Dynamic aperture at injection for different lattice options

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FCC Week 2018
April 9 – 13, Amsterdam

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

- Goal → identify lattice options with acceptable magnet field at top energy and sufficient dynamic aperture (DA) at injection energy
- DA challenge → expected reduced field quality of arc dipoles at injection energy due to Nb_3Sn conductor and potentially large swing between injection and collision energies
- Several lattice options with different arc cell design
- Injection energy options: 450, 900, 1300 GeV
- DA calculations with non-linear field errors in arc dipoles at injection energy
  - No errors
  - Systematic field errors
  - Systematic and random errors
  - Correction of b3 and b5 field errors
  - Quick look at error sensitivity in view of a better DA

More talks on lattice details and DA study from the HE-LHC team on Thursday

Lattice options and parameters at E = 13.5 TeV

	LHC design	Older HE-LHC designs		Latest most realistic designs	
	LHC V6.503 23 × 90°	**HELHC V3.1a 24 × 60°**	**HELHC V3.1a 20 × 90°**	**HELHC V0.3 18 × 90°**	**HELHC V0.3 23 × 90°**
Cells per arc	23	24	20	18	23
Cell phase advance, deg	90	60	90	90	90
Cell length, m	106.90	102.90	124.80	137.23	106.90
Dipole length, m	14.3	13.56	12.625	13.95	13.83
Dipoles per cell	6	6	8	8	6
Total main dipoles	1232	1280	1408	1280	1232
Arc dipoles fill factor	0.803	0.791	0.809	0.813	0.776
Dipole B, T	16.06	16.30	15.92	15.85	16.61
Arc quad B′, T/m	404.8	288.2	334.8	336.1	348.1
Sextupole B′′, T/m^2	4883	1891	3020	1639	2043
Max/Min arc β function, m	184 / 29	177 / 60	212 / 37	230 / 41	177 / 32
Max/Min arc dispersion, m	2.03 / 0.96	3.78 / 2.28	3.01 / 1.45	3.80 / 1.76	2.20 / 1.08
Tune, x/y	64.28 / 59.31	46.28 / 45.31	54.28 / 53.31	49.28 / 47.31	62.28 / 59.31
Momentum compaction	3.22 10^{-4}	6.50 10^{-4}	4.75 10^{-4}	5.82 10^{-4}	3.53 10^{-4}
Natural chromaticity	-86 / -82	-58 / -59	-74 / -75	-67 / -69	-85 / -85
CM energy for 16 T dipole	26.90	26.50	27.13	27.25	26.00

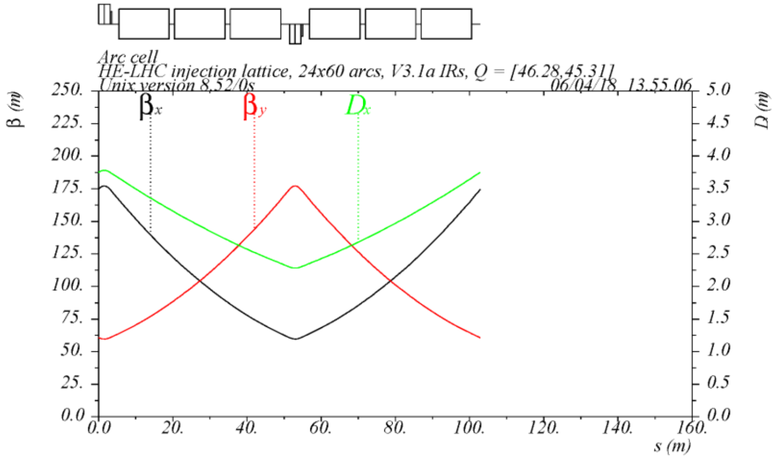
- Quad and sextupole strengths are within FCC limits (sextupole field is shown for injection β* and w/o b3 errors)
- Quad & sextupole lengths in V0.3 are adjusted for optimal field

Arc cell options

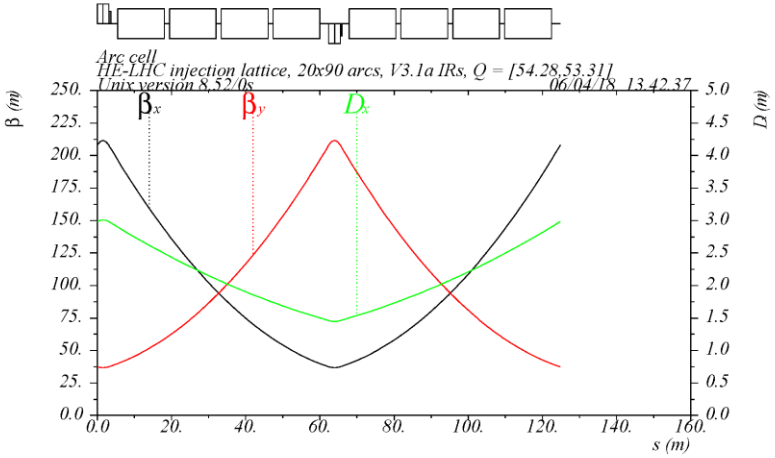
Lower number of cells	
for	**against**
lower dipole field, weaker quads and sextupoles	larger beta, dispersion and beam size → stronger effects of field errors on DA
Smaller phase advance per cell	
for	**against**
weaker quads and sextupoles	larger dispersion → impact of errors on off-momentum DA

2π*n phase advance per periodic arc (e.g. 20x90, 24x60) helps with compensation of systematic arc errors

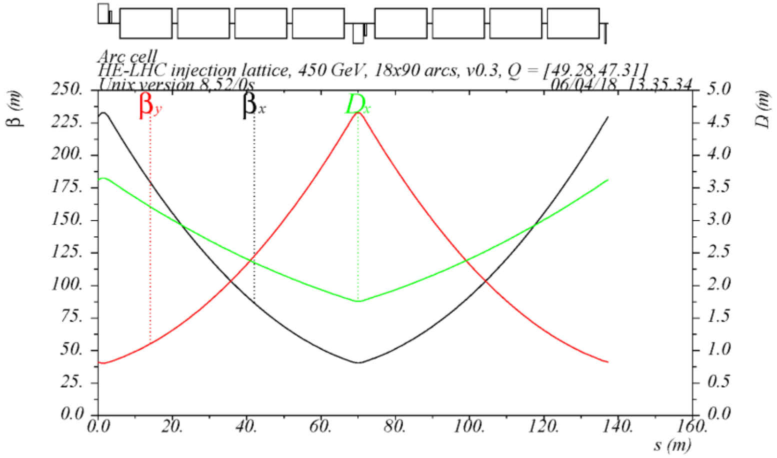
Higher injection energy → Smaller emittance, momentum spread and beam size, better field quality (at 1.3 TeV) → larger DA (σ)



