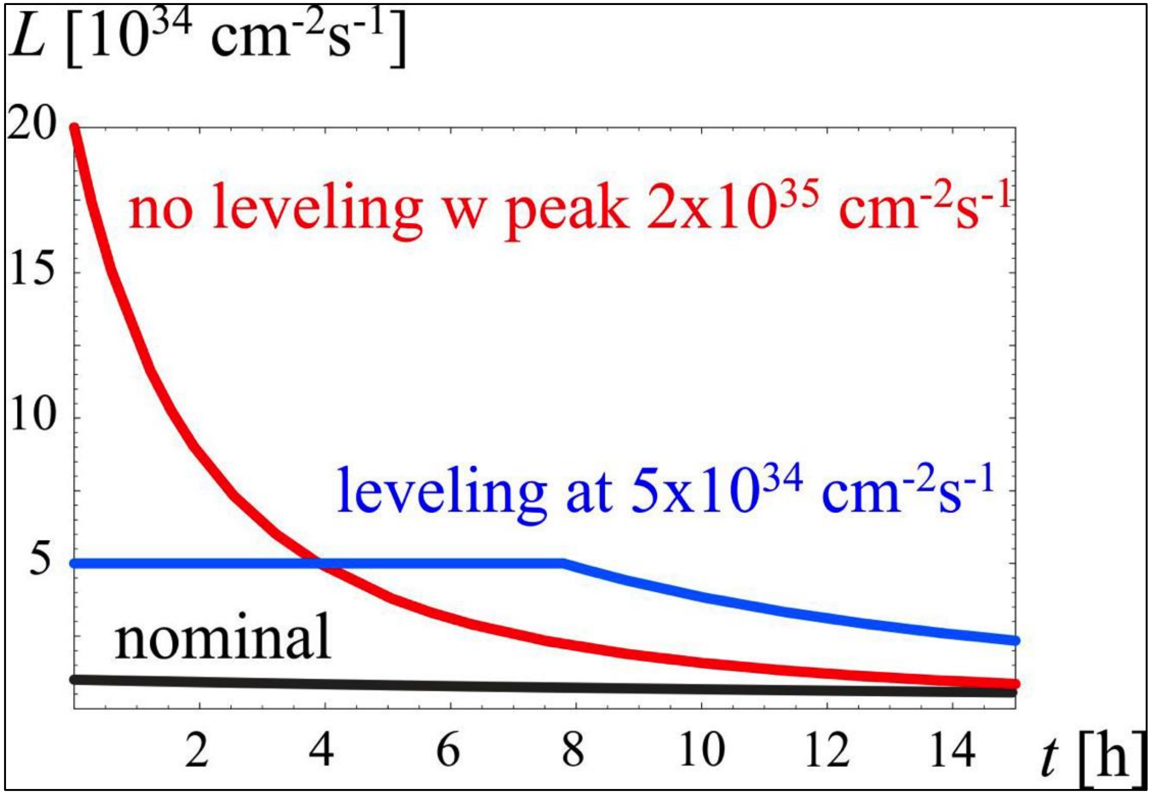
$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

Smaller β*

Smaller emittance

Smaller beam size

Operational scenario



- If we could compensate crossing angle perfectly – ~2 x10^{35} cm^{-2}s^{-1}
- Even if not – still need to artificially reduce luminosity to stay within pile-up limit of experiments - **leveling**

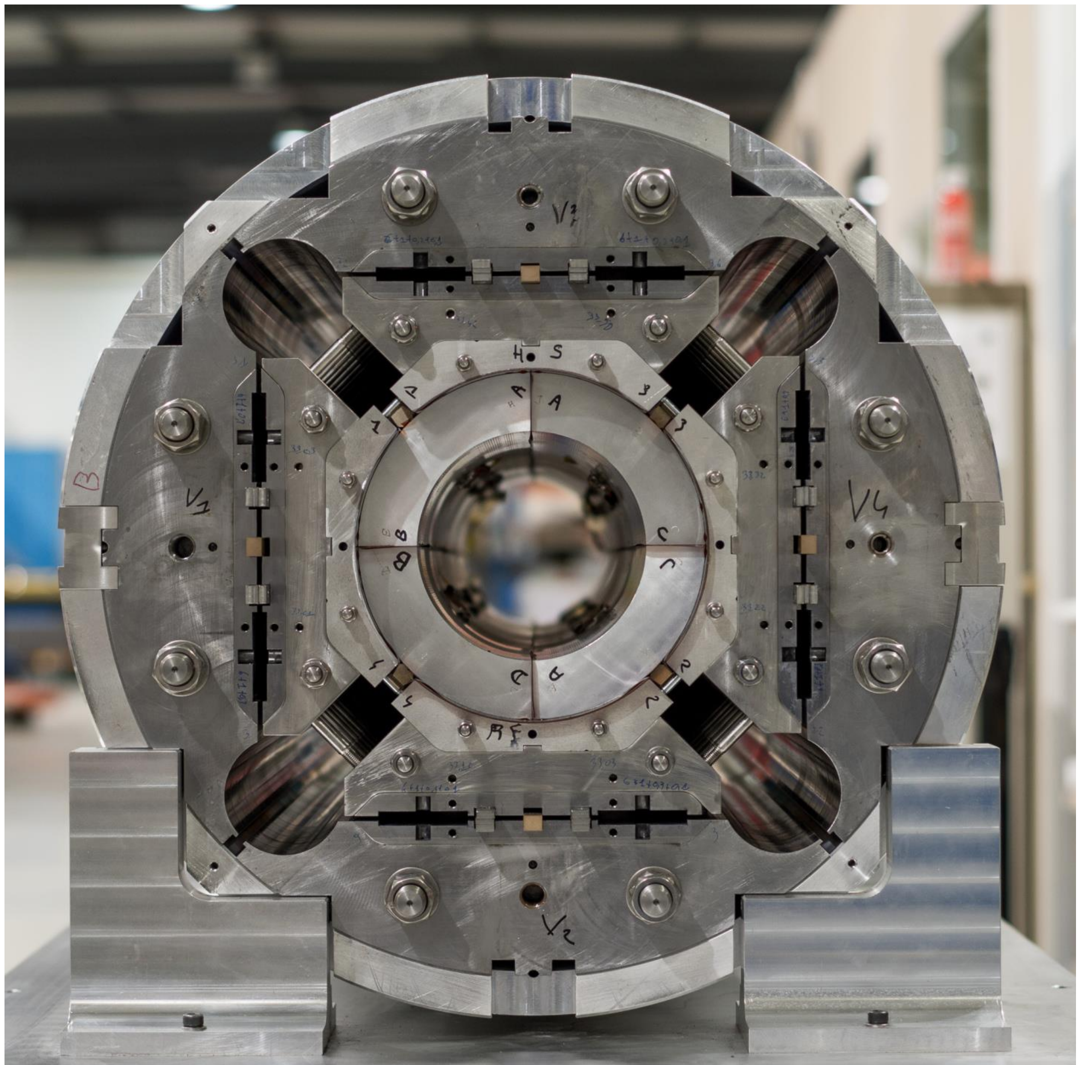
1. Squeeze harder

	2016	HL-LHC
β*	40 cm	15 cm
Beam size at IP (sigma)	17 um	7 um
β at triplet	~4.5 km	~20 km
Beam size at triplet	1.5 mm	2.6 mm
Crossing angle	370 urad	590 urad

The reduction in beam size buys a factor of 1.6 in luminosity but:

