Status of the HE-LHC Betatron Collimation System

EuroCirCol meeting

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Outline

- The High Energy Large Hadron Collider
  - Beam parameters and lattice options
  - Optics and Aperture
  - Challenges for collimation and machine protection
- Betatron collimation for the HE-LHC
  - Design options
  - Layout
  - Magnet parameters
- Collimation optics
- Betatron collimation performance
  - Without dispersion suppressor collimators
  - With dispersion suppressor collimators
- Discussion and further work

HE-LHC

- The HE-LHC is a proposed upgrade to the LHC
  - Installed in the existing LHC tunnel
  - Will use HL-LHC-like bunch parameters
- Two different lattice options:
  - 18 cells per arc with a 90 degree phase advance (18x90)
  - 23 cells per arc with a 90 degree phase advance (23x90).
- Both options have physical apertures smaller than 10 sigma at injection at 450 GeV injection energy.
- Challenging from the perspective of machine protection: Need to contend with injection oscillations, injection failure etc.

HE-LHC Parameters

Parameter	Unit	FCC-hh	**HE-LHC**	(HL)-LHC*
Circumference	Km	97.8	26.7	26.7
Center-of-mass energy	TeV	100	27	14
Injection Energy	TeV	3.3	0.45/0.90/1.30	0.45
Bunch Population [10^{11}]	ppb	1.0	2.2	(2.2) 1.15
Beam Current	A	0.5	1.12	(1.12) 0.58
Number of Bunches		10600	2808	(2760) 2808
Bunch Spacing	ns	25	25	25
IP beta function	m	0.3	0.45	(0.15) 0.55
Half Crossing angle	µm	70	165	(250) 142.5
Stored beam Energy	GJ	8.4	1.4	(0.7) 0.36
Luminosity	$10^{34} cm^{-2} s^{-1}$	30	16	1
Events per crossing		1000	460	(135) 27
N.Trans. Emittance	µm	2.2	2.5	(2.5) 3.75
Arc dipole field	T	16	16	8.33

** LHC design values.*

HE-LHC lattice options

- Two lattice options: 23x90 and 18x90.
- Aperture at 450 GeV for both options is tight: 23x90~9.4 sigma and 18x90~7.8 sigma.
- Requires extremely tight collimator settings for the 18x90 in order to protect the aperture.
- Feasibility of the 18x90 option at 450 GeV still to be demonstrated. Higher injection energies for this option are also being considered which will give a larger aperture ($A_{physical}$x1.7 sigma) at 1.3 TeV.
- Advantage of the 18x90 option is larger collision energy, more margin in arc quadrupole fields, and improved filling factor.

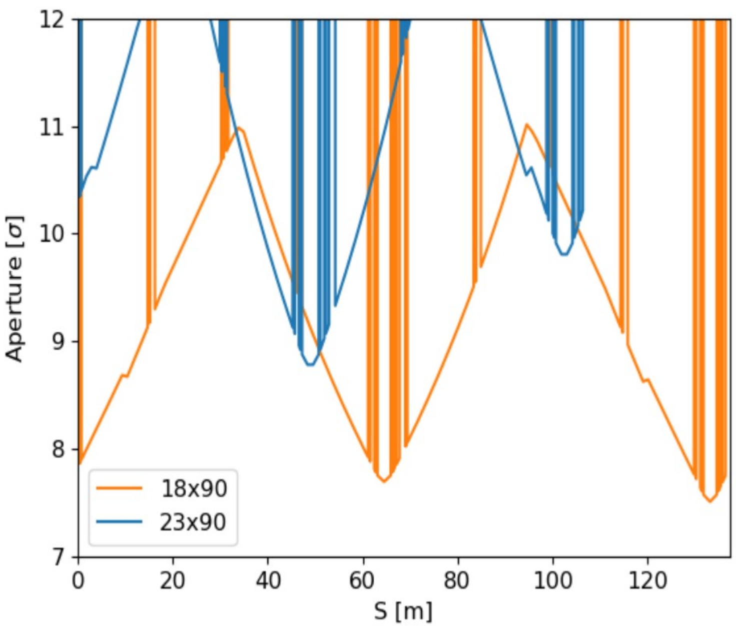


Fig 1: *n1 for the v 0.2 HE-LHC lattice options. Conical errors based on the HL-LHC. V0.4 used in these studies have an aperture of 9.4 and 7.8 sigma respectively for the 24x90 and the 18x90.*