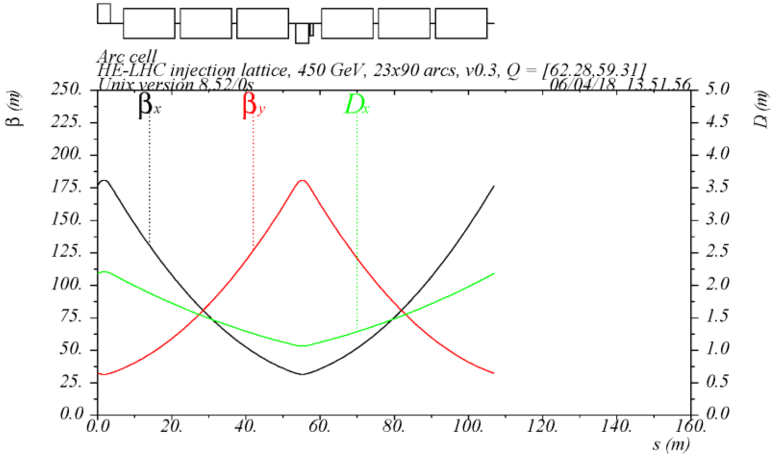
24x60 cell



20x90 cell



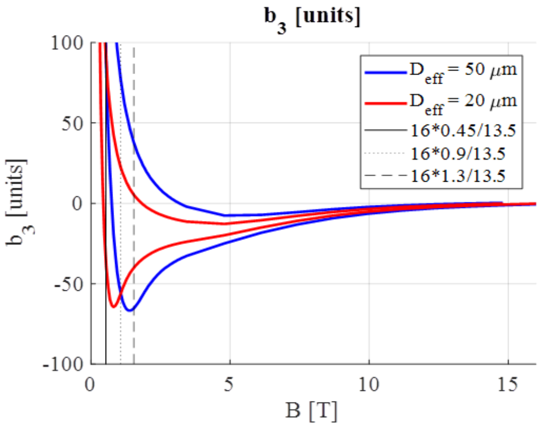
18x90 cell

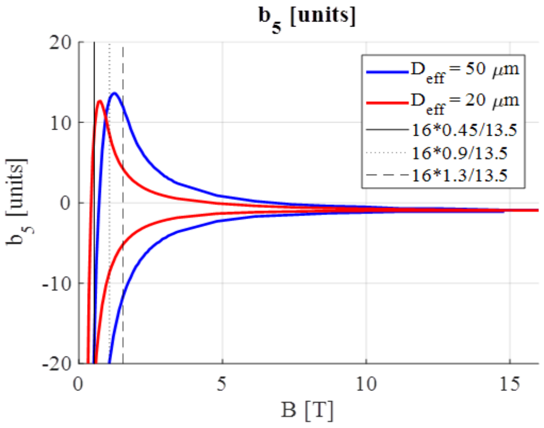


23x90 cell

HE-LHC dipole field quality at 450, 900, 1300 GeV, version 24-JAN-2018

- Large non-linear field errors in 16 T dipole at injection energy is a concern for DA
- b3s = -35 / -55 / -40 ;   b3u/r = 10 / 4 / 3 ;
  b5s = 8 / 8 / 4   at 450 / 900 / 1300 GeV
- Also feed-down from b5 to b4 may be large in options with larger beam size and at lower injection energy





for wire filament size of 20 μm

	450 GeV			900 GeV			1300 GeV		
Normal	Systematic	Uncertainty	Random	Systematic	Uncertainty	Random	Systematic	Uncertainty	Random
2	-2.230	0.922	0.922	-2.230	0.922	0.922	-2.230	0.922	0.922
3	-35.000	10.000	10.000	-55.000	4.000	4.000	-40.000	3.000	3.000
4	0.000	0.449	0.449	0.000	0.449	0.449	0.000	0.449	0.449
5	8.000	1.500	1.500	8.000	1.500	1.500	4.000	0.800	0.800
6	0.000	0.176	0.176	0.000	0.176	0.176	0.000	0.176	0.176
7	0.200	0.211	0.211	0.600	0.211	0.211	1.100	0.211	0.211
8	0.000	0.071	0.071	0.000	0.071	0.071	0.000	0.071	0.071
9	3.800	0.500	0.500	4.200	0.500	0.500	2.900	0.200	0.200
10	0.000	0.027	0.027	0.000	0.027	0.027	0.000	0.027	0.027
11	0.750	0.028	0.028	0.860	0.028	0.028	1.000	0.028	0.028
12	0.000	0.009	0.009	0.000	0.009	0.009	0.000	0.009	0.009
13	0.000	0.011	0.011	0.000	0.011	0.011	0.000	0.011	0.011
14	0.000	0.003	0.003	0.000	0.003	0.003	0.000	0.003	0.003
15	0.000	0.004	0.004	0.000	0.004	0.004	0.000	0.004	0.004
Skew									
2	0.000	1.040	1.040	0.000	1.040	1.040	0.000	1.040	1.040
3	0.000	0.678	0.678	0.000	0.678	0.678	0.000	0.678	0.678
4	0.000	0.450	0.450	0.000	0.450	0.450	0.000	0.450	0.450
5	0.000	0.317	0.317	0.000	0.317	0.317	0.000	0.317	0.317
6	0.000	0.205	0.205	0.000	0.205	0.205	0.000	0.205	0.205
7	0.000	0.116	0.116	0.000	0.116	0.116	0.000	0.116	0.116
8	0.000	0.071	0.071	0.000	0.071	0.071	0.000	0.071	0.071
9	0.000	0.041	0.041	0.000	0.041	0.041	0.000	0.041	0.041
10	0.000	0.025	0.025	0.000	0.025	0.025	0.000	0.025	0.025
11	0.000	0.016	0.016	0.000	0.016	0.016	0.000	0.016	0.016
12	0.000	0.000	0.009	0.000	0.000	0.009	0.000	0.000	0.009
13	0.000	0.000	0.005	0.000	0.000	0.005	0.000	0.000	0.005
14	0.000	0.000	0.003	0.000	0.000	0.003	0.000	0.000	0.003
15	0.000	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.002

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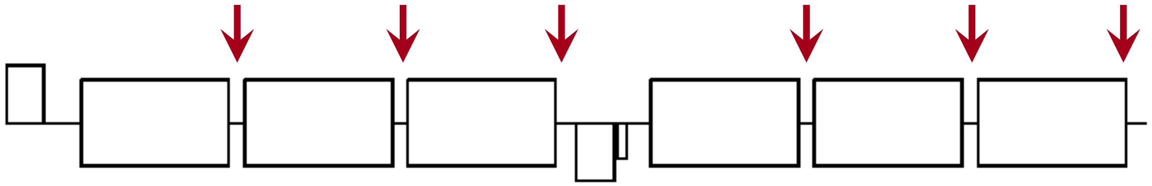
DA tracking set-up

- LEGO code (*Y. Cai, SLAC-PUB-7642,1997*)
- DA is calculated at IP, normalized to beam σ
- Short term tracking with 1024 turns (should be ok for comparison study)
  - compared to 10^4 turn tracking for a few cases
- 21 X-Y angles, 10 seeds of random errors
- Non-linear field errors (n>2) in arc dipoles; no other errors
- Random errors are increased by ≈20% compared to FQ table to compensate for missing uncertainty errors in LEGO
- Normalized emittance = 2.5 μm-rad
- Chromaticity corrected to +3 using arc sextupoles
- Synchrotron oscillation included
- RF voltage and initial momentum offset in this study

