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

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Outline

- Overview of the HE-LHC:
  - Baseline parameters and beam properties
- Overview of current progress
  - Aperture model
  - Collimation studies: Injection ✔ and collision lattices ✔
- Optics and challanges
- Beam loss maps
  - Injection energy: 450 GeV, 900 GeV and 1.3 TeV
  - Collision energy: 13.5 TeV
- Summary and future options

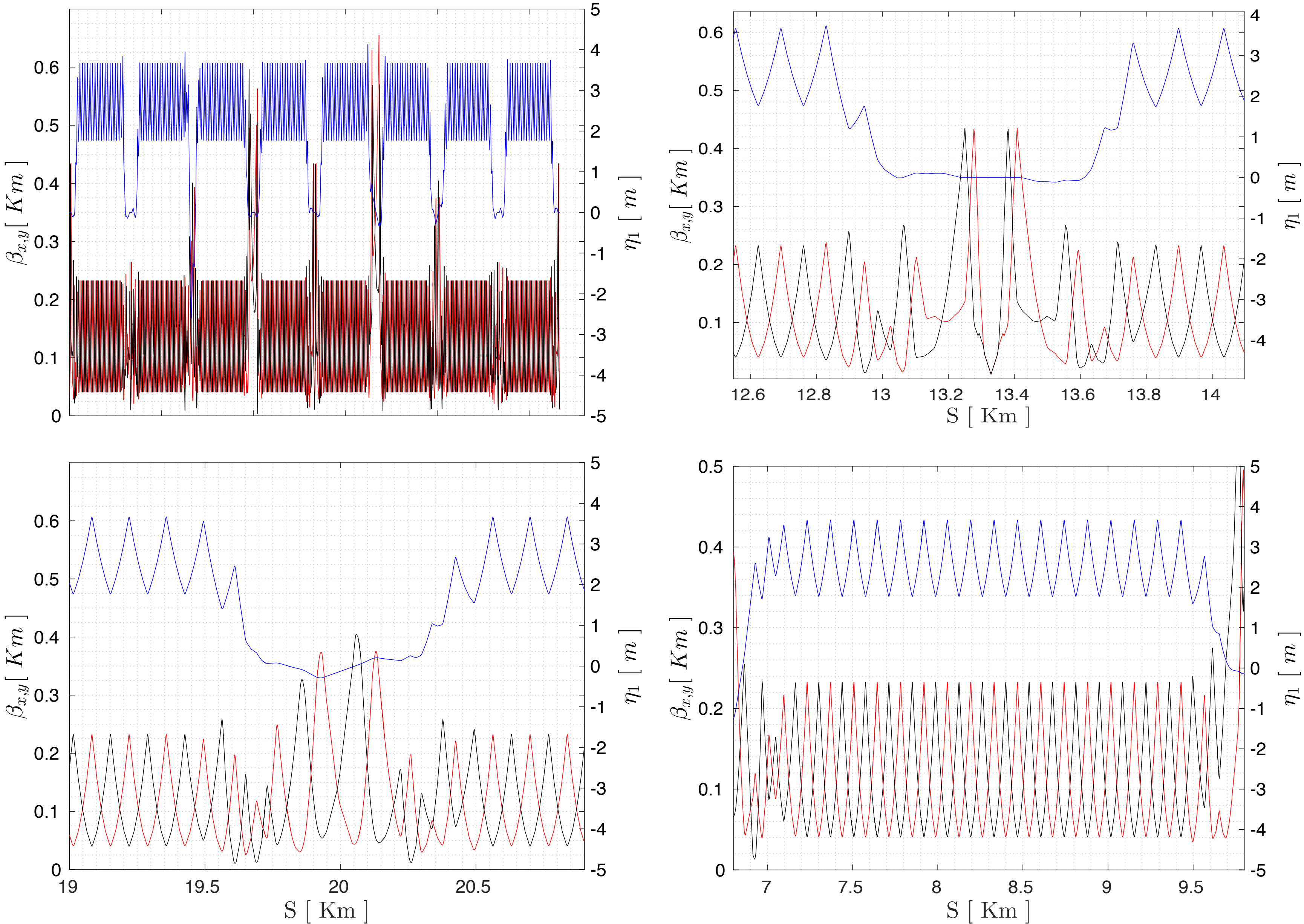
Lattice options for the HE-LHC

- Number of proposed options for the HE-LHC were suggested and investigated
  - 17 x 90, 18 x 60, 18 x 90, 20 x 90 and 24 x 90
- The LHC cannot be directly scaled to 13.5 TeV with a β^*=25cm as the maximum gradient and field strengths in the magnets are exceeded.
  - Hence the number of cells had to be reduced and the length of each cell increased, reducing the sexutpole and quadrupole strengths
- The 18 x 90 option has been selected as the baseline.
- The lattice files can all be found in the repository on AFS, working versions are v0.1 and v0.2

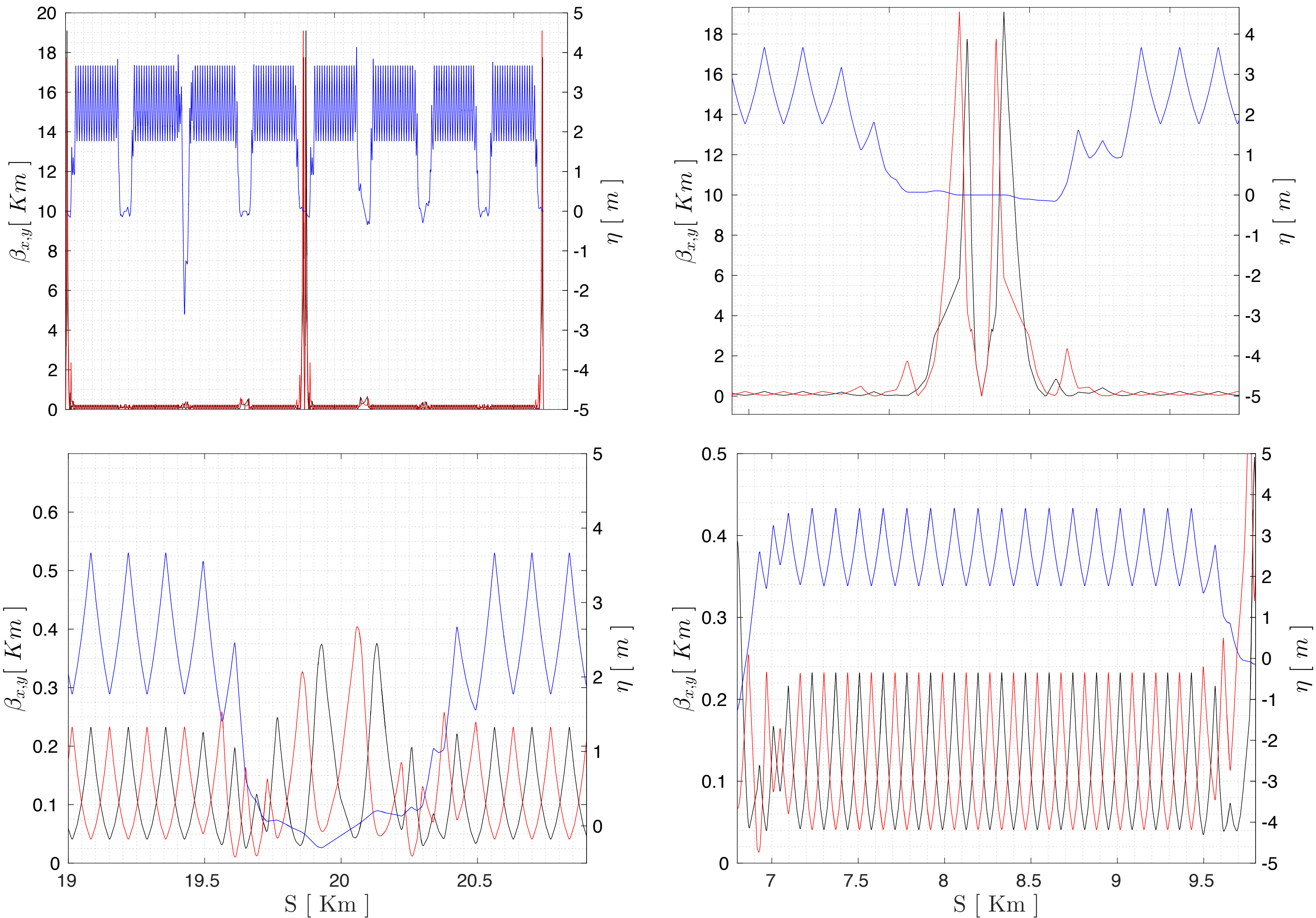
Beam and optics options for the 18 x 90 HE-LHC lattice

Parameter	LHC	HE-LHC
Arc cell phase	90/90	90/90
Arc cell length [m]	107	137.2
β max/min [m]	181/32	229/41
Dispersion max/min [m]	2.2/1.1	3.6/1.8
Dipole Field [T]	8	15.59
Bunch intensity 10^{11}ppb	1.1	2.2
Stored beam energy [GJ]	0.36	1.3
β^* [m] [inj/coll]	11/0.33	11/0.25
Injection Energy [TeV/beam]	0.450	0.450 -> 1.3
Collision energy [TeV/beam]	6.5-7.5	13.5
Emittance [μm]	2.5-3.75	2.5
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	25
Crossing angle [μrad]	150-280	260^{++}

Optics layout for the HE-LHC: injection



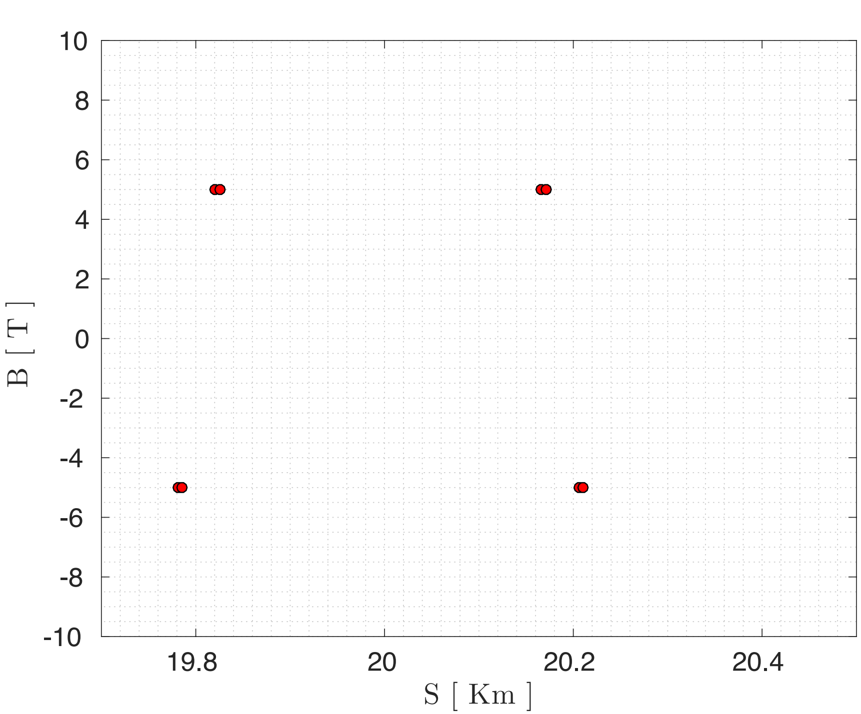
Optics layout for the HE-LHC: collision

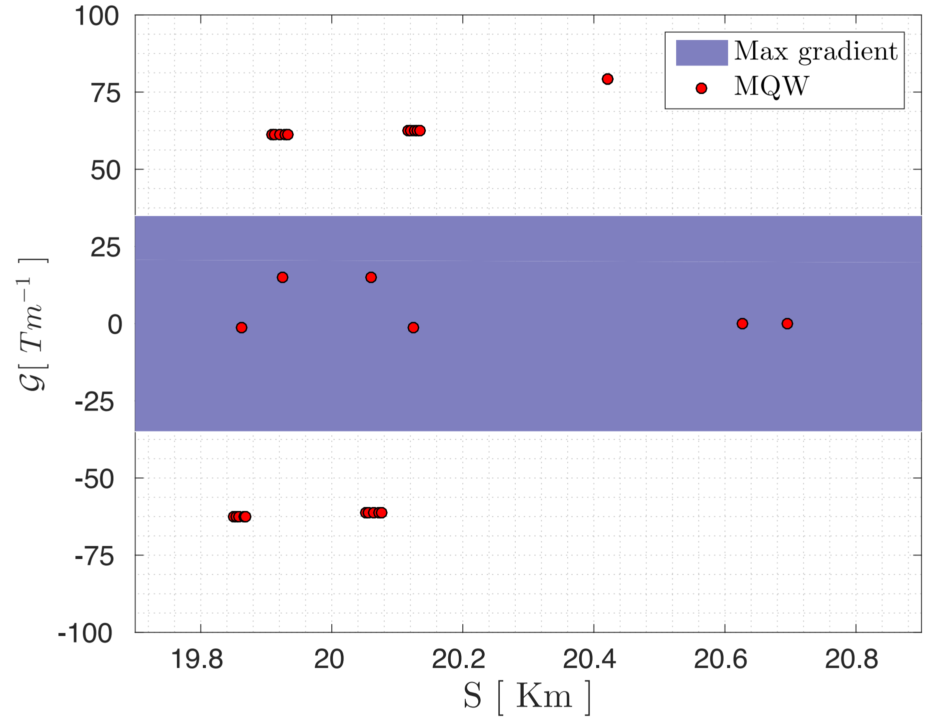


Optic Layout in IR7

- Same as the LHC for the moment.
  - LHC system, with collimators located at the same positions so same phase advance between collimators at IR.
  - Further optimisation and improvements with regard to the collimator settings.
- Due to the larger beam energy, the magnet strengths in IR7 will need to be considered to ensure that the maximum field strengths are not exceeded at collision energy.
- It is likely that a number of warm magnets will need to be replaced with superconducting magnets.
- Which magnets need to be replaced? Can we make some magnets longer?

Total number of warm and cold losses for the different energies and collimator settings





- For the same 3.1m warm dipoles in the dogleg, a field strength of about 5 T is required. In order to obtain the same integrated field strength as before, the length of the warm doglegs need to be increased to approximately 6m.
  - Space is available for large dogleg dipoles
- Similarly the quadrupole strengths or lengths need to be doubled in order to obtain the required field strength.
  - This will likely be the challenge
- A combination of warm and superconducting magnets could provide a solution. What is the energy deposition on these magnets?

