Arc Optics and Geometry

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HE-LHC Review meeting, CERN, Dec. 11, 2017

Outline

- **Introduction**
- **Arc optics**
- **Ring geometry**
- **Physical aperture**
- **Summary**

1. Introduction

➤ High Energy LHC (HE-LHC) as proton-proton collider utilizing FCC-hh magnet technology

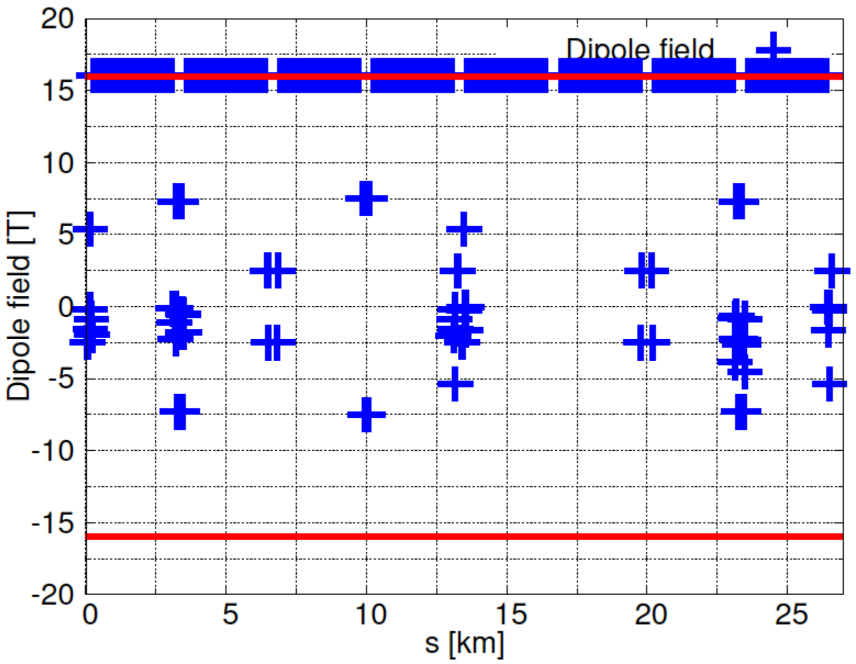
- 26.659 km ring fitting the LHC tunnel
- Centre-of-Mass beam energy from 14 to 27 TeV
- Magnets in arcs:
  - * LHC: 8.33 T dipole, 223 T/m arc quadrupole, 4430 T/m^2 sextuple with 56 mm aperture
  - * FCC-hh: 16 T dipole, 400 T/m quadrupole, 7800 T/m^2 sextuple with 50 mm aperture
- Simple scaling of the present LHC to 27 TeV CM energy yields the magnet fields exceeding the FCC specifications (next page)

1. Introduction

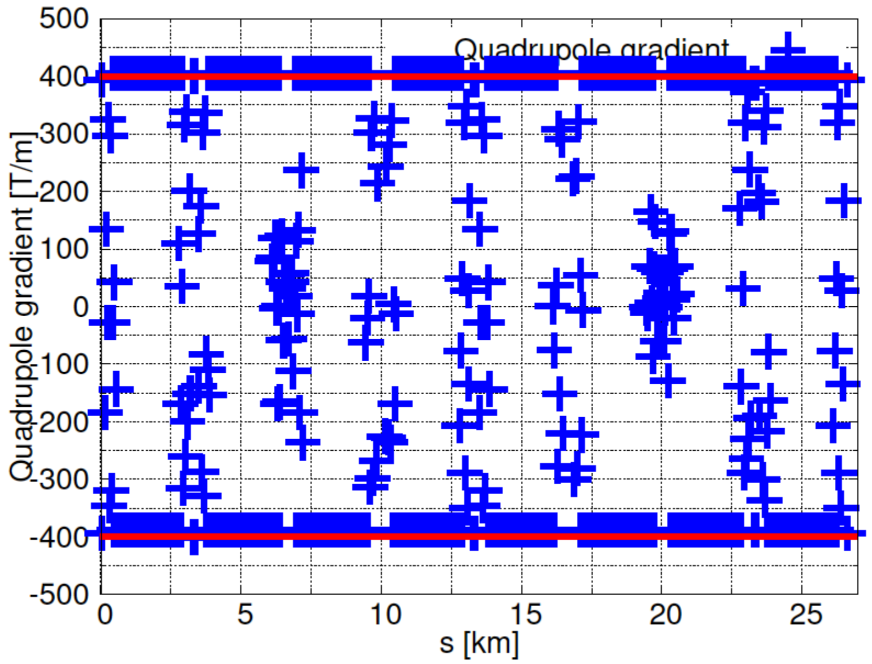
➤ Scale LHC to 27 TeV CM energy

- V6.503 as an example: β^*=55 cm at IP 1&5
- With baseline β^*=25 cm for HE-LHC, arc sextupoles will definitely exceed FCC specification
- Almost no optics flexibility

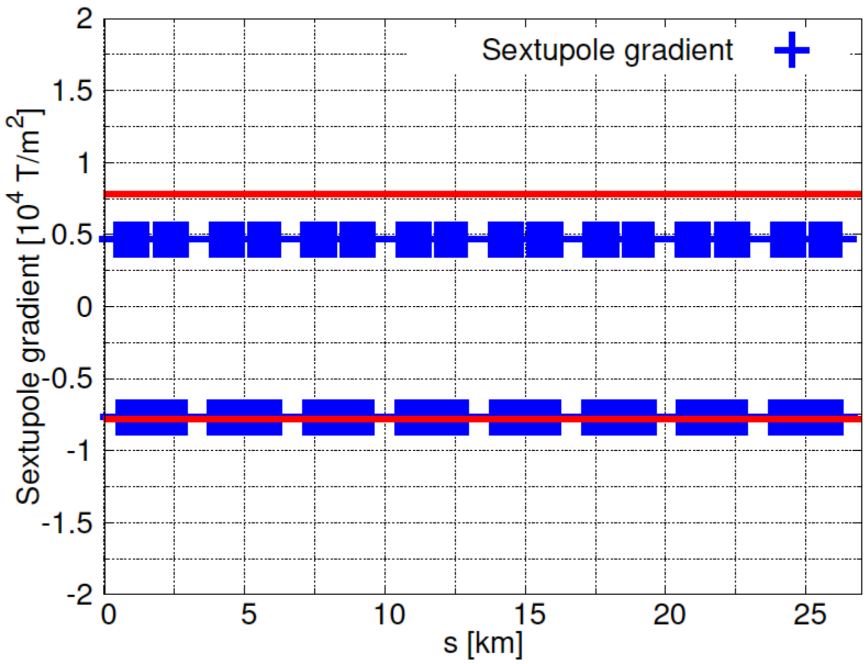
Dipole field



Quad. gradient



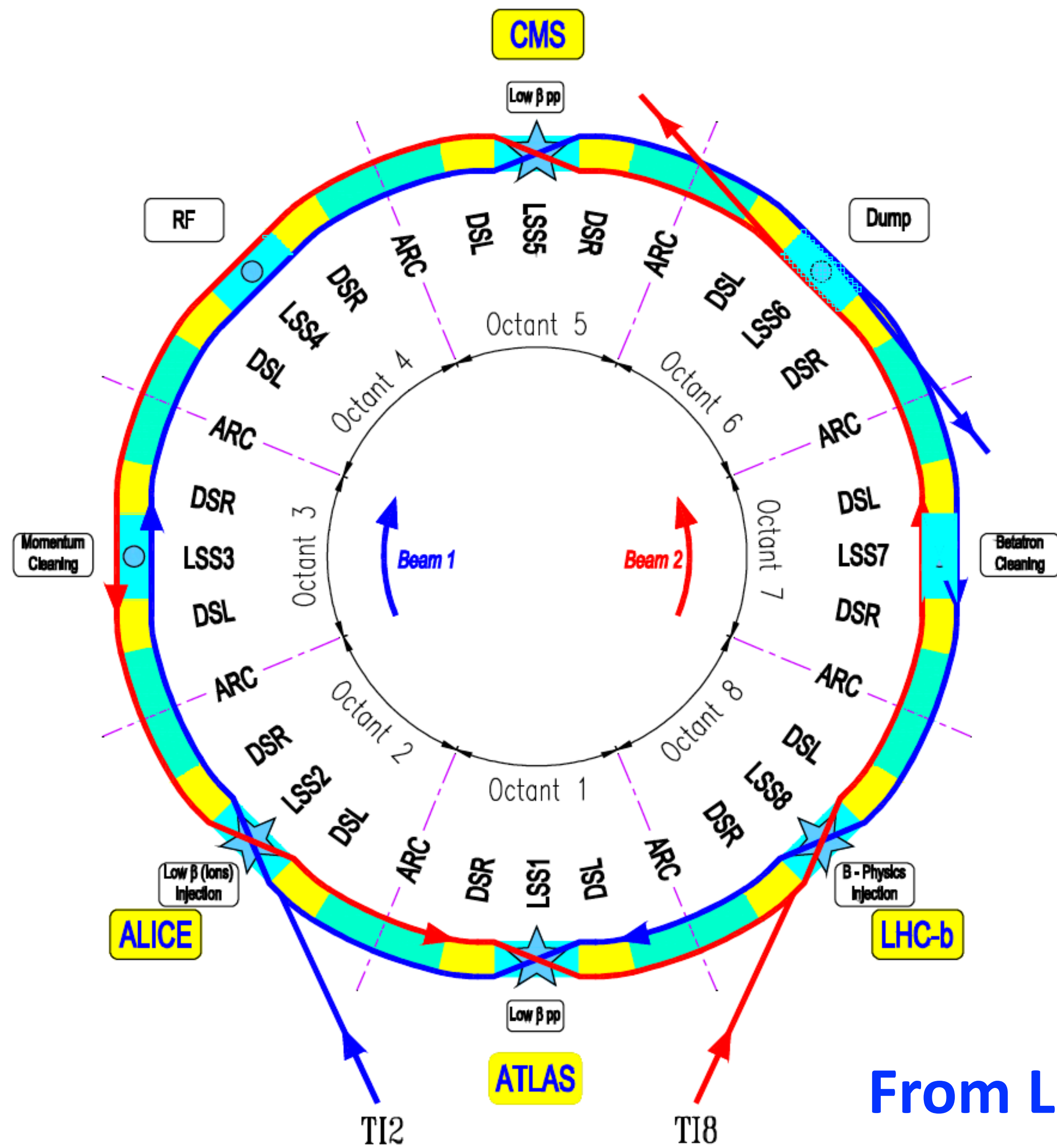
Sext. gradient



2. Arc optics

➤ Design considerations for arc optics of HE-LHC

● To fit the LHC tunnel with ring separation from 194 mm (LHC) to 204 mm (FCC-hh and HE-LHC baseline)



From LHC Design Report

2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- **To reduce quadrupole and sextupole strengths**
  - * **Reduce arc FODO cell phase advance μ_c and/or increase cell length L_c**

90 deg → 60 deg	Longer cell L_c
Weaker quads → factor of √2 (~sin(μ/2))	Weaker quads ~1/L_c
Weaker sextupoles → factor of 3 (for arcs correction)	Weaker sextupoles ~1/L_c^3
Lower cell chromaticity → factor of √3 (~tan(μ/2))	Same cell chromaticity
Similar peak β-functions	Larger peak β ~ L_c
Larger dispersion → factor of 2	Larger dispersion ~ L_c^2

Y. Nosochkov, FCC week 2017

$$\sin(\Phi/2) = \frac{1}{4}\mathrm{K_1 L_{cell}}$$

$$\beta_\pm = \frac{2\,(1 \pm \mathrm{K_1 L_{cell}}/4)}{\mathrm{K_1}\sqrt{1-(\mathrm{K_1 L_{cell}}/4)^2}} \qquad \eta_\pm = \frac{4}{\rho \mathrm{K_1^2}}\,(1 \pm \mathrm{K_1 L_{cell}}/8)$$

$$K_{2\pm} = \frac{K_1}{\eta_\pm}$$

← Only for chromaticity correction in arc cells.

