LHC Optics Impact to Magnet

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DOE LARP Review

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Outline

- Dynamic aperture study for the proposed LHC high luminosity lattice as a function of the IP triplet multipole field errors.
- Specification of the field quality for the proposed large aperture triplet quadrupoles.
- Collimation study and benchmarking of beam loss map calculation.

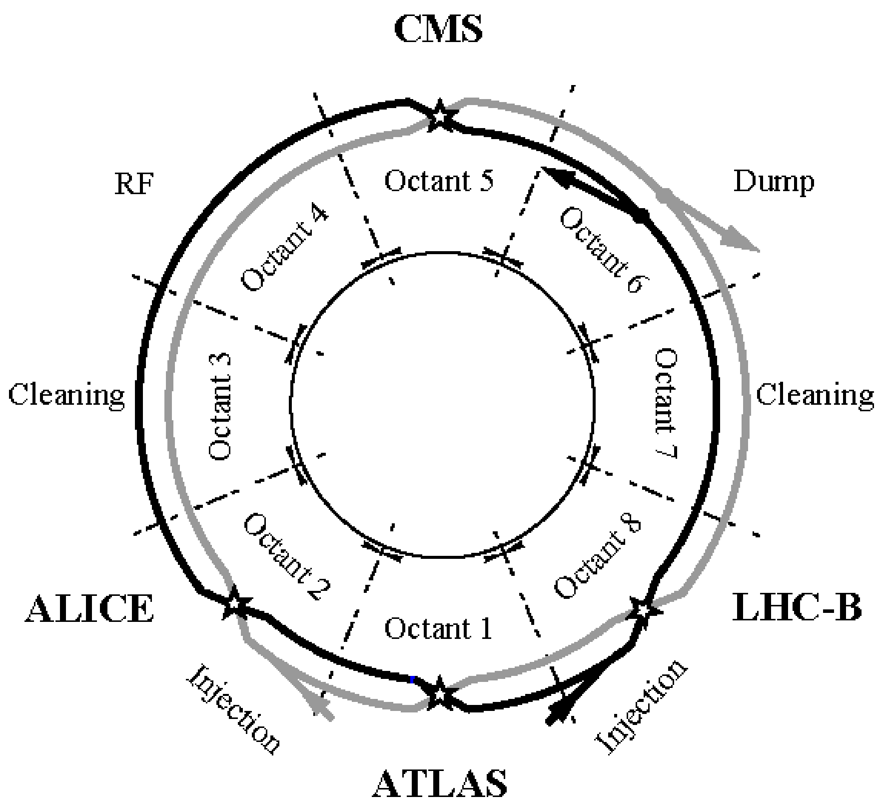
Lattice: LHC v.3.01, collision option "4444" with β^*=15/15 cm at IP1 and IP5, Nb-Ti superconducting triplet quadrupoles with 120 mm coil diameter, beam energy of 7 TeV.

Code: SixTrack.

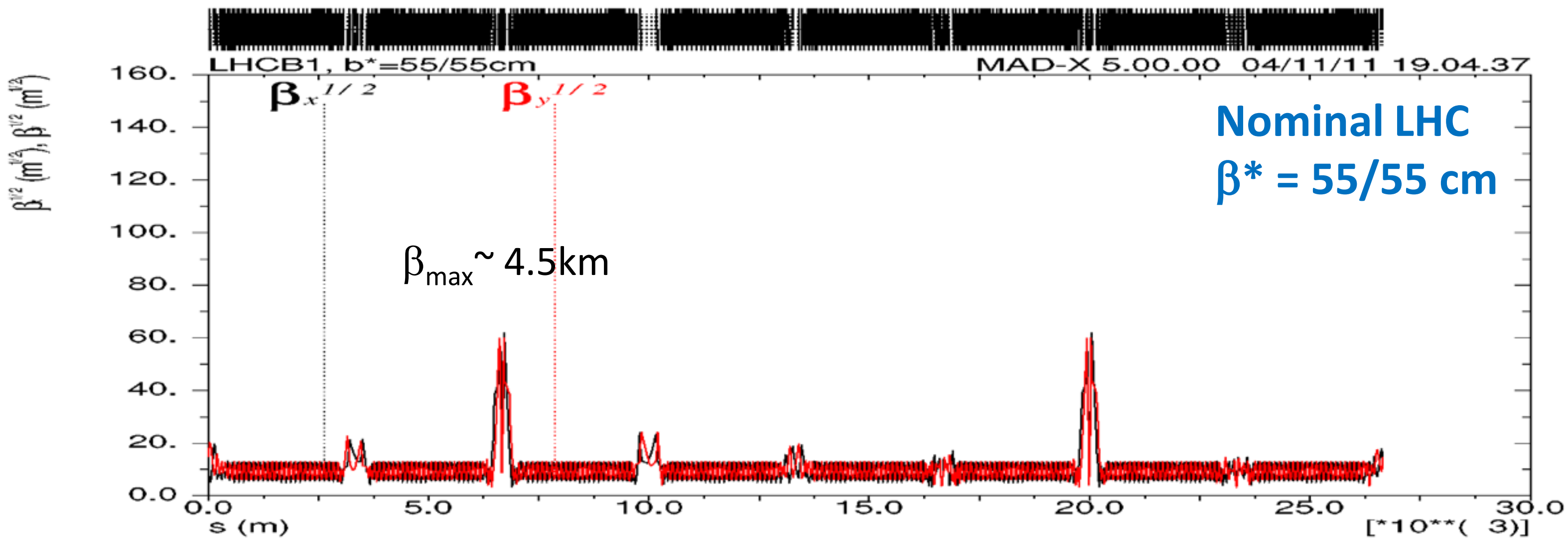
Features of the High Luminosity Lattice

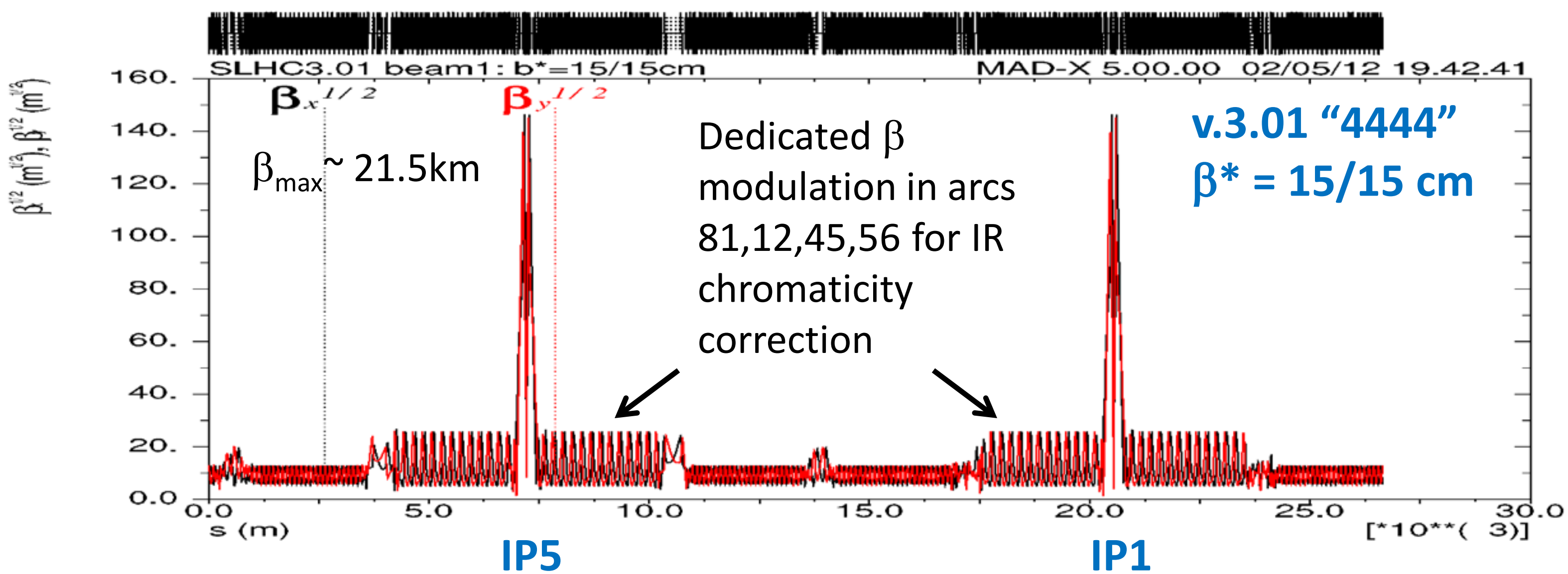
The LHC v.3.01 collision lattice has lower than nominal β^* at IP1 (ATLAS) and IP5 (CMS) crossing points resulting in higher β-functions in the IP triplet quads. A dedicated large β-modulation in the adjacent arcs is used for local cancelation of the triplet chromaticity. Large aperture triplet quads (d_c=120 mm) are proposed to accommodate larger beam size.

Impact: Higher β-functions in the triplet and adjacent arcs amplify the effects of triplet errors and sextupole aberrations causing reduction of dynamic aperture. New tolerances on triplet field quality need to be specified for an acceptable dynamic aperture in collision.

