Developments in the HE-LHC betatron collimation system

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Acknowledgements:

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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
- Betatron collimation performance
  - Without dispersion suppressor collimators
  - With dispersion suppressor collimators
- Discussion and further work

HE-LHC

- The HE-LHC is a proposed upgrade for the LHC
  - Will be installed in the existing LHC tunnel and infrastructure
  - Will use HL-LHC like bunch parameters
- Currently two proposed 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 are challenging
  - Physical apertures are small at injection
  - Losses at collision energies could cause quenches downstream of the betatron collimation system.
  - Cannot directly scale the LHC lattice to 13.5 TeV due to the limited infrastructure space.
- Challenging from the perspective of machine protection and impedance: simulations shown here are for a perfect machine, including injection oscillations, injection failures etc will make the losses worse

HE-LHC Parameters

Parameters	Unit	FCC-hh	HE-LHC	(HL)-LHC
Circumference	Km	97.8	26.7	26.7
Centre-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	(5) 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

Lattice options.

- Currently there are two lattice options for the HE-LHC.
- These are:
  - 18x90 (18 cells with 90 degree phase advance)
  - 23x90 (23 cells with 90 degree phase advance)
- The 18x90 lattice is more challenging from the perspective of available physical aperture and collimation settings. The trade-off is it allows a higher energy reach.
- The 23x90 lattice is less challenging than the above option but gives a lower energy reach.
- In this talk only the 23x90 lattice is considered whilst the feasibility of the 18x90 lattice still needs to be investigated.

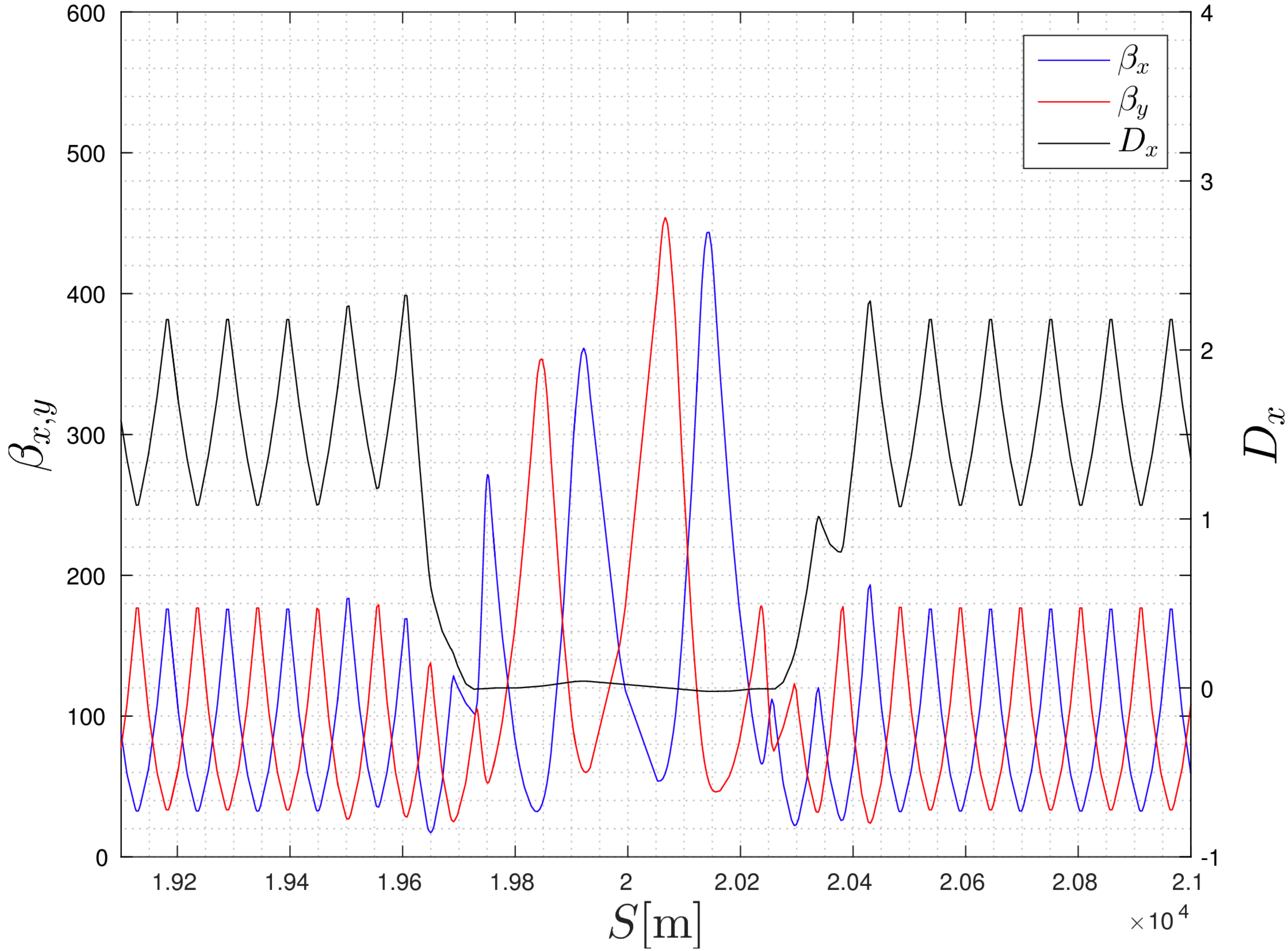
Layout and magnet parameters for IR7

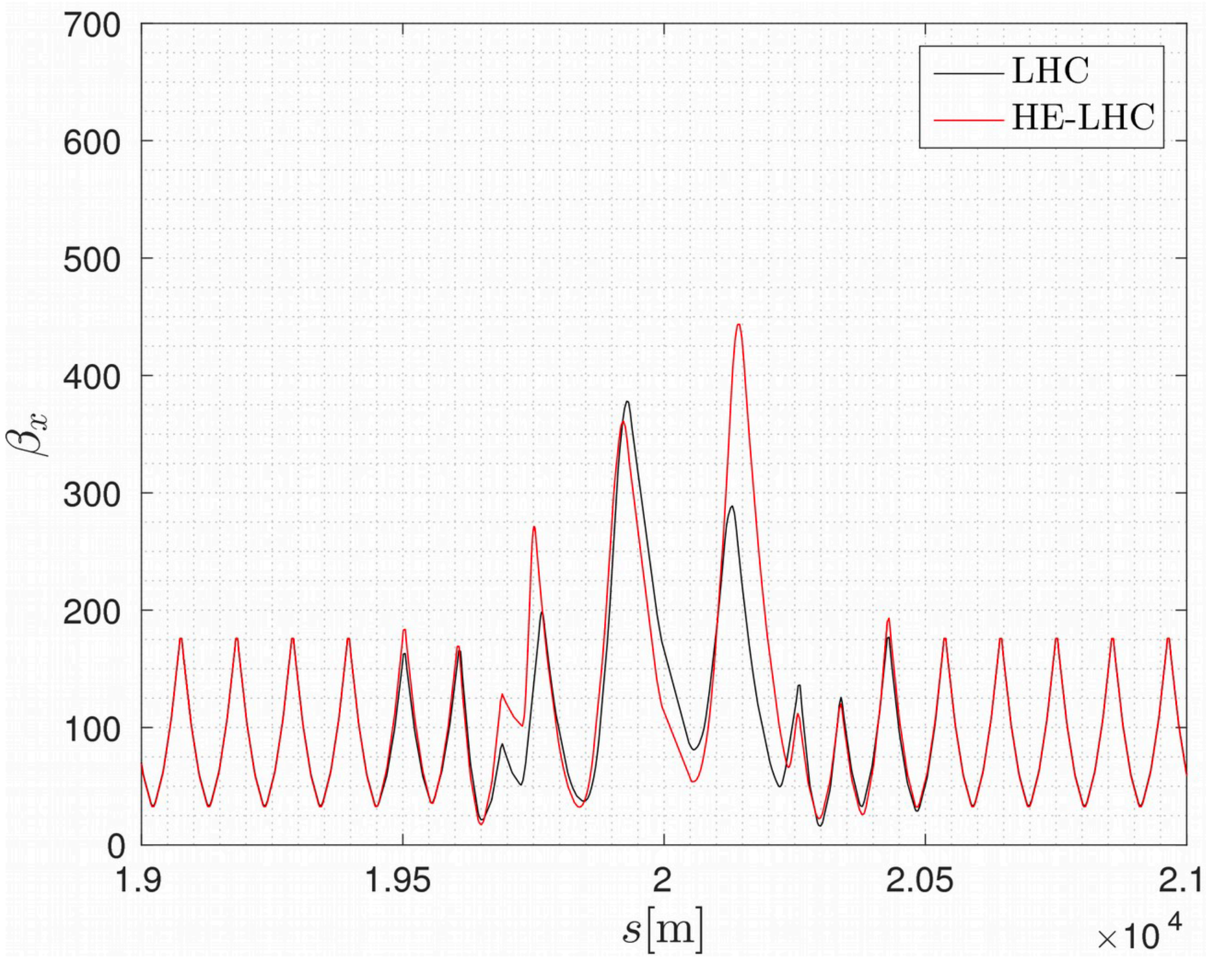
- Unlike the FCC, we cannot directly scale the length of the IR7 normal conducting magnets with beam energy.
- In the HE-LHC we are tightly restricted by the existing LHC infrastructure we need to try an utilise the space available.
- Low powered quadrupoles were replaced with fully powered quadrupoles in order to maximise the available magnetic length.
- In addition we assumed a moderate increase in normal conducting magnet performance. The assumed magnet parameters for the new IR7 are given below.

