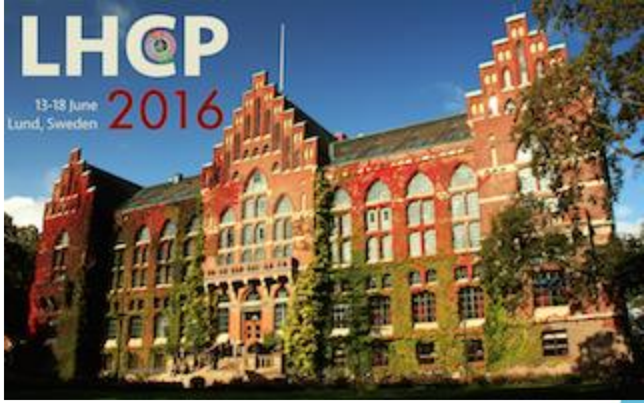
HiLumi
HL-LHC PROJECT



The HL-LHC Machine

G. Arduini – CERN

With input from many collaborators of the HL-LHC Project

LHCP2016 – Lund, Sweden – 17/06/2016

Contents

- LHC: the challenges
- LHC: limitations and prospects
- HL-LHC: why and how?

- *Disclaimer: I will focus on the LHC and on the proton performance although a lot of work is on-going in the Injectors to meet the HL-LHC requirements and on the performance enhancement for ions for Run 3 and Run 4*

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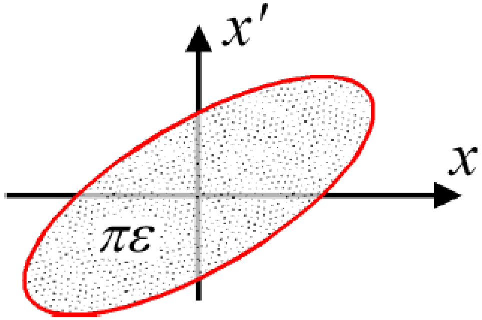
The Quest for Luminosity

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

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

(Round beams)



- To maximize L:
  - Many bunches (k) ➔ tight bunch spacing
  - Many protons per bunch (N_b)
  - Small emittance ε*

High beam “brightness” N_b/ε^*

(particles per phase space volume)

→ Injector chain performance !

→ Preservation in the LHC !!

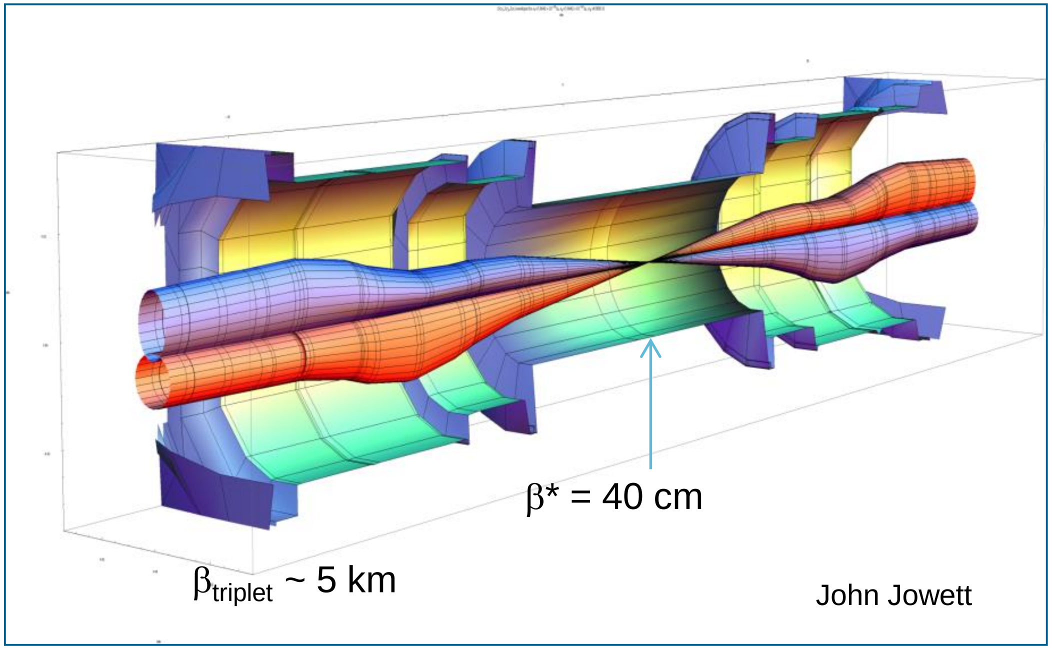
- Small β*
- Maximize the parameter F (<1) depending on the crossing angle

LHC Optics/Configuration

What limits β*?

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \boxed{\beta^*} \varepsilon^*} F$$

- The triplet quadrupoles in the high luminosity IRs define the machine aperture limit for squeezed beams, β* is constrained by:
  - the beam envelope
  - the crossing angle



John Jowett

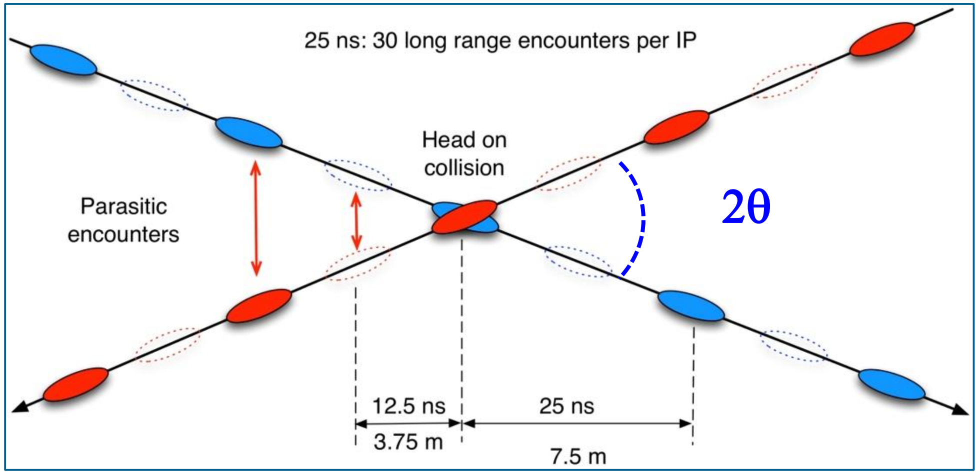
Crossing angle

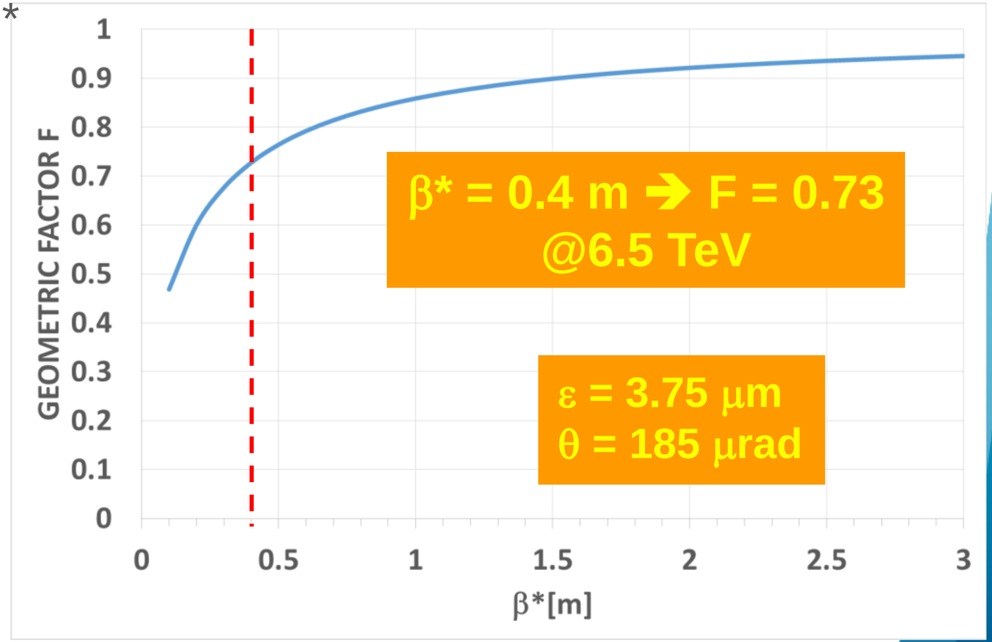
$$L = \frac{k N_b^2 f \gamma}{4 \pi \beta^* \varepsilon^*} \boxed{F}$$

- Needed to avoid parasitic collisions and minimize beam-beam effects
- Drawbacks:
  - luminosity geometric reduction factor due to bunch length σ_s and crossing angle θ becomes significant for low β^* (small beam sizes)

$$F = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_{x/y}} \tan\theta \right)^2}}$$

  - Reduction of the aperture



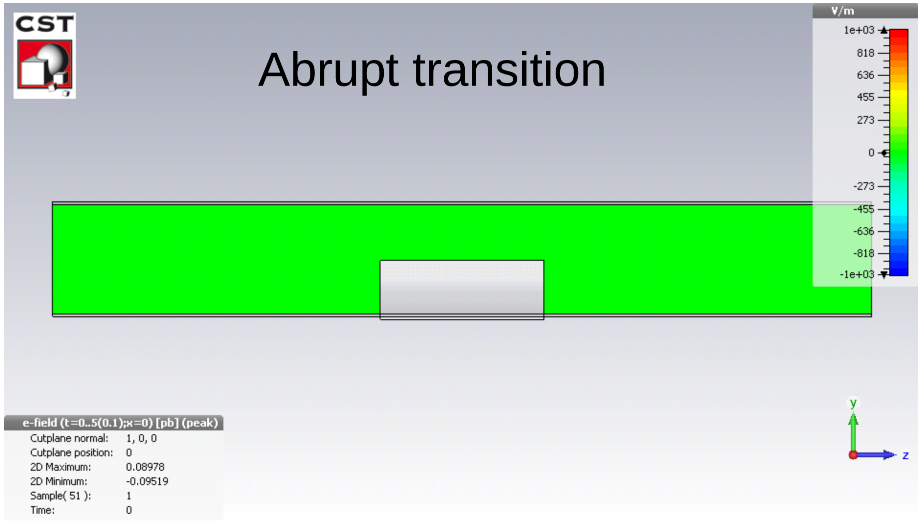


β* = 0.4 m ➔ F = 0.73 @6.5 TeV

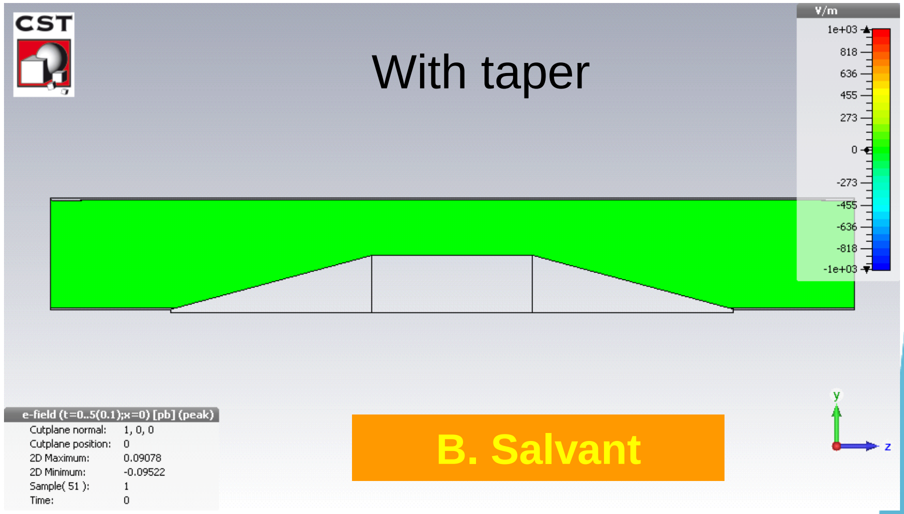
ε = 3.75 μm
θ = 185 μrad

Wake fields and Impedances

- Intense bunches generate electromagnetic fields when passing inside a structure (in particular Carbon collimators – opening of O(1 mm)!!!)
- → results in wake fields coupling with the beam and generating beam instabilities and emittance blow-up


Abrupt transition

e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.08978
2D Minimum: -0.09519
Sample(51): 1
Time: 0

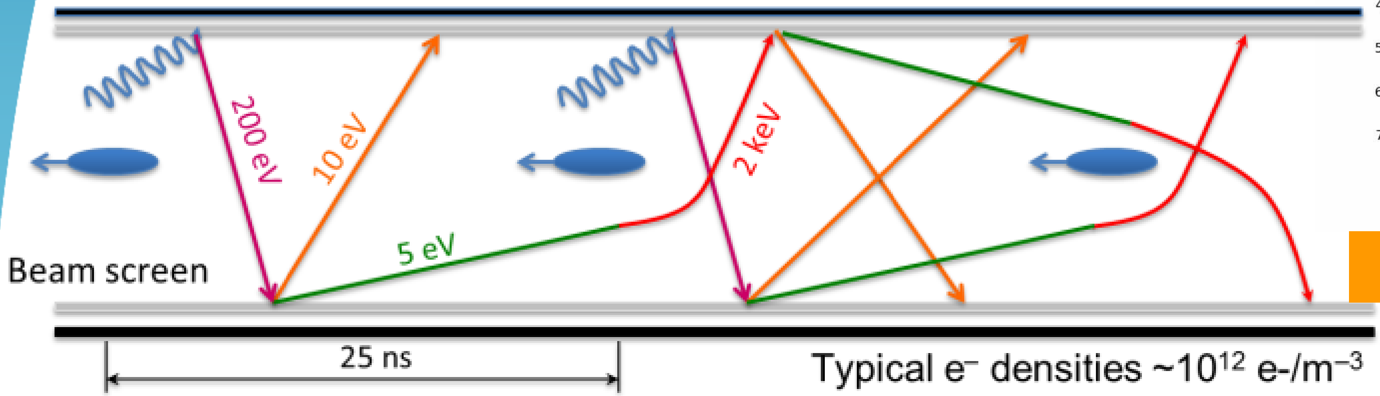

With taper

e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.09078
2D Minimum: -0.09522
Sample(51): 1
Time: 0