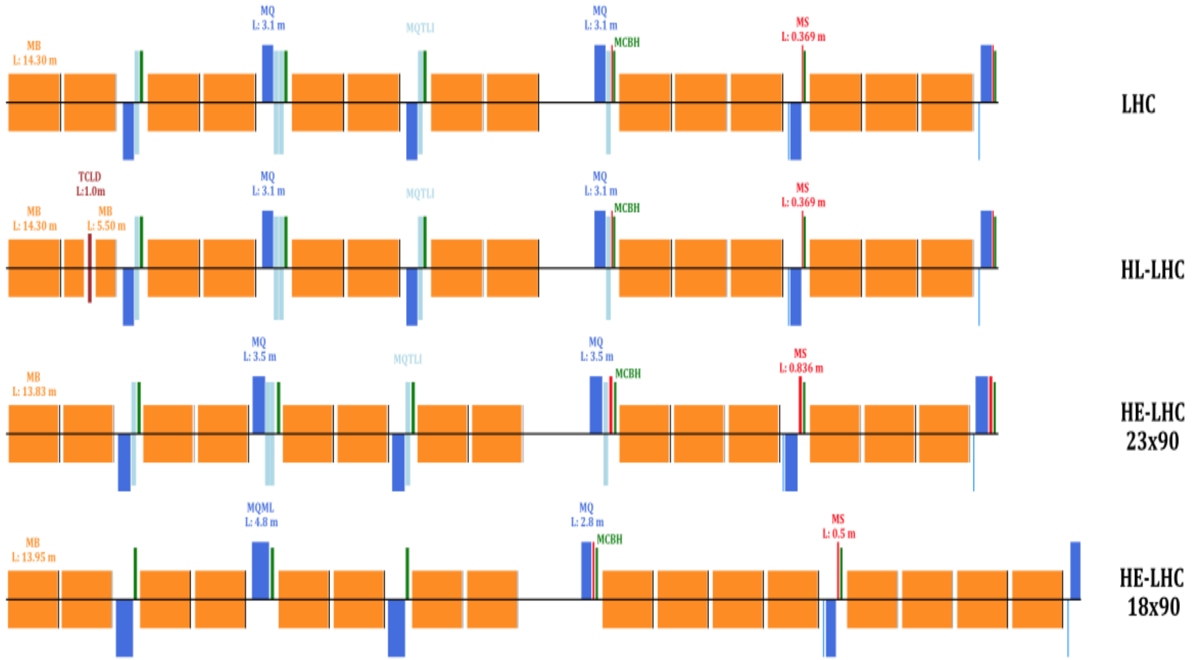
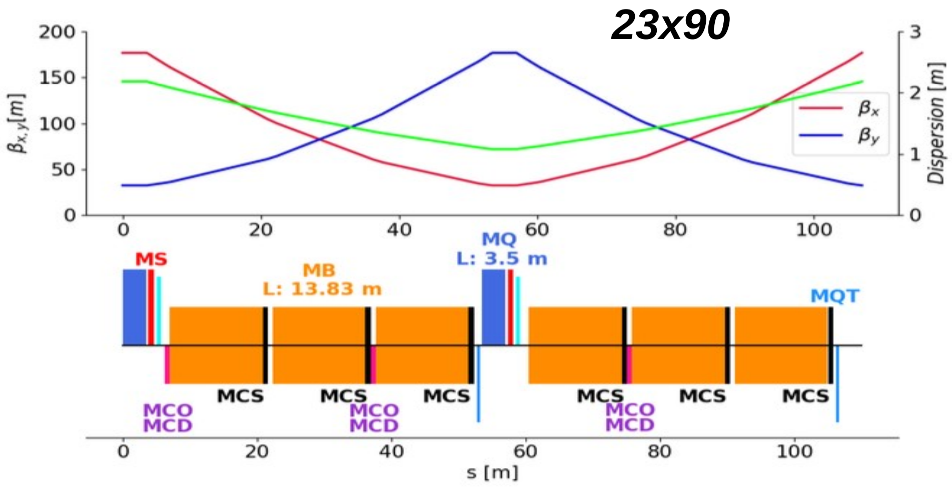
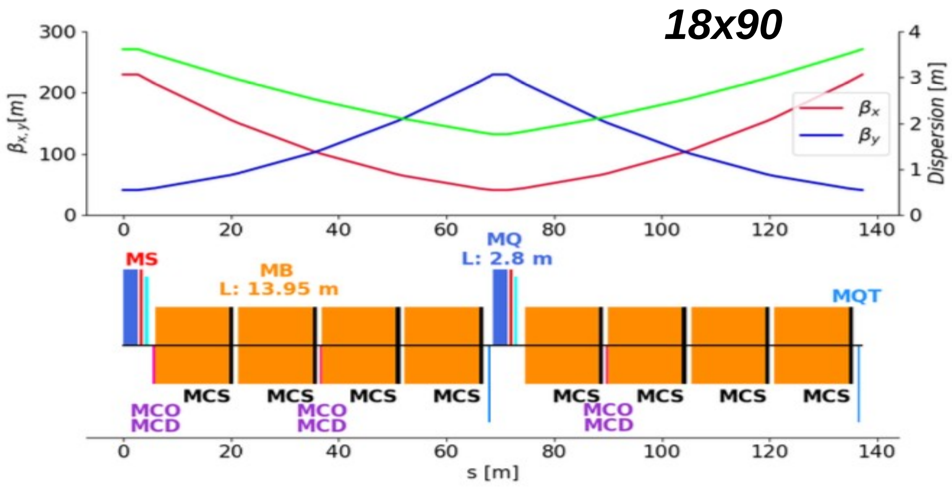


Fig 2: *DS layout left of figure and regular arc cell on the right*

HE-LHC lattice options

- Optics and magnet layout for the regular arc cell of the two lattice options (23x90 and 18x90) for V0.3 of the HE-LHC.
- These two layouts have different arc optics compared to the LHC so collimator settings should be re-evaluated.
- The maximum and minimum beta functions
  - LHC: 181/32 [m]
  - 23x90: 177/32.4 [m]
  - 18x90: 230/40 [m]
- The maximum and minimum dispersion
  - LHC: 2.2/1.1 [m]
  - 23x90: 2.2/1.1 [m]
  - 18x90: 3.6/1.76 [m]





Betatron collimation in the HE-LHC

- A number of different design options were considered for the HE-LHC betatron collimation system based on different magnet parameters and design options.
- Different beam separations in IR7 were considered. The arc separation is 204 mm for HE-LHC v0.4.
  - Trade-off between dipole magnet length, separation, and so-called neutron flux downstream.
  - For this version 20 mm separation was used in the dogleg 204->224.
  - For version 0.5 of the HE-LHC no separation at all is needed to fit the collimators in the tunnel as there is physical space. However impact on cleaning efficiency needs to be evaluated.
- For a separation of 20 mm used in v0.4, the separation dipoles did not need to have the length increased (assuming a moderate field strength increase).