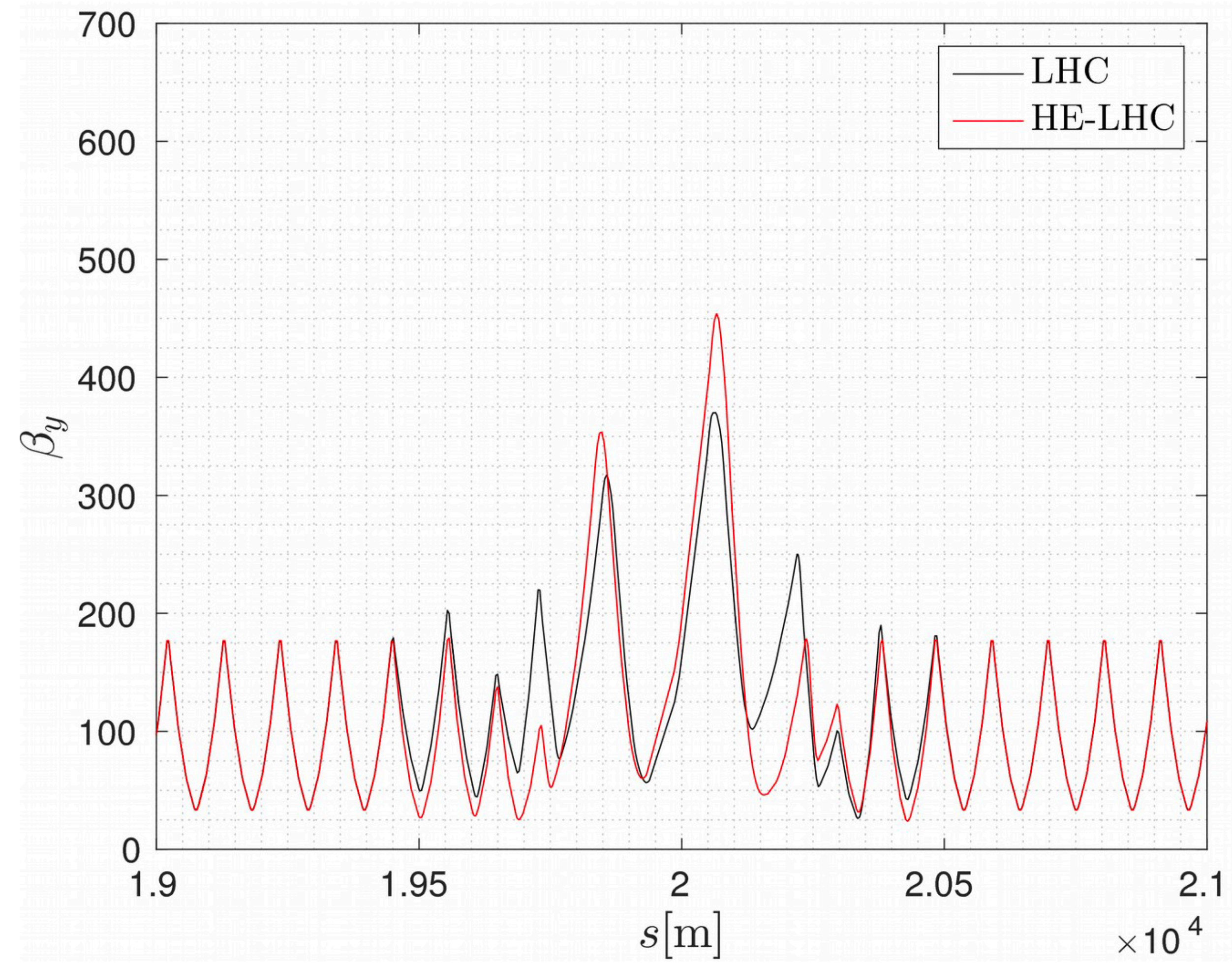
Machine	Max Dipole Field [T]	Dipole Length [m]	Max Quadrupole field [T]	Quadrupole Length [m]	Gradient [T/m]
HE-LHC	1.8	3.40	1.0	3.51	43.75
LHC	1.3	3.40	0.7	3.17	30.43

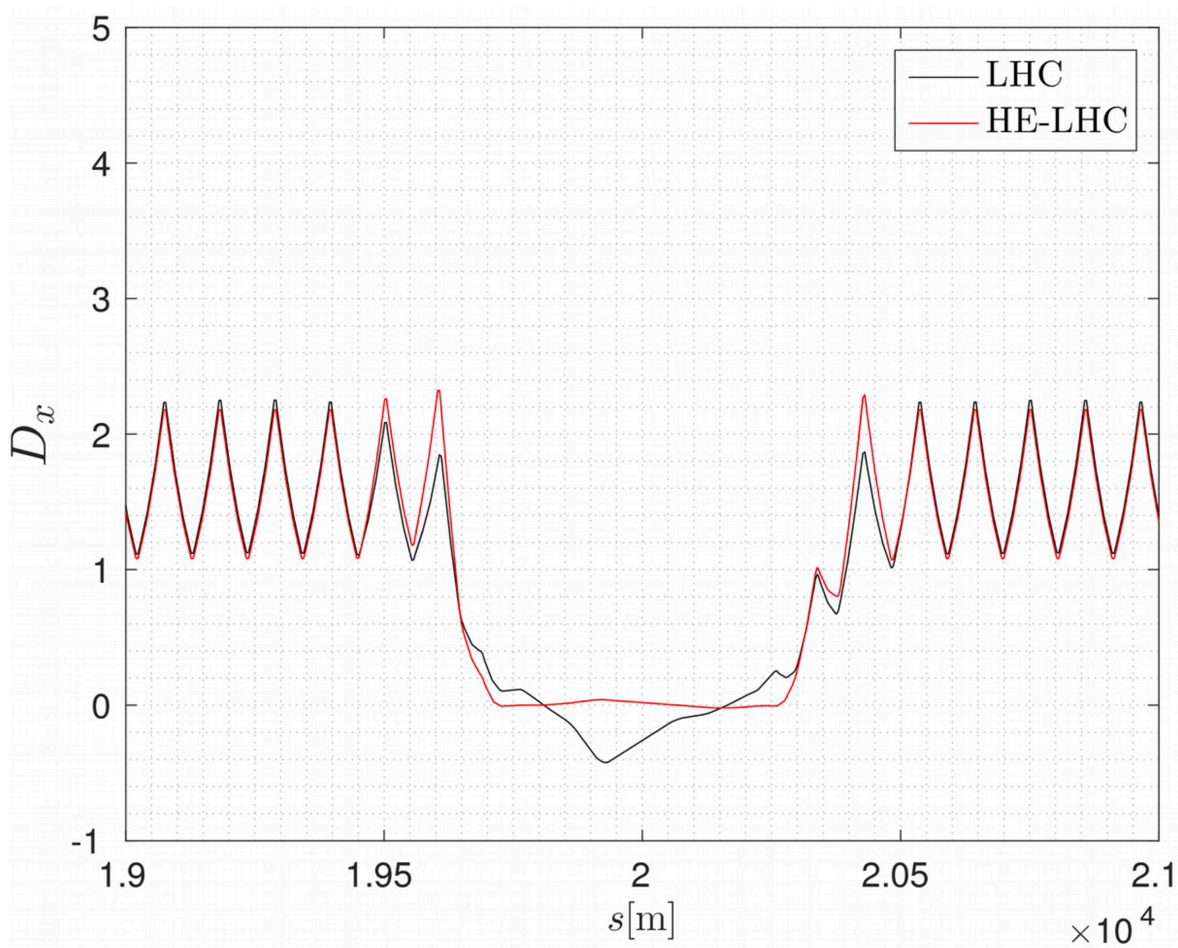
- A partially superconducting design could also be considered with the outer doglegs made superconducting but this would further complicate the design and should only be considered if absolutely necessary.
- Further studies would need to be performed in order to determine the operational viability of this option.