2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- **To reduce sensitivity to field errors: Resonance free lattice**
  - * Choose phase advance condition per arc: $N_c\mu_c=2k\pi$
  - * Cancellation of non-linear resonances => To improve dynamic aperture

    Cancellation condition (A. Verdier, PAC'99):

    $N_c(n_x\mu_{xc}+n_y\mu_{yc})=2k\pi$ & $(n_x\mu_{xc}+n_y\mu_{yc})\neq 2k'\pi$

    N_c: number of cell; μ_{xc}, μ_{yc}: Phase advance per cell
  - * 60-deg cell:

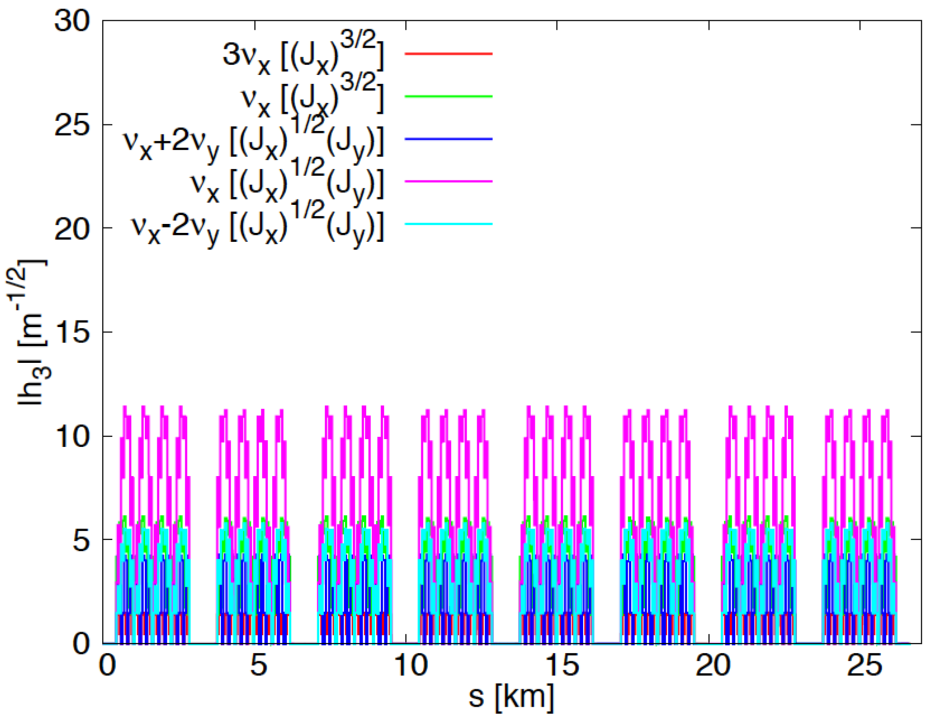
    Lowest order resonances: n_x-n_y=0 and n_x+n_y=6
  - * 90-deg cell:

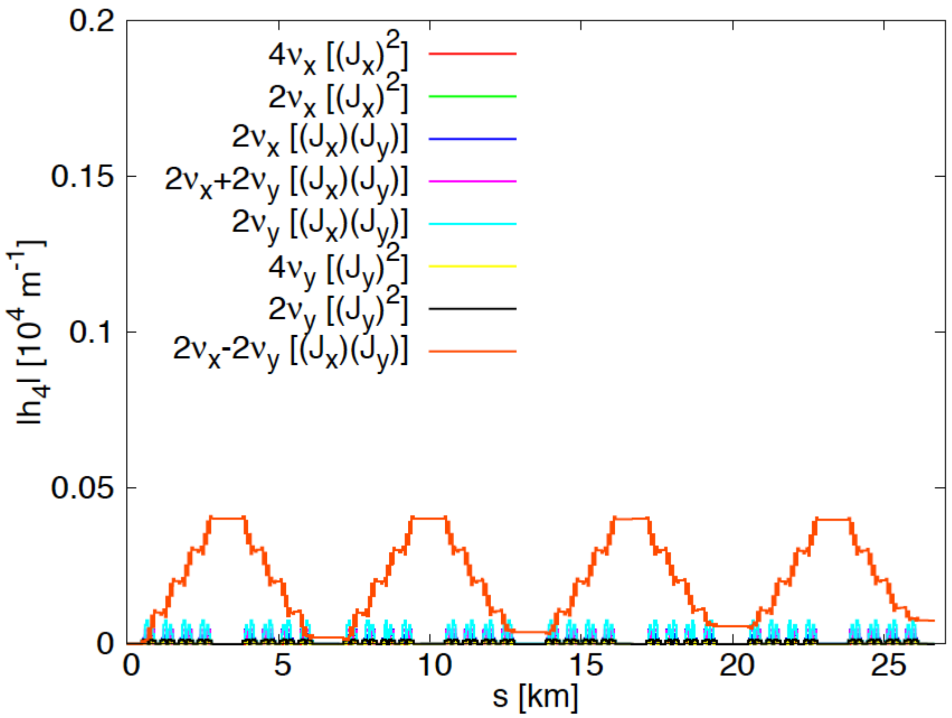
    Lowest order resonances: n_x-n_y=0 and n_x+n_y=4

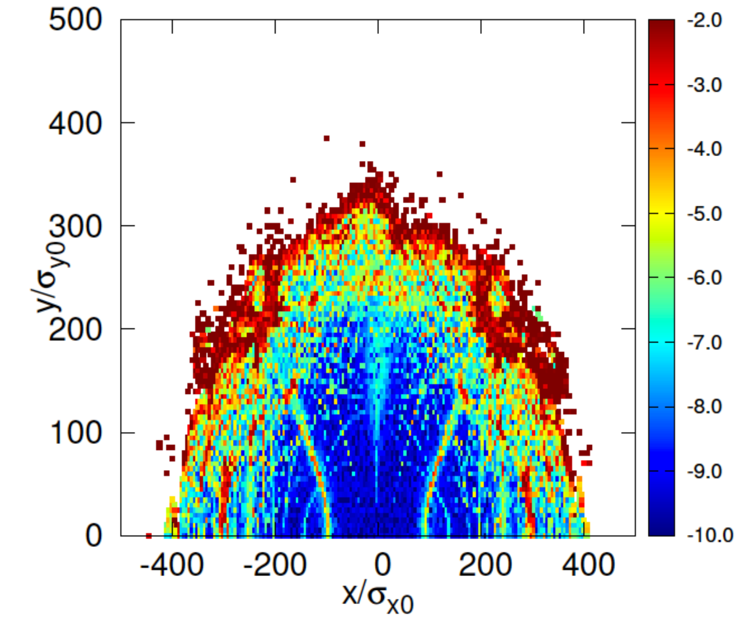
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- **To reduce sensitivity to field errors: Resonance free lattice**
  - * **Choose phase advance condition per arc: $N_c\mu_c=2k\pi$**
  - * **Cancellation of non-linear resonances => To improve dynamic aperture**
  - * **Example: Injection optics for E=450 GeV (by Y.N.)**
    N_c=24, μ_c=60 deg with basic IRs and tune (49.28, 47.31)
    RDTs by PTC and FMA tracking by SAD