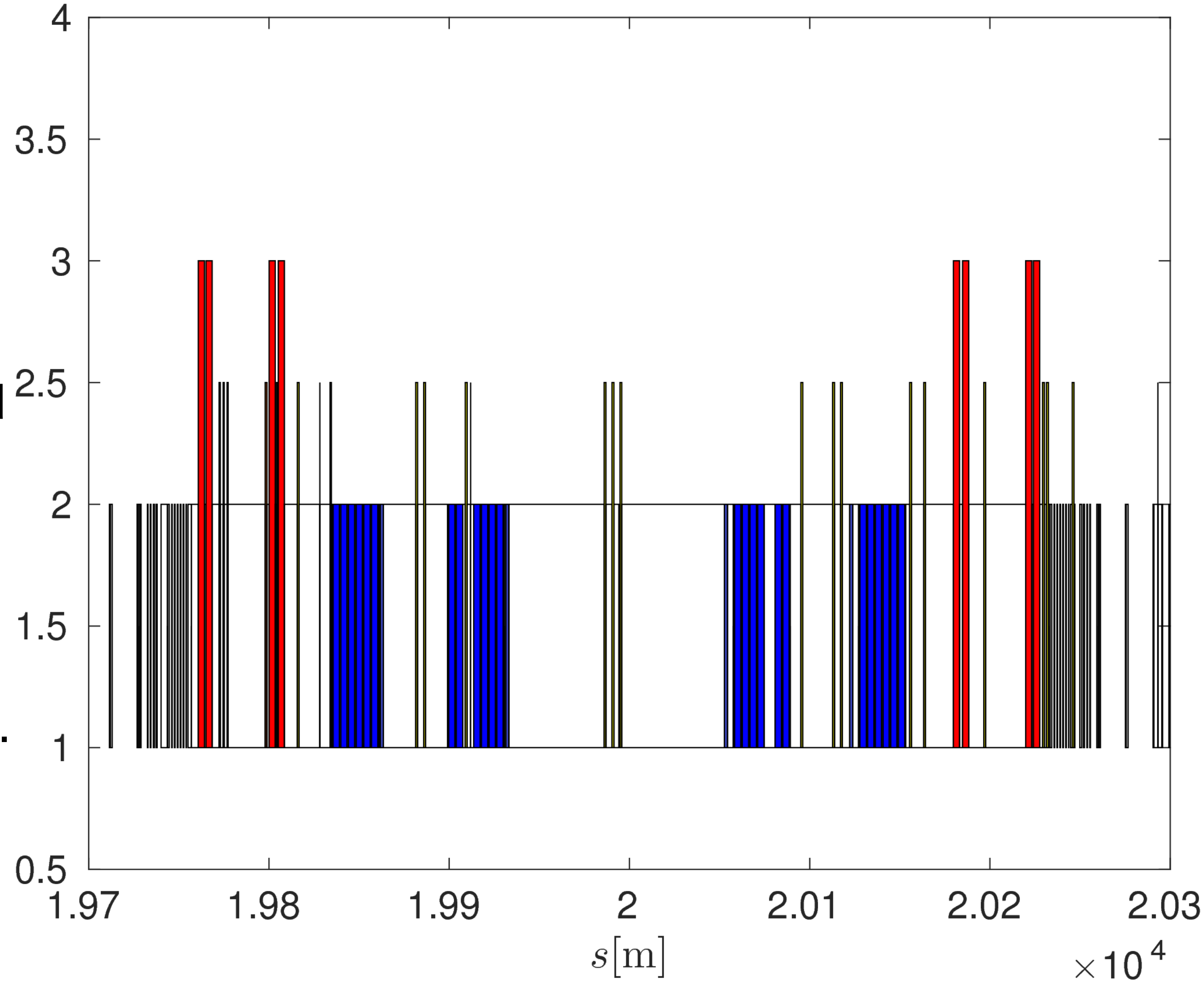
Betatron collimation in the HE-LHC

- Magnet parameters for IR7 for version 0.4 of the HE-LHC
- Assumes a moderate increase in magnet strength as suggested by A. Milanese.
- The dipoles were kept at the same length as the LHC but the field strength was increased to 1.8 T.
- Quadrupole radius remains the same as the LHC (23 mm)
- *mqwb* magnets were replaced with *mqwa* magnets.

