IR linear optics correction

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Measurement and correction of IR optics in the HL-LHC

- IR optics measurement and correction is one biggest challenges of the HL-LHC (see orevious talk).
- More precise measurements and new correction techniques are required to fulfill HL-LHC Luminosity requirements ($\Delta\beta^*/\beta^* \sim 2.5\%$).
- Definition of the optics measurement and correction strategy for HL-LHC (Rogelio's and Ewen's talks).
- We will focus on linear optics measurement and correction.

β^* measurement using K-modulation

Modulation of the strength of the last quadrupoles (usually Q1) around the IP results in a change in tune that allows to determine the β-function at the quadrupole[1].

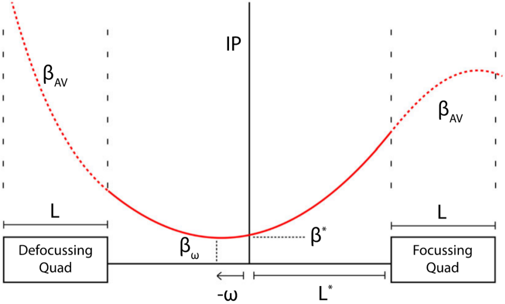
$$\beta^* = \beta_w + \frac{w^2}{\beta_w} \qquad (2)$$

The β at the quadrupole is given by:

$$\beta_{\text{av}} \approx \pm 4\pi \frac{\Delta Q}{\Delta kL} \qquad (1)$$

The value for β^* is calculated from the value of β at the quadrupole:

$$\beta^{\text{quad}}_{\text{AV}} \to (\beta_w, w) \to \beta^*$$



[1] F. Carlier, R. Tomas, Accuracy and feasibility of the β^* measurement for LHC and High Luminosity LHC using k-modulation, PRAB **20**, 011005.

K-modulation solutions

When solving the above system, two possible solutions based on the value of β_{av}:

$$\beta^* = \frac{\beta_{\text{av}} \pm \sqrt{\beta_{\text{av}} - 4L^*}}{2} \tag{3}$$

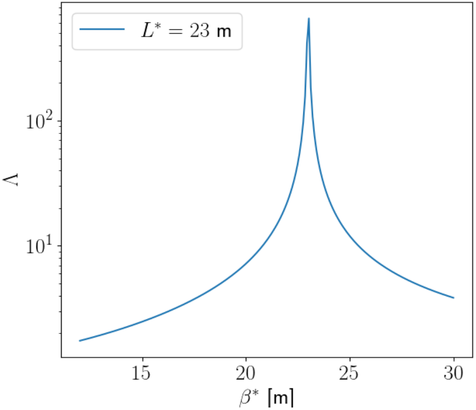
Where $-$ is the solution we are interested in. But the simplex algorithm does not distinguish between them and may converge to the wanted solution.

How can we force the algorithm to the "$-$" solution?

Special case: vdM optics[2]

- Luminosity calibration uses special (large β) optics for van der Meer scans.
- The uncertainty on β^* is closely related to uncertainty in β at the nearest quadrupole.

$$\frac{\sigma_{\beta^*}}{\beta^*} = \frac{\beta^* + \frac{L^{*2}}{\beta^*}}{|\beta^* - \frac{L^{*2}}{\beta^*}|}\frac{\sigma_\beta}{\beta} = \Lambda\frac{\sigma_\beta}{\beta} \qquad (4)$$



- Due to optics properties, when $\beta^* \approx L^*$ (case of vdM optics), a small error in β may drive a huge error in β^*.
- One should avoid $\beta^* \approx L^*$.

[2] L. van Riesen-Haupt, K-modulation developments via simultaneous beam based alignment in t he LHC, Proceeding IPAC17

β^* measurement limitations

Uncertainties in observables have a significant impact on the reconstructed value of β^*.

Uncertainties

- Tune jitter (most critical $\delta Q \sim 2.5 \cdot 10^{-5}$).
- β-beating
- Orbit shift/jitter
- Misalignment
- Quadrupole strength
- Coupling
- ...