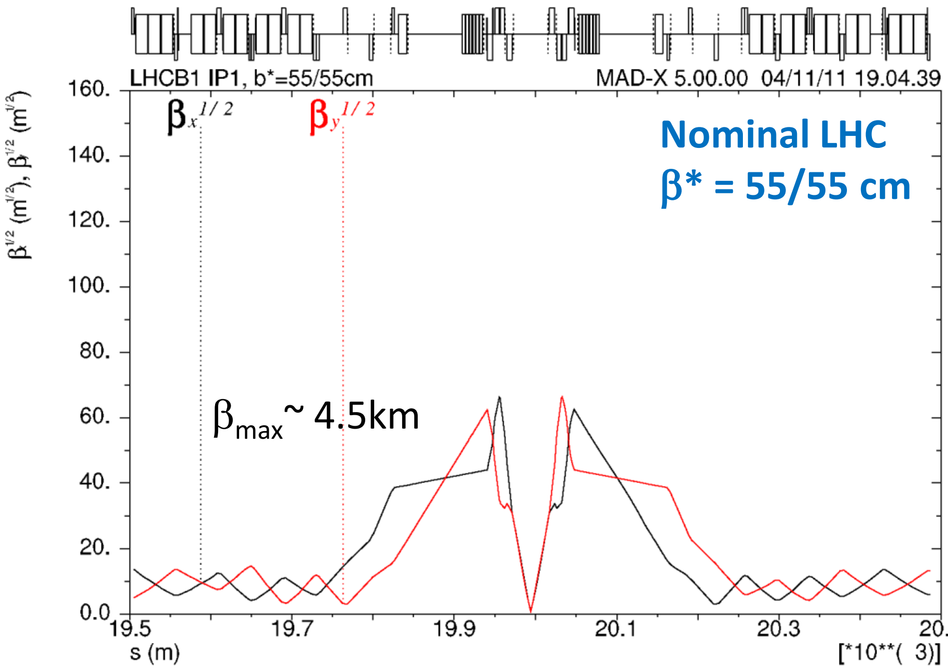


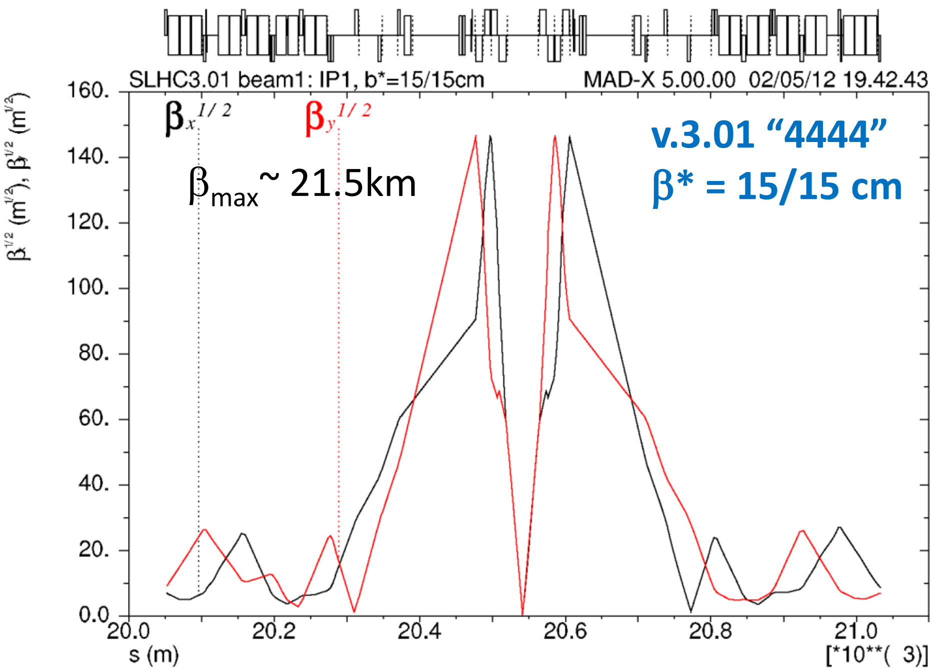
Beta Functions: Nominal LHC versus v.3.01 “4444”



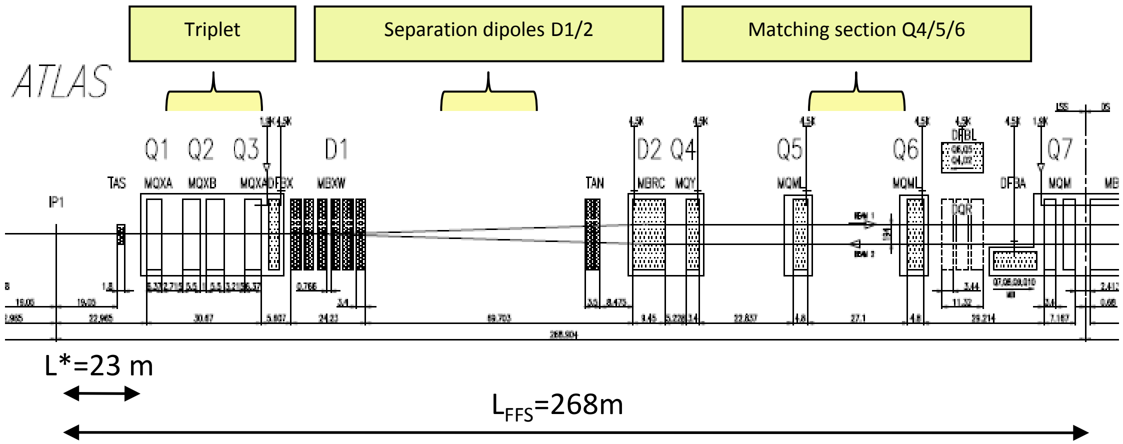


Interaction Region: Nominal LHC versus v.3.01 “4444”



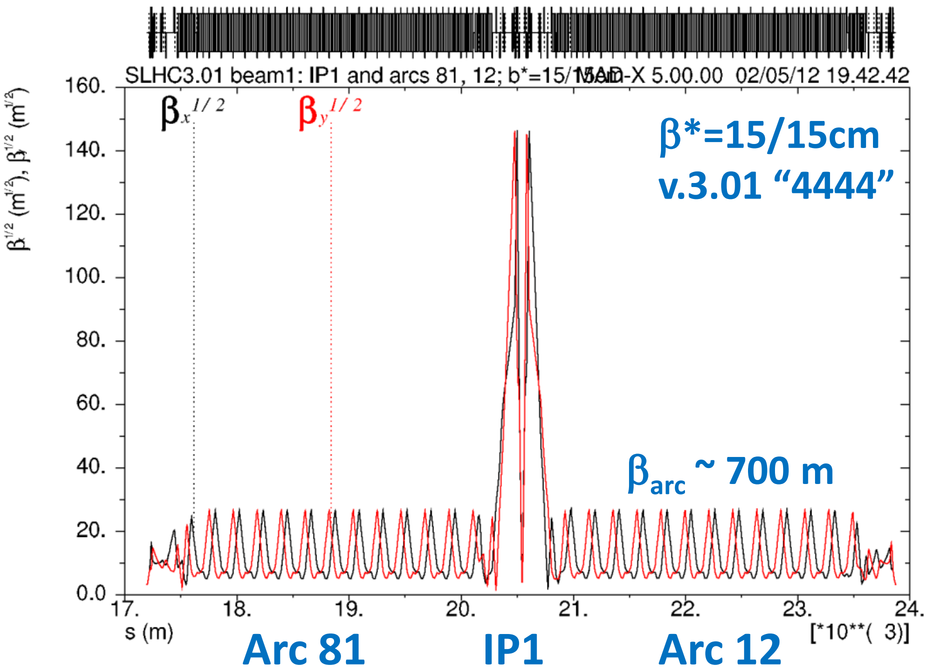


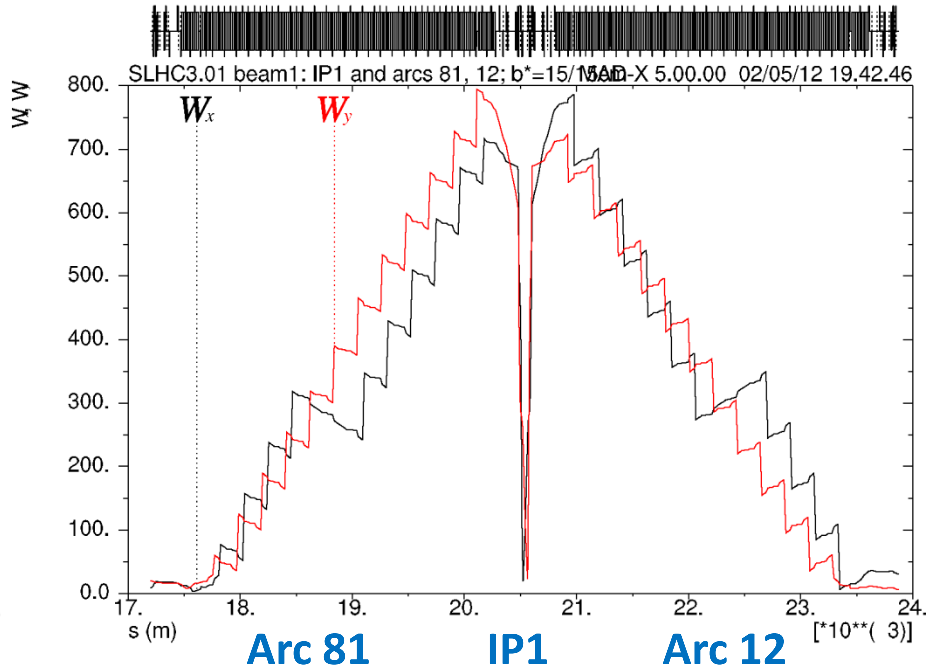
Proposed large aperture Nb-Ti superconducting triplet quadrupoles Q1,Q2,Q3 with coil diameter of d_c = 120 mm.



Achromatic Telescopic System (ATS) for Correction of IP Triplet Non-linear Chromaticity at Low β*

Peak beta functions in the IP triplets increase as $\beta_{max} \sim 1/\beta^*$ and yield higher triplet chromaticity at low β^* which requires stronger correcting sextupoles. A dedicated beta modulation is created in the arcs adjacent to IP1 and IP5 in order to raise beta functions at the sextupoles ($\beta_{sext} \sim 1/\beta^*$) and increase their effect thus avoiding exceeding their field limit. In addition, these sextupoles are arranged in -I pairs to minimize their geometric aberrations and have a proper phase advance relative to the triplets for a local correction of non-linear triplet chromaticity.





Multipole Field Scaling in a SC Quadrupole

$$B_y + iB_x = 10^{-4} B_{ref} \times \sum_{n=1}^{\infty} (b_n + ia_n)(\frac{x+iy}{r_0})^{n-1}$$

where n=1 is for a dipole, etc.
B_{ref} is main quad field at r_0

Note: the a_n,b_n coefficients are defined in 10^{-4} units.
The a_n and b_n values in the multipole field tables represent Gaussian sigmas used to generate random errors. Furthermore, they are split in two components: the“uncertainty” term (deviation from systematic) and the “random” term.

