CERN-BINP workshop for young scientists in e+e- colliders

Beam tuning simulations for ATF2 low beta* optics

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- Motivation for ultra-low β^* in ATF2
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- Tuning simulations:
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  - Optical aberrations
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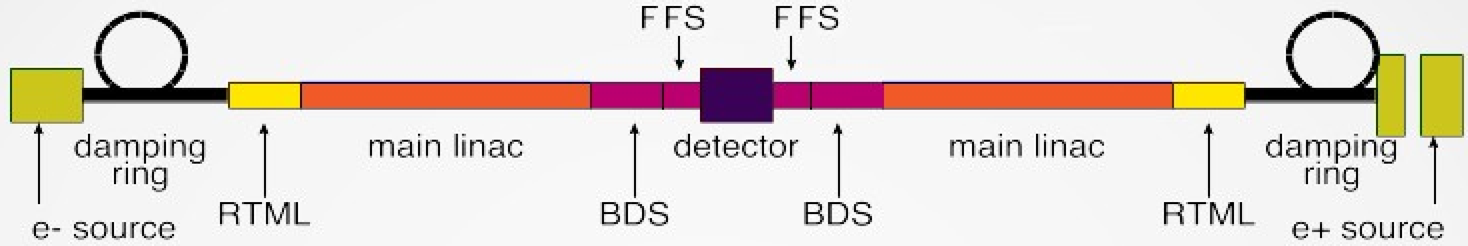
Final focus system for future linear colliders



- High luminosity is one of the most important requirements for particle colliders:

$$L = \frac{N_p^2 n_b f_{rep}}{4\pi \sigma_x^{IP} \sigma_y^{IP}} H_D$$

N_p – number of particles per bunch
n_b – number of bunches per train
f_{rep} – trains repetition rate
σ^{IP} – transverse beam size at the IP
H_D – luminosity enhancement factor

- Beam delivery system (BDS) acts on the beam coming from the main linac and prepares the beam (collimation, diagnostics, matching) for focusing.

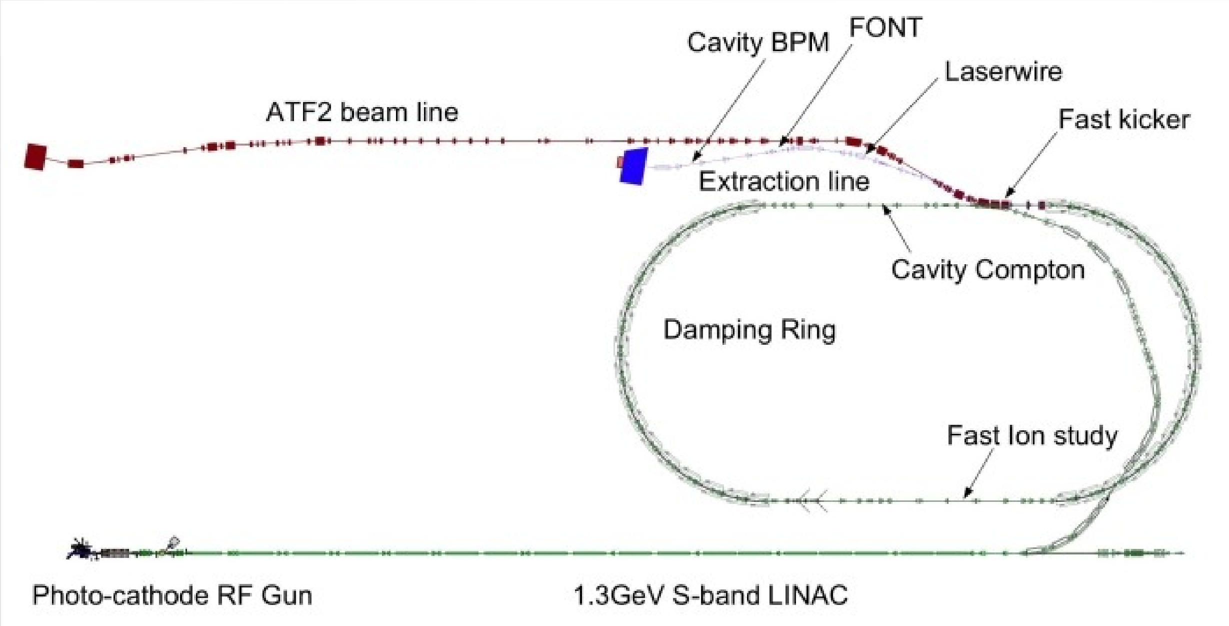
- Final focus system (FFS) is the last part of BDS where two strong quadrupole magnets focus the beam to be collided with a smallest possible beam size.