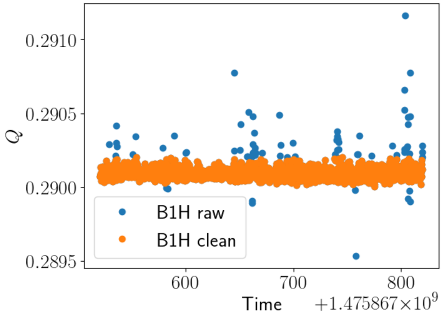


Table: Tune uncertainties during the MD devoted to vdM optics measurements

	B1	B2
$\delta Q_x [10^{-5}]$	3.2	2.3
$\delta Q_y [10^{-5}]$	3.2	3.4

Phase advance at IR [3]

β-function accross the optics drift around the IP:

$$\beta(s) = \beta_w + \frac{(s-w)^2}{\beta_w} \tag{5}$$

The phase-advance between the start and the end of the optics drift is:

$$\phi_{\mathrm{IP}} = \arctan\left(\frac{L^* - w}{\beta_w}\right) + \arctan\left(\frac{L^* + w}{\beta_w}\right) \tag{6}$$

[3] J.Coello de Portugal, New local optics measurements abd correction techniques for the LHC and its luminosity upgrade

Implementing phase advance in the penalty function (Preliminary)

The penalty function to find the optimal solution is based on the measured values of β_{av}. We can include an extra term that takes into account the deviation in phase ϕ_{IP}.

Before:

$$\chi^2 = (\Delta\beta^{\text{av}}_{\text{foc}})^2 + (\Delta\beta^{\text{av}}_{\text{def}})^2 \tag{7}$$

Now:

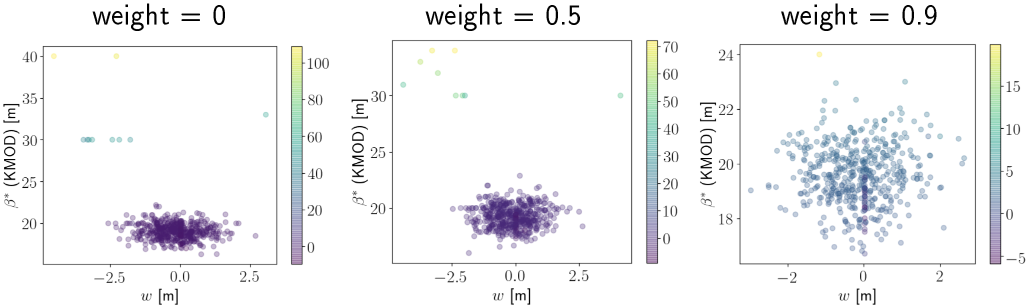
$$\chi^2 = w_1[(\Delta\beta^{\text{av}}_{\text{foc}})^2 + (\Delta\beta^{\text{av}}_{\text{def}})^2] + \Omega w_2(\Delta\phi_{\text{IP}})^2 \tag{8}$$

- Weigths: $w_1, w_2 \in [0,1], \quad w_1 + w_2 = 1.$
- Normalization/Scale factor: Ω.
  Depends on the optics choice. ($\beta_{\text{quad}} \in [200, 2000]$ m)
- For vdM optics: $\Omega = 10^3$.

Results using van der Meer optics simulated data

Simulation set up

- vdM optics (β^*(IP1/5) = 19 m). $\Omega = 10^3$.
- 500 machines simulated with random magnetic errors.
- Results, reconstructed β^* as a function of waist w:



When increasing the weight in the phase constraint, the outliers dissapear.

Measurement analysis and Further improvements

MD data from 2016 on van der Meer optics is available to be reanalized using the new implementation of K-mod.

To be done:

- Test the changes for different optics (low-β^*) far from singularities.
- Use normalization based on errorbars and compare to weight method.
- Statistical evaluation of the algorithm.
- Remove uncertainties to check that the implementation is numerically correct.

Action-Phase Jump vs. Segment by Segment

Motivation

- Need to find the best possible strategy for local and global correction for Run III and for HL-LHC.
- In particular for local correction in the IRs for HL.