Betatron collimation in the HELHC version 0.4





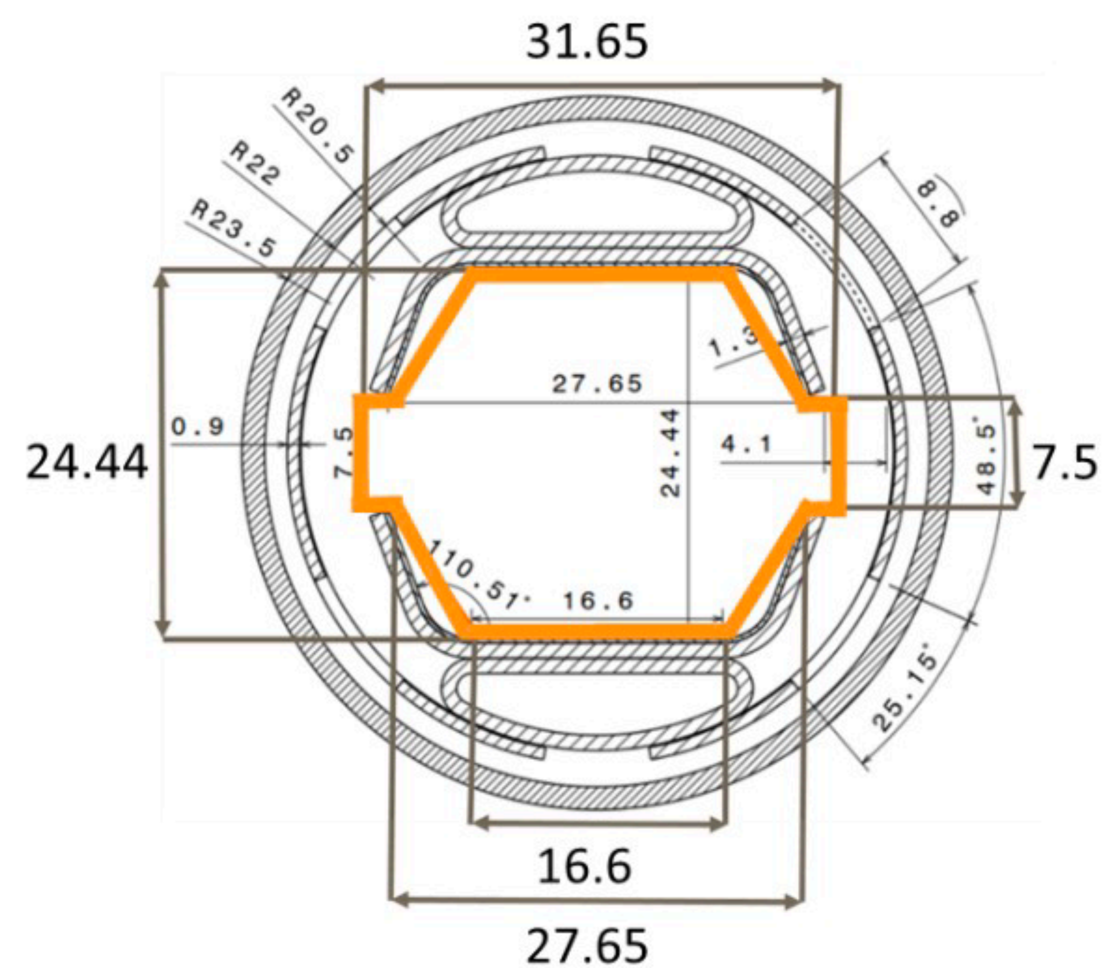




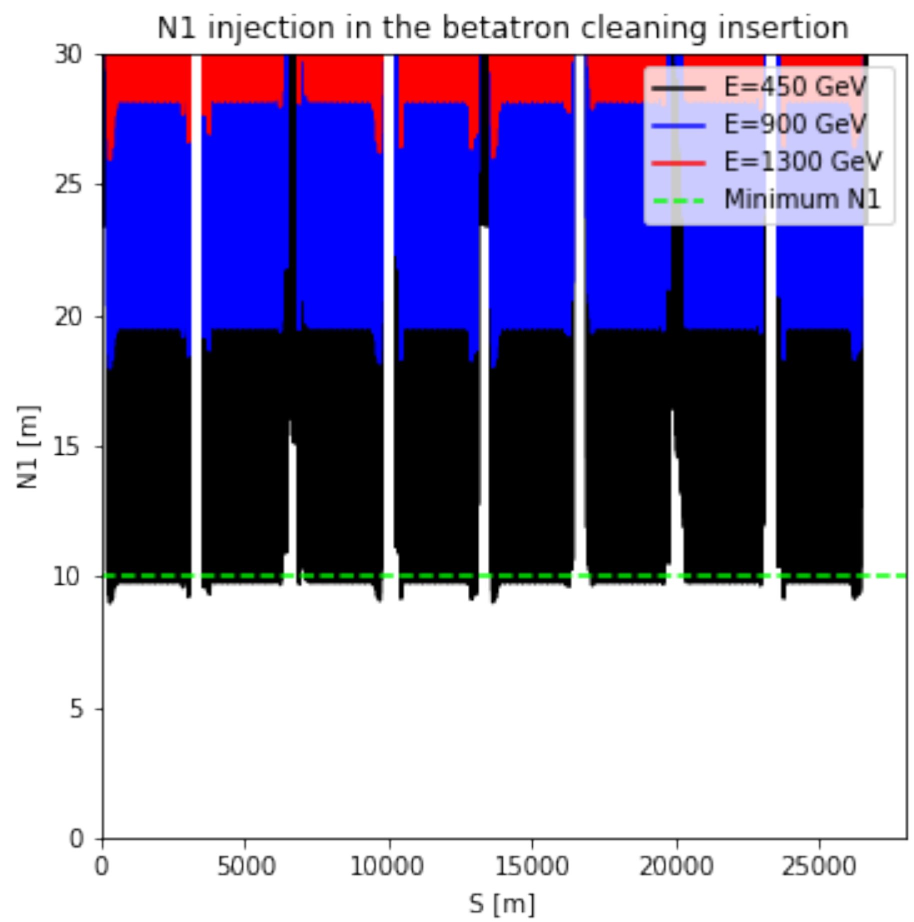
- Difference between the HE-LHC v0.4 optics and the LHC optics in the betatron collimation system.
- Differences between both the horizontal and vertical optics functions compared to the LHC.
- The dispersion through the IP is smaller for the HE-LHC. This could potentially benefit the overall performance.
- Could not retain the exact LHC optics due to changes in the magnet strengths and positions.
- Performance will be discussed in the following slides.

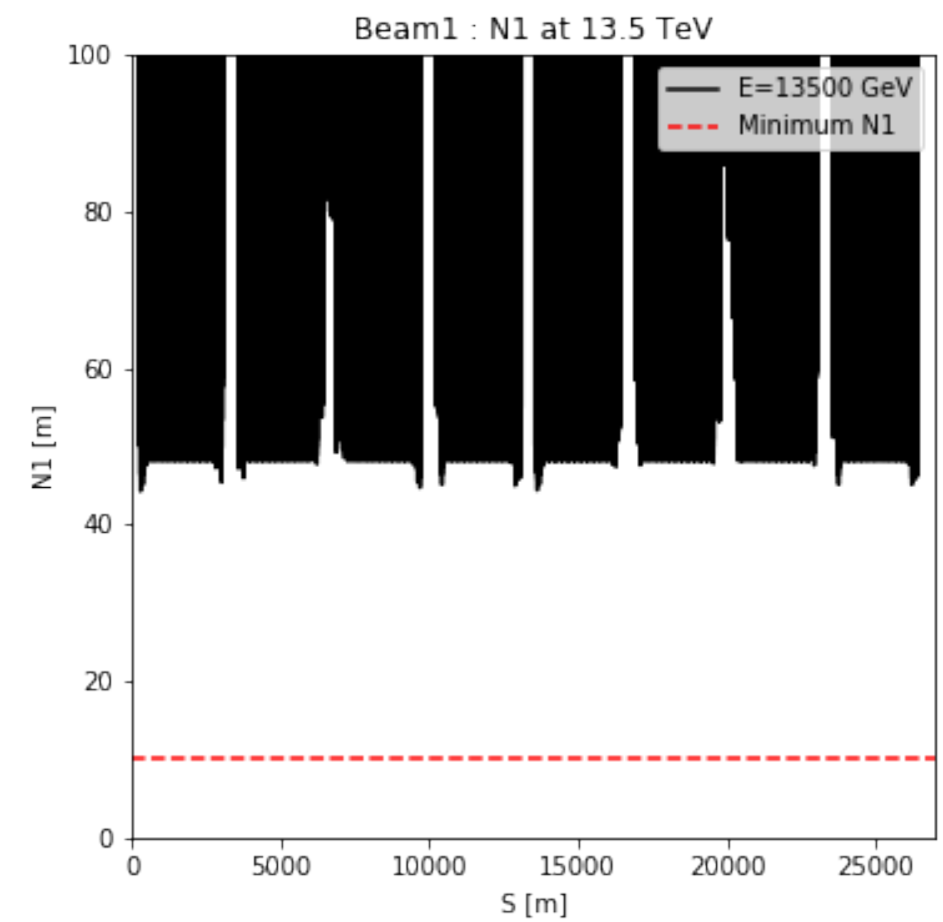
Aperture Model for v0.4 of the HE-LHC

- The HE-LHC aperture model is based on the FCC 2018 beam screen.
- In the simulation we do not include the slits.
- Not including the slits and taking the smallest horizontal distance gives a more pessimistic aperture.
- This model is generated using MADX for the HE-LHC version 0.4 with injection optics.
- The model is then used in SIXTRACK to predict the losses around the ring and in IR7