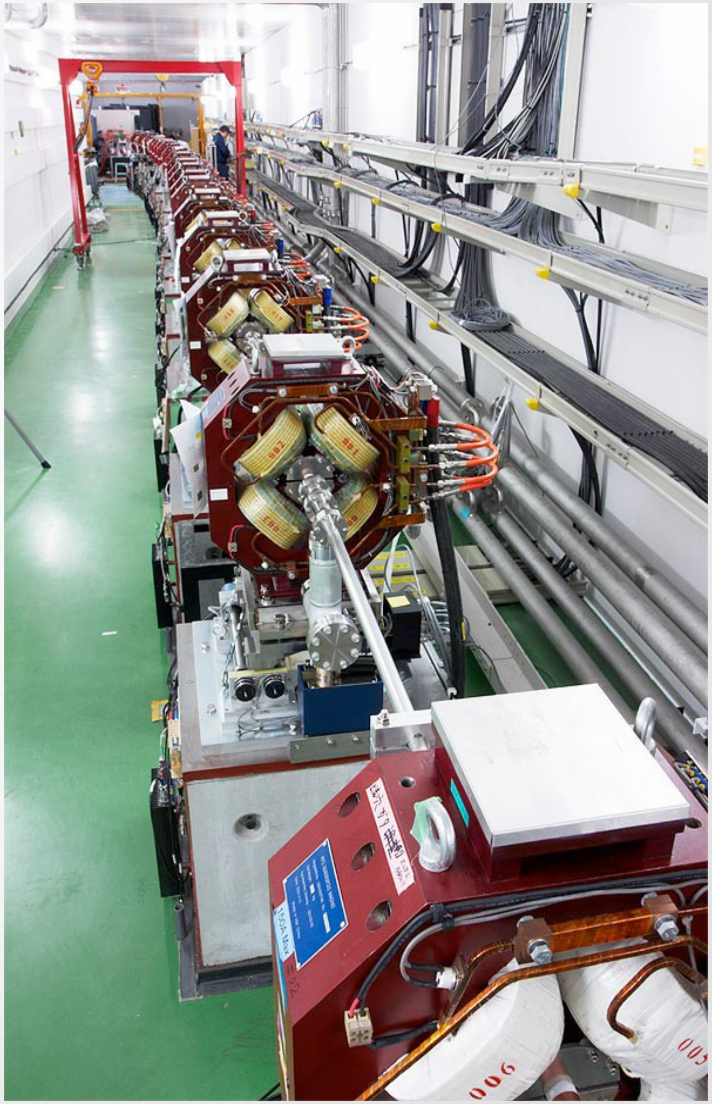
$$\sigma_{x,y}^{IP} = \sqrt{\frac{\beta_{x,y} \varepsilon_{x,y}}{\gamma}}$$

β – optical function, characterizes the focusing strength
ε – beam emittance
γ – relativistic factor

Accelerator Test Facility ATF2

- Test facility for future linear colliders located in KEK in Japan
- **World record of smallest vertical beam size: < 45 nm (design is 37 nm).**
- First Final Focus beam line using a local chromaticity correction scheme.





Motivation for ultra-low β* in ATF2

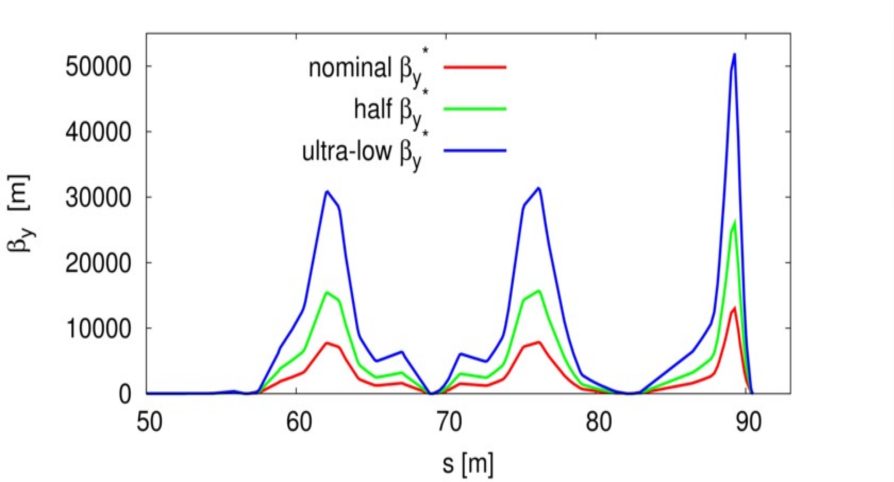
- **ATF2 ultra-low β* project aims to test a Final Focus System at the chromaticity level similar to CLIC.**
  - Larger chromaticity ξ makes the Final Focus System more difficult to operate.
  - Level of chromaticity ξ_y in ATF2 is comparable to ILC.
- **Ultra-low β* optics also reduces the IP vertical beam size to 20 nm. Close to linear collider beam sizes.**
- **Octupole magnets for stronger beam focusing are required.**