Goal of this study

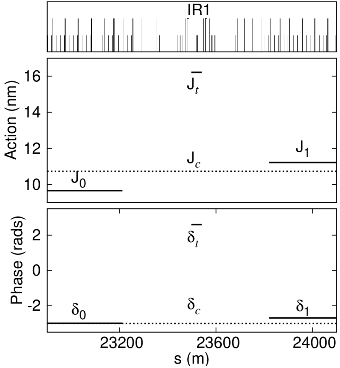
Compare Action Phase Jump (APJ) technique with classical Segment by Segment (SbS) approach on the performance of local correction in IRs.

Could APJ be useful for future optics correction?

Local correction techniques

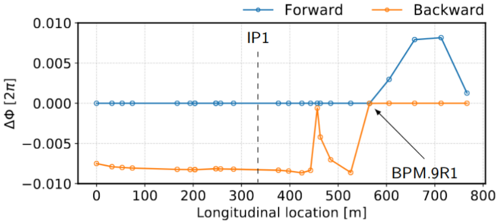
Action-Phase Jump (APJ)

Take jumps in action J and phase ϕ produced in the IR to deduce correction strengths.



Segment-by-Segment (SbS)

- Correction of errors locally at the selected segment.
- Compares model and measurement of observables of choice.
- Finds mismatches and applies correction.



Analysis scenario I

Optics and errors

- 2016 40 cm optics.
- Tabulated magnetic errors in:
  - Inner triplet.
  - Matching quadrupoles (Q4, Q5, Q6).
- Magnets used for correction:
  - SbS: Q1, Q2, Q3
  - APJ: Q2, Q3, Q4, Q6.

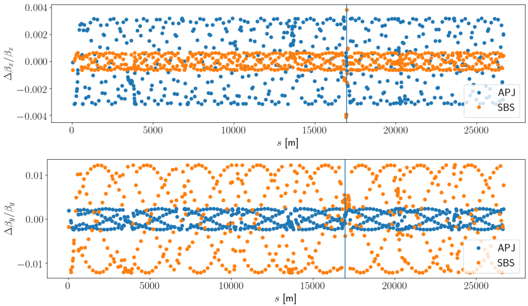
Magnet	Error $10^{-5}m^{-2}$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	0.34/-0.55
Q4L/R.B2	0.23/0.19
Q5L/R.B1	0.25/-0.08
Q5L/R.B2	0.03/0.22
Q6L/R.B1	0.05/-0.009
Q6L/R.B2	-0.12/0.03

Results scenario I

- Similar performance of both methods in this case.

$\Delta\beta/\beta$[%]	H	V
Uncorrected RMS	6.10	12.5
APJ RMS	0.22	0.17
SbS RMS	0.07	0.87
Uncorrected Max	102	73.5
APJ Max	0.33	0.26
SbS Max	0.41	1.24

β^* [cm]	H	V
Uncorrected	80.9	69.4
APJ	40.0	39.9
SbS	40.2	39.8



Analysis scenario II - large errors in matching section

Optics and errors

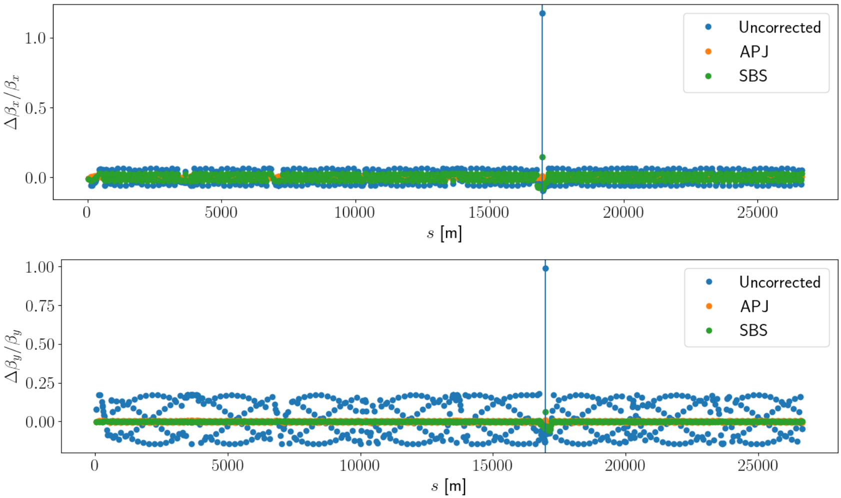
- 2016 40 cm optics.
- Magnetic errors in:
  - Inner triplet.
  - Matching quadrupoles (Q4, Q5, Q6).
- Magnets used for correction:
  - SbS: Q1, Q2, Q3
  - APJ: Q2, Q3, Q4, Q6.

