HE-LHC Collimation: Optics layout and first performance studies.

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Acknowledgements: *L. Van-Riesen-Haupt, A. Mereghetti, S. Raedelli, M. Giovannozzi, T. Risselada, D. Zhou.*

Outline

- Overview of the current design status and progress of the HE-LHC collimation
- First investigations of the LHC lattice and performance with HE-LHC aperture constraints.
- Challenges and progress on IR7 design and modification.
- Preliminary performance studies of the new modified lattice.

HE-LHC Parameters

parameter	unit	FCC-hh		**HE-LHC**	(HL-)LHC
centre-of-mass energy	TeV	100		27	14
injection energy	TeV	3.3		0.45 (?)	0.45
arc dipole field	T	16		16	8.33
circumference	km	97.8		26.7	26.7
straight-section length	m	528		528	1400
beam current	A	0.5		1.12	(1.12) 0.58
bunch population	10^{11}	1.0		2.2	(2.2) 1.15
number of bunches / beam	—	10600		2808	(2808) 2808
RF voltage	MV	24		16	(16) 16
rms bunch length	mm	~ 80		75.5	75.5
bucket half height	10^{-3}	0.075		0.21	0.36
rms momentum spread	10^{-4}	0.3		0.85	1.129
longitudinal emittance ($4\pi\sigma_z\sigma_E$)	eVs	5		4.2	2.5
bunch spacing	ns	25		25	25
norm. transv. rms emittance	μm	2.2		2.5	(2.5) 3.75
IP beta function $\beta^*_{x,y}$	m	1.1	0.3	0.25	(0.15) 0.55
initial rms IP beam size $\sigma^*_{x,y}$	μm	6.7	3.5	6.6	(8.2) 16.7
half crossing angle	μrad	37	70	(180) 133	(295) 150
Piwinski angle w/o crab cavities	—	0.42	1.51	(2.0) 1.50	(2.52) 0.65
peak luminosity per IP	10^{34} cm^{-2}s^{-1}	5	30	28	(5, levelled) 1
total cross section	mbarn	153		126	111
inelastic cross section	mbarn	108		91	85
peak no. of events / crossing	—	170	1000	800	(135) 27
rms luminous region	mm	53	49	57	(57) 45
stored energy / beam	GJ	8.4		1.4	(0.7) 0.36
energy loss per proton per turn	keV	4600		93	6.7
SR power / beam	kW	2400		100	7.3 (3.6)
SR power / length	W/m/aperture	28.4		4.6	(0.33) 0.17
transv. emittance damping time	h	1.1		3.6	25.8
no. of high-luminosity IPs	—	2	2	2	(2) 2
initial proton burn-off time	h	17	3.4	2.5	(15) 40
average turnaround time	h	5	4	3	5 (5)
optimum run time	h	11.6	3.5	3.0	(11.7) 14.2
accelerator availability	—	70%	70%	70%	(52%) 71%
luminosity per year (160 days)	fb^{-1}	≥ 250	≥ 1000	730	(350) 55

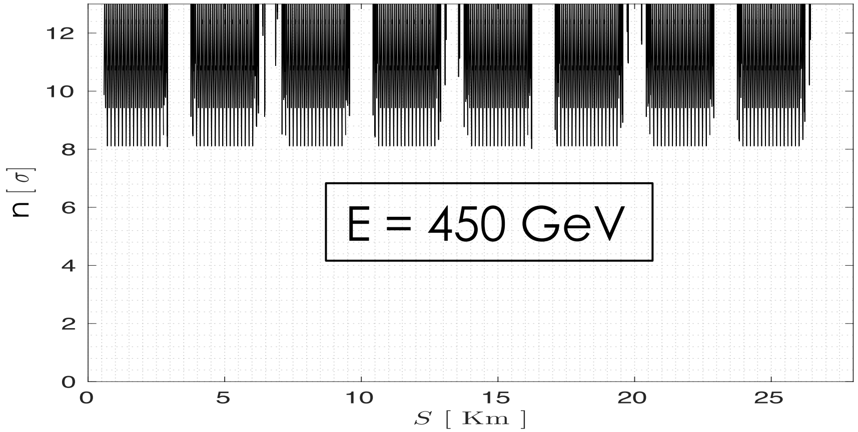
- Summary of the HE-LHC parameters
- Bunch properties are similar as for the HL-LHC.
- Larger bunch population than the LHC, smaller emittances, more SR radiation, larger stored beam energy, higher CoM collisions.
- More challenges for a collimation system which must protect the machine and clean the bunch halo of high amplitude particles.

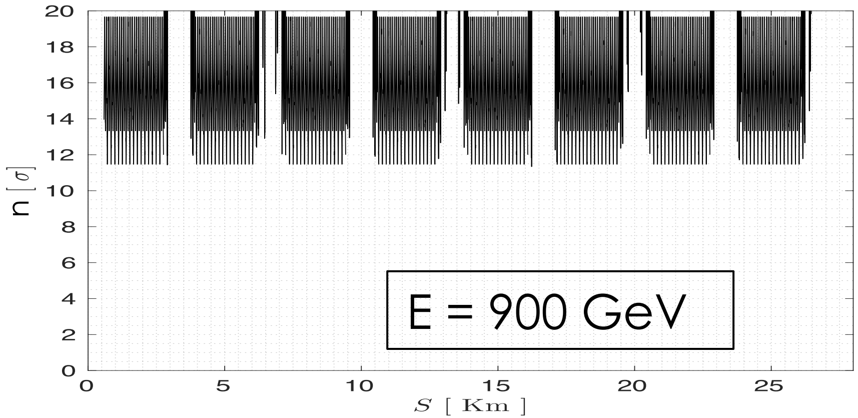
Scaling of the LHC design to HE-LHC at injection and collision

- In order to identify possible issues and show stoppers, the LHC collimation system was scaled to HE-LHC energies and apertures.
- The betatron cleaning system from the LHC was matched into the 18x90 lattice.
- For this first model no constraints were placed on the magnets
  - These will be included later meaning that the betatron collimation system will need to be modified.
- The cleaning inefficiency in the scaled model was calculated for the different injection energies, however here we only consider the 900 GeV case with injection optics and 13.5 TeV with collision optics for the loss map.
- The cleaning inefficiency is given by