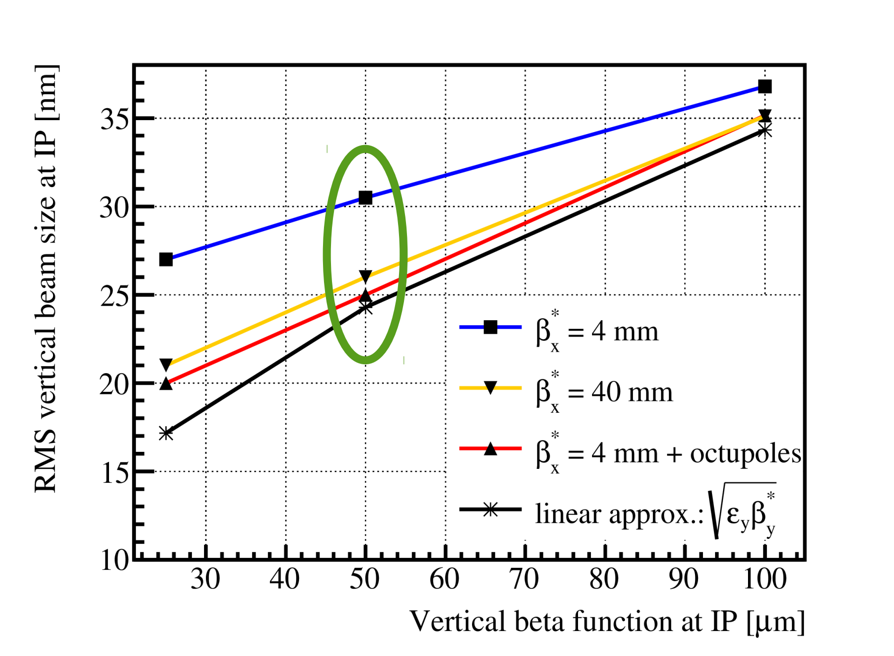
	β_y^* [μm]	$\sigma^*_{y,\,design}$ [nm]	L* [m]	$\xi_y \sim (L^*/\beta_y^*)$
ILC	480	5.9	3.5/4.5	7300/9400
CLIC	70	1	3.5	50000
ATF2 nominal	100	37 (43[a])	1	10000
ATF2 half β_y^*	50	25[b]	1	20000
ATF2 ultra-low β_y^*	25	20[b]	1	40000

[a] measured, Feb. 2016

[b] using octupoles

Optics design and optimisation





Decreased β_y* makes the FFS more sensitive to beam line imperfections. It was checked that:

- **magnetic multipole fields** and
- **fringe fields**

are limiting factors for the IP beam size.

Proposed mitigation method:

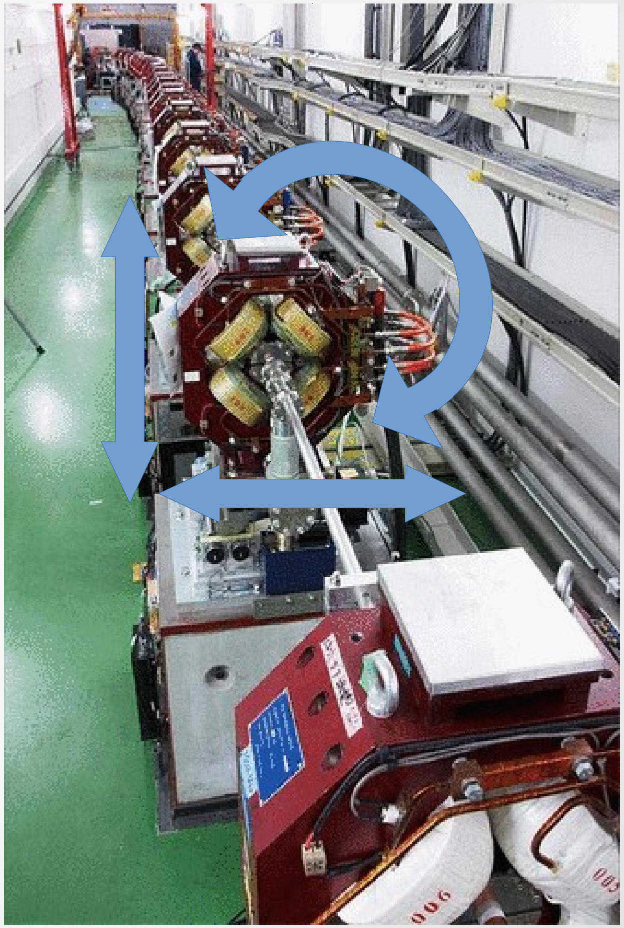
- Installation of two octupole magnets
  - Corrects both multipole fields and fringe fields.
  - Makes sextupolar correction easier.
  - **Brings the IP beam size from 27 nm to 20 nm for ultra-low β* optics.**

Tuning simulations

- The **realistic machine performance** is studied by simulating the **realistic machine errors**

case	misalignments			multipolar	strength
	Δx [μm]	Δy [μm]	$\Delta\theta$ [μrad]	errors	error [%]
nominal errors	**100**	**100**	**200**	**x1**	**0.1**
misalign. x1.5	150	150	300	x1	0.1
misalign. x2.0	200	200	400	x1	0.1
mults x3	100	100	200	x3	0.1
mults x5	100	100	200	x5	0.1
misalign. x1.5, mults x3	150	150	300	x3	0.1
misalign. x2.0, mults x5	200	200	400	x5	0.1

- 100 random machines generated.
- **Tuning** means **adjusting the machine parameters** to reach as close as possible to the **design performance**
- Two cases: with and without the orbit correction (MADX CORRECT command)
- Two sets of optics studied:
  - $\beta_x^* = 40$mm, $\beta_y^* = 50\mu$m (half β_y^*, $10\beta_x^*$)
  - $\beta_x^* = 100$mm, $\beta_y^* = 50\mu$m (half β_y^*, $25\beta_x^*$)