• Scaling with reference radius r_0 does not change the multipole field $B_{x,y}$ and does not affect dynamic aperture. Nominal r_0 = 17 mm → new triplet quad r_0 = 50 mm.

$$b_n, a_n \propto r_0^{n-2} \rightarrow (50/17)^{n-2}$$

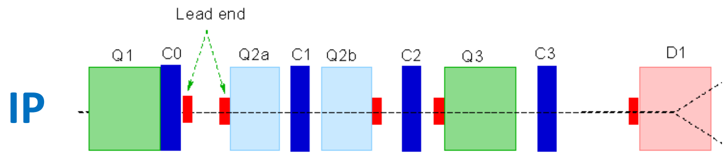
• Scaling with coil diameter d_c in a SC quad (P. Ferracin, et al, Phys. Rev. ST Accel. Beams **3**, 122403 (2000)). Nominal d_c = 70 mm → new triplet quad d_c = 120 mm.

$$b_n, a_n \propto 1/d_c^{n-1} \rightarrow (70/120)^{n-1}$$

• Scaling with peak beta function in triplet β_{max} to keep the triplet resonance driving terms constant (SLHC Project Report 0038 by S. Fartoukh). Nominal β_{max} = 4.5 km → new β_{max} = 21.5 km in lattice v.3.01 “4444”.

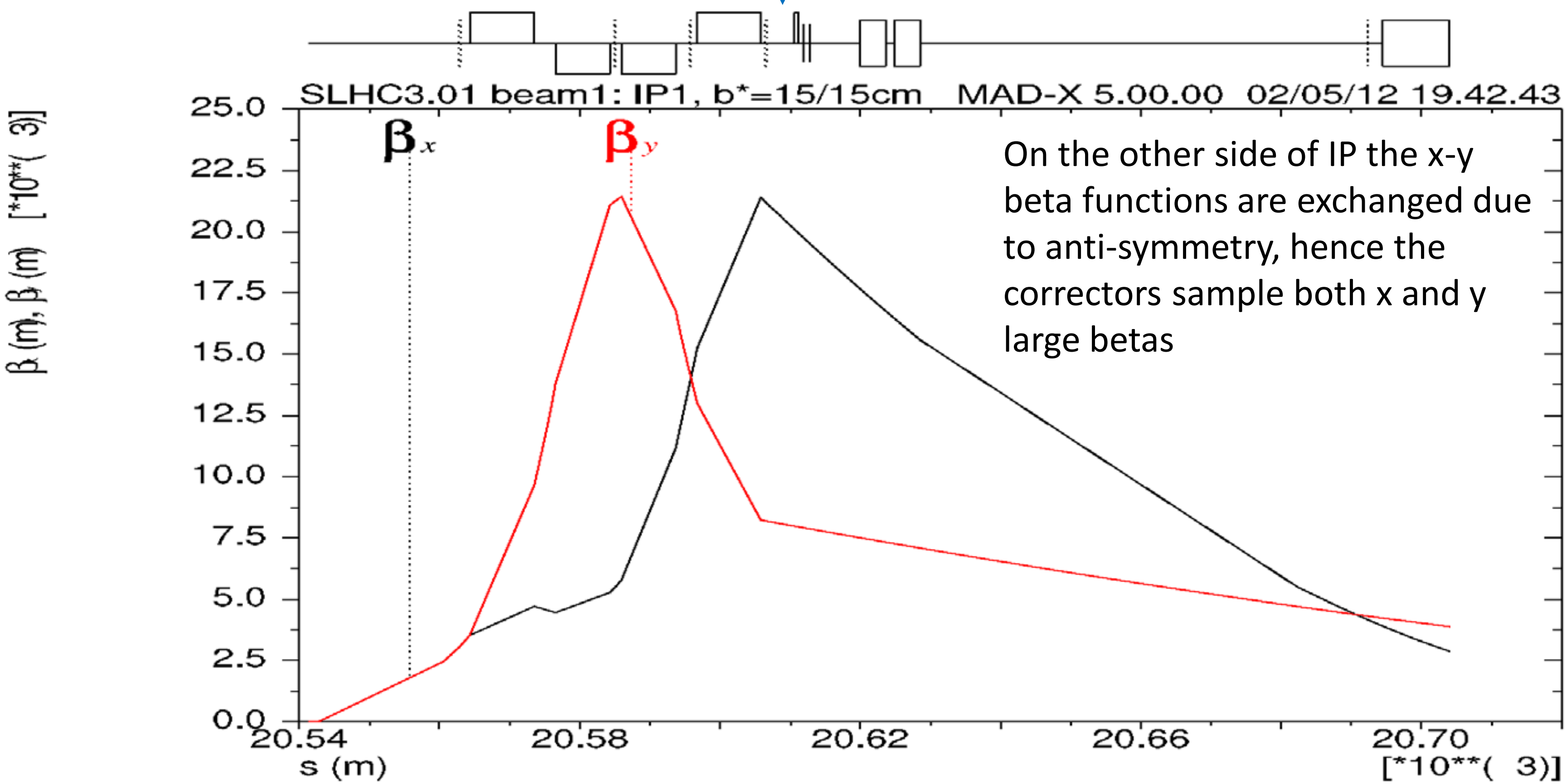
$$b_n, a_n \propto 1/\beta_{\max}^{n/2} \rightarrow (4.5/21.5)^{n/2}$$

Multipole Field Correctors in the Triplet



a3, b3, a4, b4, b6 correctors

The correctors compensate the resonance driving terms. Due to correction, the a3, b3, a4, b4, b6 coefficients are expected to be more relaxed.



On the other side of IP the x-y beta functions are exchanged due to anti-symmetry, hence the correctors sample both x and y large betas

Measured Multipoles for the Nominal Triplet Quadrupoles with d_c=70 mm at r_0=17 mm

skew	uncertainty	rms		normal	uncertainty	rms
a1	0.0000	0.0000		b1	0.0000	0.0000
a2	0.0000	0.0000		b2	0.0000	0.0000
a3	0.5235	0.6354		b3	0.4135	0.7873
a4	0.4432	0.3883		b4	0.1552	0.1563
a5	0.0874	0.1423		b5	0.1142	0.2171
a6	0.2306	0.2637		b6	0.2098	0.3088
a7	0.0254	0.0411		b7	0.0311	0.0374
a8	0.0140	0.0280		b8	0.0060	0.0096
a9	0.0127	0.0078		b9	0.0085	0.0116
a10	0.0094	0.0179		b10	0.0303	0.0086
a11	0.0046	0.0028		b11	0.0084	0.0106

Multipole Table "Target3" Scaled from the Measured Table to r_0=50 mm and d_c=120 mm

skew	uncertainty	rms		normal	uncertainty	rms
a1	0.0000	0.0000		b1	0.0000	0.0000
a2	0.0000	0.0000		b2	0.0000	0.0000
a3	0.5239	0.6359		b3	0.4139	0.7879
a4	0.7611	0.6667		b4	0.2664	0.2683
a5	0.2574	0.4191		b5	0.3365	0.6396
a6	1.1655	1.3328		b6	1.0603	1.5608
a7	0.2203	0.3564		b7	0.2701	0.3244
a8	0.2087	0.4162		b8	0.0889	0.1423
a9	0.3238	0.2003		b9	0.2165	0.2971
a10	0.4137	0.7838		b10	1.3256	0.3755
a11	0.3457	0.2116		b11	0.6340	0.7965
a12	0.1863	0.1863		b12	0.1863	0.1863
a13	0.1164	0.1164		b13	0.2328	0.1164
a14	0.4366	0.1455		b14	0.5821	0.1455

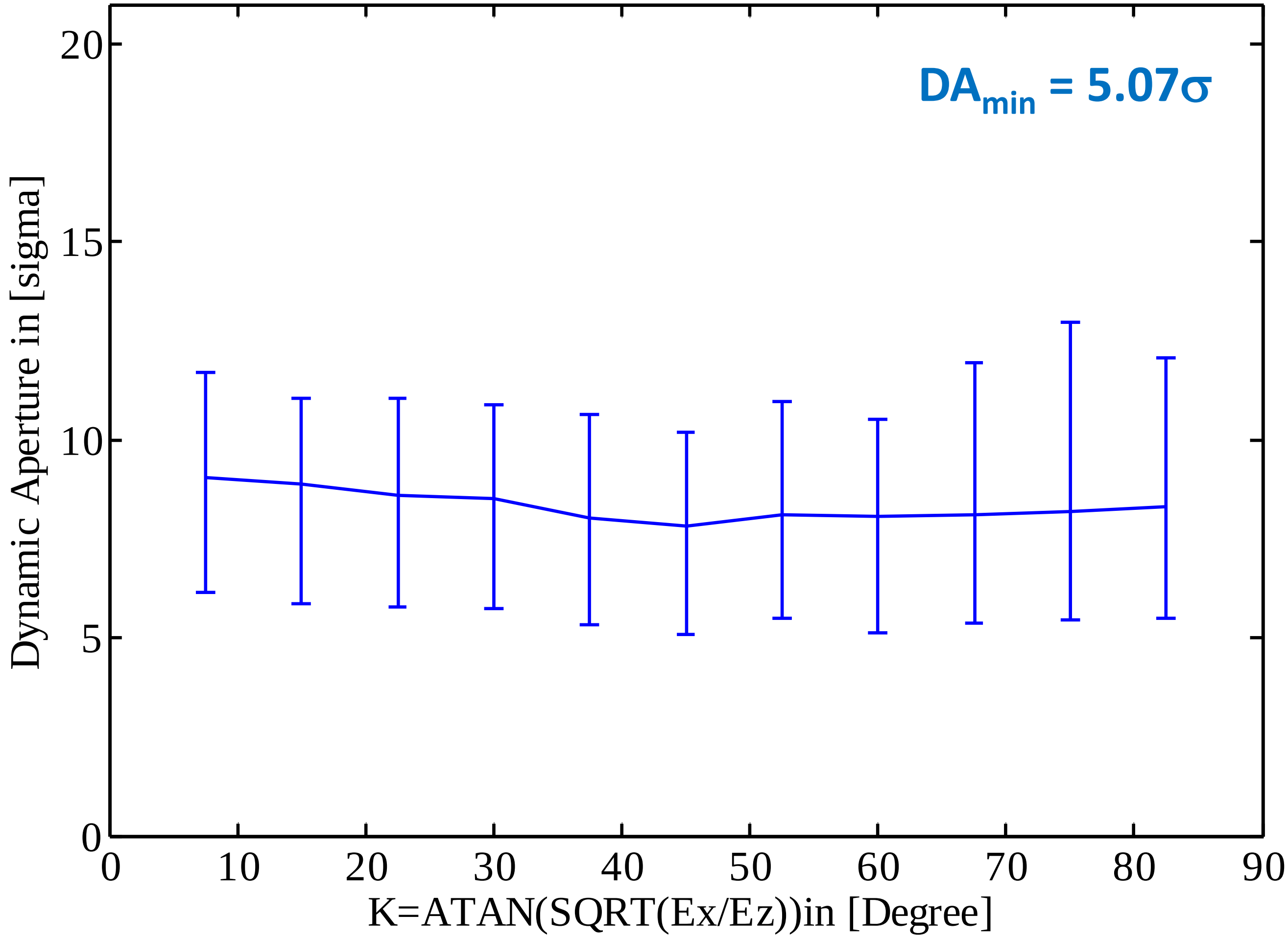
Expected values for multipoles n = 12,13,14 are added from table "ITD1_errortable_v2" (SLHC Project Report 0040)

