ULTRA-LOW β_y^* OPTICS PROPOSAL WITH NEW FINAL DOUBLET AND BETTER FIELD QUALITY AT ATF2

C. Caliari*[,1], L. Kennedy[1,2], R. Tomás[1]
[1]European Organization for Nuclear Research, Geneva, Switzerland
[2]John Adams Institute, University of Oxford, Oxford, United Kingdom

Abstract

The ultra-low β_y^* optics at the Accelerator Test Facility 2 (ATF2) enables studies of final focus systems under chromatic conditions relevant for future linear colliders. Following the installation of a new final doublet with improved field quality, the achievable beam size and the contribution of nonlinear aberrations are re-evaluated. Using high-order tracking with MAD-NG, the vertical beam size is decomposed into second- and third-order contributions, allowing a quantitative assessment of correction schemes based on sextupole and octupole magnets. In addition, recent emittance measurements provide realistic beam conditions for these studies. Strategies to enhance the experimental observability of octupole corrections are discussed.

INTRODUCTION

Future linear colliders require nanometer-scale beam sizes at the interaction point (IP), placing stringent constraints on final focus systems (FFS). ATF2 was designed to demonstrate the feasibility of local chromaticity correction and has successfully achieved vertical beam size of 41 nm [1–3].

To probe more demanding conditions relevant for CLIC [4], the ultra-low β_y^* optics reduces the vertical beta function at the IP, increasing chromaticity and sensitivity to higher-order aberrations [5]. In this regime, multipole components and fringe fields in the final doublet introduce significant nonlinear effects that limit the achievable beam size.

Recently, the final doublet magnets were replaced by a new set with improved field quality. This upgrade motivates a re-evaluation of beam size limitations and correction strategies. Previous calculations of the beam size contributions by aberrations order [6] used PTC [7] and MapClass [8] codes. This work exploits a new implementation using MAD-NG [9]. Combined with the installation of a new final doublet and recent emittance measurements from March 2026, this enables a systematic reassessment of sextupole and octupole correction strategies under realistic beam conditions.

ULTRA-LOW β_y^* OPTICS

The ultra-low β_y^* optics aims to reproduce chromaticity levels comparable to those expected in the CLIC final focus system. The vertical chromaticity approximately scales as

$$\xi_y \approx \frac{L^*}{\beta_y^*} \, . \qquad (1)$$

* conrad.caliari@cern.ch

Table 1: Vertical RMS Beam Size for the New Final Doublet in Case All Correctors Are Optimized. The Sizes Are Calculated for the Nominal Emittances, see Table 3.

Order	ultra-low β_y^* [nm]	nominal β_y^* [nm]
1	17.32	34.48
2	17.51	34.51
3	22.72	36.02
	...	
7	23.63	36.44

Starting from the nominal optics with $\beta_y^* = 100\,\mu\text{m}$, the ultra-low configuration sets $\beta_y^* = 25\,\mu\text{m}$, corresponding to an increase in chromaticity by a factor of four. Figure 1 displays linear optics functions along the ATF2 final focus. This regime enhances sensitivity to higher-order aberrations, making ATF2 a unique testbed for nonlinear correction schemes.

To mitigate nonlinear effects, the horizontal beta function at the IP can be increased by a factor of 10 called the 10×1 or 10×0.25 optics for the nominal or ultra-low β_y^*, respectively. Consequently, the average horizontal β-function along the FFS is reduced by a factor of 10, reducing sensitivity to field errors to the level expected at ILC [10]. However, it is undesirable to apply this approach to an actual linear collider as luminosity would be decreased by $\approx 1/3$. In addition, dedicated sextupole and octupole correctors are available to compensate higher-order aberrations and minimize the beam size at the IP.

QUANTIFICATION OF NONLINEAR ABERRATIONS

The vertical rms beam size is evaluated using high-order tracking in MAD-NG following the approach outlined in [6]. This allows for decomposition into contributions from different orders of the transfer map, see Table 1.

The vertical rms beam size achieved by applying order-by-order corrections for the old and new final doublet is shown in Fig. 2. The calculation for nominal emittances considers measured higher-order magnetic multipole errors for bending, quadrupole and sextupole magnets. Second-order aberrations, dominated by chromatic effects, represent the main limitation after linear optics correction. These contributions are effectively compensated using the five upright sextupole together with the four skew sextupoles magnets. With all sextupole correctors optimized, the vertical beam size approaches the design target, demonstrating that second-order aberrations can be largely controlled.

