Optics Development for HE-LHC

Y. Nosochkov, Y. Cai (SLAC)
D. Zhou (KEK)
M. Giovannozzi, T. Risselada, E. Todesco, F. Zimmermann (CERN)

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Outline

- Introduction
- Simplified model of injection lattice with basic IRs without dipoles
  - Three models with 60° and 90° arc cells
- Injection lattice with 60° arcs and realistic IR layout
- Dynamic aperture
- Impact of systematic dipole field errors
- Conclusion and outlook

Introduction

HE-LHC: 26.659 km ring fitting LHC tunnel, but higher collision beam energy → 13.5 TeV

❑ Requires stronger magnets

- Present LHC magnets → 8.33 T dipole, 223 T/m arc quadrupole, 4430 T/m^2 sextupole, 56 mm aperture
- For HE-LHC → assume "baseline" FCC magnet technology: 16 T dipole, 400 T/m quadrupole, 7800 T/m^2 sextupole, 50 mm aperture
- Dipole field must increase with energy to fit the ring → ~16 T
- Scaling LHC optics to 13.5 TeV: arc quadrupoles would slightly exceed 400 T/m; sextupoles at 7800 T/m^2 may be limiting collision β^* (M.P. Crouch)

➢ Study lattices with reduced quadrupole and sextupole strengths

❑ Field quality of dipoles for the HE-LHC energy range is not yet defined → assume pessimistic scenario with larger errors, particularly at injection energy → affects dynamic aperture, depends on injection energy (1.3 TeV proposed for HE-LHC)

➢ Design lattice with reduced sensitivity to field errors

❑ This study:

➢ Investigate lattice designs having
  - Low quadrupole and sextupole strengths
  - Reduced sensitivity to field errors

➢ As a first step, study injection type lattice (expected worse field quality than at collision energy)

➢ Focus on arcs design; not yet a detail IR study

➢ Use a simplified IR model for general study; verify one model with a realistic IR optics based on SLHCV3.1a layout

➢ Compare with LHC lattice layout V6.503

Proposal – part 1

Reduce arc FODO cell phase advance μ and / or increase cell length L_c

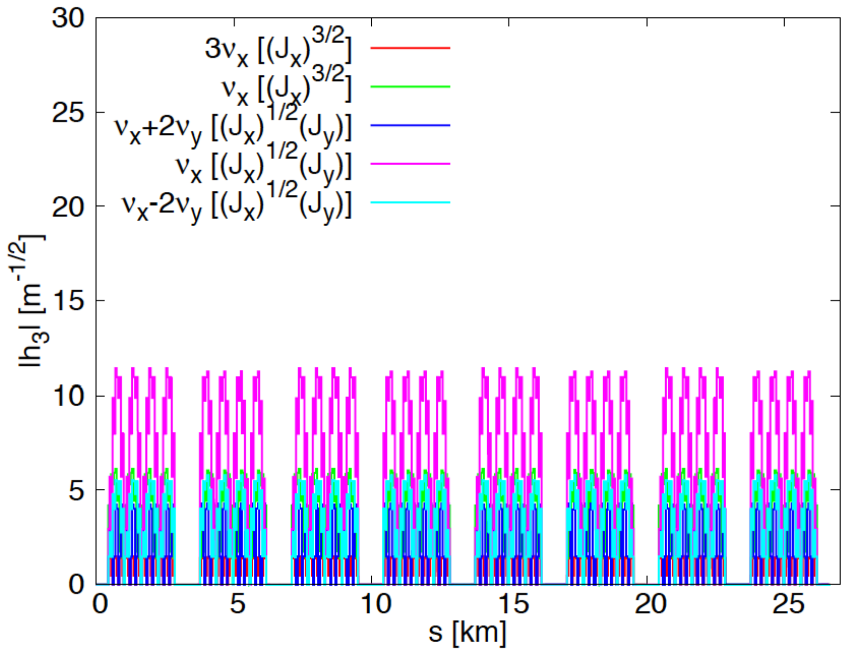
90 deg → 60 deg	Longer cell L_c
Weaker quads → factor of $\sqrt{2}$ (~sin(μ/2))	Weaker quads ~$1/L_c$
Weaker sextupoles → factor of 3 (for arcs correction)	Weaker sextupoles ~$1/L_c^3$
Lower cell chromaticity → factor of $\sqrt{3}$ (~tan(μ/2))	Same cell chromaticity
Similar peak β-functions	Larger peak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

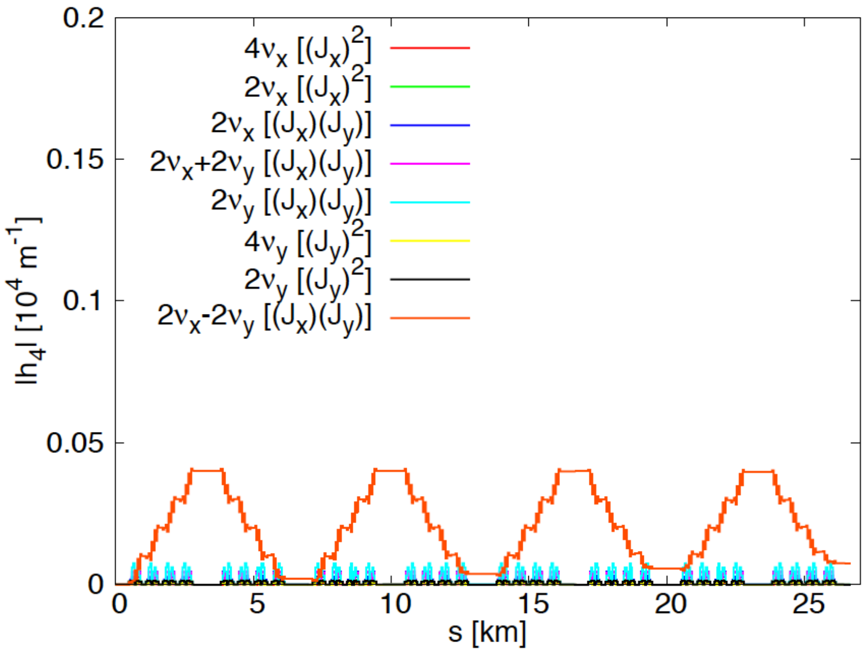
Proposal – part 2

Design arc lattice with reduced sensitivity to systematic non-linear field

- Choose cell phase advance and number of cells N_c per arc such that $N_c\mu_c = 2\pi k$
  - ➢ μ_c = 60 deg → N_c = 24, 18, … ; μ_c = 90 deg → N_c =24, 20, …
- Cancellation of many non-linear resonances from systematic non-linear field in periodic arc (*A. Verdier, PAC'99; Y. Cai, NIM, A645:168–174, 2011*)

➢ Potential improvement of dynamic aperture





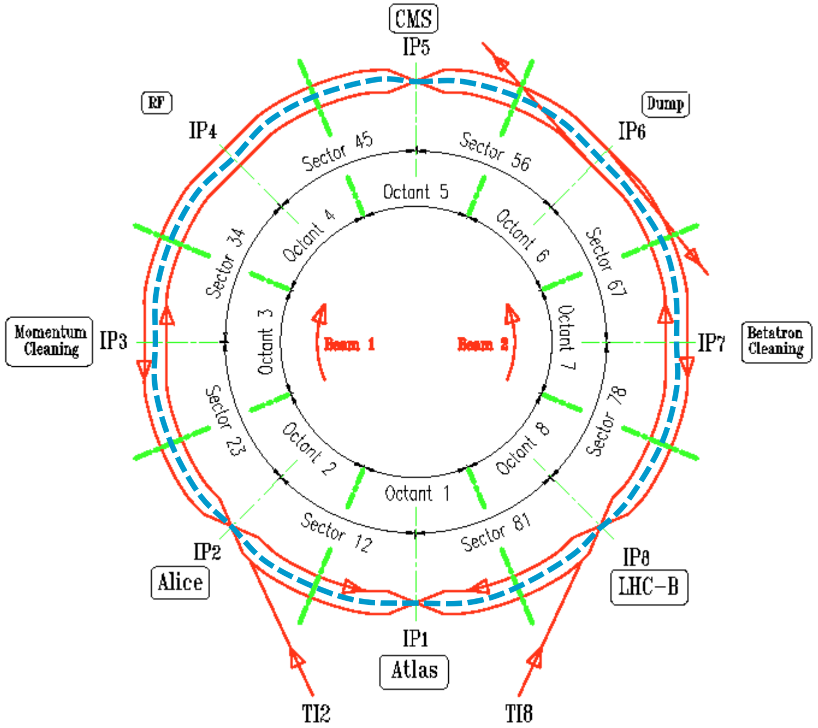
3rd and 4th order RDT from sextupoles in 60° arcs

Details in talk by D. Zhou

Lattice model

Simplified model for injection study

- C = 26658.8832 m – same as in LHC
- Same quad and sextupole lengths and same magnet-to-magnet distances as in LHC cell
- Same dispersion suppressors as in LHC
- Odd and even arcs with opposite quad polarity – same as in LHC
- Arc length = average of LHC longer & shorter arcs
- Simple IR straight with anti-symmetric optics without dipoles → 4-fold ring periodicity
- Same fractional tune (.28 / .31) as in LHC injection lattice
- Later → implement realistic IRs from SLHCV3.1a layout with separation dipoles and longer & shorter arcs



Schematic of ring layout:

- Red – two LHC rings with long & short arcs
- Blue dash – sketch of simple model with average length arcs and straight IRs (w/o dipoles)