Magnet	Error $10^{-5}\mathrm{m}^{-2}$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	-7.00/5.70
Q4L/R.B2	7.00/-5.70
Q5L/R.B1	-6.86/2.98
Q5L/R.B2	7.01/-3.45
Q6L/R.B1	41.34/-23.71
Q6L/R.B2	-31.51/20.44

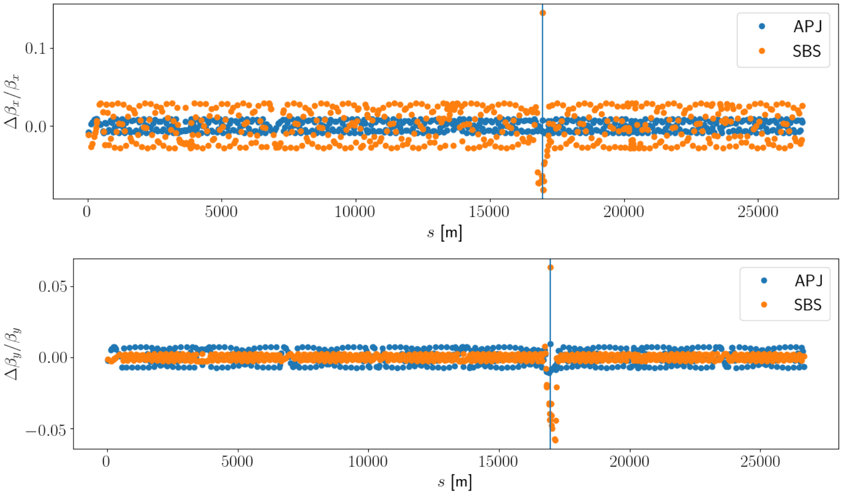
Matching section quadrupole errors

Ther errors introduced in the matching section quadrupoles are not real errors. They are deduced from corrections required in the past and might contain residual contributions from many sources.

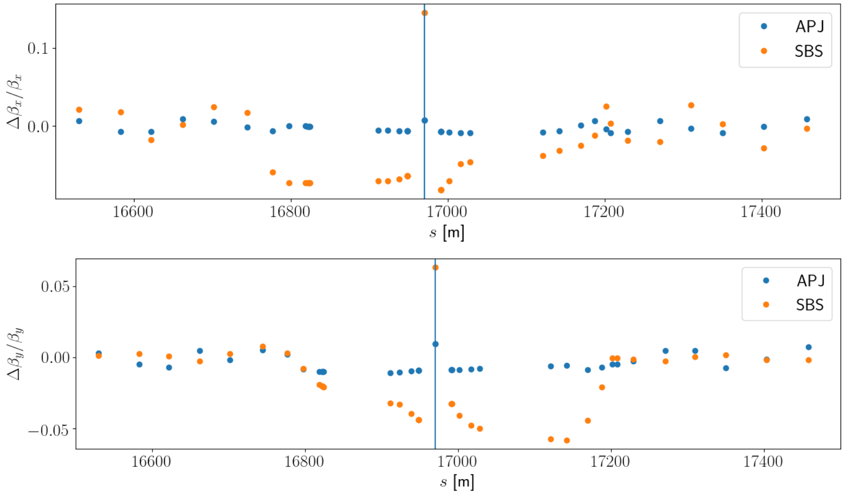
Results scenario II (B1)



Results scenario II (B1)



Results scenario II (B1)



Results scenario II (B1)

- Action-Phase jump technique seems to work better in this scenario for both residual ring β-beating and β^*.
- This is expected since errors in the matching section are quite large and APJ includes Q5 and Q6 in the correction while SbS only uses the triplet.

Ring β-beating

$\Delta\beta/\beta$	H [%]	V [%]
Uncorrected RMS	8.14	12.8
APJ RMS	0.63	0.55
SbS RMS	2.56	0.85
Uncorrected Max	117	98.6
APJ Max	0.92	1.08
SbS Max	14.5	6.31

IP optics

β^*	H	V
Uncorrected	87.0	79.4
APJ	40.3	40.4
SbS	45.8	42.5

What if matching quadrupoles are used in SbS?