Apertures at injection and collision for the 23x90 v0.4





- The aperture is calculated using HL-LHC parameters for n1, with values taken for the beta-beat fractional beam size change, parasitic dispersion, closed orbit excursion, and halo size at collision and injection.
- At injection there is a clear gain from injecting at higher energies.
  - Higher injection energies mean that the physical beam size is smaller and hence there is a gain in aperture.
  - The minimum n1 at 450 GeV is about 8.98σ. This is a very challenging from the perspective of machine protection and including injection oscillations in addition to other errors.
  - At 900 GeV the n1 improves to 17.98σ which is much more feasible.
- At collision energy the minimum n1 is 44.26 σ, however this is expected to decrease when the crossing angle is introduced giving a bottleneck in the IR. For the HL-LHC the target minimum beam stay clear is 13σ
- This again provides challenges from the perspective of machine protection when dealing with failure scenarios etc.

Beam Cleaning Performance

- Tracking simulations were performed to evaluate the cleaning inefficiency
- The simulations were performed using the symplectic tracking code SIXTRACK.
- Two variations of the code were used:
  - The standard SIXTRACK with K2 collimation.
  - The SIXTRACK-FLUKA coupling.
- The standard SIXTRACK with K2 collimation tends to give more pessimistic results whereas the SIXTRACK-FLUKA coupling version has more developed physics modules giving more detailed results.
- The SIXTRACK-FLUKA version is used to generate touches that are used in the FLUKA simulations.
- The HE-LHC aperture model was used in the tracking simulations as this model is tighter than the LHC and hence will impact the losses
- Unlike the FCC dipoles, the HE-LHC dipoles are due to be bent. Whether this is technologically feasible is yet to be determined.

Beam Cleaning Performance

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

$$\eta_c = \frac{N_{\text{leak}}(a_z > a_z^{cut})}{N_{\text{impact}}\ \delta s}$$

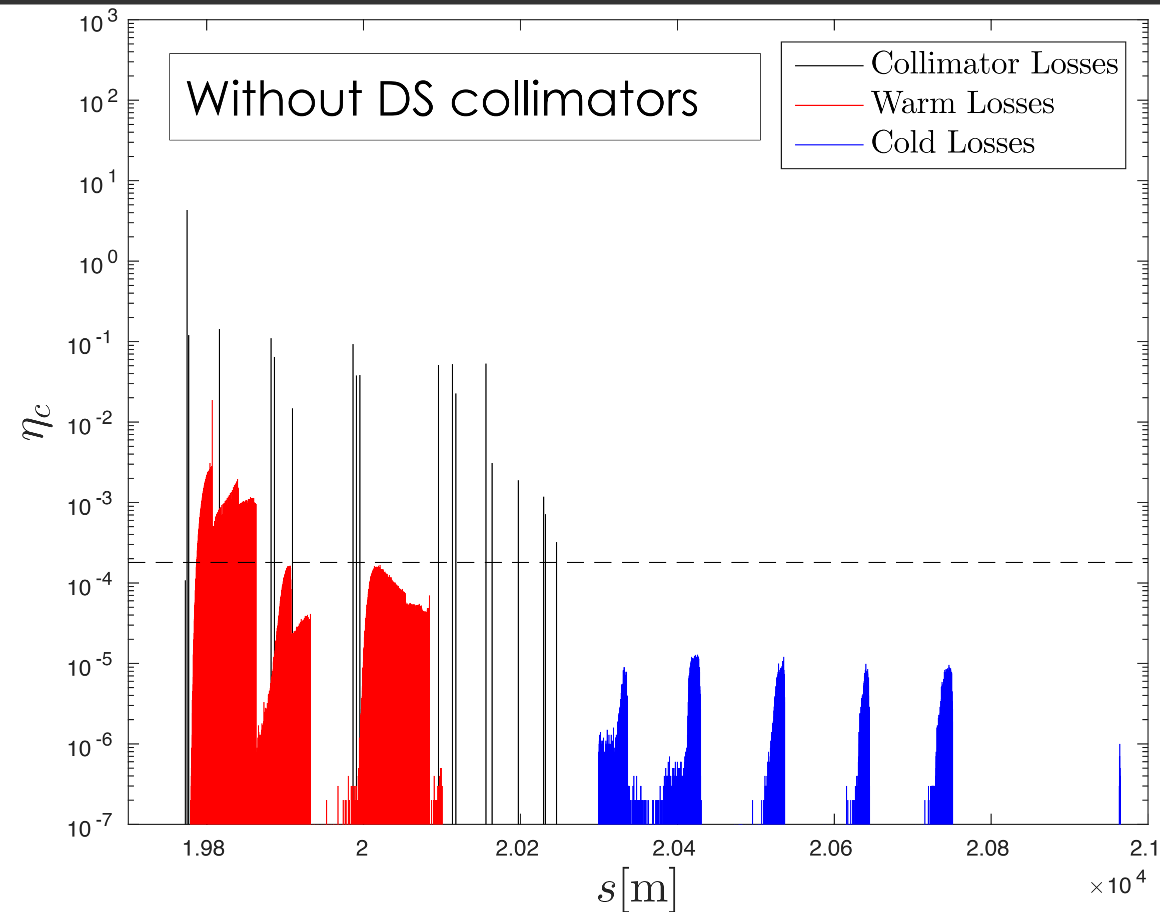
- Where N_{leak} is the number of escaping particles with a collimator cut at $a_z^{cut} > n_1$, and n_1 is the collimator gap in sigma, and N_{impact} is the number of particles that impact the collimator.
- Following on from last FCC Week and EuroCirol we use a LHC-like collimation system with two additional dispersion suppressor collimators (TCLDs) in IR7

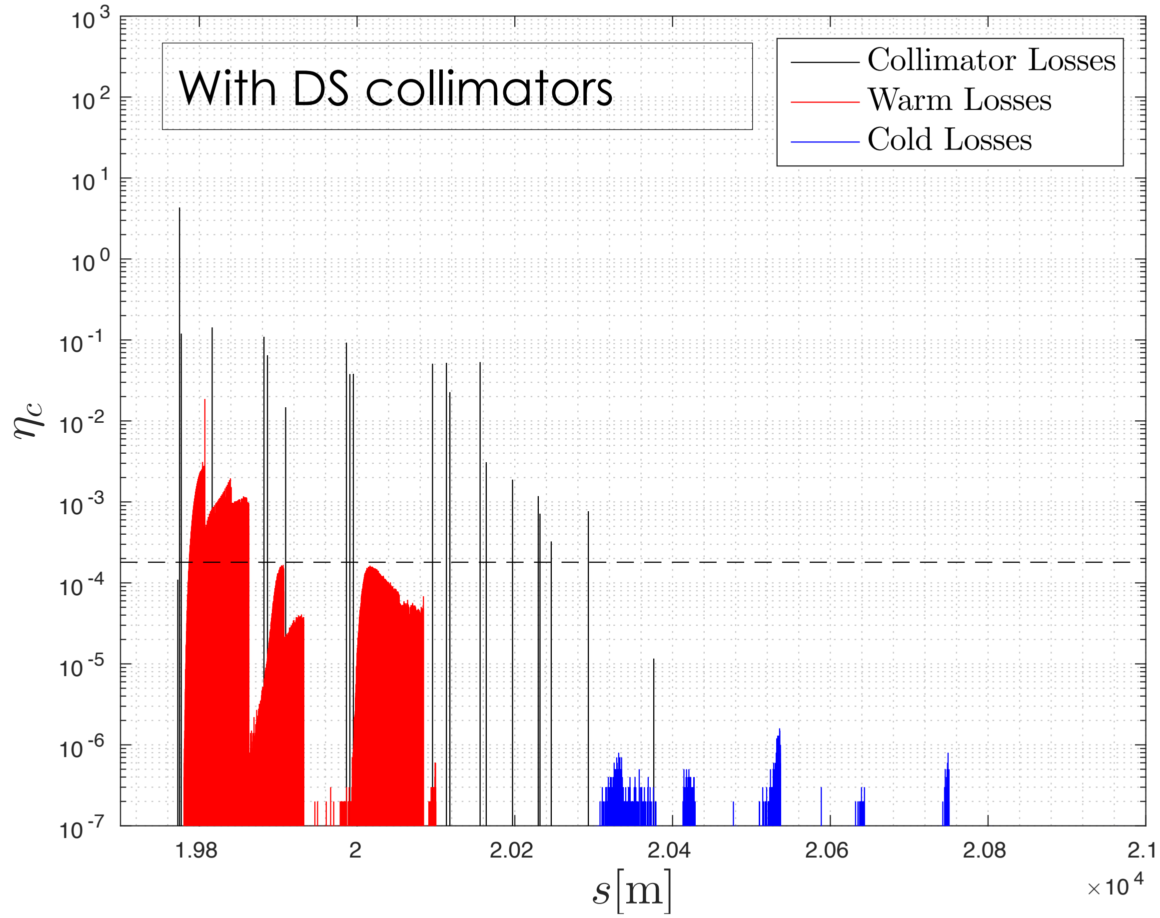
Beam Cleaning Performance at 450 GeV

- 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 in order to protect the aperture.
- The feasibility of these settings to protect the aperture whilst including imperfections still needs to be assessed.
- The DS collimators were positioned at 10/12 σ .