SixTrack Tracking Set-Up

- 60 random seeds for final tracking, 20 seeds for intermediate multipole scan
- 30 particle pairs per aperture step (2σ)
- 11 angles
- 100,000 turns
- 7 TeV beam energy
- assumed beam emittance (normalized) 3.75 um
- initial $\Delta p/p$ = 2.7e-4
- tune = 62.31, 60.32
- triplet multipole correction, arc errors and corrections are included
- arc errors are always included
- arc errors only is benchmarked against our CERN colleague’s simulation

Dynamic Aperture for Multipole Table “Target3”

The line shows average aperture for 60 seeds and the error bars show the spread between the minimum and maximum aperture for 11 angles

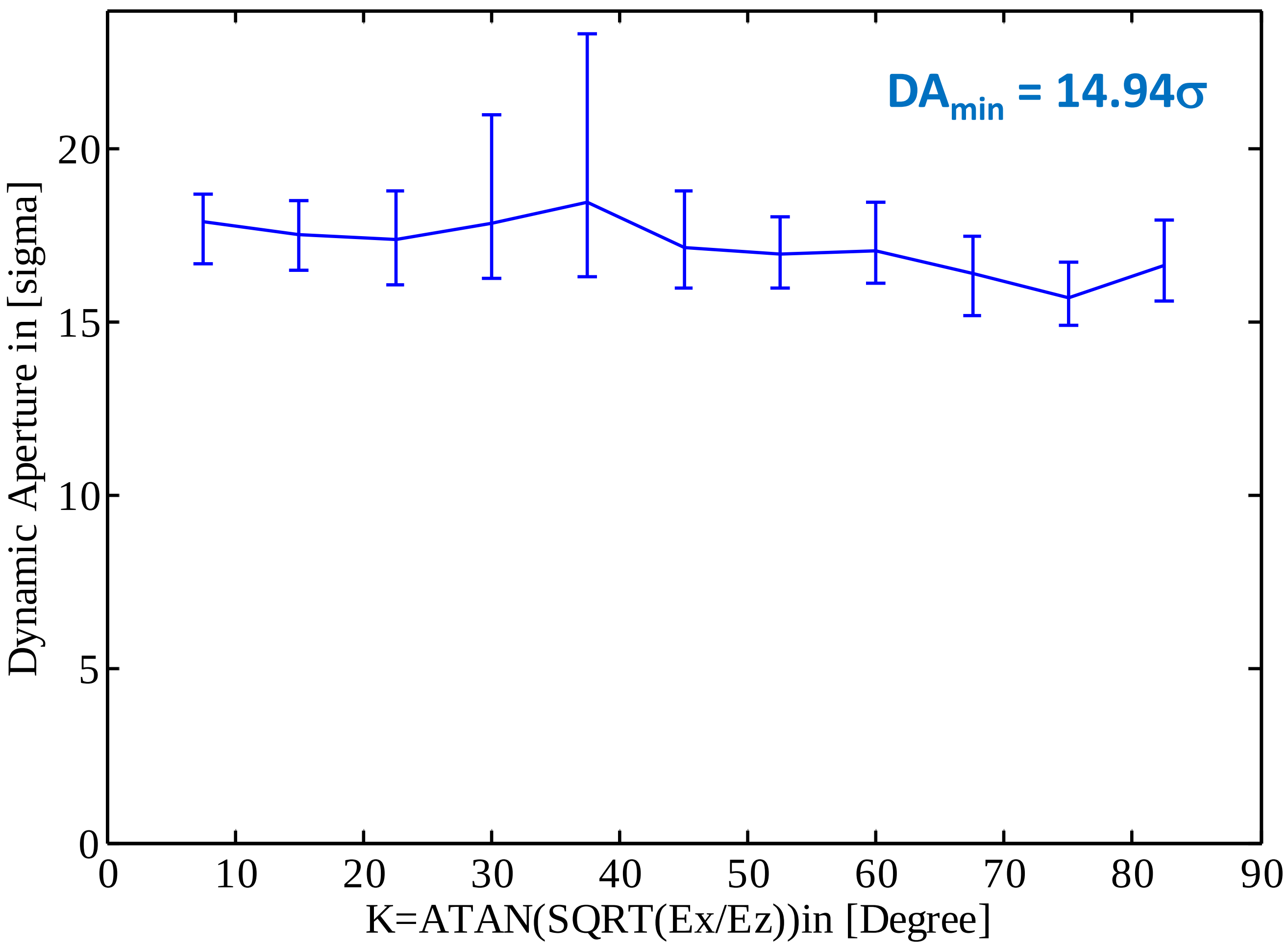


Aperture is too small

Multipole Table "Target31" Scaled from Table "Target3" to β_{max} = 21.5 km

skew	uncertainty	rms		normal	uncertainty	rms
a1	0.00000	0.00000		b1	0.00000	0.00000
a2	0.00000	0.00000		b2	0.00000	0.00000
a3	0.05016	0.06089		b3	0.03963	0.07545
a4	0.03334	0.02920		b4	0.01167	0.01175
a5	0.00516	0.00840		b5	0.00674	0.01281
a6	0.01069	0.01223		b6	0.00972	0.01431
a7	0.00092	0.00150		b7	0.00113	0.00137
a8	0.00042	0.00080		b8	0.00015	0.00027
a9	0.00029	0.00019		b9	0.00019	0.00024
a10	0.00018	0.00030		b10	0.00054	0.00018
a11	0.00007	0.00007		b11	0.00015	0.00015
a12	0.000016	0.000016		b12	0.000016	0.000016
a13	0.000004	0.000004		b13	0.000009	0.000004
a14	0.000008	0.000003		b14	0.000010	0.000003

Dynamic Aperture for Multipole Table "Target31"

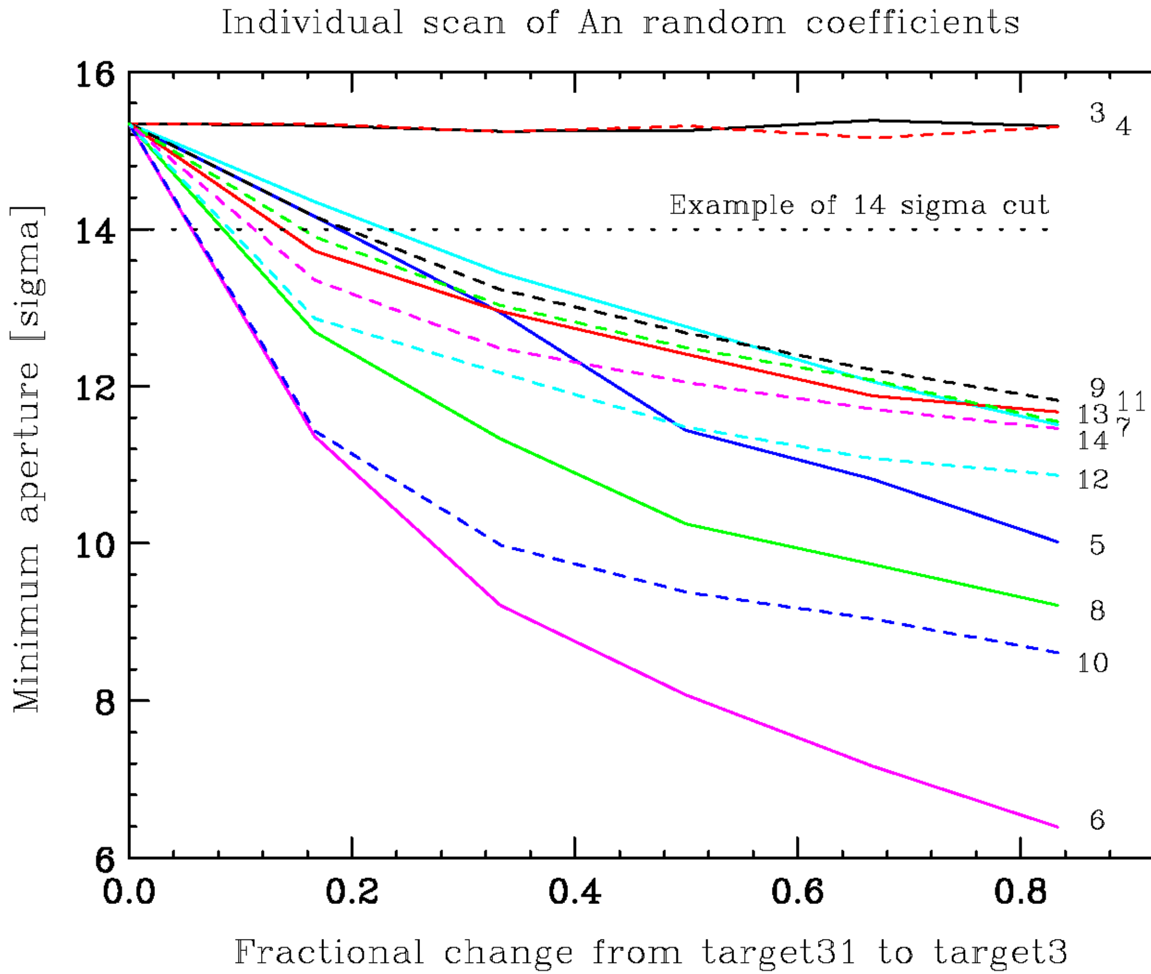


The aperture exceeds the target.