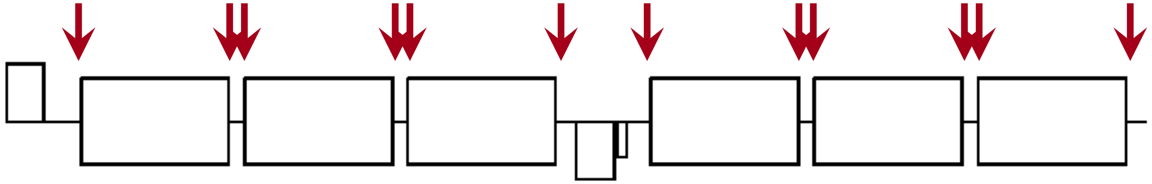
Energy, GeV	450	900	1300
Voltage, MV	14.0	12.1	10.5
$\Delta p/p$ offset, 10^{-4}	9.0	6.2	5.5

b3 and b5 corrector schemes

- b3 correction: nominal scheme with one b3 corrector per dipole
- Alternate scheme with two b3 correctors per dipole → better local correction and weaker correctors
- One corrector family is used (more families may improve the correction)

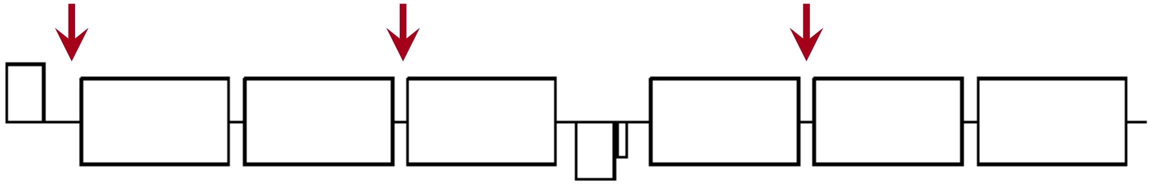


nominal: one b3 corrector per dipole



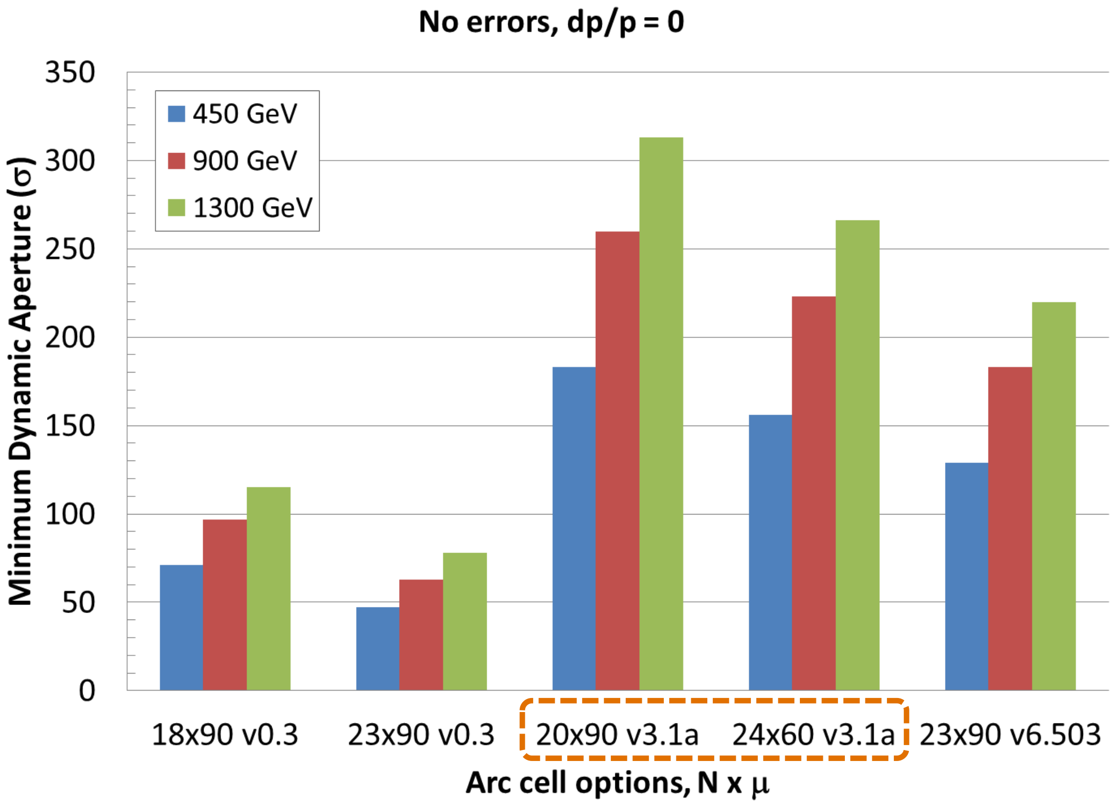
two b3 correctors per dipole

- b5 correction: scheme with three b5 correctors per periodic arc cell
- Initial study: no b5 correctors, but the FQ b5s is reduced to 30% of its value to apply some correction
- One corrector family is used

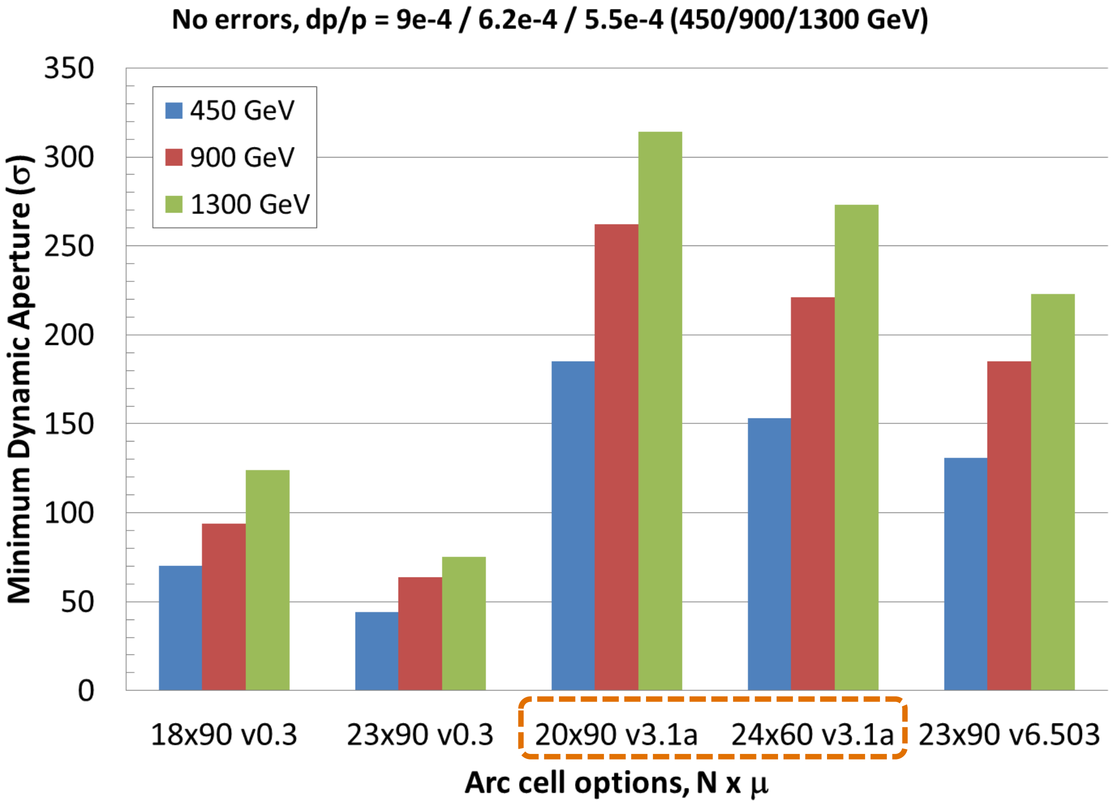


Minimum DA without errors

- Largest DA in 20x90 and 24x60 options – these designs have 2πn phase advance per arc providing compensation of the arc sextupole effects
- Smaller DA of 23x90 V0.3 lattice compared to the nominal LHC. Some differences: 2 units smaller integer X-tune, 2 units smaller tune split, different IR designs