Arc configurations studied

Nominal LHC arc has 23 cells with 90° phase advance

- L_C = 106.9 m, L_B = 14.3 m, N_B = 6

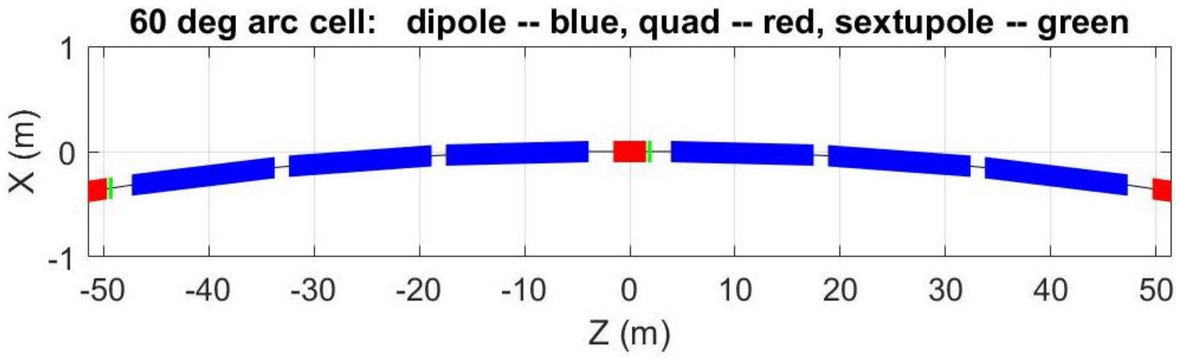
<u>Three model arcs:</u>

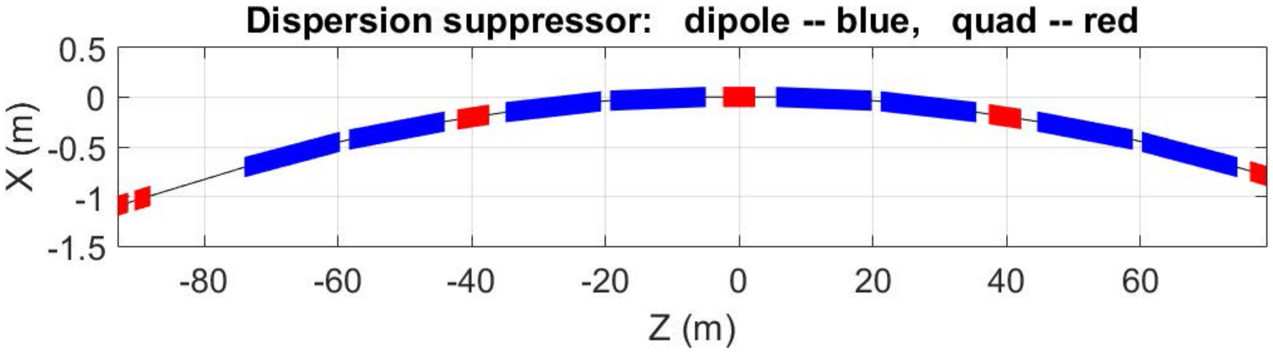
- 24 cells with 60° phase advance
  - L_C = 102.446 m, L_B = 13.56 m, N_B = 6, fill factor = 0.794
- 18 cells with 60° phase advance
  - L_C = 136.594 m, L_B = 14.10 m, N_B = 8, fill factor = 0.826 → lowest dipole field
- 20 cells with 90° phase advance
  - L_C = 122.935 m, L_B = 12.39 m, N_B = 8, fill factor = 0.806
- Dispersion suppressors in the simple model are kept identical to the LHC design (for geometry) with eight 14.3 m dipoles in DS → 2 types of dipoles (arc and DS)
- In a more realistic design (24 x 60° + SLHCV3.1a IRs), 2 types of dipoles are changed to one type dipole in the arc and DS, and geometry is rematched

Geometry

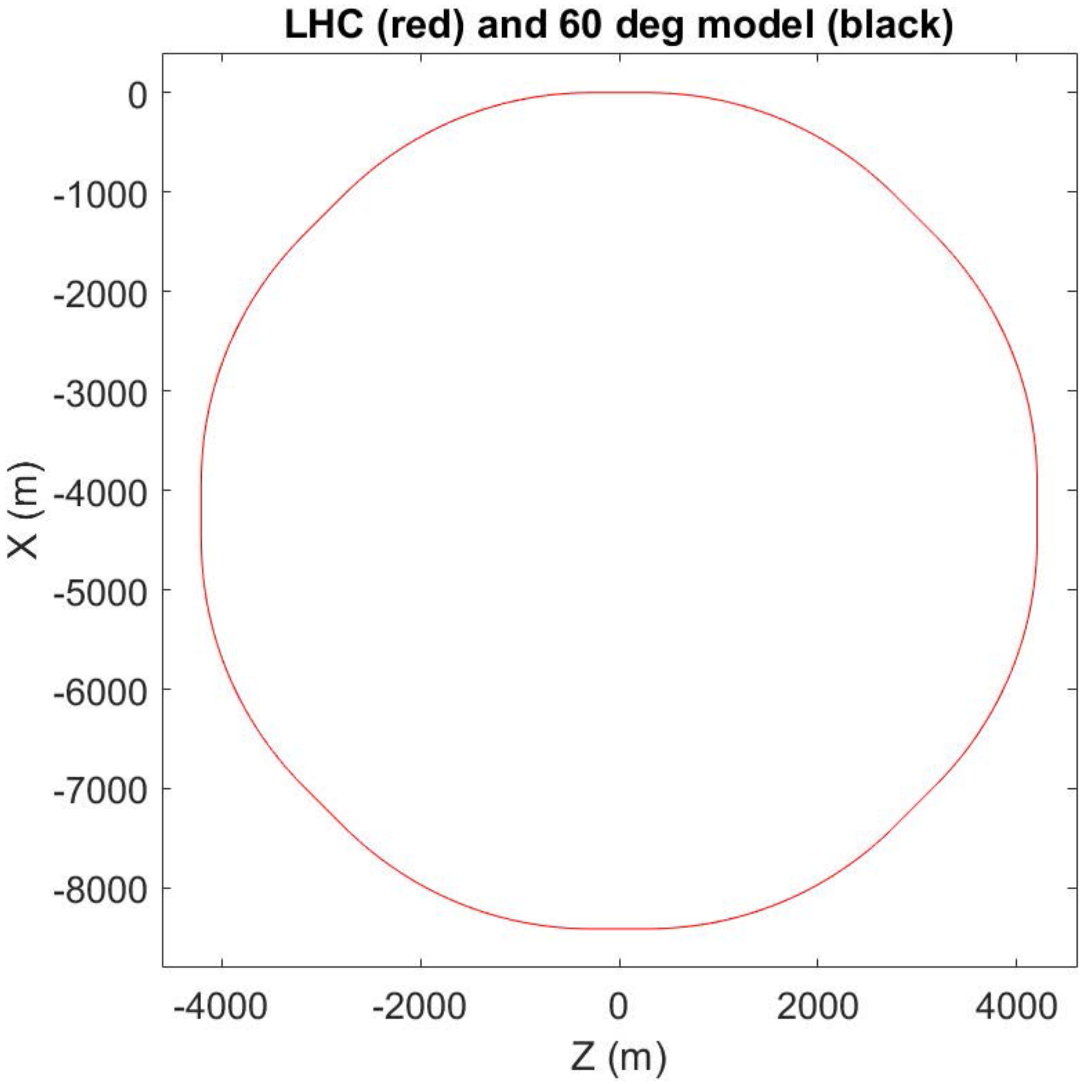
Geometry of the model ring is matched reasonably close to the LHC ring (some deviations of cm level)

One cell of 24-cell arc design





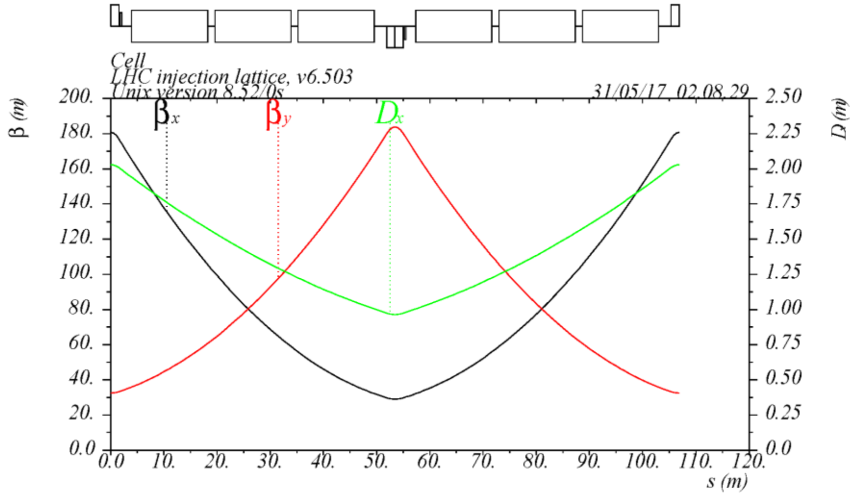
Dispersion suppressors are attached to either F or D arc quadrupole → two types of optics match



