Crab Cavity failure modes and IR protection

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Joint HiLumi LHC-LARP'
Annual Meeting 2015

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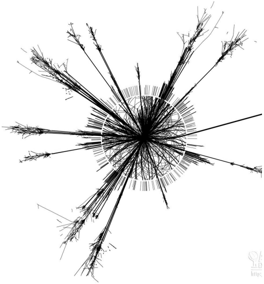
10× **more collisions** during the HL-LHC lifetime

↓

Nominal levelled luminosity:

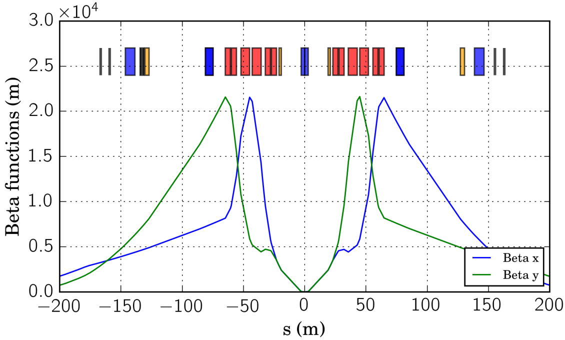
$$\boxed{\mathscr{L} = 5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$



How to increase collisions?

Reduce the **transverse beam size** $\sigma_{x,y}$ at the Interaction Point (IP)

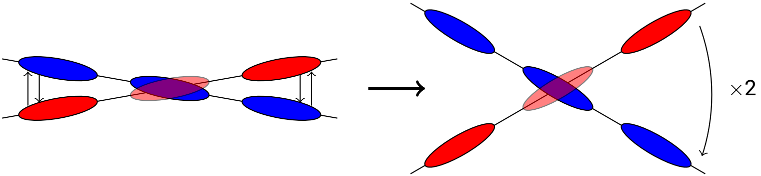
$$\sigma_i = \sqrt{\beta_i \varepsilon_i} \quad ; \quad \beta_i(s) = \beta_i^* + \frac{s^2}{\beta_i^*} \qquad (i = x, y)$$



- Larger beam sizes as we move away from the IP

Consequences

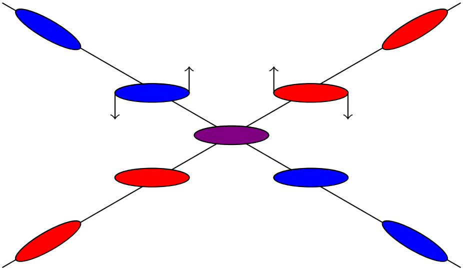
We need to **increase the crossing angle** to avoid parasitic collisions



Significant **loss in luminosity**

$$\mathscr{L} \to \frac{\mathscr{L}}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\frac{\theta}{2}\right)^2}} \sim 0.36\ \mathscr{L}$$

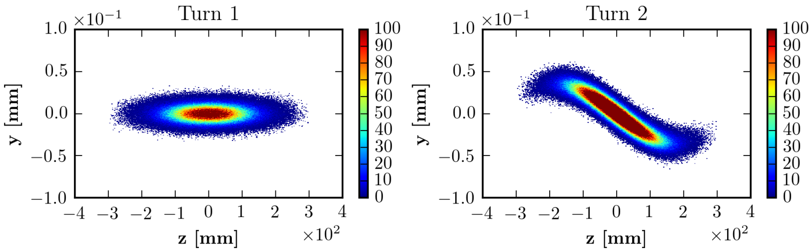
Solution? Crab Cavities



- EM forces rotate each bunch **longitudinally** by $\frac{\theta}{2}$
- The bunches collide **head on**, perfectly overlapping at the Interaction Point (IP)
- The **geometric luminosity** loss is compensated

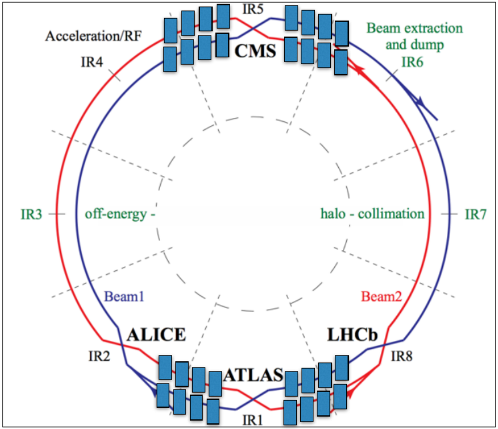
How does that look like?