Optical aberrations

- Electron tracking is simulated to obtain their IP vertical positions: y_i
- We are interested in the vertical beam size at the IP: $\sigma_y{}^*$

$$\boxed{\sigma_y^* = \sqrt{\langle y_i^2 \rangle - \langle y_i \rangle^2}}$$

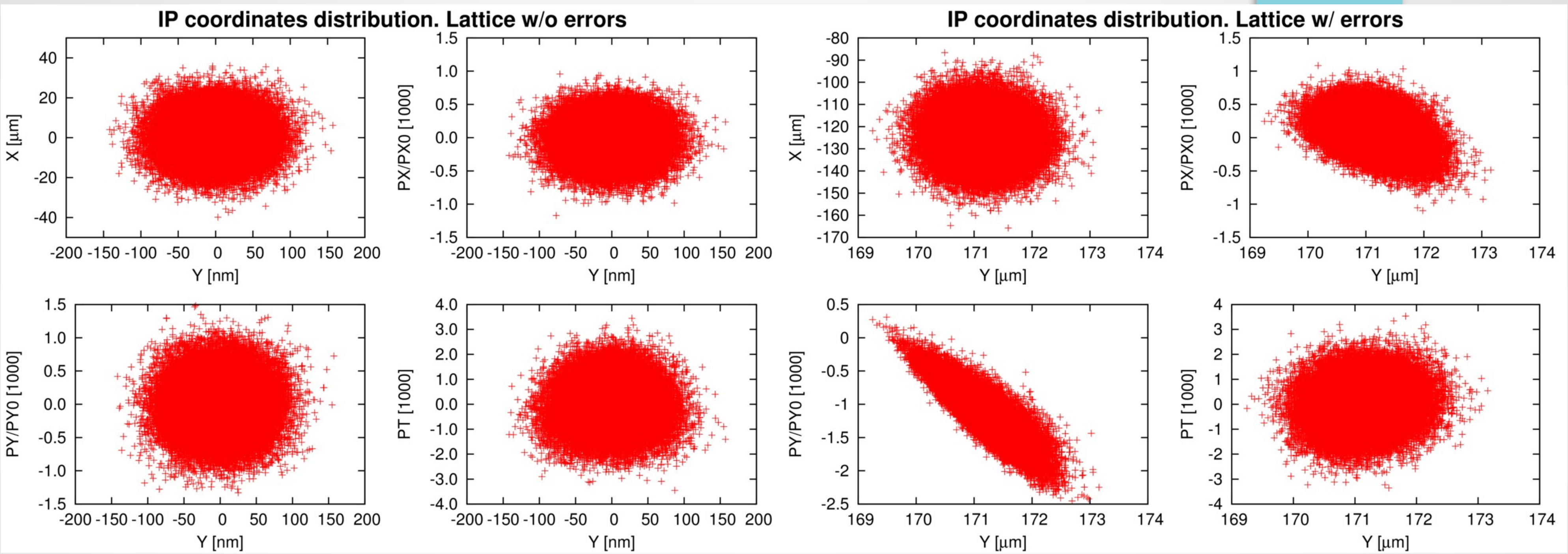
- In case of optical aberrations the electrons vertical position is correlated with the combinations of other coordinates,

$$\begin{aligned} y_i = {} & y_{i,0} + Y_1 x_i + Y_2 p_{x,i} + Y_4 p_{y,i} + Y_6 \delta + \\ & + Y_{11} x_i^2 + Y_{12} x_i p_{x,i} + Y_{14} x_i p_{y,i} + Y_{16} x_i \delta + Y_{22} p_{x,i}^2 + \\ & + Y_{24} p_{x,i} p_{y,i} + Y_{26} p_{x,i} \delta + Y_{44} p_{y,i}^2 + Y_{46} p_{y,i} \delta + Y_{66} \delta^2 + \\ & + \mathit{higher\ order\ terms}\ (\mathit{analogically}) \end{aligned}$$

- where Y_j, Y_{jk},... are the correlation coefficients for the first, second and higher order therms
- How to calculate the correlation coefficients:

$$\boxed{e.g.\ Y_{16} = \frac{\langle (y - \langle y \rangle)(x - \langle x \rangle)(\delta - \langle \delta \rangle) \rangle}{\sqrt{\langle (x - \langle x \rangle)^2 (\delta - \langle \delta \rangle)^2 \rangle}}}$$