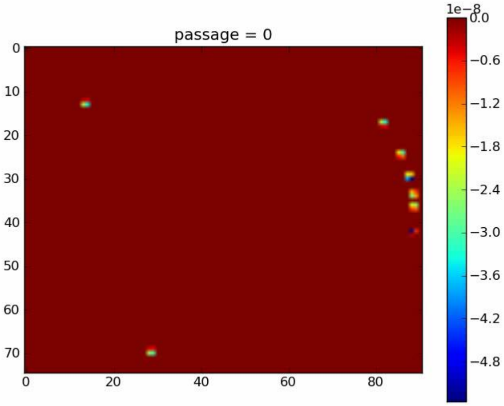
B. Salvant

- Avoid the abrupt transition for the beam fields at the location of the beam passage (taper)
- Reduce the resistivity of the material

Electron cloud effects



Typical e⁻ densities ~10^{12} e-/m^{-3}



G. Iadarola, G. Rumolo

Secondary Emission Yield [SEY]
SEY>SEY$_{th}$ ➔ avalanche effect (multipacting)

Possible consequences:

- instabilities, emittance growth, desorption, vacuum degradation, background
- energy deposition in cryo surfaces

Electron bombardment of a surface has been proven to reduce **SEY** of a material as a function of the delivered electron dose. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

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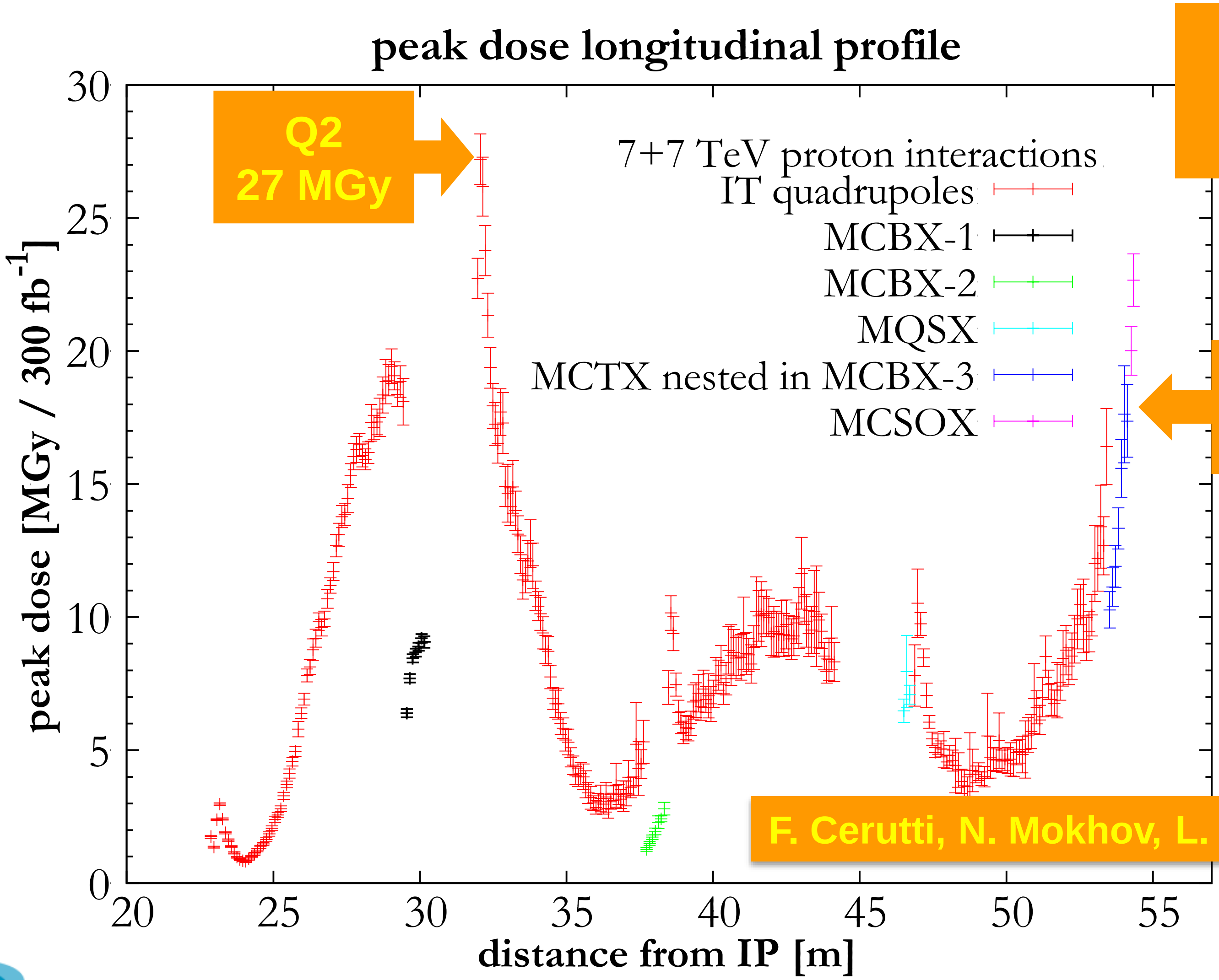
Summary: 2010-2016

Parameter	2010	2011	2012	2015-16	Nominal
Energy [TeV]	3.5	3.5	4.0	6.5	7.0
N_b [10^{11} p/bunch]	1.2	1.45	1.6	1.15	1.15
k (no. bunches)	368	1380	1380	2244/2040	2808
Bunch spacing [ns]	150	75 / 50	50	25	25
Stored energy [MJ]	25	112	140	280	362
ε^* [μm]	2.4	2.4	2.5	3.5	3.75
β^* [m]	3.5	1.5 → 1	0.6	0.8 → 0.4	0.55
Full crossing angle [μrad]	200	240	290	290 → 370	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	0.76	0.5/0.9	1.0
Beam-beam parameter/IP (ΔQ_{bbho})	-0.005	-0.006	-0.007	-0.003	-0.003
Average Pile-up @ beg. of fill	8	17	38	28	26

Limitations: Triplet radiation damage



Q2
27 MGy

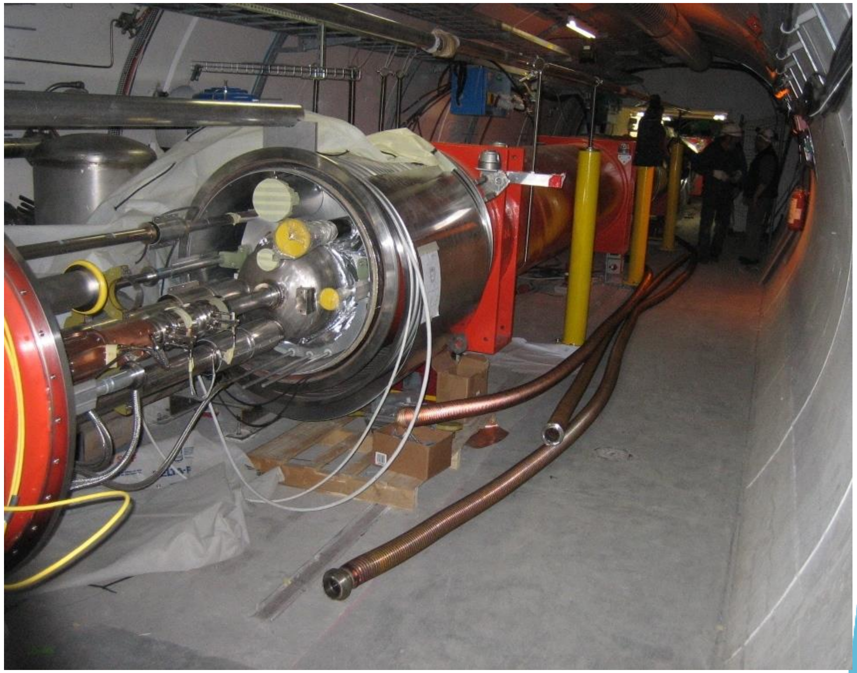
Cold bore insulation
≈ 35 MGy

MCBX3
20 MGy

F. Cerutti, N. Mokhov, L. Esposito,…

Limitations - Magnets

- Max. heat load due to luminosity debris on the cold mass of the inner triplets as a result of the reduction of the diameter of the bayonet heat exchanger (in 2007)
- Maximum instantaneous luminosity ~1.7×10^{34} $cm^{-2}s^{-1}$



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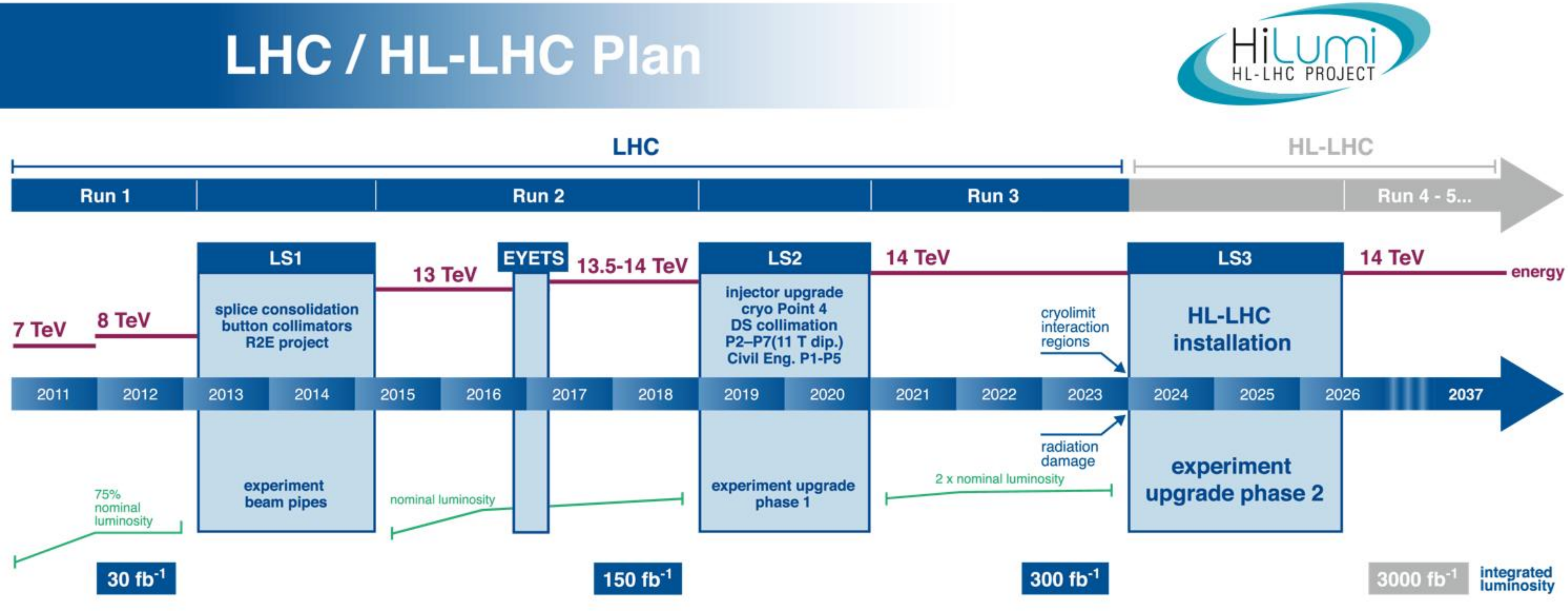
- HL-LHC: why and how?

Timeline & Goals



HL-LHC Goals

- Determine and implement a hardware configuration and a set of beam parameters allowing the LHC to reach the following targets:
  - Prepare machine for reliable operation beyond 2025 and up to ~2040 ➔ Remove LHC technical bottlenecks and limitations
  - Enable the production of **3000 fb^{-1}** by 2037 ➔ **250 fb^{-1}/yr**,
    - operating at max. average pile-up μ **~ 140** (➔ peak luminosity of ~**5×10^{34} cm^{-2} s^{-1}**) compatibly with detector capabilities

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

Ingredients for the Upgrade

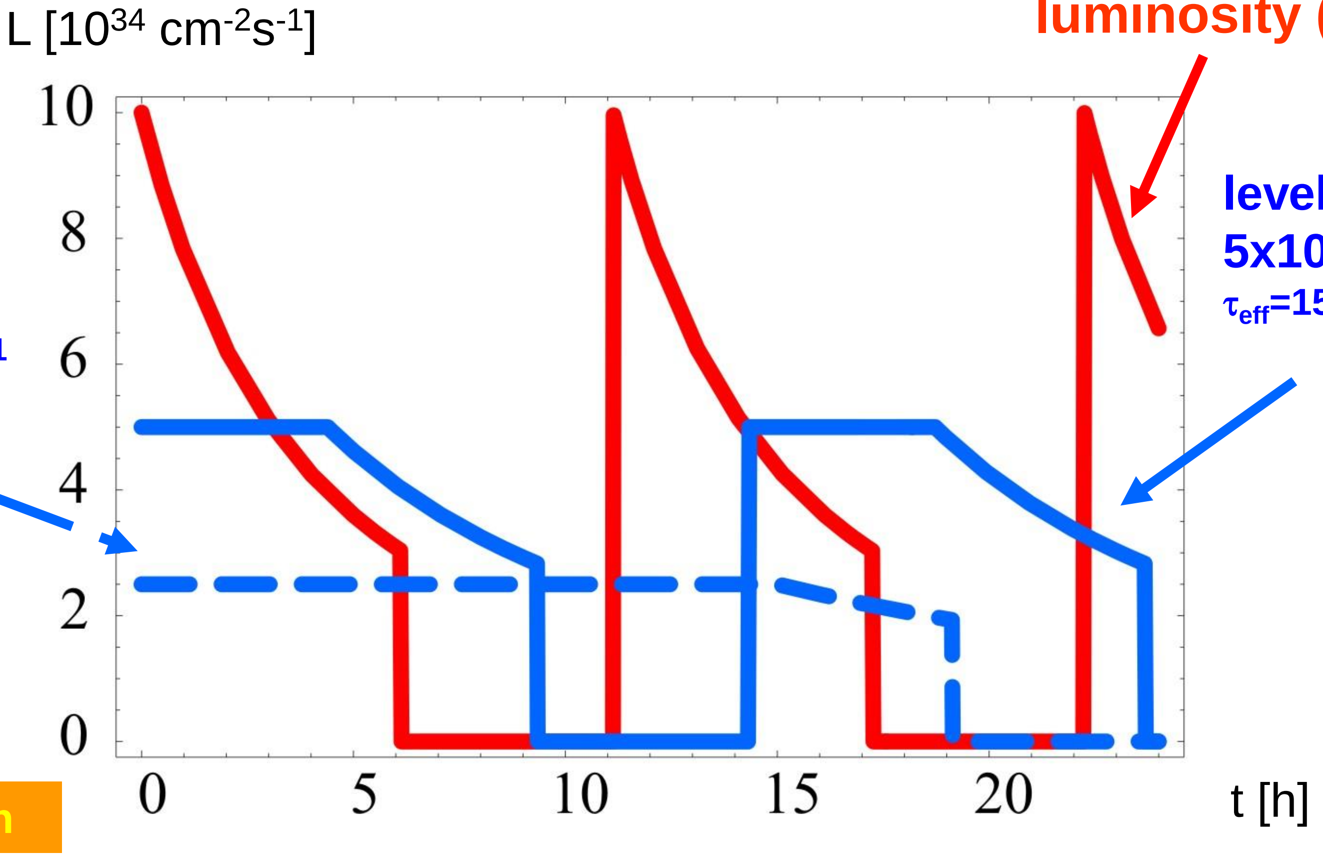
$$L = \frac{kN_b^{\ 2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