For a vertical crossing angle at the IP :



- The crab cavity (CC) kicks the bunch in $(y' - z)$
- After the passage through the triplet $\rightarrow$ $(y - z)$

Where?

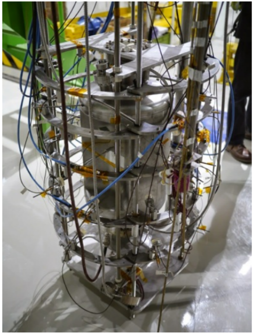


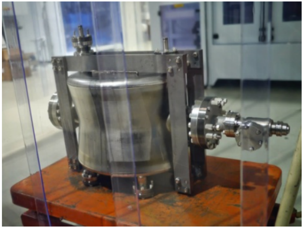
The tilt is compensated downstream
by a second group of CCs

Baseline

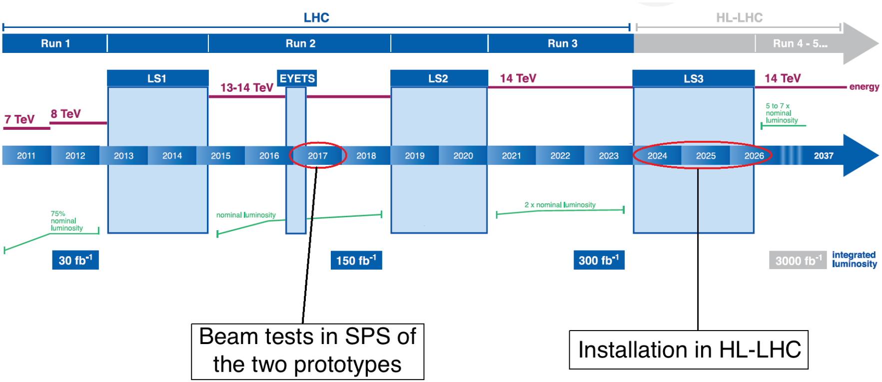
- Elliptical cavities used in KEK
- Space limitations in the LHC led to unconventional shapes
- Two prototypes are considered:

RF Dipole & **Double Quarter Wave**





Baseline



LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
5 to 7 x nominal luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
75% nominal luminosity
nominal luminosity
2 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated luminosity
Beam tests in SPS of the two prototypes
Installation in HL-LHC

What does it mean for Machine Protection?

Risks come from the **energy stored** in the system
and the **power** when operating

RISK = Probability $\times$ Consequences

$$\boxed{E_{\mathrm{beam}_{LHC}} = 362\ \mathrm{MJ} \;\rightarrow\; E_{\mathrm{beam}_{HL-LHC}} = 700\ \mathrm{MJ}}$$

Machine-Experiment Interface

Machine and experiments have, to some extent,
conflicting requirements

MACHINE

- Increased energy, luminosity, intensity
- Larger apertures ($\times 2$ in the triplet)

EXPERIMENT

- Inner detectors closer to the beam (30 % reduction)
- Low backgrounds, radiation and activation