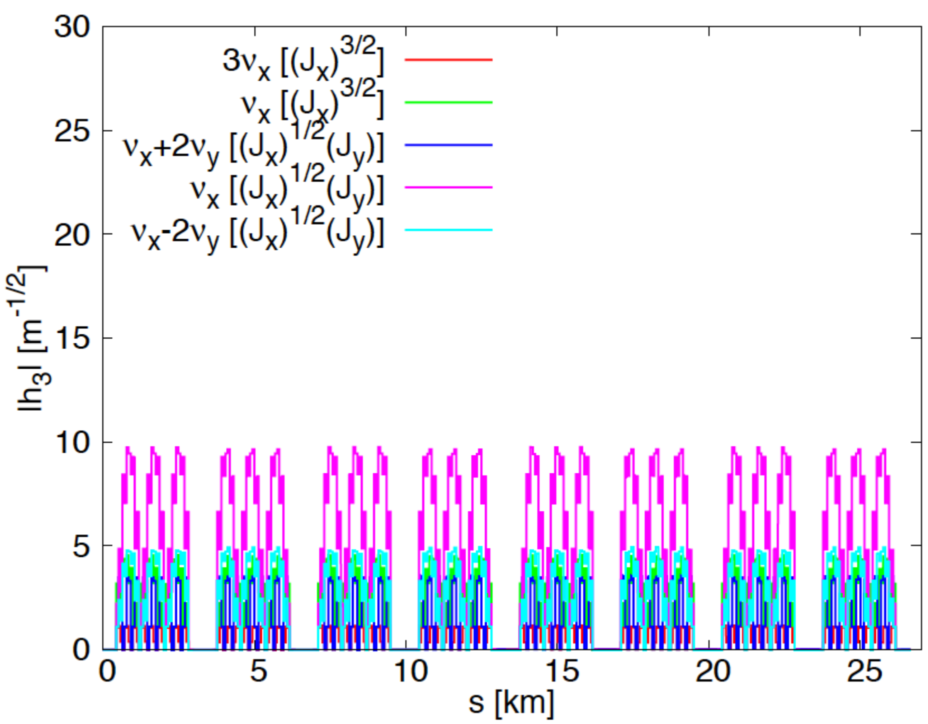


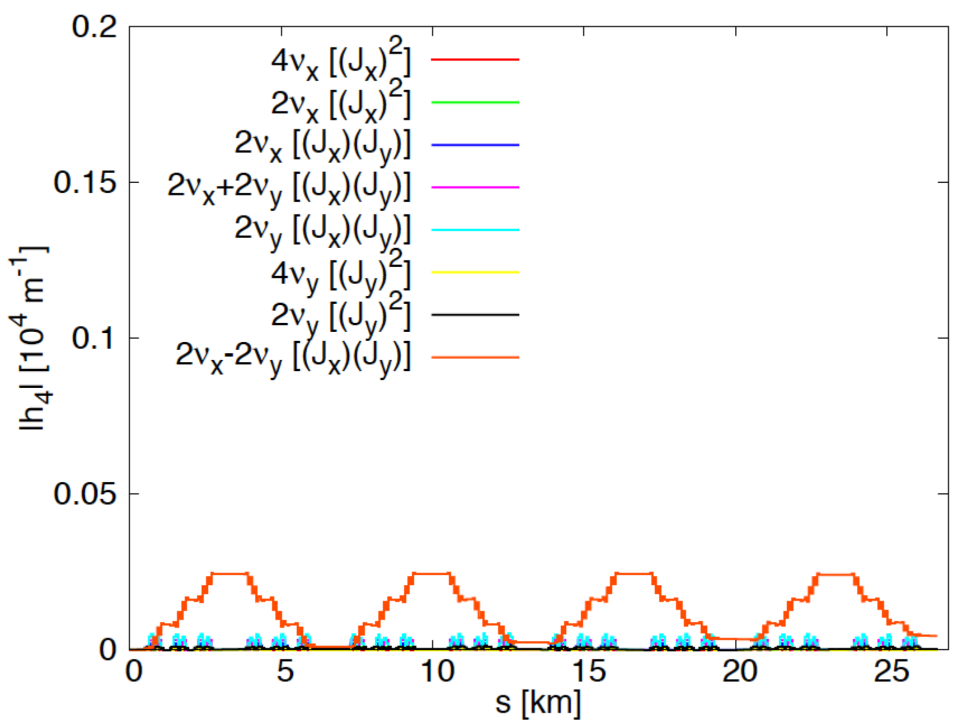


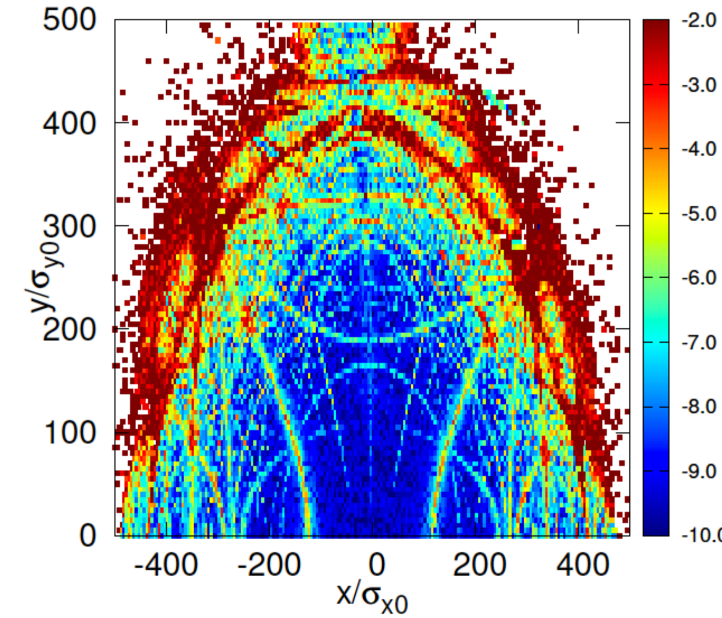
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- **To reduce sensitivity to field errors: Resonance free lattice**
  - * Choose phase advance condition per arc: $N_c\mu_c=2k\pi$
  - * Cancellation of non-linear resonances => To improve dynamic aperture
  - * Example: Injection optics for E=450 GeV (by Y.N.)
    N_c=18, μ_c=60 deg with basic IRs and tune (37.28, 39.31)
    RDTs by PTC and FMA tracking by SAD







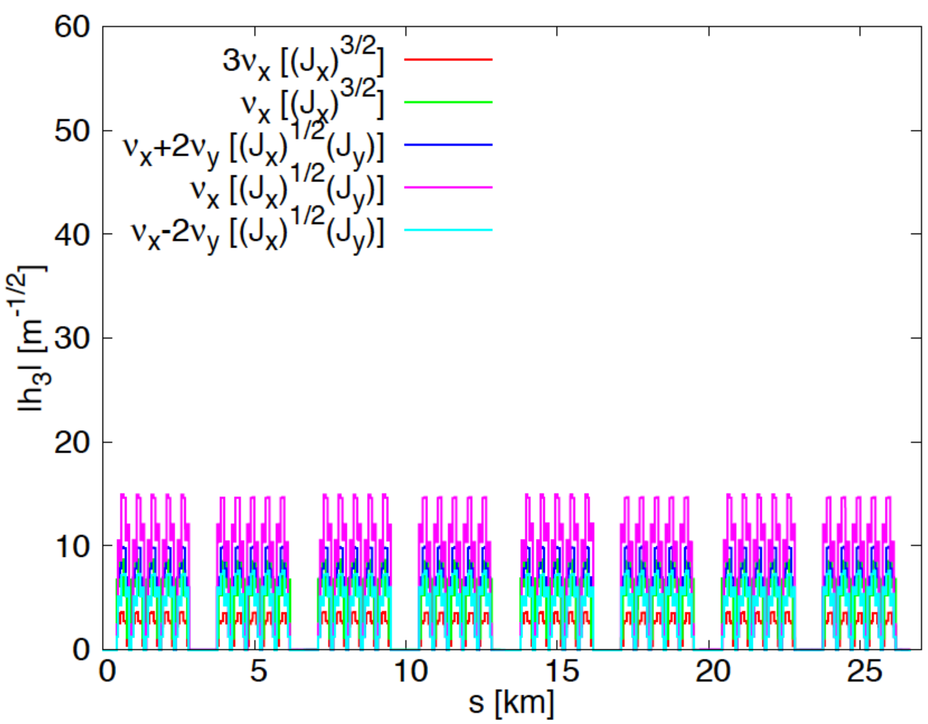
2. Arc optics

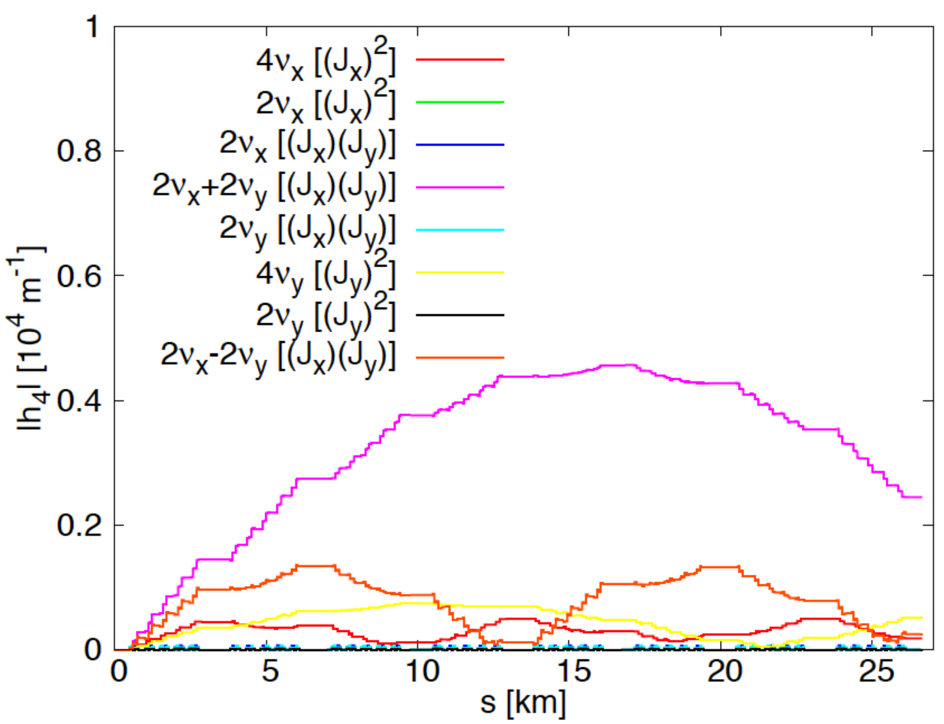
➤ Design considerations for arc optics of HE-LHC

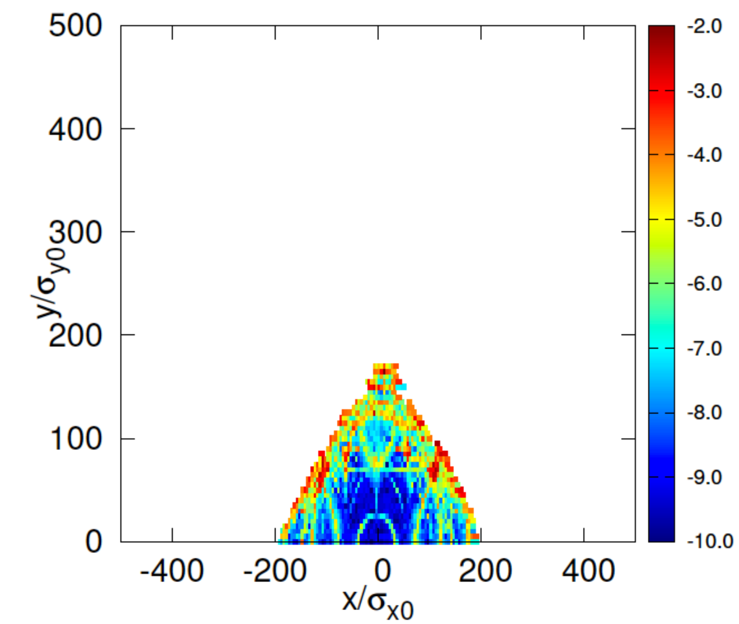
- **To reduce sensitivity to field errors: Resonance free lattice**
  - * **Choose phase advance condition per arc: $N_c\mu_c=2k\pi$**
  - * **Cancellation of non-linear resonances => To improve dynamic aperture**
  - * **Example: Injection optics for E=450 GeV (by Y.N.)**

    N_c=20, μ_c=90 deg with basic IRs and tune (56.28, 57.31)