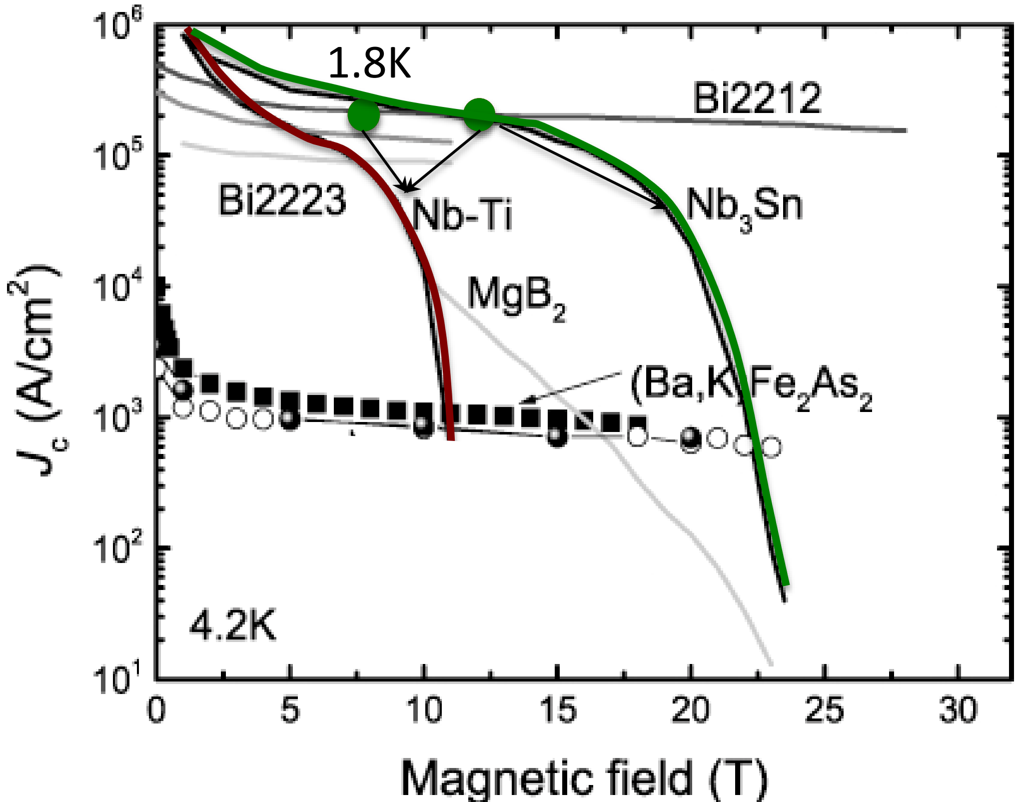
- Bigger beams in inner triplets and so
- Larger crossing angle
- And thus larger aperture in inner triplets is required.

Challenge:
build a wide aperture quadrupole



Triplets or low-β quads

- Present LHC triplets: 210 T/m, 70 mm coil aperture
  - 8 T @ coil - approaching limit of NbTi
- HL-LHC triplet: 140 T/m, 150 mm coil aperture
  - Around 12 T @ coil
  - **Requires Nb_3Sn technology**

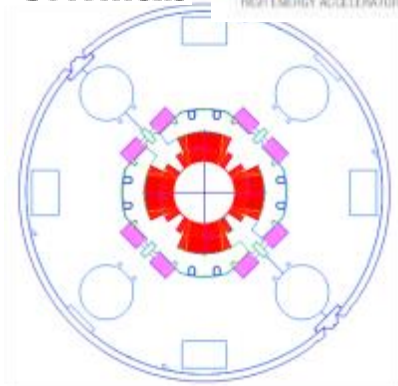


LHC low-β quads

US-LARP/CERN collaboration spanning 25 years

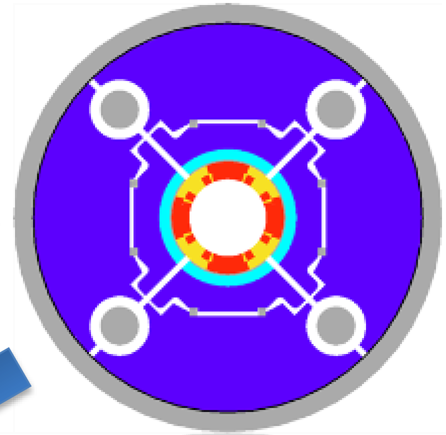
Fermilab KEK

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



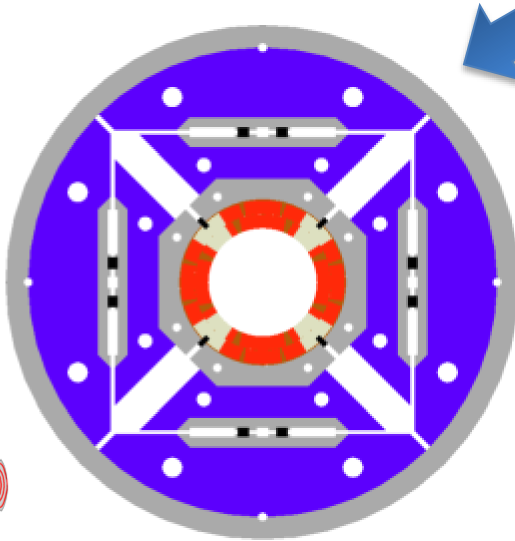
LARP

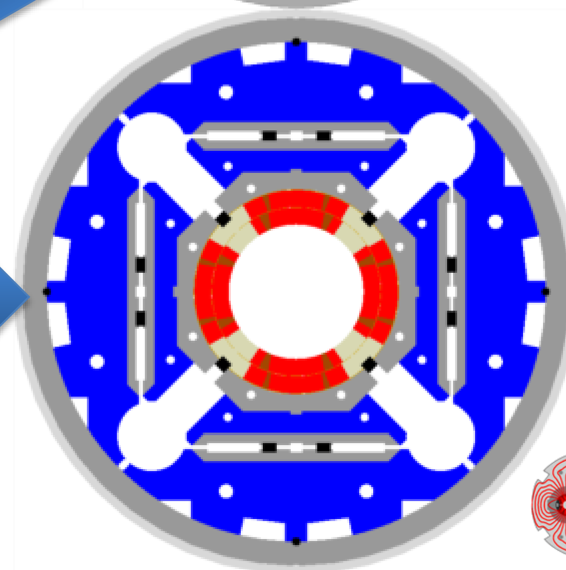
LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010



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

LARP





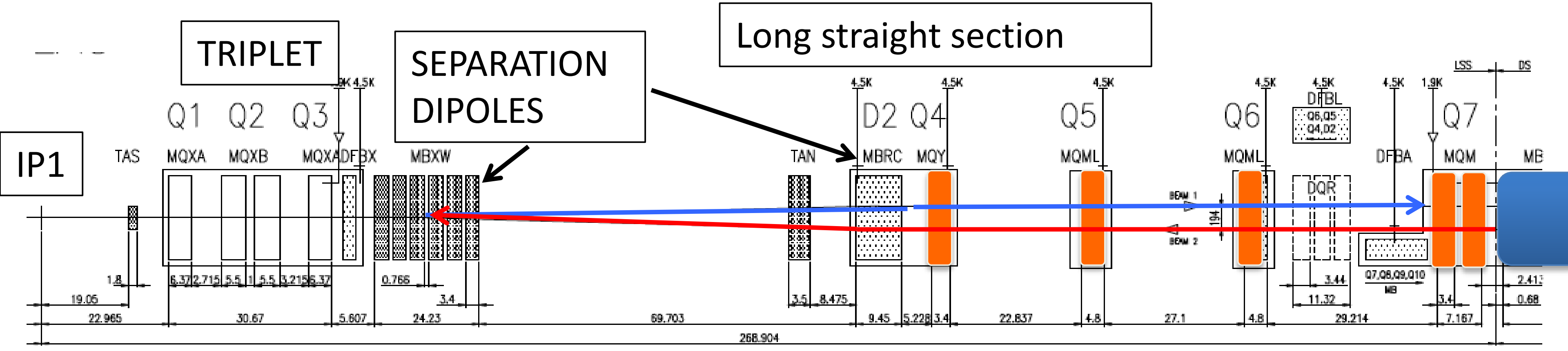
LARP & CERN
MQXF
∅150 mm,
B_{peak}~ 12.1 T
2013-2020

LARP CERN

- Mid-March 2016 , a short prototype of the quadrupole magnet underwent its first testing phase at the Fermilab.
- Prototype is 1.5 m long, whereas the final magnets will be 4.2 or 7.15 m
- During the tests, a peak magnetic field of 12.5 Tesla was measured on the coils, compared to 8 Tesla for the LHC's current quadrupole magnets.

Squeeze

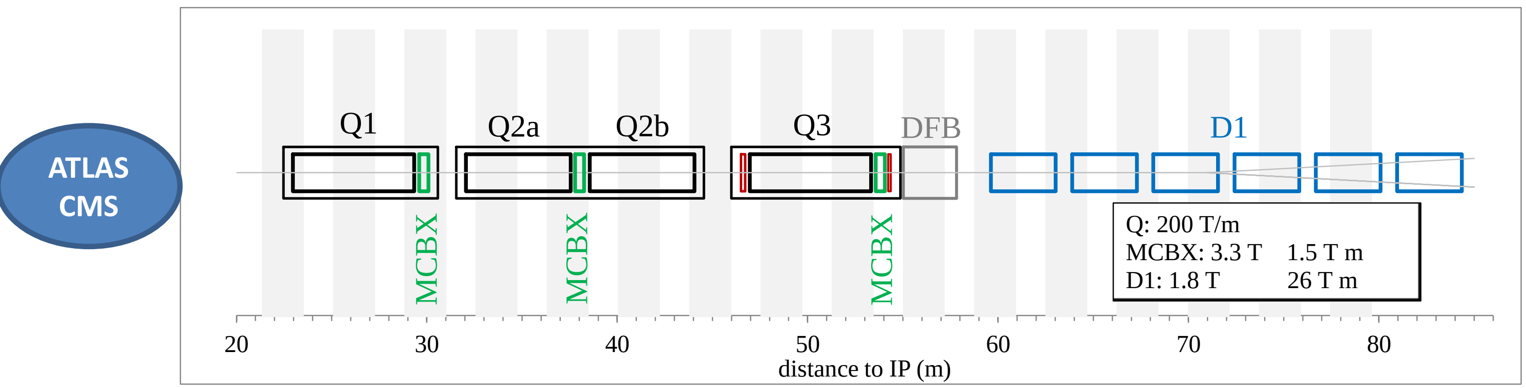
- Going to use quadrupoles both sides of a given IP all the way out to the arc to control the optics during the squeeze.
- Current in the inner triplets doesn't actually change very much during the squeeze – but the beam size does.