Outlook and prospects

β^* measurements

- K-modulation techniques present some limitations.
- The analysis technique has been improved and the IR phase advance has been included as a constraint to force optimal solution. Promissing but still some work to do.
- Additional tests and comparisons to be done including measured data.
- To be tested in low-β^* optics (LHC and HL-LHC).

IR linear corrections

- For small matching section errors, the two methods converge to similar results.
- Assuming large errors in the matching section, APJ seems to give better results for local correction in IRs when errors in matching section are considered.
- Where are mathcing section errors coming from?
- Can we improve SbS?
- APJ as a tool to be used from 2021.
- Use other LHC and HL-LHC optics.

Extra slides

Segment by segment and k-mod

Correction is based on SbS techniques and the matching is made taking including k-mod data.

- Load model.
- Load tracking data.
- Perform analysis and get optics.
- Load k-mod data (previously simulated).
- Run IR1 segment.
- Launch matching tool.
  - Phase B1/B2
  - Amplitude from k-mod B1/B2.
  - Select common quadrupoles.
  - Run match.
- Test correction.

Implementation

1. Measurement data.
   - AC dipole excitation...
2. Model data.
   - From twiss with errors included.
3. Phase from k-mod.
   - Formula above using guessed β^* and w.

Result: Correction strengths

APJ

corrq2l1 = 1.08469551968e-05
corrq2r1 = -7.73363949149e-06
corrq3l1 = 1.55571068315e-05
corrq3r1 = -2.79531489154e-05
corrq4l1.B1 = 0.0001092
corrq4l1.B2 = -0.0001094
corrq4r1.B1 = -7.3e-05
corrq4r1.B2 = 7.31e-05
corrq6l1.B1 = -0.0003845
corrq6l1.B2 = 0.0003202
corrq6r1.B1 = 0.0002205
corrq6r1.B2 = -0.0001932

Magnet	Error $10^{-5}m^{-2}$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	-7.00/5.70
Q4L/R.B2	7.00/-5.70
Q5L/R.B1	-6.86/2.98
Q5L/R.B2	7.01/-3.45
Q6L/R.B1	41.34/-23.71
Q6L/R.B2	-31.51/20.44

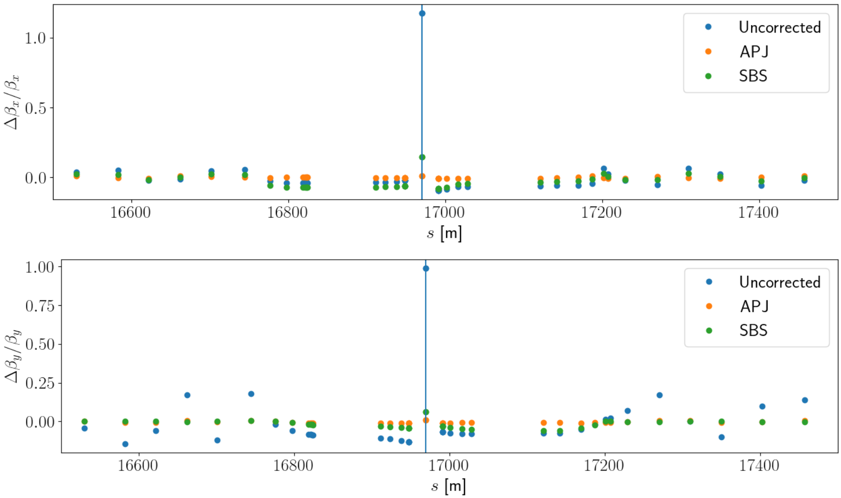
Result: Correction strengths

SbS

dkqx.l1 = + 7.617246286e-06
dktqx2.l1 = - 1.015731896e-05
dktqx1.l1 = + 3.317201257e-05
dkqx.r1 = + 1.048958008e-05
dktqx1.r1 = - 0.0001551090389
dktqx2.r1 = - 2.039382267e-05