    RDTs by PTC and FMA tracking by SAD







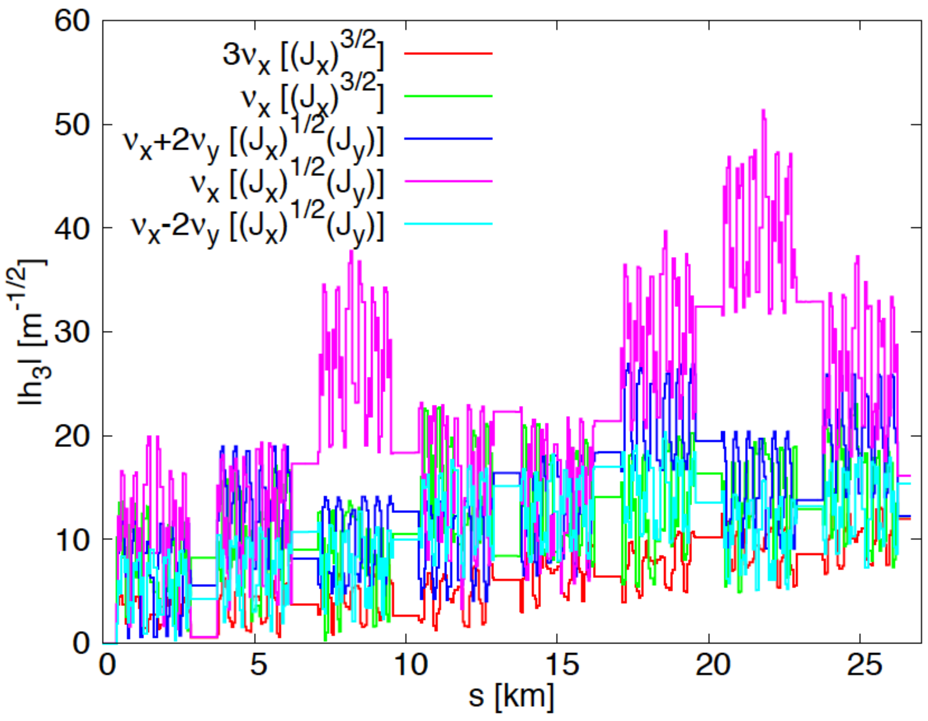
2. Arc optics

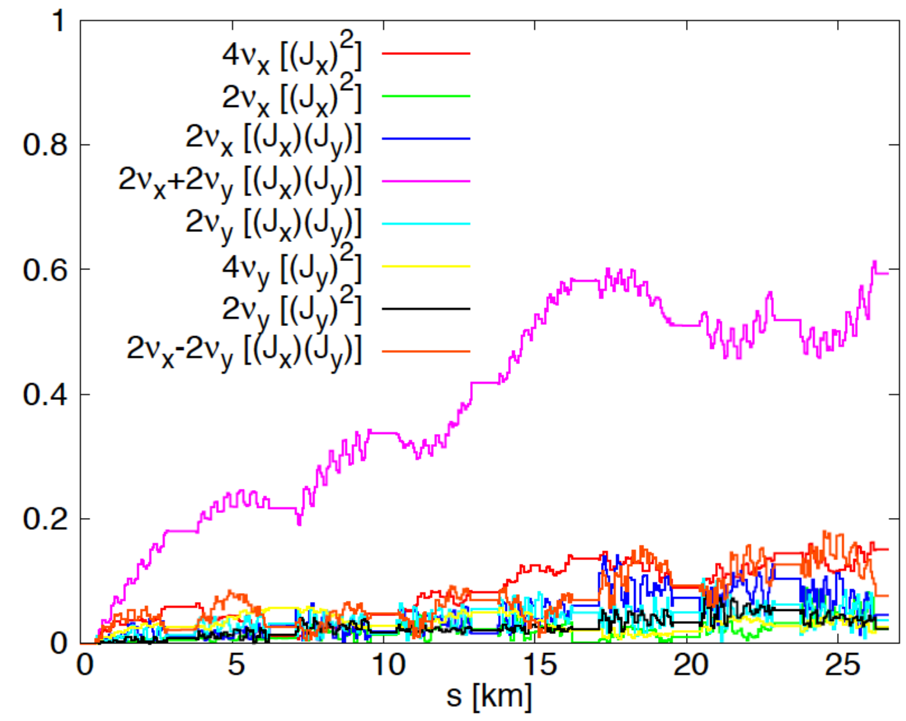
➤ Design considerations for arc optics of HE-LHC

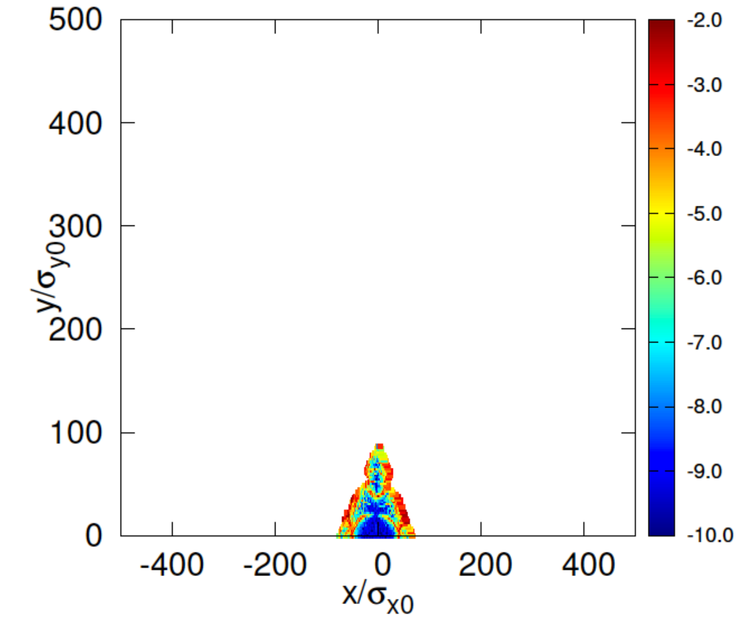
- **To reduce sensitivity to field errors: Resonance free lattice**
  - * Choose phase advance condition per arc: $N_c\mu_c=2k\pi$
  - * Cancellation of non-linear resonances => To improve dynamic aperture
  - * Example: Injection optics for LHC (V6.503)

    N_c=23, μ_c=~90 deg with basic IRs and tune (64.28, 59.31)

    RDTs by PTC and FMA tracking by SAD







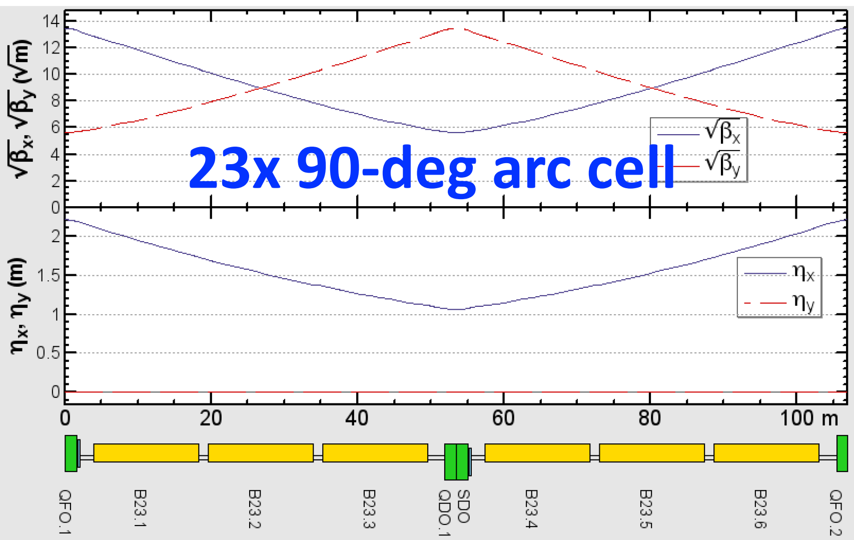
2. Arc optics

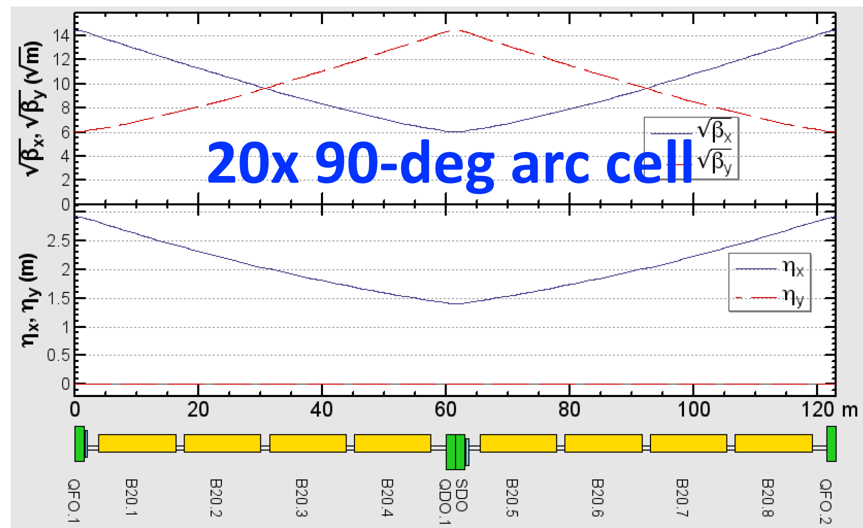
- Details in talk "Dynamic aperture" by Y. Nosochkov

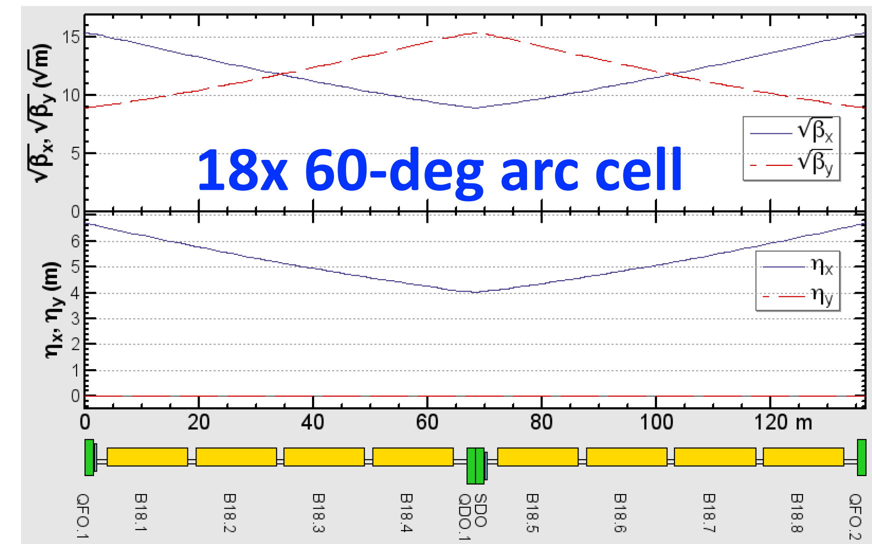
- General features for arcs of HE-LHC lattice model
  - C = 26658.8832 m same as in LHC
  - Same quad and sext. lengths as in LHC
  - Same magnet-to-magnet distances as in LHC cell
  - Similar layout of dispersion suppressors as in LHC
  - Odd and even arcs with opposite quad polarity - same as in LHC
  - Arc length close to LHC with adjustment in better fitting tunnel geometry