Arc cells: LHC and 3 models

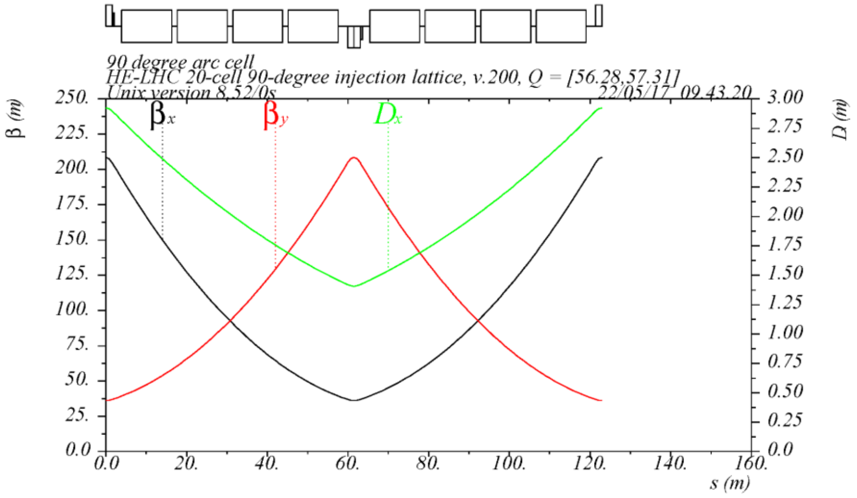
LHC V6.503
23 x 90° arc
L_c = 106.9 m

$\beta_{\pm}$ = 184 / 29.1 m, $\eta_{\pm}$ = 2.03 / 0.96 m



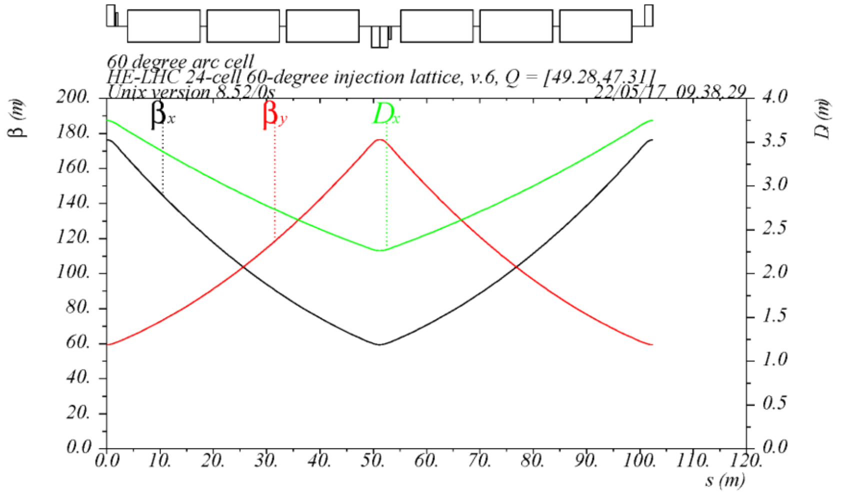
Model
20 x 90° arc
L_c = 122.94 m

$\beta_{\pm}$ = 208.6 / 36.2 m, $\eta_{\pm}$ = 2.92 / 1.41 m



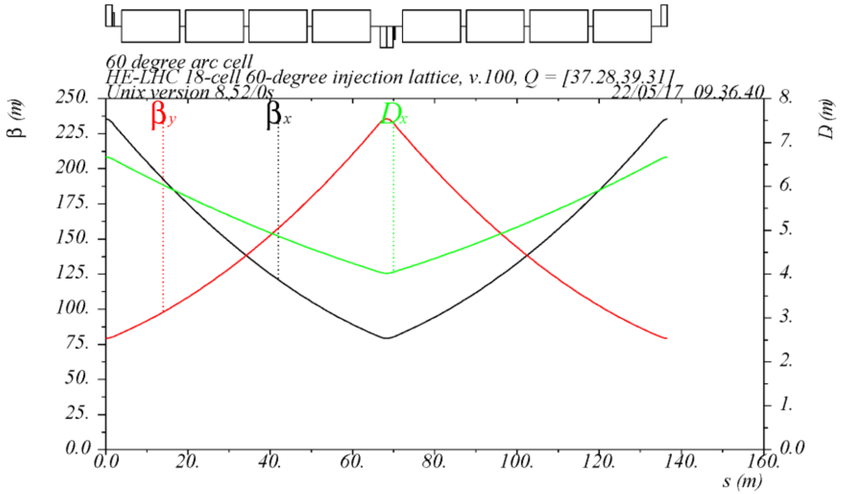
Model
24 x 60° arc
L_c = 102.45 m

$\beta_{\pm}$ = 176.5 / 59.5 m, $\eta_{\pm}$ = 3.75 / 2.26 m



Model
18 x 60° arc
L_c = 136.59 m

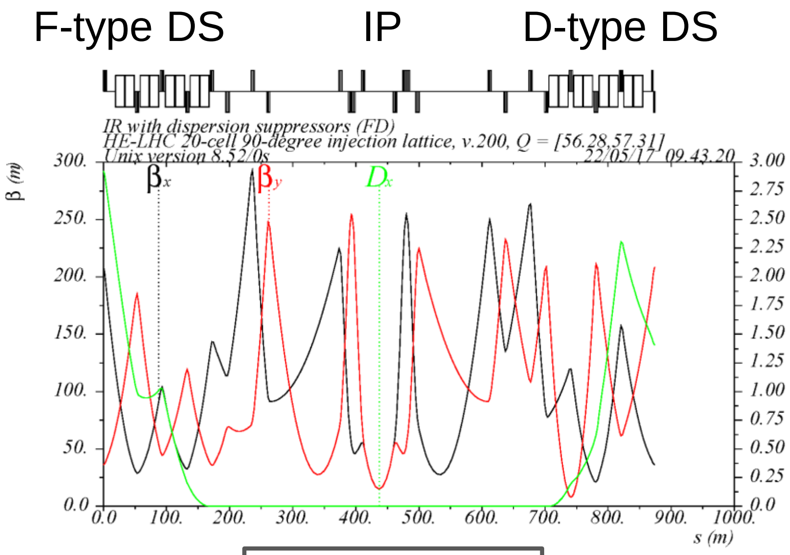
$\beta_{\pm}$ = 235.6 / 79.2 m, $\eta_{\pm}$ = 6.67 / 4.02 m



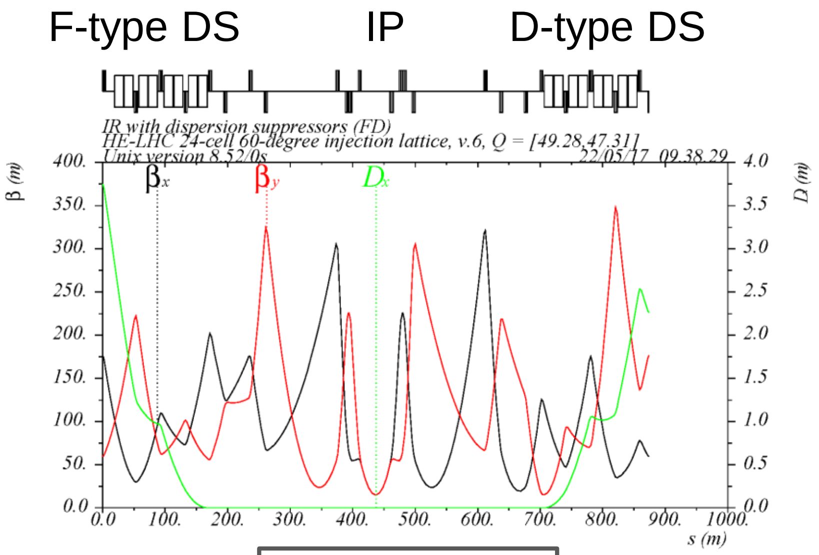
Large β & η →
For collimation
>1 TeV injection energy
(F. Zimmermann)

IR straight and dispersion suppressors

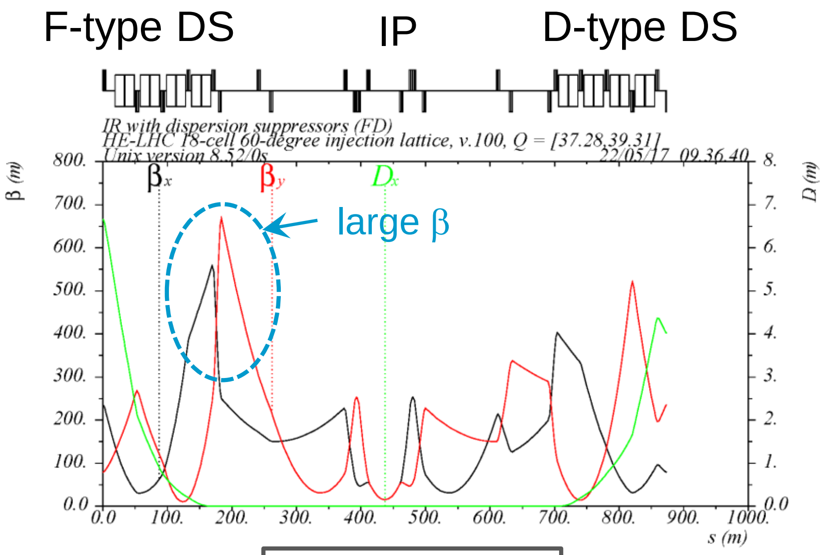
- LHC-type dispersion suppressor made of 2 FODO cells with eight 14.3 m dipoles
- Two types of DS optics (attached to F or D arc quad); IR dispersion is exactly cancelled
- Simple IR model with IP triplets and matching quads; no IR dipoles; small injection-type β
- ➢ Findings:
  - LHC-type DS matches better to 90° arcs, less optimal for 60° arcs, especially for a longer cell (18 x 60°); the match could be improved by adjustment of the adjacent 1-2 arc quads (small adjustments are preferred to minimize impact on non-linear field cancellation properties in the arc)