Power load from losses in IR7

- Using scaling of the LHC to HE-LHC, the power loads delivered to the collimators can be estimated.

Machine	Stored Beam energy (GJ)	Power loss for 12 minute beam lifetime (MW)
LHC	0.36	0.50
HE-LHC	1.3	1.81
FCC	8.4	11.80

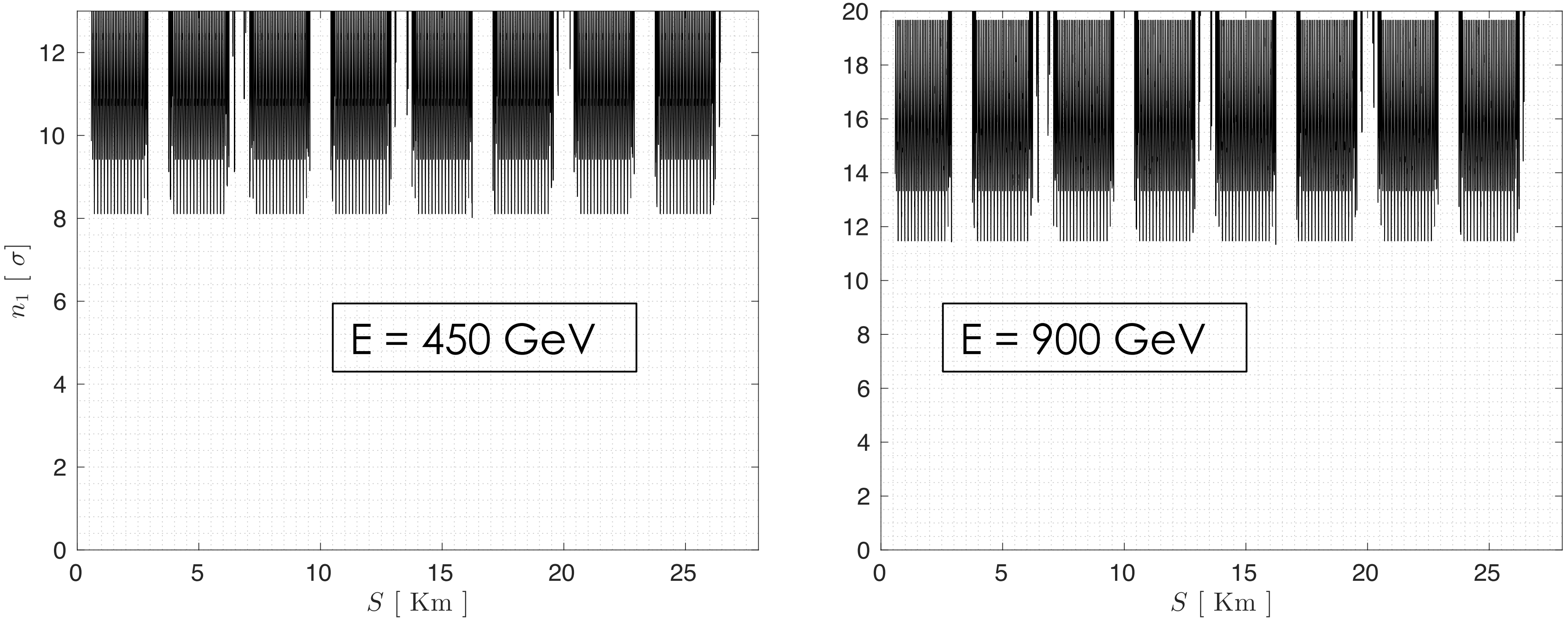
- The collimation system will need to deal with about 1.81 MW with approximately ~10%-12% of that energy being delivered to the warm dipoles. 90% of this energy will be deposited onto two dipole modules downstream of the TCPs.
- Power load to second dipoles: 0.12*0.9*(1.81/2)=0.0815 MW (for 12 min lifetime)
- This will likely require a significant amount of shielding to avoid quenches. ***FLUKA Coupling in Sixtrack in progress***
- A combination of both superconducting and warm magnets may be a good compromise if space is restricted.

Aperture model for the HE-LHC and n1 at bottle neck

- Currently for all of the collimation studies, the LHC aperture files have been used.
- These will slightly underestimate the losses, however the choice of beam screen etc for the HE-LHC has still not been determined.
- A new aperture model is available which includes the new IRs. The collimator openings etc will be updated as soon as possible to determine which settings are required to protect the aperture bottleneck.
- A number of challenges for 450 GeV injection
  - Aperture is small with n1≈ 8 σ.
  - Aperture and the errors improve with increasing energy.
  - However for 900-1300 GeV a ***SC SPS*** will be required,
- Aperture bottleneck from the low betastar experiments at approximately ≈15 σ for collision optics.

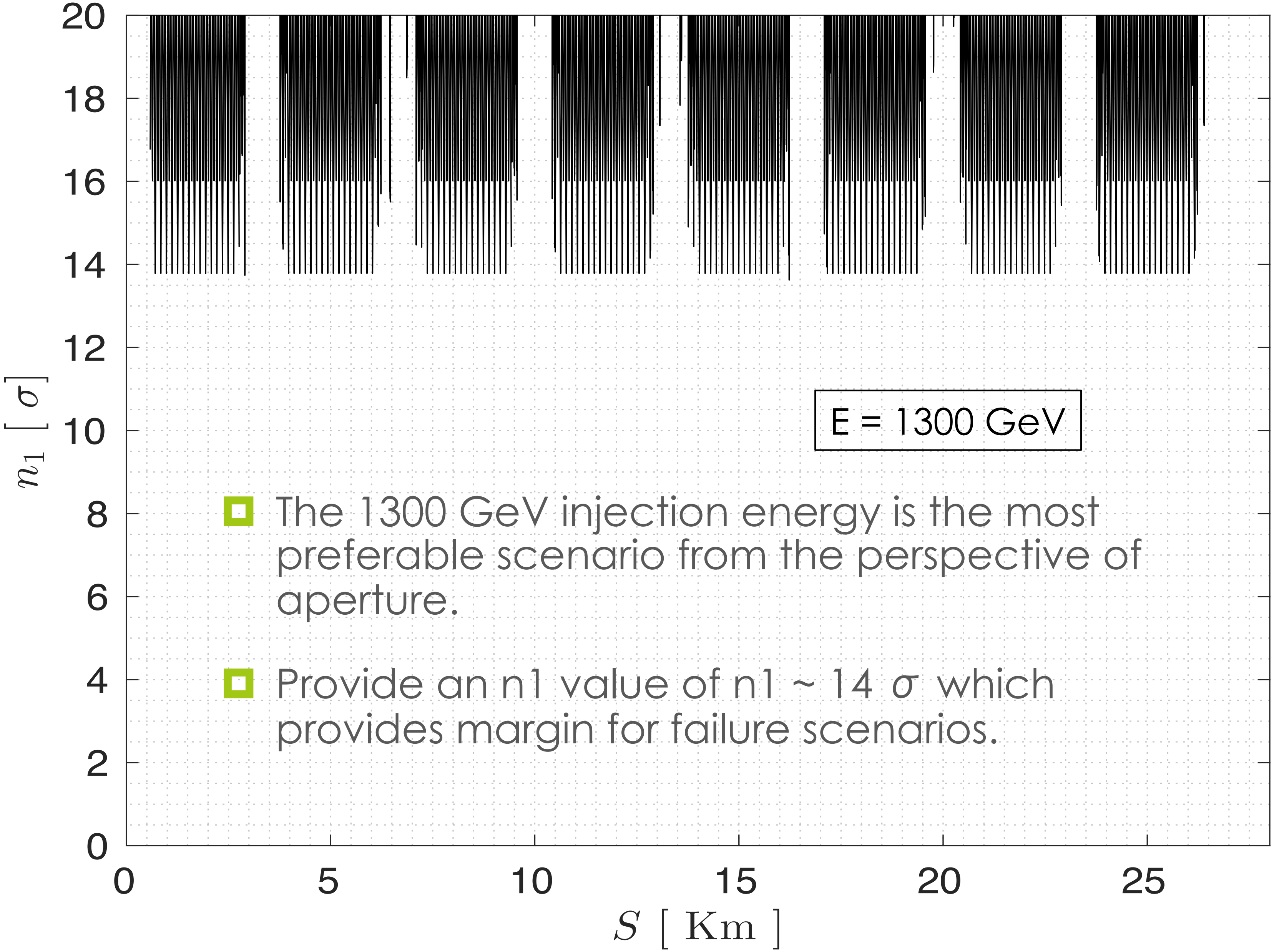
Aperture Parameters	Closed orbit [m]	dP max	Parasitic dispersion	Beta Beating
n1	0.002	$8.6e^{-4}$	0.14	1.05

Aperture model for the HE-LHC at different injection energies



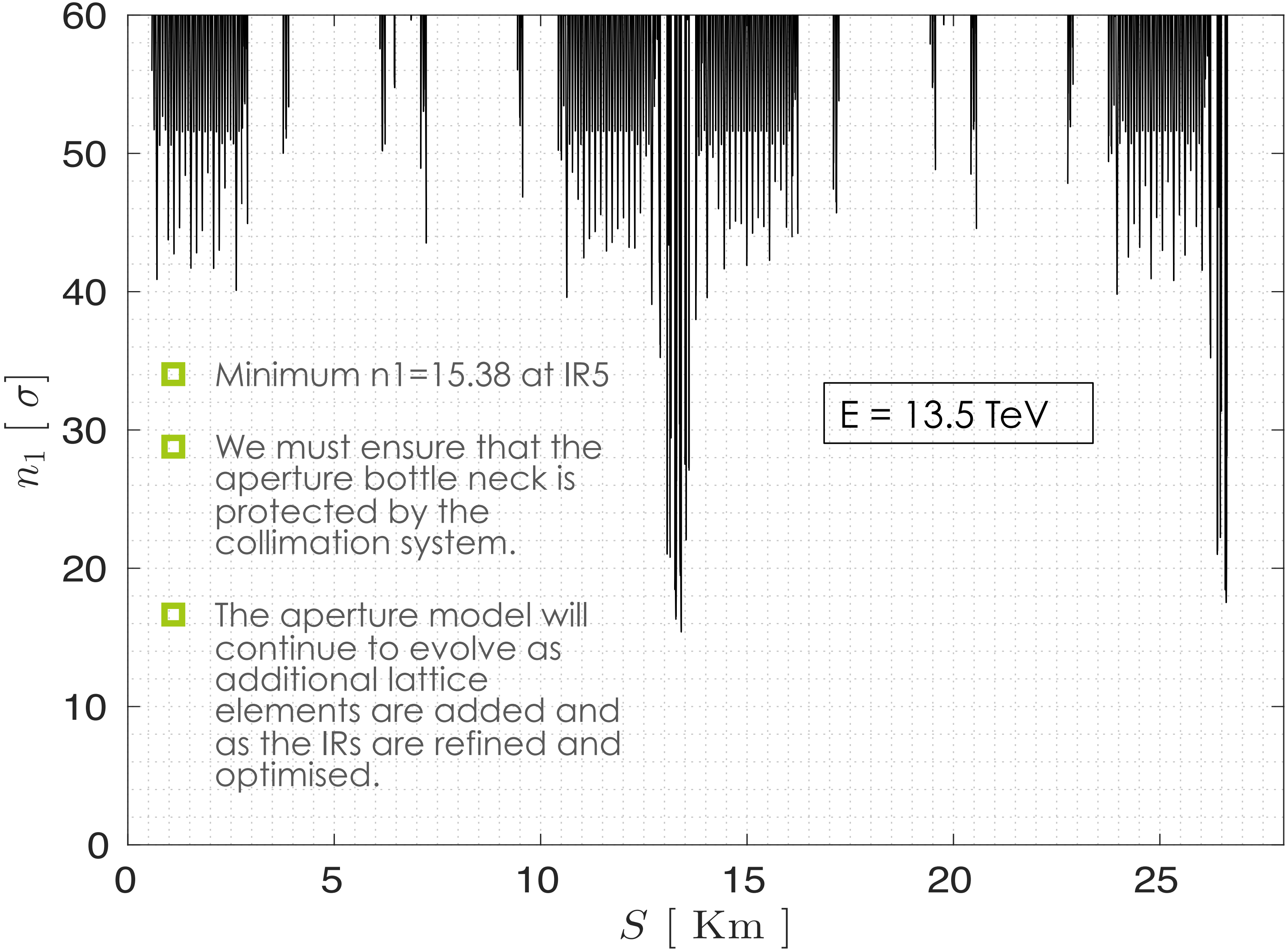
- A number of challenges from the perspective of injection.
- The aperture is very tight at 450 GeV and is smaller than 10σ.
- This does not provide significant margin for failed injection/ injection oscillations etc and other failure scenarios.
- At larger injection energies there is an additional improvement of the uncertainty and systematic errors in the magnets which is beneficial for dynamic aperture studies and beam lifetimes

Aperture model for the HE-LHC at different injection energies



- The 1300 GeV injection energy is the most preferable scenario from the perspective of aperture.
- Provide an n1 value of n1 ~ 14 σ which provides margin for failure scenarios.