Crab cavities and protection

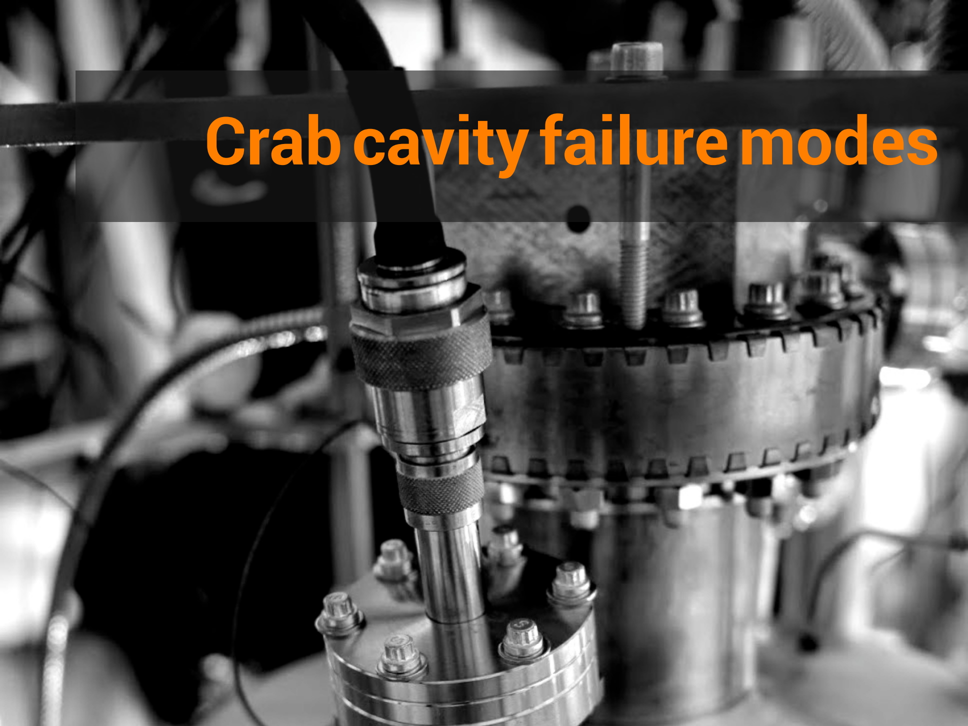
- Crab cavities have **very fast failure times** ($\sim$ few LHC turns)
- They have **never been used in a hadron machine before**

An uncontrolled release of the energy damages the equipment and **reduces the operation time**

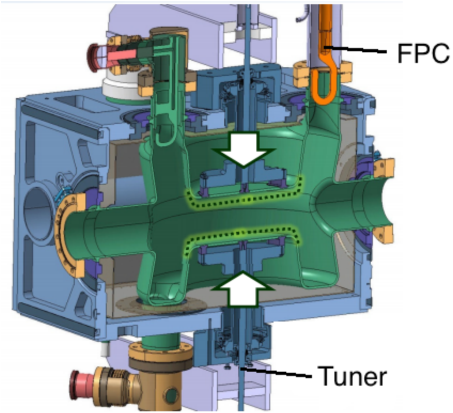
(We do want our $\int \mathscr{L}\, dt = 3000\ \mathrm{fb}^{-1}$ by the end of the HL-LHC lifetime!)

$\Rightarrow$ Motivation to carry out detailed studies in order to assure a **safe and stable operation**

Crab cavity failure modes



Design

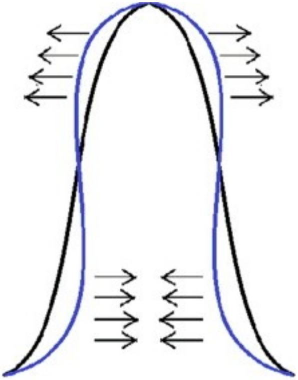


- **FPC**: fundamental RF power coupler (feeds the signal)
- **Tuner**: compensantes cavity deformations

Image from *Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities*, S. Verdú-Andrés, IPAC'15

Cavity deformations

- EM field induces surface current and **charges in the walls of the cavity**
- This generates **pressure** on the **cavity surface**
- The **resonating frequency** of the cavity starts **changing dynamically**:
  $\Rightarrow$ **Lorentz force detuning**
- If the tuner doesn't compensate it ($\sim$ ms), the **input power will be reflected back through the coupler**