$$\eta(s) = \frac{n_{\mathrm{lost}}(s)}{n_{\mathrm{total}}\Delta s}$$

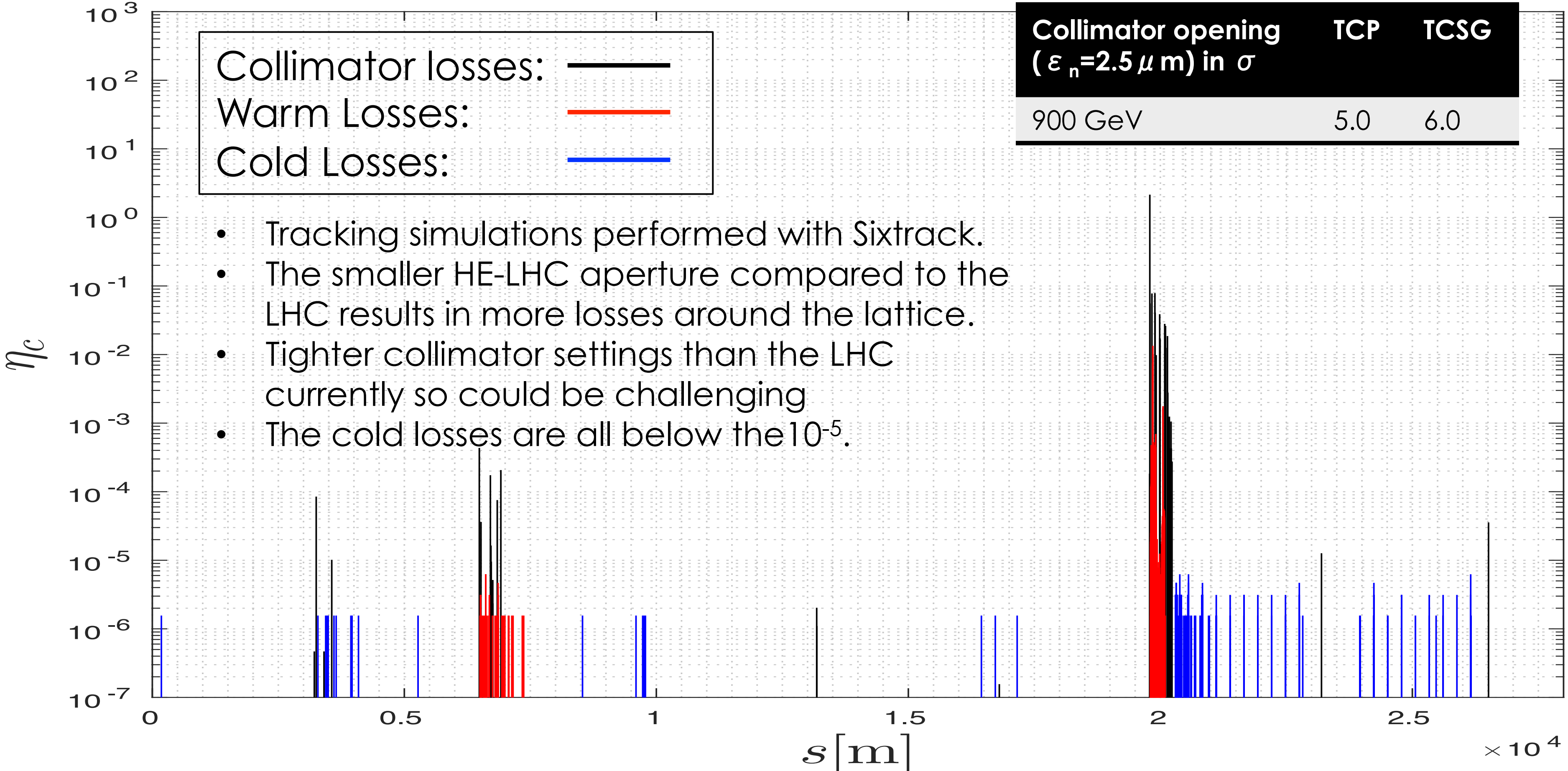
Collimation at injection





- Three different energies proposed.
  - 450 GeV, 900 GeV, and 1300 GeV.
- At injection energy one of the biggest issue is the physical aperture. *See talks by J. Kientzel et al.*
- For the 18x90 lattice at 900 GeV this is ~10 σ in the arcs, normally a design value of is used 12-13 σ .
- Extremely challenging from the perspective of machine protection, and would require protection protocols to deal with injection oscillations and failure scenarios.
- A higher injection energy would be preferred from the perspective of machine protection to give additional physical aperture. **for a slightly older version of the lattice*

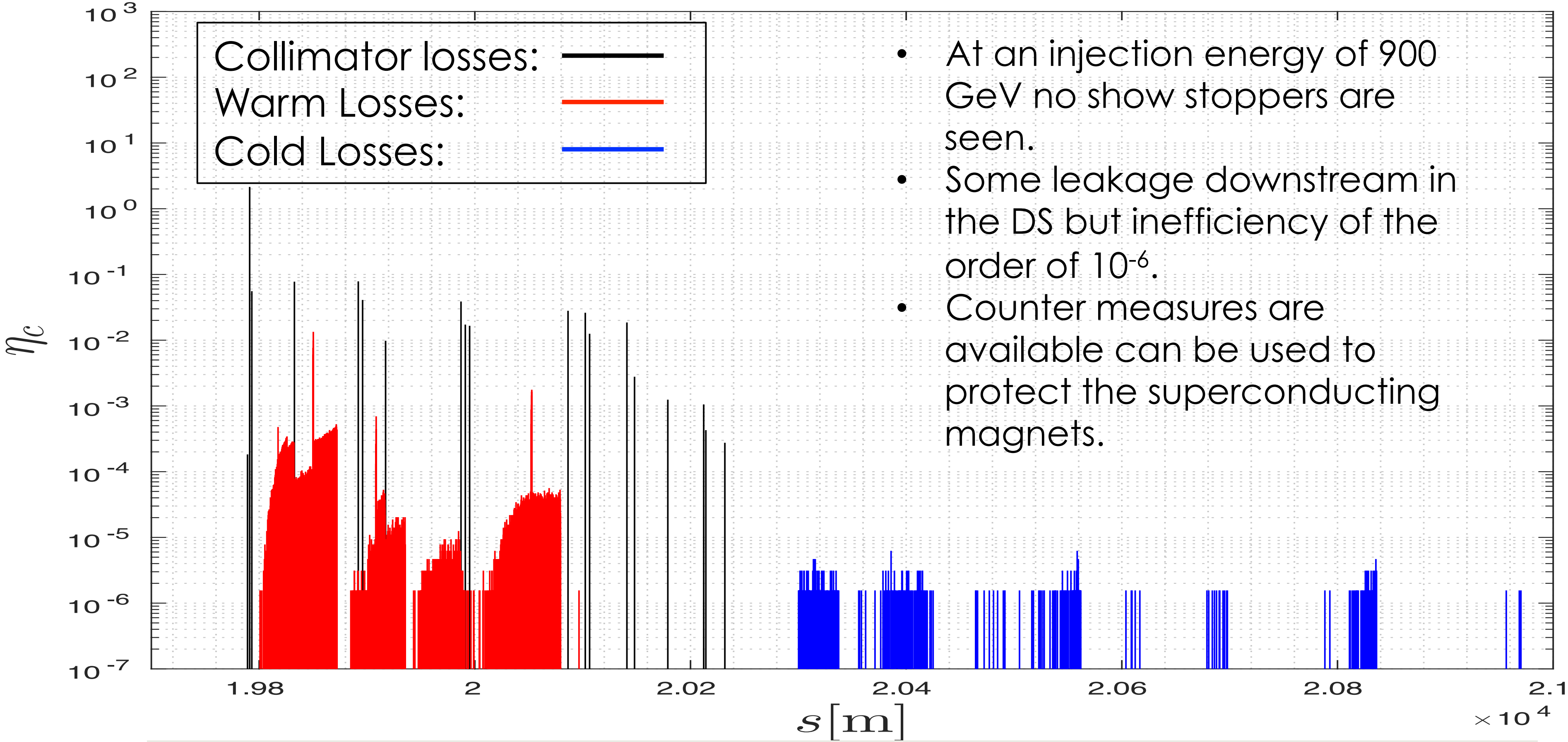
Loss maps at injection 900 GeV



Collimator opening (ε_n=2.5 μm) in σ	TCP	TCSG
900 GeV	5.0	6.0

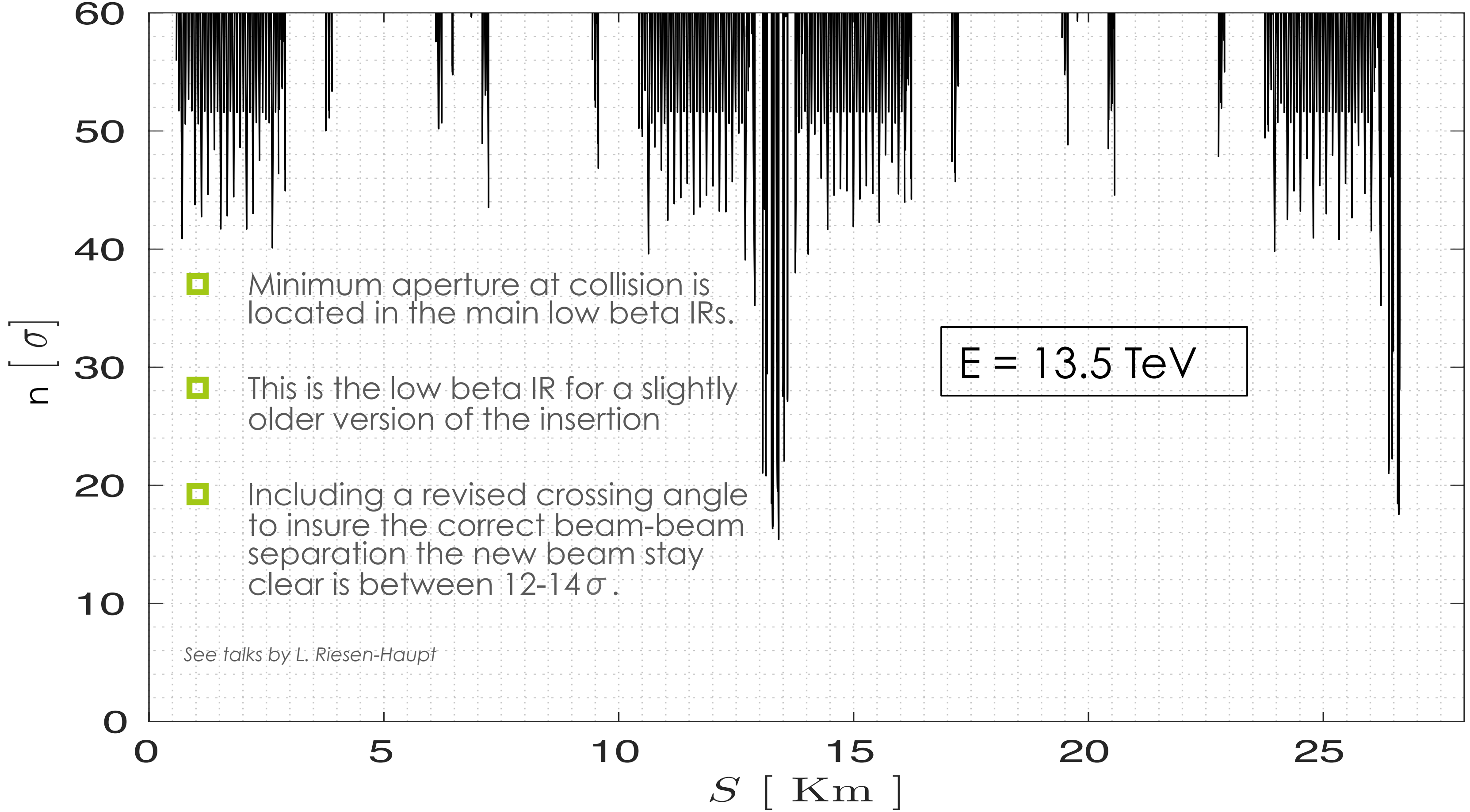
- Tracking simulations performed with Sixtrack.
- The smaller HE-LHC aperture compared to the LHC results in more losses around the lattice.
- Tighter collimator settings than the LHC currently so could be challenging
- The cold losses are all below the10^{-5}.