Aperture model for the HE-LHC at collision



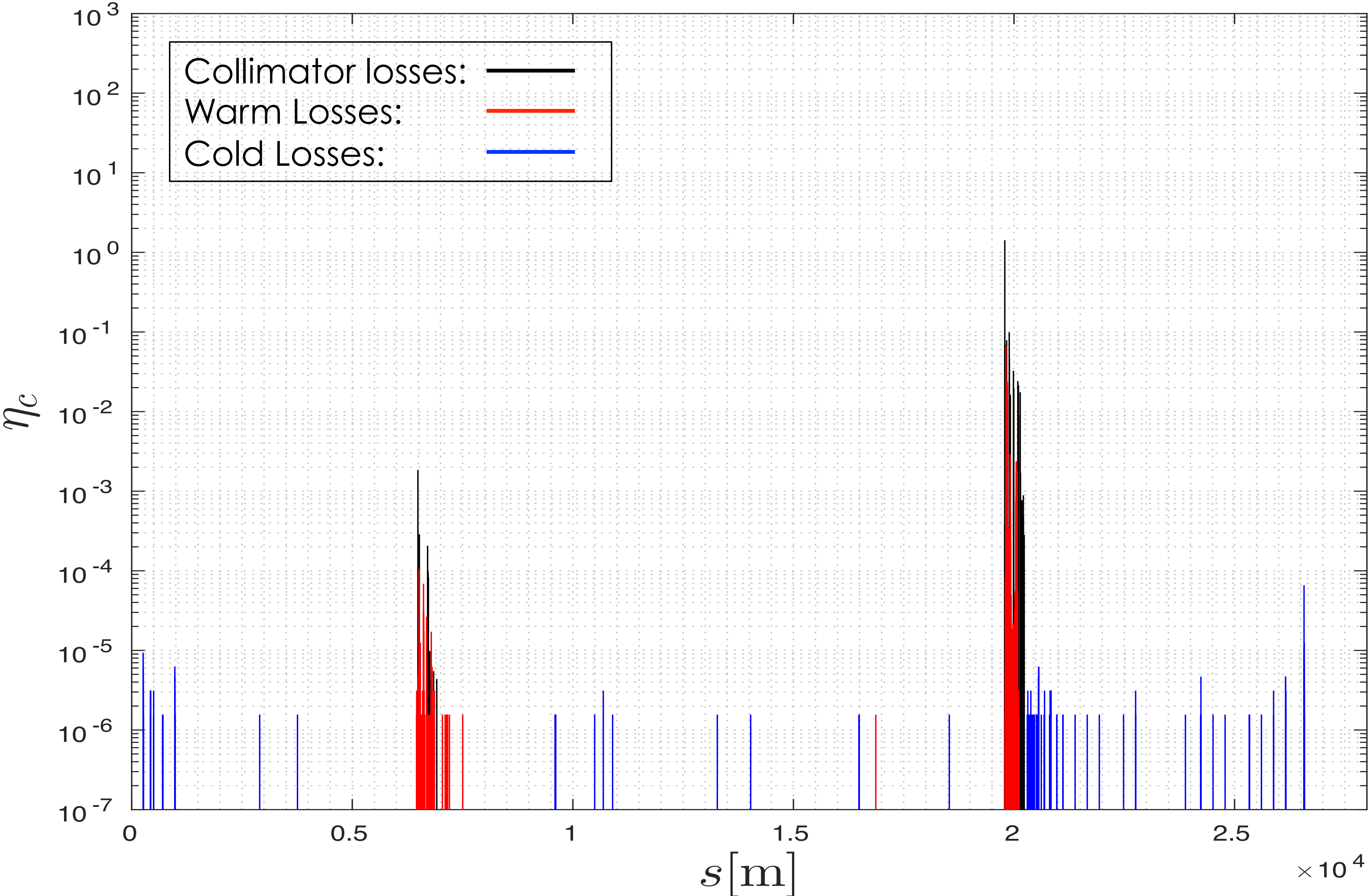
- Minimum n1=15.38 at IR5
- We must ensure that the aperture bottle neck is protected by the collimation system.
- The aperture model will continue to evolve as additional lattice elements are added and as the IRs are refined and optimised.

Scaled collimator settings

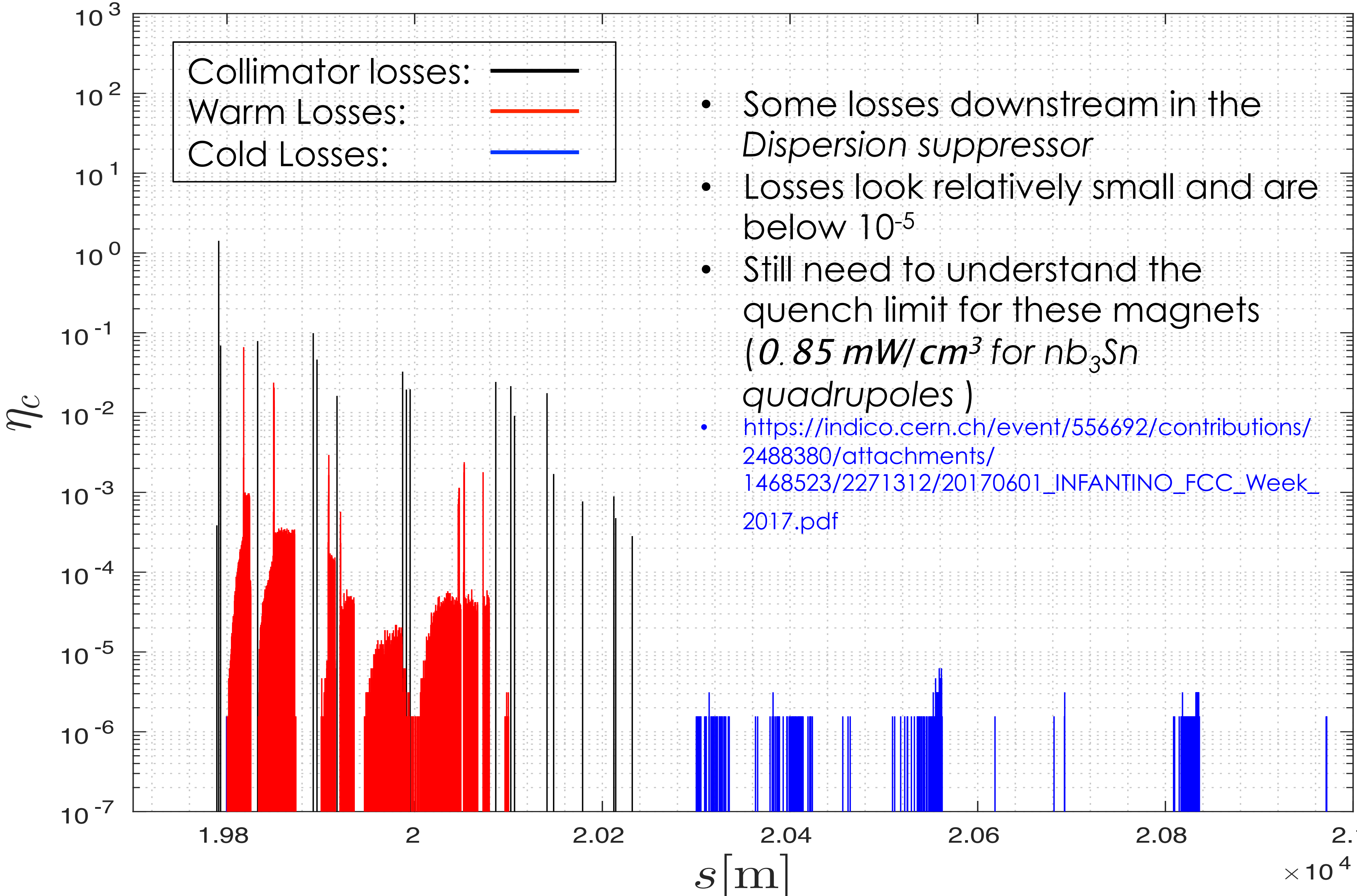
- The LHC collimation system was taken “as is” and inserted into the HE-LHC lattice
- This allows the LHC collimation performance to be evaluated for the higher energy and to determine what adjustments need to be made. The LHC is an optimistic scenario for the losses.
- The aim would be to produce a number of different options for the betatron collimation
  - Firstly a basic scaled version of collimation system from the LHC → HE-LHC
  - An alternative collimation system which employs some more “exotic” technology: E-lens, combined cleaning
- At injection the losses do not change much, still at 450 GeV. So the LHC system is a good place to start.
- ***Loss maps shown here still use the LHC aperture model!***

Energy [TeV]	TCP IR3/7 [σ]	TCSG IR3/7 [σ]	TCLA IR3/7 [σ]
0.450/0.900/1300	8.0/5.7	9.3/6.7	12.0/10.0

Injection energy: 450 GeV with LHC collimation settings

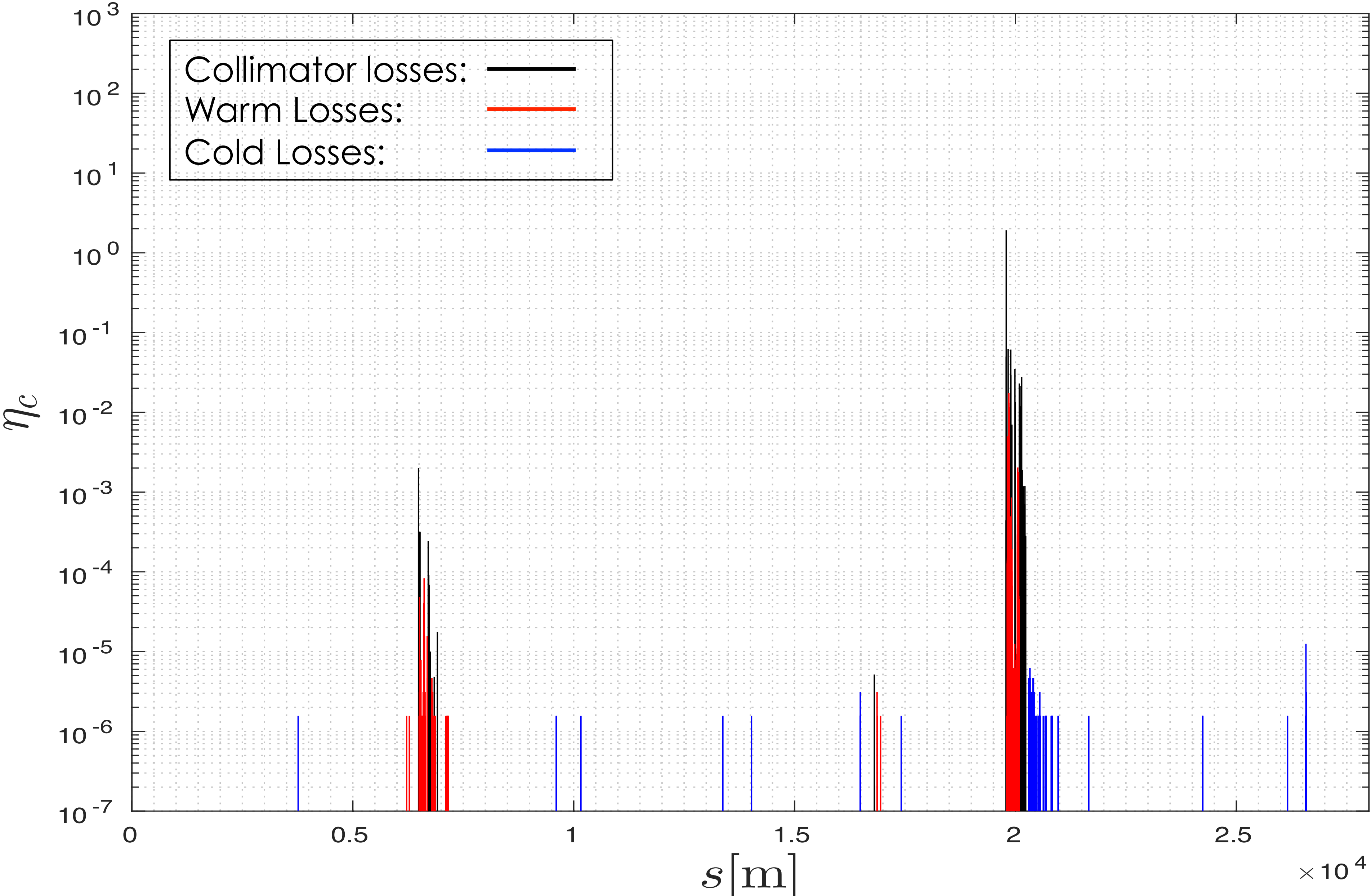


Betatron cleaning at 450 GeV with LHC collimation settings

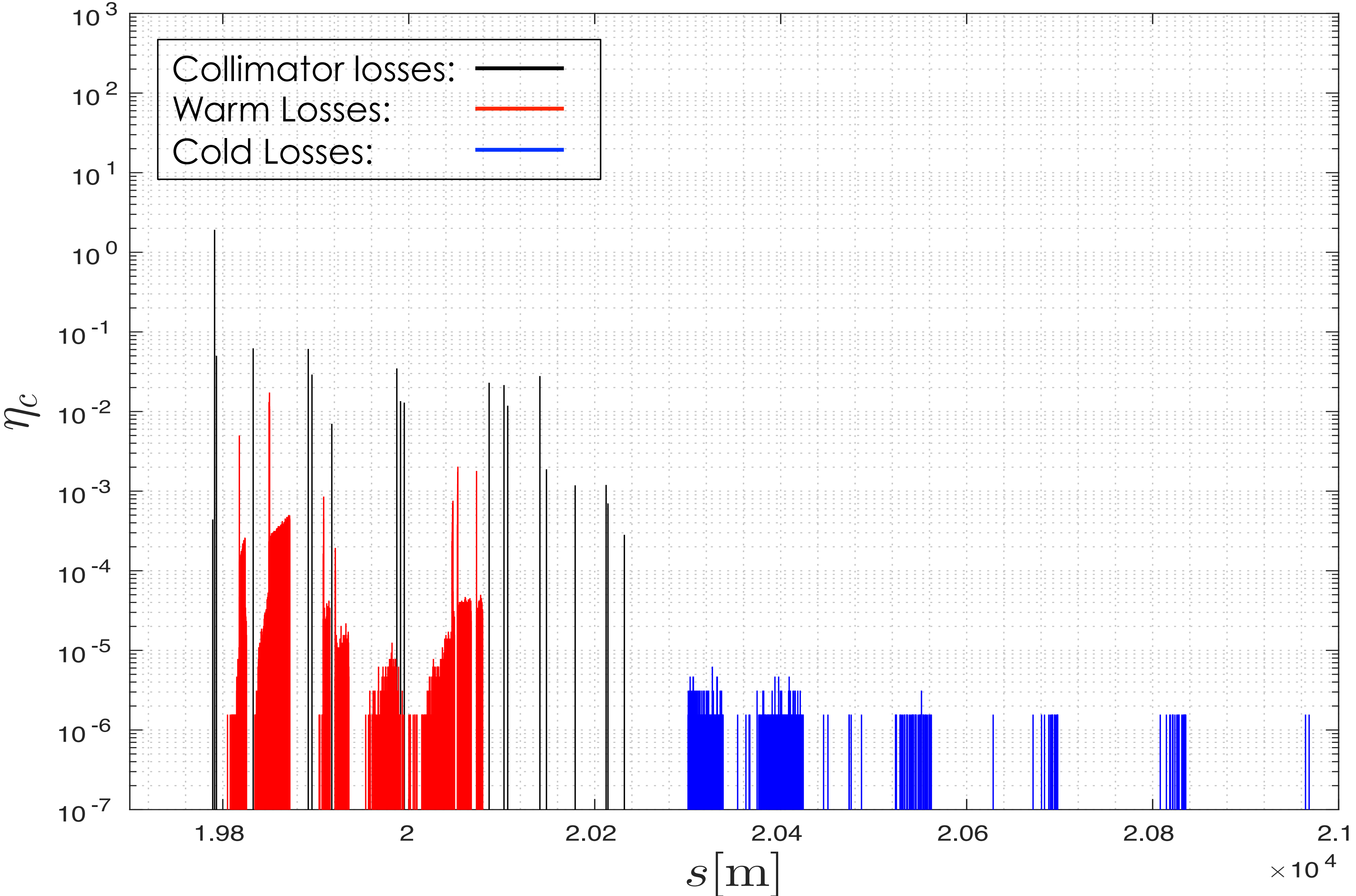


- Some losses downstream in the *Dispersion suppressor*
- Losses look relatively small and are below 10^{-5}
- Still need to understand the quench limit for these magnets (*0.85 mW/cm³ for nb₃Sn quadrupoles*)
- https://indico.cern.ch/event/556692/contributions/2488380/attachments/1468523/2271312/20170601_INFANTINO_FCC_Week_2017.pdf