Collimator gapsize	σ	Half gap [mm]
Primary	5.7	3.81
Secondary	6.7	4.21
Injection (TDI)	6.8	3.27
TCLI	8.0	6.36
Absorbers	11.5	4.45
DS Collimator	10.0/12.0	3.55/5.33

Beam Cleaning Performance at 450 GeV





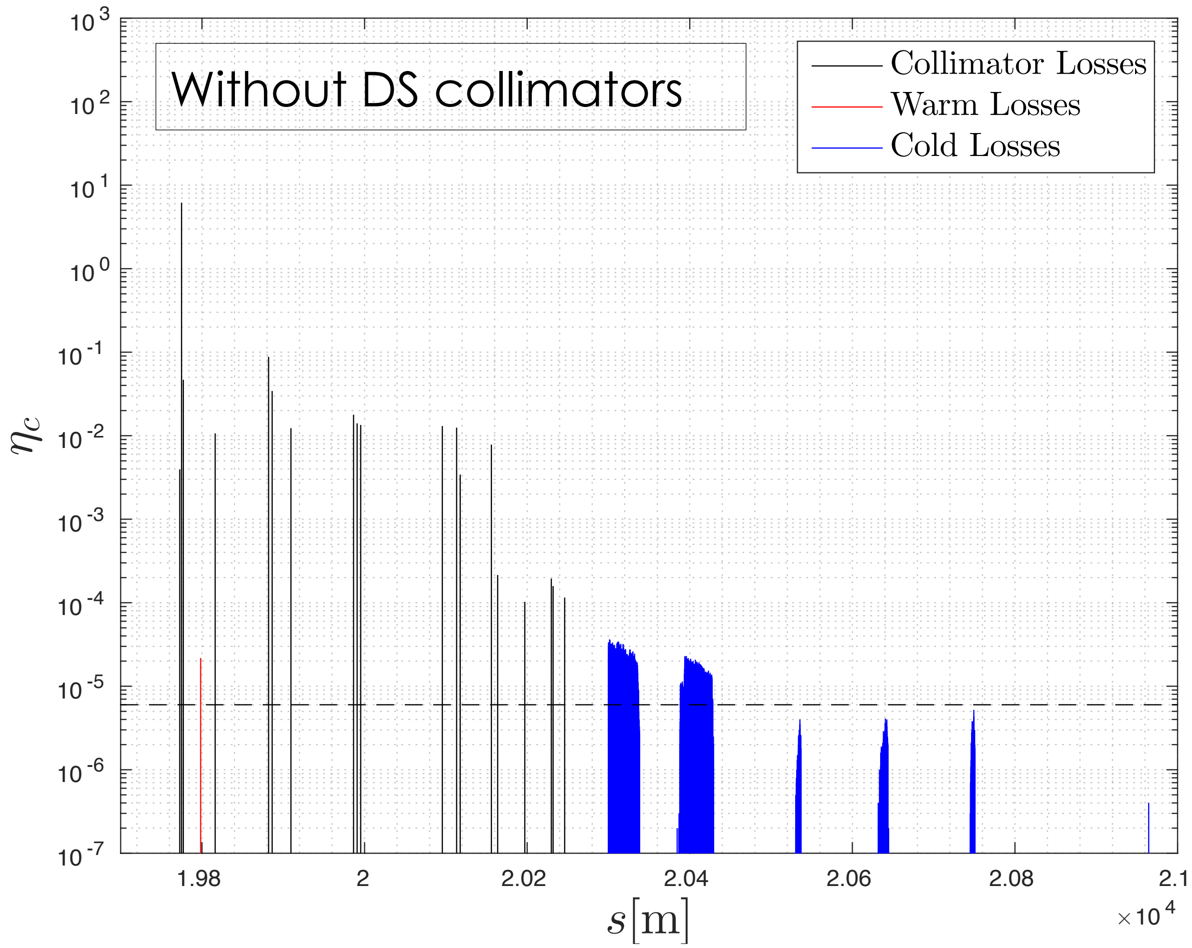
- Injection at 450 GeV is challenging for the HE-LHC with regards to collimation as the physical aperture is smaller than 9σ.
- Very challenging from the perspective of a collimation system which must protect this aperture from both normal operational losses due to beam processes and unexpected failure scenarios.
- For scenarios with and without DS collimators, the warm losses do not change.
- The largest gain comes in the cold section where the dispersion starts to ramp up to 4m. At this point the DS collimators intercept these particles and prevent them being lost in the superconducting coils of the cold magnets.

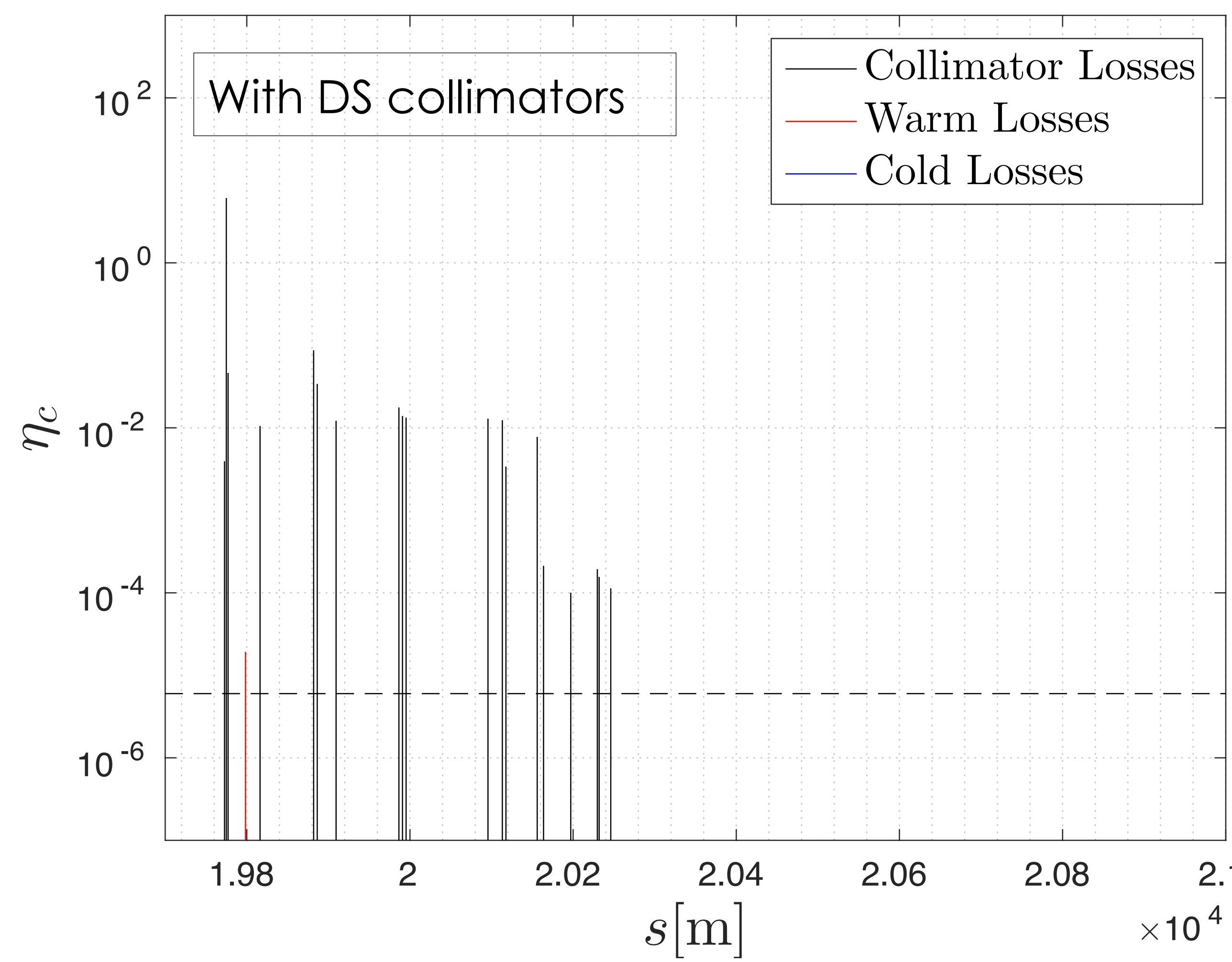
Beam Cleaning Performance at 13.5 TeV

- First preliminary collimator settings at a collision energy of 13.5 TeV 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 in order to protect the aperture.
- The feasibility of these settings to protect the aperture whilst including imperfections still needs to be assessed.
- The DS collimators were positioned at 18.1/22.2 σ and were opened slightly because at the original setting of 10/12 σ the half gap size was 0.8 mm.