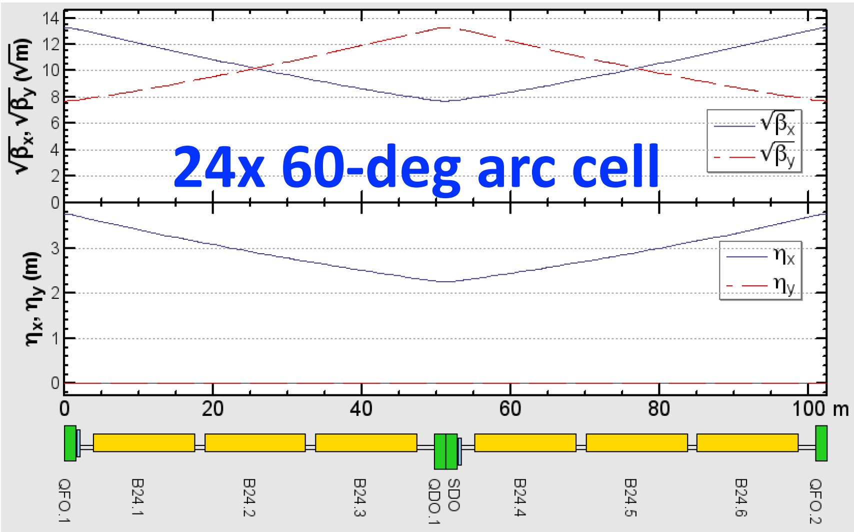
2. Arc optics

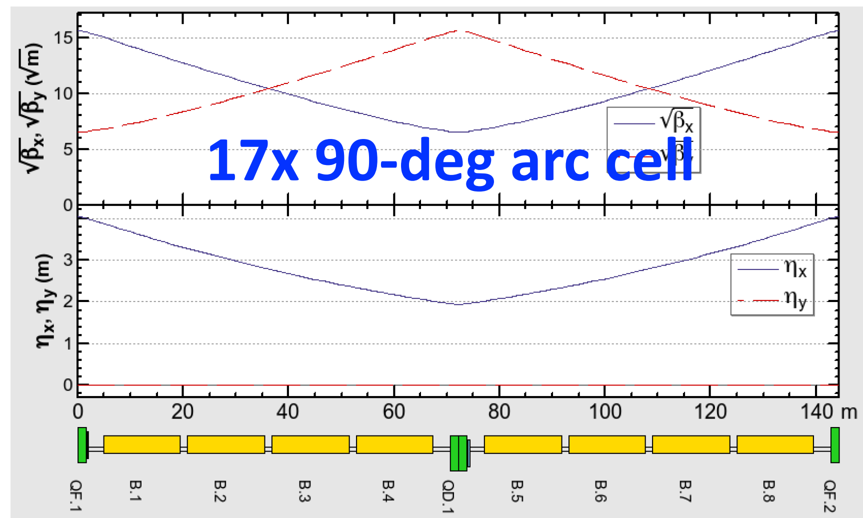
➤ **Options for arc cells**

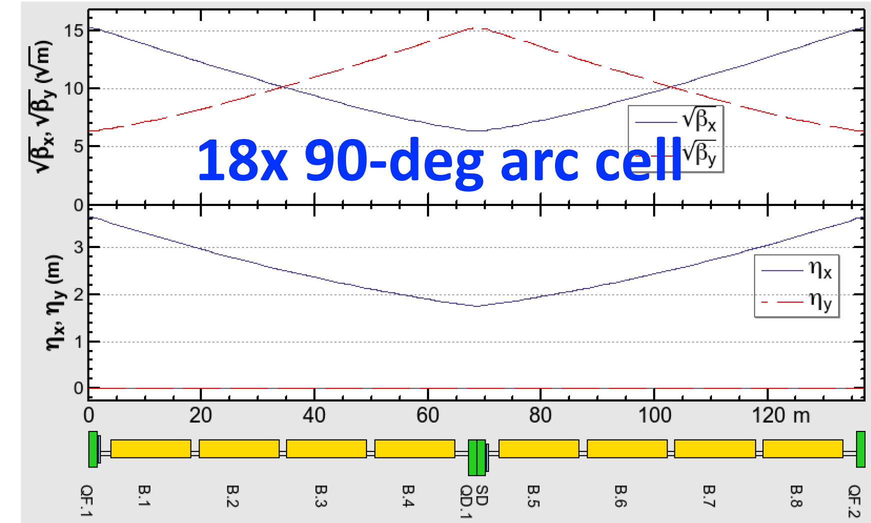












2. Arc optics

➤ Parameters for arc cells of injection optics

- FCC: 16 T dipole, 400 T/m quad., 7800 T/m² sext. with 50 mm aperture

	LHC	17x90	18x60	18x90	20x90	24x60
Arc cell phase	~90/90	90/90	60/60	90/90	90/90	60/60
Arc cell length [m]	107	144.4	137.2		124.8	102.9
K1 [m^{-2}]	0.009	0.0064	0.0048	0.0068	0.0076	0.0064
$\beta_{max/min}$ [m]	181/32	241/43	234/80	229/41	208/37	175/61
$\eta_{max/min}$ [m]	2.2/1.1	4/2	6.9/4.1	3.6/1.8	3.0/1.5	3.8/2.3
Dipole length [m]	14.3 [x6]	14.6 [x8]	14.18 [x8]		12.625 [x8]	13.56 [x6]
Dipole field [T] @13.5TeV	16.06	15.94	15.59		15.92	16.3
Quad. grad. [T/m] @13.5TeV	405	289	215	304	340	288
Sext. grad. [T/m²] @13.5TeV	4826	2035	~870	2470	2943	1997
Filling factor	0.802	0.809	0.827		0.809	0.791

2. Arc optics

➤ Global parameters for injection optics

- C=26658.8832 m
- Matching of 18x60 and 24x60 lattices not optimized

	LHC	17x90	18x60	18x90	20x90	24x60
Tune [x/y]	64.28/59.31	49.28/47.31	37.23/36.06	50.28/49.31	54.28/53.31	46.1/45.8
Nat. Chrom. [x/y]	-86.2/-81.5	-67.9/-68.0	-48.7/-48.4	-68.7/-70.5	-73.9/-74.9	-57.3/-57.7
Cor. Chrom. [x/y]	2/2	1/1	-	0.6/1	1/1	-
Mom. Compact.	3.22E-04	6.2E-04	1.14E-03	5.71E-04	4.75E-04	6.51E-04
β* (m) [x/y]	11/11	10/10	10/10	10/10	10/10	10/10
Beam separation at arcs (mm)	194	204	204	204	204	204

2. Arc optics

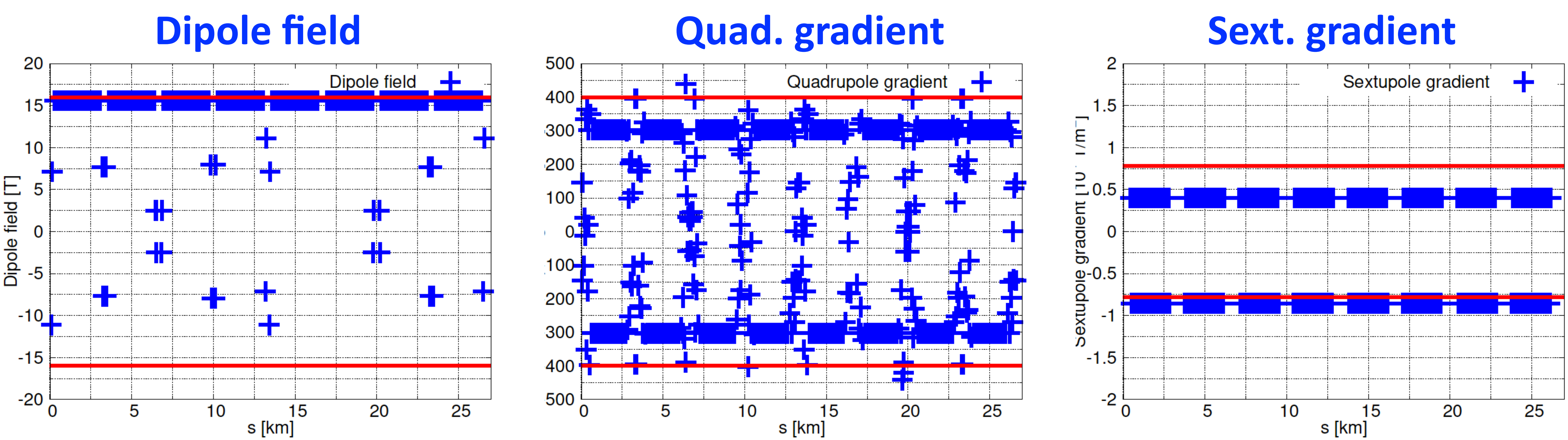
➤ **18x90 arc scheme chosen as the baseline with respect to overall performance**

- **Best filling factor and consequent lowest dipole field => Gain in operational margin**
- **Quadrupole strengths well below FCC limit**
- **Acceptable sextupole strengths (though exceed FCC limit)**
- **Physical aperture (To be discussed in next pages. Also details in talk by F. Zimmermann)**
- **Dynamic aperture (Details in talk by N. Nosochkov)**
- **Matching to IRs (Details in talks by M. Hofer and L. Riesen-Haupt)**

2. Arc optics

➤ HE-LHC collision optics at 27 TeV CM energy

- **V0.2 as an example:**
  - * 18x90 arcs, β^*=25 cm at IP 1&5
- **Dipoles/quadrupoles below FCC specifications**
- **Sextupoles exceed FCC specification**
  - * Natural chrom.: $(-69.8, -71.1)_{injection}$ => $(-246.6, -263.4)_{collision}$
  - * Solutions: Longer sext./Smaller μ_c per cell/Larger β^*



2. Arc optics

➤ HE-LHC collision optics at 27 TeV CM energy

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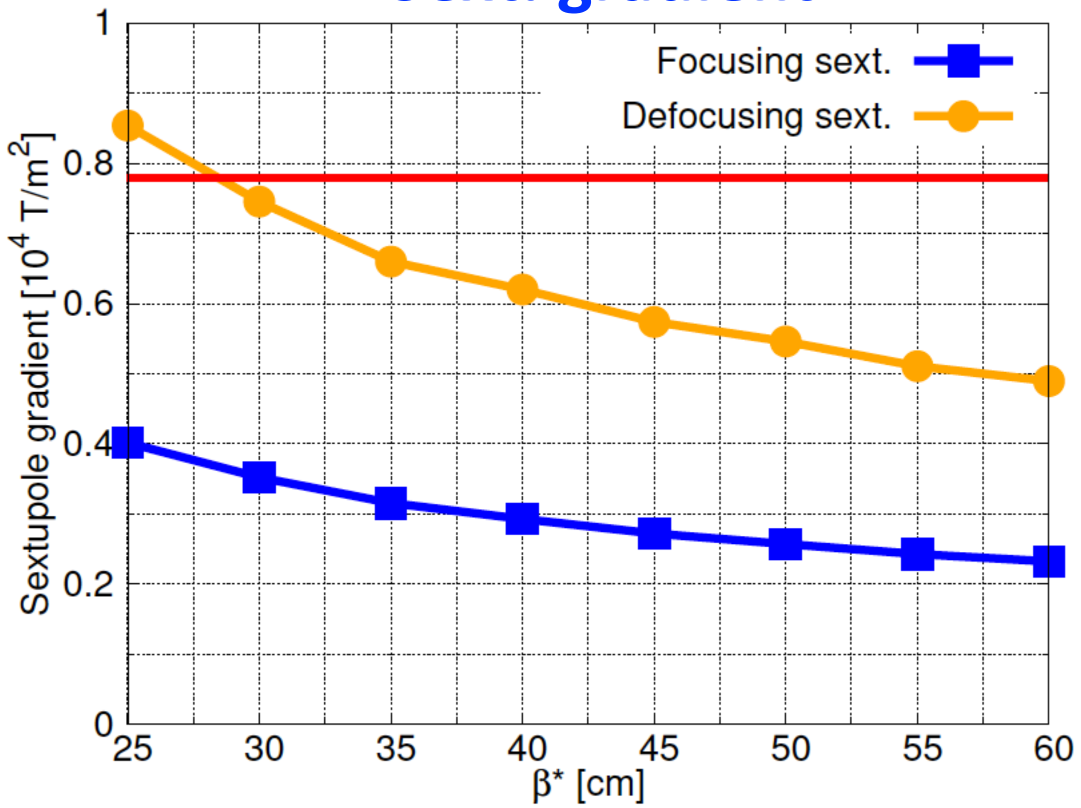
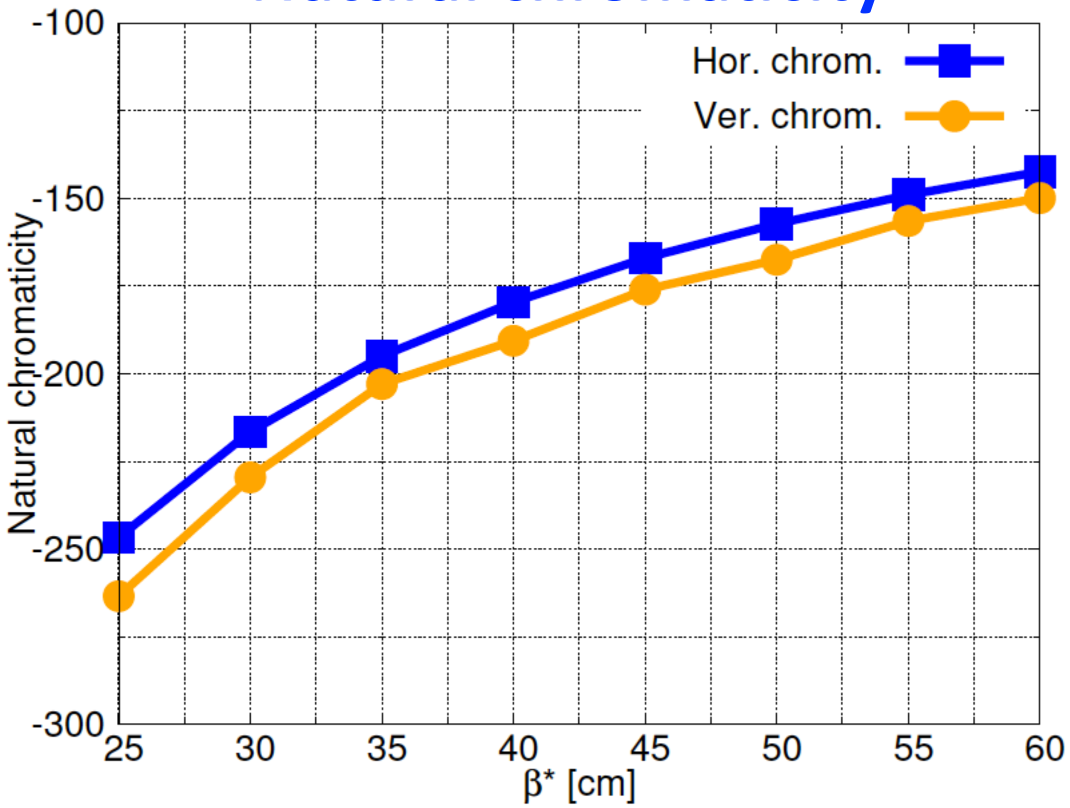
  - * **18x90 arcs, β^*=25 cm at IP 1&5**
- **Dipoles/quadrupoles below FCC specifications**
- **Sextupoles exceed FCC specification**
  - * **Natural chrom.: $(-69.8, -71.1)_{injection}$ => $(-246.6, -263.4)_{collision}$**
  - * **Solutions: Longer sext./Smaller μ_c per cell/Larger β^***