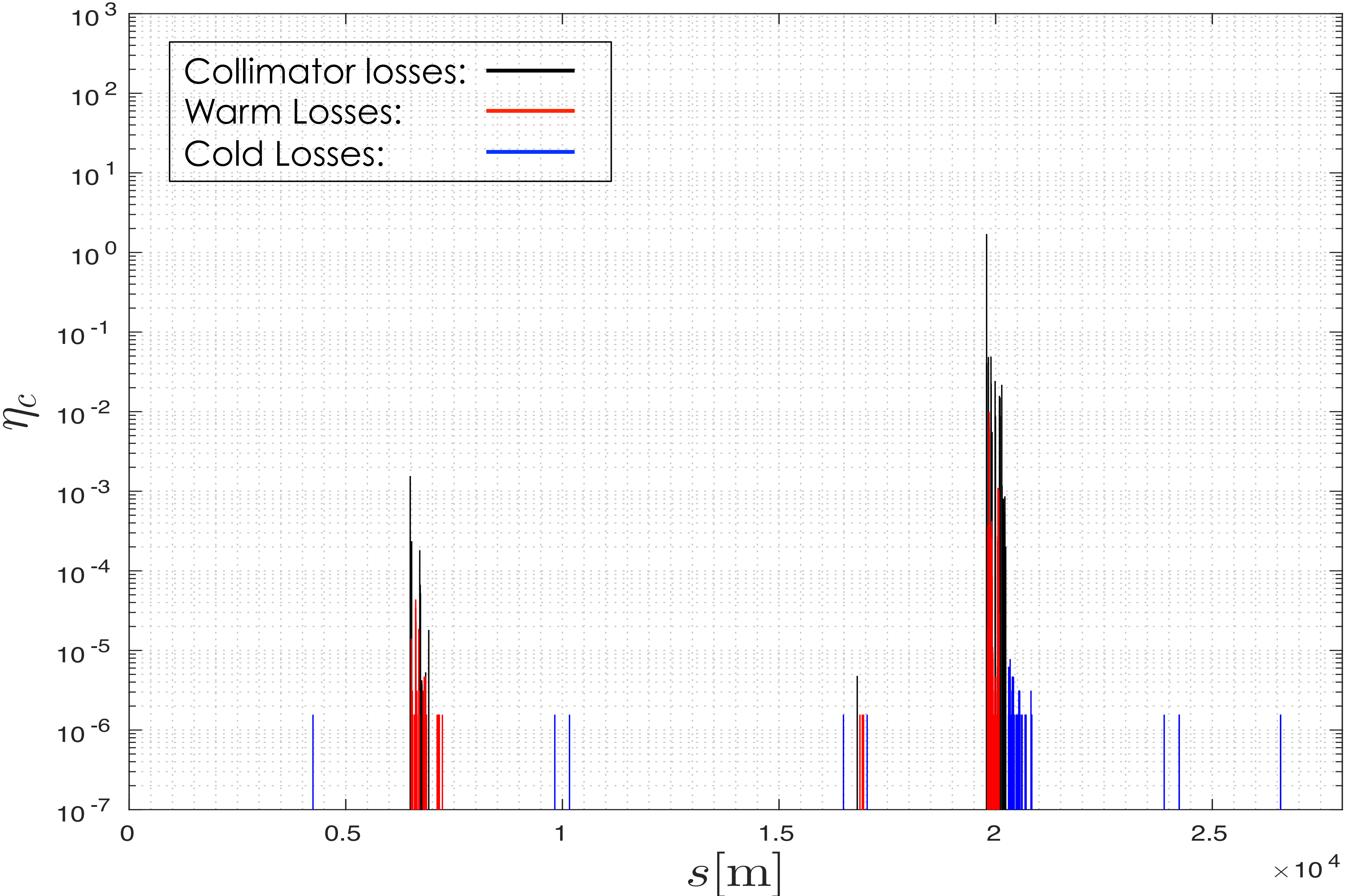
Injection energy: 900 GeV with LHC collimation settings



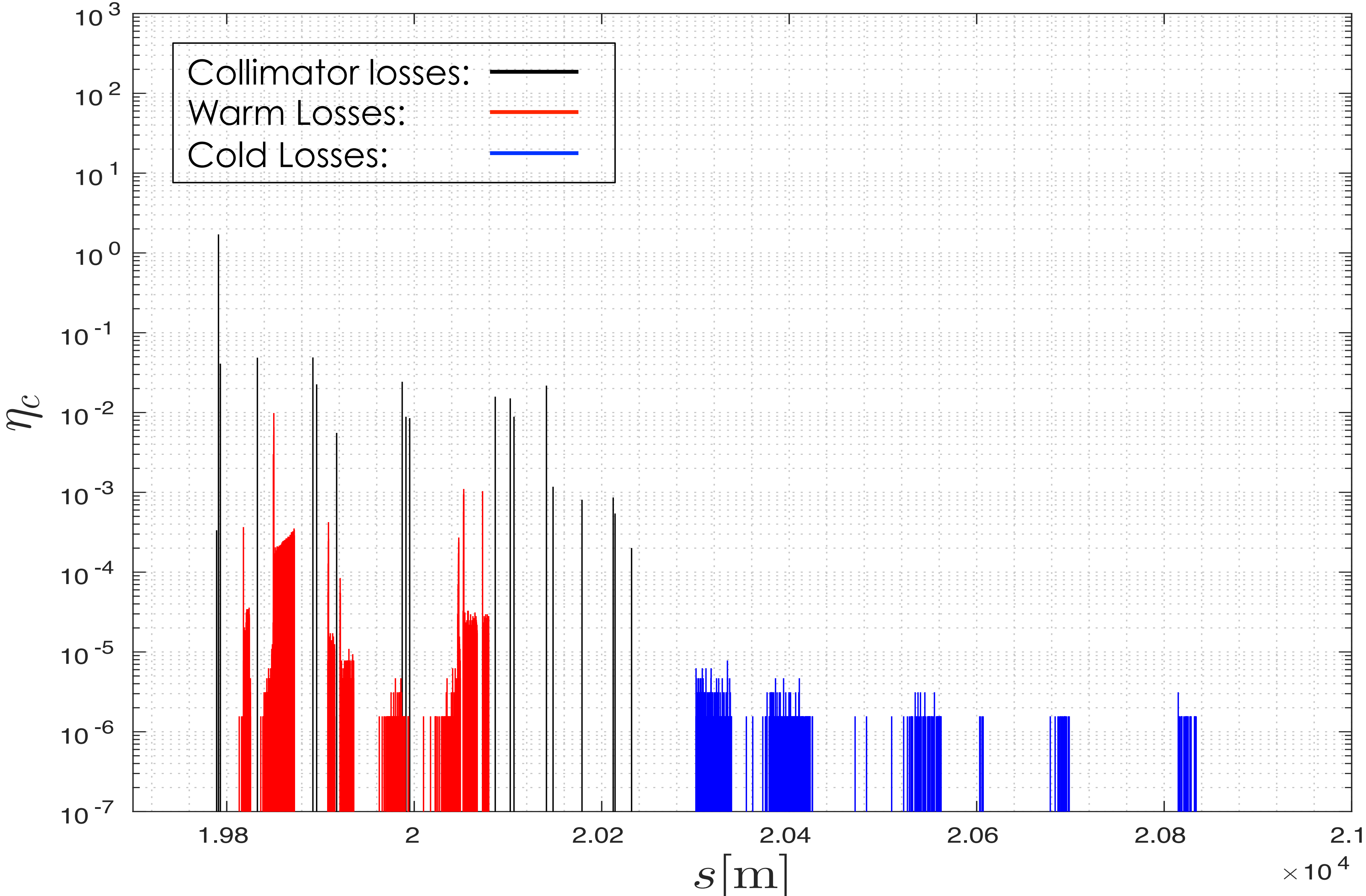
Betatron cleaning at 900 GeV with LHC collimation settings