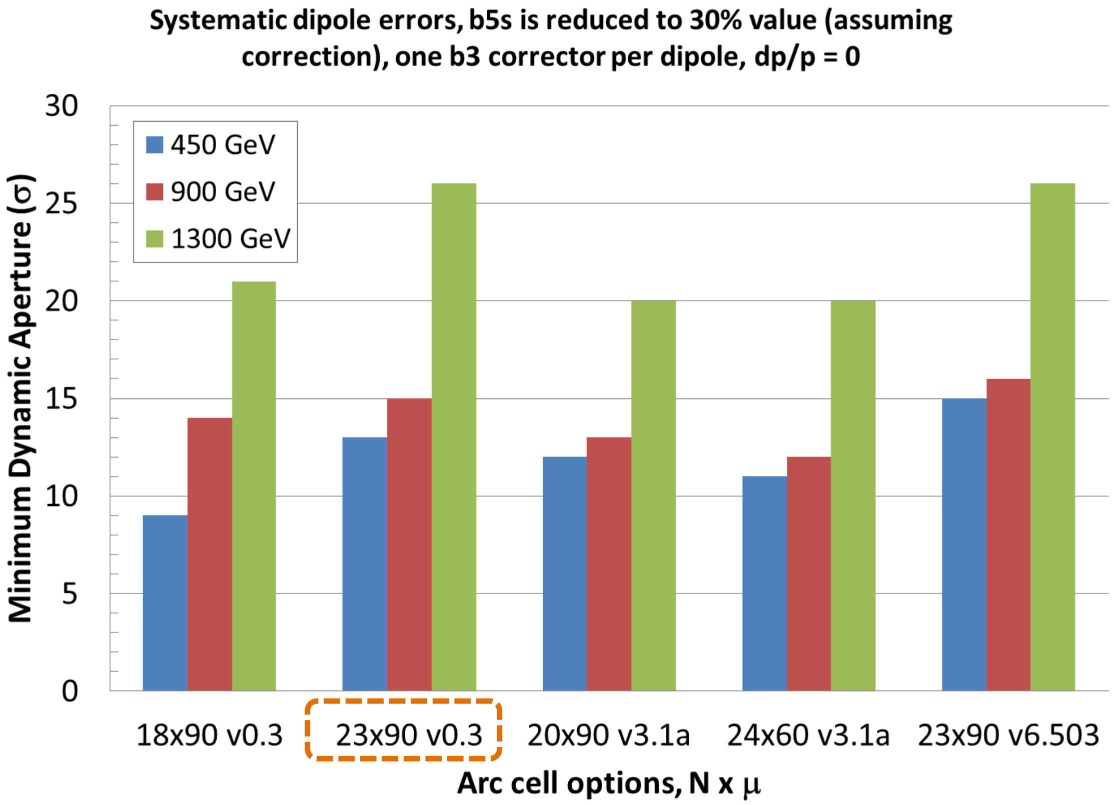
Δp/p = 0



Δp/p offset

Systematic field errors, one b3 corrector per dipole

- Best DA in 23x90 option
- DA is maximum at 1.3 TeV due to the smaller beam size and smaller errors
- Impact of momentum dependent effects
- no b5 correctors, b5s reduced to 30%



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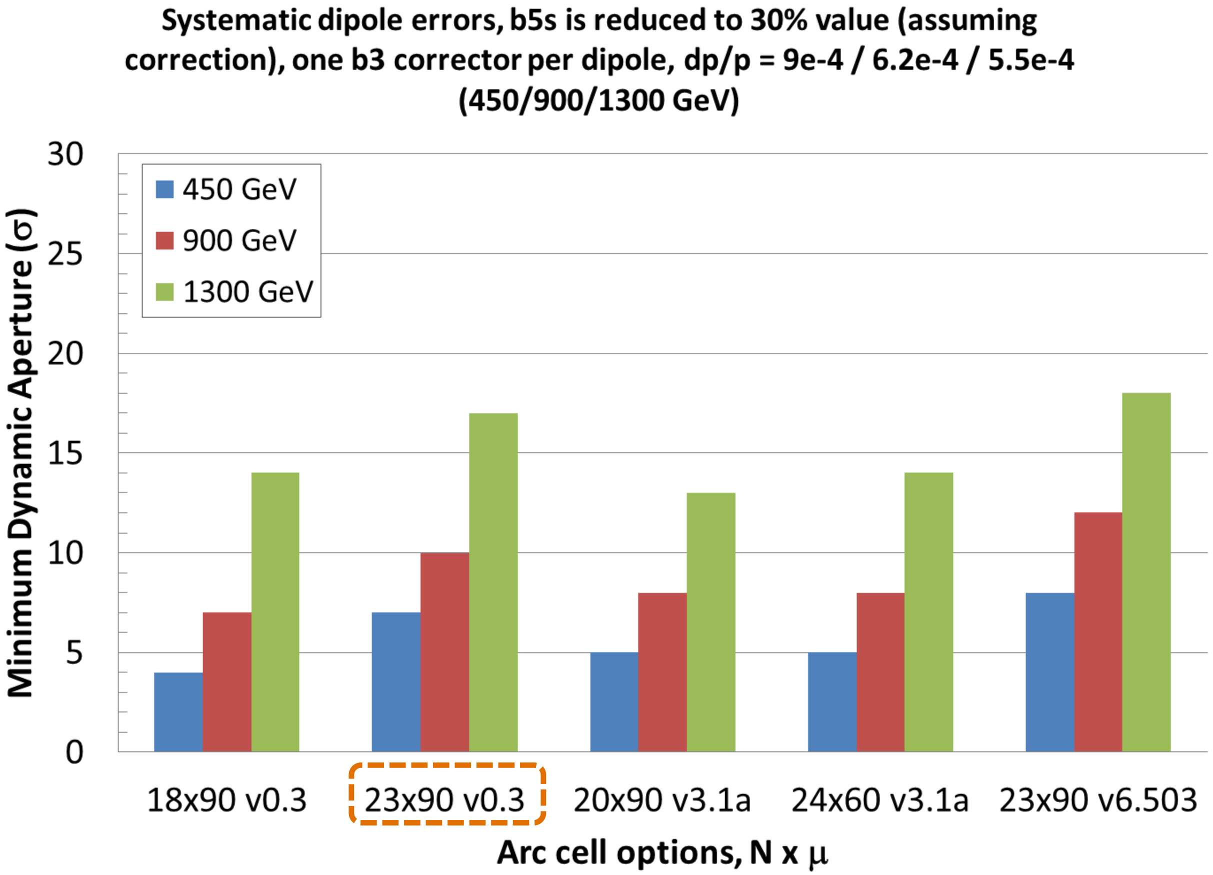
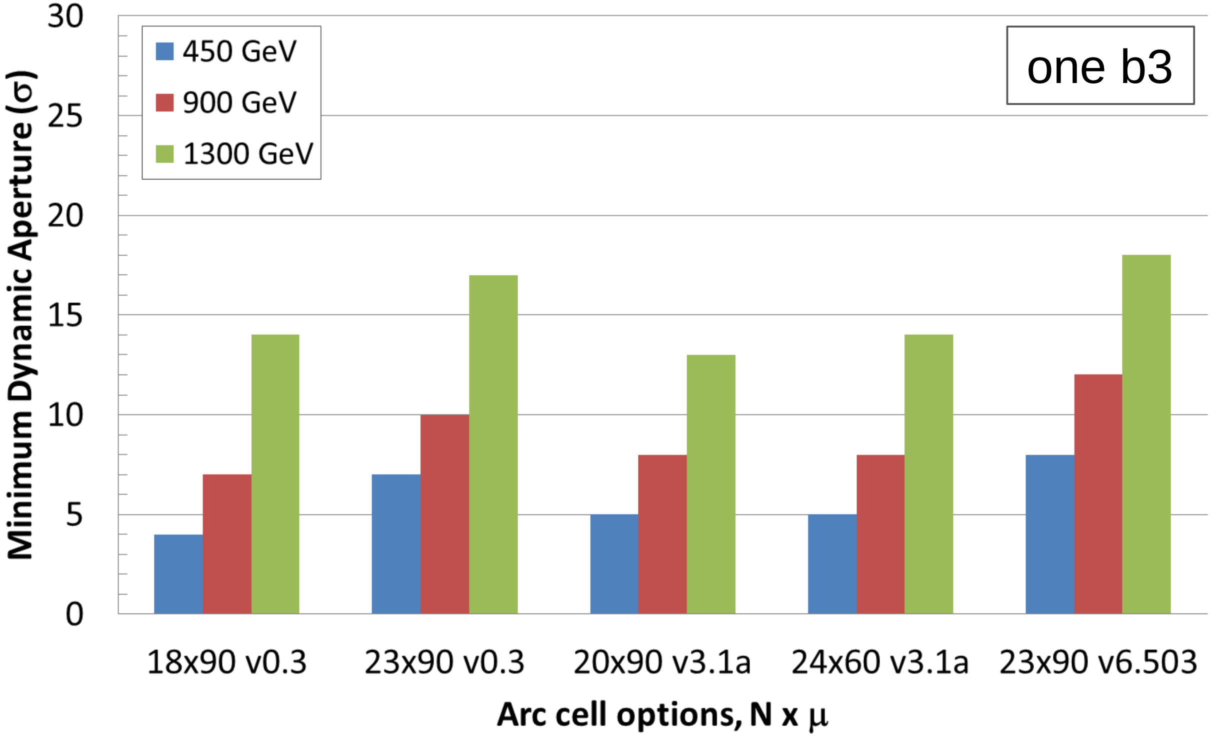