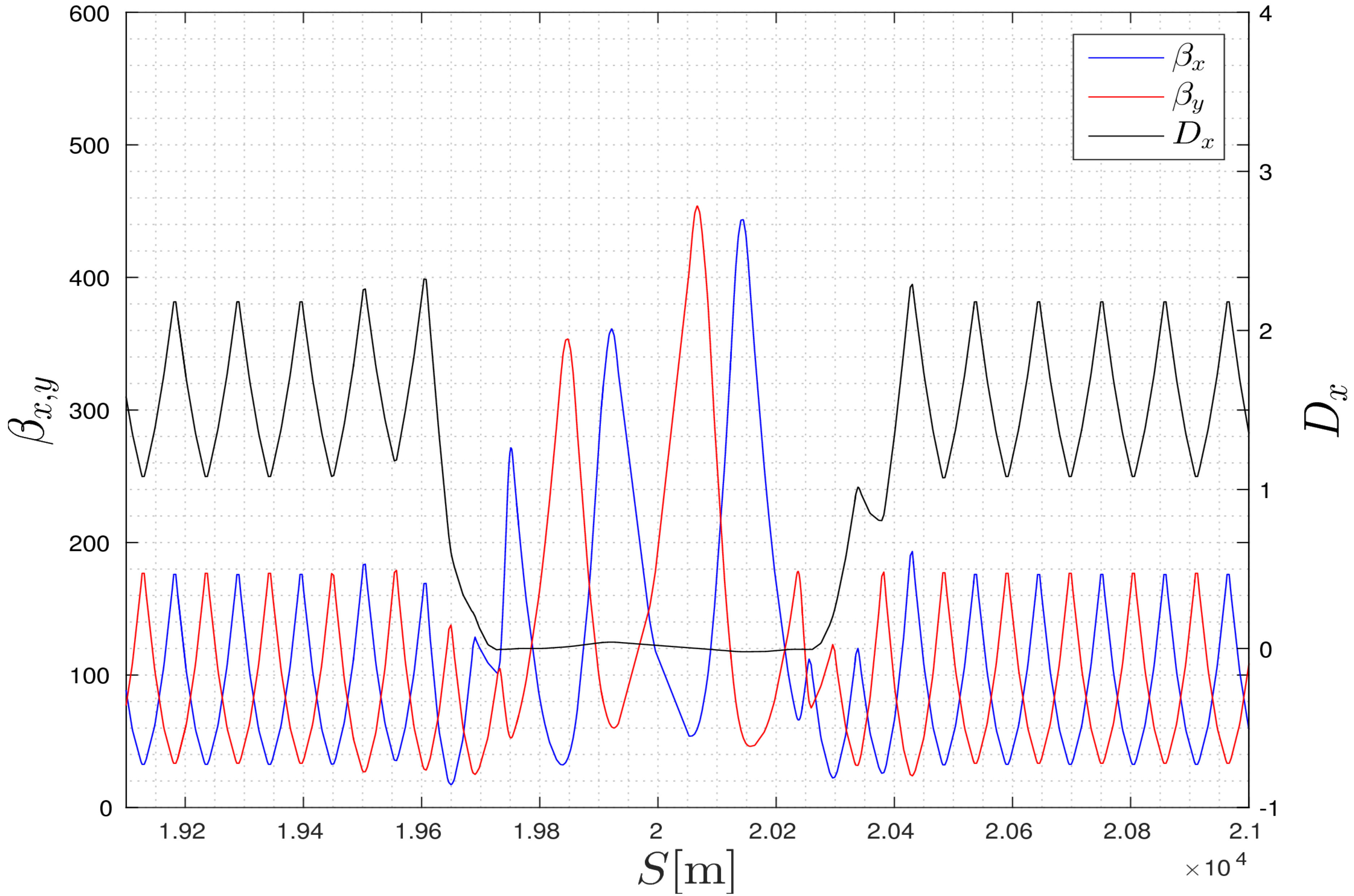
	Dipole Field [T]	**Dipole Length [m]**	**Quadrupole Field [T]**	**Quadrupole Length [m]**	**Gradient [T/m]**
HE-LHC:	1.8	3.40	1.0	3.51	43.75
LHC:	1.3	3.40	0.7	3.17	30.43

Betatron collimation in the HE-LHC

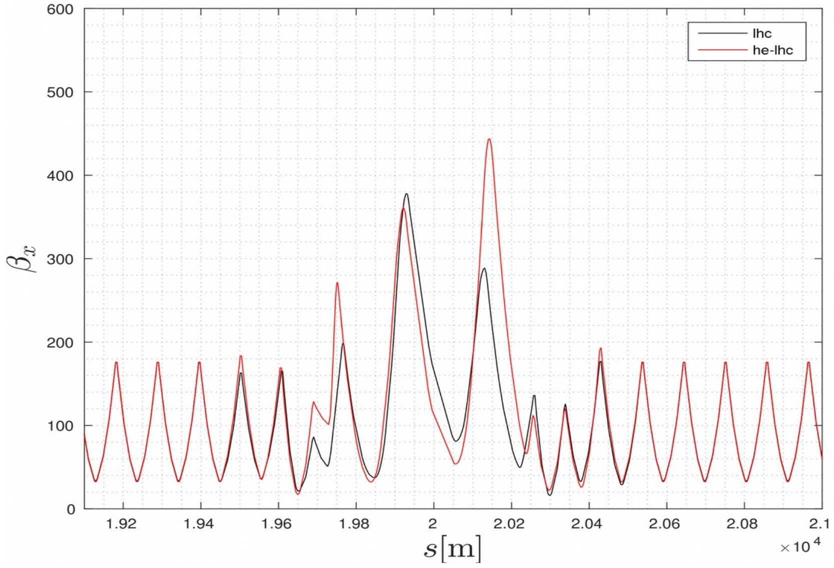
- New layout for the betatron IR7 matched by T. Risselada.
- Red represents the dogleg dipoles
- Blue represents the warm quadrupoles and black/others represent collimators, and miscellaneous elements such as BPM's or correctors.
- White represents drifts.