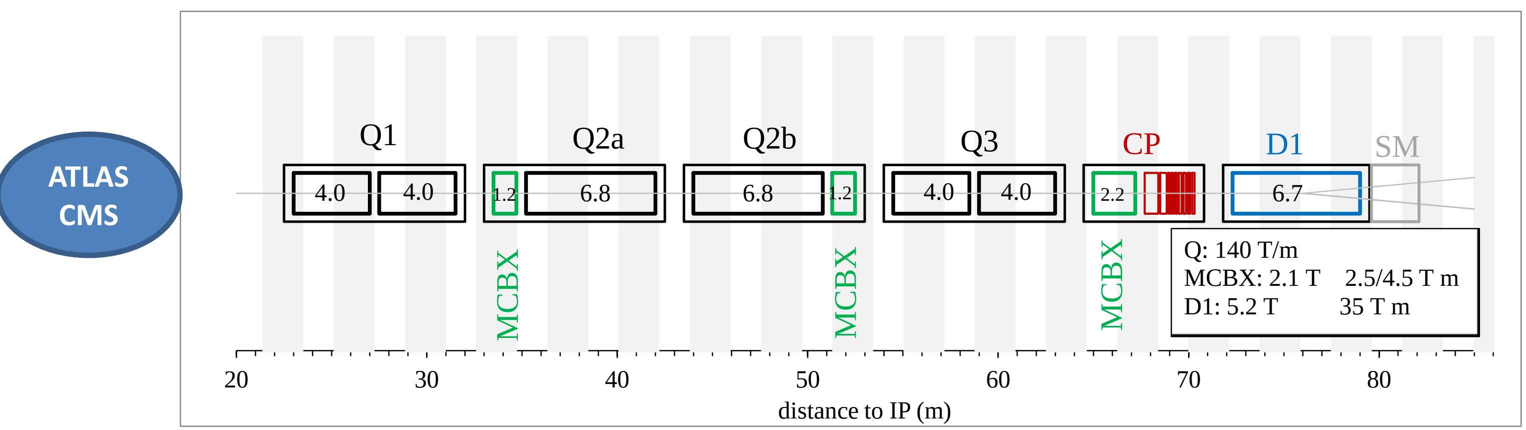
New interaction region layout

New triplets are not enough by themselves

- Superconducting separation dipoles (D1)
- Corrector package
- And beyond…



LHC



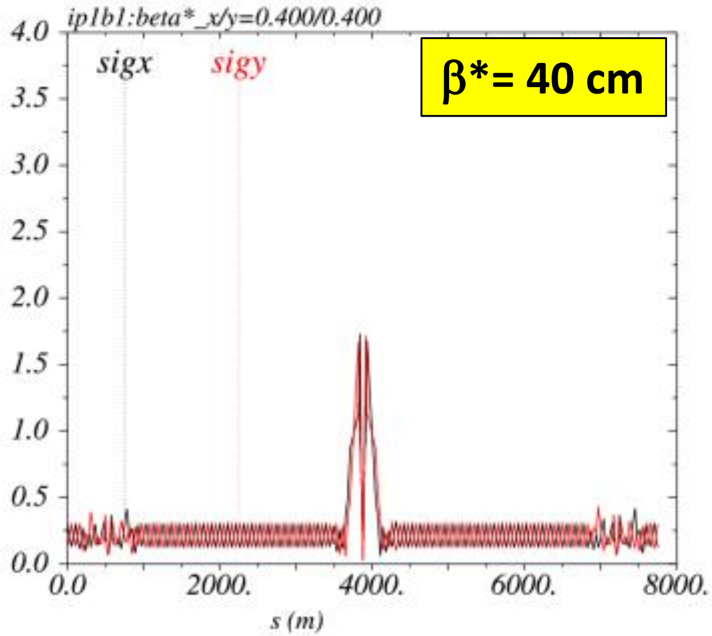
HL-LHC

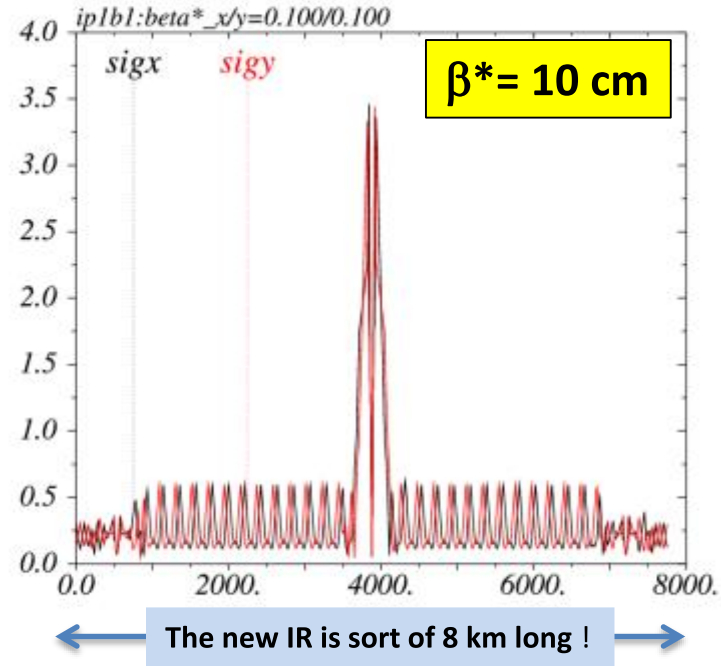
Low beta* optics (ATS)

(S. Fartoukh)

Small β^* is limited not only by aperture but : optics matching, chromatic effects...