Δp/p offset

Systematic field errors, one vs two b3 correctors per dipole

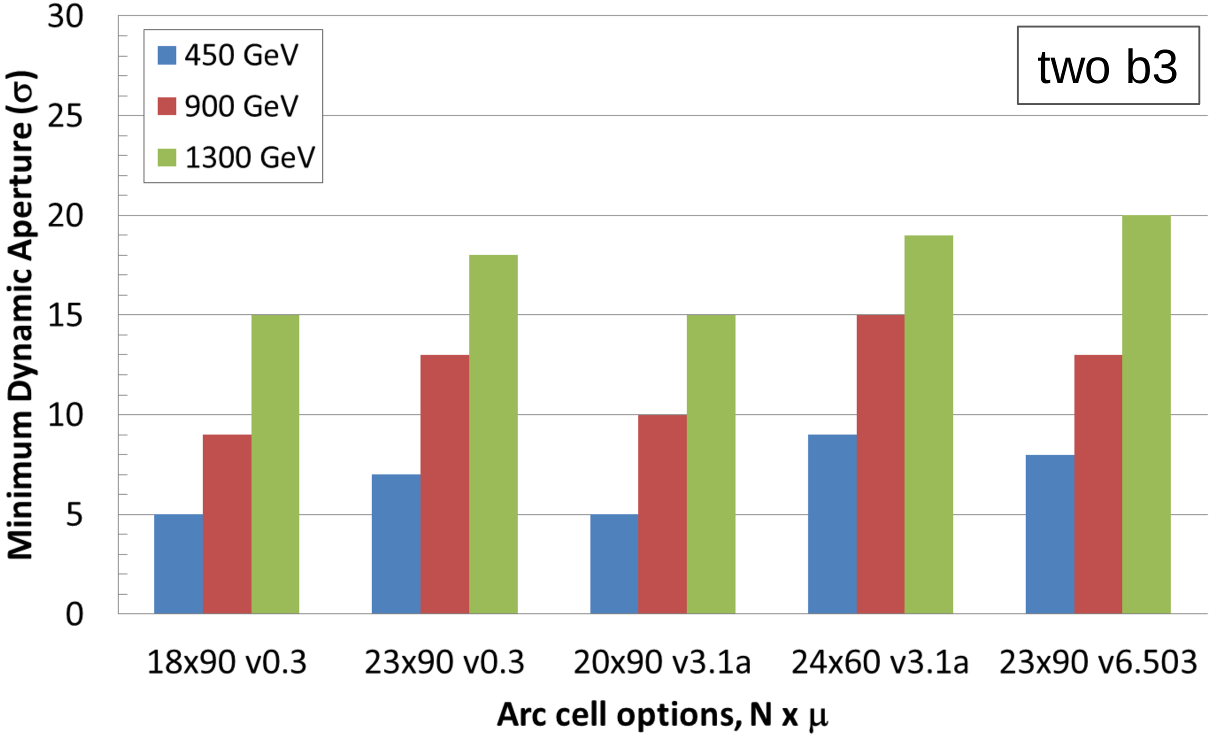
- Small DA improvement with two b3 correctors per dipole
- b3 corrector gradient B′′ at 1.3 TeV reaches ~5600 T/m^2 in the nominal corrector scheme (half-strength in two corrector scheme)

Systematic dipole errors, b5s is reduced to 30% value (assuming correction), one b3 corrector per dipole, dp/p = 9e-4 / 6.2e-4 / 5.5e-4 (450/900/1300 GeV)