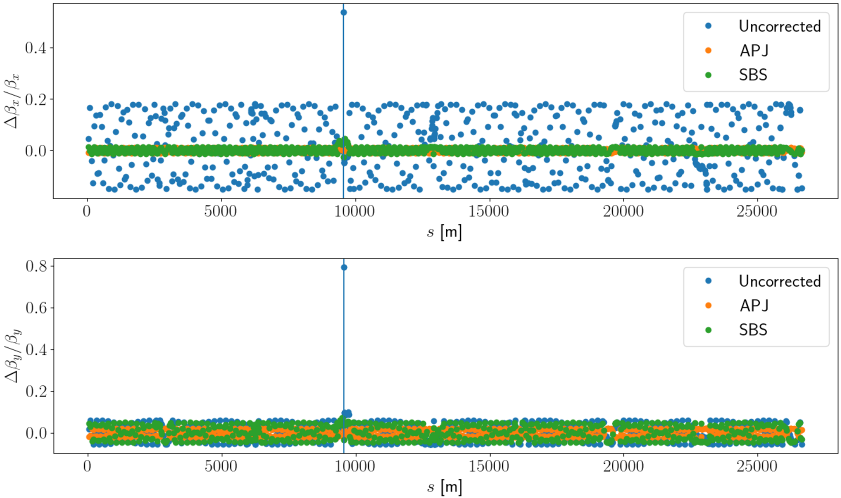
Magnet	Error $10^{-5}m^{-2}$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	-7.00/5.70
Q4L/R.B2	7.00/-5.70
Q5L/R.B1	-6.86/2.98
Q5L/R.B2	7.01/-3.45
Q6L/R.B1	41.34/-23.71
Q6L/R.B2	-31.51/20.44

Results (B1)



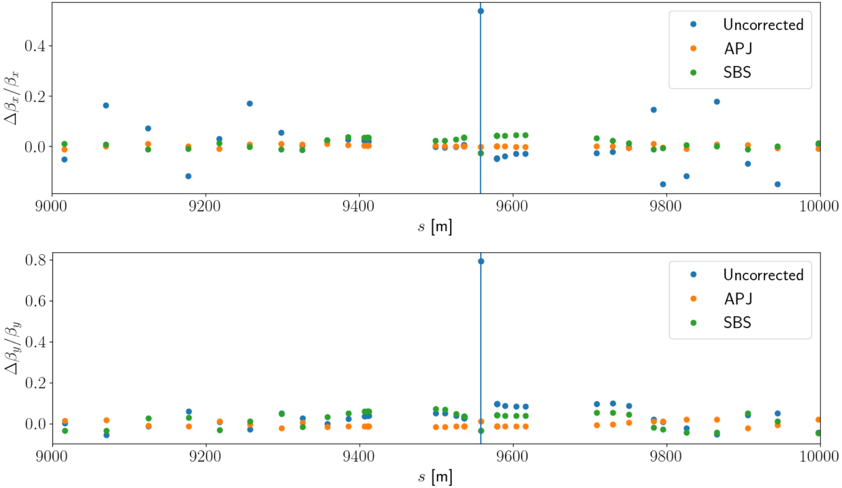
1.0
0.5
0.0
$\Delta\beta_x/\beta_x$
16600
16800
17000
17200
17400
s [m]
Uncorrected
APJ
SBS
1.00
0.75
0.50
0.25
0.00
$\Delta\beta_y/\beta_y$
16600
16800
17000
17200
17400
s [m]
Uncorrected
APJ
SBS

Results (B2)