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

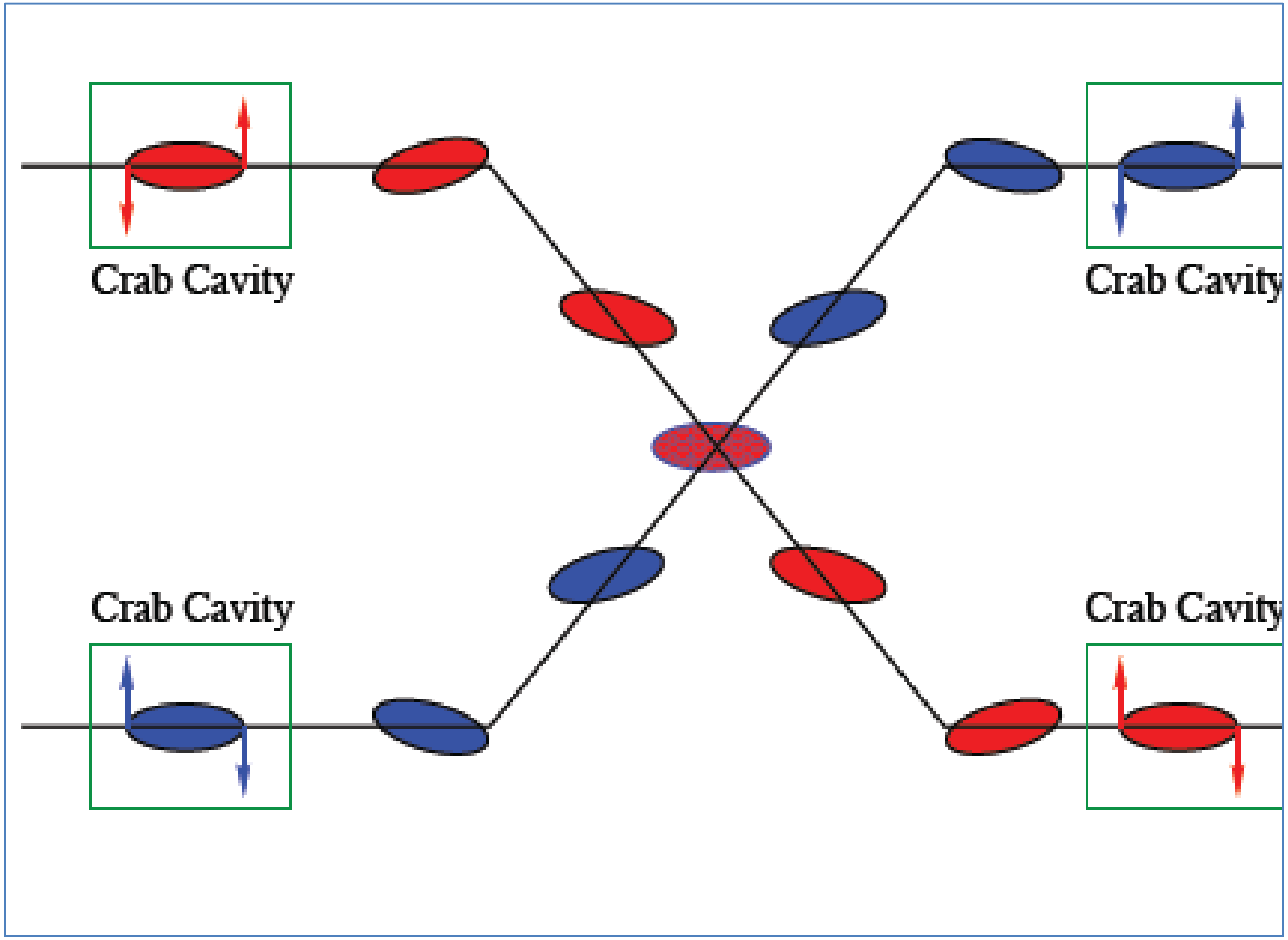




Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

2. Crossing angle compensation

Attempt to claw back the very significant reduction in luminosity from the large crossing angle



Crab Cavity

- Create a oscillating transverse electric field
- Kick head and tail of the bunch in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP

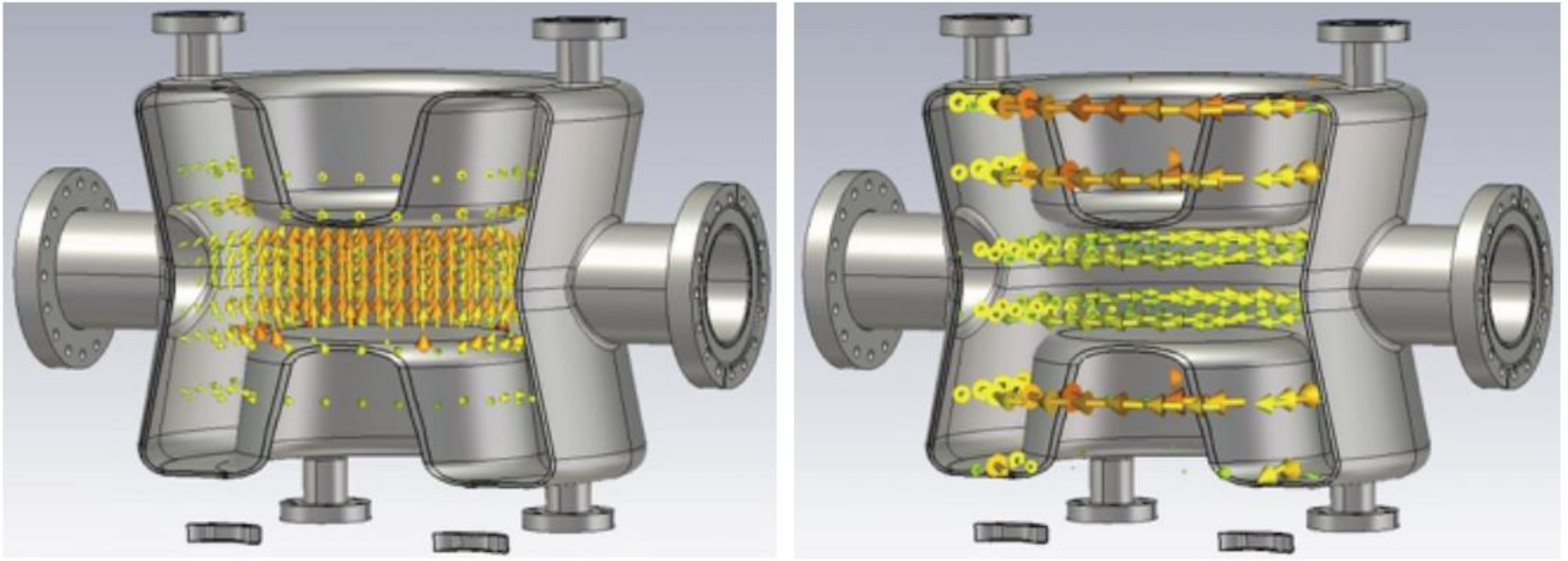
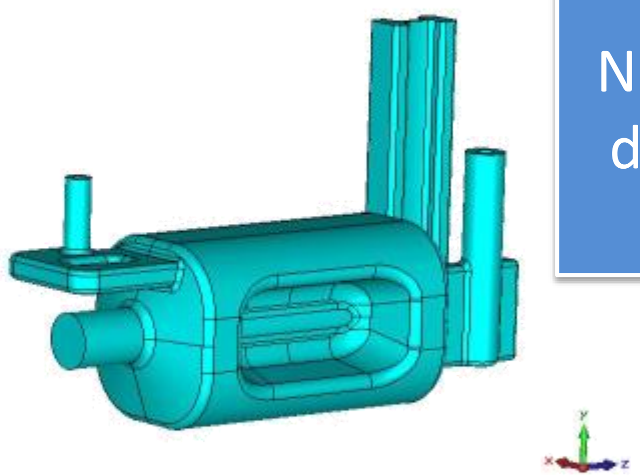


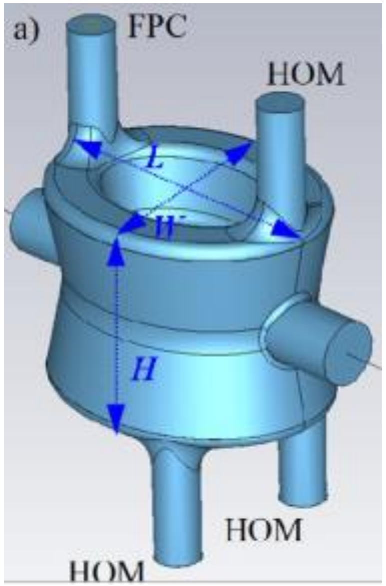
Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

Crab cavity development



Major R&D program

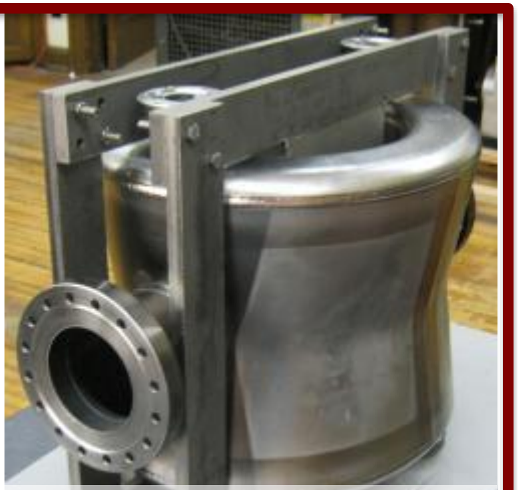
Now concentrate on two designs in order for test installation in SPS