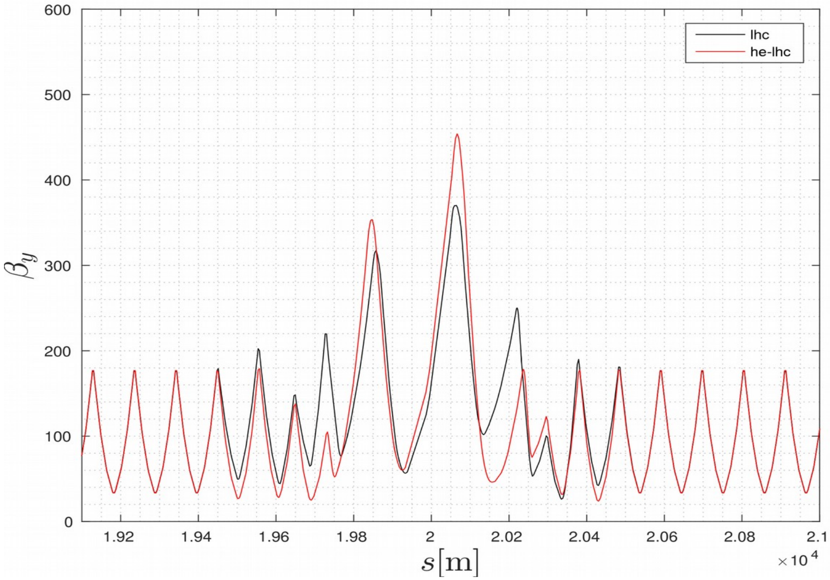


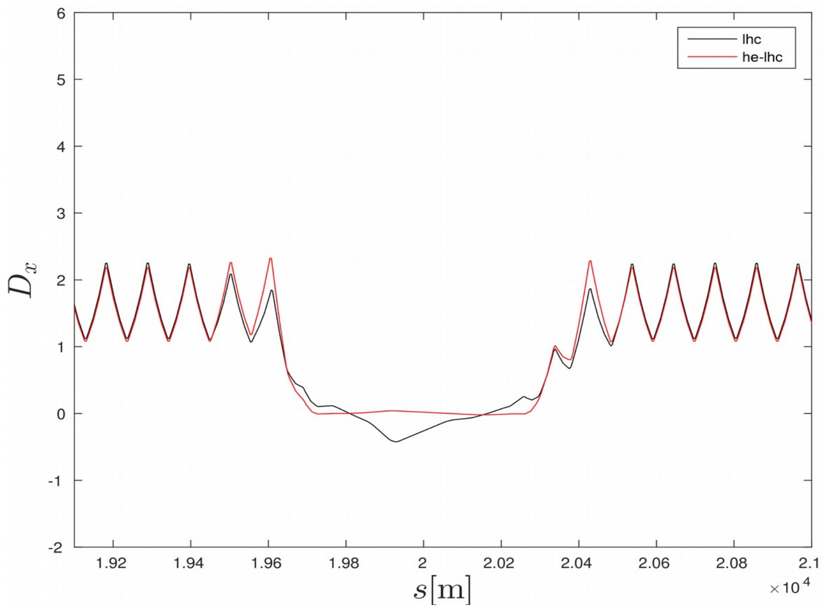
Betatron collimation in the HE-LHC



IR7 Optics comparison: HE-LHC and LHC

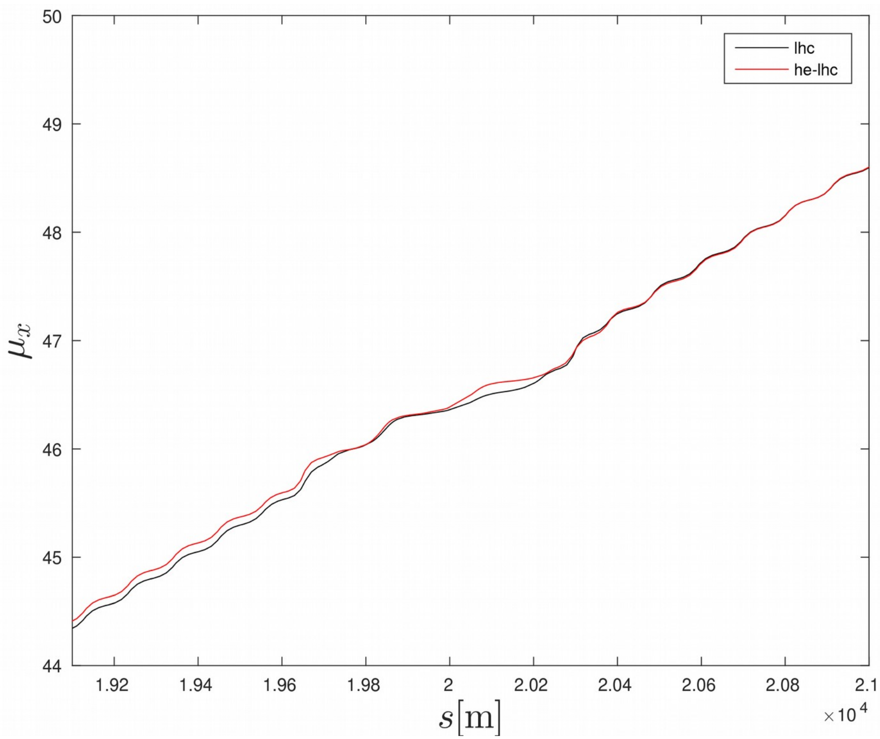


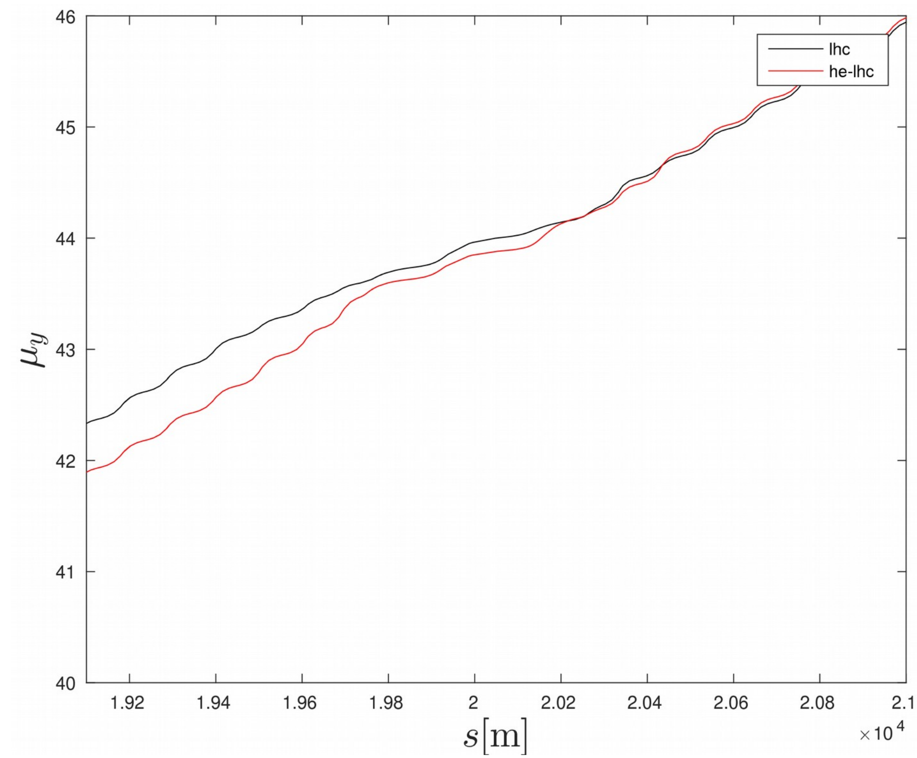




- Large differences between the two different optics in both the horizontal and vertical beta functions.
- The dispersion is also different over the insertion region when compared to the LHC.
- The impact of the change in optics on the cleaning performance is investigated through tracking studies shown later