The multipole coefficients can be relaxed somewhat.

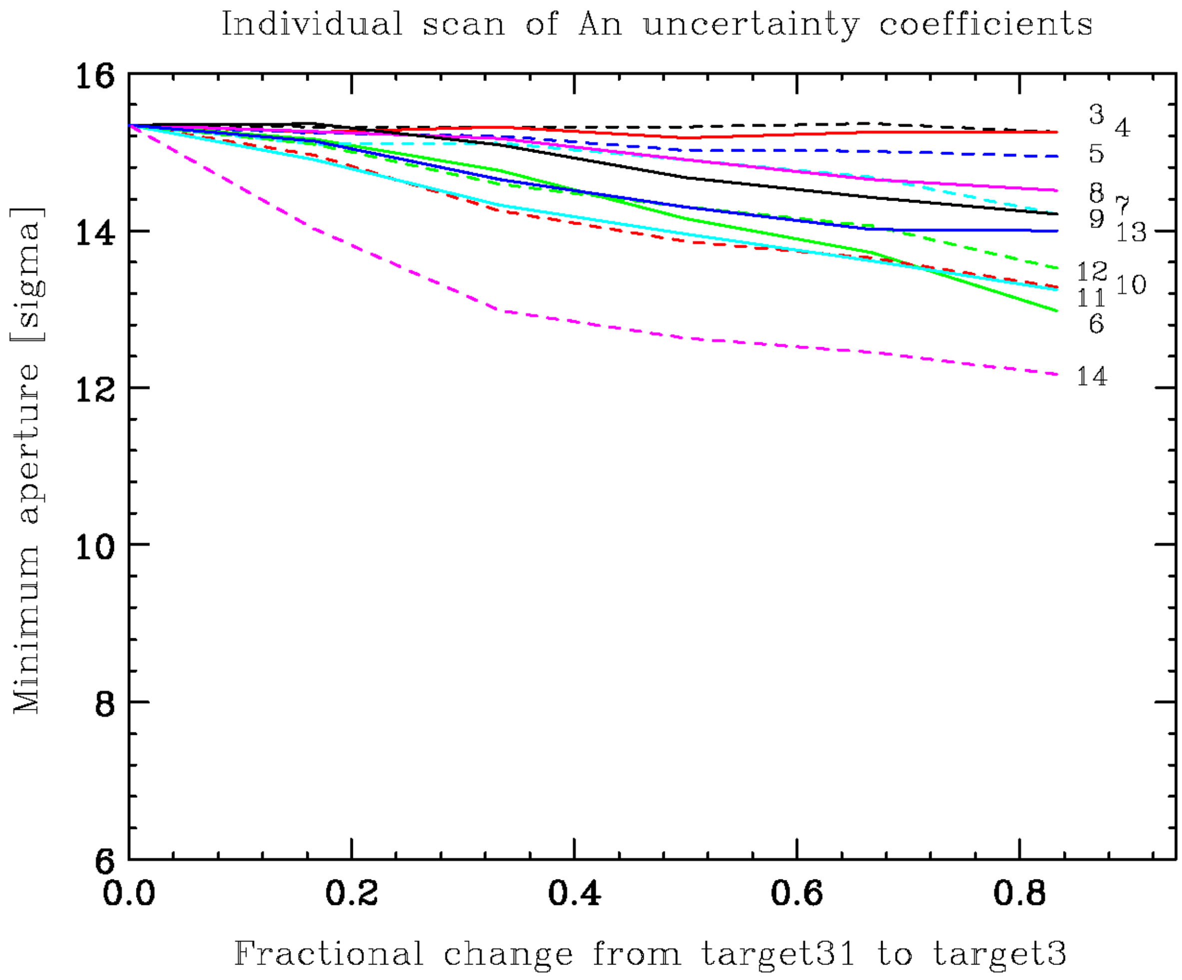
Option-1: Individual Scan of a_n Random Values

Each multipole coefficient is scanned individually between “target3” and “target31” values while other multipoles are at “target31” values.