Double ¼-wave: coaxial couplers with hook-type antenna

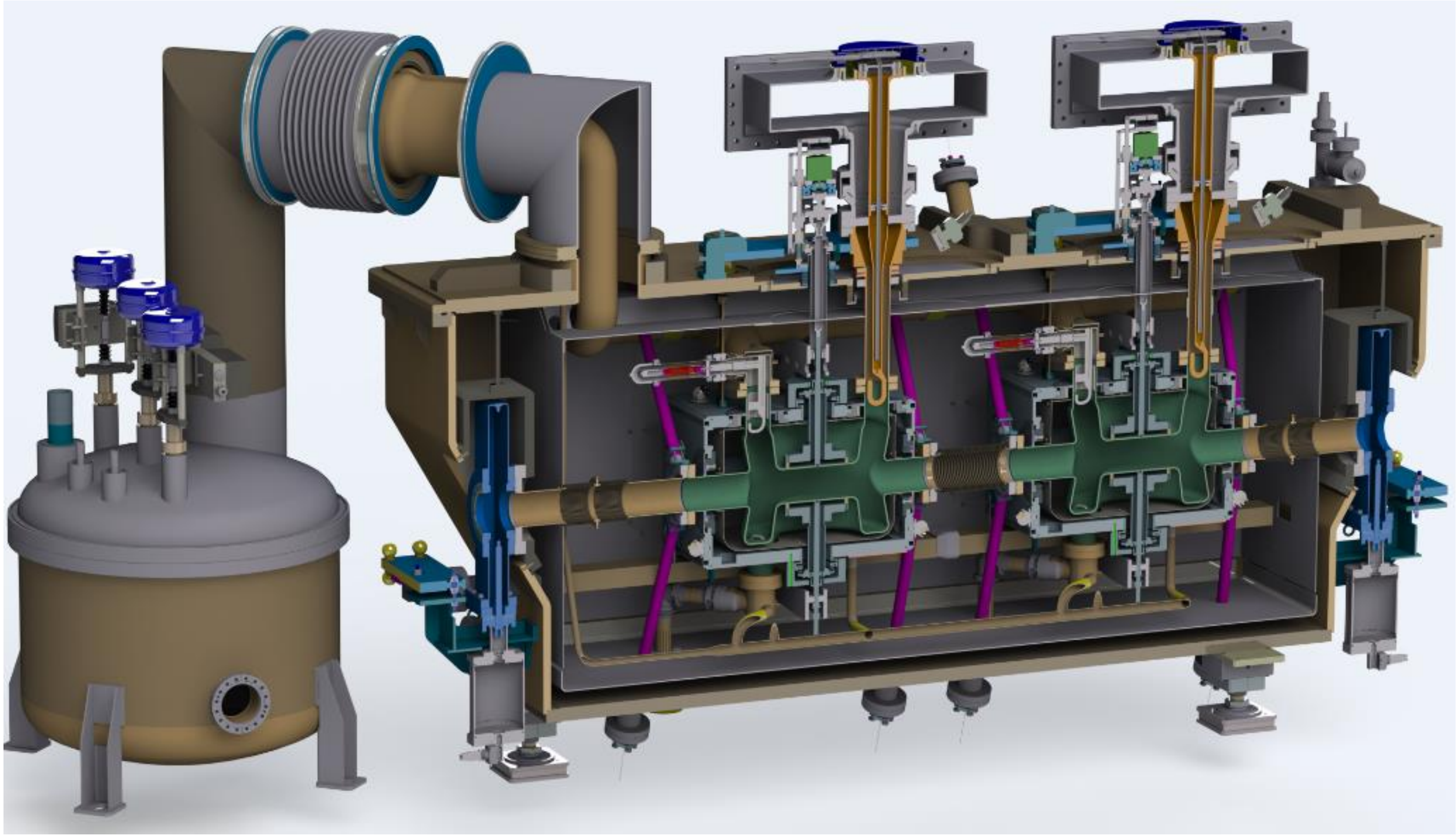
RF Dipole: waveguide or waveguide-coax couplers

RF-Dipole Nb prototype [ODU-SLAC]

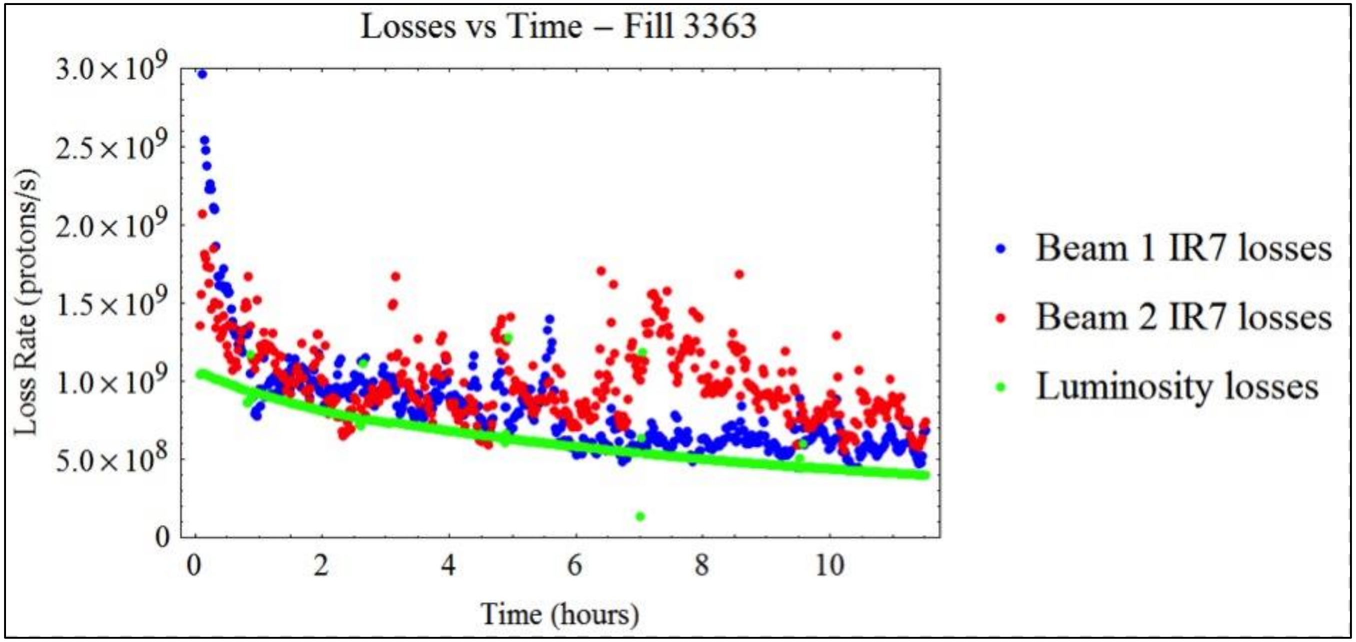


DQWR prototype (17-Jan-2013) [BNL]

Tests in SPS 2018



Serious stuff!