Δp/p offset

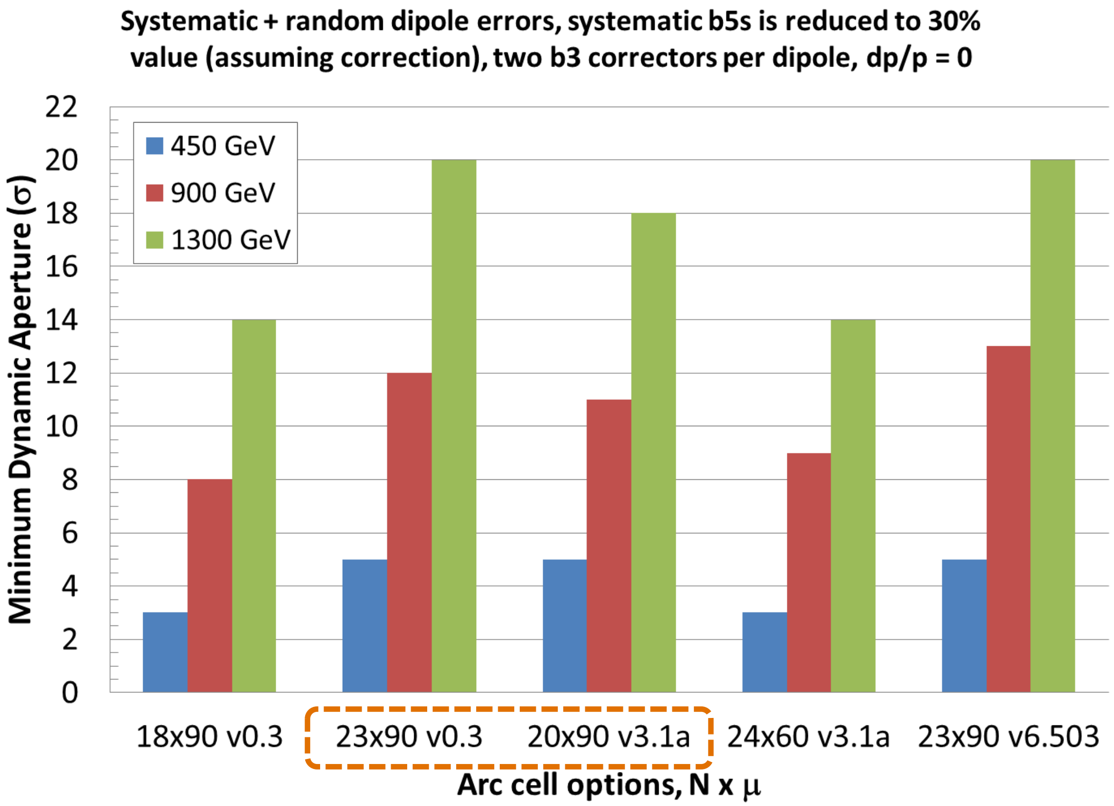
Systematic dipole errors, b5s is reduced to 30% value (assuming correction), two b3 correctors per dipole, dp/p = 9e-4 / 6.2e-4 / 5.5e-4 (450/900/1300 GeV)



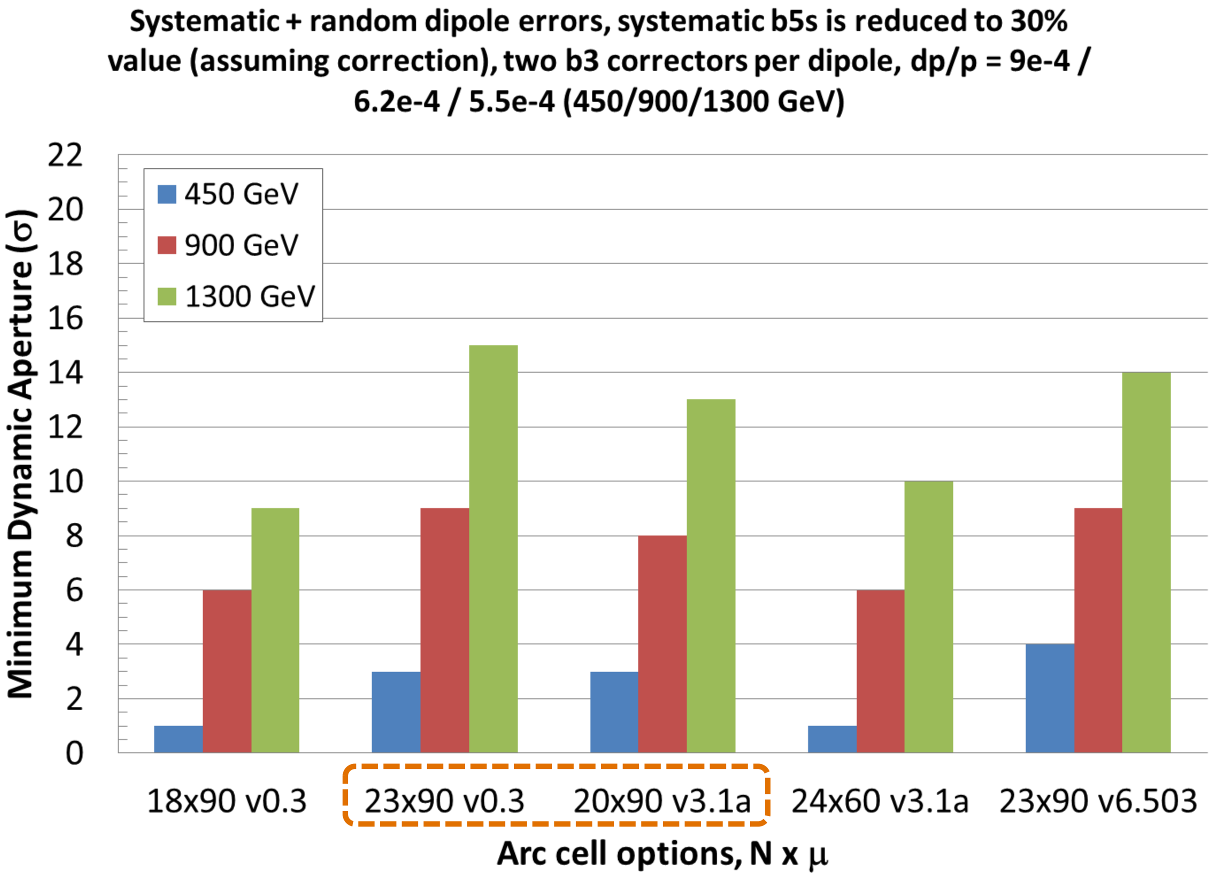
Δp/p offset

Systematic + random field errors, two b3 correctors per dipole

- Acceptable DA in 23x90 option (best) at 1.3 TeV and in 20x90 option
- Other options and 450 and 900 GeV energies have DA <10σ
- no b5 correctors, b5s reduced to 30%