Sext. gradient



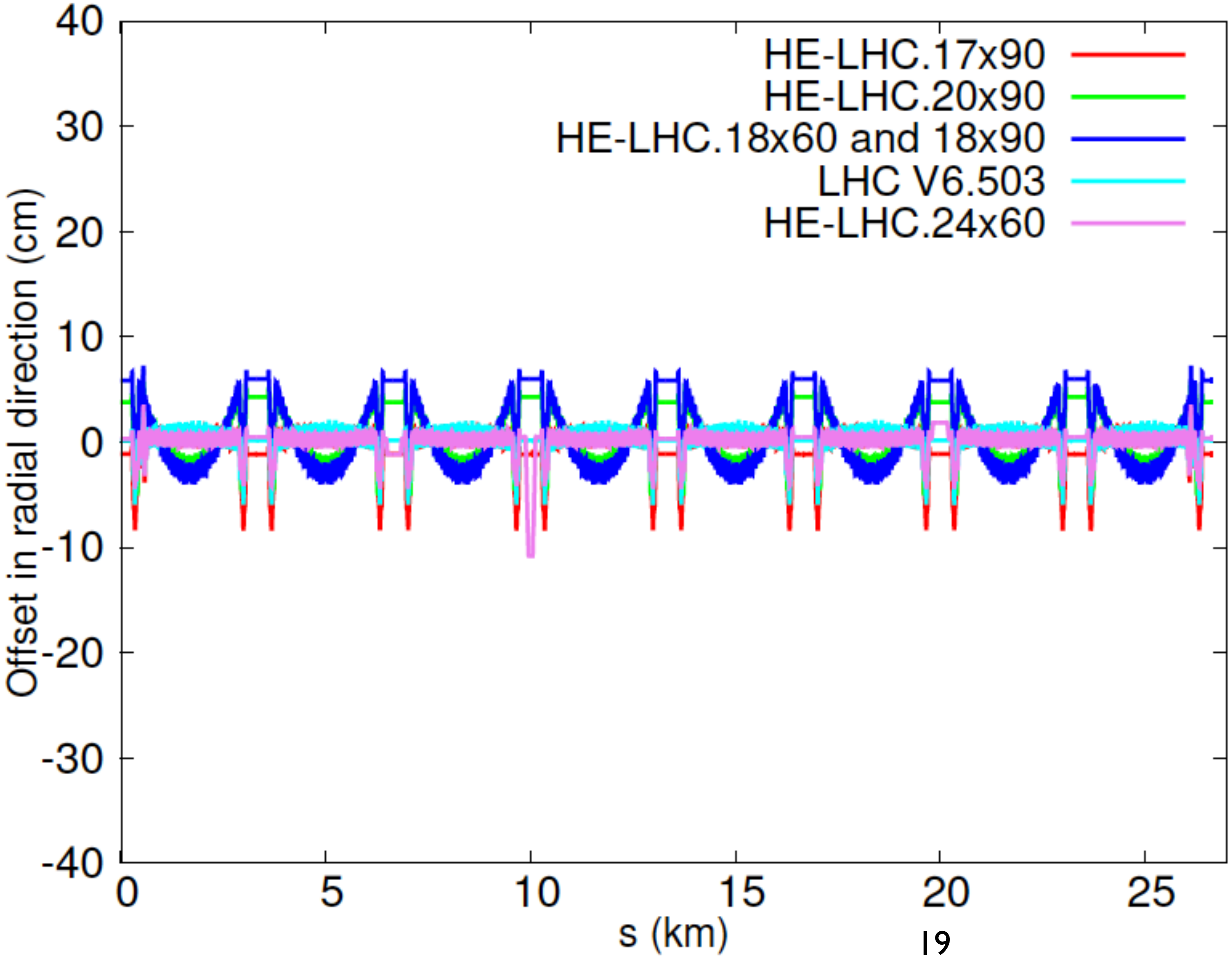
Natural chromaticity



3. Ring geometry

➤ **Compare the survey of LEP and (HE-)LHC**

- Comparison of “average” ring
- Use similar strategy as in LHC for geometry optimization by T. Risselada



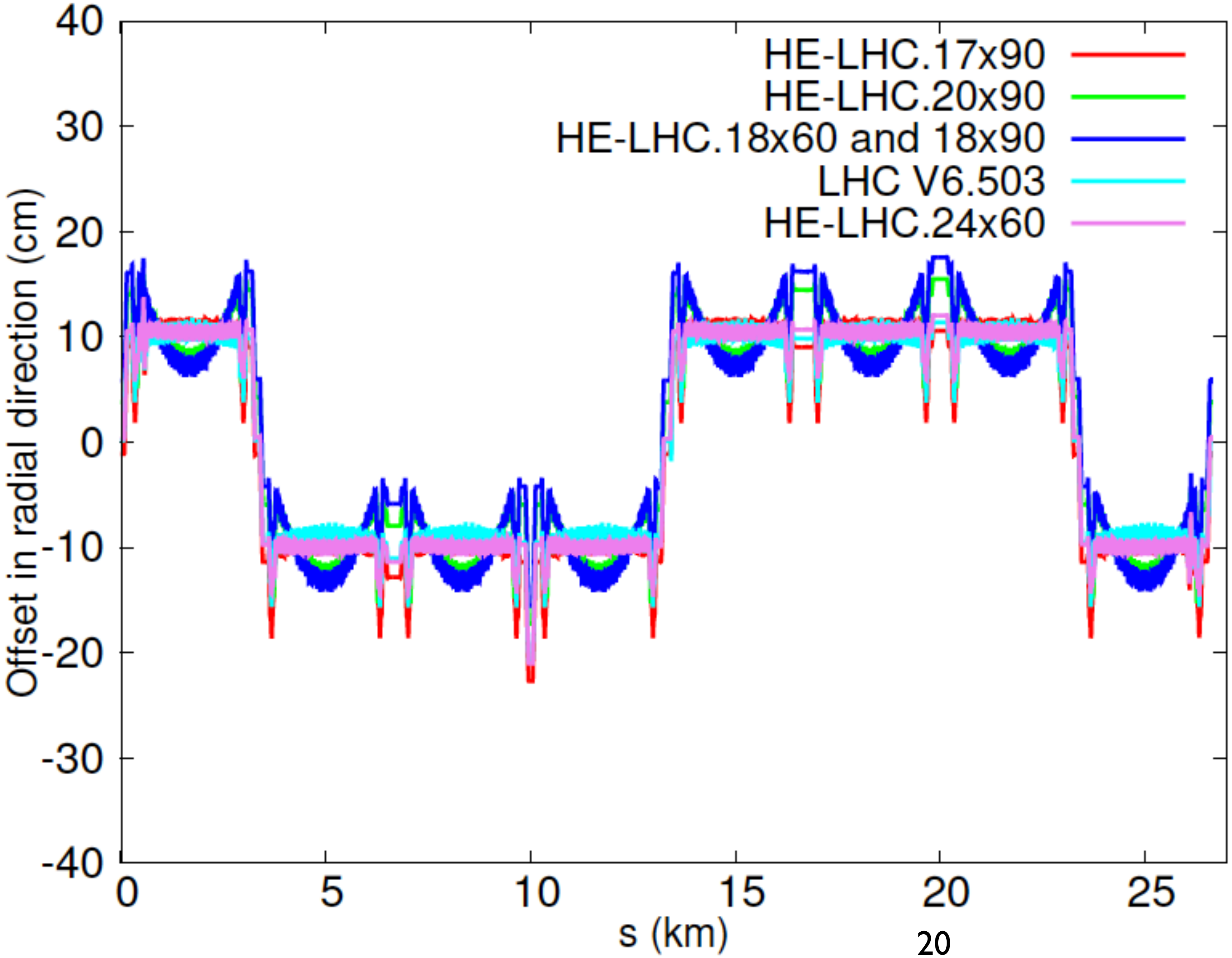
NOTE (T.R.):

1) Maximum offset in radial direction: <~11cm comparing to LEP survey
2) Good ring geometry for all candidates

3. Ring geometry

➤ Compare the survey of LEP and (HE-)LHC

- Ring separation at arcs: 204 mm
- The effort of geometry optimization was the price to pay for using the same main bends in the arcs and in the dispersion suppressors.