- Operation at pile-up/pile-up density limit (set by the experiments) by choosing parameters that allow higher than design pile-up:
  - Beam brightness and in particular bunch population to sustain burn-off over long periods ➔ LHC Injector Upgrade
  - Maximize number of bunches to minimize pile-up ➔ 25 ns
  - Low β* optics
  - Large crossing angle to minimize the beam-beam effects
  - Fight the reduction factor F by crab crossing

- Improve 'Machine Efficiency' ➔ minimize the number of unscheduled beam aborts

Ingredients for the Upgrade

$$L = \frac{kN_b^2 f \gamma}{4\pi \boxed{\beta^*} \varepsilon^*} F$$



Virtual peak luminosity (F=1)

leveling at 5×10^{34}cm^{-2}s^{-1}

τ_{eff}=15 h, T_{ta}=5 h

leveling at 2.5×10^{34}cm^{-2}s^{-1}

τ_{eff}=30 h, T_{ta}=5 h

F. Zimmermann

HL-LHC Parameters

Parameter	**Nominal**	**HL-LHC**
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.12
Stored Beam Energy [MJ]	362	677
Full crossing angle [μrad]	285	590
Beam separation [σ]	9.9	12.5
Min β^* [m]	0.55	0.15
Normalized emittance ε_n [μm]	3.75	2.5
r.m.s. bunch length [m]	0.075	0.081
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	21.3 (7.2)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.1
Levelled Pile-up/Pile-up density [evt. / evt./mm]	26/0.2	140/1.25

Challenges

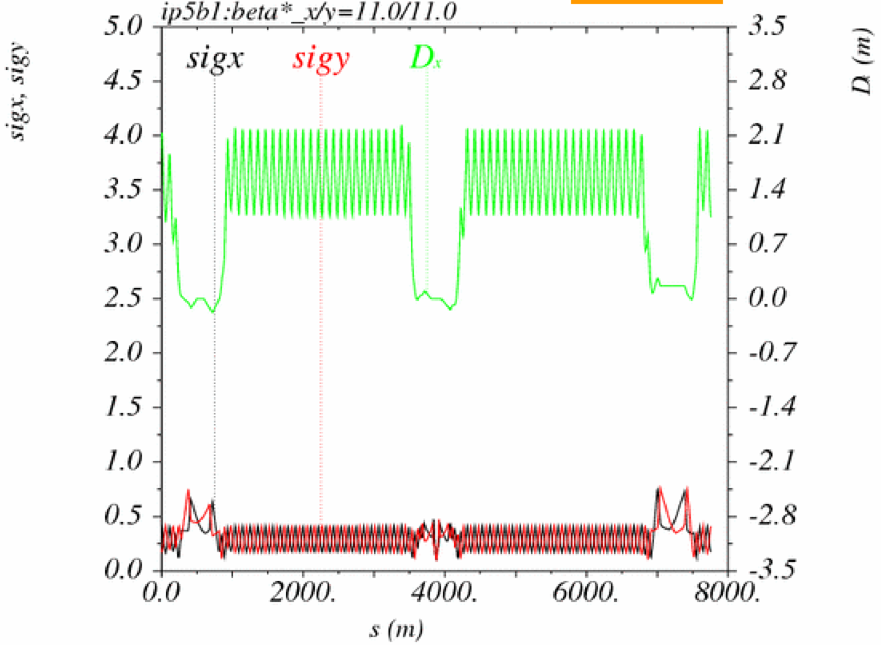
- Low β* optics and large aperture triplets
- Operation of the crab cavities in a high intensity hadron machine
- Operation with large stored energy ➔ halo, losses ➔ collimation
- Beam stability and minimization of impedance
- Electron cloud mitigation with 25 ns beams
- Reliability!!

Low β*

- An “almost” standard squeeze (local to IP1/5), **(pre-squeeze)**
- A further reduction of β* **(squeeze)**: acting on IR2/8 for squeezing IR1 and IR4/6 for IR5, inducing β-beating in adjacent sectors ➔ large crossing angle ➔ larger aperture triplet (reduced gradient ➔ longer) and matching section

ATS=Achromatic Telescopic Squeeze

β* [m]



IR4

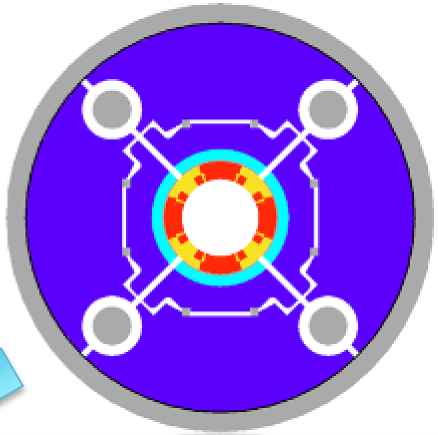
IR5

IR6

S. Fartoukh

From LHC to HL-LHC triplets

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

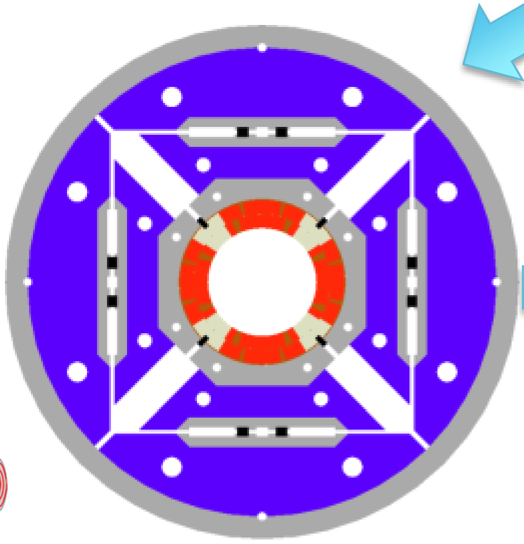


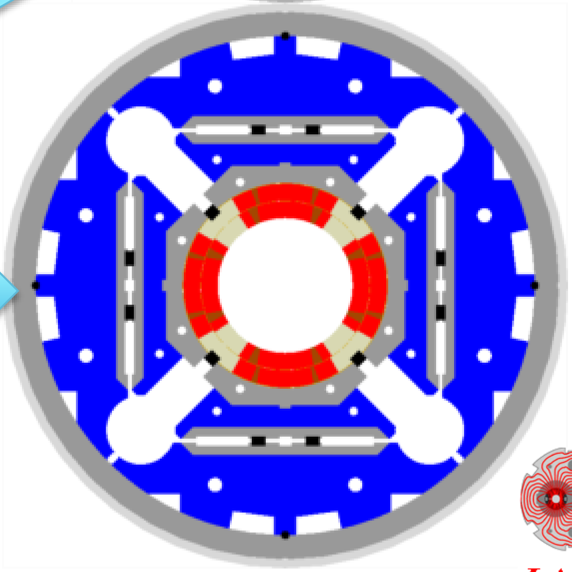
LARP

LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
Nb_3Sn
2004-2010

LARP HQ, ∅120 mm,
B_{peak}~ 12 T
Nb_3Sn
2008-2014

LARP





LARP & CERN
MQXF,∅150 mm,
B_{peak}~ 12.1 T
Nb_3Sn
2013-2020

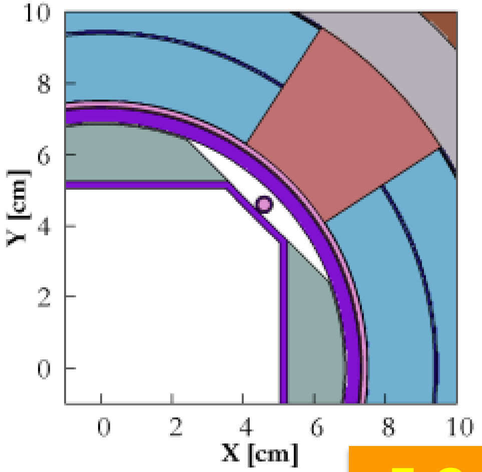
LARP

Shielding against Radiation Damage

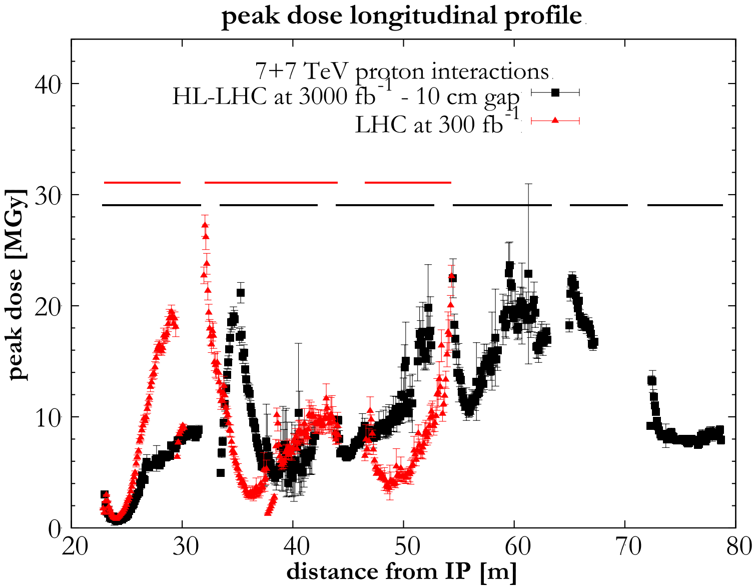
- Tungsten shielding on the beam screen 16 mm in Q1 and 6 mm elsewhere

- More than 600 W in the cold masses as well as in the beam screen (i.e. 1.2-1.3 kW in total)!! ➔ New Cryogenics plants

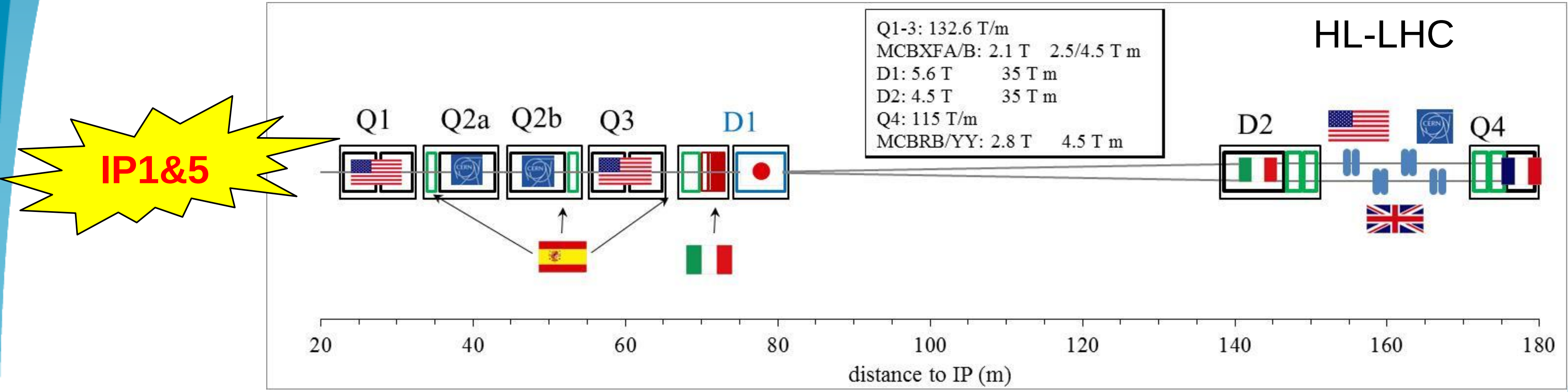
- Expect same integrated radiation dose in HL-LHC after 3000 fb^{-1} as in LHC after 300 fb^{-1}!!