Loss maps at injection 900 GeV



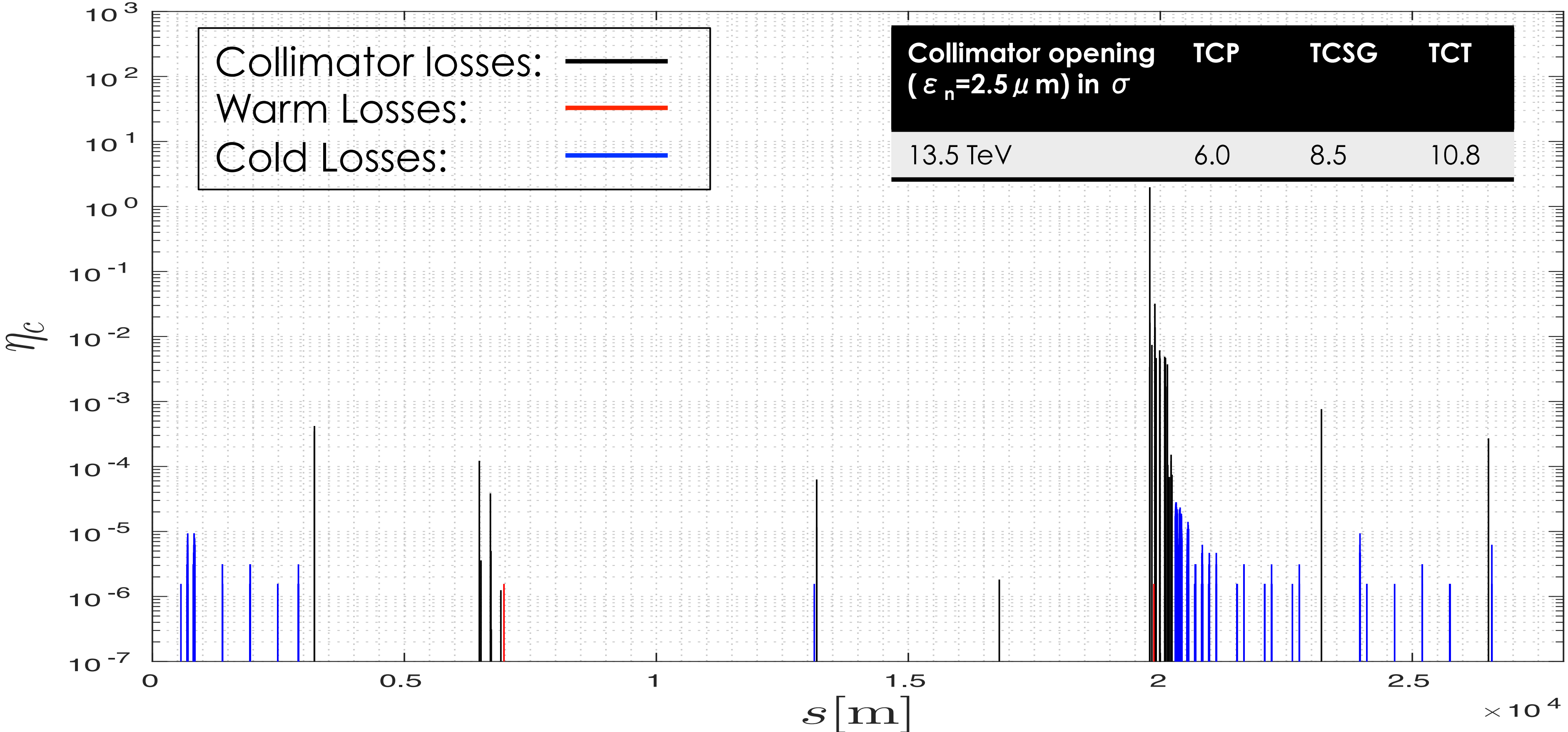
- At an injection energy of 900 GeV no show stoppers are seen.
- Some leakage downstream in the DS but inefficiency of the order of 10^{-6}.
- Counter measures are available can be used to protect the superconducting magnets.

Aperture model for the HE-LHC at collision



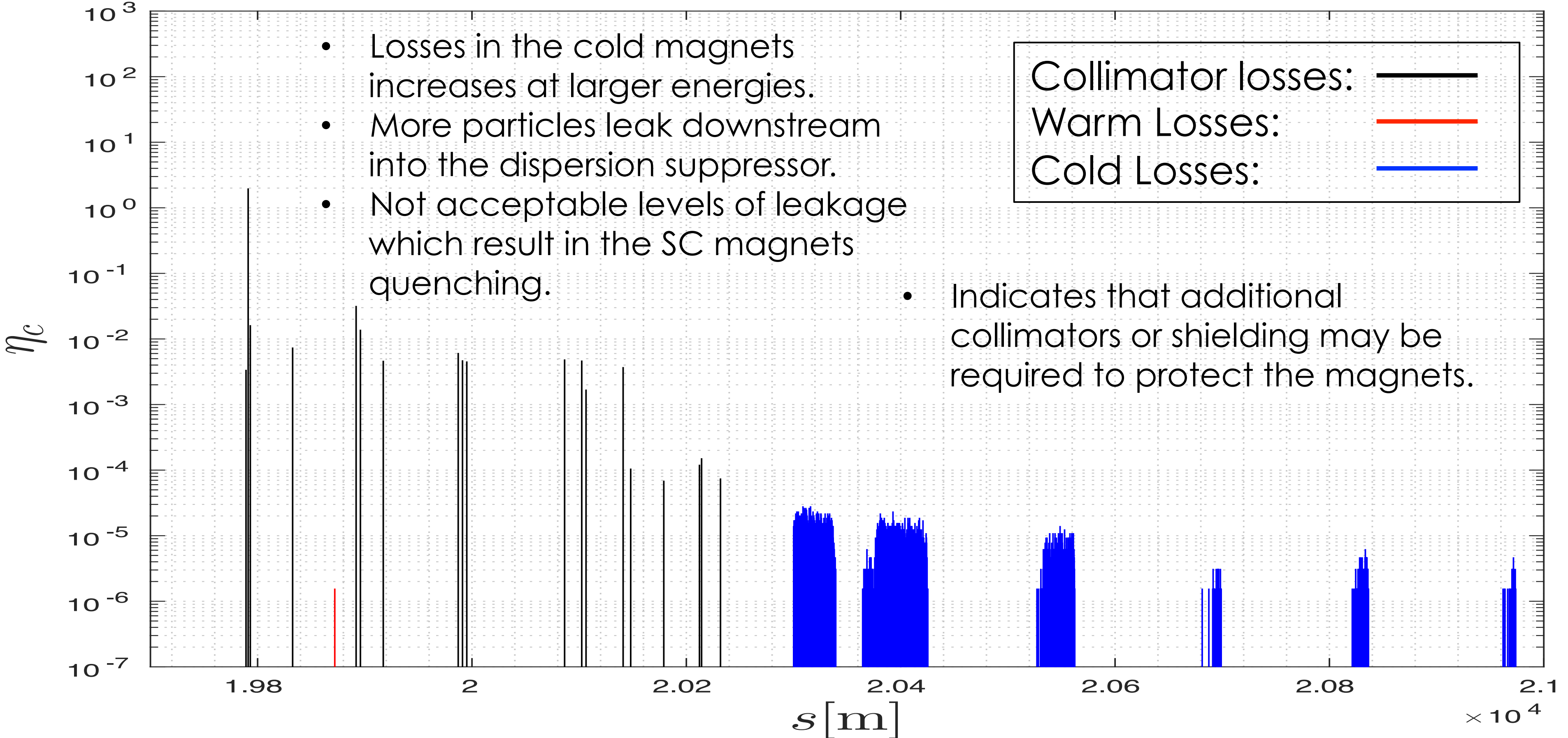
- Minimum aperture at collision is located in the main low beta IRs.
- This is the low beta IR for a slightly older version of the insertion
- Including a revised crossing angle to insure the correct beam-beam separation the new beam stay clear is between 12-14 σ .