IR + 2 DS
20 x 90° arc



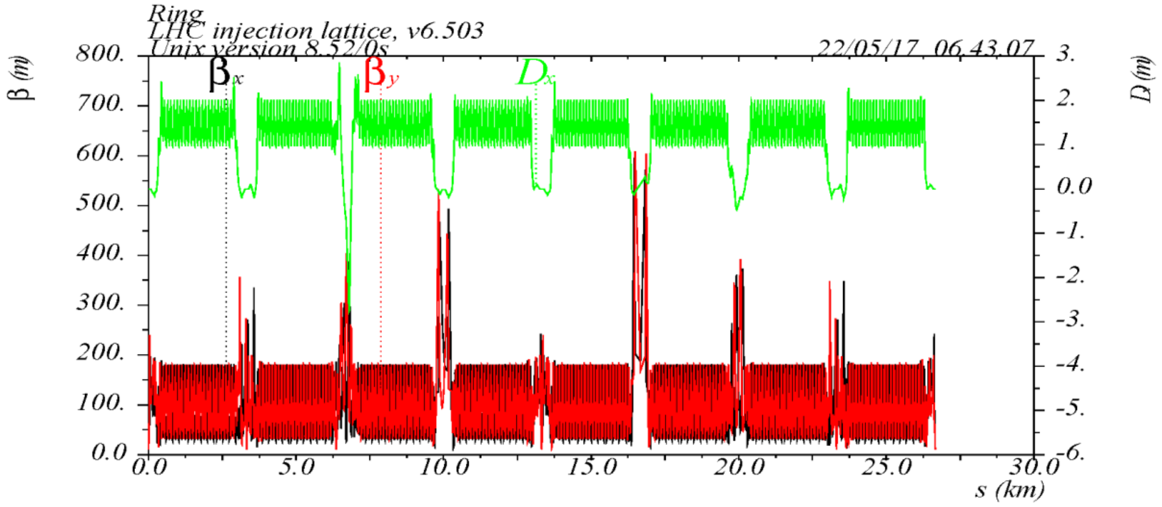
IR + 2 DS
24 x 60° arc



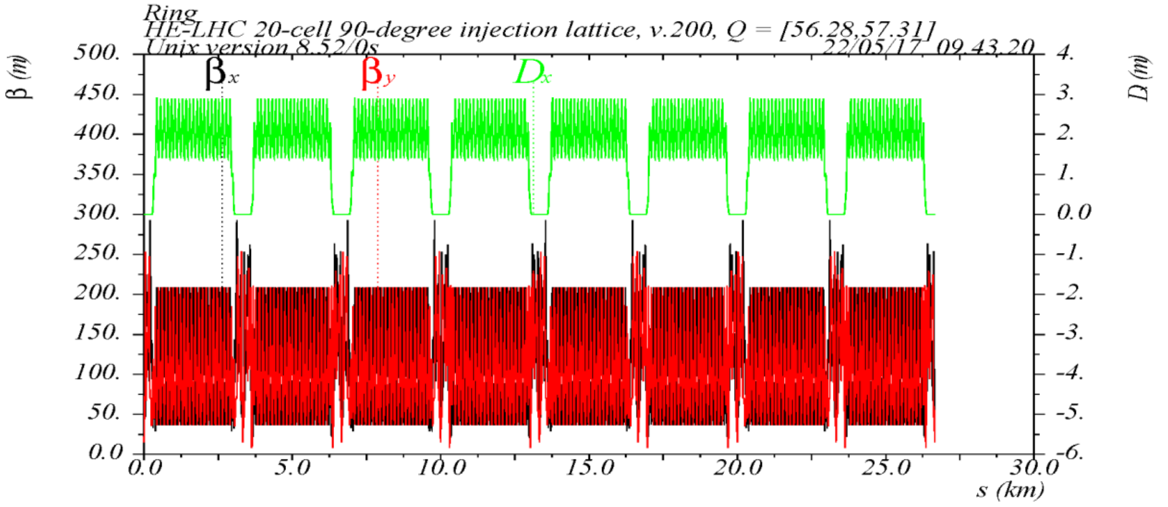
IR + 2 DS
18 x 60° arc

Complete ring: LHC and 3 models

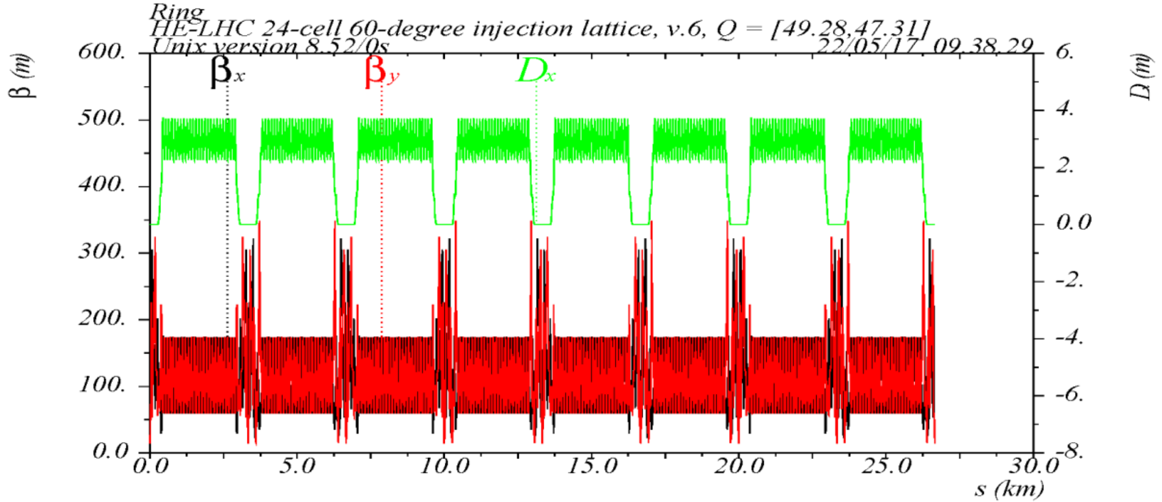
LHC V6.503, 23 x 90° arc, Q = 64.28, 59.31