NOTE (T.R.):

1) **Maximum offset in radial direction: <~11cm comparing to LEP survey**
2) **Good ring geometry for all candidates**

4. Physical aperture

➤ Estimate of physical aperture using "1-D" model

- Ref. J.B. Jeanneret and T. Risselada, LHC Project Note 66, 1996
- n1 method: Indicate the geometrical acceptance
- Assumed parameters:
  * Tolerances in hardware misalignment and orbit distortion: t_x=(2+1) mm
  * Tolerance for beta beating: k_β=1.05
  * Tolerance for dispersion distortion: f_{arc}=0.14
  * Momentum spread: δ_p=8.6*10^{-4}
  * Normalized emittance: ε_x=2.5 μm
  * Half beam screen width: L_x=15 mm(FCC-hh), 19 mm(scaled-LHC), 22 mm(LHC)

$$n1_x = \frac{L_x - t_x - (1 + f_{\mathrm{arc}})D_x\delta_p}{k_\beta \sigma_x}$$

$$\sigma_x = \sqrt{\beta_x \epsilon_x}$$

$$\sin(\Phi/2) = \frac{1}{4}\mathrm{K}_1\mathrm{L}_{\mathrm{cell}}$$

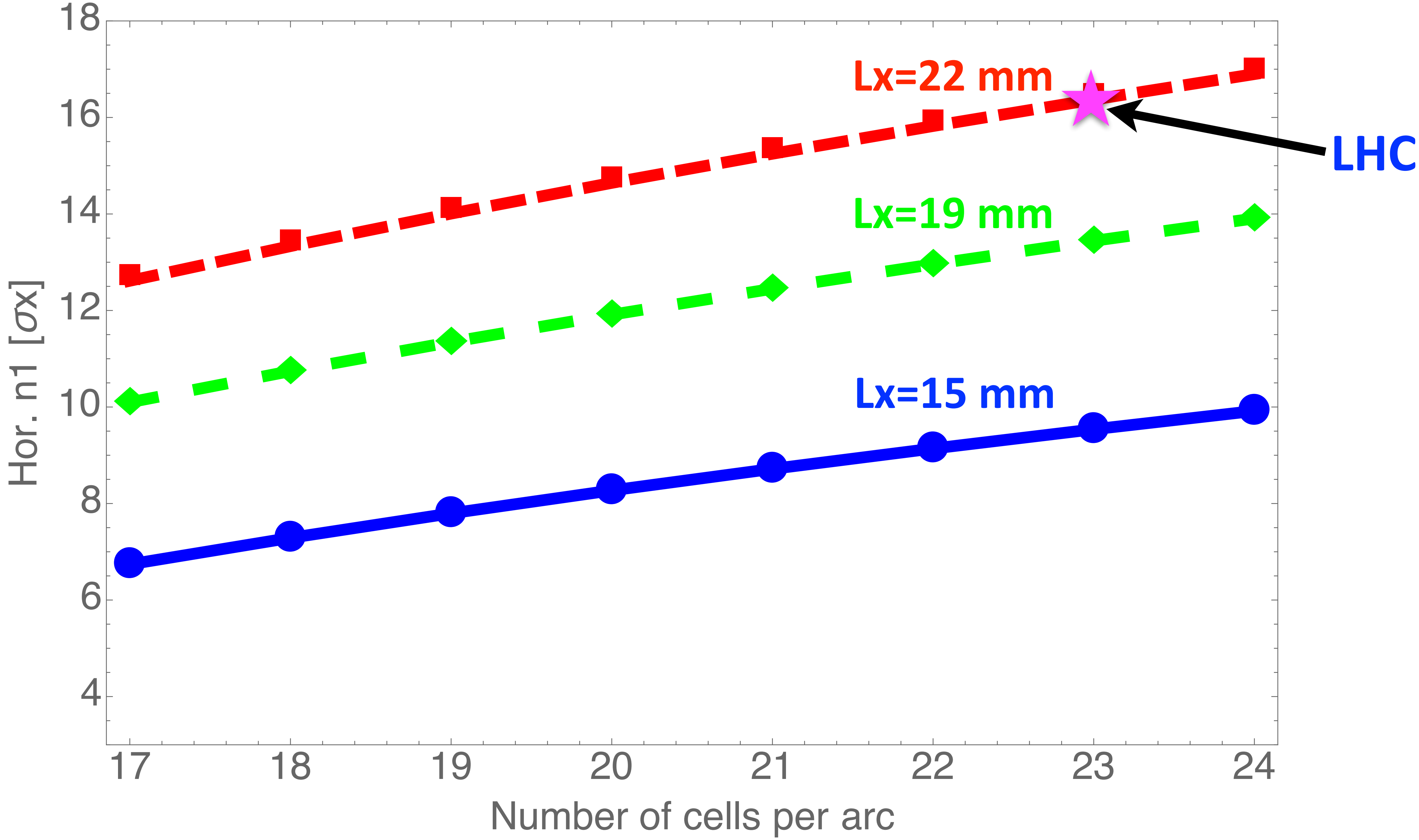
$$\beta_\pm = \frac{2\left(1 \pm \mathrm{K}_1\mathrm{L}_{\mathrm{cell}}/4\right)}{\mathrm{K}_1\sqrt{1-\left(\mathrm{K}_1\mathrm{L}_{\mathrm{cell}}/4\right)^2}}$$

$$\eta_\pm = \frac{4}{\rho\mathrm{K}_1^2}\left(1 \pm \mathrm{K}_1\mathrm{L}_{\mathrm{cell}}/8\right)$$

4. Physical aperture

➤ n1 at QF for N-cell arcs at E_{inj}=450 GeV

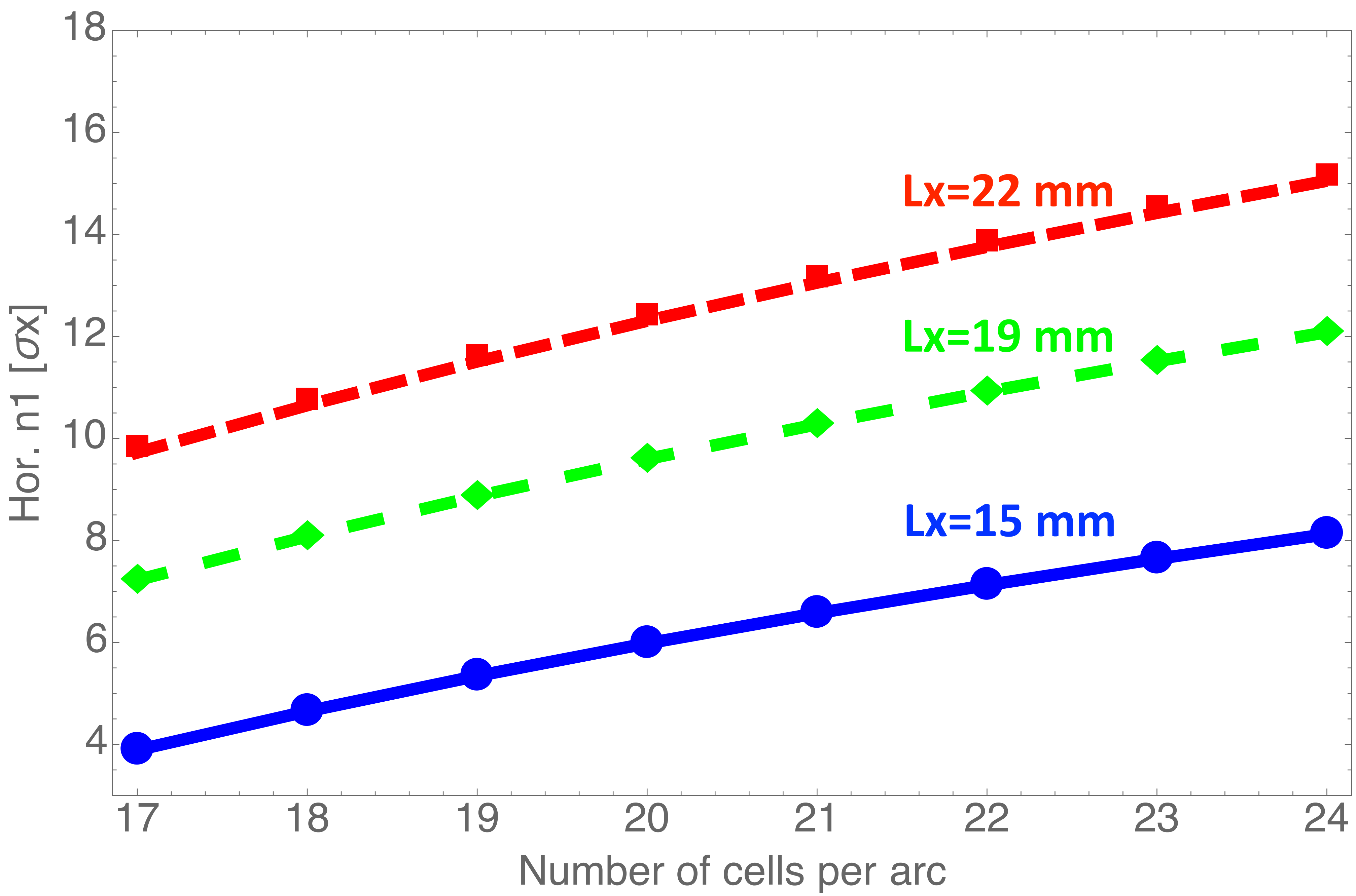
- Phase advance per cell: 90 deg [Assume fixed arc length: 2460 m]
- t_x=(2+1) mm, f_{arc}=0.14, δ_p=8.6*10^{-4}, ε_x=2.5 μm, k_β=1.05



4. Physical aperture

➤ n1 at QF for N-cell arcs at E_{inj}=450 GeV

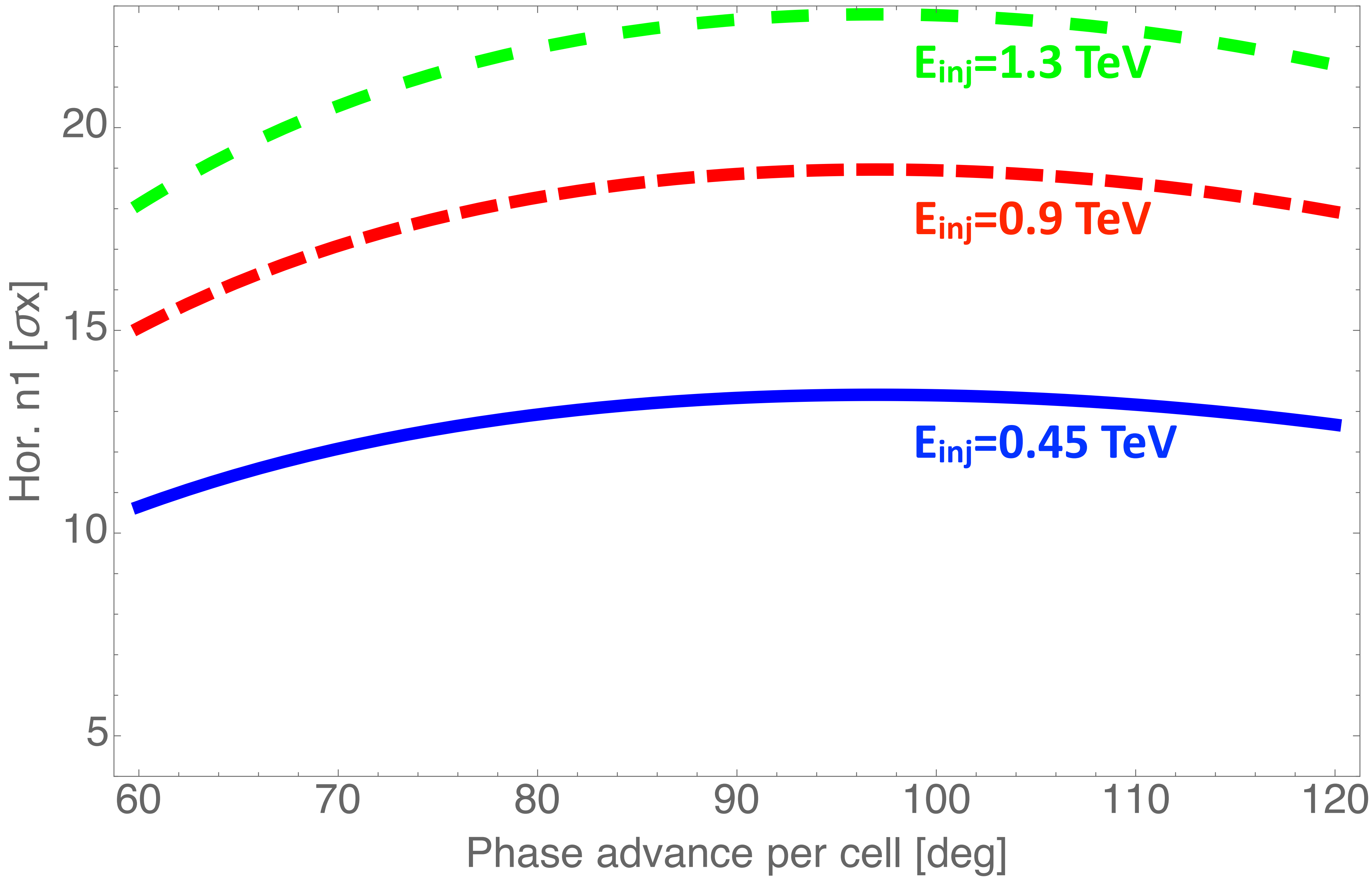
- Phase advance per cell: 60 deg [Assume fixed arc length: 2460 m]
- t_x=(2+1) mm, f_{arc}=0.14, δ_p=8.6*10^{-4}, ε_x=2.5 μm, k_β=1.05