Loss maps at collision optics @ 13.5 TeV for the scaled LHC collimation system



Collimator opening (ε_n=2.5 μm) in σ	TCP	TCSG	TCT
13.5 TeV	6.0	8.5	10.8

Loss maps at collision energy for the scaled LHC collimation system



- Losses in the cold magnets increases at larger energies.
- More particles leak downstream into the dispersion suppressor.
- Not acceptable levels of leakage which result in the SC magnets quenching.
- Indicates that additional collimators or shielding may be required to protect the magnets.

Challenges for IR7 in the HE-LHC

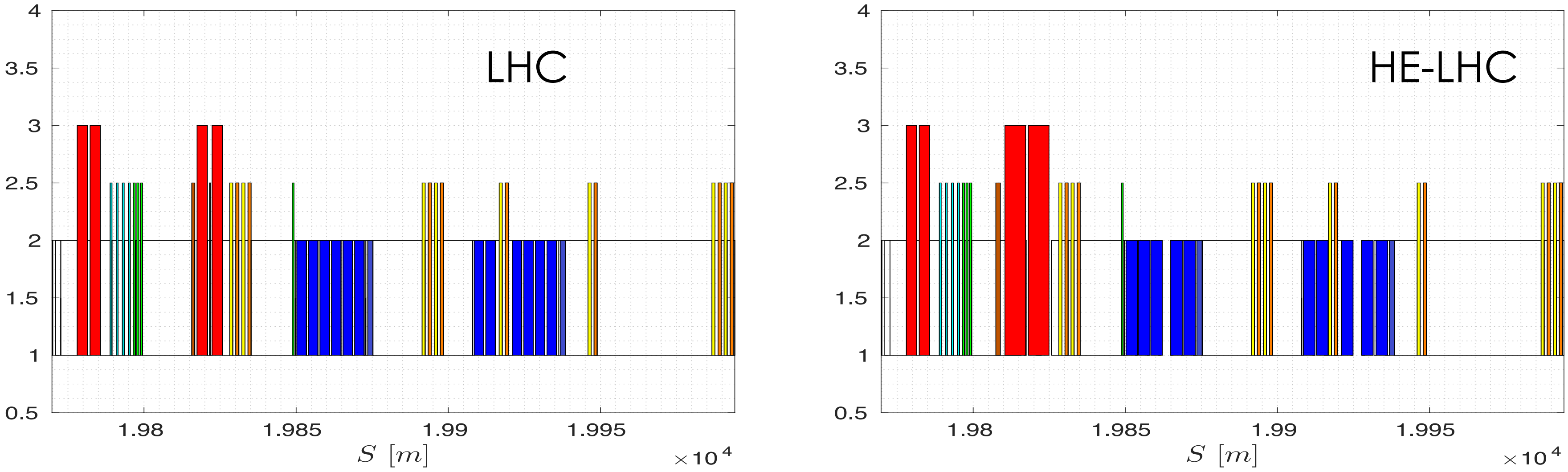
- Previous model assumes unrealistic magnet parameters. Additional magnet and technological limitations will further constrain the design choices.

- Superconducting magnets
  - Using superconducting magnets in the current LHC warm section would be extremely challenging due to the power load delivered to the magnets. Approximately **1.81 MW** of power is deposited into the IR7 collimation system.
  - Could use additional shielding to protect the magnets but SC magnets should be avoided where possible.

- Warm magnets
  - Warm magnets are limited in field strength so need to increase the length but we are constrained by the length of the insertion.
  - Here we have assumed aggressive parameter values for the warm magnets. Further investigation with magnet designers is on-going to further refine the achievable parameters.
  - Dipoles with **2T** field strength, quadrupoles with 20mm aperture and **1T** at the pole

- Using these magnet parameters we modify the LHC IR7 and keep the beta functions, dispersion, and phase advance as close to the LHC values as possible.

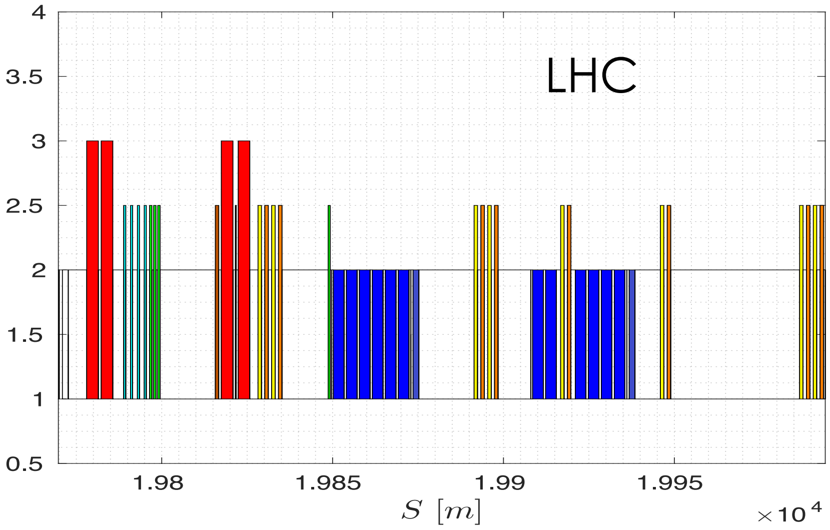
A First Design of the HE-LHC IR7 compared to the LHC.

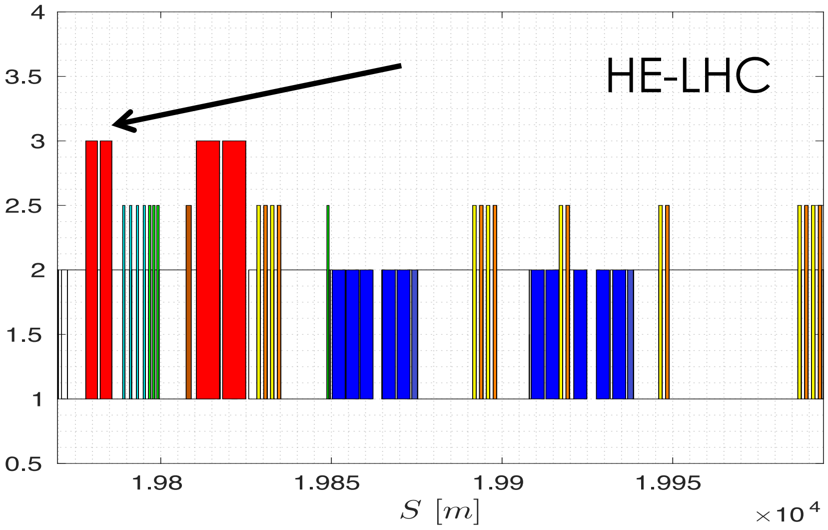


- The layout for the LHC IR7 (left) and the modified HE-LHC IR7 (right) can be seen above.

- The red boxes correspond to the dogleg dipole magnets, blue boxes correspond to the normal conducting quadrupoles, and green shows the collimators. The brown boxes are miscellaneous elements such as BPMs etc.