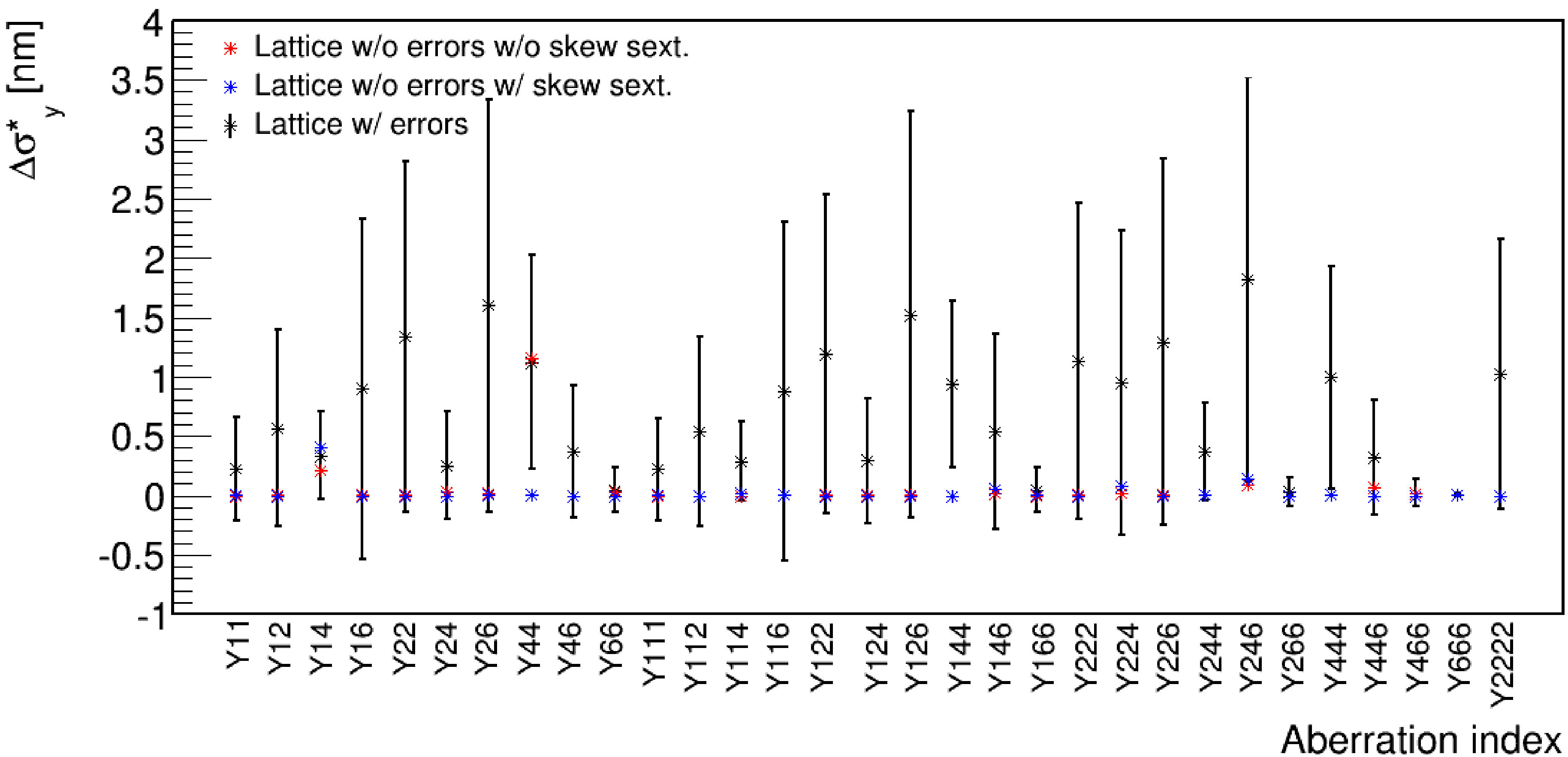
Optical aberrations example



- The vertical position (Y) of particles at the IP is not correlated with other particles IP coordinates → The optical aberrations are small.
- The vertical position (Y) of particles at the IP is correlated with other particles IP coordinates → The optical aberrations are important and cause the overall beam size increase.

Optical aberrations with nominal errors

Multipolar errors present in all cases.



- Points with error bars show the mean and standard deviation for 100 seeds
- Y26, Y22, Y44, Y16 are the dominant second order aberrations

Tuning knobs - linear

- **Sextupole offset** → additional, well-controlled quadrupole field
- *Linear knobs → combination of normal sextupoles transverse movements that corrects only one aberration term without affecting the others (orthogonality):*
  - Horizontal offset: Vertical waist position knob (Ay knob, Y_4 correlation)
  - Vertical offset: Vertical dispersion knob (Ey knob, Y_6 correlation)
  - Vertical offset: x'y coupling knob (C2 knob, Y_2 correlation)
- Details in: Phys. Rev. ST Accel. Beams 17, 023501

Tuning knobs - nonlinear

- **Sextupole strength** → additional 2nd-order field
- *Nonlinear knobs → combination of sextupoles strength changes that correct only one aberration term without affecting the others (orthogonality):*
  - Normal sextupoles: Y_{24}, Y_{46} knobs
  - Skew sextupoles: Y_{22}, Y_{26}, Y_{44}, Y_{66} knobs