Injection energy: 1300 GeV with LHC collimation settings



Betatron cleaning at 1300 GeV with LHC collimation settings

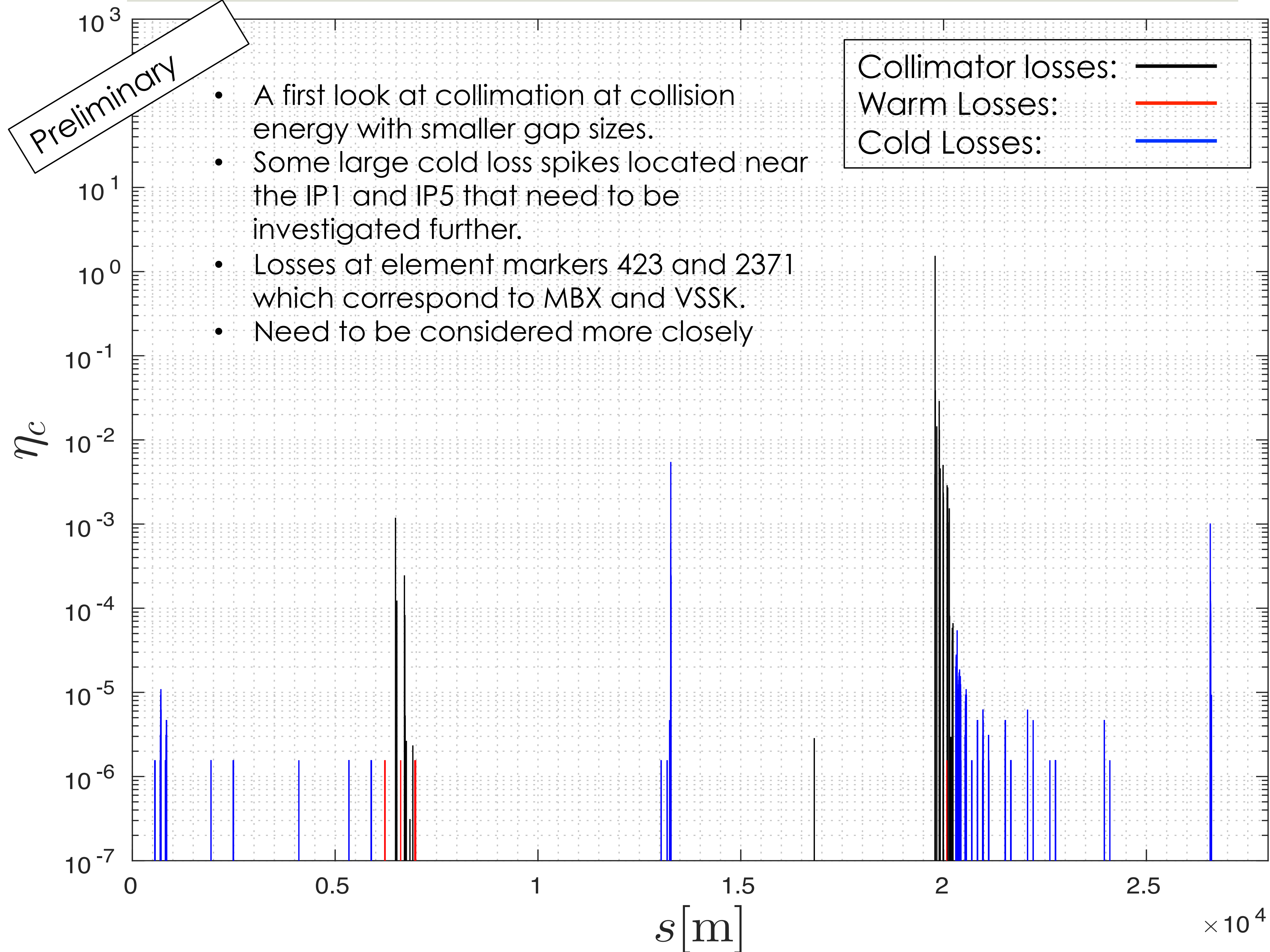


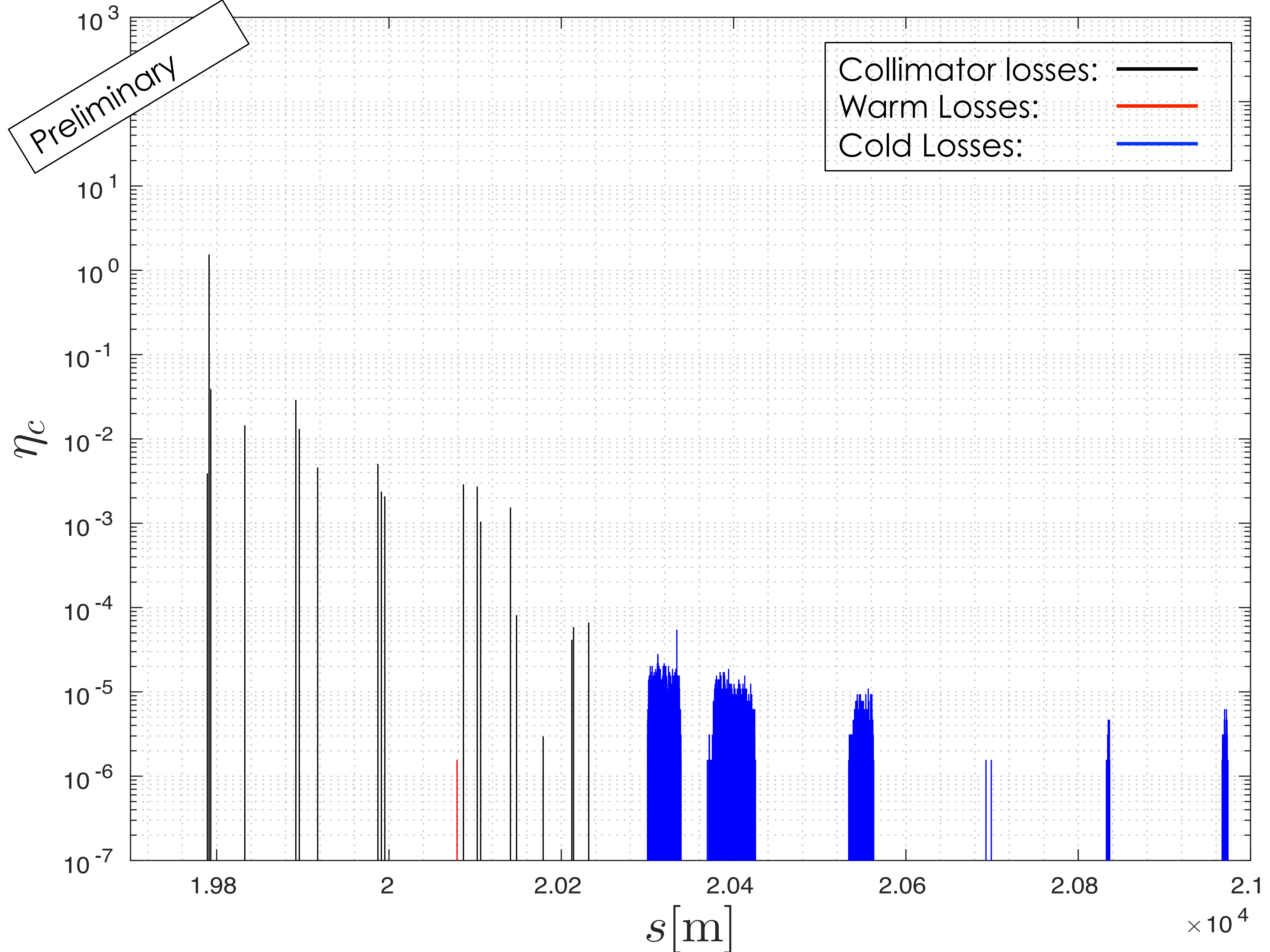
Collision energy

- The loss maps were repeated for collision energy of 13.5 TeV to get a comparison.
- The collimator settings were selected so that the openings scale with the energy, from HL-LHC/LHC to the HE-LHC at 13.5 TeV.
- Parameters used for these simulations were as per the nominal, with 25 cm β^* and 2.2E^{11} ppb
- The collimator gaps for the HL-LHC were reduced by $\sqrt{2}$
- Smaller gaps are bad for impendence with Z proportional to r^{-3}

Energy [TeV]	TCP IR3/7 [σ]	TCSG IR3/7 [σ]	TCLA IR3/7 [σ]
13.500	12.0/4.7	15/6.4	23.7/12.7

- A first look at collimation at collision energy with smaller gap sizes.
- Some large cold loss spikes located near the IP1 and IP5 that need to be investigated further.
- Losses at element markers 423 and 2371 which correspond to MBX and VSSK.
- Need to be considered more closely




Preliminary
Collimator losses:
Warm Losses:
Cold Losses:
10^{3}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
η_c
1.98
2
2.02
2.04
2.06
2.08
2.1
$\times 10^{4}$
$s[\mathrm{m}]$

Optics challenges for HE-LHC at collision

- There are a number of open challenges for the HE-LHC collimation system.
  - Reduce the cold loss spikes around IR1 and IR5, by including additional collimators and investigate further.
- Do the warm magnets need to be replaced with superconducting magnets?
  - Is the maximum gradient for the warm magnets still 30-35 T/m? or has there been an improvement since the LHC?
  - Do we have to replace all of the warm magnets? Or can we include a few SC magnets at a few choice places? Ensuring that there is enough room and minimise the shielding required?
- What is the radiation damage and collimator lifetime?
  - Energy deposition in the superconducting magnets
  - → FLUKA studies (*on-going for HE-LHC*)

More “exotic” options for collimation

- Hollow Electron lens
  - Could be useful to control halo population (reduce the)
  - However unlikely to be useful to mitigate impendence since we still need to protect the bottle neck and shield from luminosity debris around the high luminosity experiments.
  - Studies will begin shortly to investigate the impact on performance and halo cleaning
- Combining momentum and betatron cleaning sections?
- Rotatable collimators or liquid metal collimators?
  - To maximise the collimator lifetimes from radiation damage.

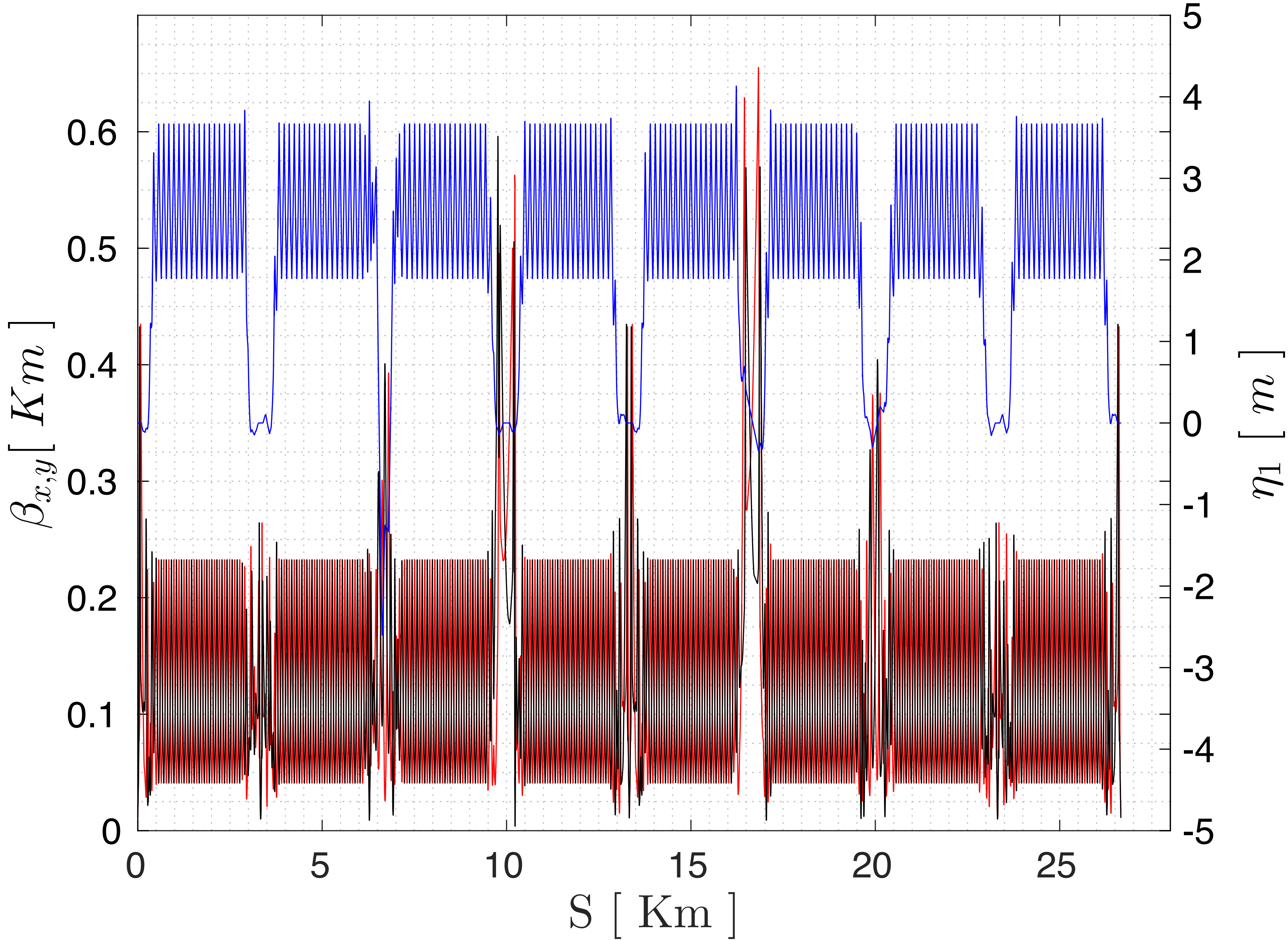
Summary

- Baseline optics for HE-LHC is available now at injection and collision energies.
- Loss maps for the various proposed injection energies have been presented.
  - Need to know whether injection is at 450 GeV or higher?
  - For injection energy at 450 GeV we may encounter problems with both physical and dynamic aperture (due to magnet errors).
  - At collision there are spikes in the cold losses near IR1 and IR5 that need to be investigated further (dispersion suppressor collimators etc which are being considered)
- Additionally at collision energy issues arise with maximum field strengths in IR7 and IR3.
  - Superconducting magnets will need to be considered
  - Need a better idea of the limits of the warm magnet technology.
  - Collaboration with the FLUKA team to investigate further
- Currently the studies were all performed using the LHC aperture model (***optimistic***) but an updated aperture model is available and these studies will be repeated.

Further work

- Update loss maps with new aperture model and develop collision setup further
  - Reduce the cold loss spikes around the IR1 and IR5
- FLUKA coupling on-going and detailed FLUKA studies to be performed.
- Need more information about magnet quench limits:
  - How accurate are the estimate quench limits shown during FCC week?
  - Are we still limited to LHC warm magnet specs?
- Different failure scenarios to be investigated
  - Injection failure,
  - Asynchronous dump
- Momentum cleaning and losses through the ramp.

Spare slides



$\beta_{x,y}$ [Km]
η_1 [m]
S [Km]
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0.1
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0.3
0.4
0.5
0.6
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-4
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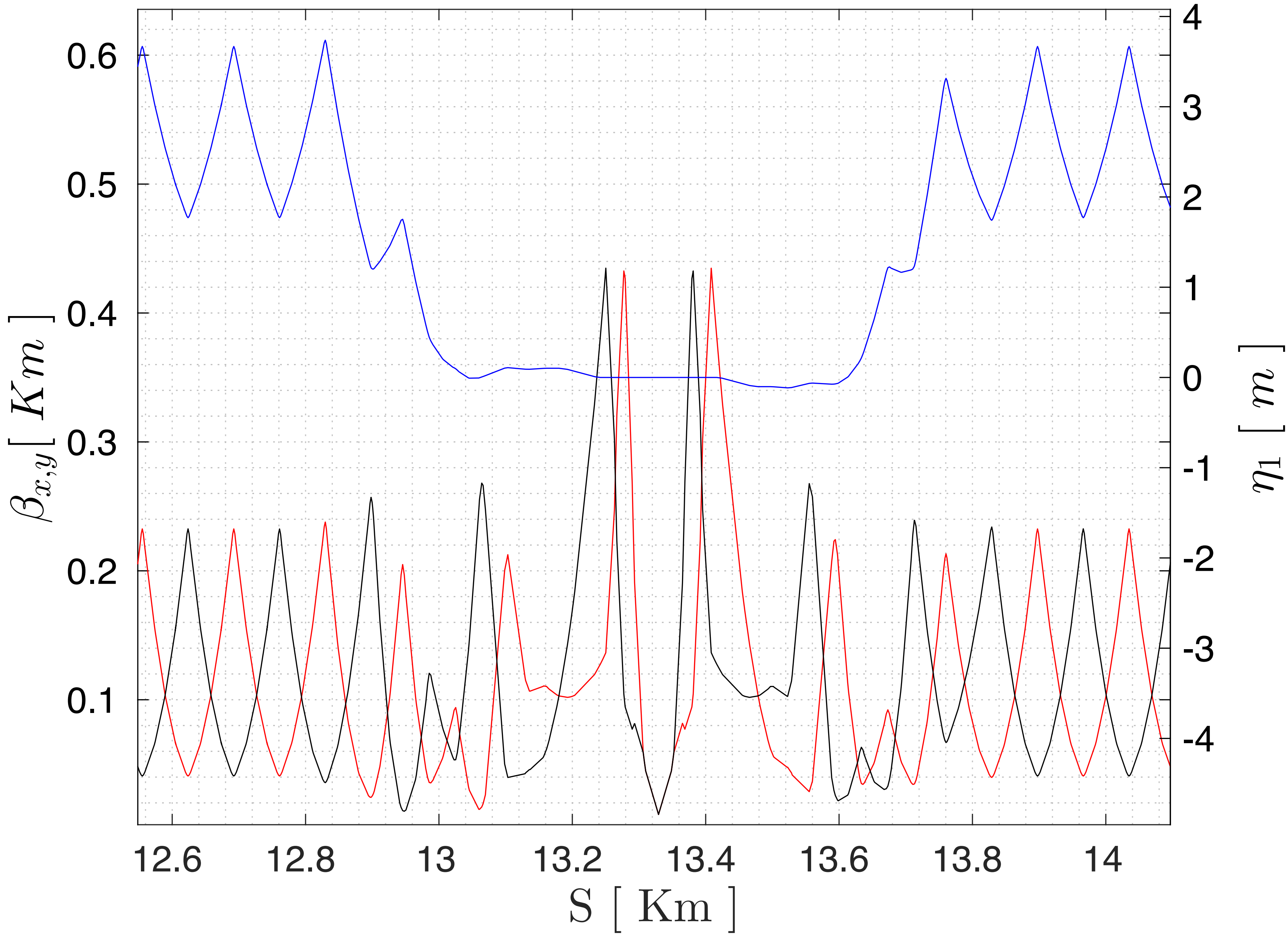
5
10
15
20
25