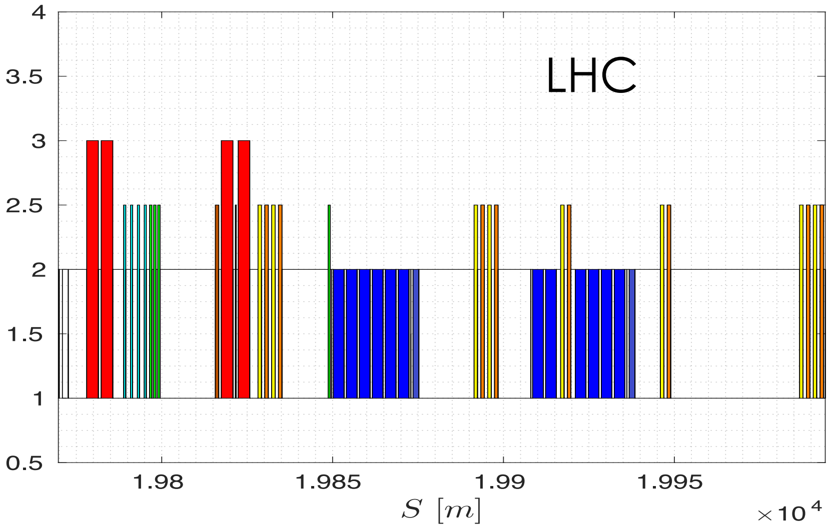
A First Design of the HE-LHC IR7 compared to the LHC.

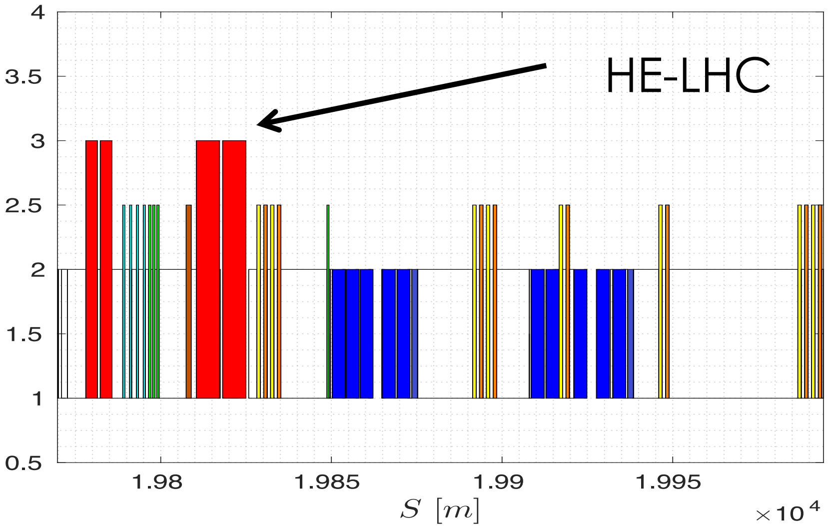




- Outer dogleg dipoles are made superconducting and remain in the same position.
  - Could possibly be made normal conducting if space permits, or a combination of both.
  - The second dipole may need to be made warm conducting or shielding may be required to protect the magnet from the showers produced by the counter rotating beam.
- More work required to make exact determination of whether we can use SC magnets here. Work will commence soon with the FLUKA team to perform energy deposition studies.

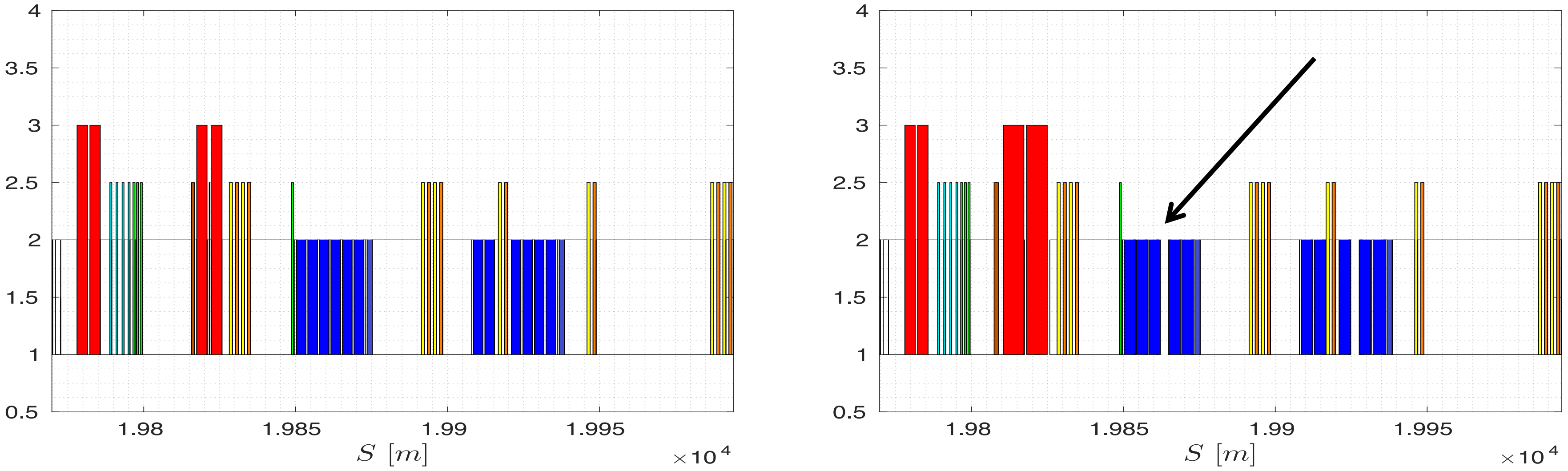
A First Design of the HE-LHC IR7 compared to the LHC.





- The inner dogleg dipoles have been increased to a length of 6.8 m but remain normal conducting.
- These magnets receive a larger dose than the outer dogleg dipoles so hence using superconducting magnets would be extremely challenging.
- The collimator protecting the face of these magnets is a passive absorber and hence is not part of the collimation hierarchy. It is shifted upstream to continue to protect the magnet.

A First Design of the HE-LHC IR7 compared to the LHC.



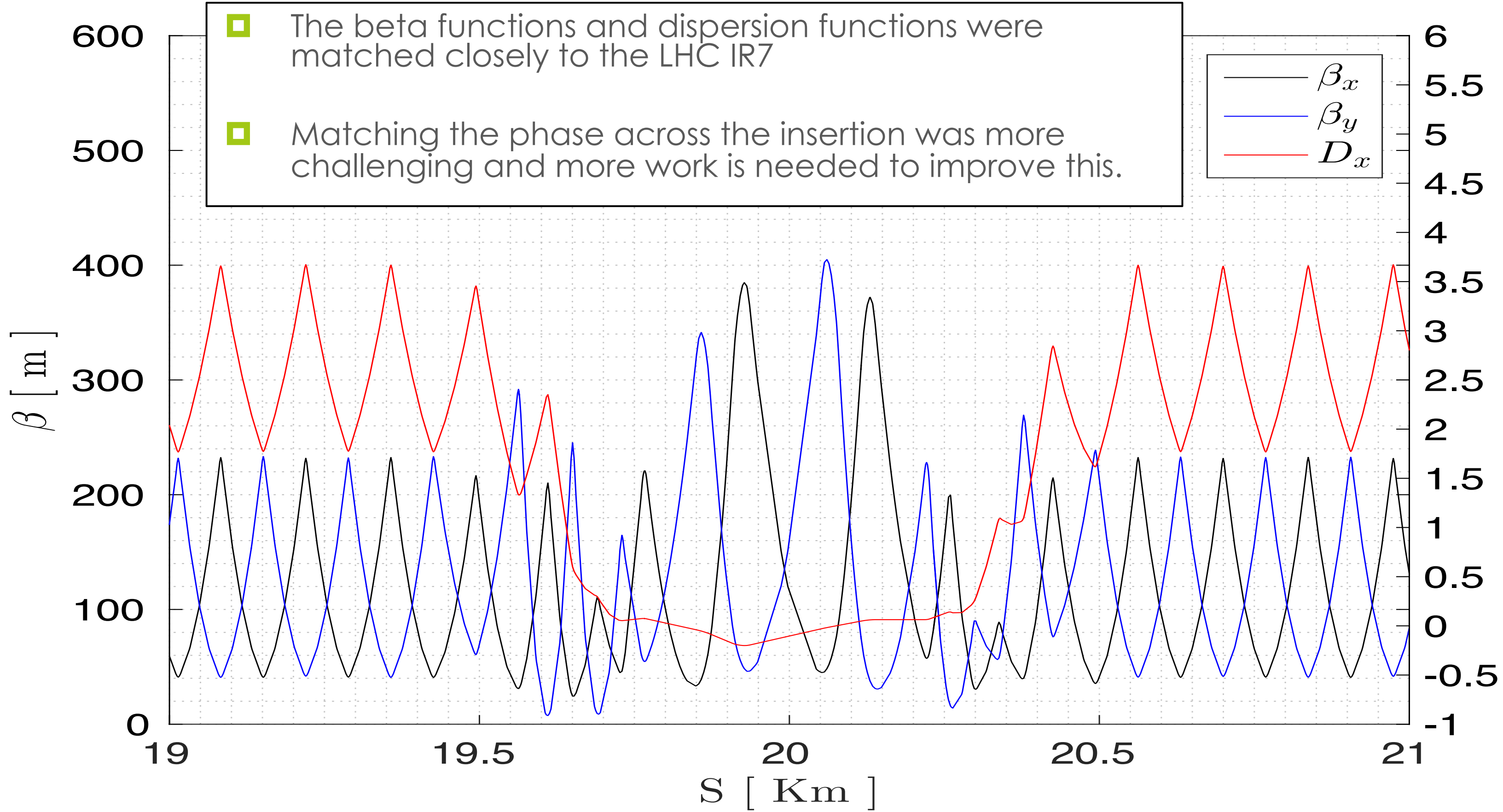
- Of the normal conducting quadrupoles, one in each module (MQWB) had a much smaller powering. This was removed allowing room to increase the MQWAs.