- Details in: Phys. Rev. ST Accel. Beams 17, 023501

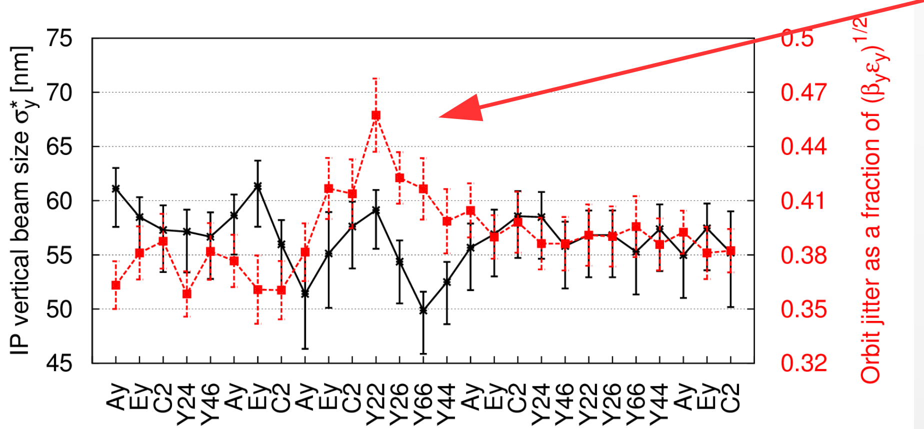
Knobs applied in the simulations

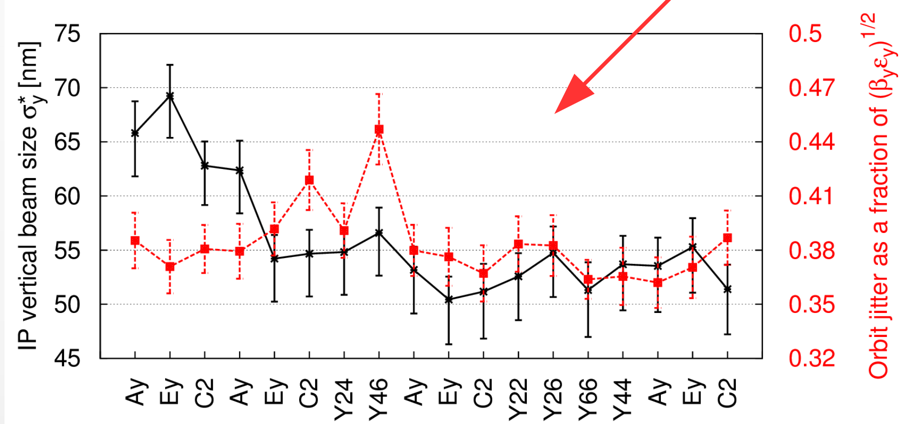
- The same number and order as in experiment:
  - Ay, Ey, C2
  - Y24, Y46
  - (Ay, Ey, C2)x2
  - Y22, Y26, Y66, Y44
  - Ay, Ey, C2
  - Y24, Y46
  - Y22, Y26, Y66, Y44
  - Ay, Ey, C2

Tuning simulations results vs. experimental results

case	misalignments			multipolar	$\sigma^*_{y,sim}$ [nm] w/o orbit corr.		$\sigma^*_{y,sim}$ [nm] w/ orbit corr.	
	Δx [μm]	Δy [μm]	$\Delta\theta$ [μrad]	errors	half β^*_y, $10\beta^*_x$	half β^*_y, $25\beta^*_x$	half β^*_y, $10\beta^*_x$	half β^*_y, $25\beta^*_x$
nominal errors	100	100	200	x1	39 ± 10	38 ± 7	32 ± 3	32 ± 3
misalign. x1.5	150	150	300	x1	52 ± 22	49 ± 13	36 ± 8	35 ± 5
misalign. x2.0	200	200	400	x1	67 ± 30	62 ± 20	39 ± 10	40 ± 8
mults x3	100	100	200	x3	44 ± 10	46 ± 10	38 ± 6	37 ± 5
mults x5	100	100	200	x5	61 ± 14	54 ± 11	45 ± 8	44 ± 7
misalign. x1.5, mults x3	100	100	200	x5	62 ± 24	55 ± 16	42 ± 7	42 ± 8
misalign. x2.0, mults x5	100	100	200	x5	85 ± 33	74 ± 22	54 ± 12	55 ± 11
experiment	-	-	-	-	-	-	$(58^{+4}_{-5})^a$	$(51^{+5}_{-6})^a$

[a] Orbit correction in the experiment is different than in the simulation.