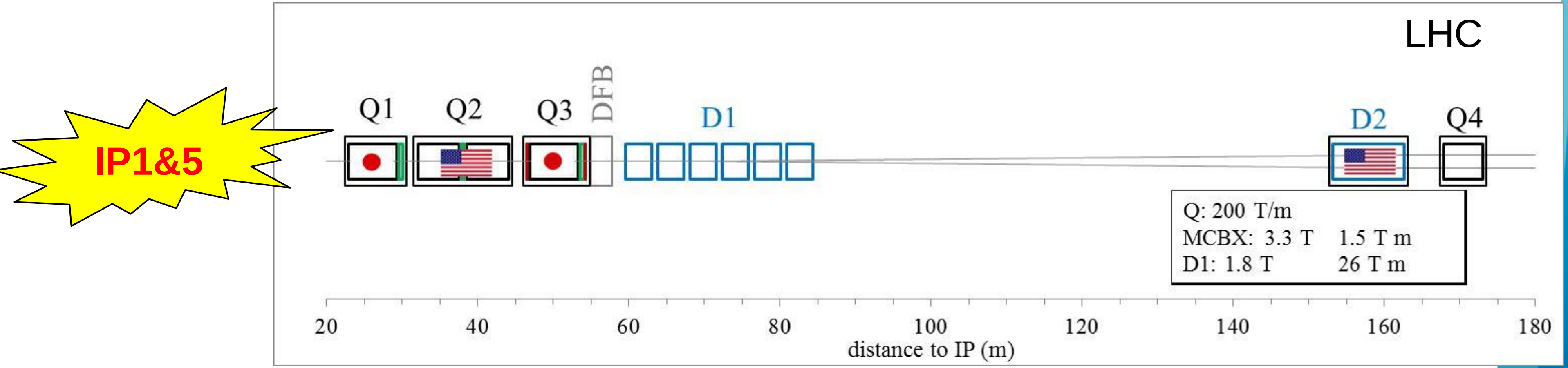
F. Cerutti, L. Esposito



The HL-LHC Interaction Region



Q1-3: 132.6 T/m
MCBXFA/B: 2.1 T 2.5/4.5 T m
D1: 5.6 T 35 T m
D2: 4.5 T 35 T m
Q4: 115 T/m
MCBRB/YY: 2.8 T 4.5 T m

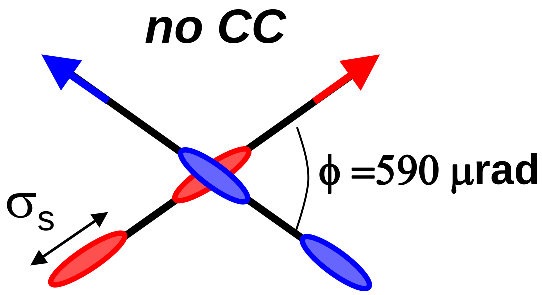


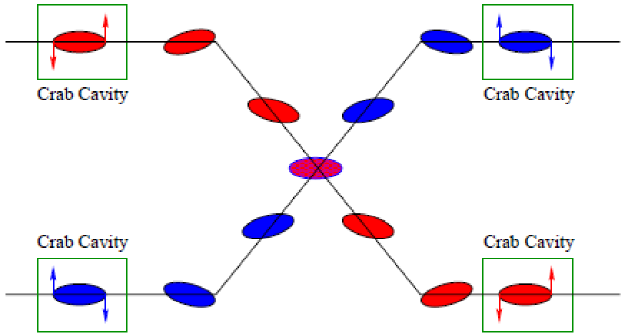
Q: 200 T/m
MCBX: 3.3 T 1.5 T m
D1: 1.8 T 26 T m

Crab cavities

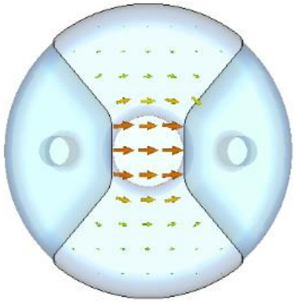
$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} \boxed{F}$$

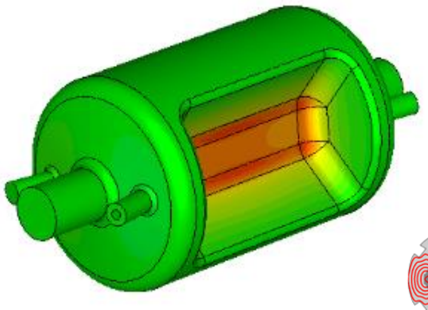
- Crab-cavities (CC) to deflect the bunch head and tail transversely to counteract the luminosity loss from the large crossing angles and small beam sizes at HL-LHC and to reduce pile-up density
  - On both sides of IP1 and IP5





Transverse Electric Field





- CCs have never been used in a hadron machine there are many challenges: noise on the beam, machine protection etc. ➔ SPS tests in 2018 ➔ Staged Installation (2 crab cavities/IP side/beam)

Collimation Upgrade

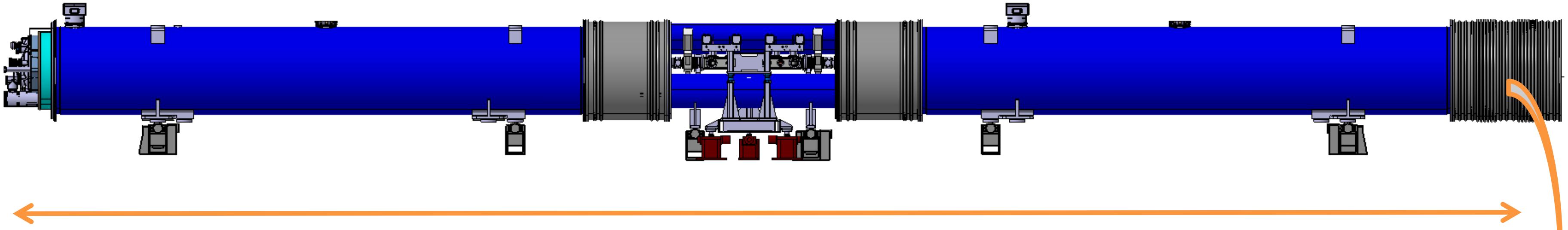
- Worry about beam losses:
  - Failure Scenarios ➔ Local beam Impact
    - Equipment damage
    - Machine Protection
  - Lifetime & Loss Spikes ➔ Distributed losses
    - Magnet Quench
    - Radiation to Electronics and Single Event Upsets
    - Machine efficiency

- New collimators in the Dispersion Suppressors around the betatron collimation section (LSS7)

- Hollow electron lens for halo depletion (not yet in the baseline but being considered)

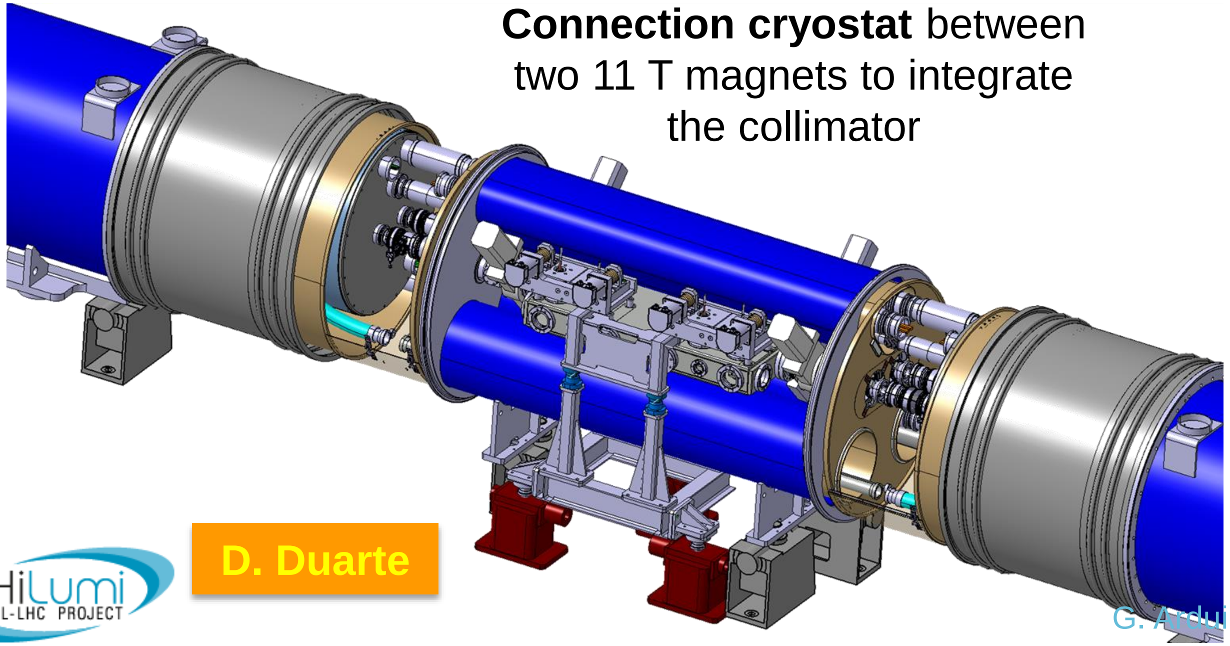
Dispersion Suppressor Collimators with 11 T Dipoles

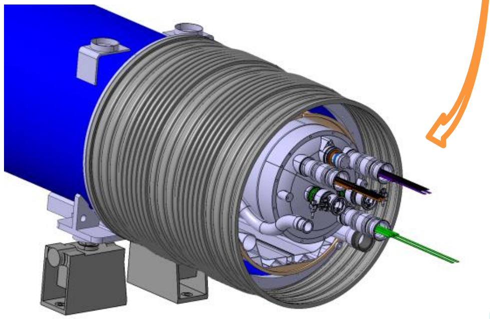
LHC MB replaced by **3 cryostats + collimator**, all independently supported and aligned:



Same 15660 mm length between interconnect planes as an LHC MB

Connection cryostat between two 11 T magnets to integrate the collimator

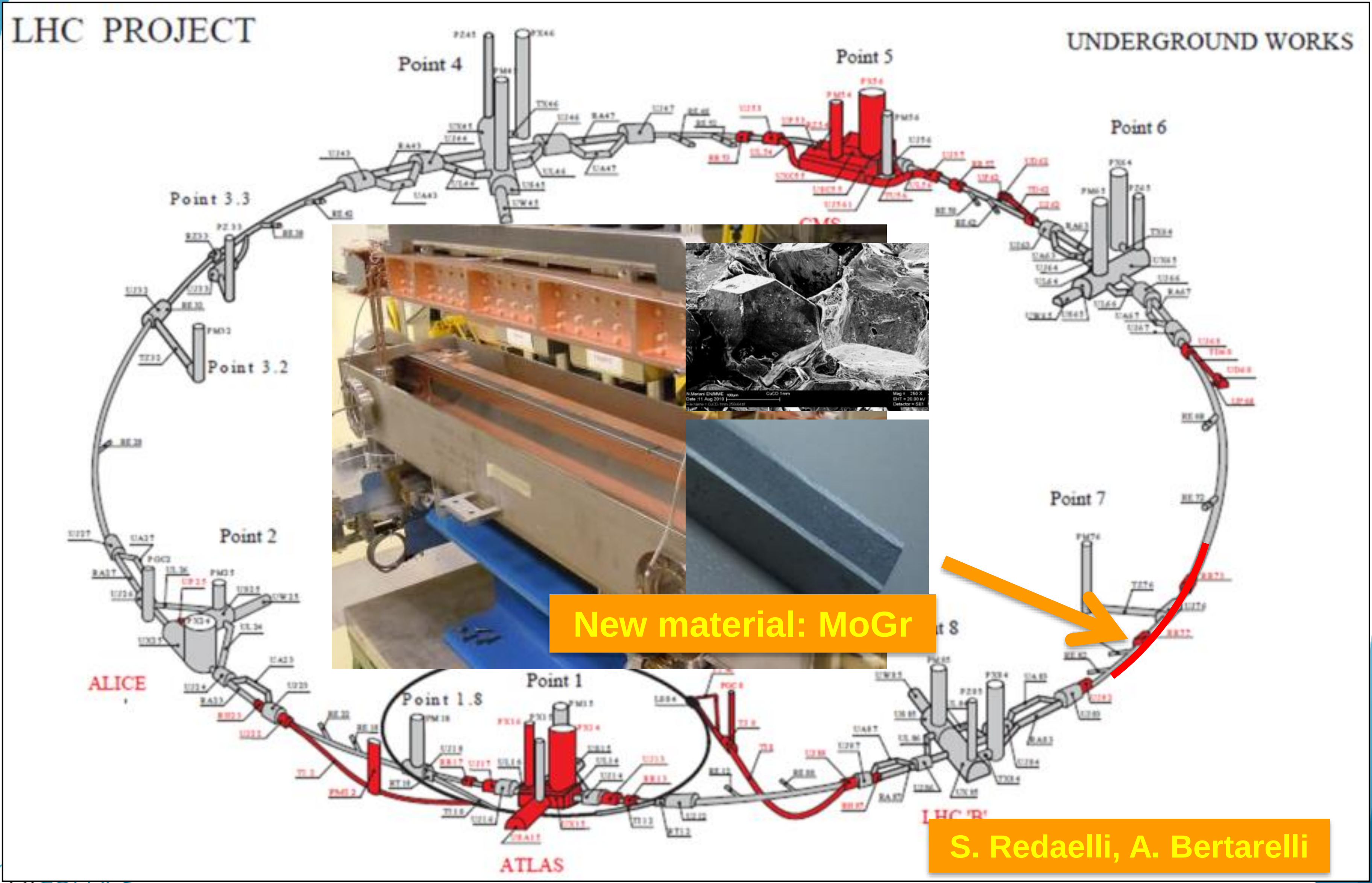




Same interfaces at the extremities: **no changes to nearby magnets**, standard interconnection procedures & tooling