Collimator gapsize	σ	Half gap [mm]
Primary	6.7	0.82
Secondary	9.1	1.32
Absorbers	11.5	1.04
DS Collimator	18.1/22.2	1.17/1.54

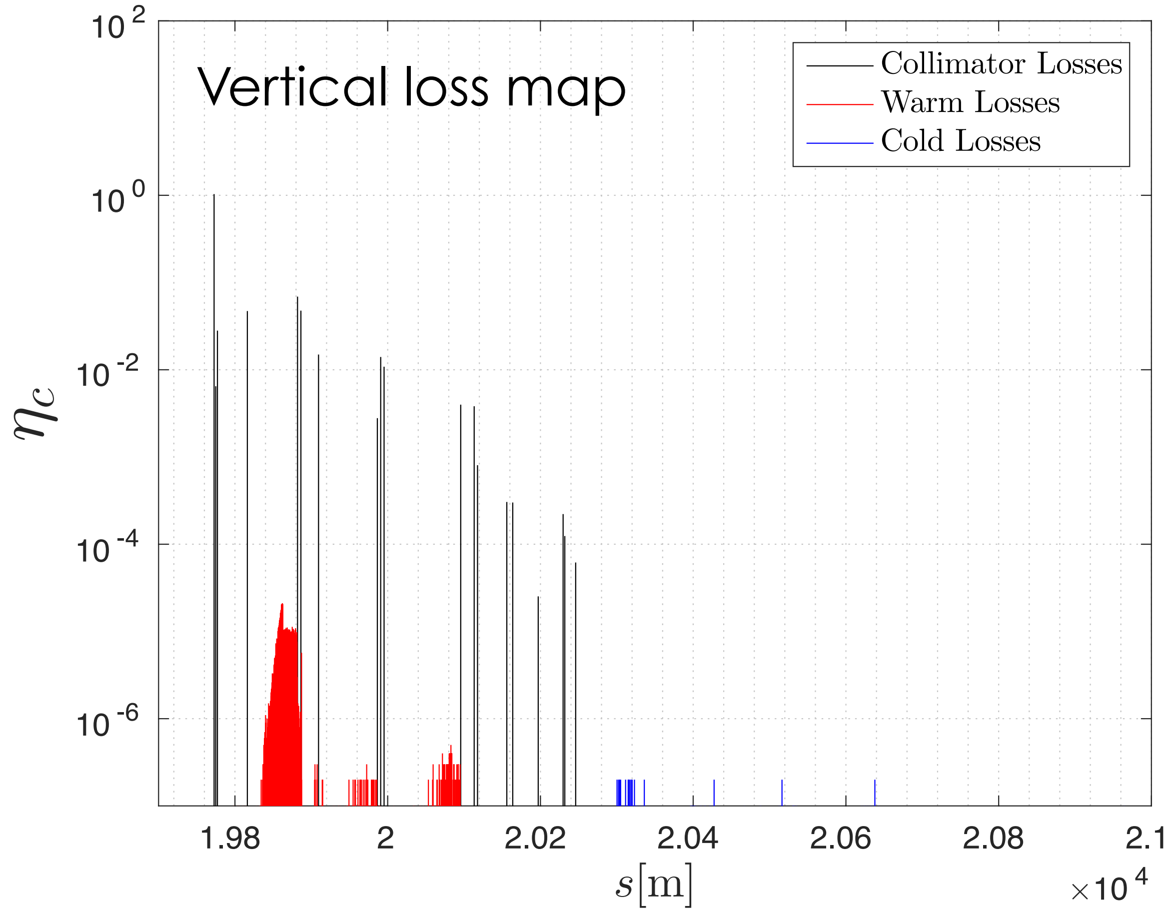
Beam Cleaning Performance at 13.5 TeV

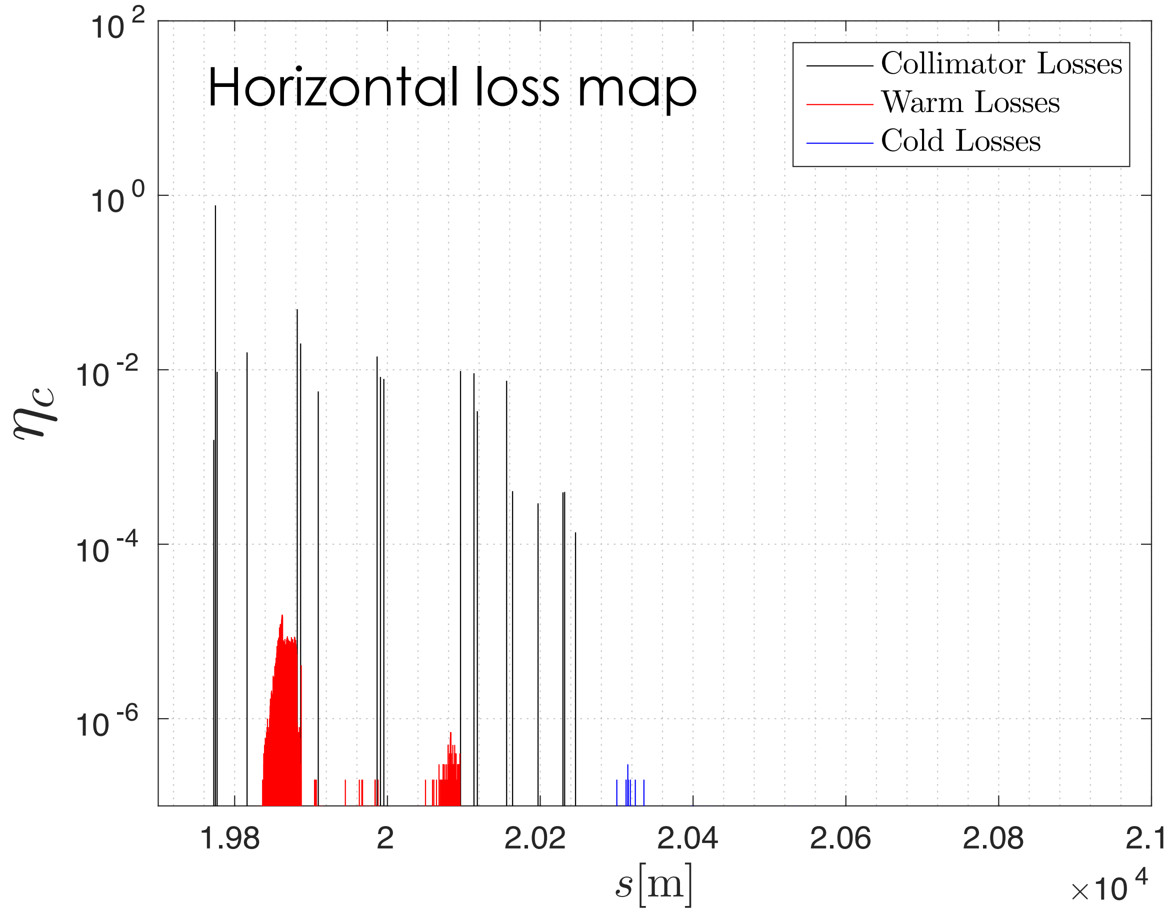




- At collision energy we see a significant improvement in the loss maps when we compare with and without DS collimators.
- The DS collimators work effectively once again to capture the off-momentum particles and prevent them being lost downstream in the superconducting coils.
- At a collision energy of 13.5 TeV, the estimated quench limit is 0.6×10^{-5} m^{-1}. Without DS collimators the losses downstream of IR7 would very likely cause the superconducting magnets to quench.

Betatron collimation performance for unsqueezed optics at collision energy with TCLDs using SIXTRACK-FLUKA





- The study for the lattice with dispersion suppressor collimators at collision energy is repeated using `SIXTRACK-FLUKA` coupling.
- The losses in the warm section are more developed compared to the original `SIXTRACK` version and we observe some leakage downstream in the cold section.
- The DS collimators capture a significant amount of the off-momentum particles and protect the superconducting magnets downstream. The amount of losses in the vertical and horizontal plane are both below 10^{-7} corresponding to the resolution of our simulations.
- Overall however the collimation system performs exceptionally well at collision.