Power lost through the coupler

The **external quality factor** Q_{ext} is proportional to the time it takes to **dissipate the energy** stored in the cavity **through the coupler** (when the RF sources are off)

$$\boxed{Q_{ext} = \frac{\omega U}{P_{out}}} \qquad \left\{ \begin{array}{l} \omega = \text{angular frequency of the CC} \\ U = \text{stored energy in the cavity} \\ P_{out} = \text{power lost through the coupler} \end{array} \right.$$

$$\Rightarrow P_{out} = \left\{ \begin{array}{c} -dU/dt \\ \dfrac{\omega U}{Q_{ext}} \end{array} \right\} \rightarrow \left. \begin{array}{l} U = U_0 . e^{-\frac{\omega t}{Q_{ext}}} \\ U \propto V^2 \end{array} \right\} V = V_0 . e^{-\frac{\omega t}{2Q_{ext}}}$$

Power lost through the coupler

$$\Rightarrow \quad V_0 . e^{-\frac{\omega t}{2Q_{ext}}} = V_0 . e^{-\frac{t}{\tau}}$$

The time constant of the process is τ:

$$\boxed{\tau = \frac{2 . Q_{ext}}{\omega}}$$

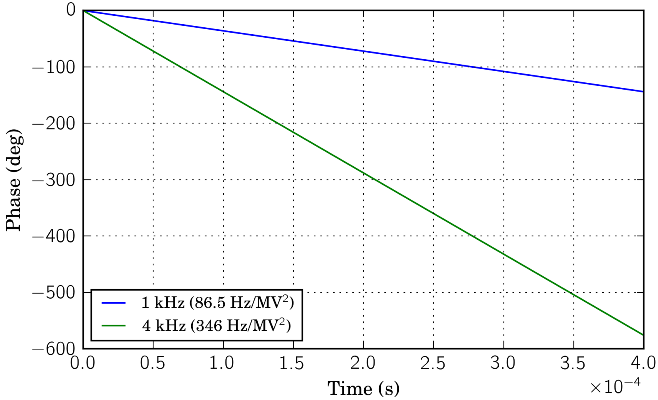
For the HL-LHC parameters:

- $f_{cc} = 400.79$ MHz
- $Q_{ext} = 3.10^5 - 5.10^5$

$\Rightarrow \quad \tau =$ 238 - 397 µs $\approx$ **2 - 4 LHC turns**

Phase shift caused by a detuning

- A Lorentz detuning is foreseen in the **1 kHz** range
- A **4 kHz** detuning was measured in the lab
  (no boundary conditions - not real, just for illustration)