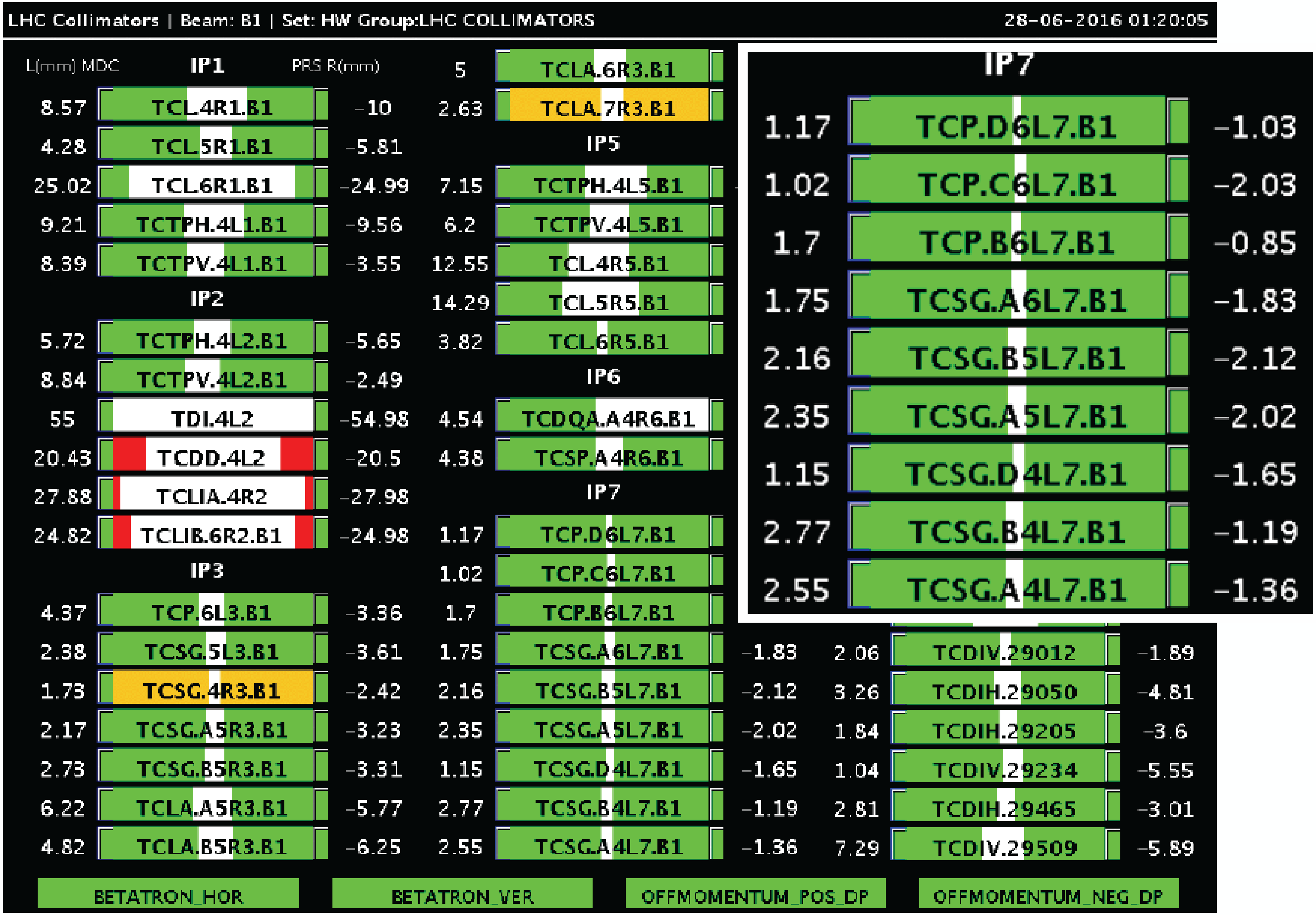


Losses in Stable Beams 2012: 50 ns, 1370 bunches, 1.6e11 ppb

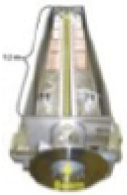
3. DEALING WITH THE REGIME

High bunch intensity, high luminosity, potentially high losses, high radiation

Complete system, Beam 1

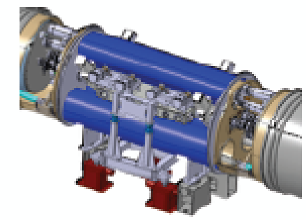


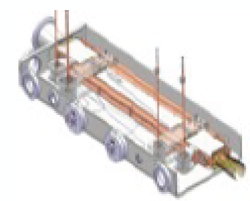
HL-LHC collimation upgrade

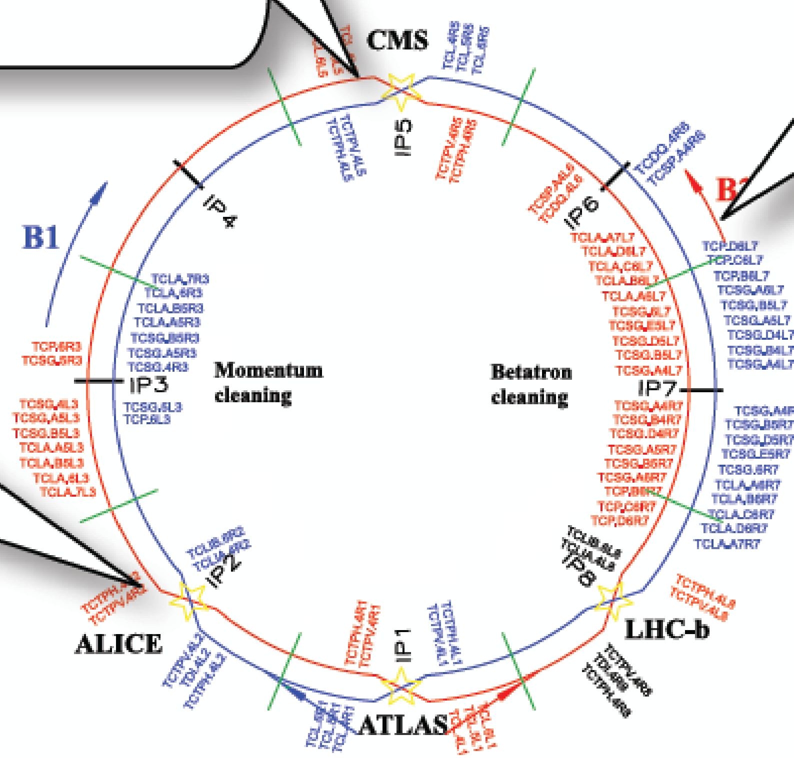


Completely new layouts
Novel materials: TCTs in CuCD
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

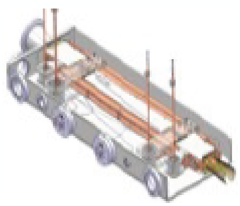
Cleaning: DS coll. + 11T dipoles, 2 units per beam



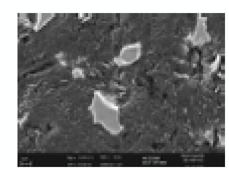


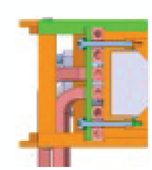


Ion physics debris: DS collimation



Low-impedance, high robustness secondary collimators: Mo coated MoGr



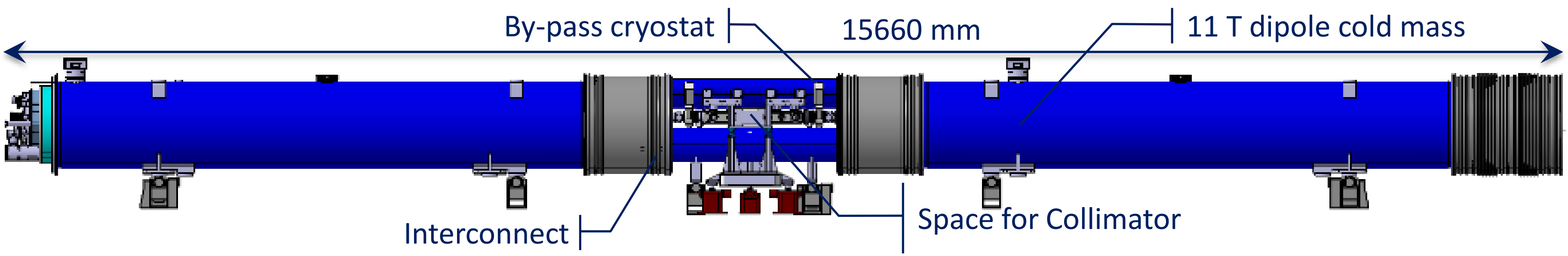


Dispersion Suppressor collimation

Protecting the dispersion suppressors (DS) from collimation or luminosity debris

Off-momentum debris gets swept into cold mass by first main dipoles encounter after the collision point

- Replace a 8.3 T Nb-Ti dipole with two **11 T Nb_3Sn dipoles**
  - Leaving enough space for a 0.8 m long room temperature collimator



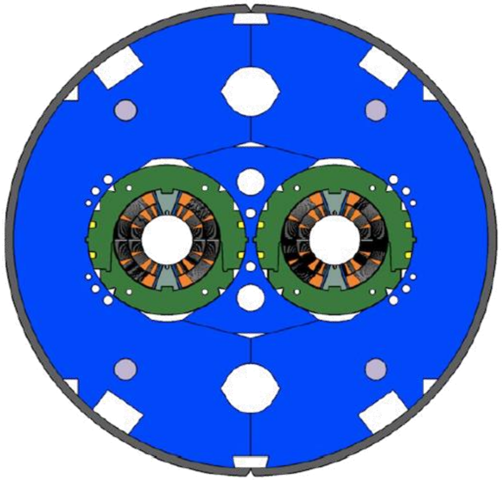
First units needed for IP7 in LS2

Prototyping of cryogenics bypass

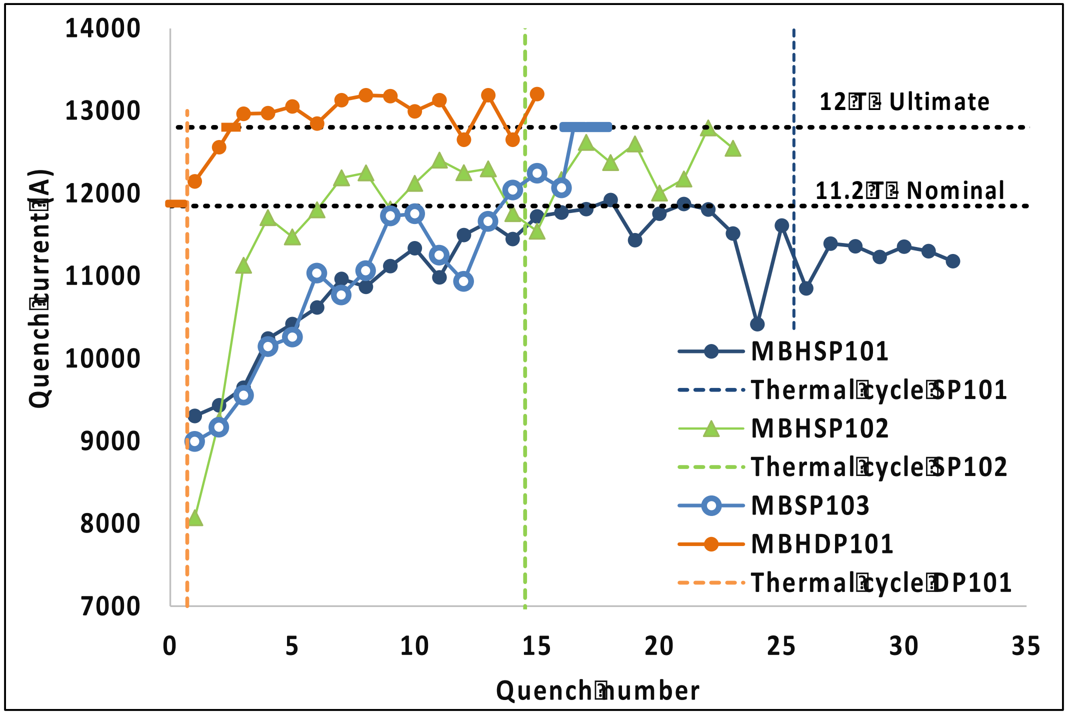
Prototyping of the by-pass cryostat for the installation of a warm collimator in the cold dispersion suppressors.