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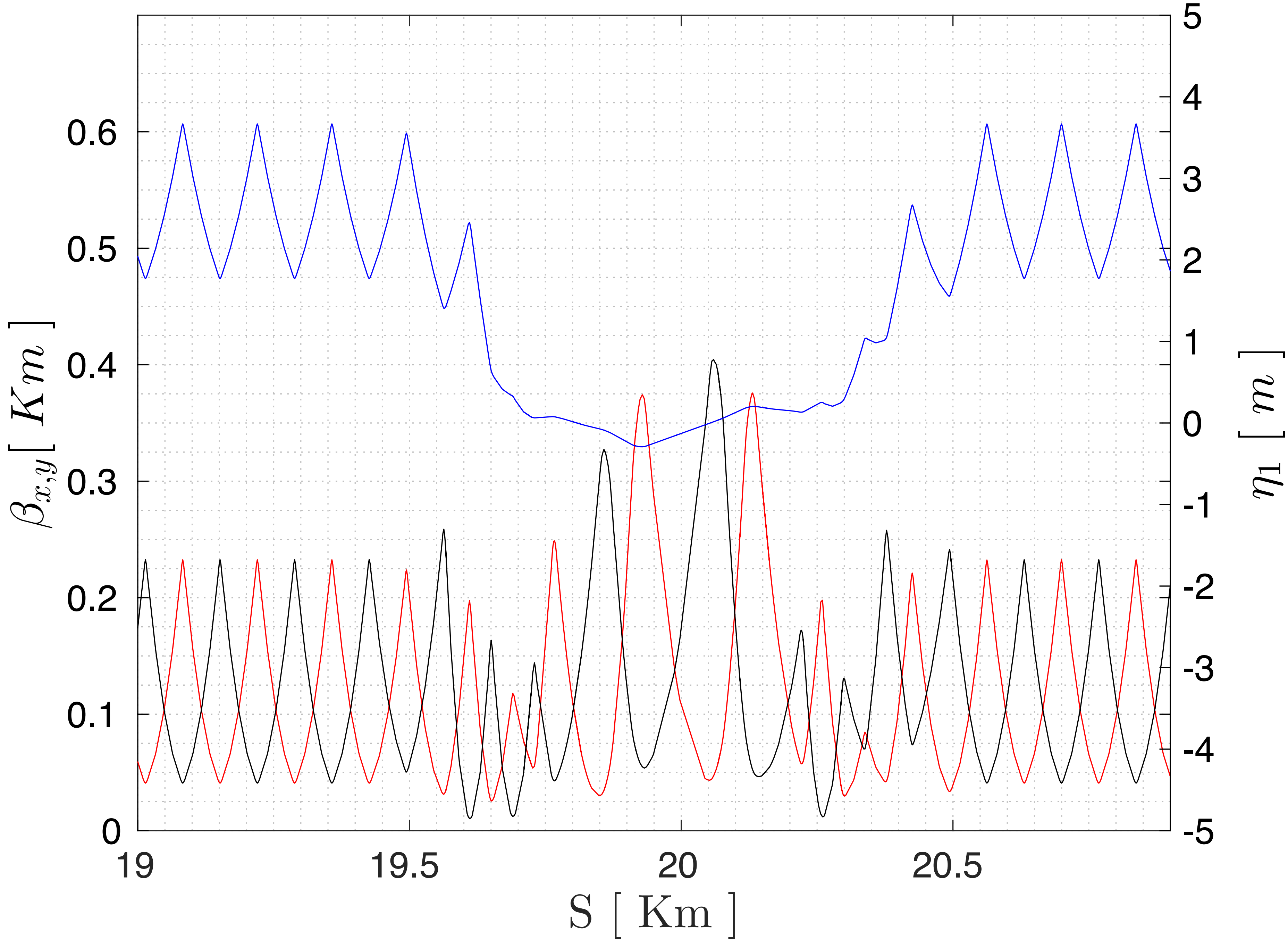
14
S [Km]



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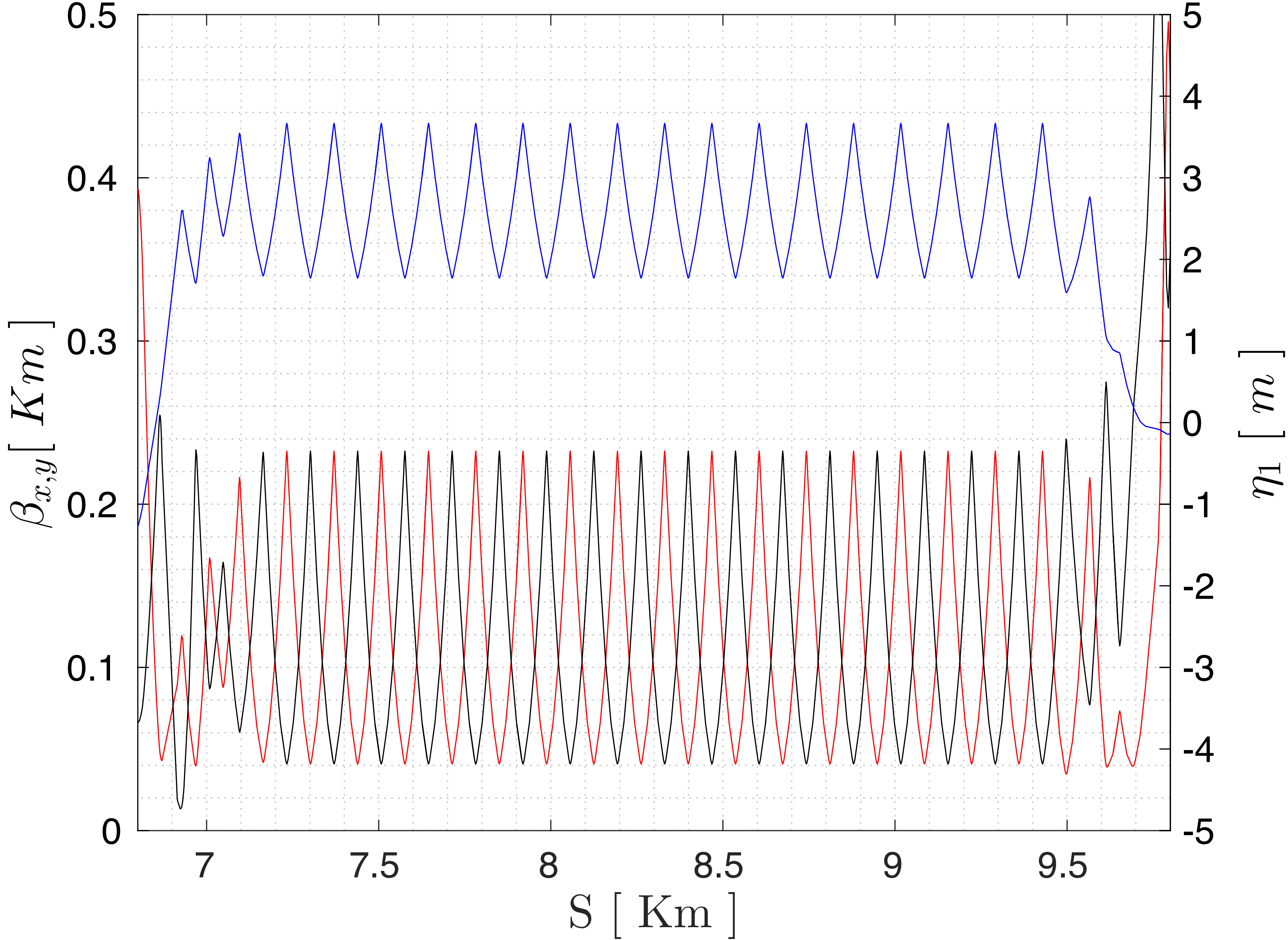
$\beta_{x,y}$[Km]
η_1 [m]
S [Km]



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η_1 [m]
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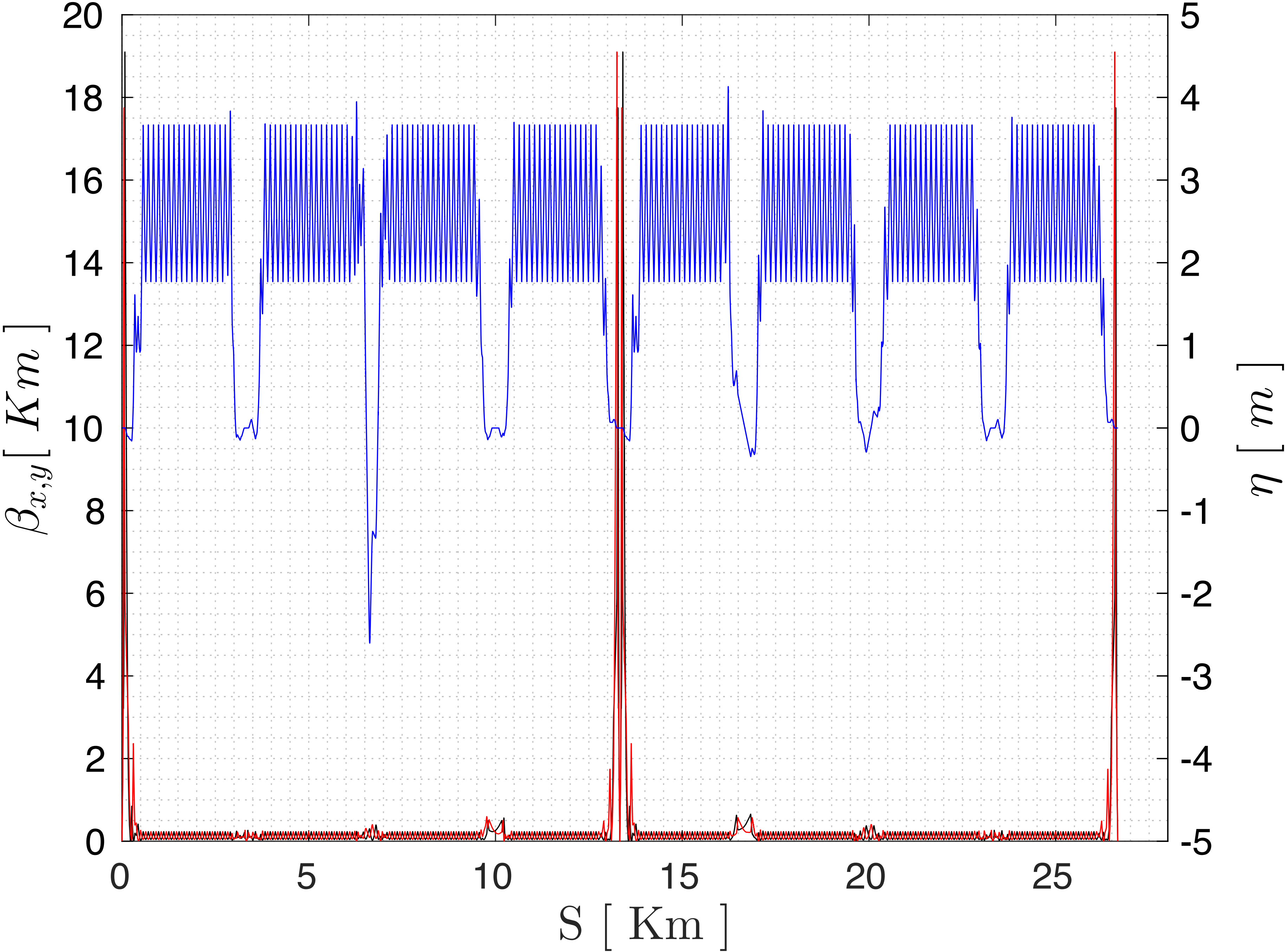
S [Km]



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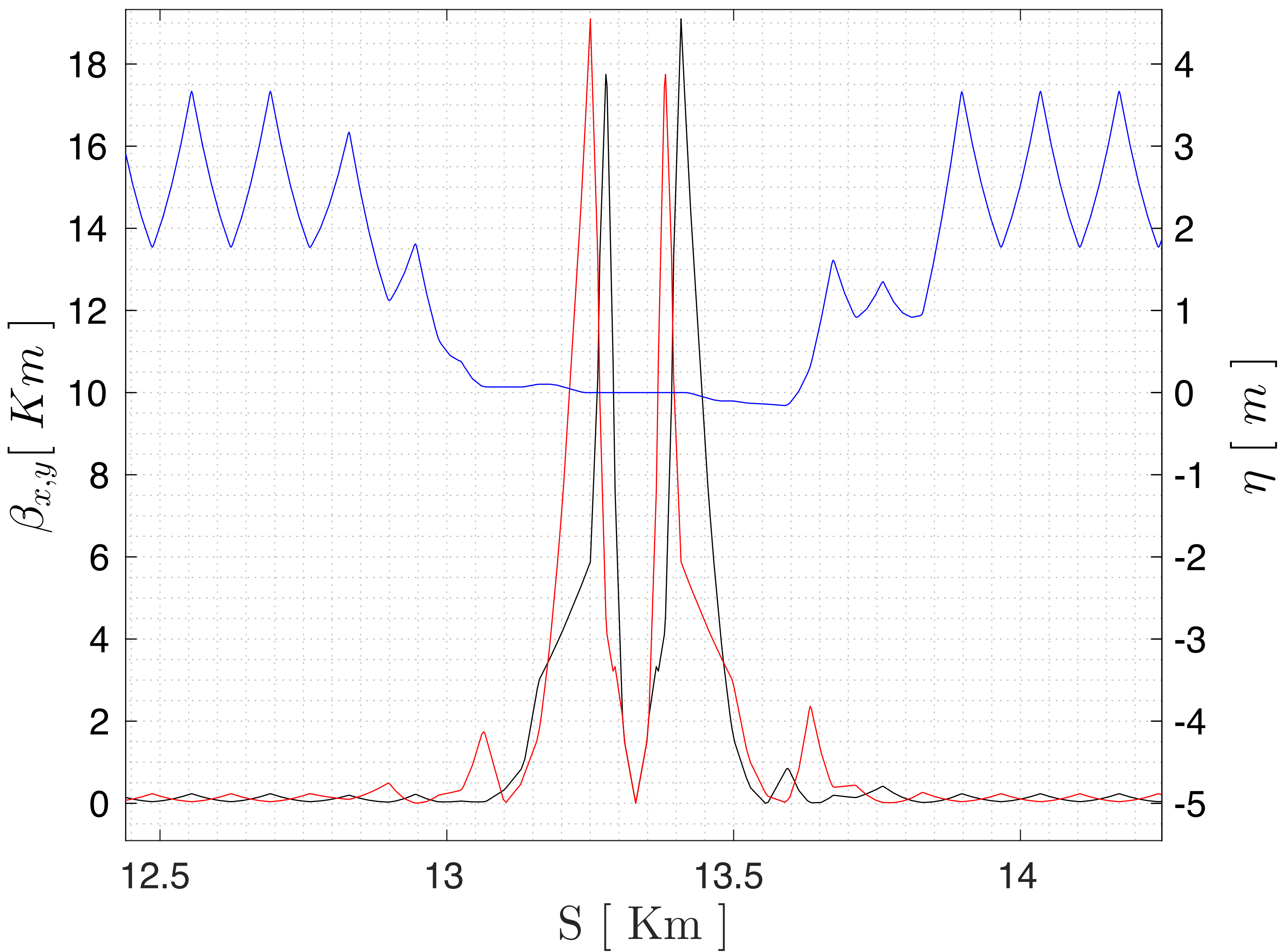