D. Duarte

Low Impedance Collimators in LSS7

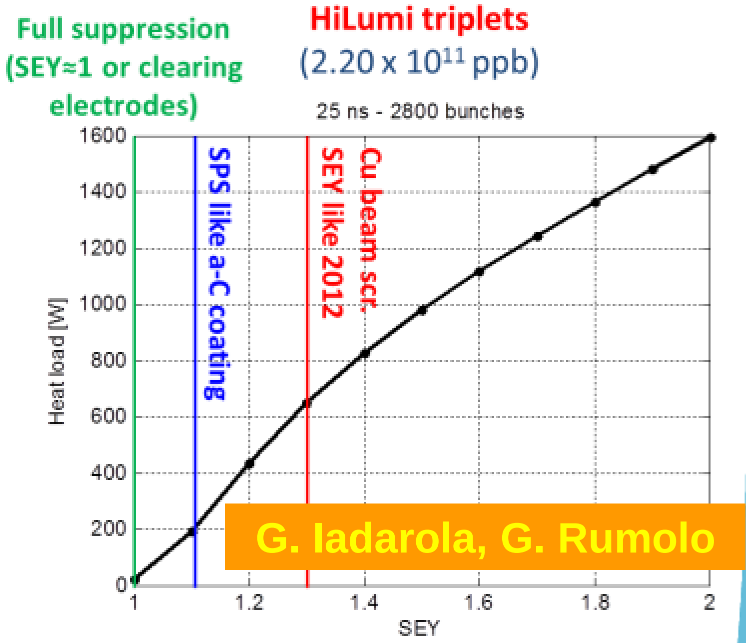


New material: MoGr

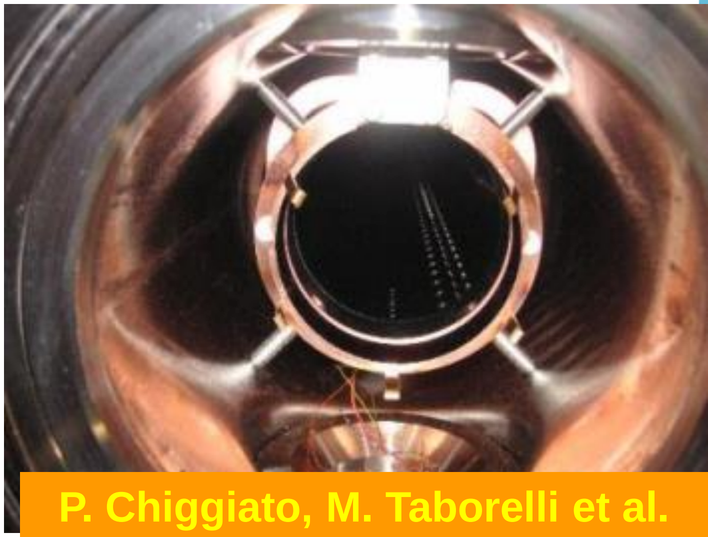
S. Redaelli, A. Bertarelli

25 ns operation (e-cloud)

- HL-LHC triplets/matching section + Triplet/D1 in IP2 and 8:
  - Expect no suppression of the electron cloud with scrubbing ➔ a-C coatings (SEY ~ 1.1) to minimize heat load on the beam screen.
- Laboratory and in-situ tests (SPS) ongoing to characterize the properties of these coatings at room and cryogenic temperatures
- Irradiation tests to evaluate aging effects.

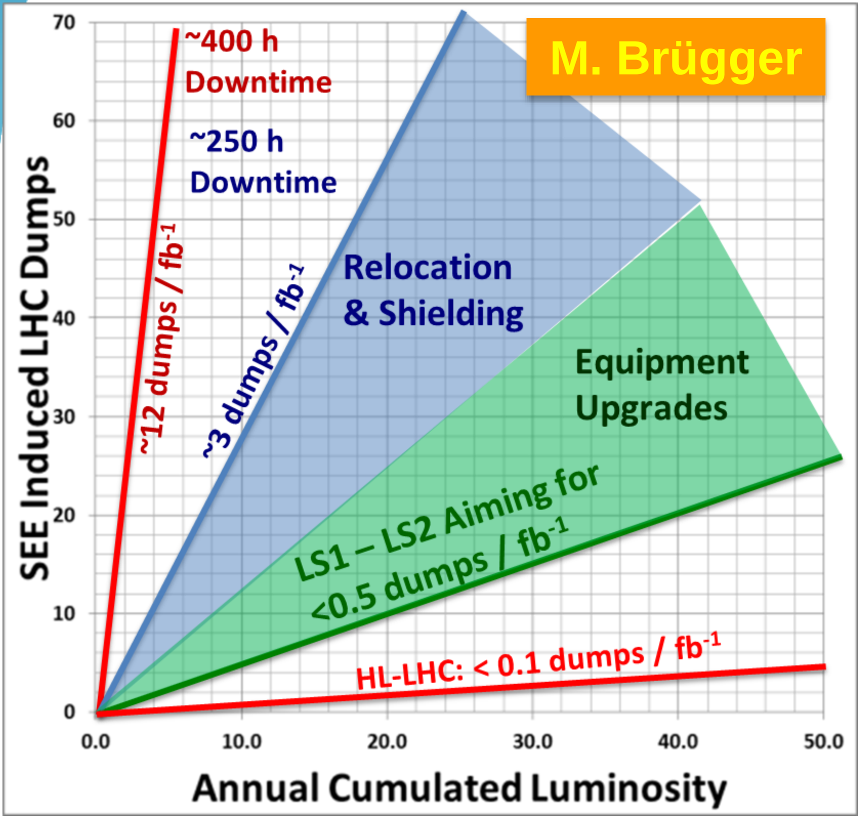


G. Iadarola, G. Rumolo



P. Chiggiato, M. Taborelli et al.

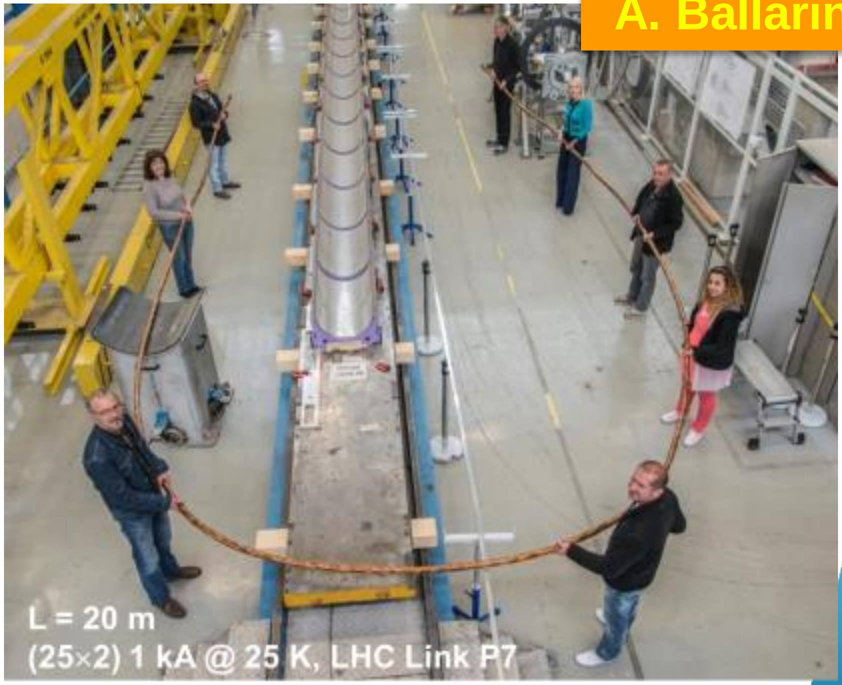
Radiation to Electronics (R2E)



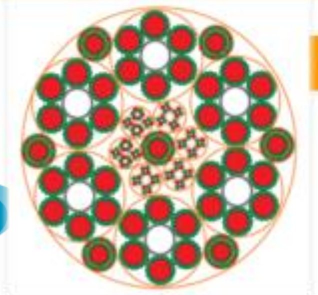
M. Brügger

- R2E consolidation during LS1 not sufficient for the HL-LHC era (~2 fb^{-1}/ day) ➔ 1 dump/day due to SEU
- PC far from tunnel ➔ SC links (HTS)
- QPS systems out of the tunnel

A. Ballarino

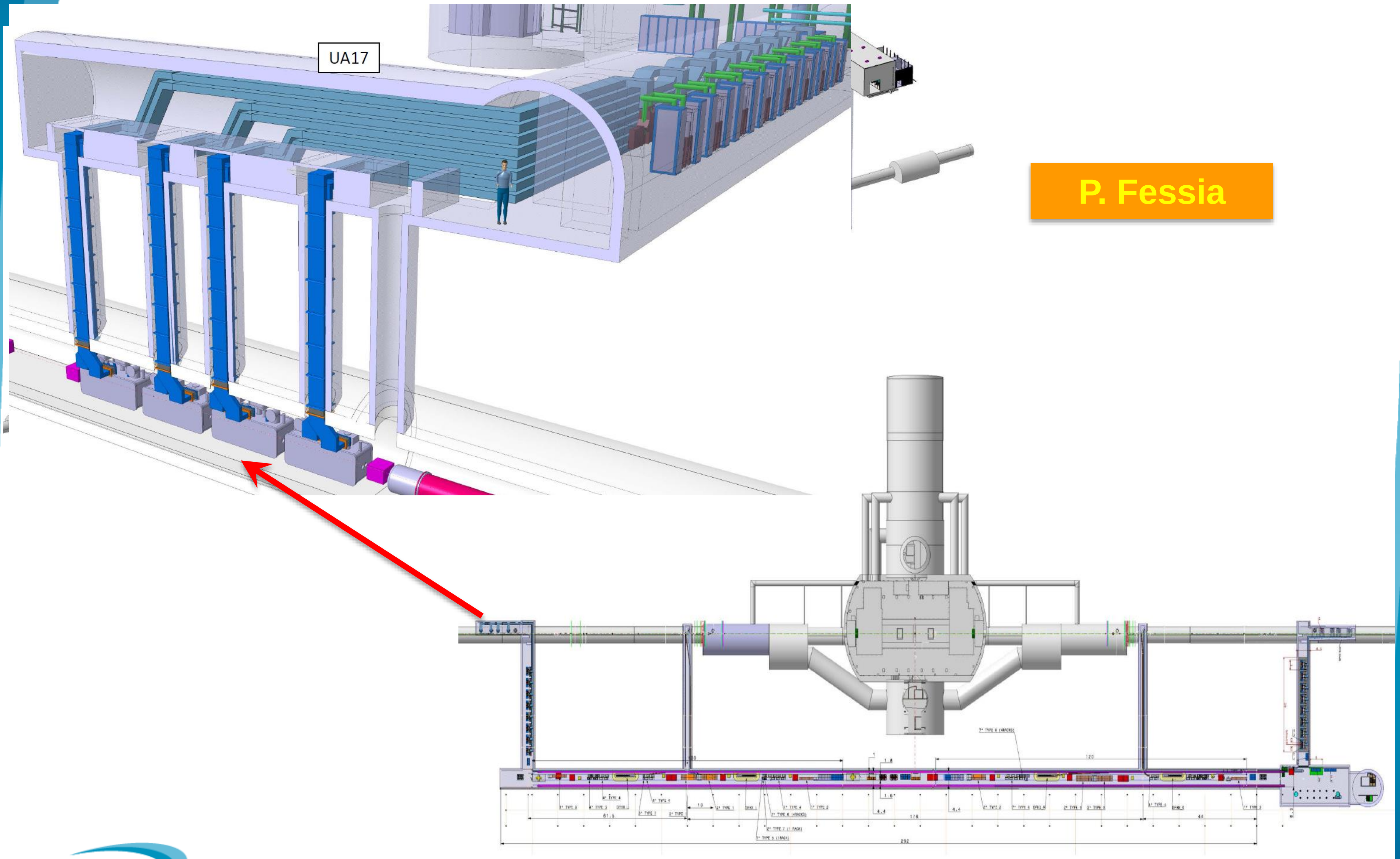


Φ = 65 mm, $|I_{tot}|$=150 kA



Φ = 0.98 mm

Civil engineering



P. Fessia

Concluding remarks

- The progress in the performance of the LHC has been so far breath-taking
  - Some of the (beam dynamics) challenges and limitations have been outlined
  - We are exploring (and mastering) higher energies and operation with 25 ns (all but trivial). Aim for 300 fb^{-1} by the end of Run 3
  - This experience is providing critical input for the LHC upgrade
- Luminosity performance and choices for the upgrade are now constrained by the acceptable detector pile-up/pile-up density
  - To reach 3000 fb^{-1} by ~2037 we are pushing even further the above challenges…
  - New technologies are being developed (with enormous progress in recent years) to achieve these parameters

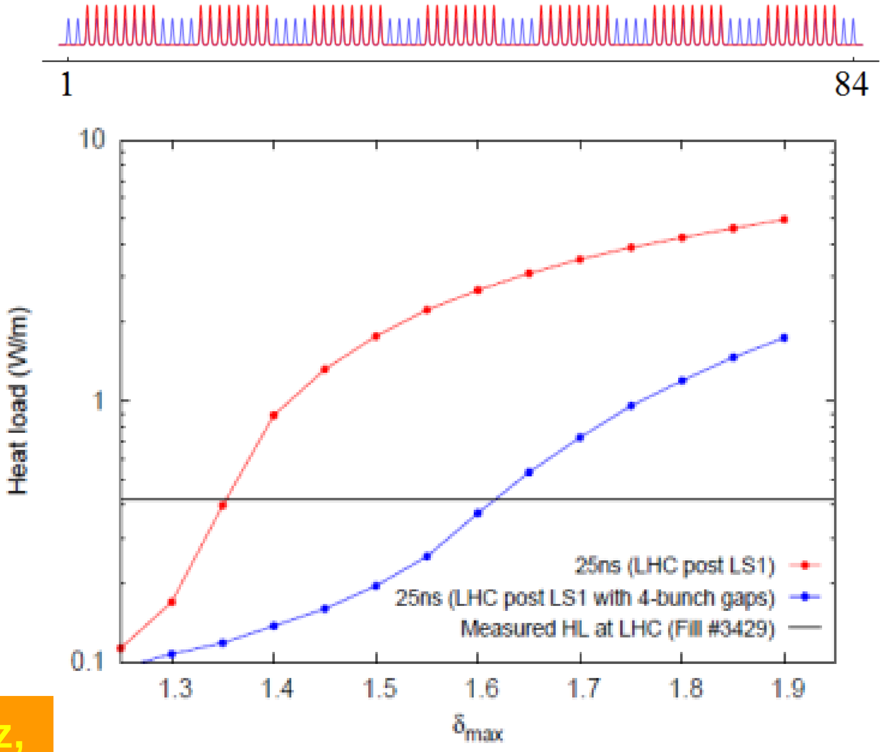
Thank you for your attention!