Challenges of including the DS collimators

- The DS collimators clearly mitigate the number of losses downstream in the cold section of the betatron collimation system.
- However these collimators take up considerable space in the lattice and unlike the HL-LHC which uses 11 T dipoles, we cannot use 22 T magnets.
- Therefore additional space has to be made between Q7- MB8 as well Q10-MB11.
- This adds a number of challenges for the optics and design team.
  - The DS collimators are difficult to place in the lattice (especially for the 18x90 lattice) due to the limited space and we cant use > 20 T magnets.
  - The DS collimators induce a large survey offset from the LHC and hence make it difficult to fit the HE-LHC in the LHC tunnel.

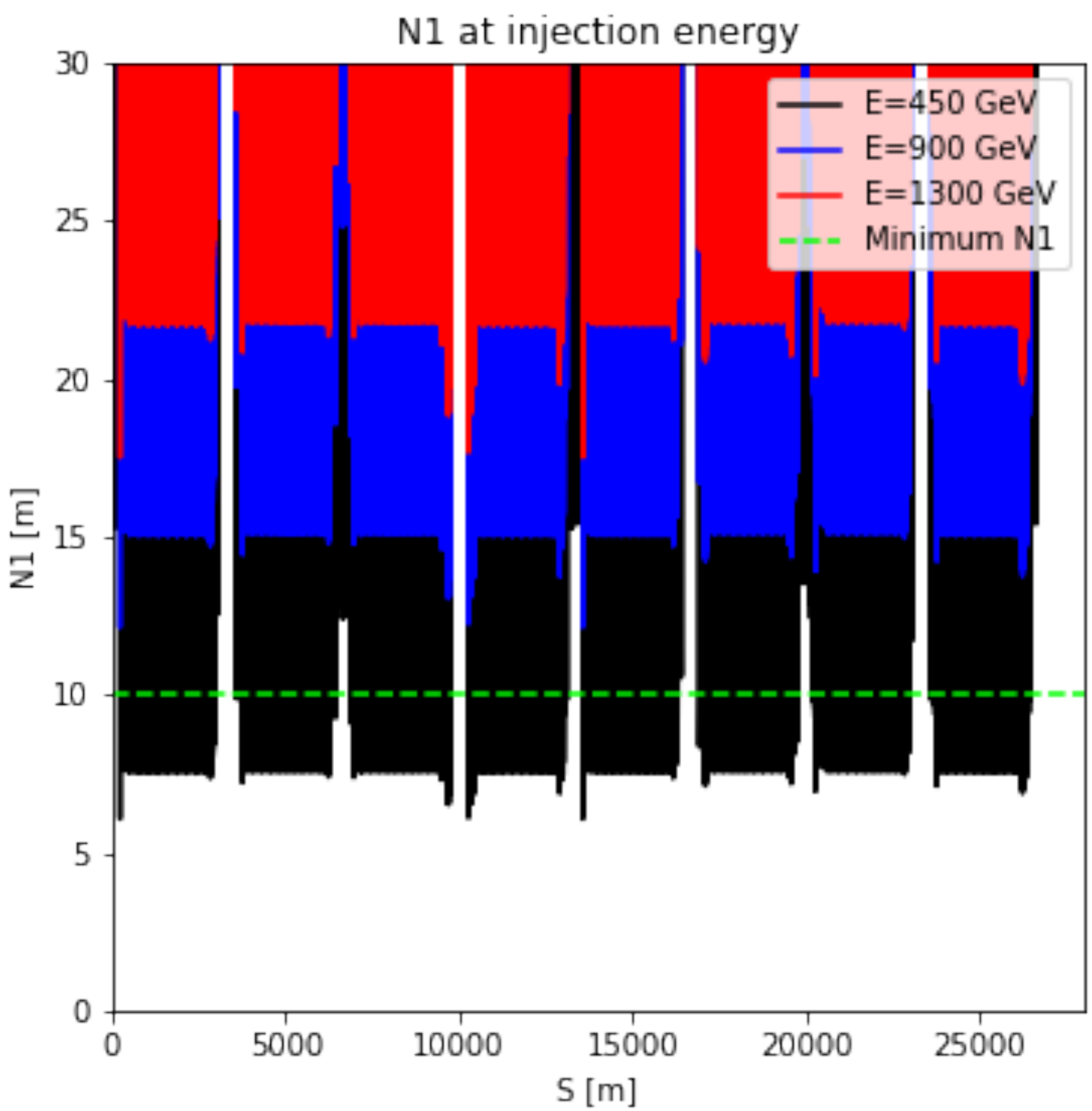
Summary and further work

- Overall the v0.4 IR7 performs exceptionally well with DS collimators and losses downstream in the cold section are mitigated substantially.
  - The system has been verified with FLUKA studies (see talk by M. Varasteh) and issues and challenges such as power load on the collimators have been discussed.
- Further studies need to be performed to verify that the proposed system works in all scenarios and with the limitations identified.
- Additional scenarios to be considered are:
  - Full ring collimation
  - Losses with failure scenarios
- New lattice for 18x90 is also available now with beam 1 and beam 2. Some changes in the IR7 optics that need to be verified with studies (on-going now)
- In future iterations novel collimation methods could be considered and employed
    - Electron lens for active halo control
    - Crystal collimation