$\beta_{x,y}$ [Km]
η [m]
S [Km]
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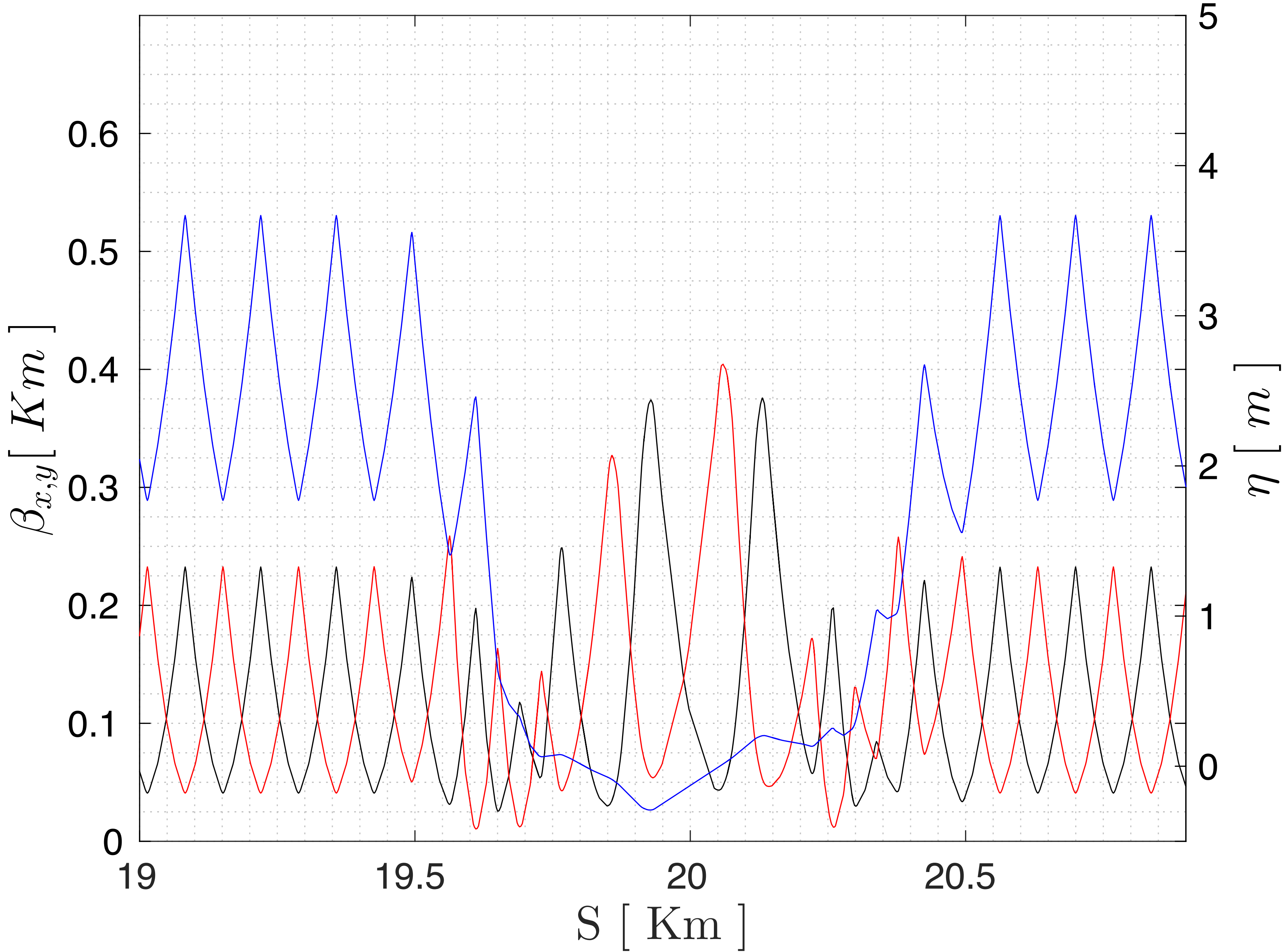
12.5
13
13.5
14



0.6
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$\beta_{x,y}$[Km]
5
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η [m]
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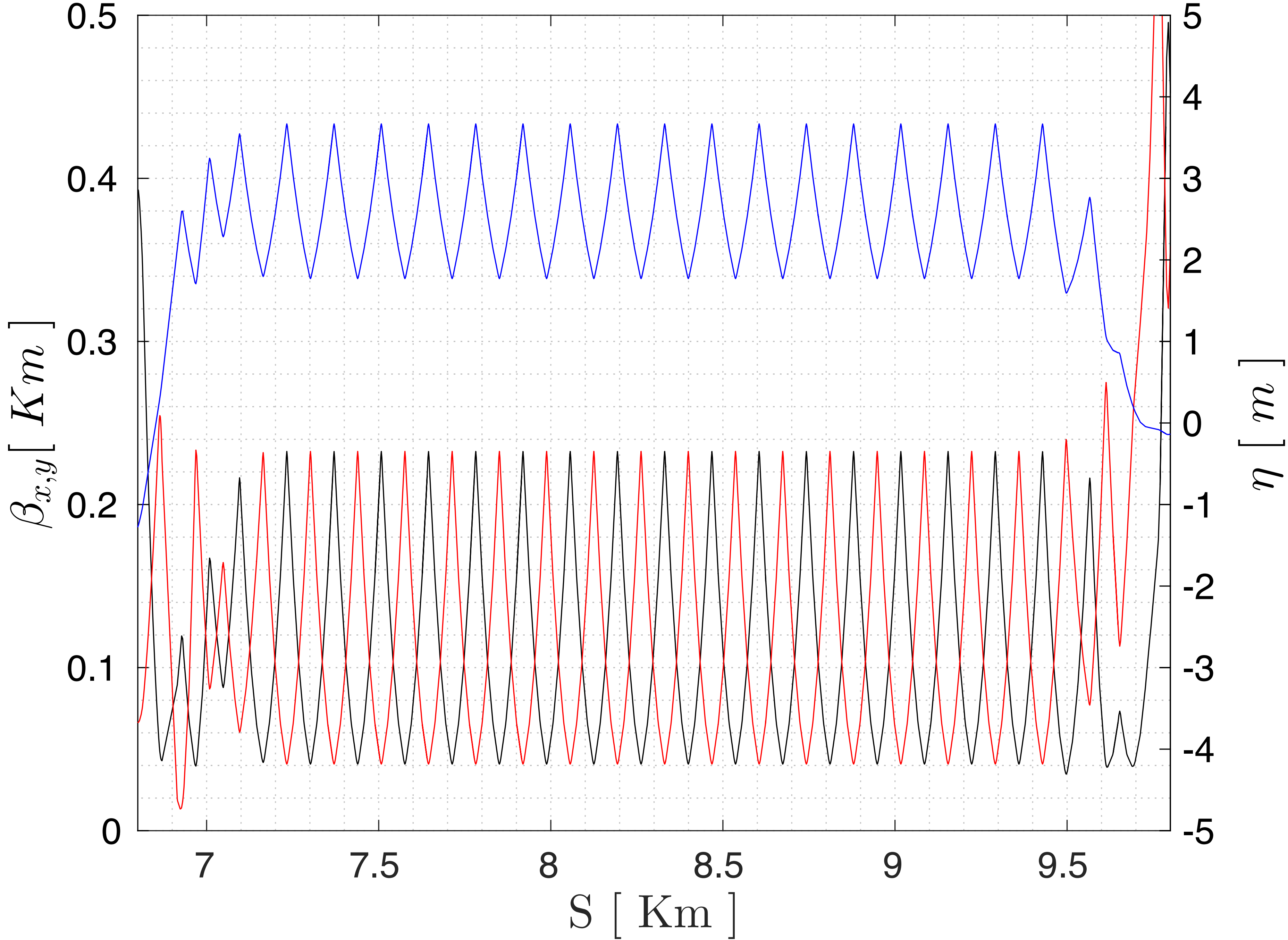
20
20.5
S [Km]



0.5
0.4
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$\beta_{x,y}$[Km]
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0
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-2
-3
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η [m]
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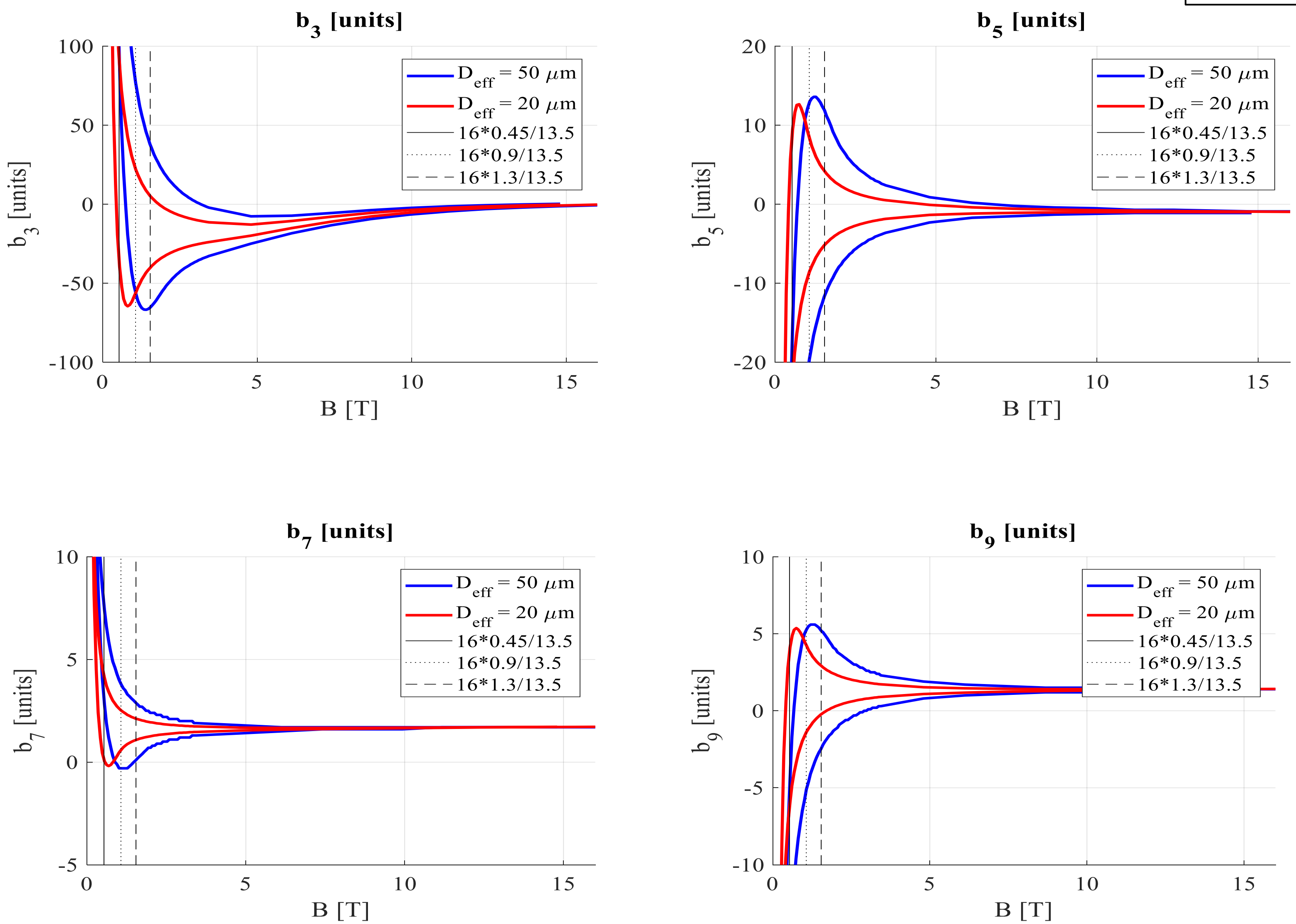
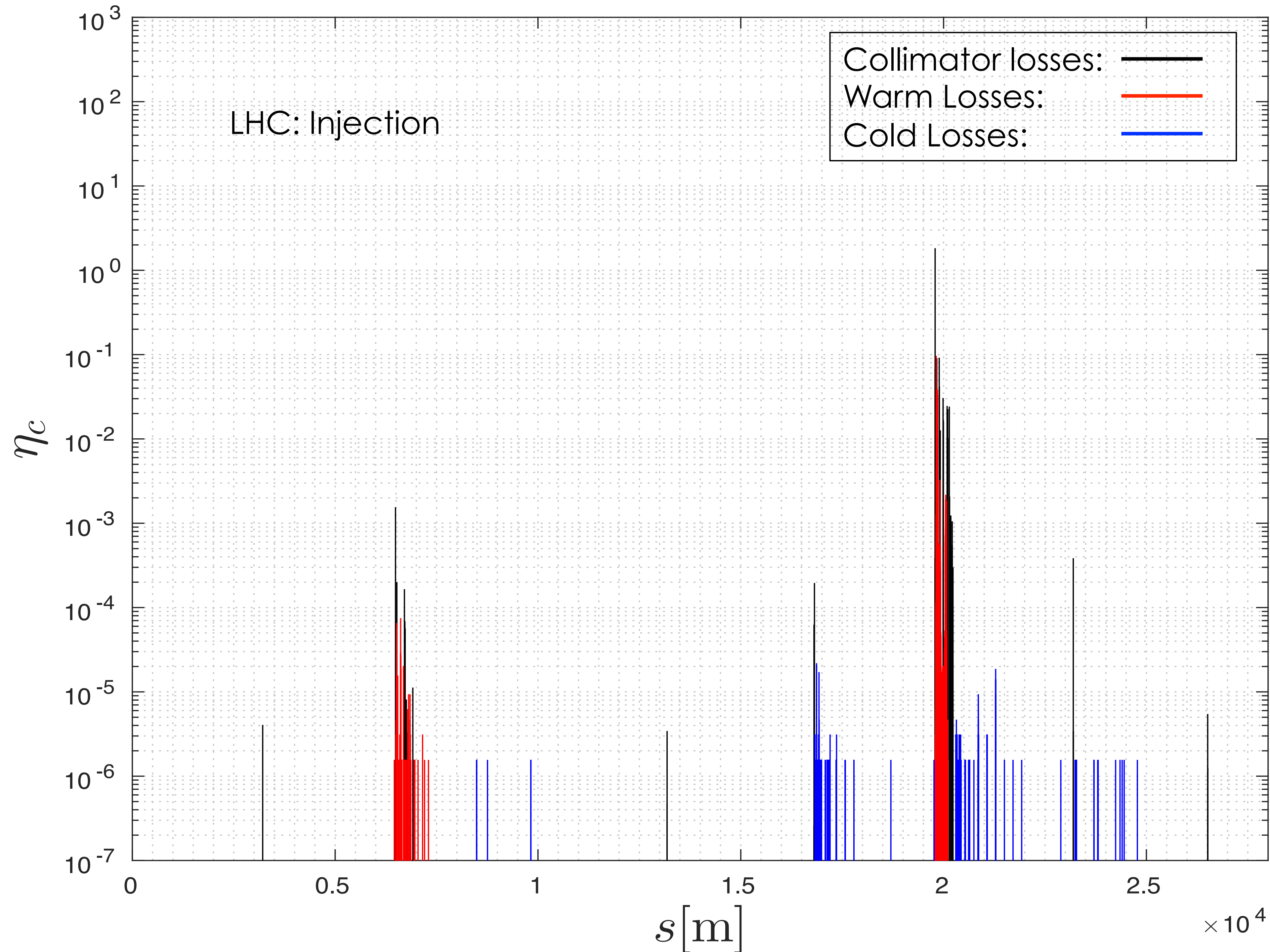
8
8.5
9
9.5
S [Km]