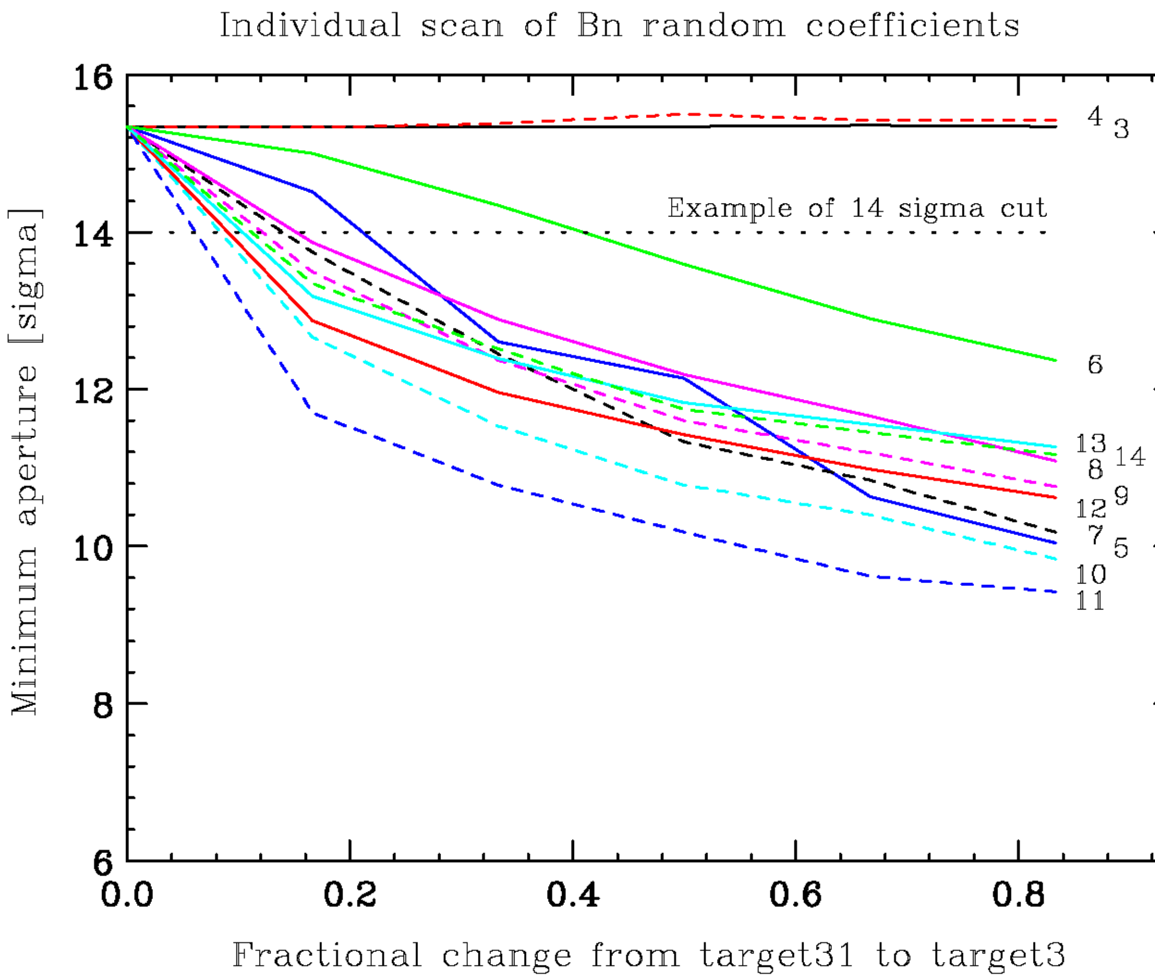


Note the a3, a4 do not affect aperture due to the triplet multipole correctors

Option-1: Individual Scan of a_n Uncertainty Values

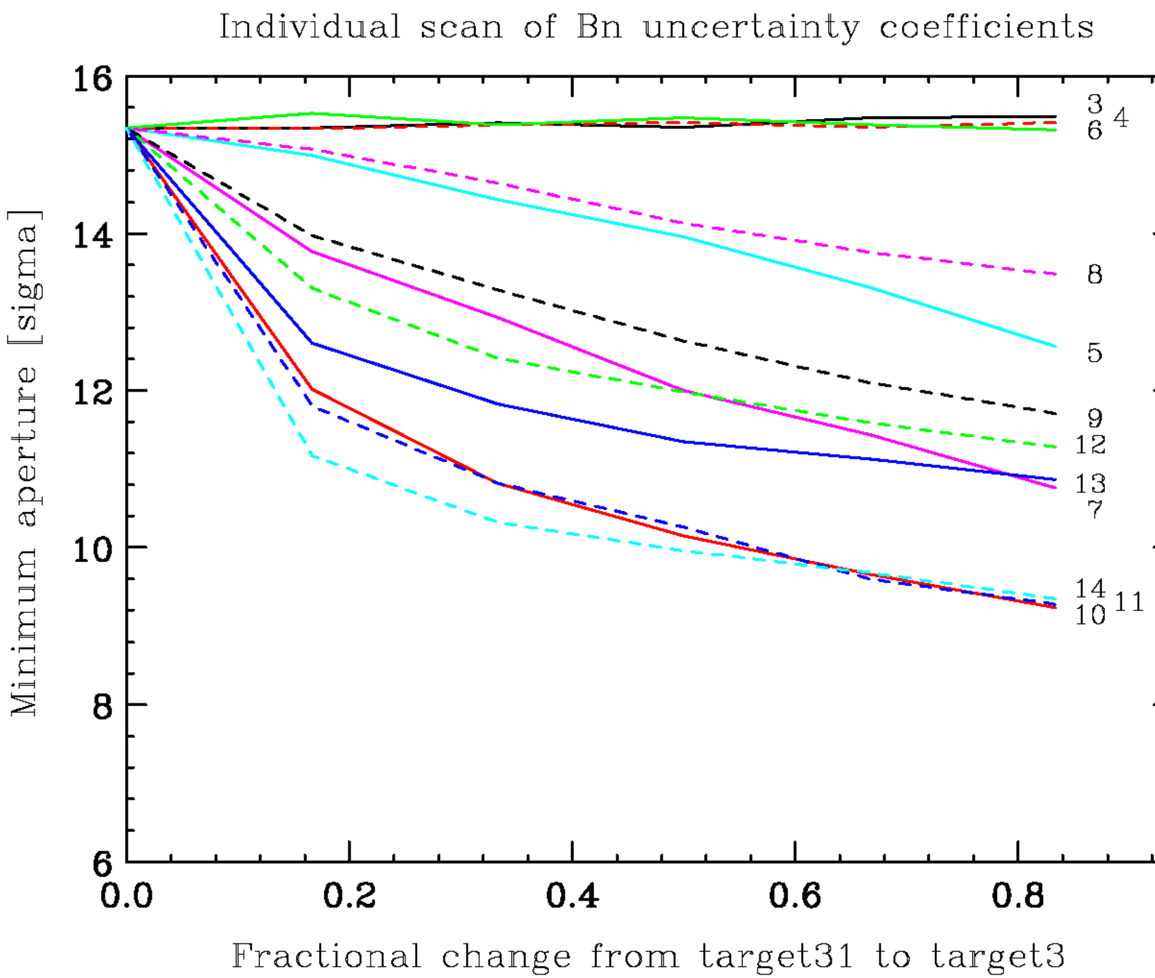


Option-1: Individual Scan of b_n Random Values



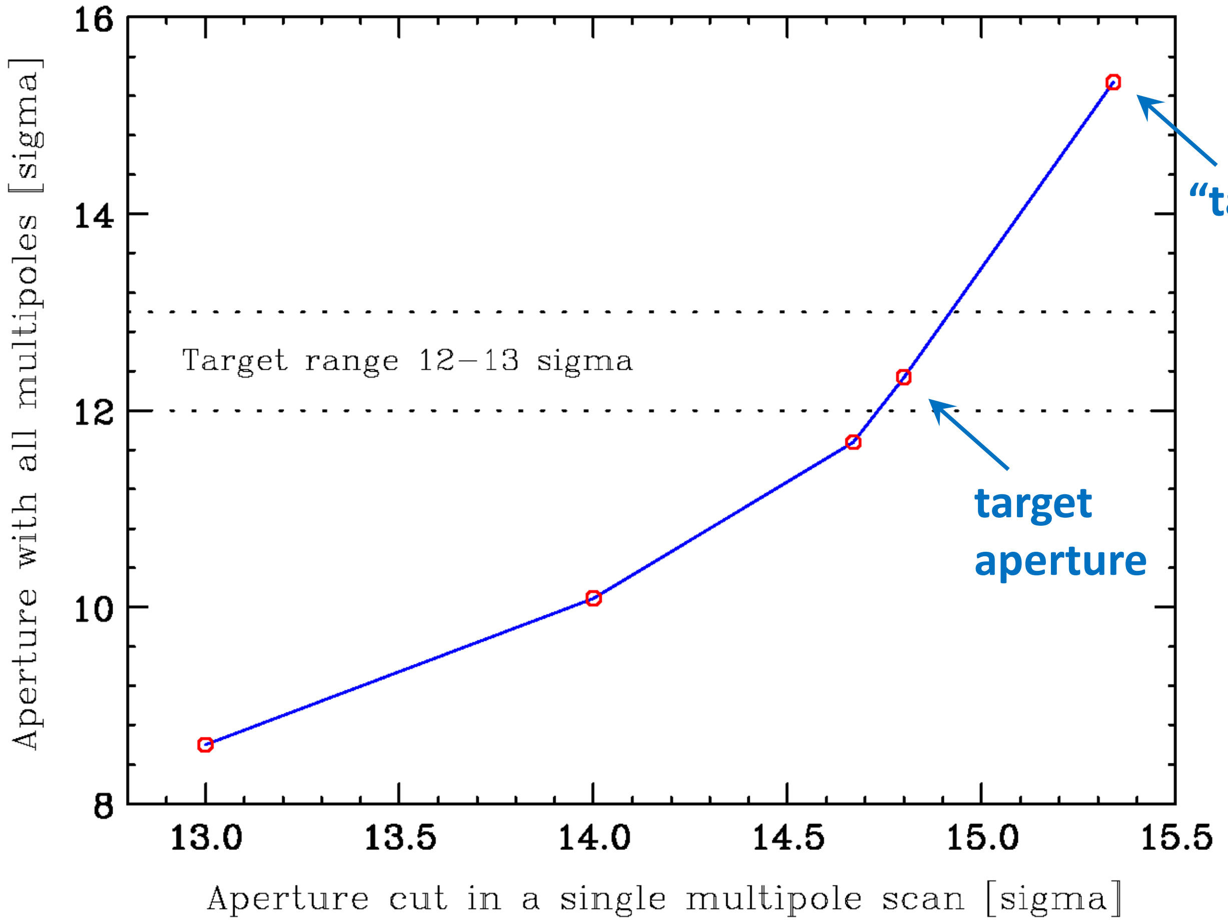
The aperture is not sensitive to b3, b4 due to the triplet multipole correctors, but the b6 still has impact on the aperture.

Option-1: Individual Scan of b_n Uncertainty Values



Option-1: Final Multipole Scaling for Target Aperture

All coefficients are set to correspond to the same value of dynamic aperture in the individual scans (aperture cut). After a few iterations of the aperture cut, the target aperture can be reached. In this case, it corresponds to the aperture cut of 14.8σ, i.e. quite close to the "target31" table.



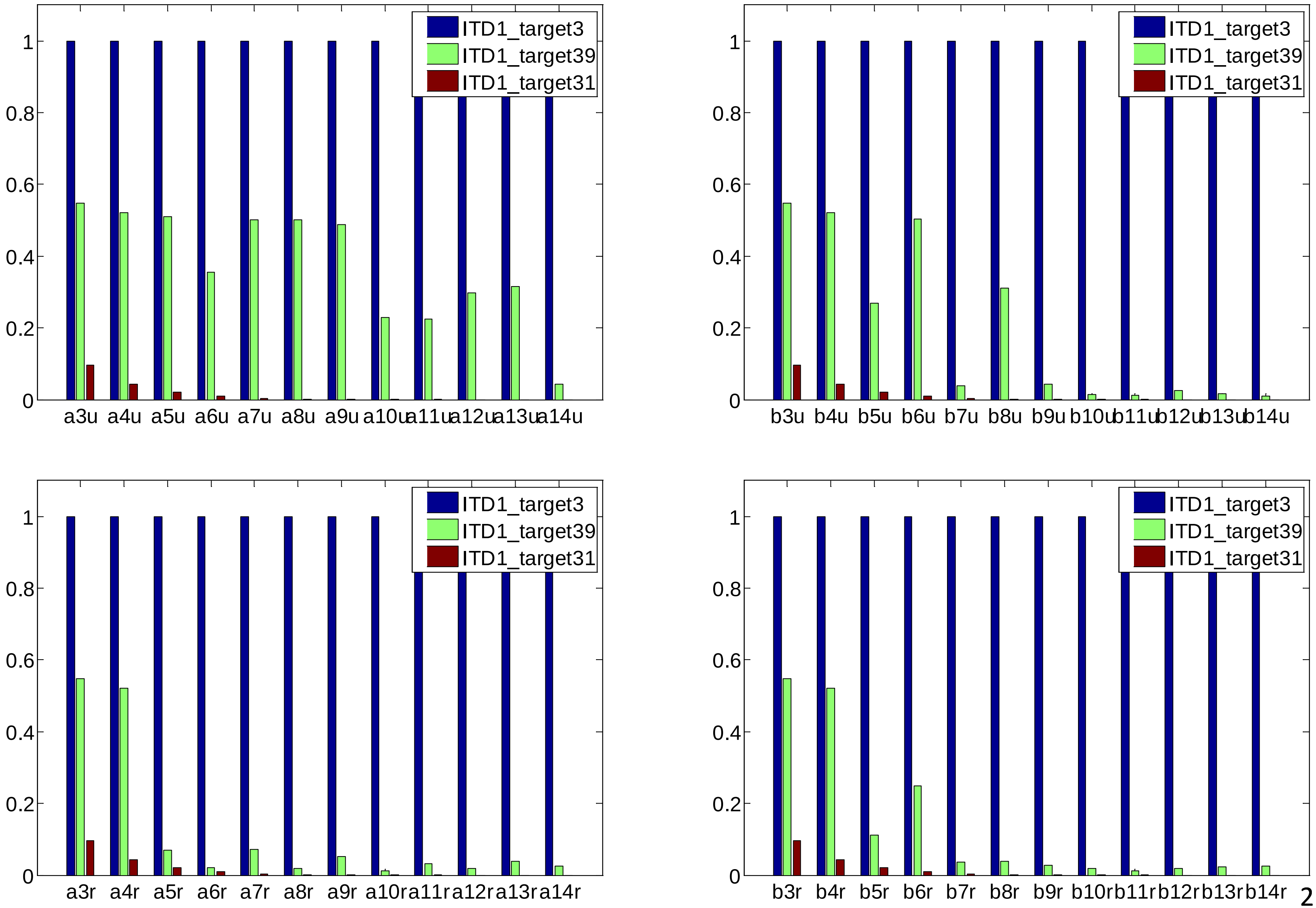
Final Multipole Table “Target39” in Option-1 at r_0=50 mm

skew	uncertainty	rms		normal	uncertainty	rms
a1	0.00000	0.00000		b1	0.00000	0.00000
a2	0.00000	0.00000		b2	0.00000	0.00000
a3	0.28701	0.34839		b3	0.22675	0.43166
a4	0.39722	0.34797		b4	0.13905	0.14002
a5	0.13129	0.02945		b5	0.09018	0.07111
a6	0.41458	0.02698		b6	0.53501	0.38921
a7	0.11063	0.02557		b7	0.01031	0.01215
a8	0.10452	0.00820		b8	0.02766	0.00557
a9	0.15817	0.01044		b9	0.00911	0.00844
a10	0.09435	0.00924		b10	0.01872	0.00674
a11	0.07756	0.00700		b11	0.00820	0.00998
a12	0.05541	0.00354		b12	0.00456	0.00363
a13	0.03679	0.00442		b13	0.00396	0.00268
a14	0.01892	0.00364		b14	0.00611	0.00364