IR7 Optics comparison: HE-LHC and LHC

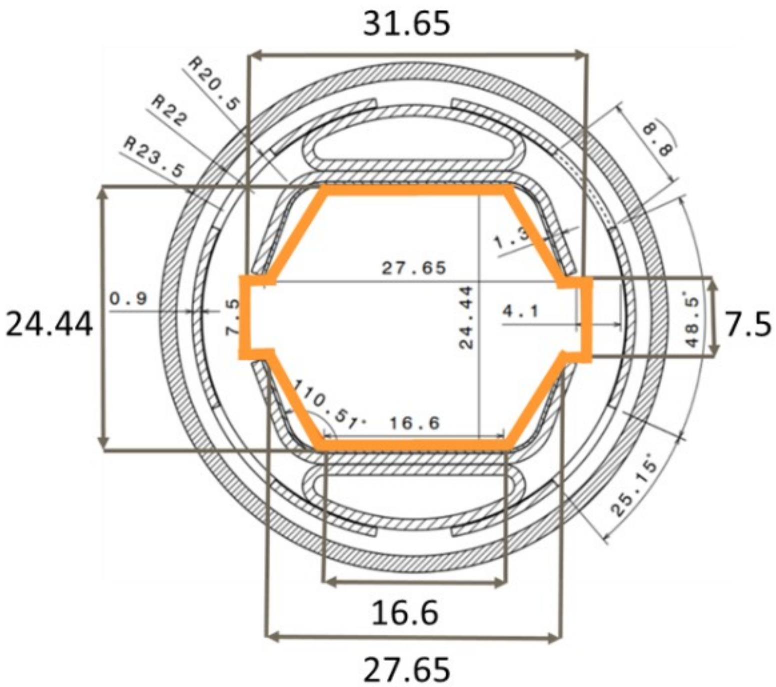




- The phase advance was matched closely to the LHC and the same matching constraints in the LHC at the TCP were enforced.
- This should help to ensure the same or comparable cleaning efficiency as the LHC, since the LHC collimation system was optimised for the LHC optics and is based on numerical studies.

Beam Cleaning Performance

- Tracking simulations were performed to evaluate the cleaning efficiency
- The simulations were performed using the symplectic tracking code SIXTRACK.
- 1E8 particles tracked over 1E6 turns used in the simulations to improve the statistics and the resolution.
- The HE-LHC aperture model was used in the tracking simulations as this is tighter than the LHC and would impact the losses.
- Unlike the FCC dipoles, the HE-LHC dipoles are bent.



Beam Cleaning Performance

- The performance of the new betatron collimation system was calculated using the so-called cleaning inefficiency.
- The unnormalised cleaning inefficiency is calculated using

$$\eta_c = \frac{N_{\mathrm{leak}}(a_z > a_z^{\mathrm{cut}})}{N_{\mathrm{impact}}},$$

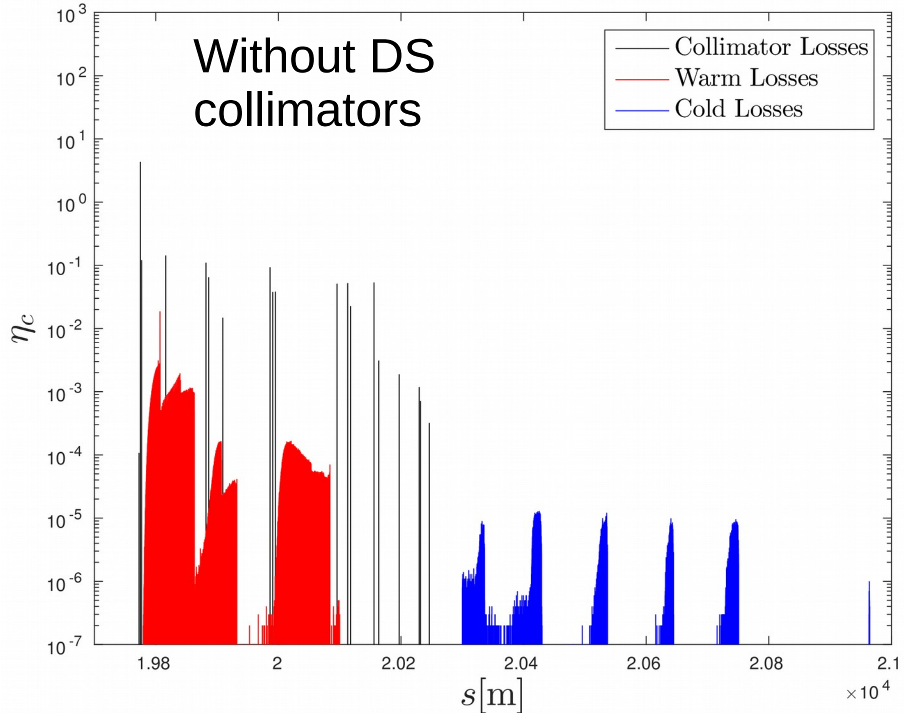
- Where N_{leak} is the number of escaping particles with a collimator cut at $a_z^{cut} > n_1$, n_1 is the collimator gap in sigma, and N_{impact} is the number of impacting particles.
- The cleaning inefficiency is normalised over distance since the losses are not localised.