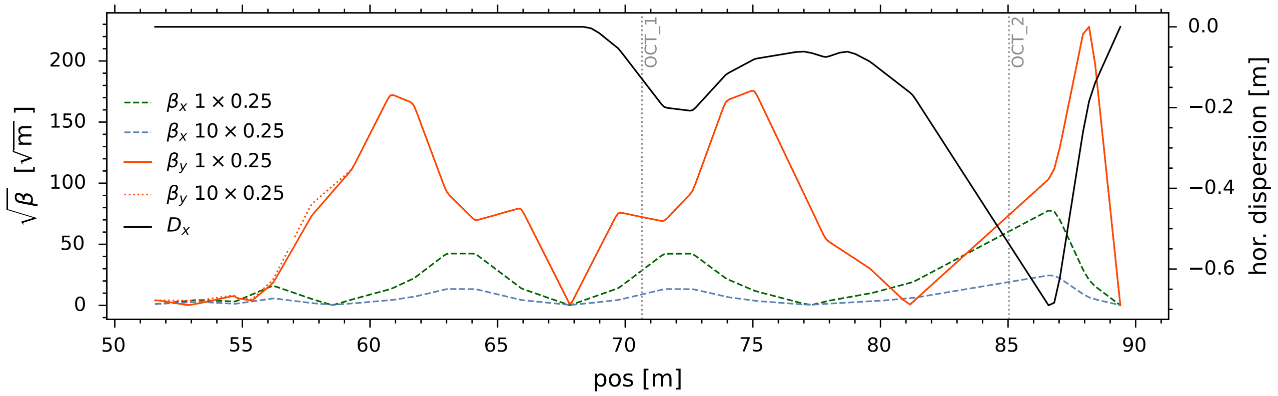

Figure 1: Vertical (orange) and horizontal β-function for the nominal 1×0.25 (green) and relaxed 10×0.25 (blue) for the ultra-low β_y^* optics. The horizontal dispersion is shown in black. The location of the octpole correctors OCT1 and OCT2 is indicated in gray.

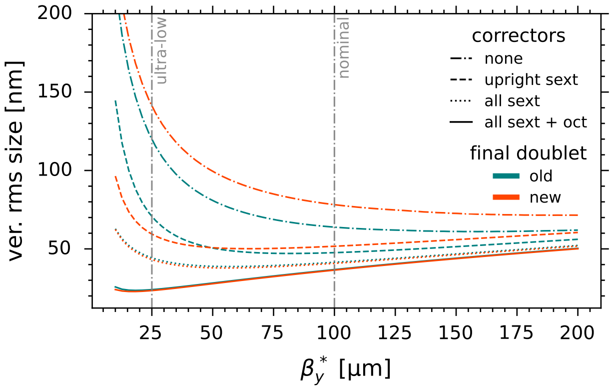

Figure 2: Achievable vertical rms beam size for the nominal β_x^* for the old and new final doublet. The dash pattern indicates whether upright sextupoles, upright and skew sextupoles or all sextupoles in combination with octupoles are powered to correct aberrations. The beam size is calculated using nominal emittances and by taking aberrations up to 7th-order into account.

After correction of second-order aberrations, third-order terms become the dominant limitation to the achievable beam size. These contributions arise primarily from multipole components and fringe fields in the final doublet. The remaining third-order aberrations increase the vertical beam size significantly, particularly for the ultra-low β_y^* optics where the sensitivity to nonlinear effects is enhanced.

The new final doublet quadrupoles exhibit reduced higher-order multipole components for the dominant 2nd- and 3rd-order terms, as shown in Table 2. This results in a slight increase in the rms vertical beam size compared to the old doublet: the multipole errors of the previous magnets, while uncontrolled, happened to partially cancel upstream chromatic aberrations. With the new, cleaner doublet, this accidental compensation is absent, and the residual beam size is determined more purely by the optical design rather than error-driven cancellations. In case skew sextupole and octupole corrector magnets are powered, similar beam sizes of 36.4 nm and 23.6 nm are reachable for the 1×1 and 1×0.25 optics, respectively.

OCTUPOLES CORRECTION OF THIRD-ORDER ABERRATIONS

Two octupole magnets installed in ATF2 provide a means to compensate dominant third-order aberrations [11]. Simulations with the new final doublet indicate that, with all sextupole correctors optimized, octupole correction reduces the vertical beam size from 36.4 nm to 23.6 nm for the 1×0.25 optics — a reduction driven primarily by the cleaner multipole content of the new quadrupoles, which removes the accidental third-order cancellations present in the old doublet. However, the Shintake monitor, with a typical resolution of order a few nanometers near its design operating point, faces difficulty resolving changes in beam size around 30 nm. Furthermore, under typical experimental conditions, where beam sizes remain well above the design regime, the relative contribution of third-order terms is diluted by larger lower-order residuals, making the octupole effect difficult to isolate directly. Beam-based alignment of the octupoles is sucessfully demonstrated by monitoring the β-function waist shift at the IP [12].