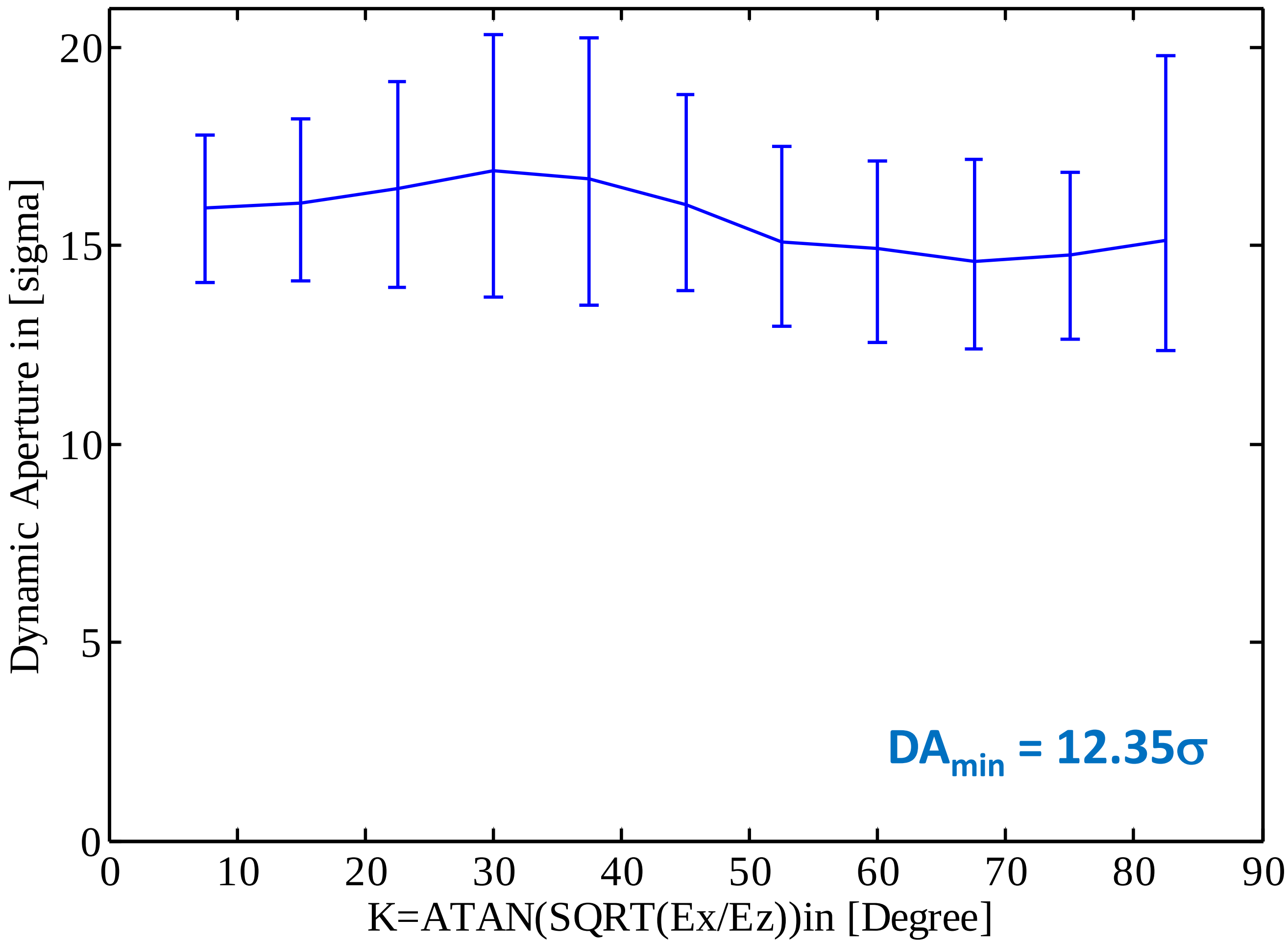
In addition to the described option-1 procedure, in this table we limited the least sensitive coefficients to be not larger than the mid-value between “target3” and “target31” tables in order to help relaxing the other more sensitive coefficients. In this case, the aperture cut is 14.7σ.

Comparison of “Target3”, “Target31” and “Target39” Tables

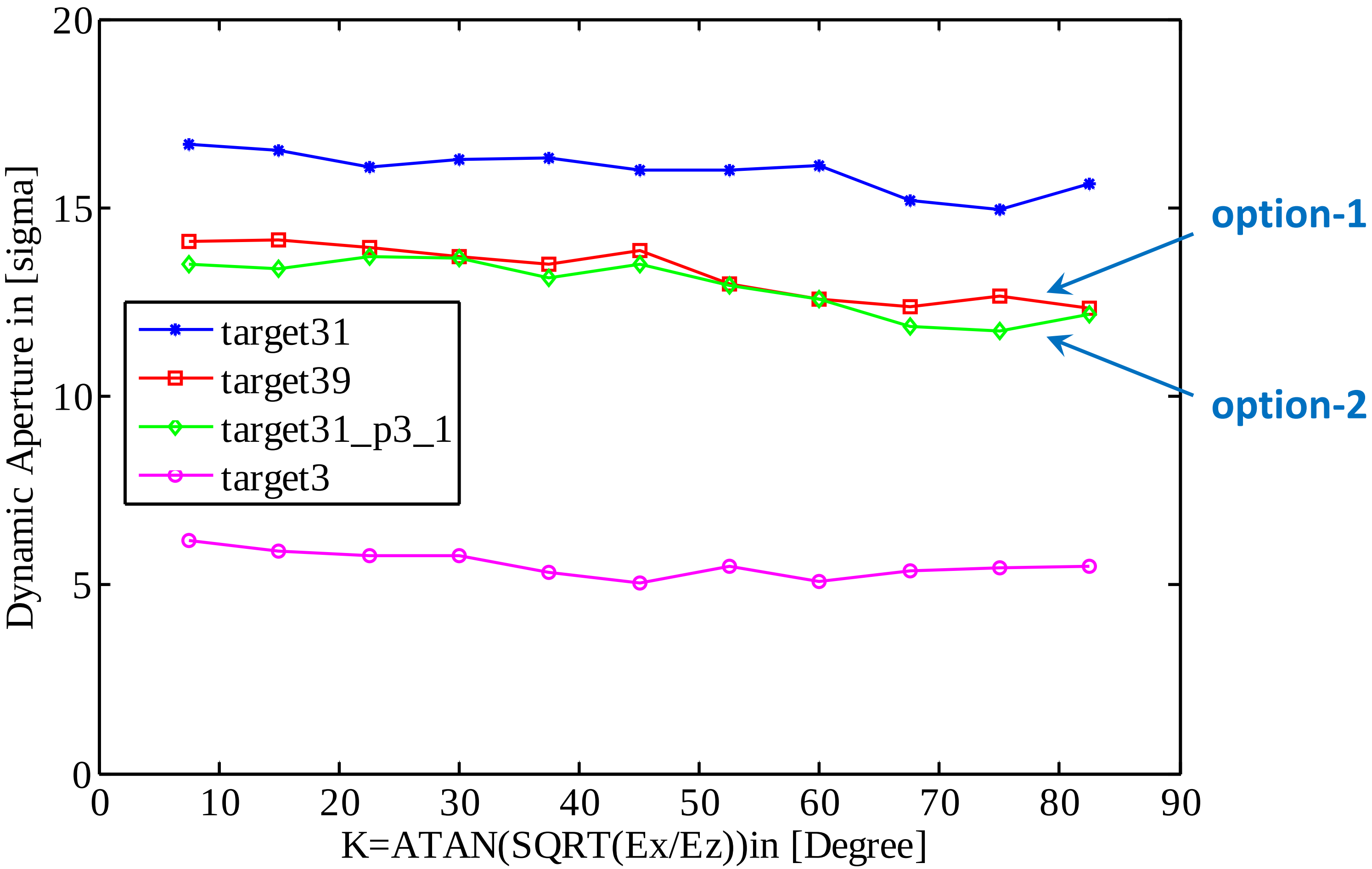
(Normalized to “Target3” Values)



Dynamic Aperture for Multipole Table “Target39”