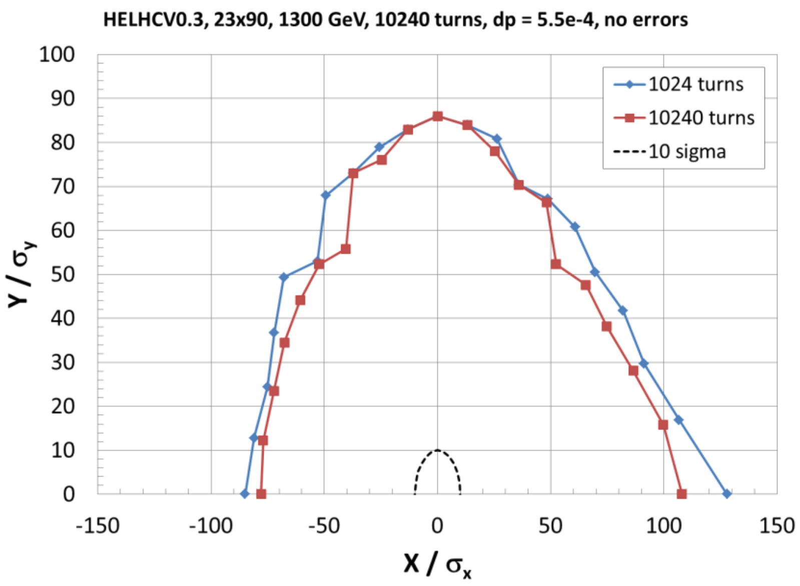
Δp/p = 0



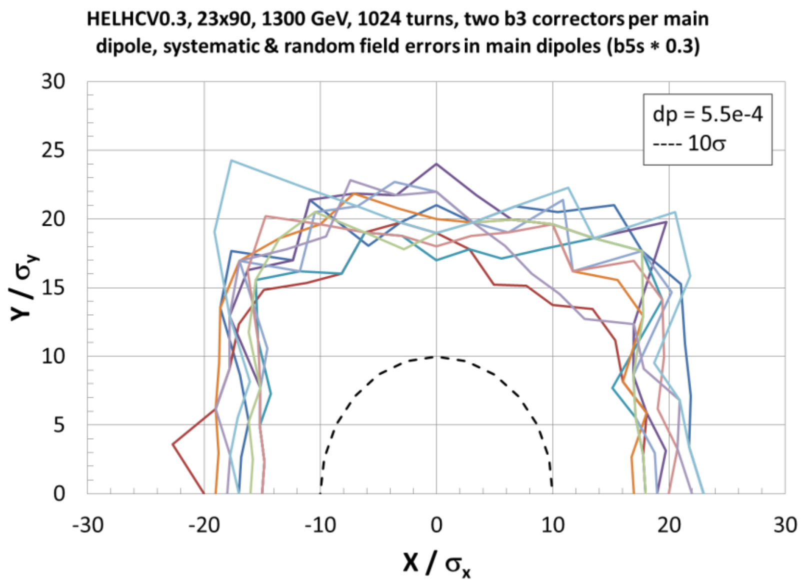
Δp/p offset

Comparison to longer term tracking

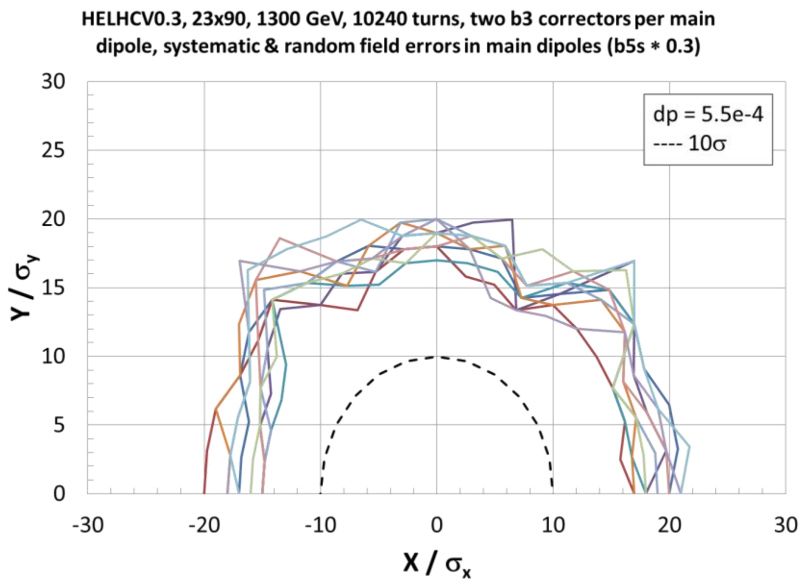
- 1024 turns vs 10 times longer tracking
  - for 23x90 lattice at 1.3 TeV, with two b3 correctors per dipole
- Without errors → 75σ DA at 10^3 turns vs 69σ at 10^4 turns
- With dipole non-linear field errors → minimum DA (~15σ) is almost unchanged at 10^3 and 10^4 turns, but maximum DA is reduced by a few σ's
- No large DA reduction, acceptable for comparison study



no errors, 1k vs 10k turns



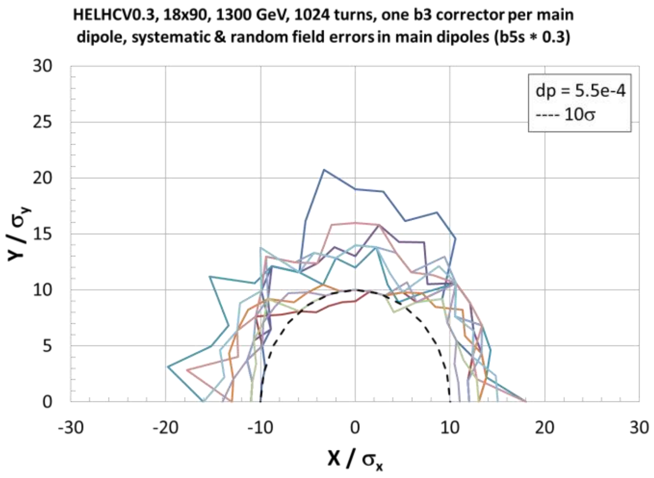
with errors, 1k turns



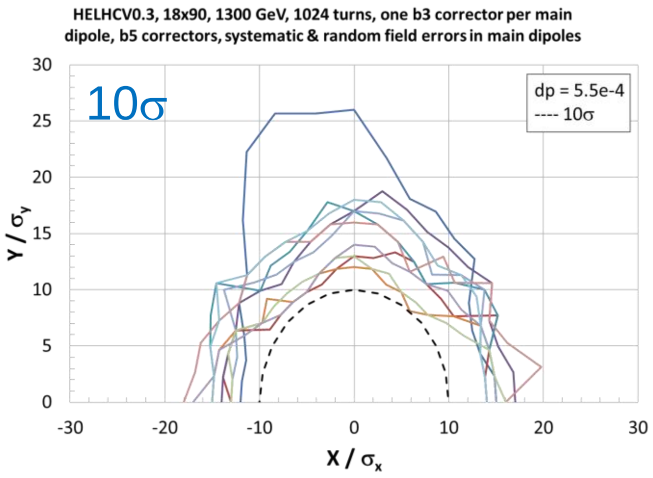
with errors, 10k turns

DA with b5 correctors

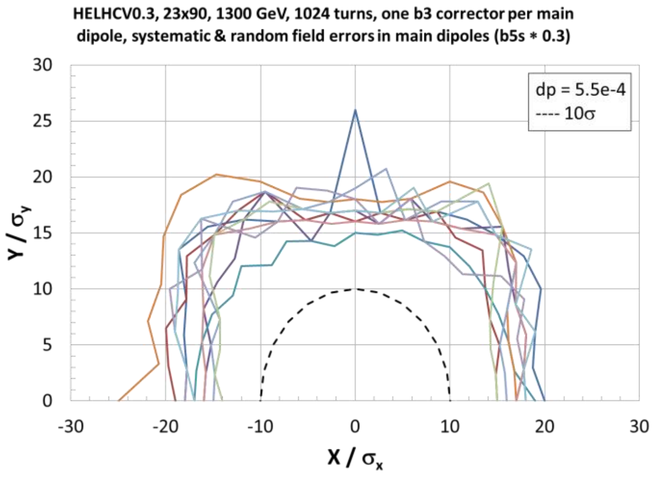
- Initial study was done with a “dummy” b5 correction – w/o b5 correctors but with b5s reduced to 30% of FQ value
- Use b5 correctors in the 18x90 and 23x90 options and compare vs the DA of “dummy” correction at 1.3 TeV
- Performed with systematic and random dipole field errors, and nominal b3 correction scheme
- Small DA improvement with the b5 correctors vs the “dummy” scheme
- The DA of 18x90 option needs further improvement