Recent measurements performed in March 2026 using the mOTR system [13] yield horizontal and vertical emittances of approximately 1.4 nm and 30 pm in non-optimized damping ring conditions, see Table 3. These values exceed the nominal design parameters by factors of approximately 1.1 and 2.5 in the horizontal and vertical planes, respectively. Rather than treating this as a limitation, the elevated emittance can be exploited to enhance the experimental observability of octupole corrections: larger emittances increase the beam size and amplify the contribution of higher-order aberrations, shifting the operating point into a regime where third-order effects are more prominent and corrections more easily resolved.

Two complementary simulation-based strategies are considered, both targeting operating conditions where the octupole effect is large enough to be resolved by the Shintake

Table 2: Comparison of Relative Strengths of the Multipole Components w.r.t. the Upright Quadrupole Component for the Old and New Final Doublet Magnets. The Units are m^{1-n} for a Given Order n.

	QF1				QD0			
	Old		New		Old		New	
Order	**Up**	**Skew**	**Up**	**Skew**	**Up**	**Skew**	**Up**	**Skew**
2	1.72×10^{-3}	-2.72×10^{-3}	-3.30×10^{-4}	-1.57×10^{-4}	1.84×10^{-2}	-1.76×10^{-2}	3.48×10^{-6}	-1×10^{-4}
3	-1.83×10^{-1}	3.12×10^{-2}	2.02×10^{-1}	-3.28×10^{-4}	-1.32	-8.55×10^{-1}	1.65×10^{-3}	2.1×10^{-3}
4	-8.97×10^{-1}	-4.35	-6.63×10^{1}	5.66×10^{-2}	-7.79×10^{2}	-3.63×10^{2}	-3.39×10^{-2}	1.26×10^{-1}
5	5.37×10^{3}	-1.29×10^{2}	7.35	-6.99×10^{-2}	-2.16×10^{6}	-1.31×10^{5}	-7.46×10^{1}	-1.32×10^{-1}
6	2.26×10^{4}	-1.68×10^{4}	8.83×10^{2}	-1.44×10^{1}	1.28×10^{7}	-1.56×10^{7}	-1.92×10^{1}	-5.07×10^{1}

Table 3: Geometric Emittances in ATF2 for the Damping Ring (DR) Being Either Tuned or Not. a) Measured in March 2026 using the mOTR system. b) Emittances Measured in [3] Using the Shintake-Monitor.

	ϵ_x [nm]	ϵ_y [nm]
nominal design	1.2	12
DR not tuned $^{a)}$	1.362(377)	29.77(45)
DR tuned $^{b)}$	-	7.7(3)

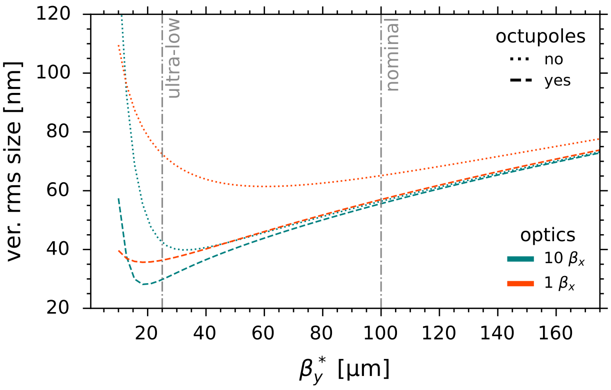

Figure 3: ATF2 vertical rms beam size as a function of β_y for the nominal and 10-times larger β_x in case of relaxed emittances $\epsilon_x = 1.4$ nm, $\epsilon_y = 30$ pm. Dashed and dotted lines indicate 7th-order beam sizes with and without octupole correction, respectively. Simulations include all known nonlinear multipole components.

monitor. The first approach operates in 10×0.25 optics for non-optimized emittances ($\epsilon_x = 1.4$ nm, $\epsilon_y = 30$ pm). Simulated vertical rms beam sizes are shown in Fig. 3. With all sextupole correctors optimized, octupole correction reduces the vertical beam size from 42.4 nm to 29.8 nm. This reduction of 13 nm, crossing the operationally significant 40 nm threshold, is well within the resolution of the Shintake monitor, which has been demonstrated to resolve beam sizes in this range.