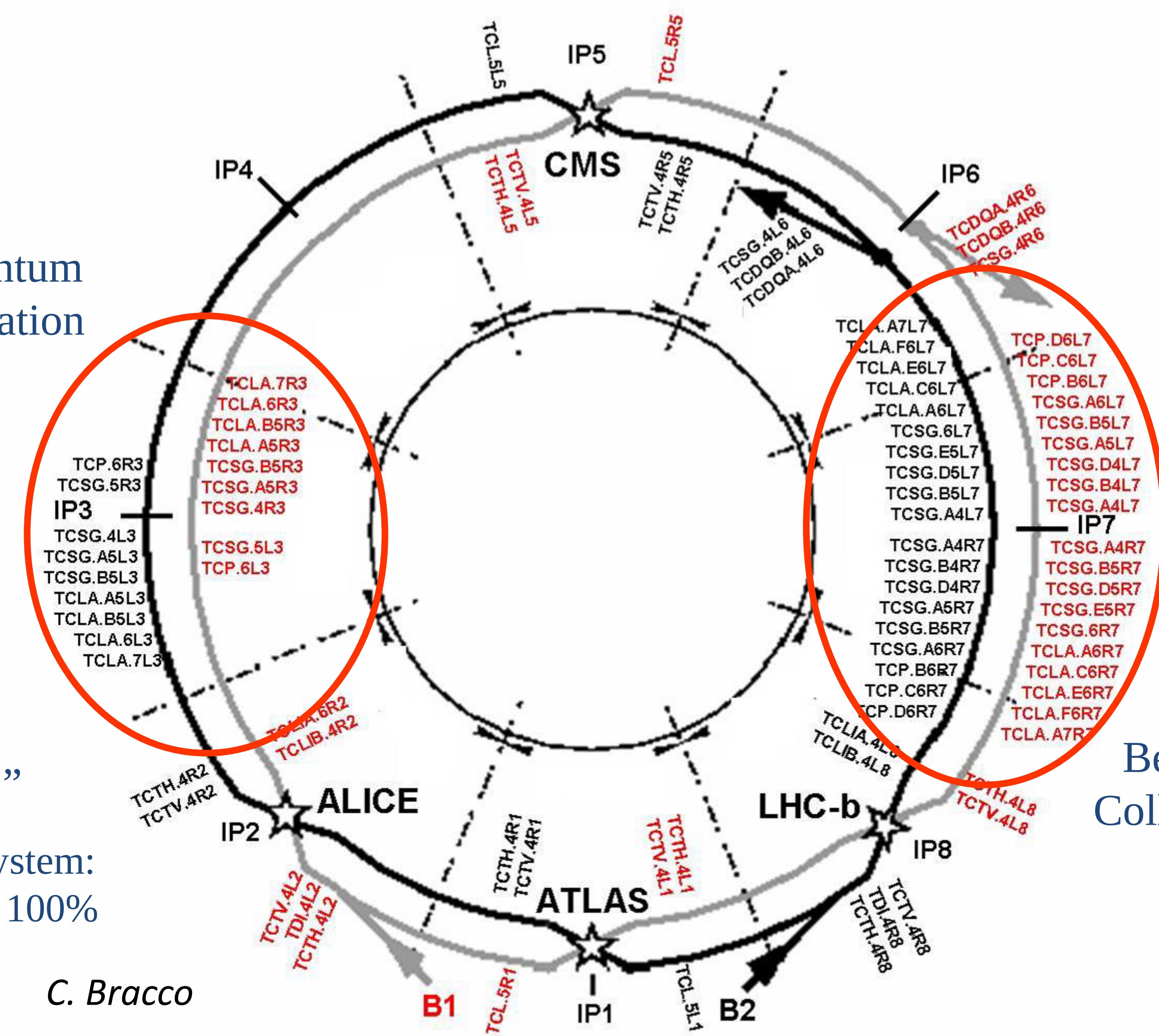


Comparison of Dynamic Aperture



LHC Collimation System

Momentum Collimation



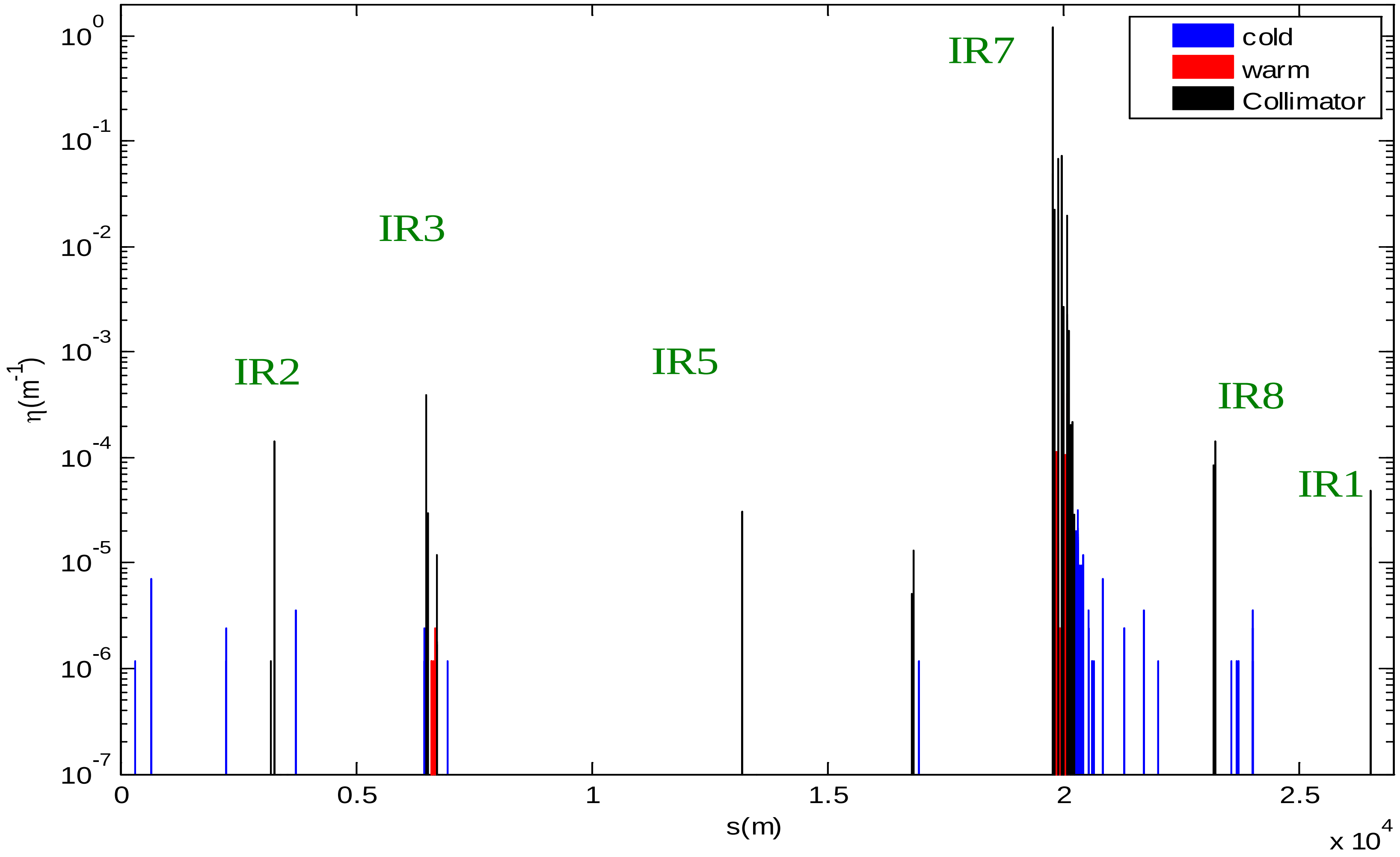
Betatron Collimation

"Phase 1"

"Final" system: Layout is 100% frozen!

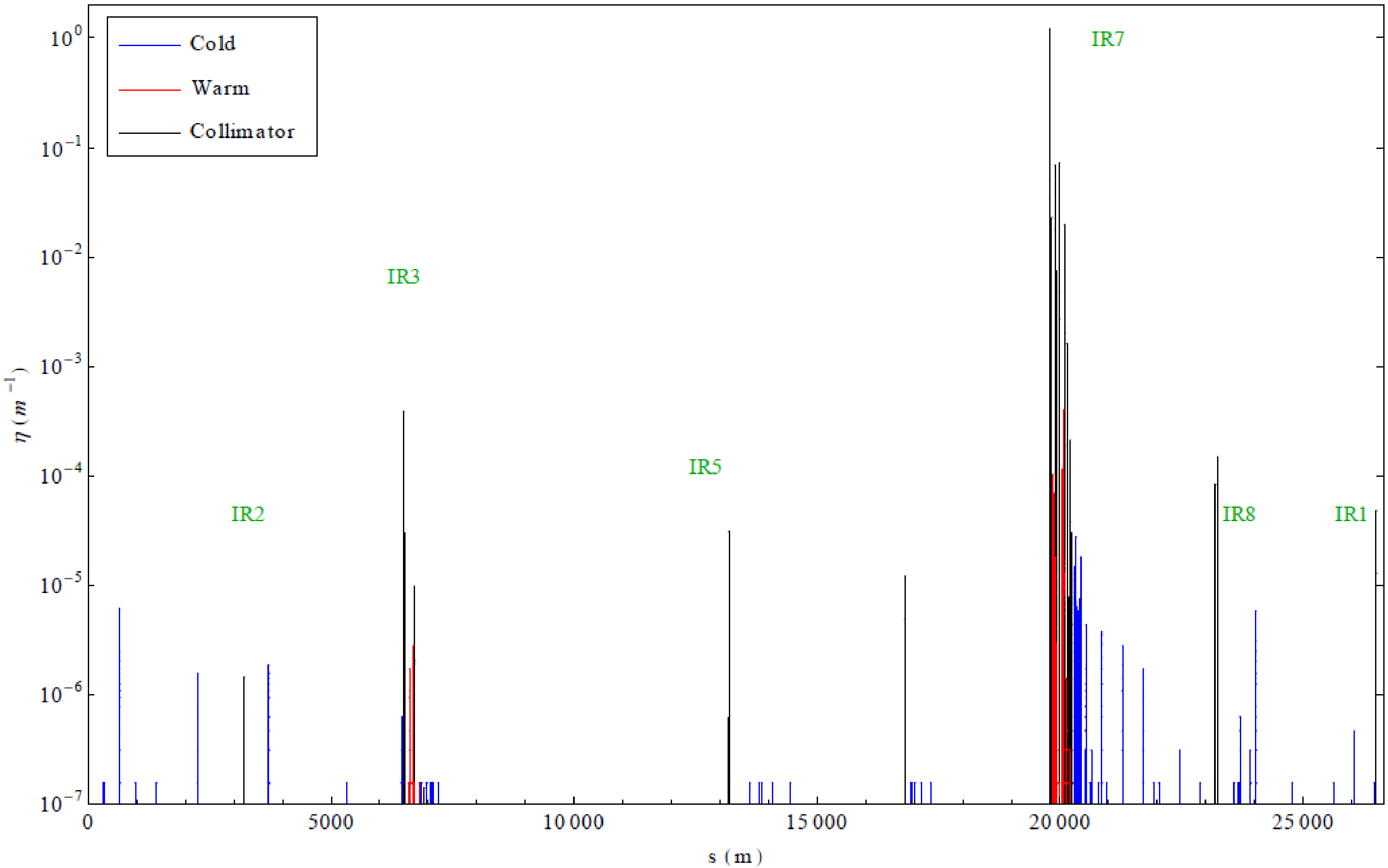
C. Bracco

Beam Loss Map for LHC Collimation System



Loss map of beam-1 at β*=1.5 m with horizontal halo, sheet beam. This is a statistical result of 1000 random seeds with 64*100 particles per seed. This calculation is to benchmark against similar calculation by R. Bruce at CERN (see next page).

Original Loss Map Calculation by Roderik Bruce at CERN



Summary & Plan

• Dynamic aperture has been studied as a function of multipole field errors in the proposed 120 mm aperture triplet quadrupoles for the LHC lattice v.3.01, collision option “4444”.

• As a starting point, the study used the measured field for the nominal triplet quads which was then re-scaled for the new reference radius, larger quad coil diameter and higher triplet peak beta function.

• The target minimum dynamic aperture of 12-13σ has been reached by scanning the triplet multipole field coefficients.

• Calculation of beam loss maps has been successfully benchmarked against a similar calculation at CERN for the nominal lattice.

• Refine specifications and correction schemes for final triplets based on the measurements of the magnets

• Make specifications for the other magnets.