11 T dipole prototypes

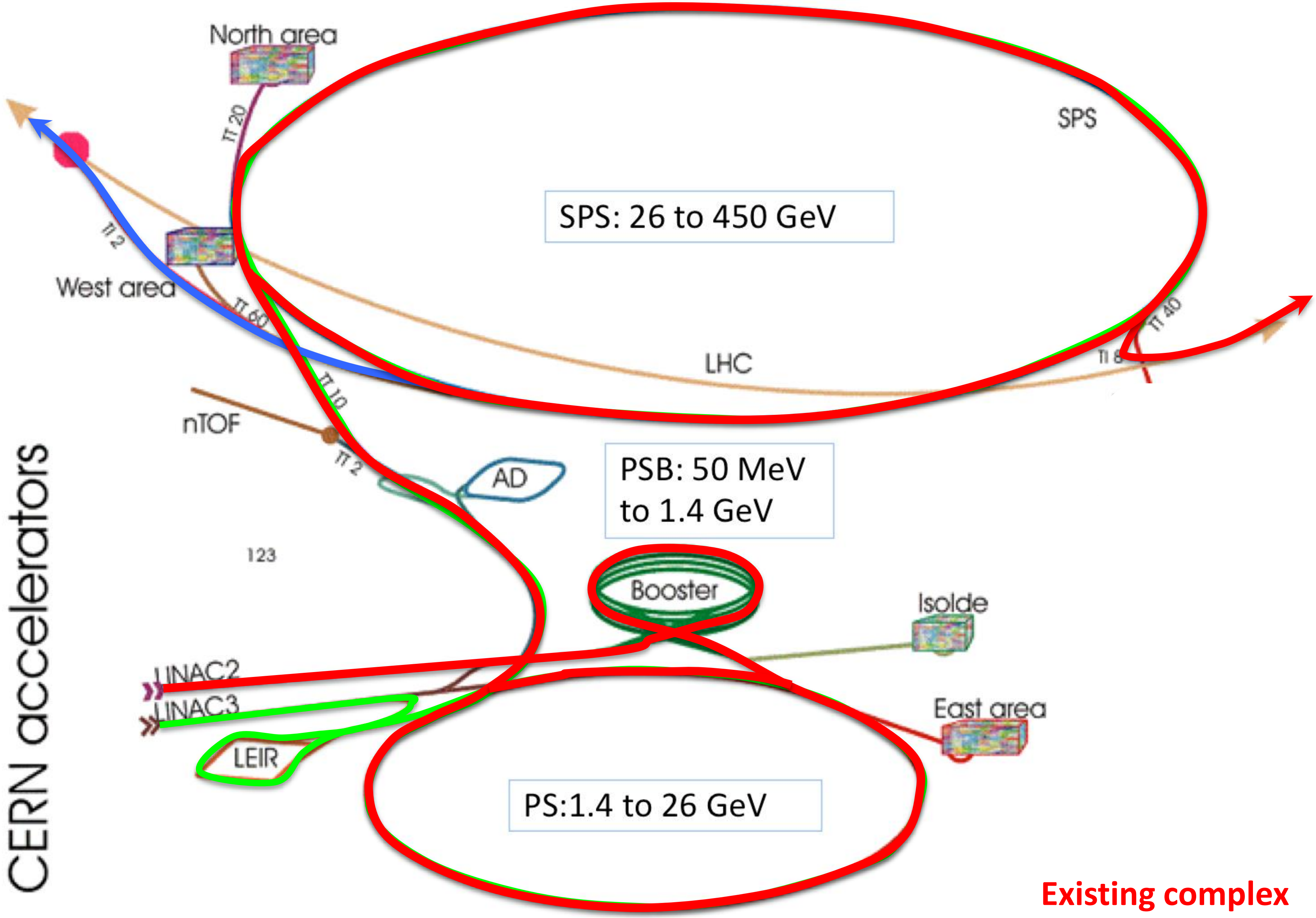
Cold tests results



MBHDP101



Courtesy F. Savary



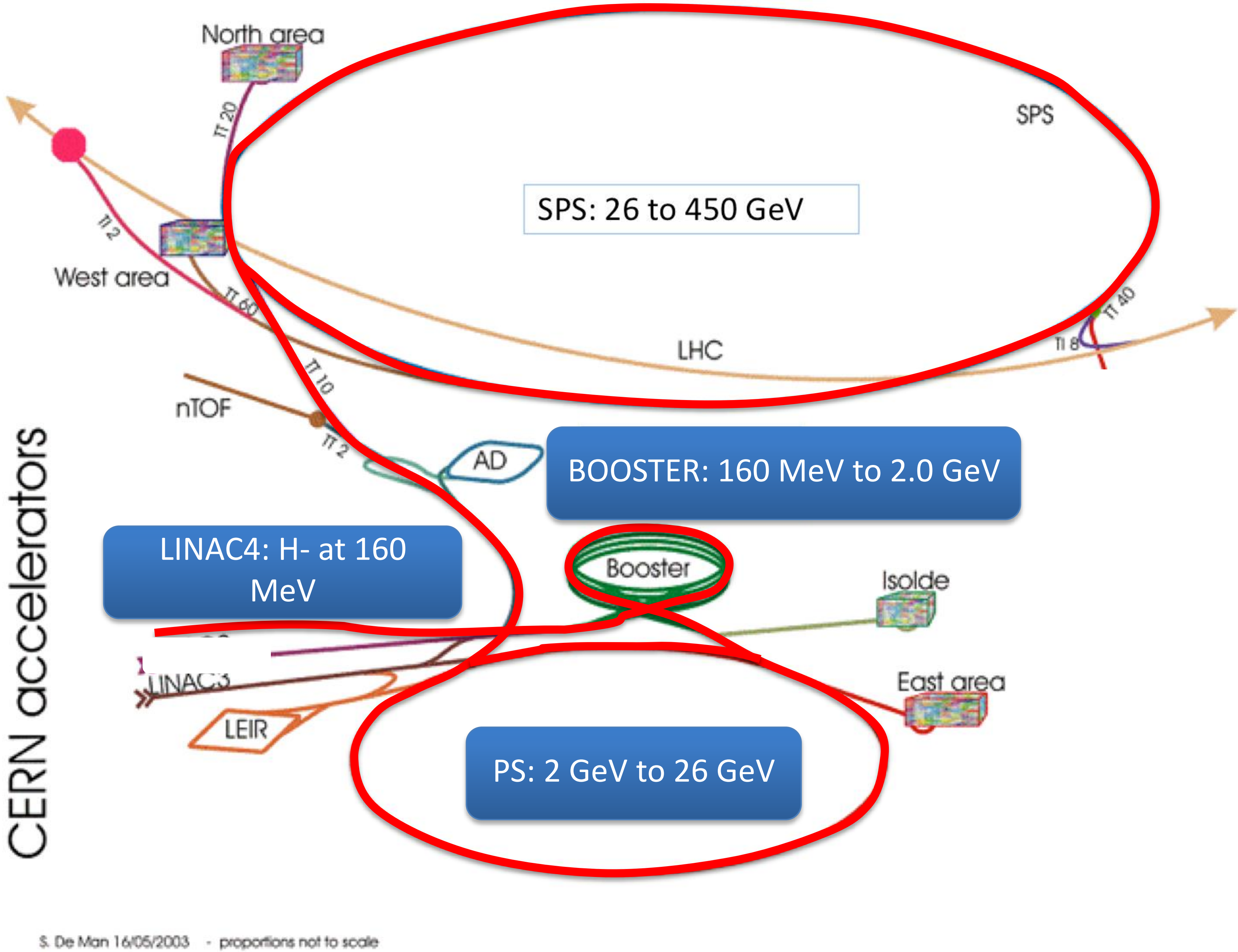
4. Beams from injectors

LIU proton target → HL-LHC beam parameters

25 ns	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)
2012	1.2	2.6	1.5
HL-LHC	2.3	2.1	1.7