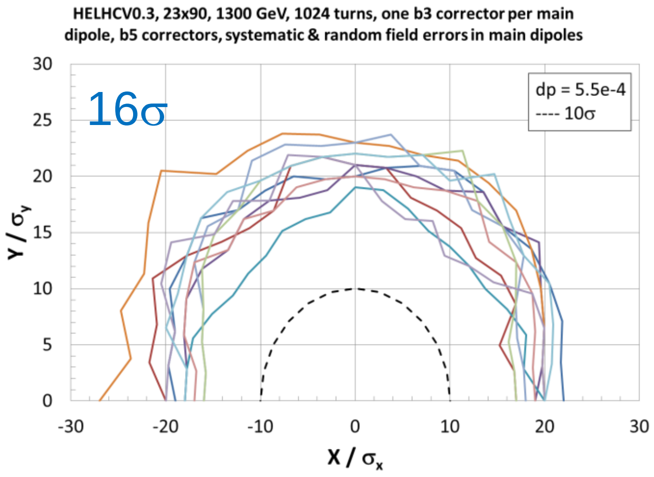
18x90 b5s*0.3 no corr



18x90 b5 correctors



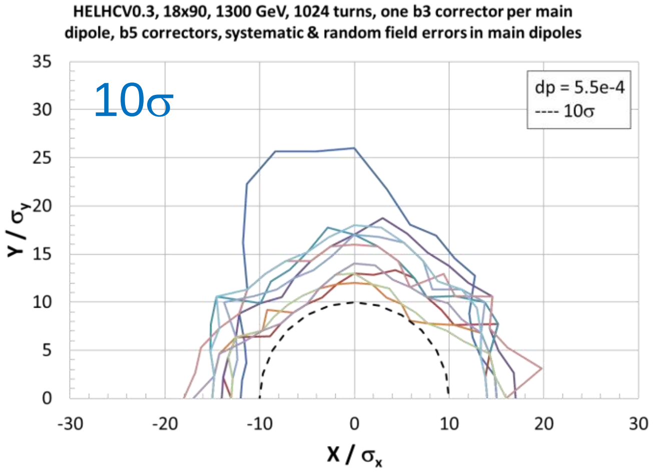
23x90 b5s*0.3 no corr



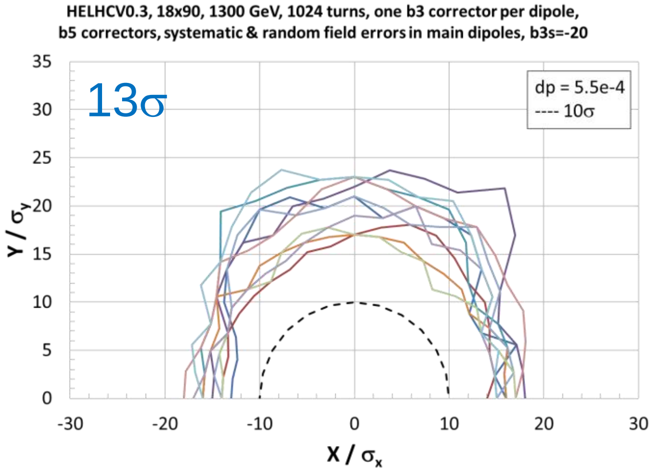
23x90 b5 correctors

Field quality and DA improvement

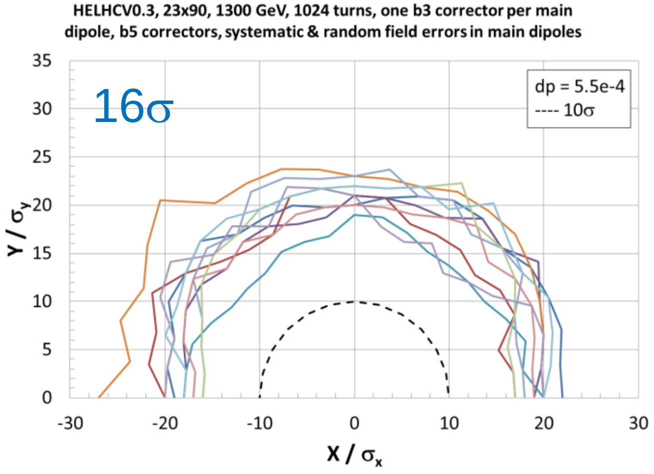
- A quick look shows DA improvement from 10σ to 13σ in 18x90 option and a better vertical DA in 23x90 option, when b3s is reduced from -40 to -20 at 1.3 TeV
- Performed for short-term tracking with systematic and random field errors in arc dipoles, one b3 corrector per dipole, and b5 correctors
- A systematic study of DA sensitivity to dipole field errors should be performed to develop a strategy for a target FQ (with feedback from magnet group)



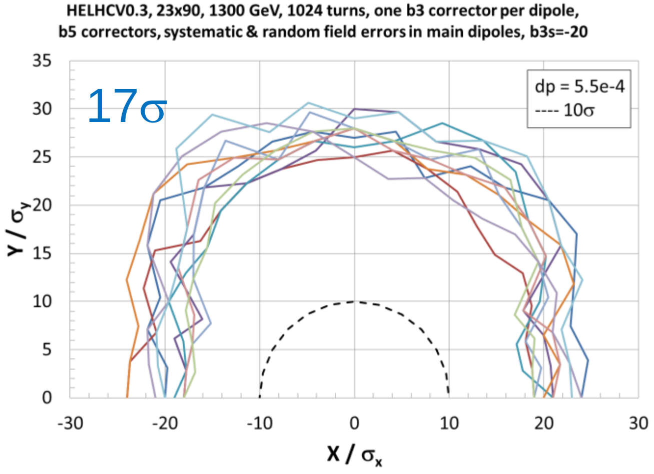
18x90 b3s=-40



18x90 b3s=-20



23x90 b3s=-40



23x90 b3s=-20

Conclusions

- Dynamic aperture of four lattice options with non-linear field errors in arc dipoles has been compared using short-term tracking
- The largest DA (~16σ) is achieved with the 23x90 option at 1.3 TeV (smaller beam size → reduced effects of field errors); however it requires a stronger dipole, thus limiting the collision energy
- The DA of 18x90 option requires further improvement (e.g. better field quality); this option's advantage is the lowest dipole field compatible with 27 TeV
- The 20x90 option could be also considered, as it showed an intermediate performance between the 23x90 and 18x90 options for both the DA and the dipole field
- Compensation of systematic b3 and b5 errors using b3, b5 correctors is needed for maximum DA
- The 450 and 900 GeV injection energy options so far did not provide sufficient DA due to larger field errors and beam size
- DA improvement may be possible with optimization of the lattice and field quality specifications
- These results may be somewhat optimistic due to short-term tracking → long-term tracking studies should be performed for the selected options
- There are more errors to be added to the simulations (other magnets, misalignment, …) → more impact on DA → to be studied

Thank you!

Sensitivity to individual systematic errors

- 18x90 lattice option
- DA with one systematic bn error at a time (no other errors)
- Two cases for b3s and b5s: with and w/o correctors
- In case of b3s w/o b3 correctors, the linear chromaticity is corrected using main sextupoles → but DA is very poor → b3 correctors are needed to locally correct the errors
- Similarly, with only b5s error and without b5 correctors the DA is already tight → b5 correctors should be used