Thanks for listening

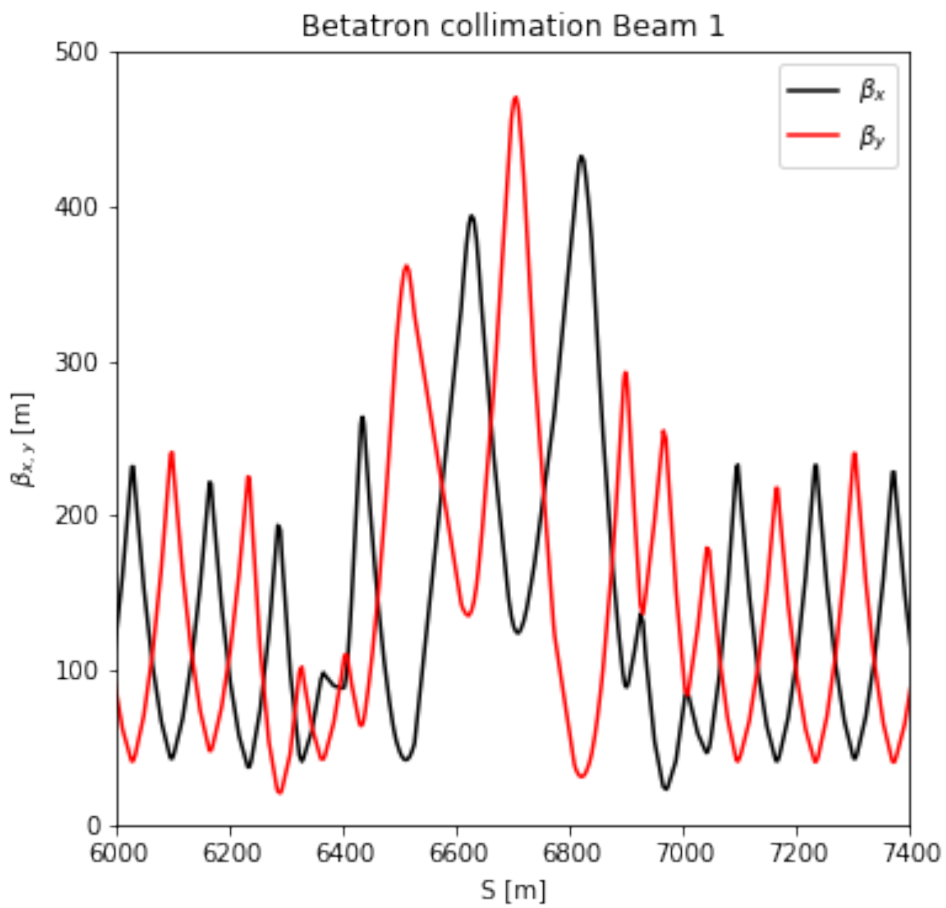
Backup slides

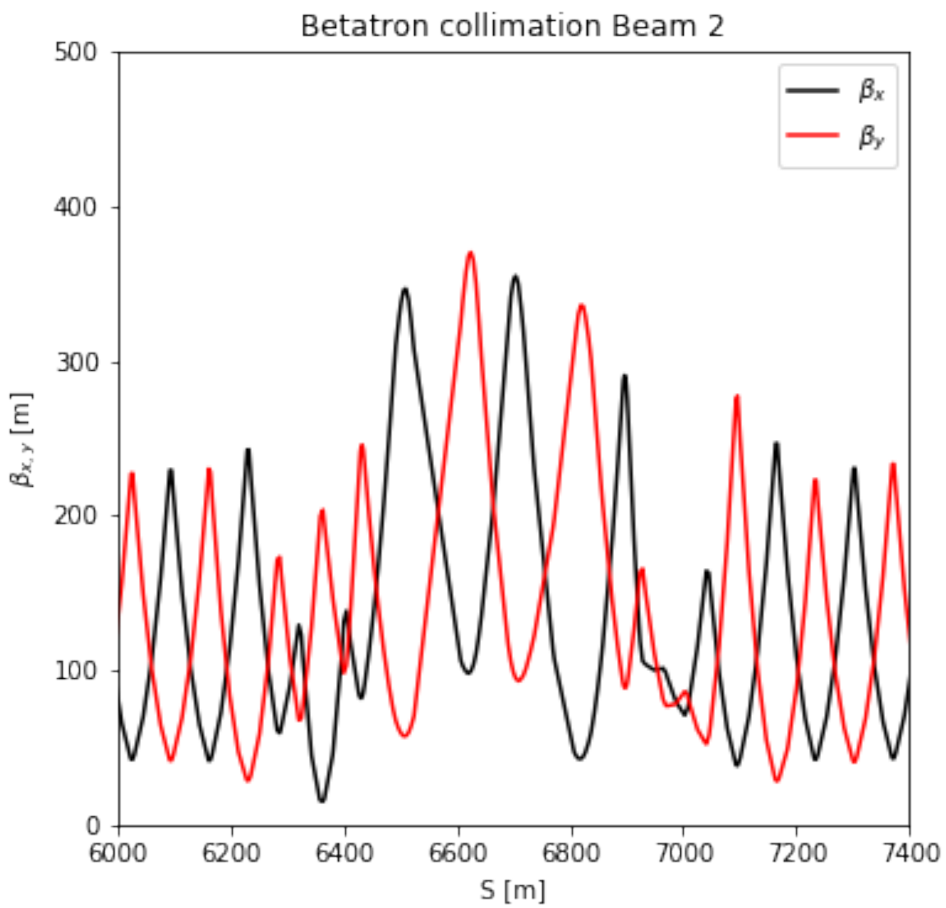
18x90 lattice and physical aperture



- The physical aperture for the 18x90 lattice at various injection energies.
- The minimum targeted N1 is 10 sigma.
- The 450 GeV option is the cheapest options that does not require an upgrade of the SPS but it gives a very small physical aperture
- The N1 is approximately 5 sigma.
- This is probably unfeasible since the entire collimation hierarchy needs to fit within this aperture to protect the machine.

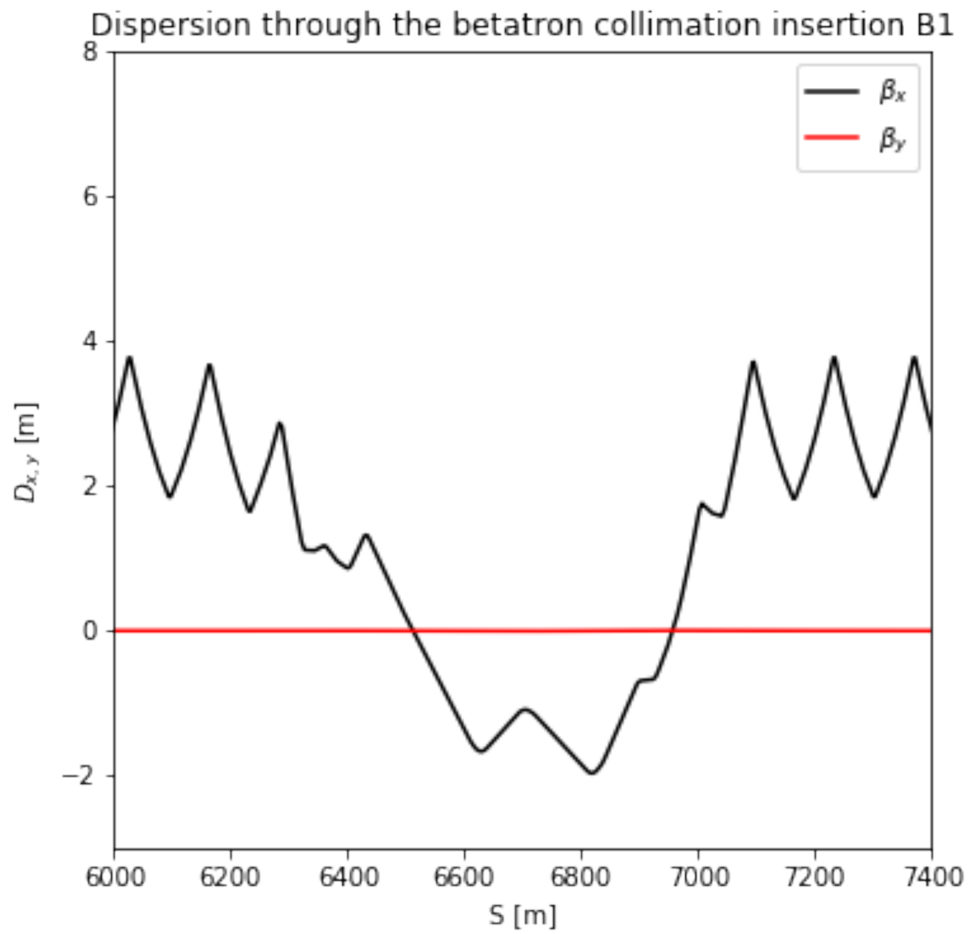
Preliminary investigation of the new 18x90 HE-LHC lattice

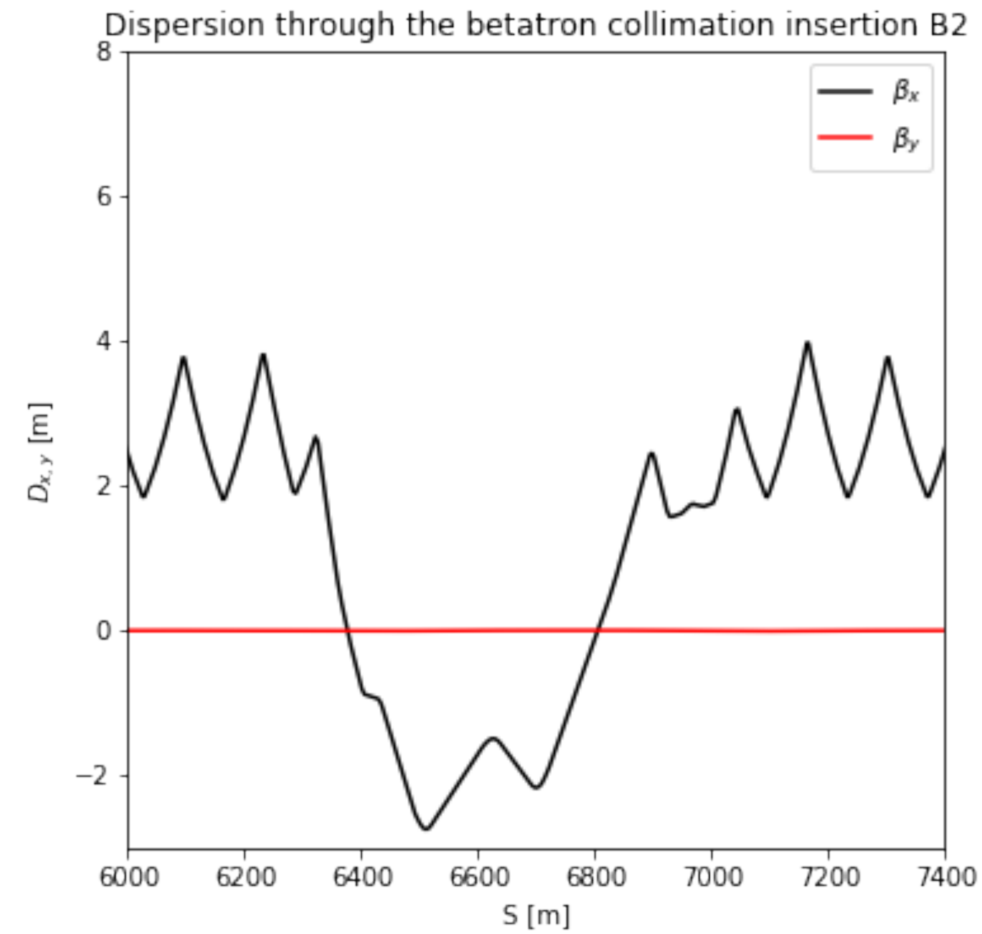




- The dispersion through the betatron collimation system is very different from version 0.4
- Optics difference between beam 1 and beam 2.
  - The impact of the optics changes on the beam losses still need to be investigated.

Preliminary investigation of the new 18x90 HE-LHC lattice





- The dispersion through the betatron collimation system is very different from version 0.4
- Much like the beta-functions there is also a difference in the dispersion through the betatron collimation system with regard to beam 1 and beam 2.
- The impact of this dispersion needs to be fully tested and understood with regard to the performance of the machine.