Acknowledgements: N. Biancacci, O. Brüning, R. Bruce, P. Chiggiato, S. Claudet, R. De Maria, S. Fartoukh, M. Giovannozzi, G. Iadarola, E. Métral, Y. Papaphilippou, T. Pieloni, S. Redaelli, L. Rossi, G. Rumolo, B. Salvant, E. Shaposhnikova, R. Tomas and many others...

25 ns operation (e-cloud)

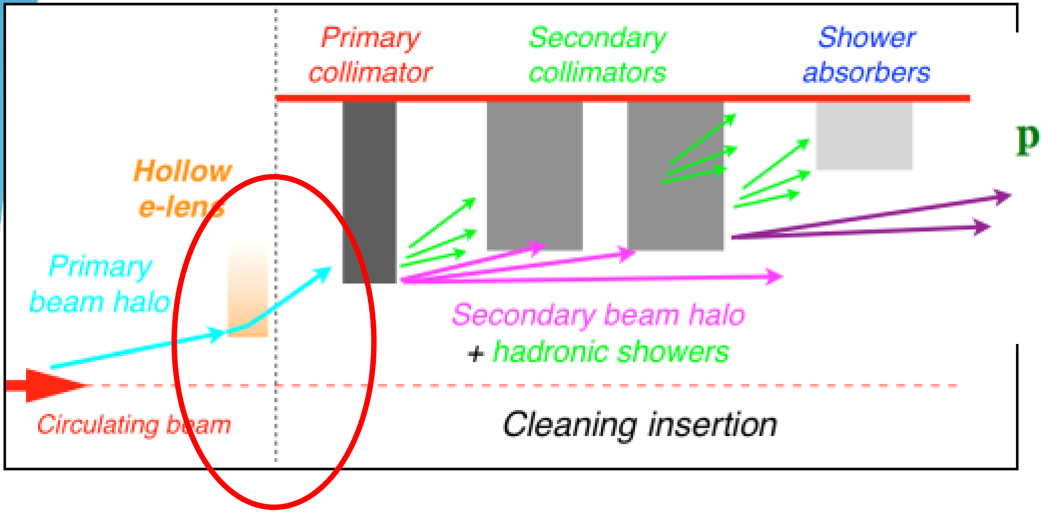
- Relies on scrubbing to suppress electron cloud in the dipoles (heat load and beam stability)

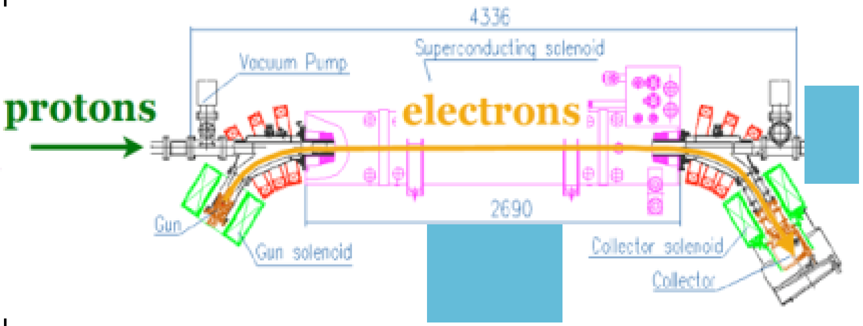
- Alternatives:
  - ‘ad-hoc’ 25 ns filling schemes to minimize electron cloud build-up (e.g. 8b+4e scheme) ➔ reduction of the integrated luminosity to 190 fb^{-1}/y (w.r.t. ~260 fb^{-1} for nominal scenario) but with longer fills (9 to 10 h)

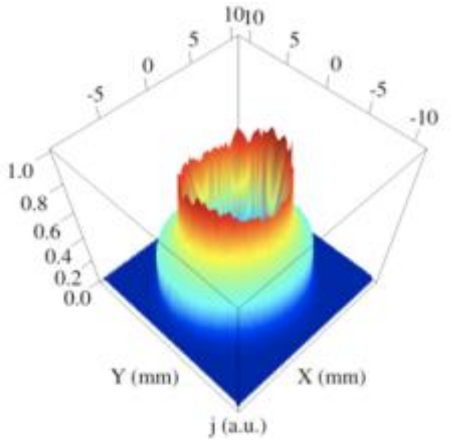


H. Damerau, O. Dominguez, G. Iadarola, G. Rumolo

Halo control: hollow e-lens







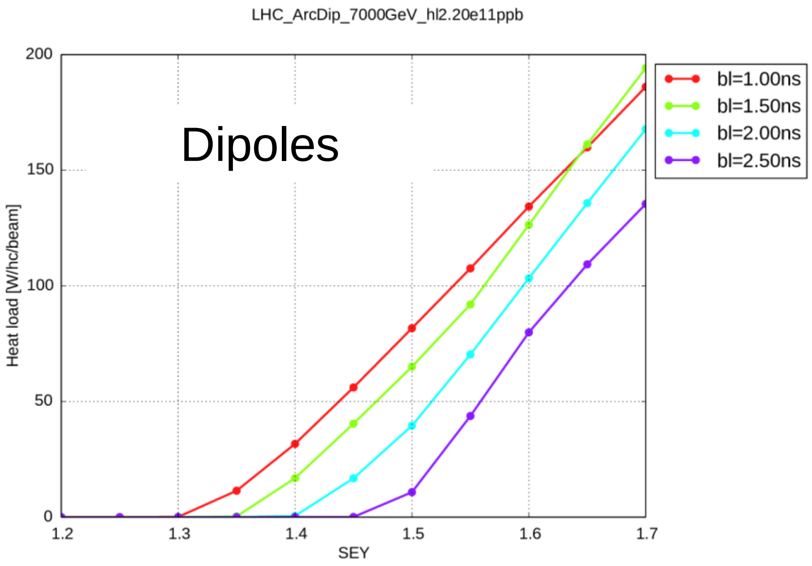
- Potential of hollow e-lens:
  - Control the halo dynamics without affecting the beam core;
  - Control the time-profile of beam losses (avoid loss spikes);
  - Control the steady halo population (crucial in case of CC fast failures).

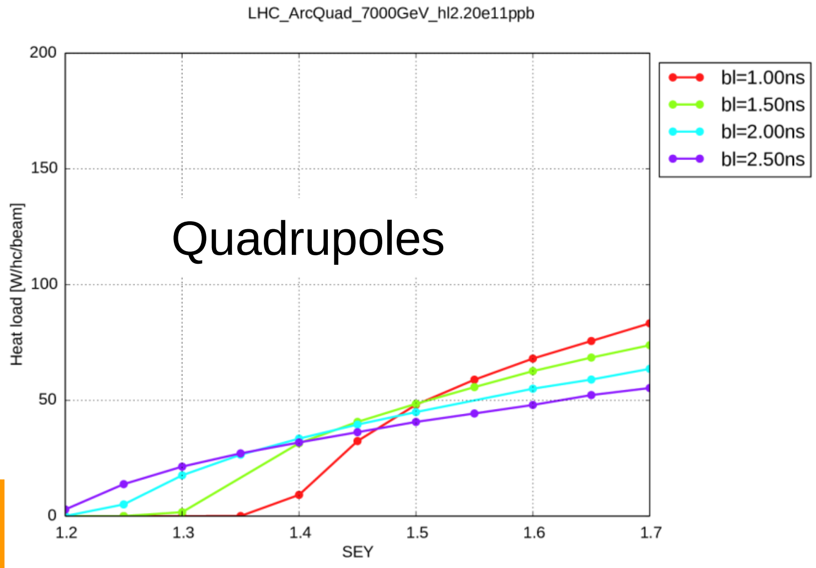
S. Redaelli
Collaboration with FNAL

200 MHz

- Longer bunches captured on a 200 MHz system could significantly reduce electron cloud effects:
    - Strong beneficial effect on dipoles (main limitation)
    - Weak effect on quadrupoles, even detrimental for low SEY
- Negligible reduction of the integrated luminosity
- Beam-beam effects studied and did not show any show-stopper
- Need to take a decision by 2018 in order to be ready for LS3