4. Physical aperture

➤ n1 for 18-cell arcs with LHC beam screen: L_x=22 mm

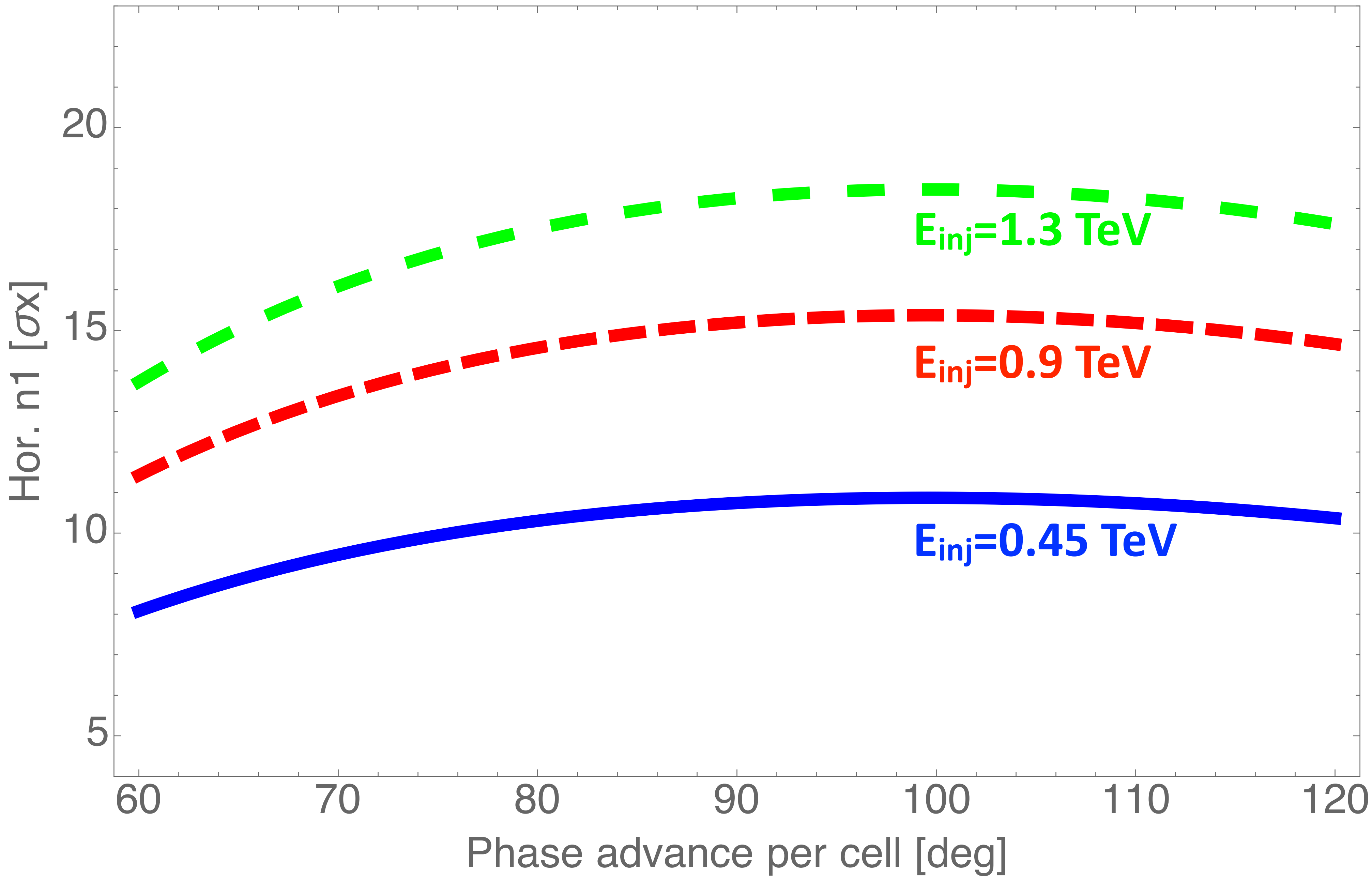
- n1=13.3/18.9/22.7 @E_{inj}=0.45/0.9/1.3 TeV @90 deg/cell
- t_x=(2+1) mm, f_{arc}=0.14, δ_p=8.6*10^{-4}, ε_x=2.5 μm, k_β=1.05



4. Physical aperture

➤ **n1 for 18-cell arcs with scaled-LHC screen: L_x=19 mm**

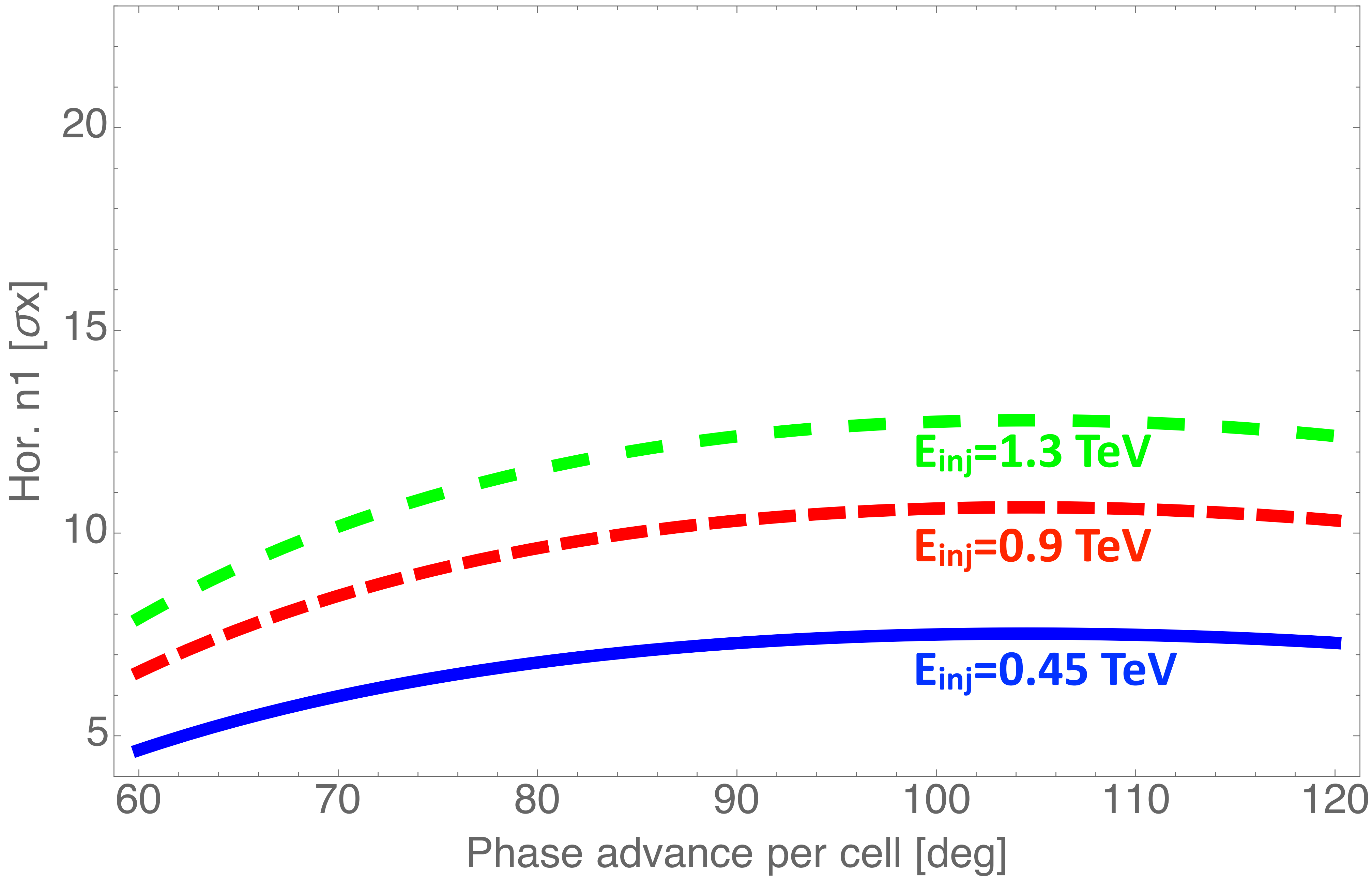
- **n1=10.7/15.2/18.3 @E_{inj}=0.45/0.9/1.3 TeV @90 deg/cell**
- **t_x=(2+1) mm, f_{arc}=0.14, δ_p=8.6*10^{-4}, ε_x=2.5 µm, k_β=1.05**



4. Physical aperture

➤ **n1 for 18-cell arcs with FCC-hh beam screen: L_x=15 mm**

- **n1=7.3/10.3/12.4 @E_{inj}=0.45/0.9/1.3 TeV @90 deg/cell**
- **t_x=(2+1) mm, f_{arc}=0.14, δ_p=8.6*10^{-4}, ε_x=2.5 µm, k_β=1.05**



5. Summary

➤ **Arc optics**

- Reduce dipole field by increasing filling factor
- Reduce quad and sext. strengths by increasing cell length and/or reduce phase advance per cell
- 18x90 arc scheme chosen as the baseline with respect to overall performance

➤ **Ring geometry**

- Geometry is not a limit in choosing arc scheme
- Further refinement can be done but should not change beam dynamics

➤ **Physical aperture**

- Can be a concern when reducing number of arc cells
- Increasing injection beam energy and/or reducing beam emittance is preferred in the current baseline design (18x90)