- The MWQAs were increased from 3.1 m to 3.8 m and a slightly larger field strength was used. A 1T field at the pole and a smaller aperture of 20mm was assumed.

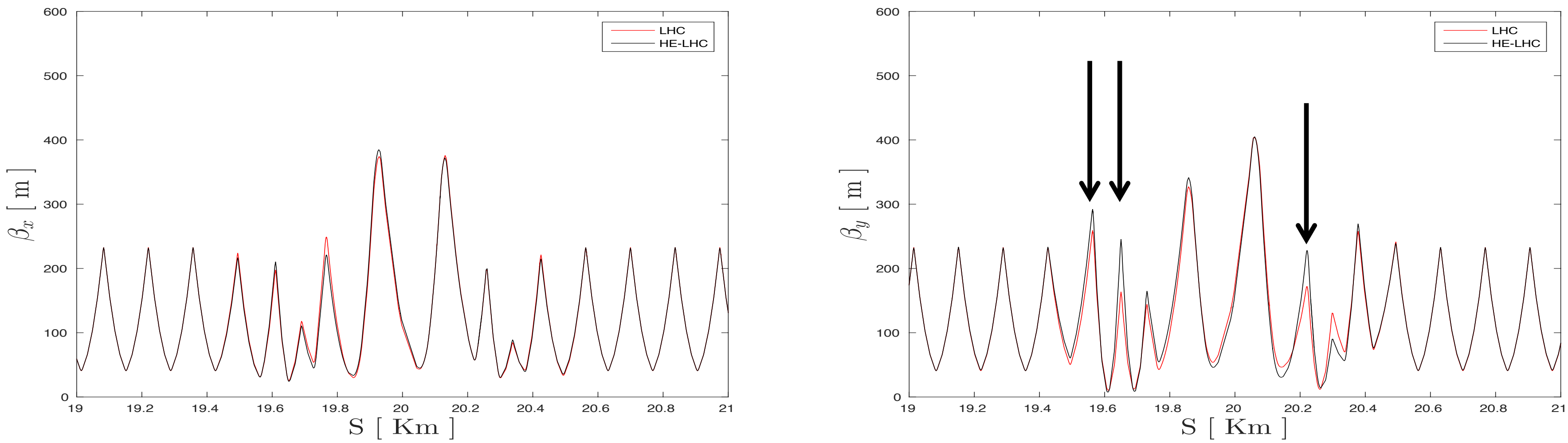
- The larger field strengths assumed for the warm magnets are challenging with the current LHC design. Further optimisation and closer work with magnet designers are required to ensure that these parameters are within reach.

HE-LHC modified IR7 optics compared to LHC

- The beta functions and dispersion functions were matched closely to the LHC IR7
- Matching the phase across the insertion was more challenging and more work is needed to improve this.

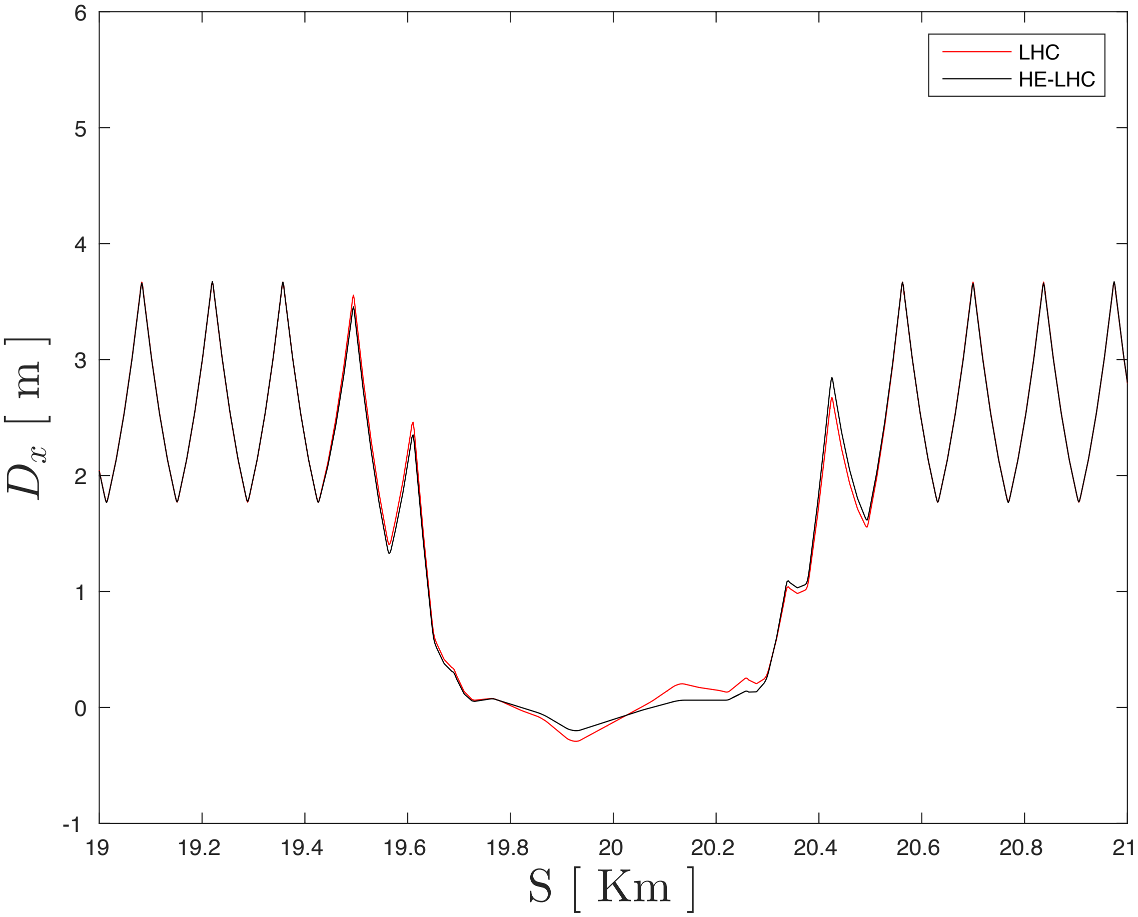


HE-LHC modified IR7 optics compared to LHC



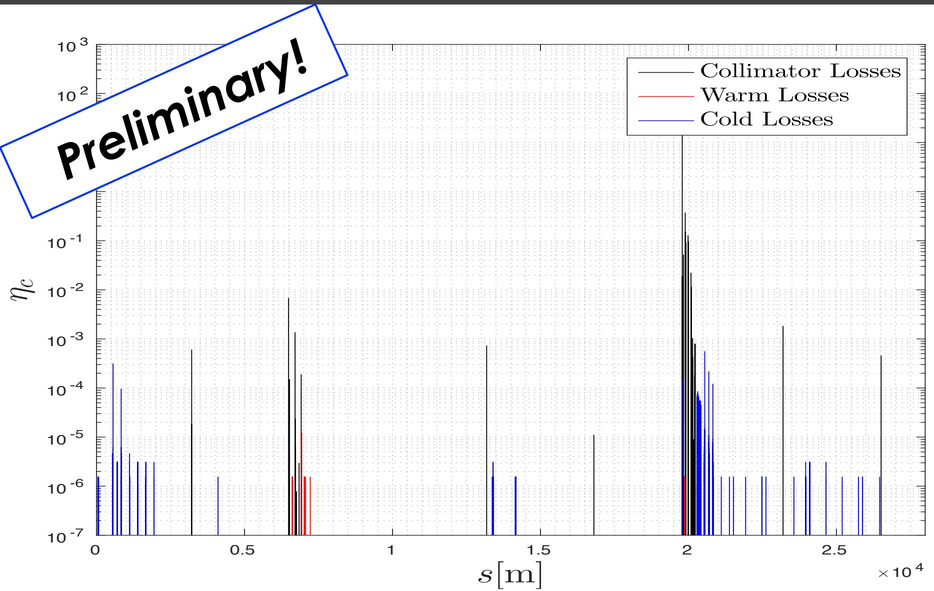
- These plots show a comparison between the beta functions in the new modified IR7 compared to the LHC beta functions.
- The functions are matched closely to the LHC but there are some small differences (maximum difference is approximately 10-12%).
- Largest differences are in the vertical beta functions.