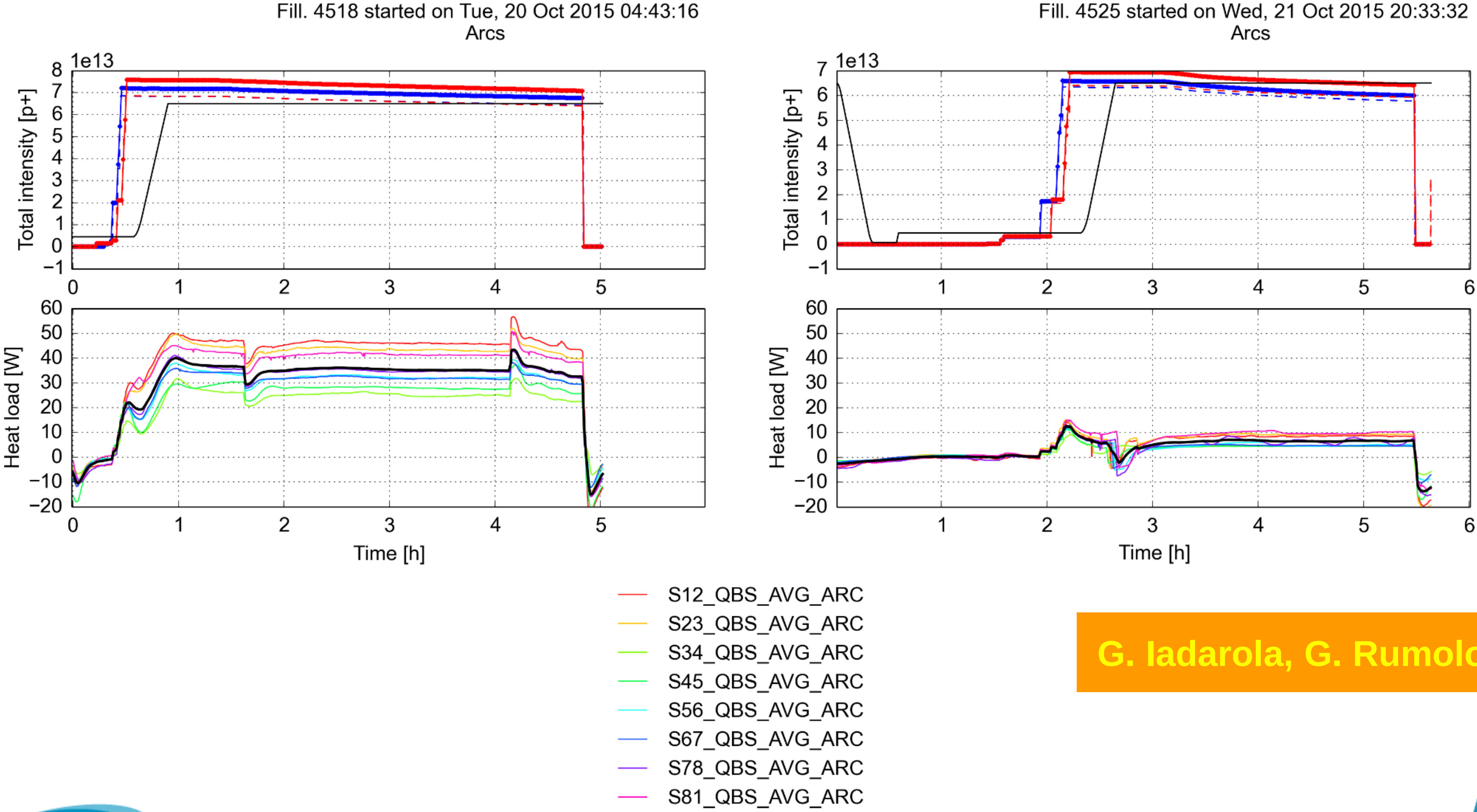
G. Iadarola, G. Rumolo, R. Tomas





8b+4e: a validated alternative

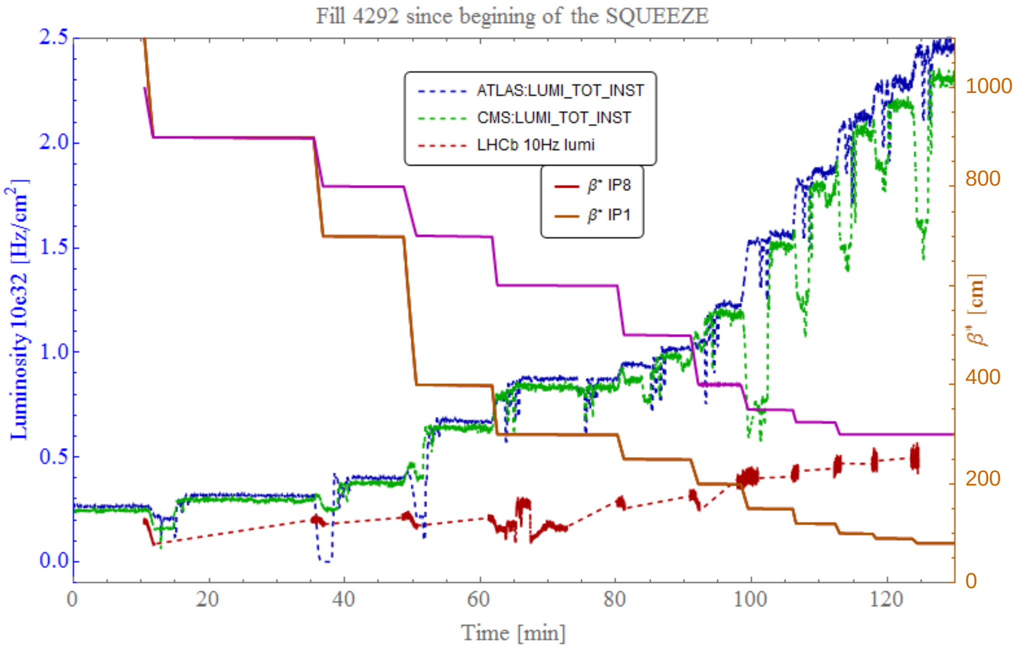
Standard 25 ns **8b+4e**



G. Iadarola, G. Rumolo

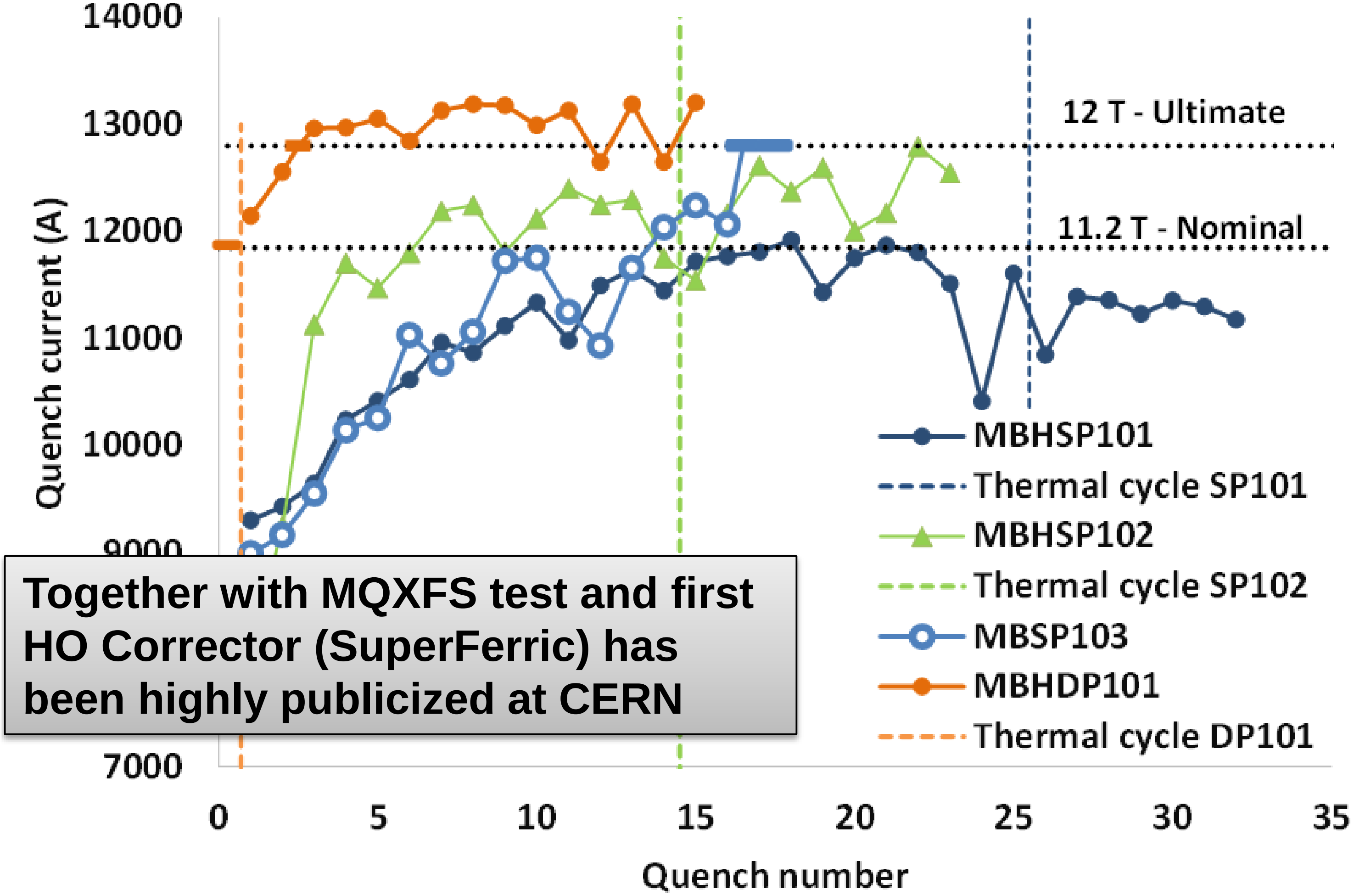
β* levelling

- Successful test (at low intensity) with 3 points collided and squeezed at the same time:
    - Reproducible and deterministic
    - Change in beam separation below **1 sigma** (green band) in most cases.
    - Good agreement between the applied luminosity trims and separation values tracked by the BPMs (IP1/IP5) ➔ can be used for active feedback (next step)



A. Gorzawski, J. Wenninger

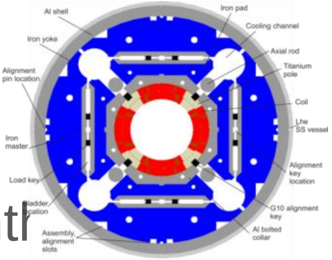
11 T dipole recent results



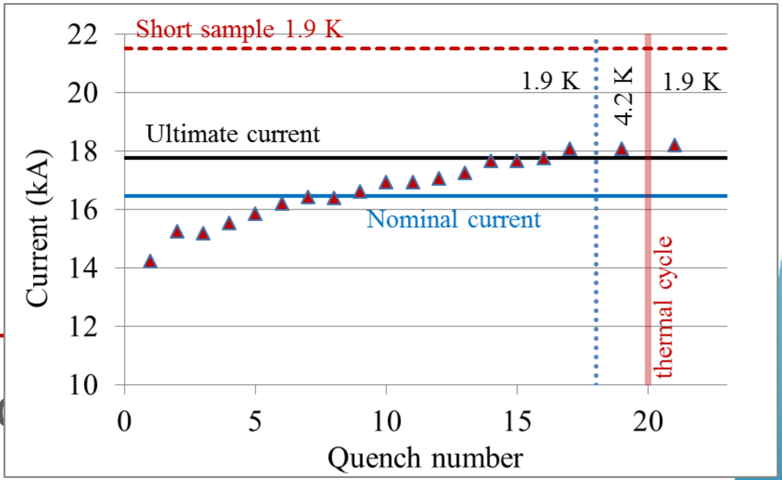
Together with MQXFS test and first HO Corrector (SuperFerric) has been highly publicized at CERN

- Total number of quenches at 1.9 K: 86
- Very limited detraining after thermal cycles, apart from coil 107
- 94 % of short sample reached.

- Nb$_3$Sn quad in collaboration with US, 11.5 T peak field
  - Q1/Q3 from US, Q2a Q2b from CERN [see P. Ferracin talk]
  - Same cross-section, common program for short model
- Status: model
  - First short model successfully tested in March (~6 month
    delay)
    - Ultimate reached, perfect memory after thermal cycle
  - Included two CERN and two LARP coils
    - Second test with larger load in July



- Status: prototype
  - In BNL mirror test in July (4.2 m)
  - At CERN tooling being commission
  - Winding of 7 m coil (copper) started



MQXFS1a test result [G. Chlachidze, et al.]

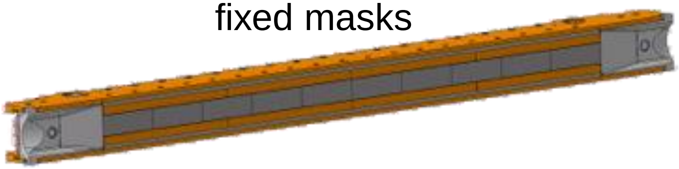
Baseline upgrades

Completely new layouts

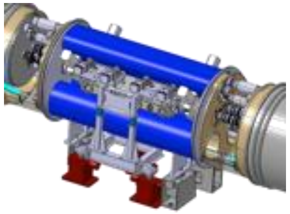
Novel materials: TCTs in CuCD

IR1+IR5, per beam:

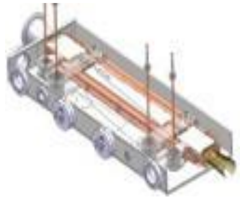
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

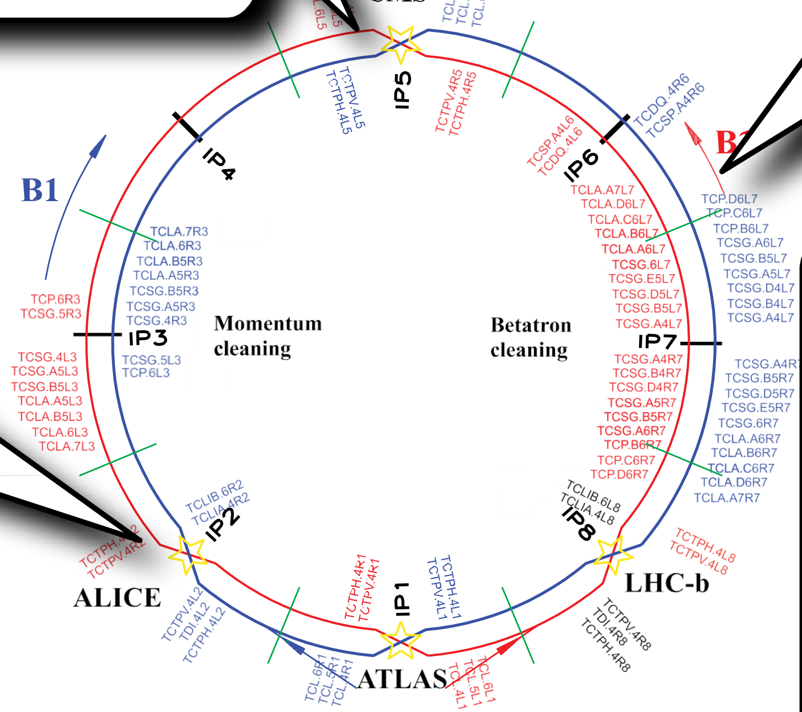


Cleaning: DS coll. + 11T dipoles, 2 units per beam

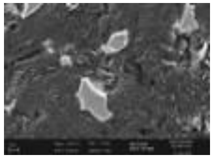


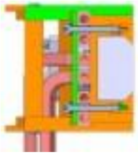
Ion physics debris: DS collimation

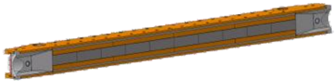




Low-impedance, high robustness secondary collimators: Mo coated MoGr

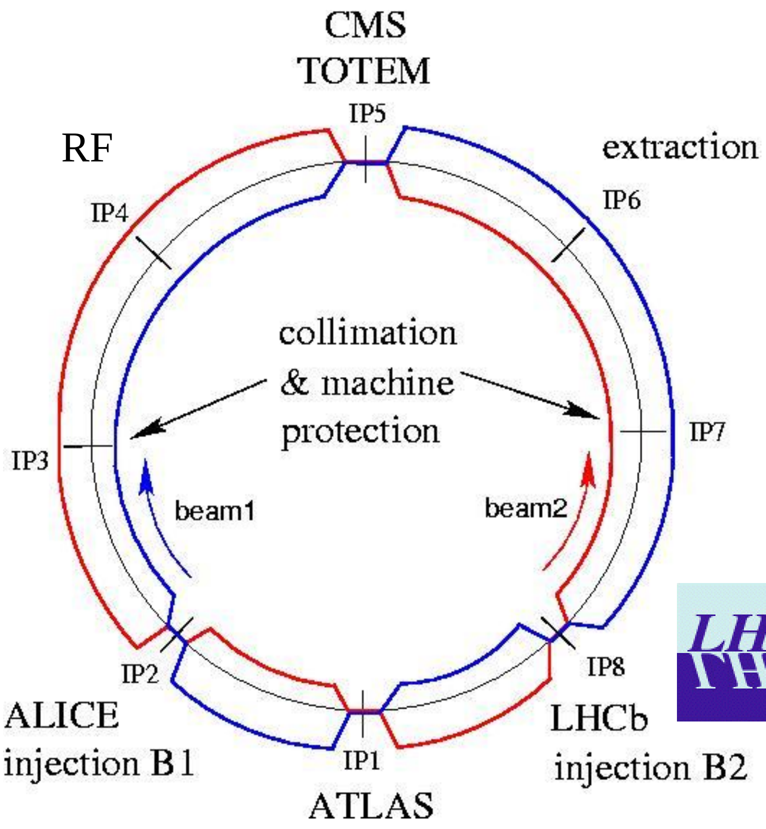






LHC layout

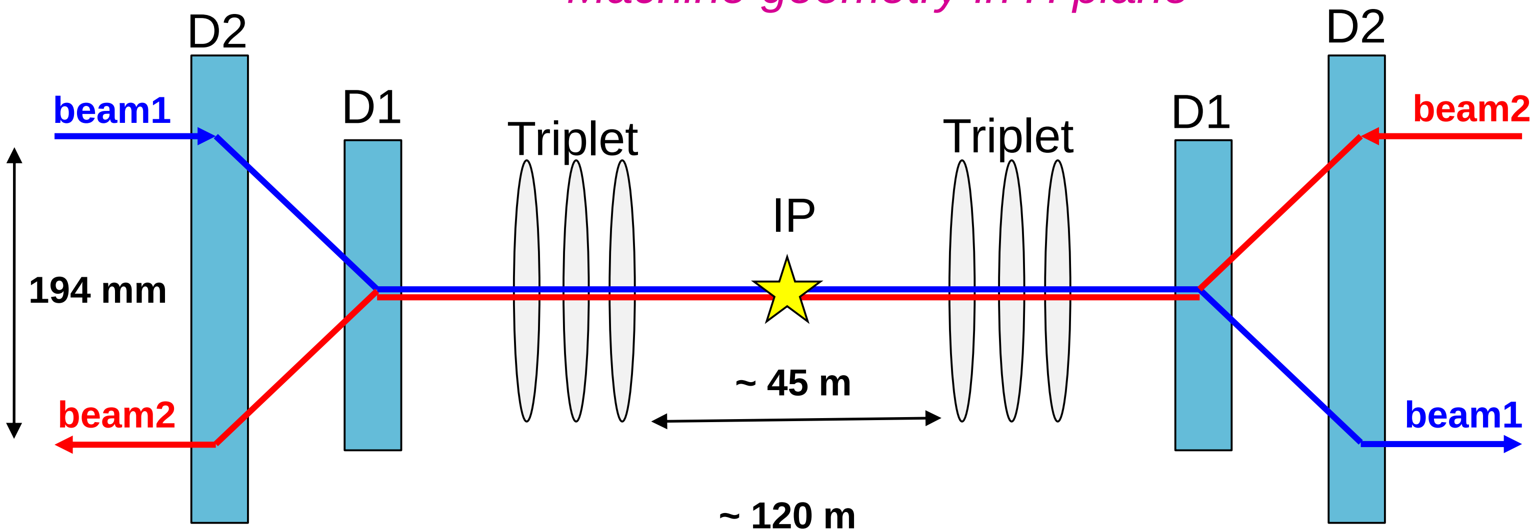
- Total length: ~26.7 km
  - 8 arcs (aka sectors): ~2.8 km each
  - 8 long straight sections: ~700 m each
- 2-in-1 magnet design with separate vacuum chambers
  - p-p, ion/ion, or p/ion collisions
  - beams cross in 4 points



Interaction regions geometry

- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane,
- The beams move from inner to outer bore (or vice-versa),
- The triplet quadrupoles are used to focus the beam at the IP.