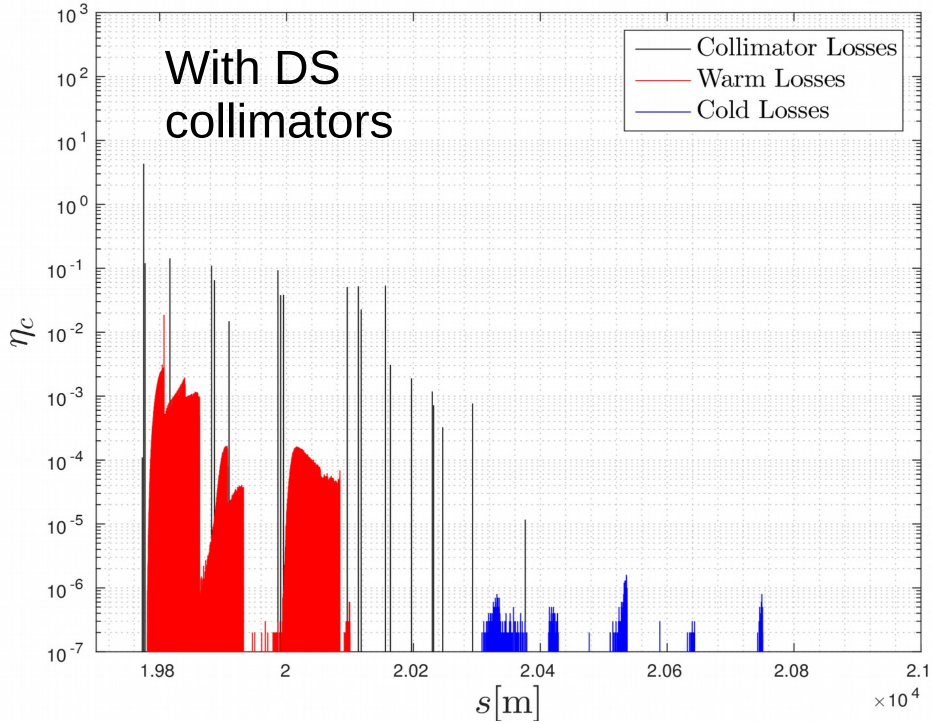
Beam Cleaning Performance at 450 GeV

- First preliminary collimator settings at injection energy of 450 GeV and emittance of 2.5 μm.
- Originally the LHC settings were used however due to the tighter aperture of the HE-LHC, the LHC collimator settings were modified to protect the aperture.
- The feasibility of these settings to protect the aperture whilst including imperfections still need to assessed
- The TCLAs were reduced to 9.0 sigma but the TCLDs were positioned at 10/12 sigma.

Collimator	σ	**Half-gap** mm
TCP	5.7	3.81
TCSG	6.7	4.21
TDI	6.8	3.27
TCLI	8.0	6.36
TCLA	9.0	4.45
TCLD	10.0/12.0	3.55/5.33

Beam Cleaning at Injection optics and 450 GeV





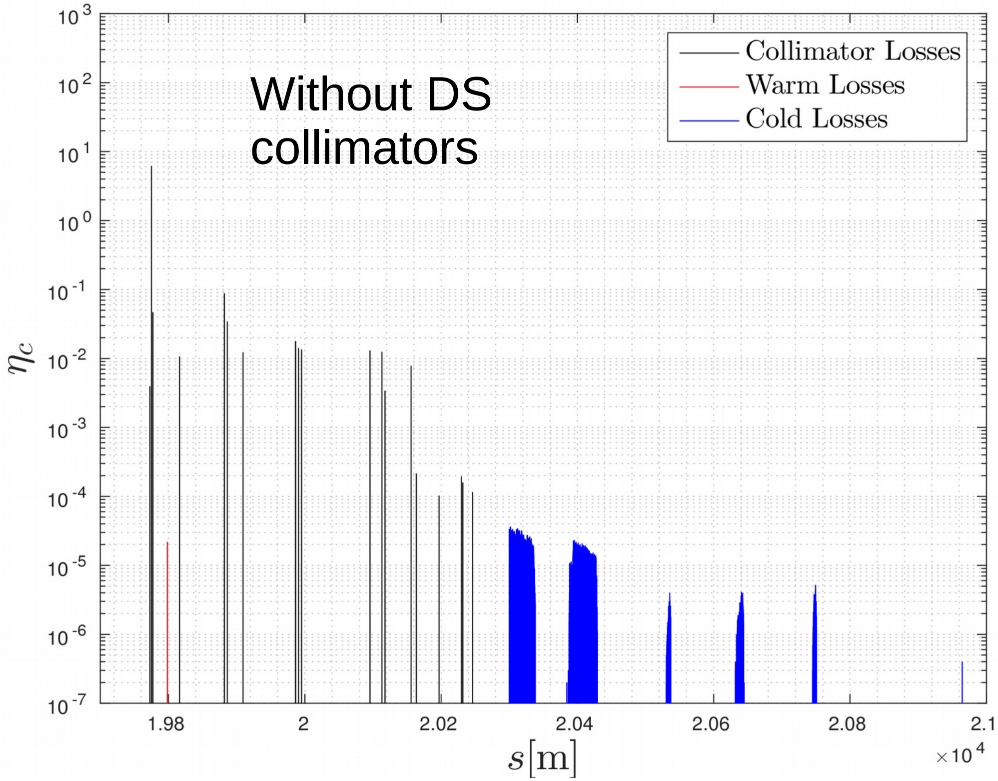
Significant improvement in the cleaning performance when the TCLD collimators are included in modules R8 and R10, even when the collimators are placed outside the smallest aperture bottleneck. This is because the collimators catch the off-momentum particles and help to protect the cold aperture.