Tuning simulations results

case	misalignments			multipolar	$\sigma^*_{y,sim}$ [nm] w/o orbit corr.		$\sigma^*_{y,sim}$ [nm] w/ orbit corr.	
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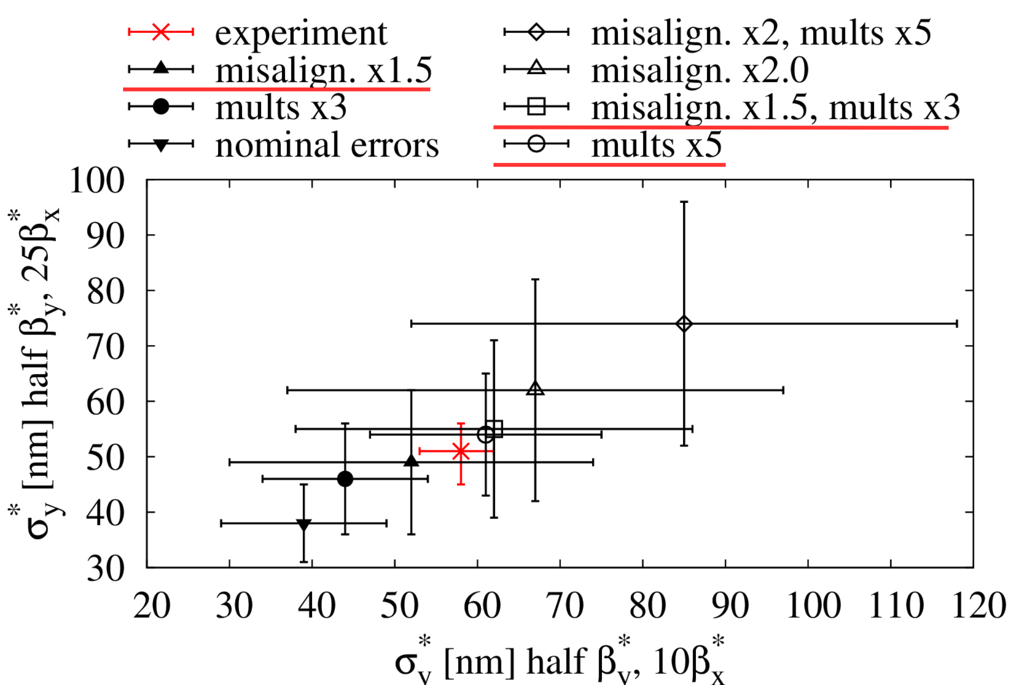
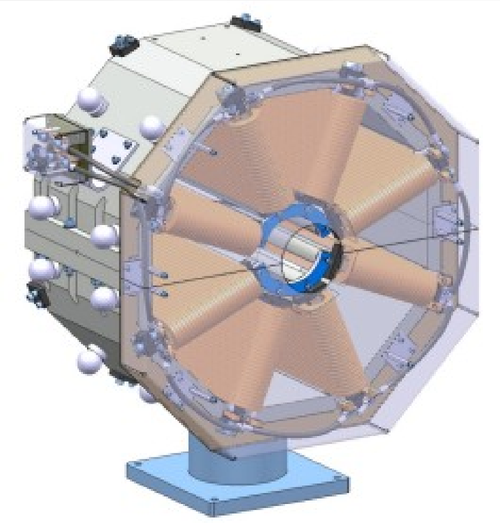


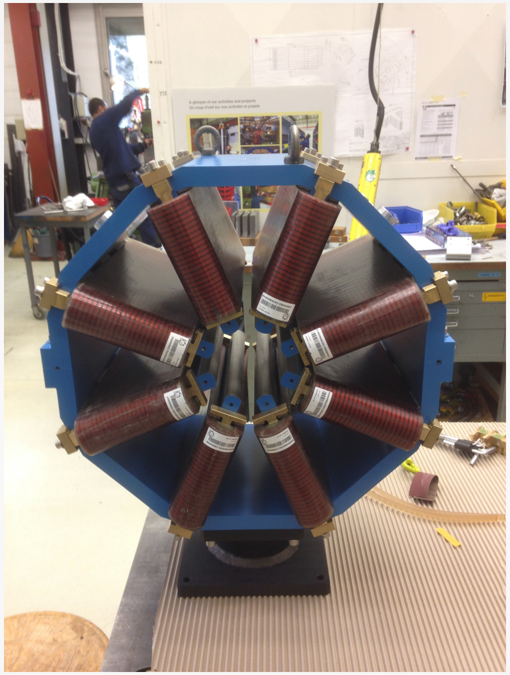
Conclusions

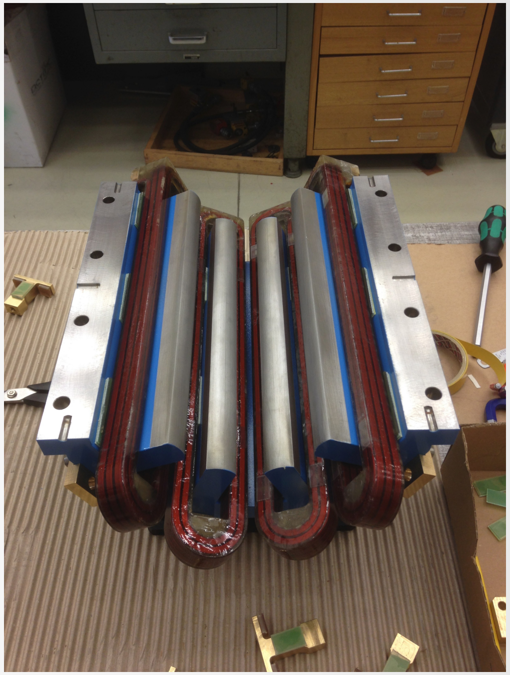
- The realistic (nominal) errors applied in the simulations do not reproduce the measured beam sizes,
- The simulation results get closer to the measured beam sizes for the following set of errors (w/o orbit correction):
  - misalign. x1.5,
  - mults x5,
  - misalign. x1.5, mults x3.
- The orbit correction included in the simulations highly improves the simulation results.
- Results are submitted to be published in Phys. Rev. Accel. and Beams.