Machine geometry in H plane

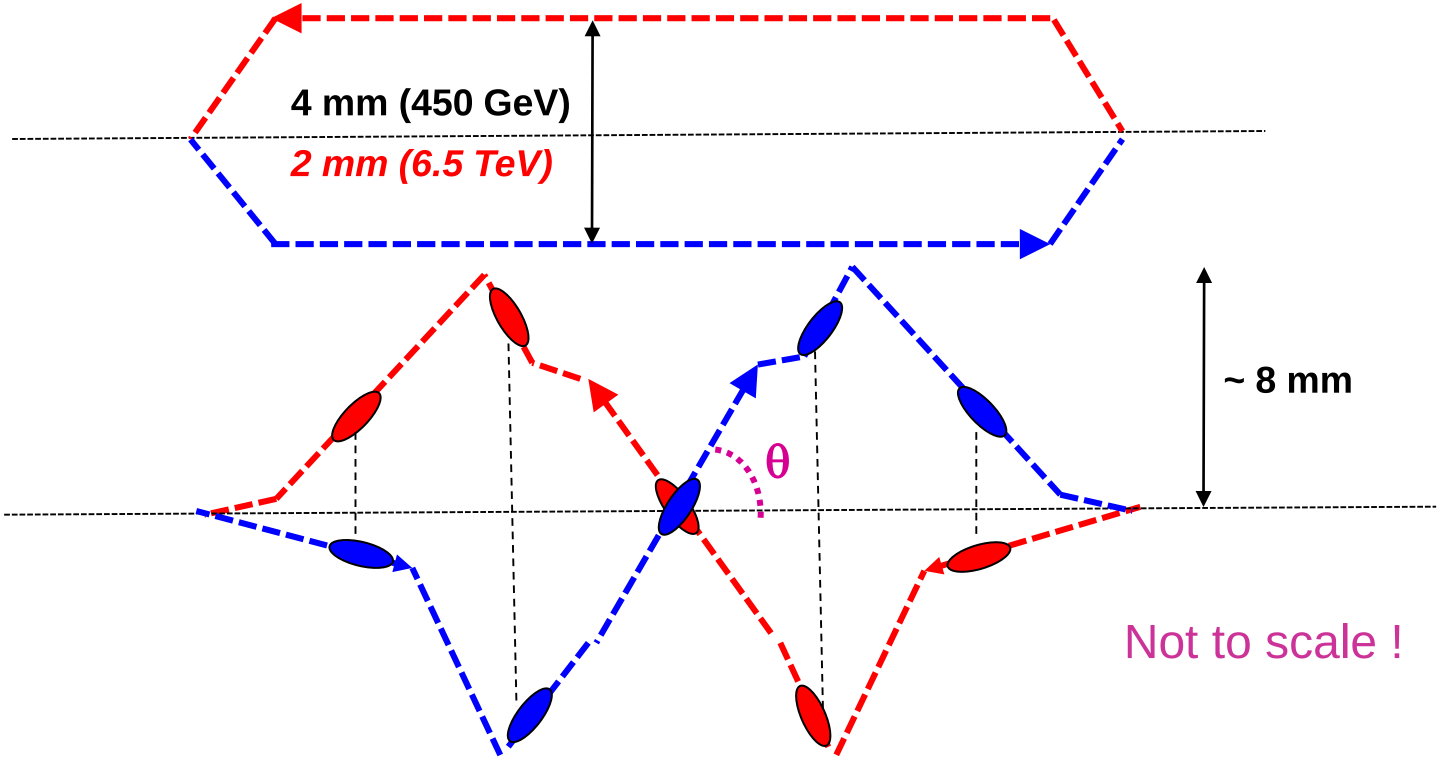


D1,D2 :
separation/recombination dipoles

Common vacuum chamber

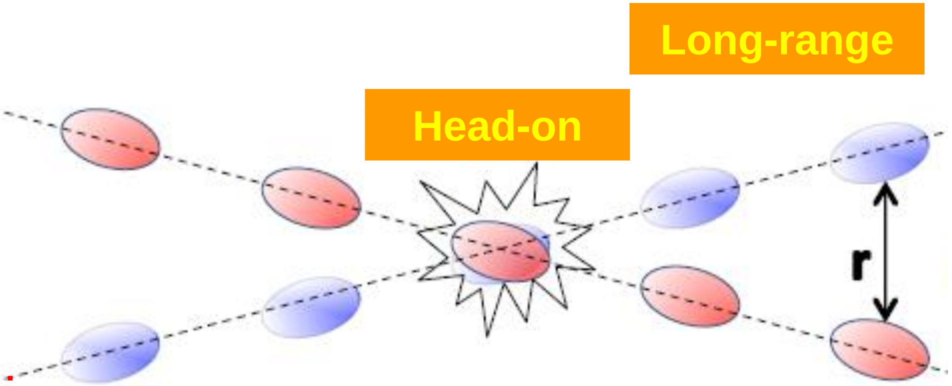
Separation and crossing

- Because of the tight bunch spacing and to prevent undesired parasitic collisions in the common vacuum chamber:
  - Parallel separation in one plane, collapsed to bring the beams in collision
  - Crossing angle in the other plane



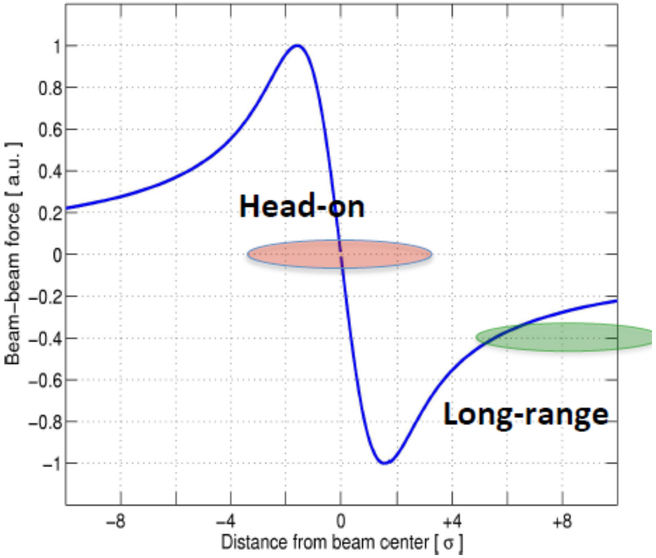
Not to scale !

Beam-beam effects



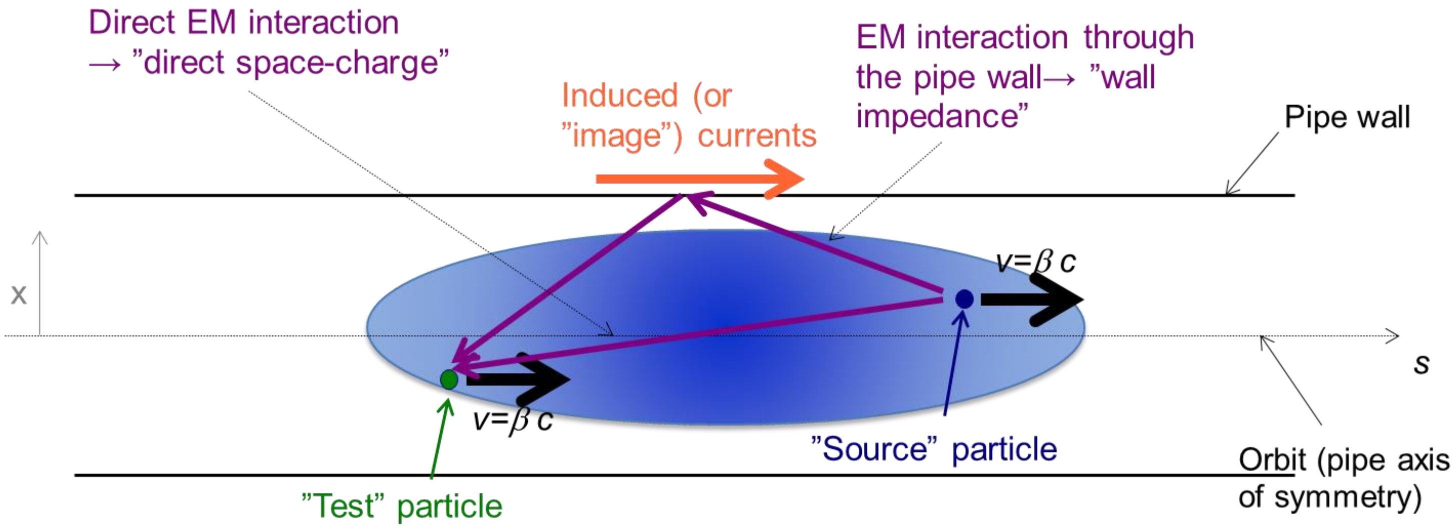
$$\Delta Q_{bb} \propto \frac{N_b}{\varepsilon_n}$$

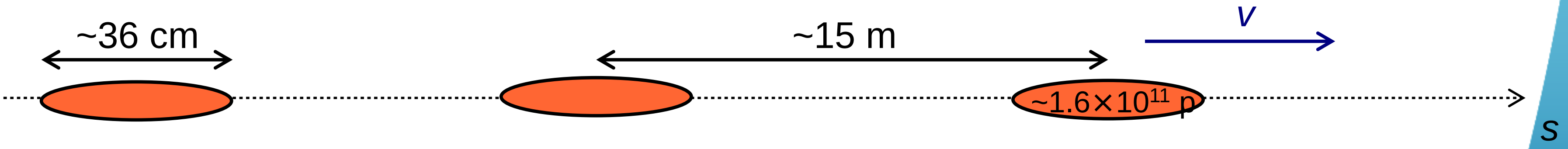
- Strong non linear fields when counter-rotating beams share vacuum chamber.
- ➔ spread in betatronic frequencies ➔ risk of overlapping resonances driven by magnetic errors
- Minimize magnetic field errors and noise ➔ Paid off for the LHC
- Devise correction schemes and sorting ➔ Paid off for the LHC
- Initially expected to have limit at ΔQ_{BB} ~ 0.003/IP ➔ exceeded by a factor 2



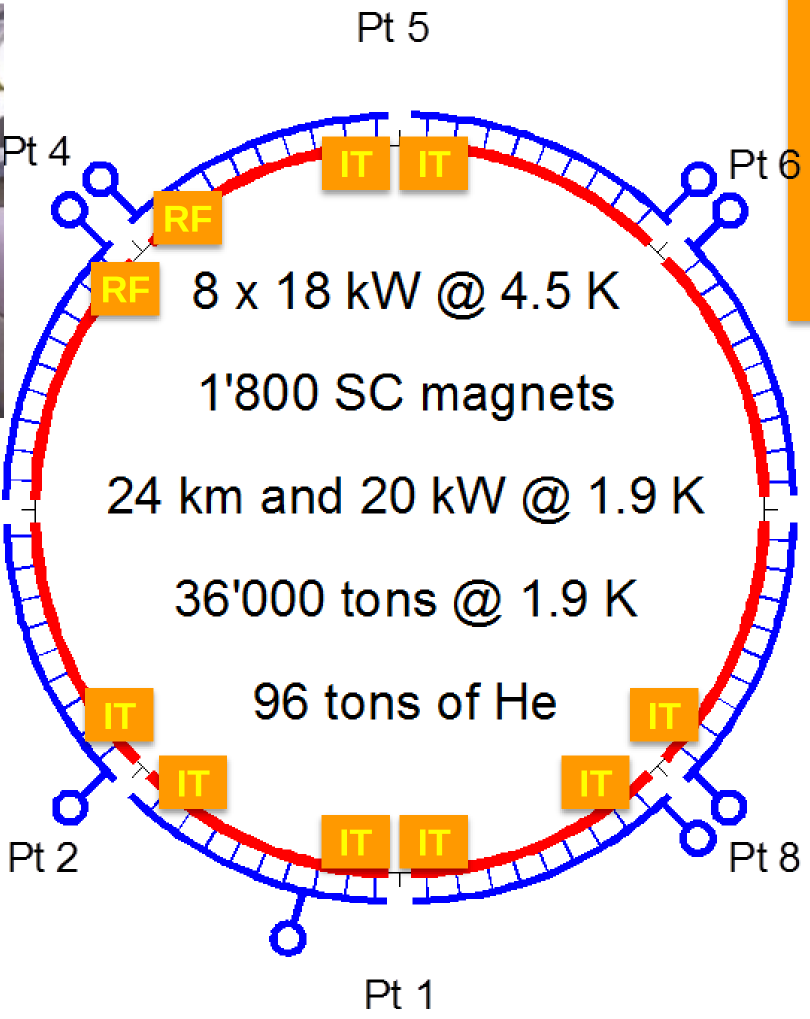
Wake fields and instabilities

- Wake fields can couple the head and tail of a bunch or consecutive bunches leading to instabilities





Limitations: Cryogenics



8 x 18 kW @ 4.5 K

1'800 SC magnets

24 km and 20 kW @ 1.9 K

36'000 tons @ 1.9 K

96 tons of He

○ Cryogenic plant

Cryo power limitation in Pt 4, interdependency of different systems, reduced flexibility and no/little redundancy