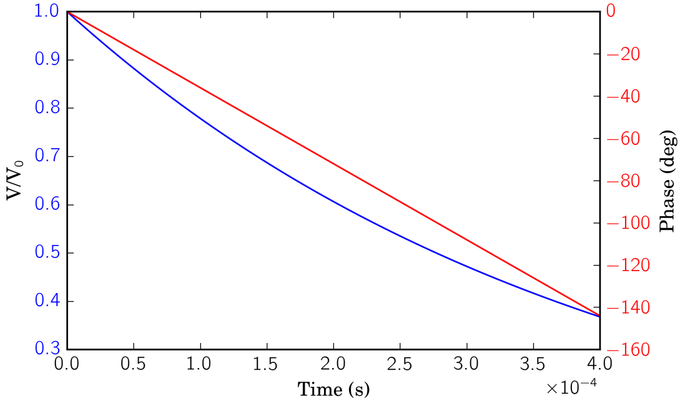
$$\Delta\phi = \Delta\omega . t$$

$$\Delta\phi = 2\pi\Delta f . t$$

Crab cavity and cryomodule development for HL-LHC, F. Carra et al., SRF2015

Phase and voltage

Example: 1 kHz detuning and $\tau = 400$ μs

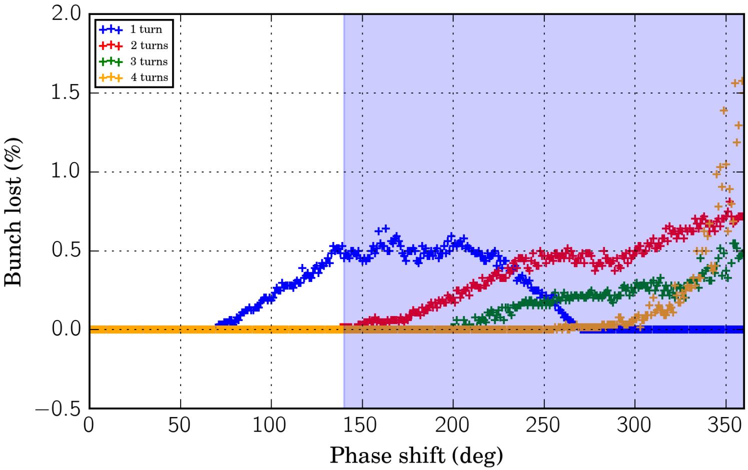


Tracking simulations

- Tracking code: **SixTrack** (using DYNK module and collimation routine)
- **One bunch** (gaussian transversely, matched to the RF bucket longitudinally)
- **Beam 1**
- **HL-LHC optics** (1.0)
- **4 CCs** installed at 160 m from IP1
- CCs are failed **downstream** (after collision)
- **Phase** failures, **voltage** is kept constant

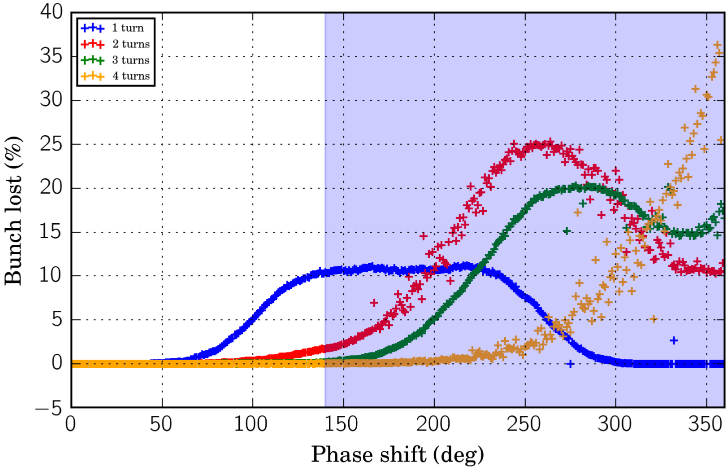
General functionality for turn-dependent element properties in SixTrack, K. Sjobak et al., IPAC'15

Failure of 2 CCs

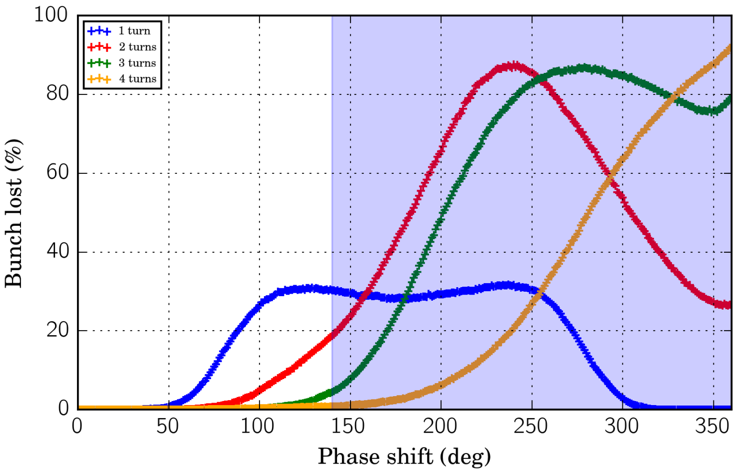


Simulations of fast crab cavity failures in the high luminosity Large Hadron Collider, B.Y Rendón et al., Phys. Rev.