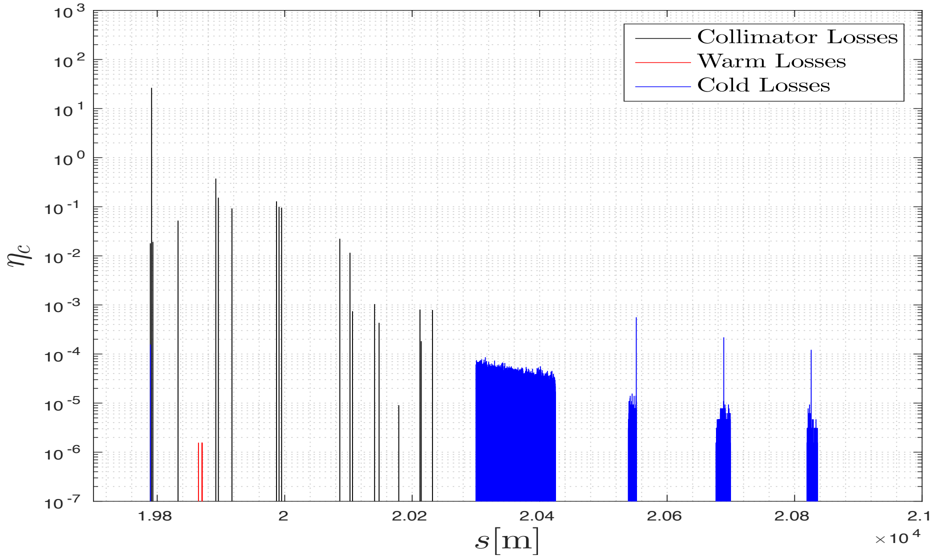
HE-LHC modified IR7 optics compared to LHC



- The dispersion was matched very closely to the LHC.
- The new lattice has slightly larger dispersion after the warm section towards the dispersion suppressor but maybe this can be improved in order to avoid losses downstream.
- However the optics is matched very well to the LHC values. Future iterations will be need to ensure that the phase advance constraints are matched for easy integration in new lattices.

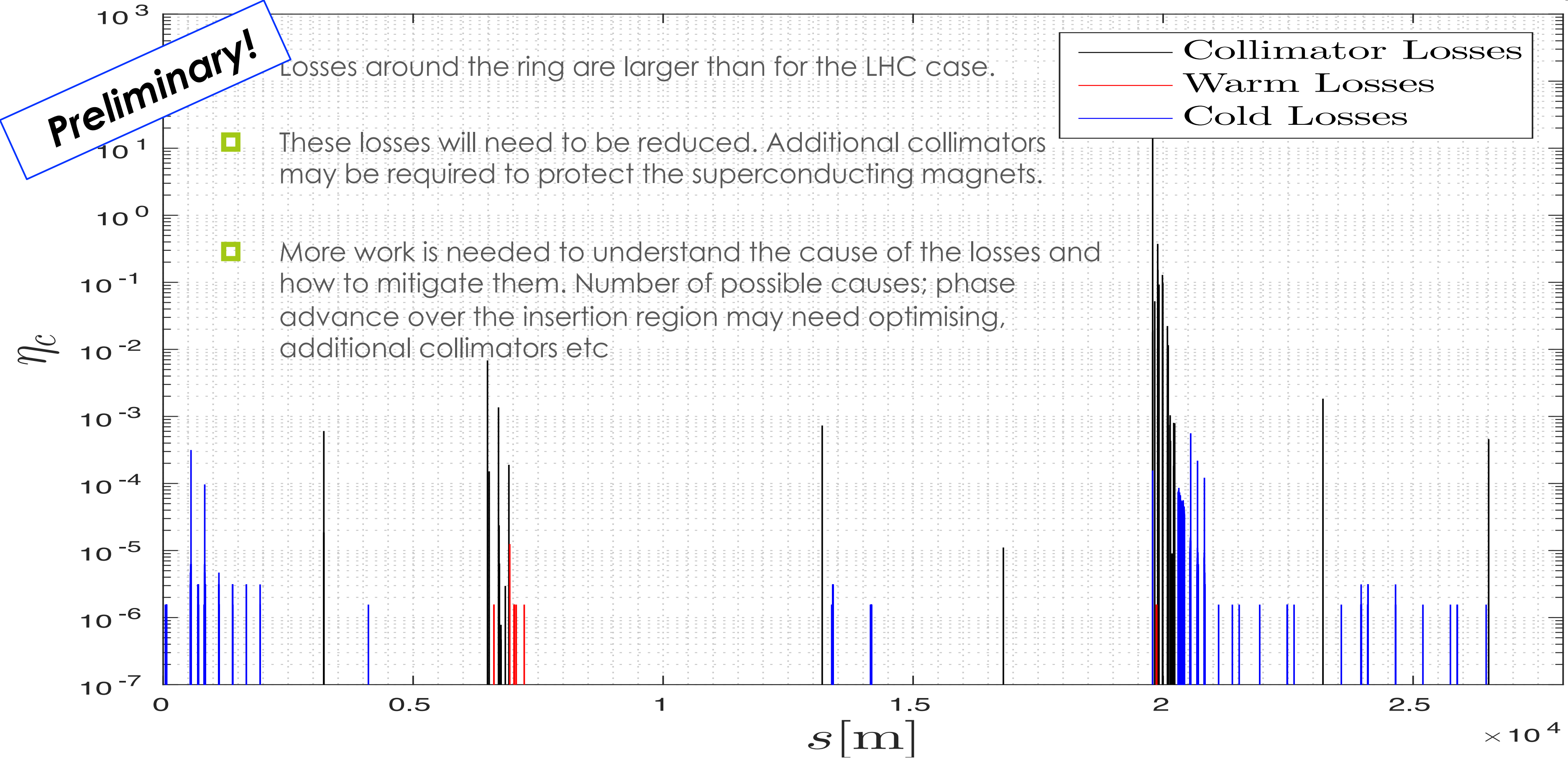
Performance of the new IR7.





- Using the modified layout and optics a thin lens version of the lattice was created and used in sixtrack to generate the HE-LHC loss maps
- Beam loss maps were generated for collision optics at 13.5 TeV using the HE-LHC 18x90 lattice (version 0.2) with an adapted IR7. Work on integrating this new layout into the 23x90 lattice is on-going. The 23x90 lattice is more challenging an there is less margin in the field strengths.