Magnetic error scaling with injection energy

S.Bermudez



Comparison to LHC



Collimator losses:
Warm Losses:
Cold Losses:
LHC: Injection
η_c
$s[\mathrm{m}]$
$\times 10^4$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
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10^{-6}
10^{-7}
0
0.5
1
1.5
2
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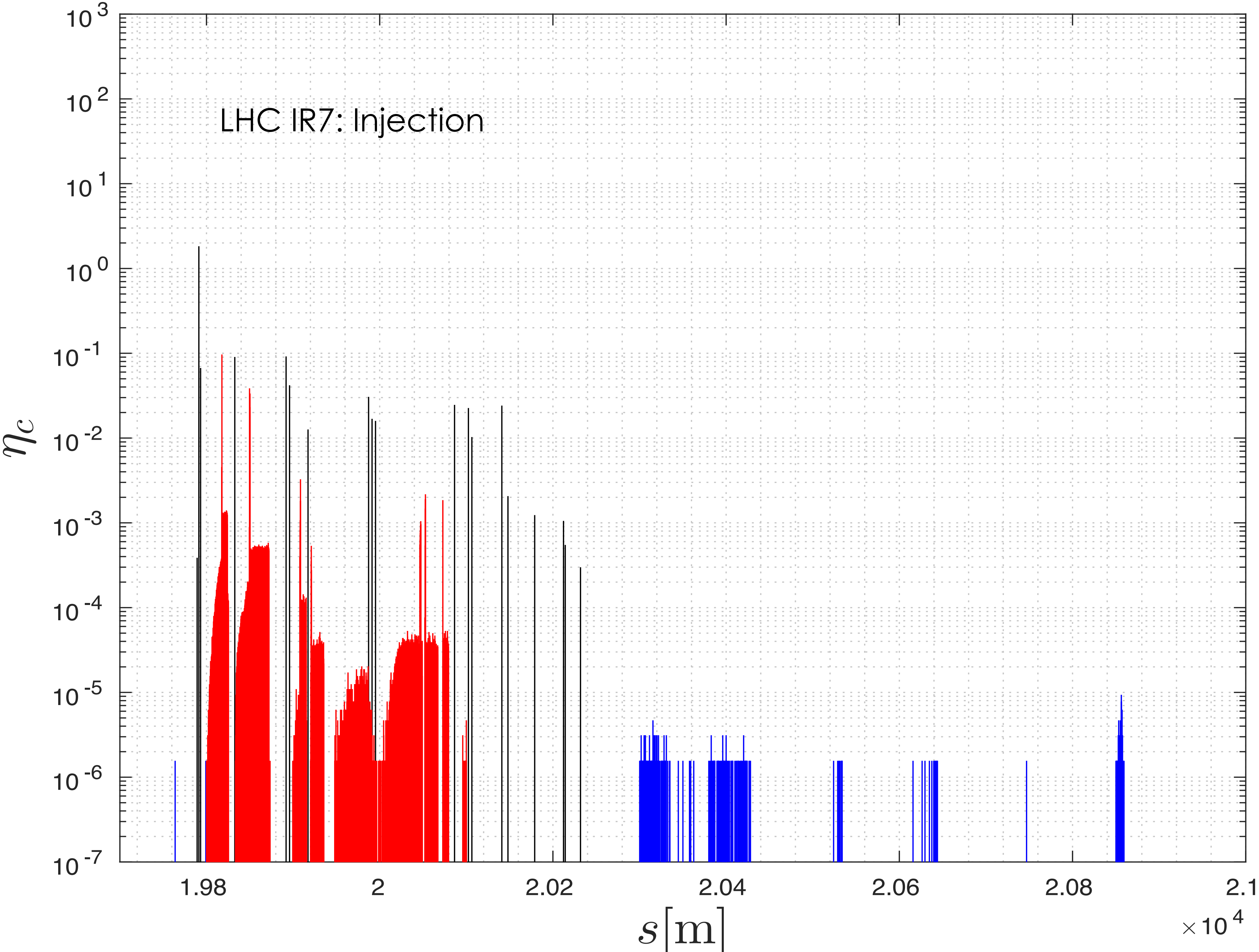
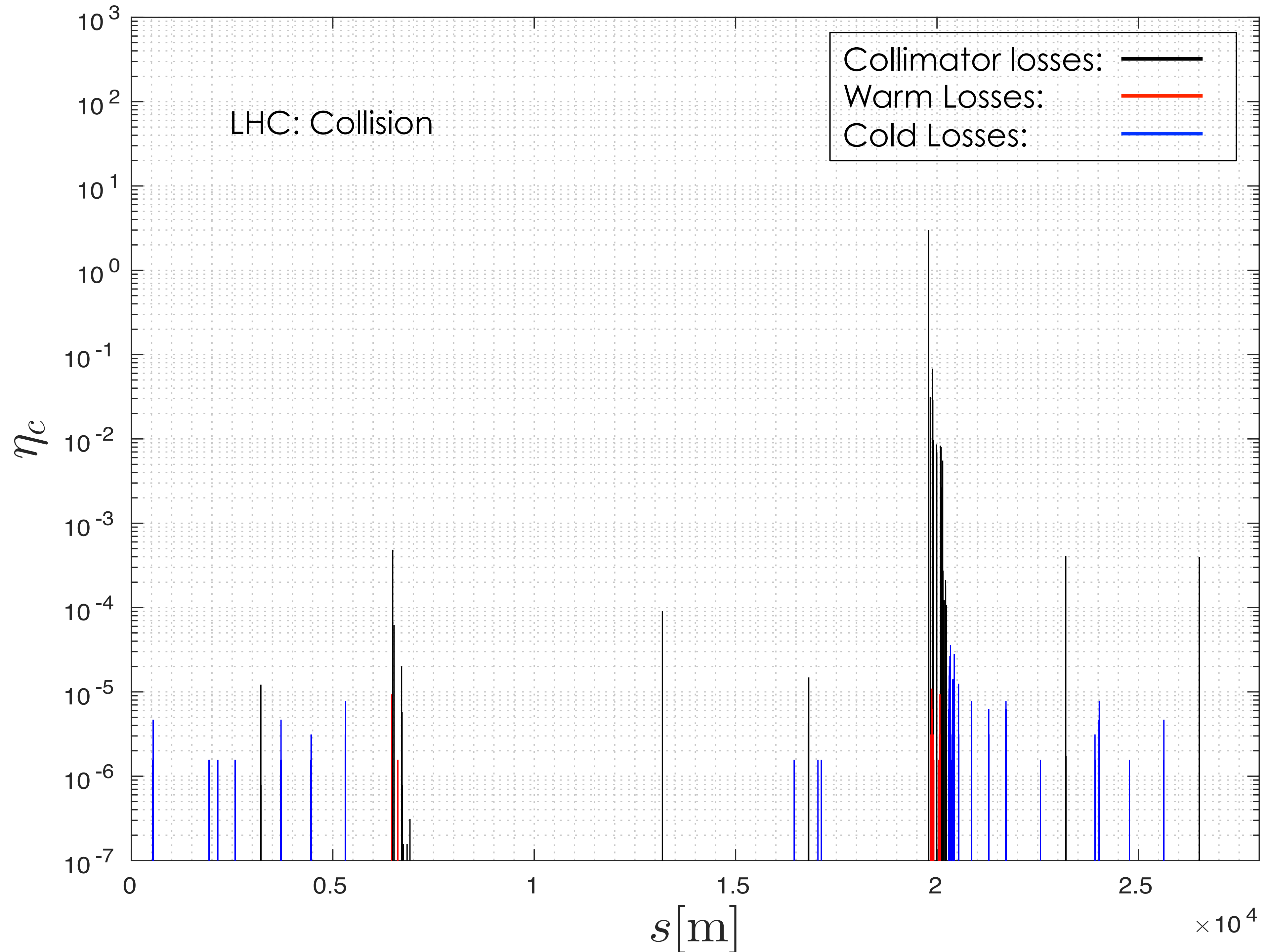
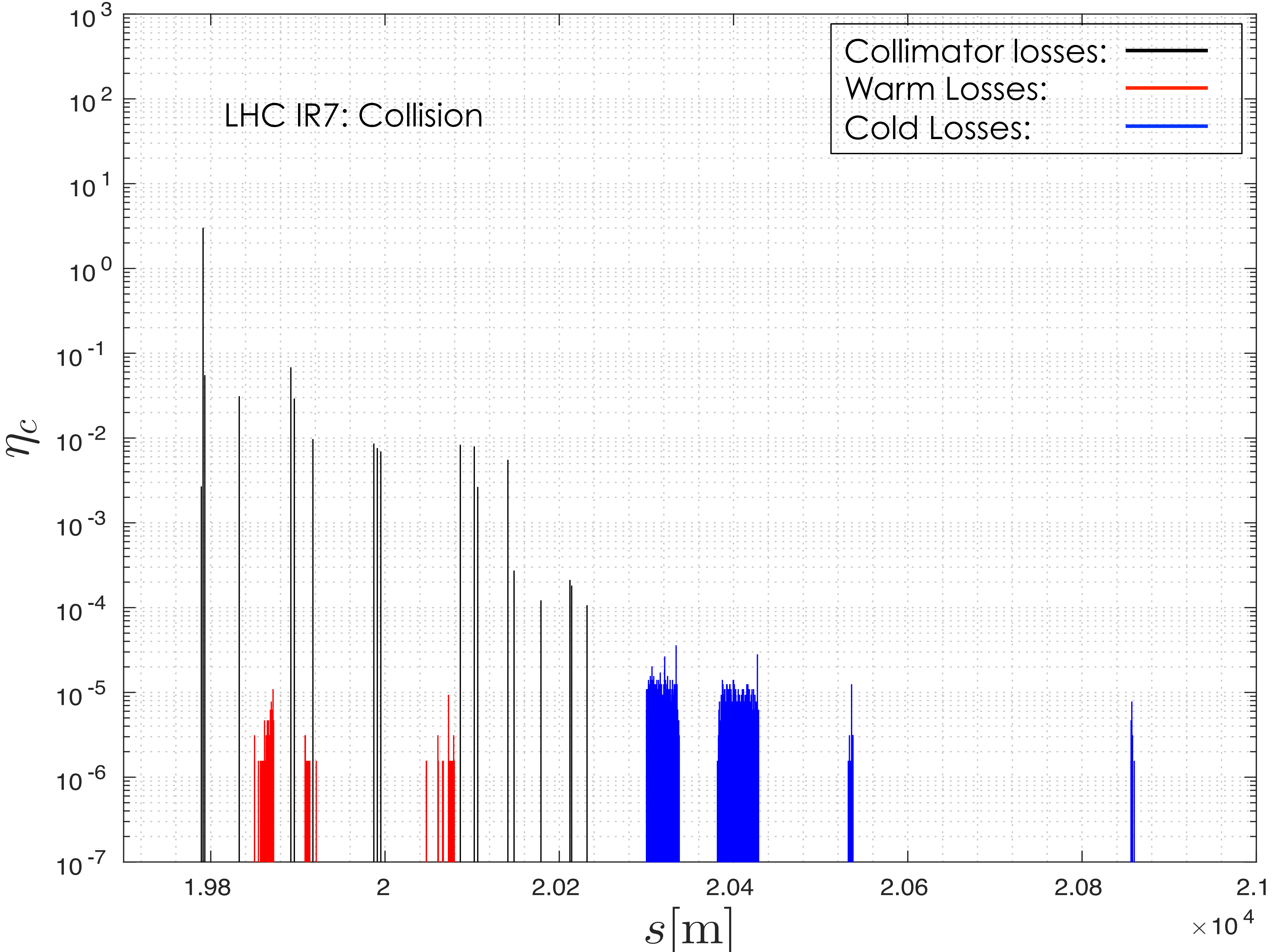


LHC IR7: Injection
η_c
$s[\mathrm{m}]$
$\times 10^4$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1.98
2
2.02
2.04
2.06
2.08
2.1



Collimator losses:
Warm Losses:
Cold Losses:
LHC: Collision
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
η_c
0
0.5
1
1.5
2
2.5
$\times 10^4$
$s[\mathrm{m}]$



LHC IR7: Collision
Collimator losses:
Warm Losses:
Cold Losses:
η_c
$s[\mathrm{m}]$
$\times 10^4$
10^3
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