Failure of 3 CCs

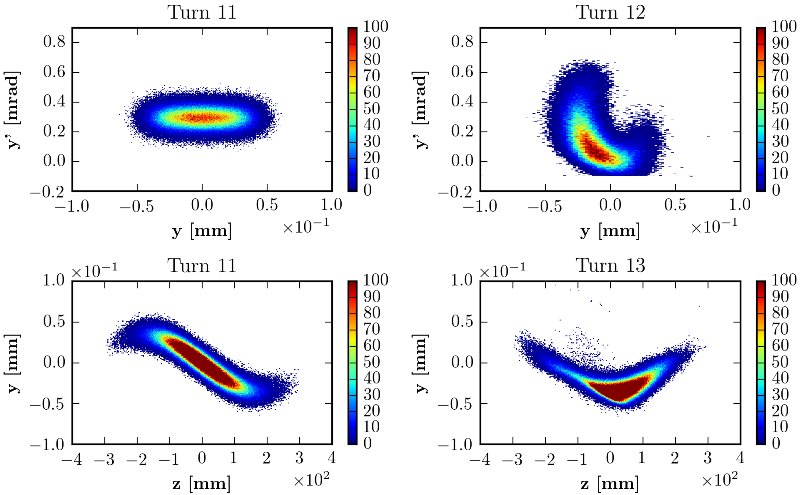


Failure of 4 CCs

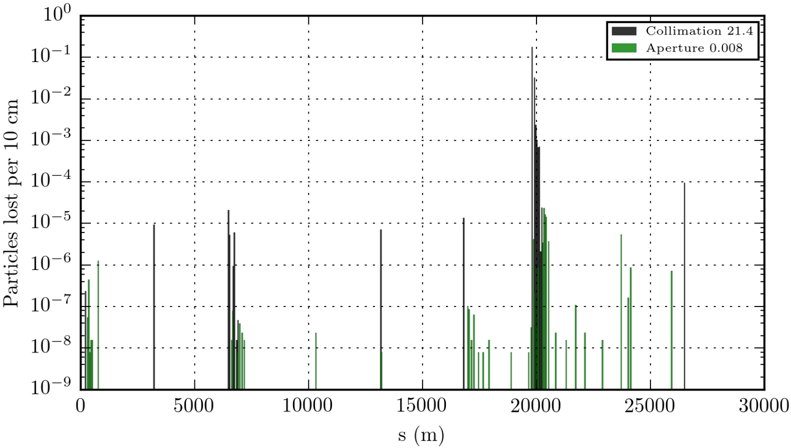


A **quench** could cause a bigger detuning, hence a bigger phase shift

90 deg phase shift in 1 turn (4 CCs)



90 deg phase shift in 1 turn (4 CCs)



Interaction Region protection

Collimation system

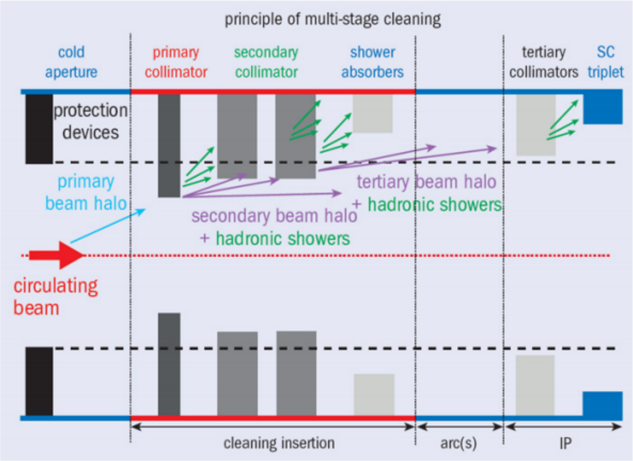
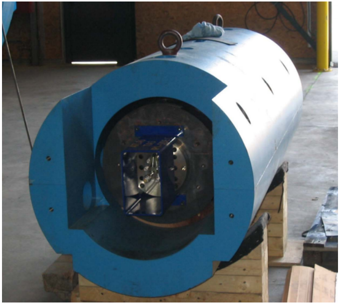