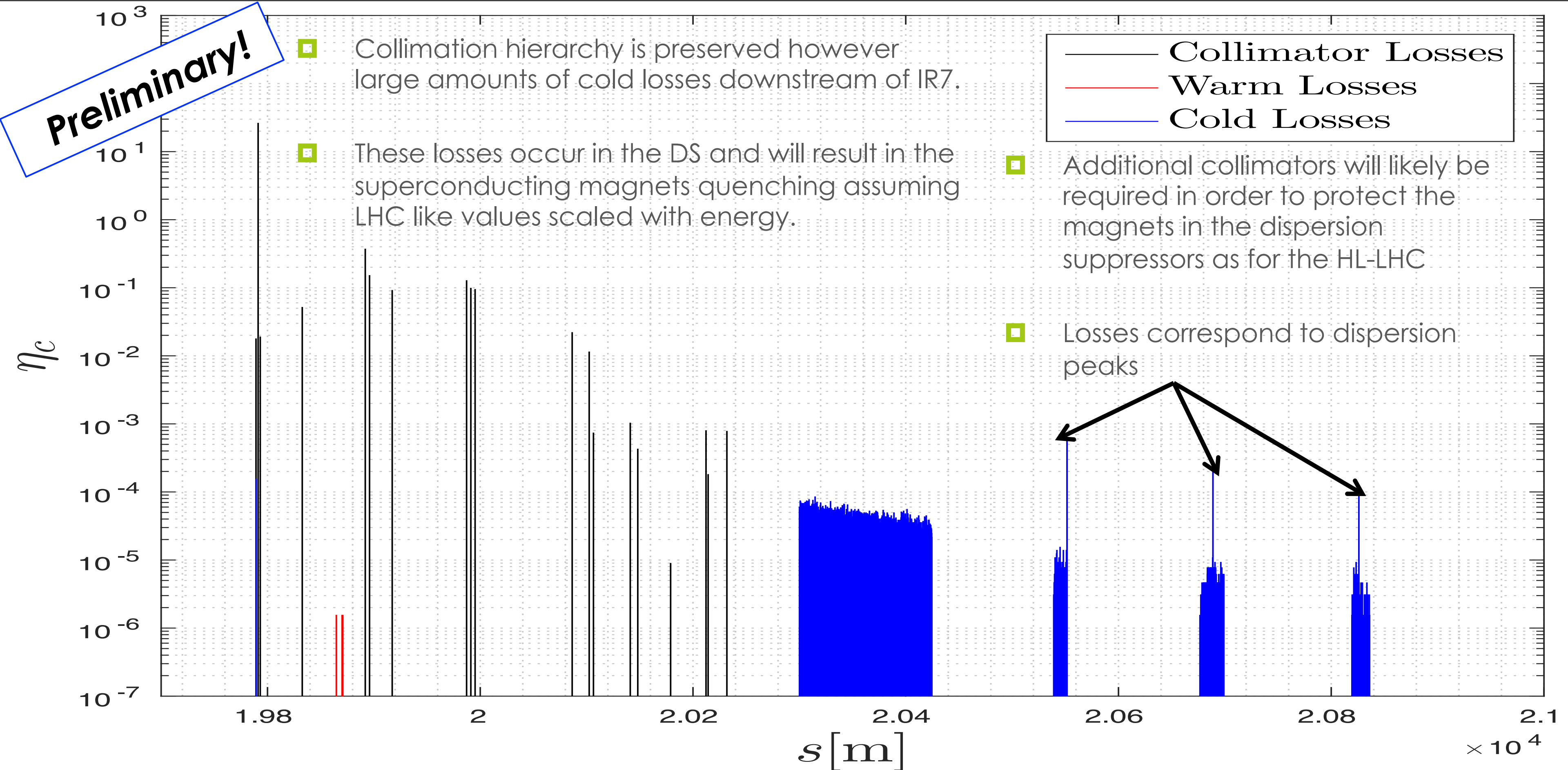
Performance of the new IR7.



Losses around the ring are larger than for the LHC case.

- These losses will need to be reduced. Additional collimators may be required to protect the superconducting magnets.
- More work is needed to understand the cause of the losses and how to mitigate them. Number of possible causes; phase advance over the insertion region may need optimising, additional collimators etc

Performance of the new IR7.



- Collimation hierarchy is preserved however large amounts of cold losses downstream of IR7.
- These losses occur in the DS and will result in the superconducting magnets quenching assuming LHC like values scaled with energy.
- Additional collimators will likely be required in order to protect the magnets in the dispersion suppressors as for the HL-LHC
- Losses correspond to dispersion peaks

Summary and further work

- The first steps in designing a betatron collimation system for the HE-LHC has been presented.
    - Initially considered a scaled LHC with HE-LHC magnet apertures. Loss maps look worse than the LHC and this assumes a completely superconducting collimation system, but a number of options are available.
    - Pure superconducting section is not practically feasible due to the large power loss delivered to this section.

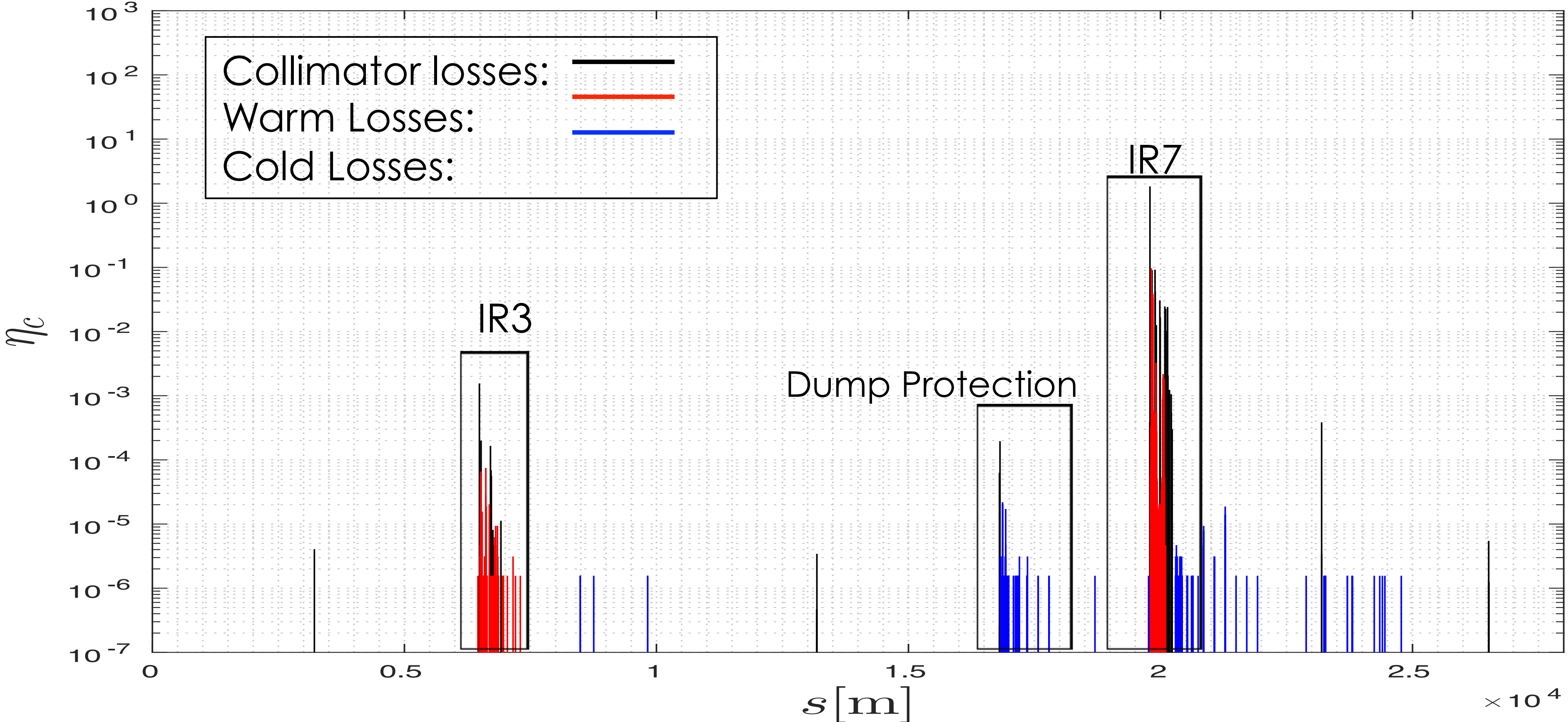
- The design aim was to modify the LHC betatron collimation system to cope with the HE-LHC beam energy and parameters.
    - We assumed aggressive magnet parameters: 2T warm dipoles, 1T pole field and 20mm aperture for the warm quadrupoles.
    - Assumed only superconducting outer dipoles (to save space) although further iterations of the design may replace one or both of these magnets with normal conducting magnets.
    - May need to consider less aggressive parameter choices for the magnets, how does this impact the design?

Summary and further work

- A first preliminary design of the HE-LHC design has been presented with the corresponding loss maps.
- More losses than the LHC but a number of options are available to mitigate these.
    - Firstly the optics can be improved with further matching and constraints. Improved optics will also allow easier integration into future lattice versions.
    - If this does not improve the losses then additional collimators can be envisaged to protect the superconducting magnets in the dispersion suppressors. These will be included in the next version of the insertion.
- Next when the losses have been mitigated, probably with a combination of both additional collimators and improving the optics, Energy deposition studies can be performed to determine points where additional shielding could be required and on the feasibility of superconducting outer dogleg dipoles.
- Still along way to go but we are making progress

SPARE SLIDES

Collimation in the LHC: At Flat bottom



Collimation in the LHC: At IR7 @ Flat bottom