Extra slides

Octupole magnets for ATF2







Octupoles are already assembled and tested at CERN. In next weeks they will be shipped to KEK and installed in ATF2.

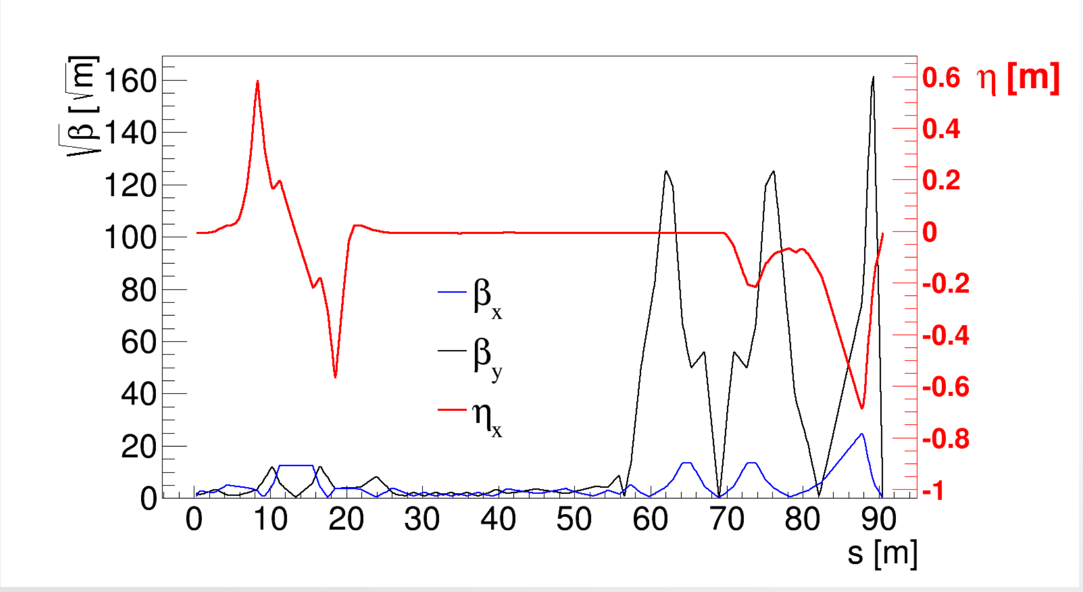
	G [T/m^3]	tunability	magnetic length [mm]	aperture radius [mm]	ampere-turns per coil [A]	# of turns per coil	I [A]	power max. [W]
OCT1	6820	-90%/+20%	300	52	1800	60	30	152
OCT2	708	-90%/+20%	300	52	180	6	30	15.2

Half β_y^* experiment (10x0.5 optics)

Collecting the experience and having a training before the ultra-low β^* optics:

- Preparing tools for optics modification, measurement and control;
- Checking the beam size tuning performance in more demanding conditions;
- Finding the issues and addressing them;
- Finding the minimum beam size without octupoles.

notation	β_x^* [mm]	β_y^* [μm]
1x1	4	100
10x1	40	100
10x0.5	40	50
25x0.5	100	50

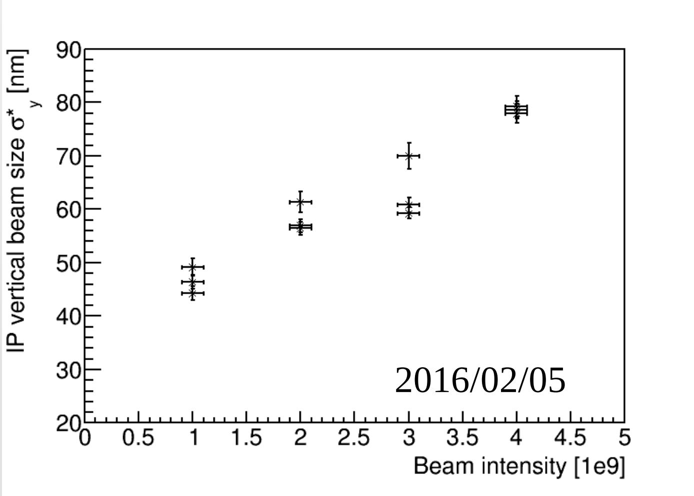


10x0.5 optics (on the plot) has been tested in ATF2 since December 2014.

The expected IP vertical beam size is 26 nm, assuming vertical emittance $\varepsilon_y = 12$pm.

Goal-1 recent achievements

- Measured beam size of ~ 43 nm. Close to goal-1 requirement: 37 nm.
- The β_y* value was roughly estimated to be between 110 and 140 μm for the matching target of 100 μm;
- Beam size reaches above 60nm when skew sextupoles are turned off → strong nonlinearities!
- In the simulations the skew sextupoles are not needed to reach 37 nm.
- Operated at low beam intensity (10^9 e^-/bunch) because of strong intensity dependence.



Final modulation in this week

T. Okugi, 5Feb2016, ATF2 Operation Meeting

with linear and nonlinear knobs

More than 50% modulation was kept about 1 day.