The second approach applies the 1×0.25 ultra-low β_y^* optics at nominal emittances. Here, the increased chromaticity enhances sensitivity to third-order aberrations even without elevated emittance. Simulations indicate that octupole correction reduces the vertical beam size from 44.5 nm to 23.2 nm — a reduction of 21 nm that represents the more demanding but higher-impact demonstration scenario. Both strategies remain to be validated experimentally and are contingent on achieving sufficient sextupole tuning as a prerequisite. The choice between them will depend on the damping ring tuning state achievable during a dedicated run.

CONCLUSION

The ultra-low β_y^* optics at ATF2 has been re-evaluated following the installation of a new final doublet, using MAD-NG as a replacement for the PTC/MapClass framework. The vertical beam size decomposition confirms that second-order aberrations can be largely controlled with sextupole correctors. Third-order contributions cannot be fully compensated with the available octupoles, leaving final beam sizes of 23.6 nm and 36.4 nm for the ultra-low and nominal β_y^* optics respectively.

The improved field quality of the new doublet removes accidental error-driven cancellations present in the old magnets, making the correction landscape more predictable.

Two simulation-based strategies are proposed to bring the octupole effect within the resolution of the Shintake monitor: operating in 10×0.35 optics with easily achievable non-optimized emittances, or exploiting the enhanced chromaticity of the 1×0.25 optics at nominal emittances. Experimental validation is the natural next step, contingent on achieving the required sextupole tuning baseline, and will inform the design of final focus correction schemes for future linear colliders such as CLIC and ILC.

REFERENCES

[1] T. Okugi, "Achievement of Small Beam Size at ATF2 Beamline", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 27–31. doi:10.18429/JACoW-LINAC2016-MO3A02

[2] R. Yang *et al.*, "Tuning the ultralow β^* optics at the KEK Accelerator Test Facility 2", *Phys. Rev. Accel. Beams*, vol. 23, no. 7, p. 071003, 2020. doi:10.1103/PhysRevAccelBeams.23.071003

[3] M. Patecki *et al.*, "Probing half β_y^* optics in the Accelerator Test Facility 2", *Phys. Rev. Accel. Beams*, vol. 19, no. 10,

p. 101001, 2016.
doi:10.1103/PhysRevAccelBeams.19.101001

[4] E. Sicking and R. Ström, “From precision physics to the energy frontier with the Compact Linear Collider”, *Nature Phys.*, vol. 16, no. 4, pp. 386–392, 2020.
doi:10.1038/s41567-020-0834-8

[5] R. Tomás *et al.*, “ATF2 Ultra-Low IP Betas Proposal”, in *Proc. PAC’09*, Vancouver, Canada, May 2029, pp. 2540–2542, 2010.

[6] R. Tomás, “Nonlinear optimization of beam lines”, *Phys. Rev. ST Accel. Beams*, vol. 9, p. 081001, 2006.
doi:10.1103/PhysRevSTAB.9.081001

[7] P. K. Skowronski, F. Schmidt, and E. Forest, “Advances in MAD-X using PTC”, *Conf. Proc. C*, vol. 070625, p. 3381, 2007. doi:10.1109/PAC.2007.4440432

[8] R. Tomás, “MAPCLASS: a code to optimize high order aberrations”, CERN, Geneva, Rep. AB-Note-2006-017, CERN-AB-Note-2006-017, 2006. https://cds.cern.ch/record/944769

[9] L. Deniau, “MAD-NG, a standalone multiplatform tool for linear and non-linear optics design and optimisation”, 2025, arXiv: 2412.16006 [cs.CE],

[10] T. Okugi *et al.*, “Linear and second order optics corrections for the KEK Accelerator Test Facility final focus beam line”, *Phys. Rev. ST Accel. Beams*, vol. 17, no. 2, p. 023501, 2014.
doi:10.1103/PhysRevSTAB.17.023501

[11] R. Tomas Garcia, M. Modena, and F. Plassard, “Low-β^* Study and Octupoles”, CERN, Geneva, Rep. Rep. E-Jade.Del.9-BeamSize-1-v1.0, Mar. 2017. https://www.e-jade.eu/sites/sites_custom/site_e-jade/content/e49893/e65922/e65932/D9.WP2.Beamsize1.pdf

[12] A. Pastushenko *et al.*, “Tunability Study of the Ultra-Low β^* Optics at ATF2 with New Octupole Setup and Tuning Knobs”, pp. 752–755.
doi:10.18429/JACoW-IPAC2021-MOPAB231

[13] A. Faus-Golfe, J. Navarro, N. Fuster Martinez, J. Resta Lopez, and J. Giner Navarro, “Emittance reconstruction from measured beam sizes in ATF2 and perspectives for ILC”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 819, pp. 122–138, 2016.
doi:10.1016/j.nima.2016.02.064