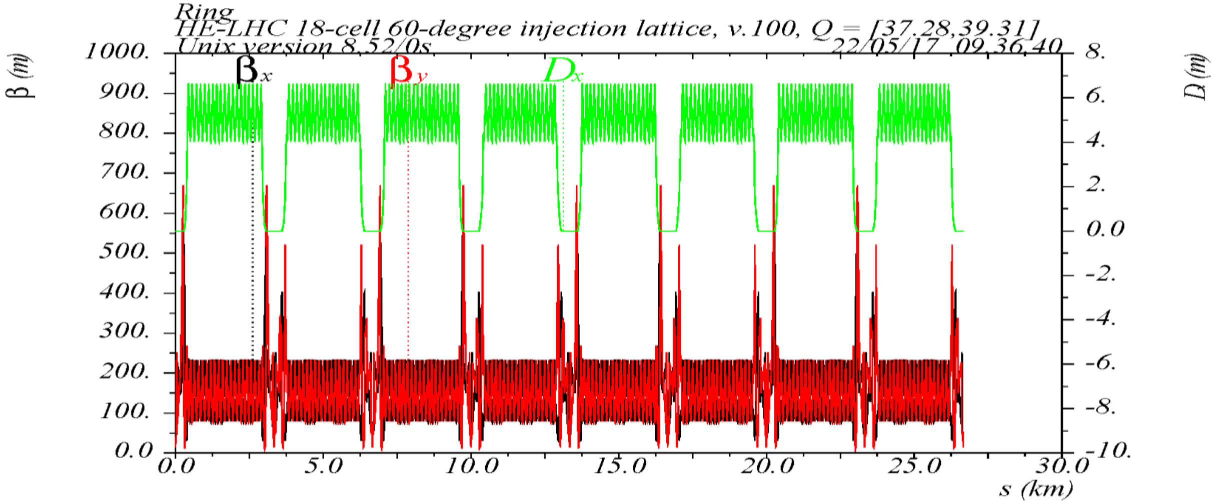
Model, 20 x 90° arc, Q = 56.28, 57.31



Model, 24 x 60° arc, Q = 49.28, 47.31

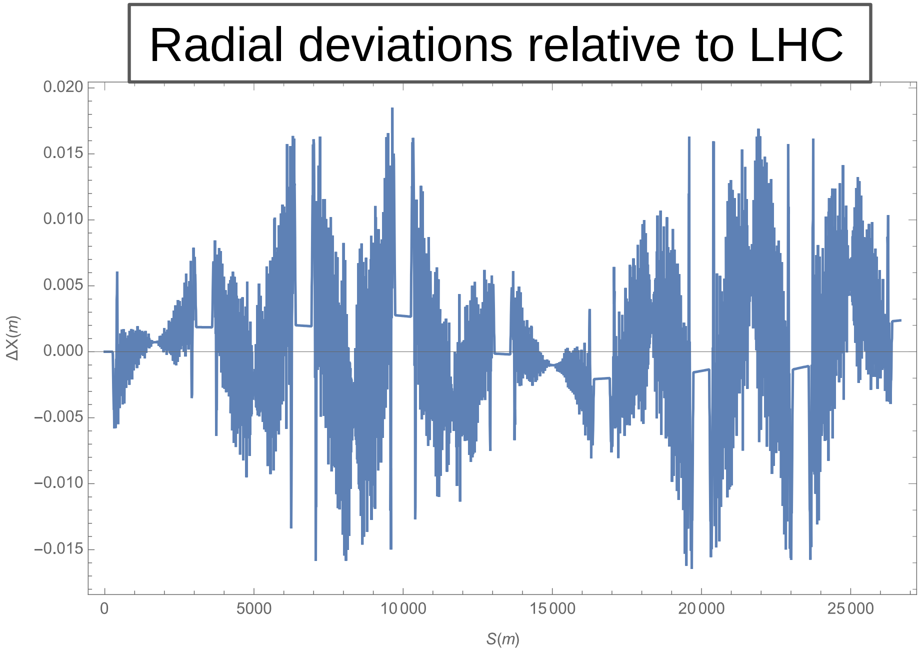


Model, 18 x 60° arc, Q = 37.28, 39.31



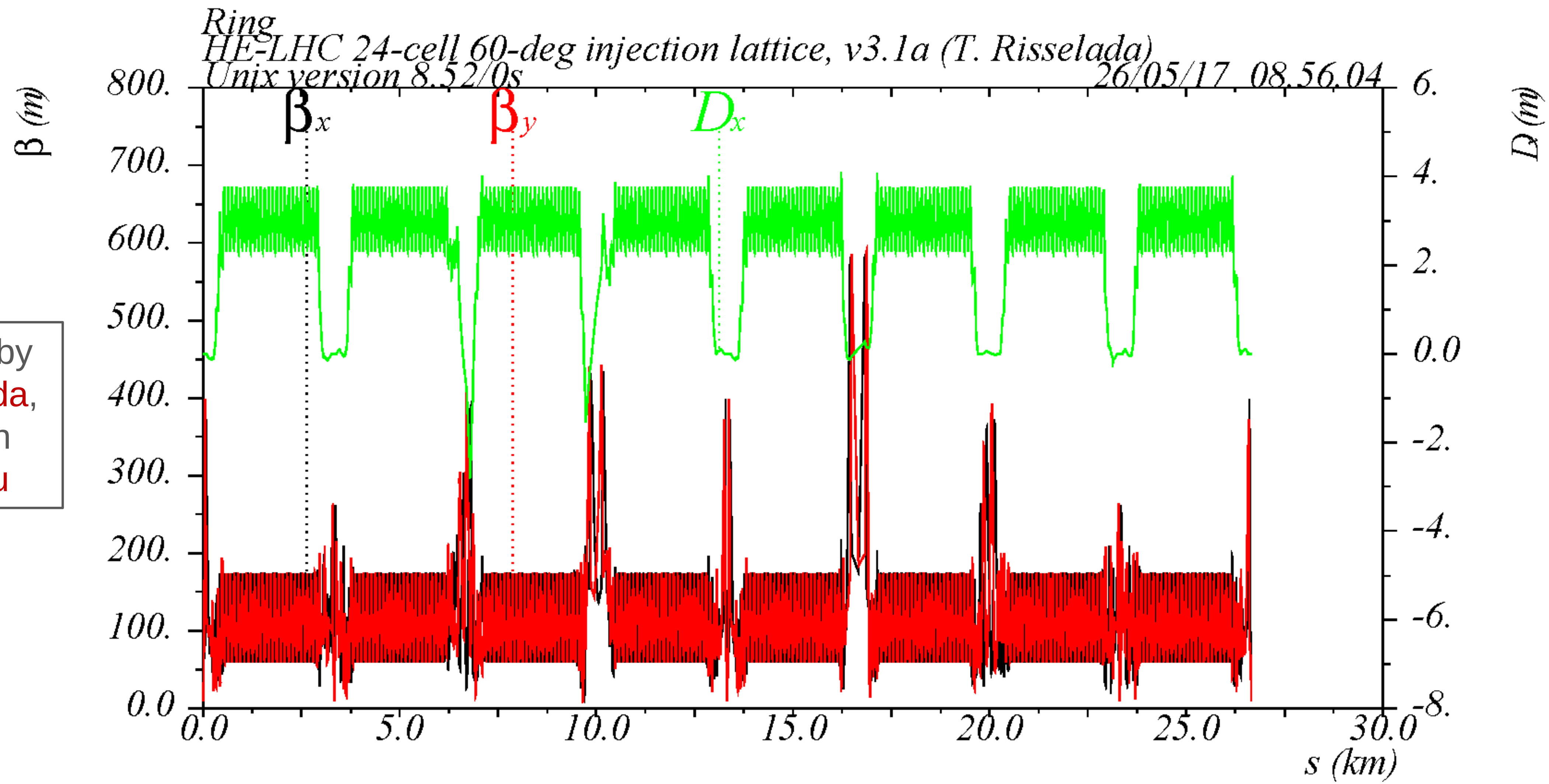
24 x 60° model + realistic IRs (T. Risselada)

- Arcs with 24 x 60° cells are combined with IRs from SLHCV3.1a layout (differs from LHC only in IR1, 5) as suggested by S. Fartoukh
- Separation dipoles included for a realistic layout for the clock-wise beam
- One type of dipole (13.56 m) is used in the arcs and DS
- Small adjustments to length of arc cell and DS for geometry match (radial deviations within ~cm level compared to LHC)
- Improvement to optics match from arcs to DS to IR using 1-2 quad adjustments in the last arc cell
- Strong SC separation dipoles due to increased separation (250 mm used) and reduced distance (specifications per D. Shoerling):
  - 12 T D1, D2;   8T D3, D4 (IR4)
- 1.8 T for NC dipoles D3, D4 → preliminary layout of IR3, 7 → should be carefully reviewed



Complete ring with 24 x 60° arcs and SLHCV3.1a IRs

Optics files available at official repository /afs/cern.ch/eng/lhc/optics/HELHC



Designed by T. Risselada, tune match by D. Zhou

Injection lattice parameters at 13.5 TeV

	LHC V6.503 23 x 90 deg	Model 24 x 60 deg	Model 18 x 60 deg	Model 20 x 90 deg	SLHCV3.1a 24 x 60 deg
Cell length, m	106.90	102.45	136.59	122.94	102.89
Dipole length, m	14.3	13.56 (1)	14.1 (1)	12.39 (1)	13.56
Number of dipoles	1232	1280	1280	1424 (2)	1280
Dipole B, T	16.06	16.30 (1)	15.68 (1)	16.04 (1)	16.30
Cell quad B′, T/m	404.8	289.5	215.9	340.0	288.2
Sextupole B″, T/m^2 (3)	4883	2057	1103	3366	1891
Max/Min arc β, m	184 / 29	177 / 60	236 / 79	209 / 36	178 / 60
Max/Min arc η, m	2.03 / 0.96	3.75 / 2.26	6.67 / 4.02	2.92 / 1.41	3.78 / 2.28
Tune, x/y	64.28 / 59.31	49.28 / 47.31	37.28 / 39.31	56.28 / 57.31	46.28 / 45.31
Momentum compaction	3.22 10^{-4}	6.41 10^{-4}	1.13 10^{-3}	4.57 10^{-4}	6.50 10^{-4}
Natural chromaticity	-86 / -82	-63 / -63	-53 / -63	-78 / -80	-58 / -59

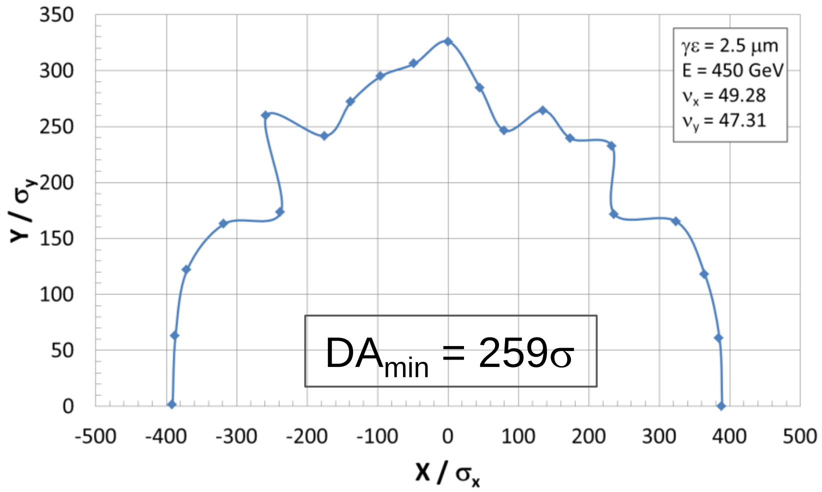
(1) Extrapolating to one type of dipole in arcs and DS (2) Assuming additional dipole in each DS in 20 x 90 deg model
(3) For injection optics chromaticity **FCC baseline target: 16 T dipole, 400 T/m quad, 7800 T/m^2 sextupole**

Dynamic aperture studies

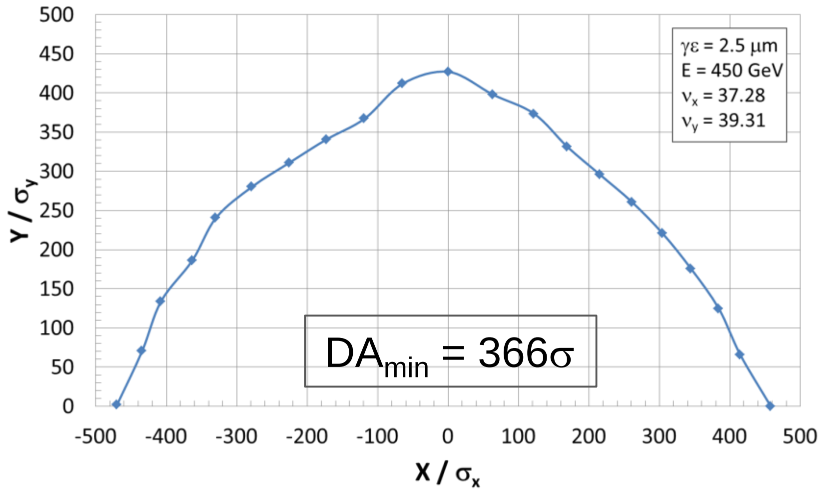
- Tracking using LEGO code (*Y. Cai, SLAC-PUB-7642,1997*)
- DA is calculated at IP (β = 15 m in model lattice)
- DA is shown in number of beam σ at 450 GeV
    - 1.7 times more sigma's at 1.3 TeV injection energy proposed for HE-LHC
- Normalized emittance = 2.5 μm-rad
- Chromaticity corrected to +3 using SF, SD arc sextupoles
- 21 angles in x-y space
- Nominally 1024 turns tracking, but also tested at 10^4 turns → 5-10% underestimate
- Initial dp/p = 7.5 10^{-4}