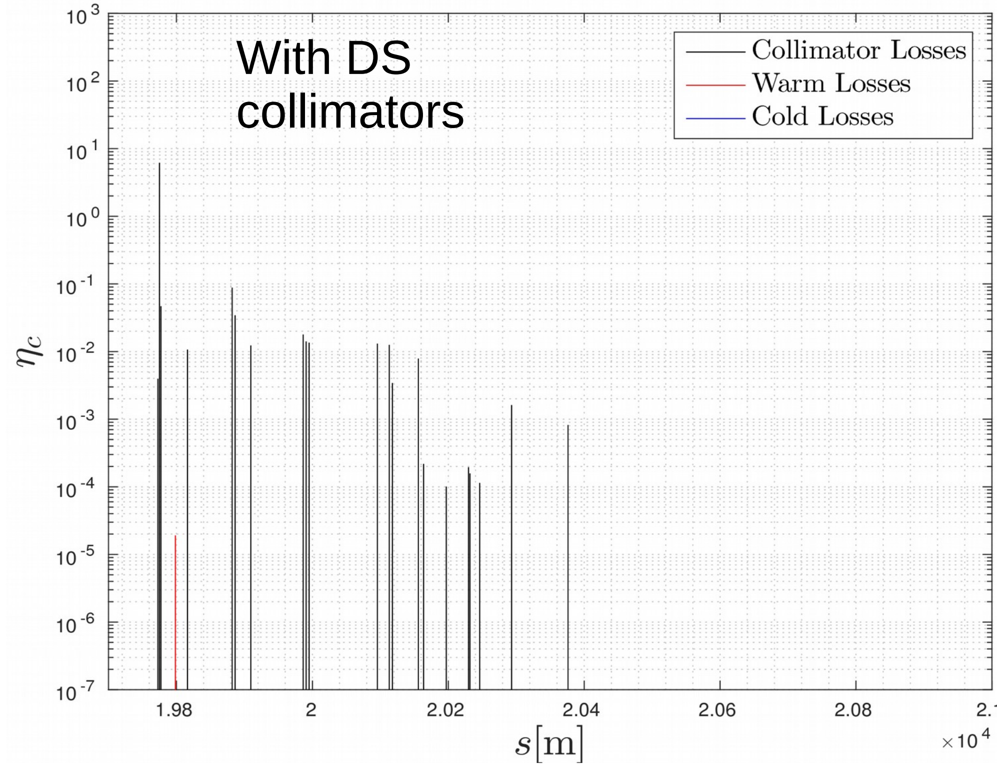
Beam Cleaning Performance at 13.5 TeV

- Proposed preliminary collimator settings at collision energy but at injection optics (no collision optics for v0.4).
- The proposed settings in sigma are based on the HL-LHC.
- Normally the TCLDs would have the same opening as the TCLAs however this resulted in a very tight half-gap of approximately 0.6 mm
- Hence the TCLDs were opened to 18.1/22.2 sigma and there was no noticeable impact on the cleaning performance because the DS collimators still catch the off-momentum particles.
- The TCP half-gap at collision is tight < 1mm and maybe challenging. Further impedance studies will need to be undertaken to demonstrate the feasibility of the opening.

Collimator	σ	**Half-gap** mm
TCP	6.7	0.82
TCSG	9.1	1.32
TCLA	11.5	1.04
TCLD	18.1/22.2	1.17/1.54

Beam Cleaning at 13.5 TeV





As seen previously at injection, the DS collimators significantly improve the collimation performance by protecting the cold aperture from the off momentum particles. Without the DS collimators the losses downstream in the cold aperture are certainly unacceptable and would cause magnet quenches. This new design layout will need to be fully evaluated using FLUKA.

Discussion

- A design for the HE-LHC betatron collimation system has been presented for the 23x90 lattice.
- The IR7 was modified for the HE-LHC.
  - The field strength for the *mbw* magnets was increased to 1.8 T but the length remained the same.
  - The *mqwb* magnets were replaced with *mqwa* magnets to gain more integrated strength.
  - In addition, the field strength at the pole was increased from 0.7 T to 1.0 T and the length of the quadrupoles were increased.
- Performance with the new layout was simulated
  - Performance at both collision and injection energies was good as long as DS collimators were used.
  - Some of the collimator settings need to be evaluated.
  - These studies were all performed considering a perfect machine: no element offsets, magnetic errors, orbit misalignment's

Further work

- Further studies need to be performed to verify that the proposed system works.
- Energy deposition in warm section in IR7 need to be simulated as well as the thermo-mechanical response in the losses.
- Cold section losses in IR7 need to be studied in detail to simulate energy deposition in the magnets downstream.
- Investigation of the collimator performance in 18x90
- Different versions of the layout (without DS collimators) could still be investigated.
- Full ring collimation needed, including studies of IR3.
- No collision optics yet for v0.4 so need to wait for v0.5 which has some additional changes to the arc optics, aperture, DS collimator and re-evaluate performance.

Backup Slides

Version Summary

- v0.2: 18x90 only, magnetic distances were off, most insertions were from SLHC.
- V0.3: 18x90 and 23x90, low beta insertions changed couldnt get required beta star, only injections optics, mismatched optics in some IPs causing bottlenecks, IR6 updated.
- V0.4: rematched, magnetic parameters/distances changed in cells, still no collision optics, new IR7, larger beam separation (204)
- v0.5: collision optics, beam 1 and beam 2, increased beam separation to 250mm, DS changed as well as IP1 and IP5, New IR3 and IR7 matched in. Optimised geometry.

Momentum Collimation in IR3

- Two different proposals by T. Risselada
  - Layout scaling: multiply all element lengths and focal lengths from Q6L->Q6R by some scaling factor
  - MQWBs replaced with MQWA with different gradients
- Layout scaling produced scaled betatron functions but the betatron phases remained the same. Scaled dispersion function only obtainable with scaled dogleg separation. Hence the collimation performance should be close to the LHC
- New IR3 performance needs to be studied with sixtrack/fluka
- Details of method in https://indico.cern.ch/event/739469/contributions/3052460/attachments/1673964/2688725/IR3_optics_update.pdf

Momentum Collimation in IR3