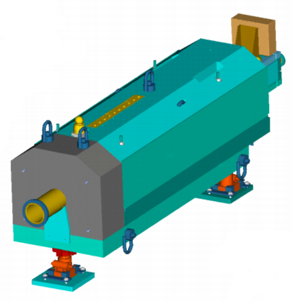
Image from *HL-LHC Preliminary Design Report*

Other passive absorbers



TAS: Target Absorber Secondaries

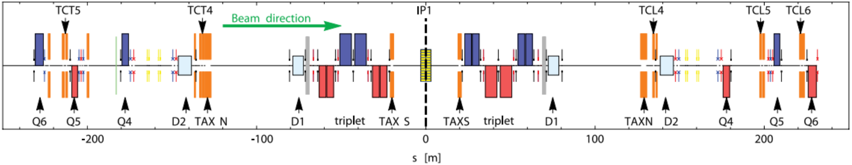
- Old radius: 30 mm
- New radius: 54 mm

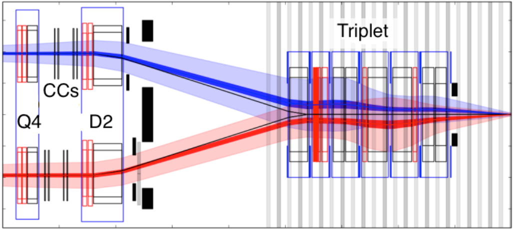


TAN: Target Absorber Neutral

- Old radius: 26 mm
- New radius: 40 mm

Layout in the Interaction Regions





Images from *Collimation Upgrades for HL-LHC*, S.Redaelli et al. and *HL-LHC Preliminary Design Report*.

Ongoing simulations

Machine description

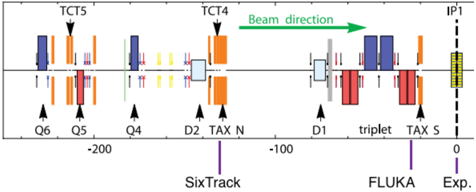
Failure scenario

SixTrack + Collimation tools

Losses and impact distributions

FLUKA simulation of long straight sections (LSS)

Particle showers toward experiment



- Experiments are very interested to understand the **absolute fluence of particles** that can occur in catastrophic beam loss events.

Ongoing simulations

- Preliminary simulations show that the damaging fluence in CMS tracker is reached when about **1e11 protons are lost at the TCTs**
- **A smaller TAS radius reduced the amount of background particles** leaking through, and hence the damaging level is reached with a stronger beam loss.

Conclusions

- Tracking tools have been extended to deal with CC failures
- Waiting for lab results about the real behavior of CCs
- Ongoing simulations with the FLUKA team and the experiments:
  - Assess the damage to the experiments in a CC failure scenario
  - Investigate the role of the TAS/TAN/TCT in experiment protection

Ackowledgements

These studies have been carried out with the collaboration of the **LHC Background Study Group**, the **FLUKA team**, the **collimation team** and the **RF group**

Helmut Burkhardt, Roderik Bruce, Rama Calaga, Franceso Cerutti, Sunil Chitra, Karim Gibrán Hernández Chahín, Moritz Guthoff, Regina Kwee-Hinzmann, Anton Lechner, Alick Macpherson, Antonio Sbrizzi, Kyrre Sjobak

Not to miss

Please, check out the following talks tomorrow in the **Joint Plenary Session with Experiments** for more detailed information (**Main Auditorium**):

- 8:45 AM
  Overview of aperture, risks, losses, collimation and background
  Helmut BURKHARDT
- 9:15 AM
  Sources of failures and their tracking
  Kyrre SJOBAK
- 9:35 AM
  Effects of losses and LHC/HL-LHC comparison in ATLAS and CMS
  Antonio SBRIZZI and Moritz GUTHOFF

Thank you!