Dynamic aperture without errors

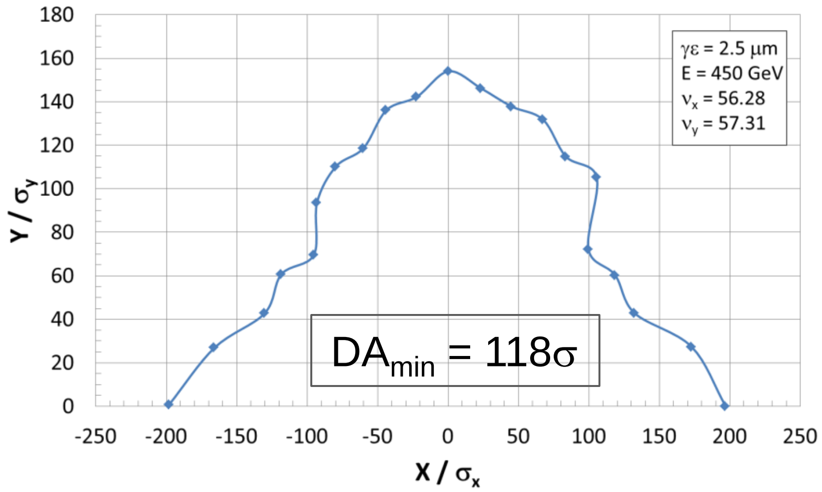
24 x 60-degree arc cells and basic IRs; no errors



18 x 60-degree arc cells and basic IRs; no errors



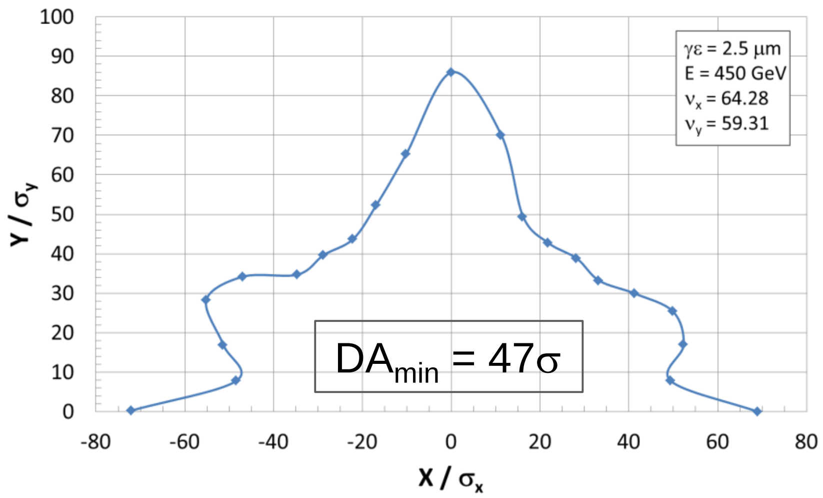
20 x 90-degree arc cells and basic IRs; no errors



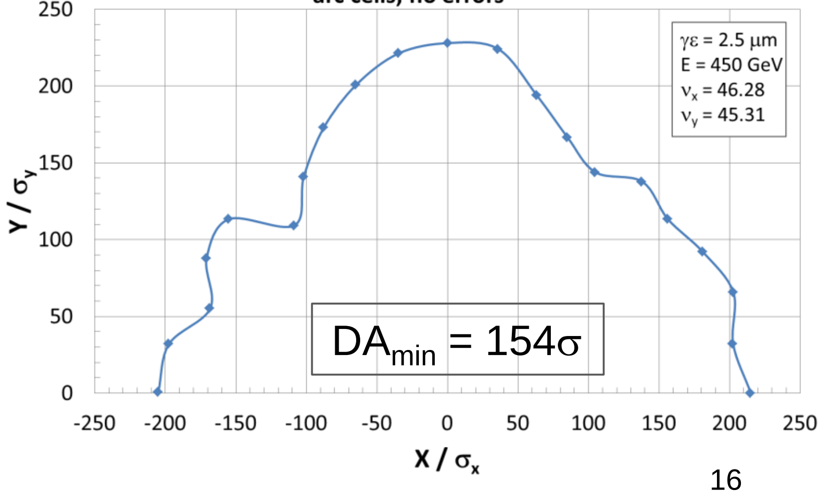
- Huge DA for model lattices due to built-in arc non-linear compensation (cancellation of sextupole effects), but also due to 4-fold periodicity
- Larger DA of SLHCV3.1a model compared to LHC V6.503, due to 60° arcs with weaker sextupoles, but arc compensation may not be perfect due to quad adjustments at arc ends

→ May not be a completely fair comparison, but indicates that non-linear field compensation works

LHC V6.503 injection lattice, 23 x 90-degree arc cells; no errors

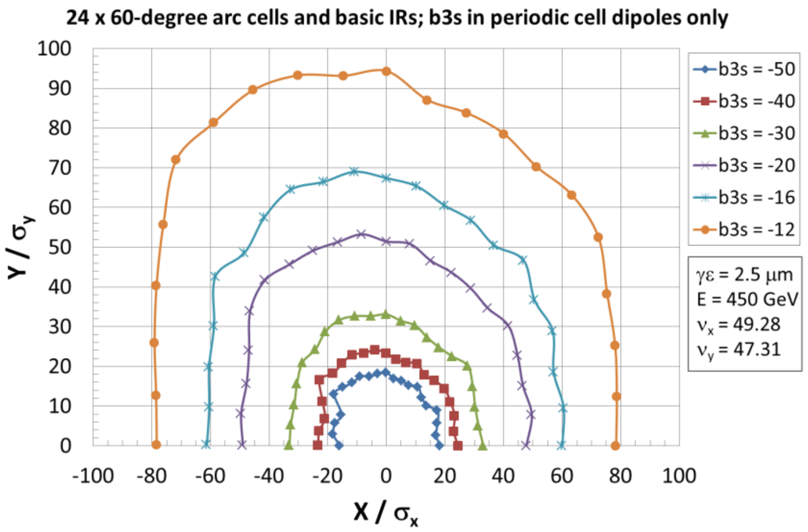


LHC V3.1a injection lattice modified to include 24 x 60-degree arc cells; no errors

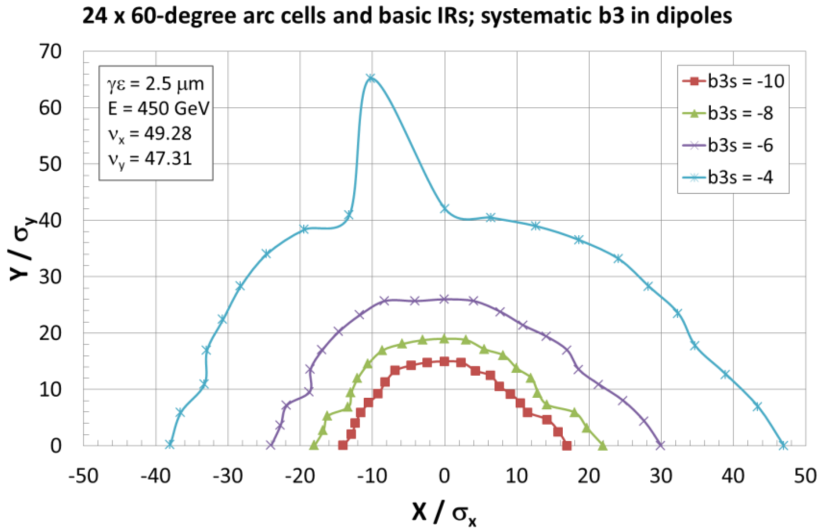


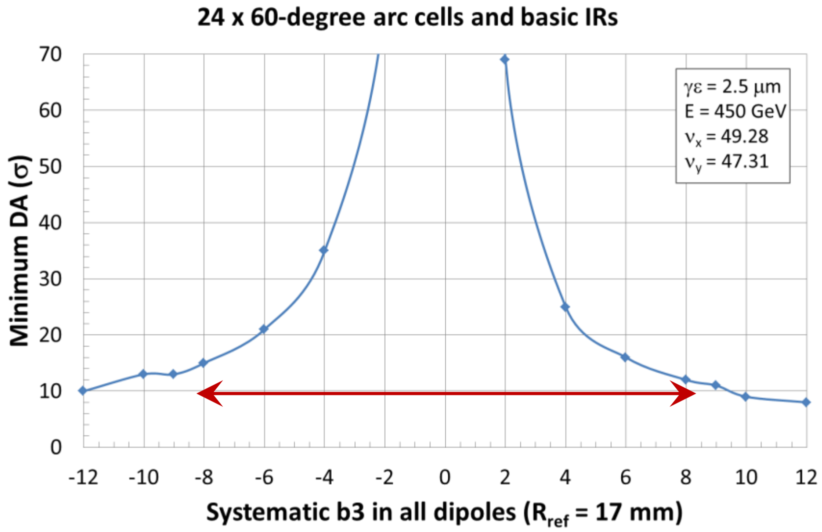
24 x 60 deg model with systematic b3s in dipoles