Injectors must produce 25 ns proton beams with about double intensity and higher brightness

A cascade of improvements is needed across the whole injector chain to reach this target


North area
TT 20
SPS
SPS: 26 to 450 GeV
TI 2
West area
TT 60
LHC
TI 8
TT 40
TT 10
nTOF
TT 2
AD
BOOSTER: 160 MeV to 2.0 GeV
LINAC4: H- at 160 MeV
Booster
Isolde
LINAC3
East area
LEIR
PS: 2 GeV to 26 GeV
CERN accelerators
S. De Man 16/05/2003 - proportions not to scale

Main means to achieve the target HL-LHC proton beam parameters

Linac4 in for Linac2	• **H^- injection into PSB at 160 MeV** • Expected double brightness for LHC beams out of the PSB
Booster	• **Increase energy to 2 GeV** • New RF system • New main power supply
PS	• **Injection at 2 GeV** • **Beam production schemes** • **Feedback systems**: new wide-band longitudinal feedback; transverse feedback against head-tail and e-cloud instabilities
SPS	• **Power upgrade of the main 200 MHz RF system** • **Electron cloud mitigation** through a-C coating (baseline) or beam induced scrubbing

Many other options plus a full ion upgrade program

Malika Meddahi

A few other challenges

Very bright beams, very high bunch population, very high beam current

- Beam stability
  - New low impedance collimators
- Beam lifetime & loss spikes
  - Magnet quenches
- Machine protection
  - Failure scenarios - local beam impact - equipment damage
  - Quench protection
- Machine availability
  - Radiation to electronics (SEUs etc.)...

Powering cold circuits

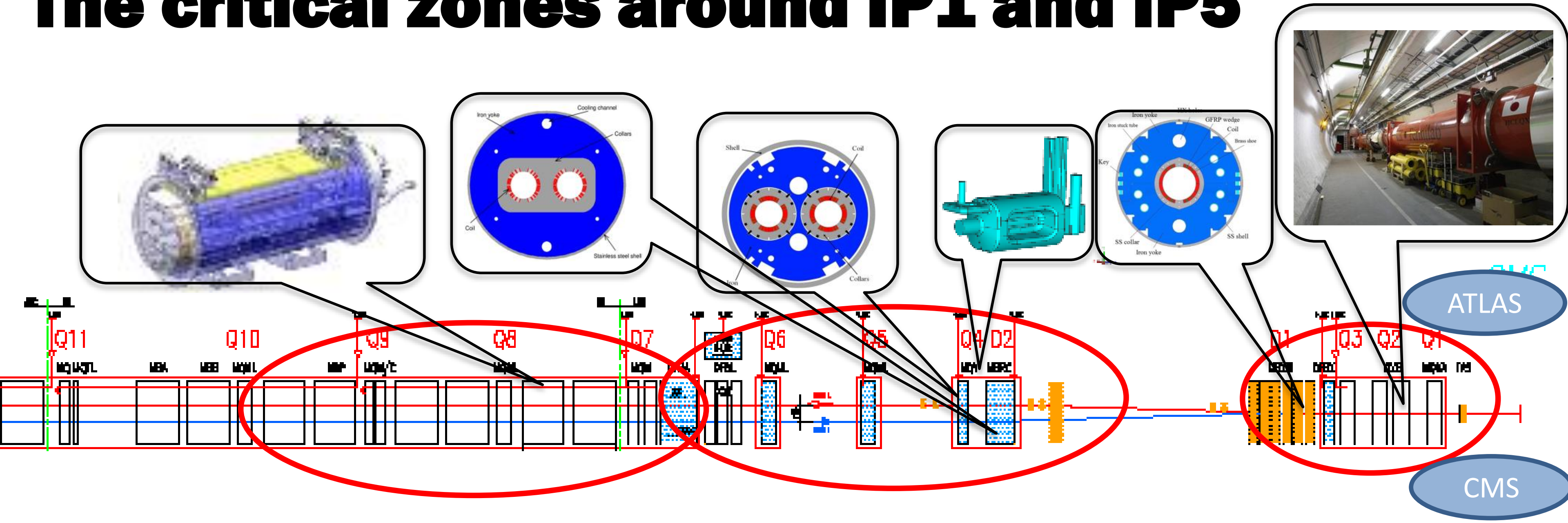
To avoid radiation to electronics and personnel – move power converters out of the tunnel. **High Temperature Superconducting (HTS) links.**

To summarize

5×10^{34} $cm^{-2}s^{-1}$ and 250 fb^{-1} per year

1. New inner triplet magnets plus new configuration of interaction regions
2. Reduce effect of crossing angle – main (but not only approach) – crab cavities
3. Dealing with extremely challenging regime – collimator upgrades – s/c links etc.
4. Major program of upgrades in injectors

The critical zones around IP1 and IP5

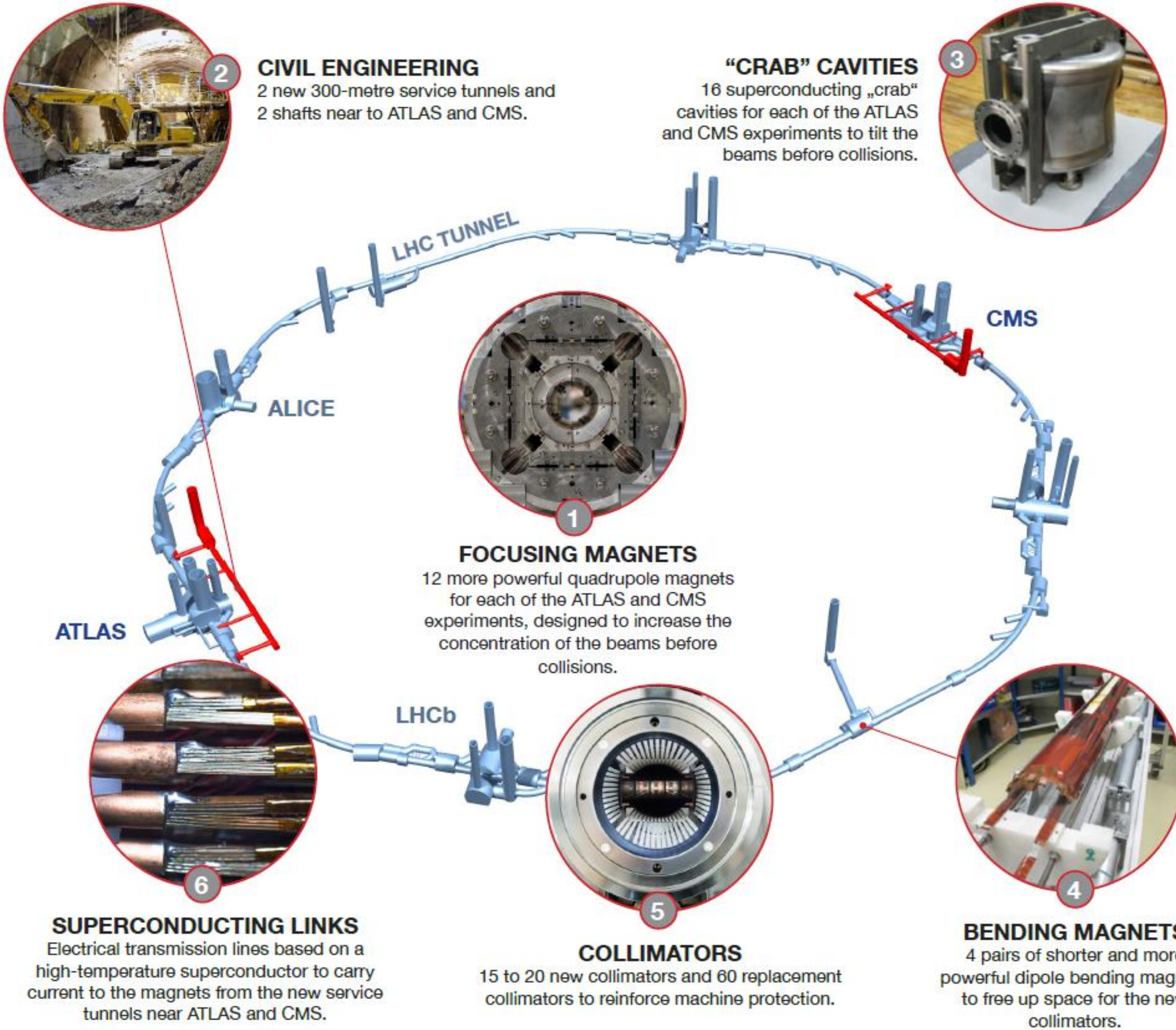


3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

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

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



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