- Dipole FQ for HE-LHC is not yet defined. Estimates for FCC suggest b3s = 6, b5s = -1, b3r < 1, b5r < 0.1 for FCC injection (R_{ref} = 17 mm) (*E. Todesco, FCC Week 2016*)
- Observe very large acceptable b3s range (50 units) if b3s is only in periodic cell dipoles → confirms arc compensation properties
- If b3s is in both arc cells and DS dipoles, the range is ~8 units (but without other errors)
- Large chromaticity from b3s is corrected by arc sextupoles. Using dipole b3 correctors (as in LHC) may help improving the DA (the correctors not included in this study).



b3s in periodic cell dipoles only

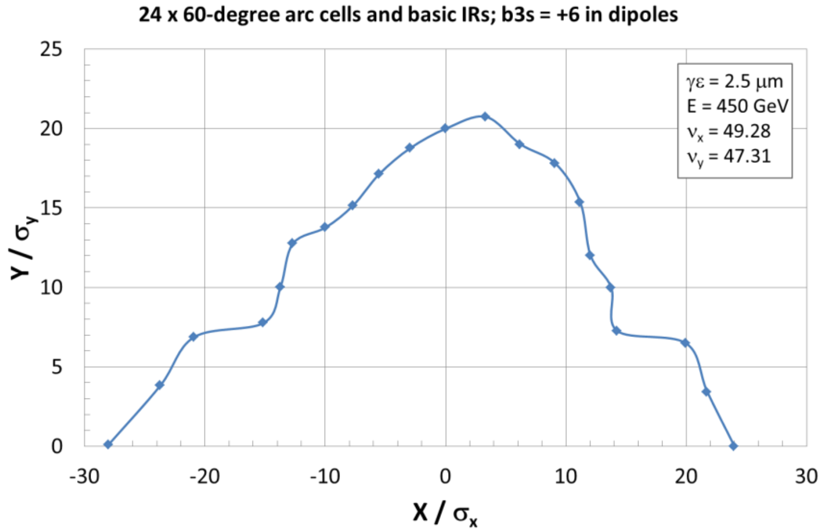


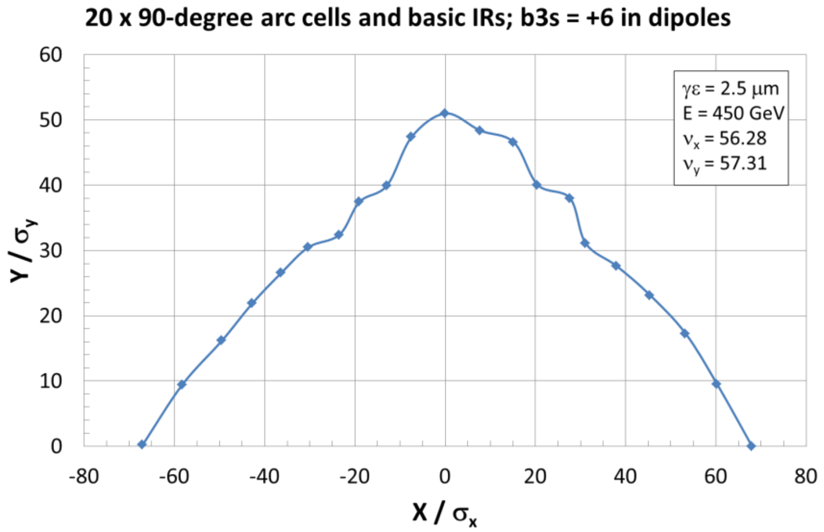


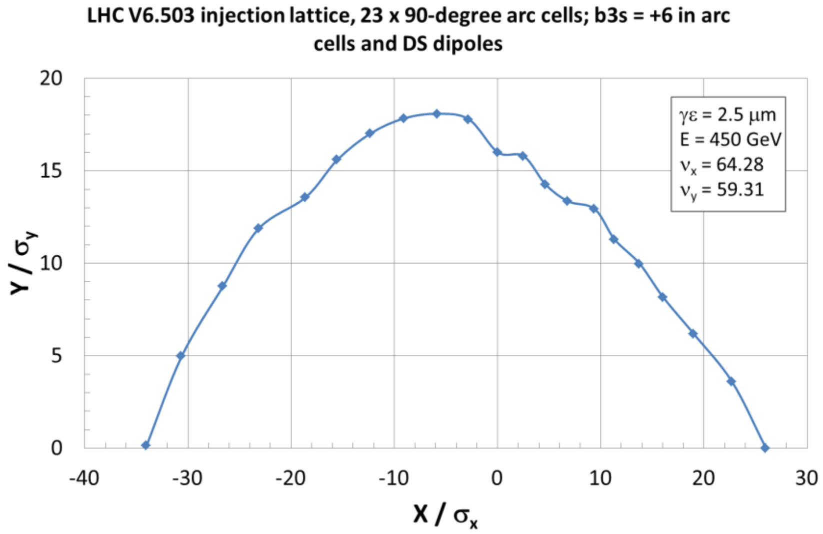
b3s in arc and DS dipoles

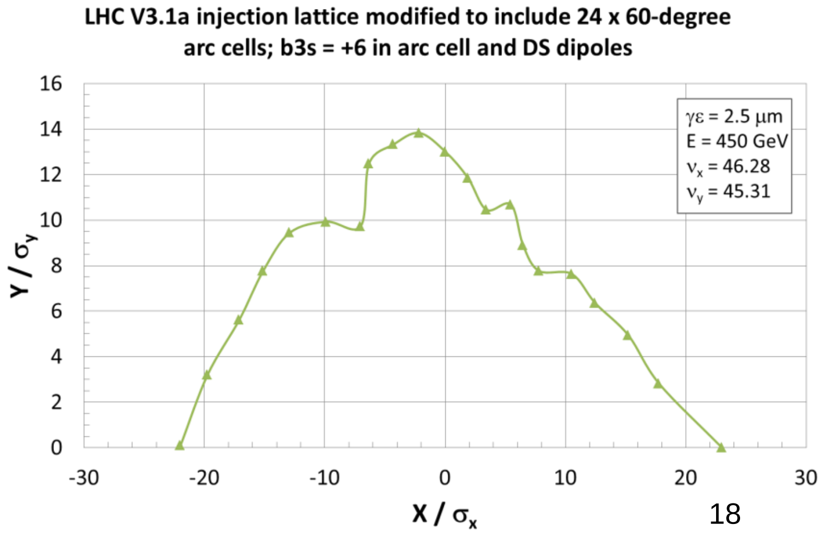
DA for b3s = +6 in dipoles

- Try b3s = +6 as estimated for FCC (E. Todesco)
- Sufficient DA for all lattices except 18 x 60° model
- Largest aperture for 20 x 90° model
- Small DA for 18 x 60° model (not shown), possibly due to large beta functions at dipoles in dispersion suppressors. Should investigate if the DA can be increased by improving the match with adjustment of 1-2 quads in the adjacent to DS arc cell.



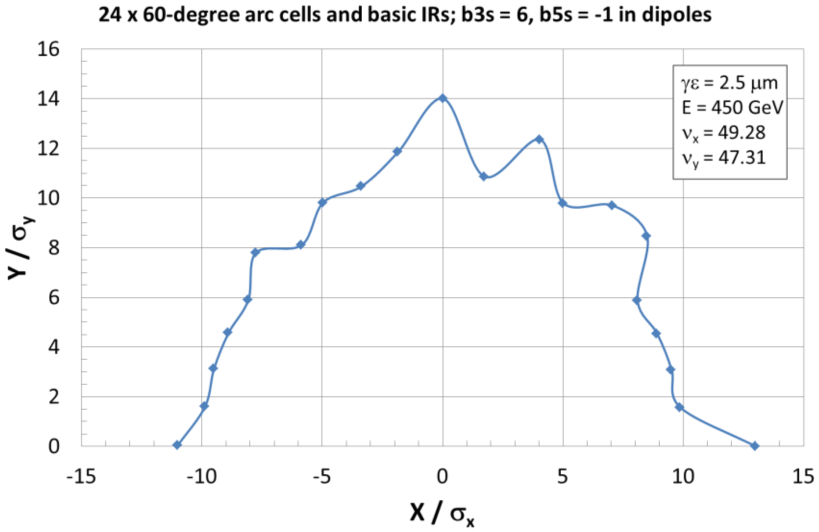


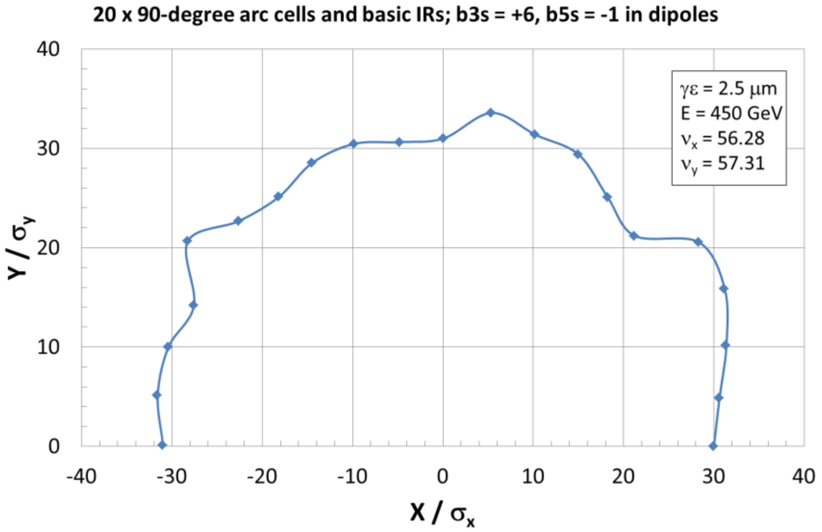


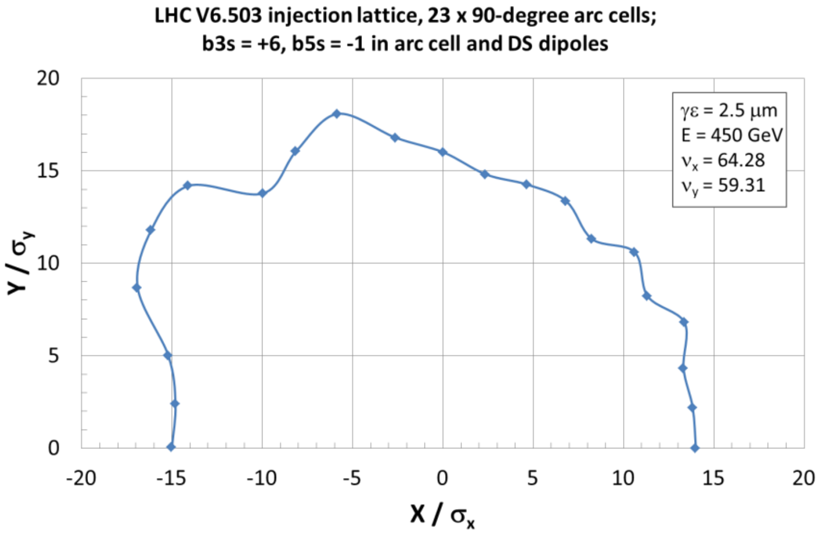


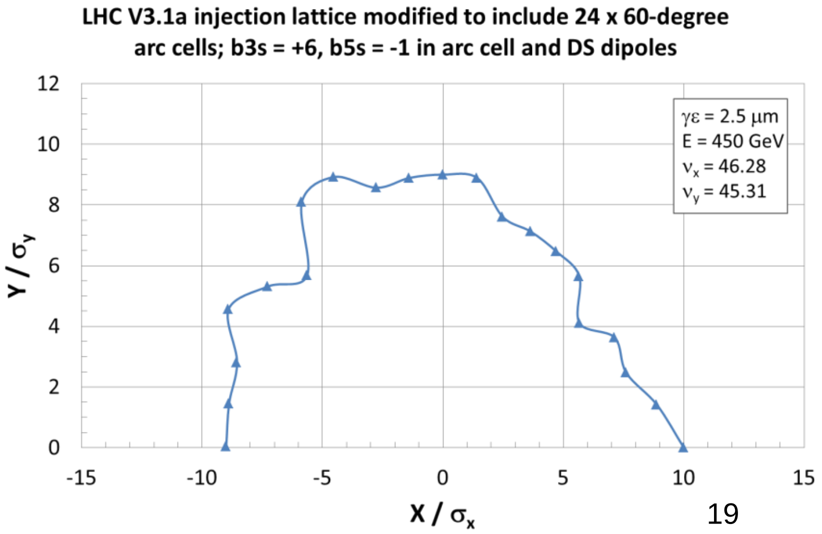
DA for b3s = +6 and b5s = -1 in dipoles

- Comfortably large aperture for 20 x 90° model
- Stronger b5 impact on 24 x 60° model and modified SLHCV3.1a. DA is near 10σ at 450 GeV → acceptable at 1.3 TeV injection energy (σ is 1.7 times smaller)
- Sufficient DA of LHC V6.503 lattice
- Small DA for 18 x 60° model (not shown) due to impact of b3s → improvements are needed
- Some of the b5 impact could be due to Qx-4Qy resonance being within ~0.01 near the injection working point
- Including b5 correctors for dipoles may help improving the DA





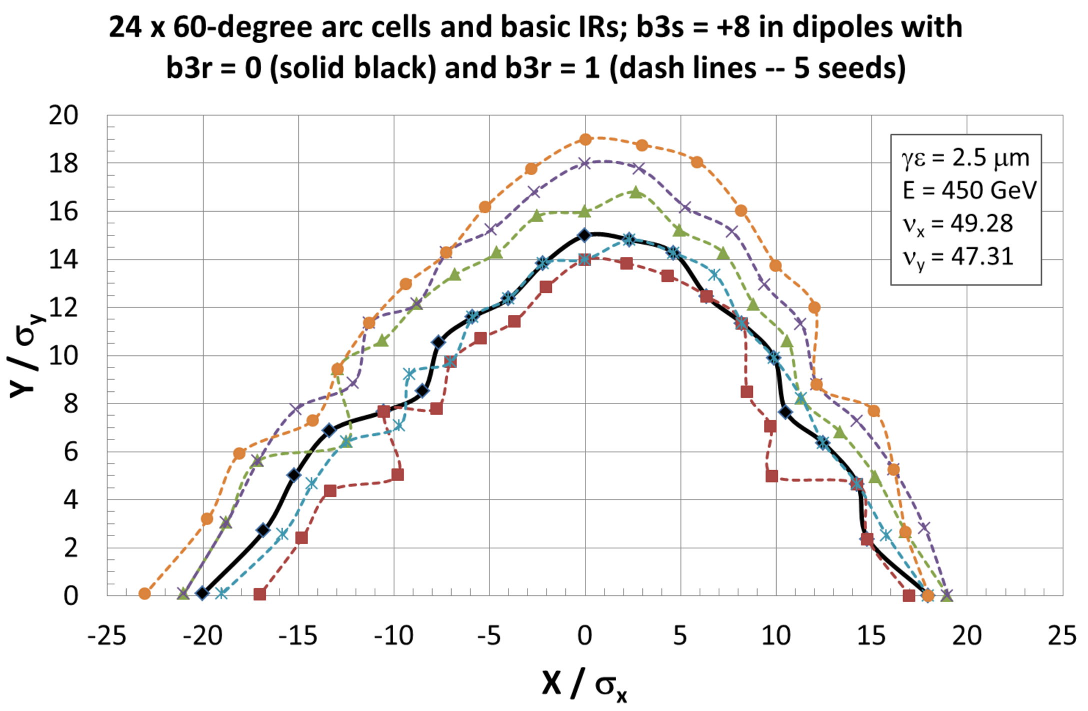


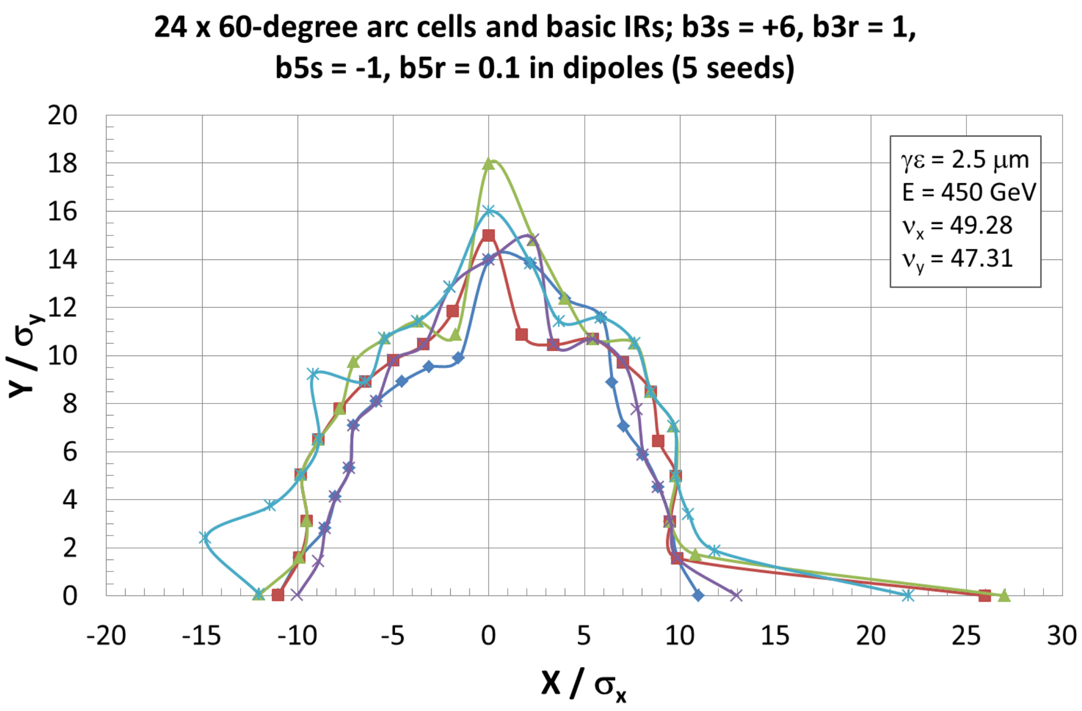


Systematic and random b3, b5 in dipoles

Limited study of random error effects for 24 x 60° simple model

- b3s = +8, b3r = 1, 5 random seeds → moderate DA reduction due to random b3
- b3s = +6, b3r = 1, b5s = -1, b5r = 0.1 → not significant impact from b3r, b5r compared to systematic error only (shown on previous page)





Conclusions and Outlook

- HE-LHC injection lattice models with reduced quad and sextupole strengths and compensation of systematic non-linear field in arcs have been studied, including a realistic design based on SLHCV3.1a IRs
- The 18-cell 60° model has the lowest magnet strengths with dipole field <15.7 T. But the present optics needs improvements to satisfy acceptable DA with dipole errors.
- The 20-cell 90° model may satisfy the 16 T target with some adjustments. It provides the largest DA (so far), but requires stronger quads and sextupoles than 60° models.
- The 24-cell 60° lattices have acceptable DA, but the dipole field is 0.3 T above the target

A lot of more work to be done

- ➢ The 18-cell x 60° lattice requires optimization to improve the DA
- ➢ A detailed look at realistic IR designs such as separation layout, dipole requirements, layout of injection and extraction systems, collimation scheme, etc…
- ➢ More comprehensive tracking simulations

Thank you for your attention!