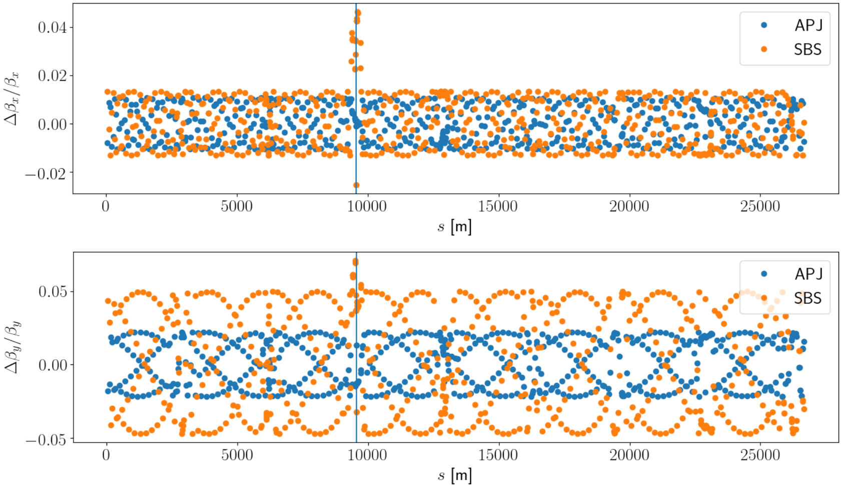
0.4
0.2
0.0
$\Delta\beta_x/\beta_x$
0
5000
10000
15000
20000
25000
s [m]
Uncorrected
APJ
SBS
0.8
0.6
0.4
0.2
0.0
$\Delta\beta_y/\beta_y$
0
5000
10000
15000
20000
25000
s [m]
Uncorrected
APJ
SBS

Results (B2)



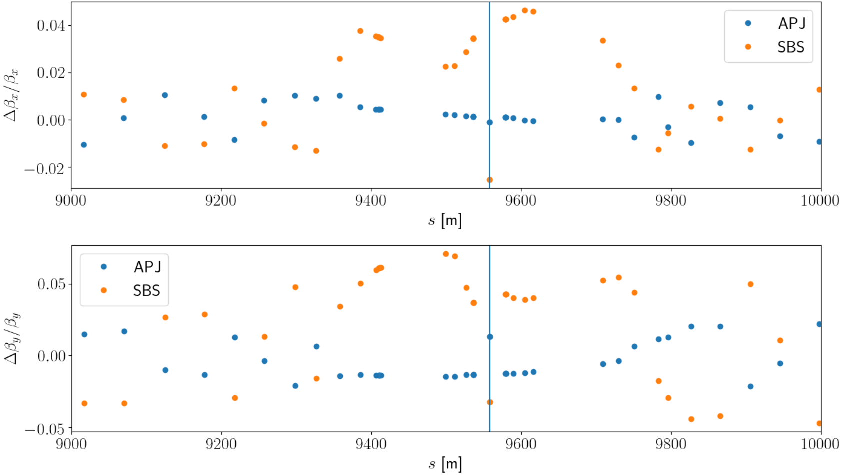
Uncorrected
APJ
SBS
$\Delta\beta_x/\beta_x$
0.4
0.2
0.0
9000
9200
9400
9600
9800
10000
s [m]
Uncorrected
APJ
SBS
$\Delta\beta_y/\beta_y$
0.8
0.6
0.4
0.2
0.0
9000
9200
9400
9600
9800
10000
s [m]

Results (B2)



$\Delta\beta_x/\beta_x$
0.04
0.02
0.00
−0.02
0
5000
10000
15000
20000
25000
s [m]
APJ
SBS
$\Delta\beta_y/\beta_y$
0.05
0.00
−0.05
0
5000
10000
15000
20000
25000
s [m]
APJ
SBS

Results (B2)



APJ
SBS
$\Delta\beta_x/\beta_x$
0.04
0.02
0.00
−0.02
9000
9200
9400
9600
9800
10000
s [m]
APJ
SBS
$\Delta\beta_y/\beta_y$
0.05
0.00
−0.05
9000
9200
9400
9600
9800
10000
s [m]

Results: small errors (B2)

$\Delta\beta/\beta[\%]$	H	V
Uncorrected RMS	13.9	6.22
APJ RMS	0.17	0.20
SbS RMS	1.48	0.40
Uncorrected Max	79.3	105
APJ Max	0.25	0.29
SbS Max	2.18	0.59

β^* [cm]	H	V
Uncorrected	71.7	82.1
APJ	39.9	40.0
SbS	40.2	40.2

Results (B2)

β-beating

$\Delta\beta/\beta[\%]$	H	V
Uncorrected RMS	11.8	6.16
APJ RMS	0.73	1.57
SbS RMS	1.19	3.57
Uncorrected Max	53.6	79.19
APJ Max	1.06	2.21
SbS Max	4.62	7.08

IP optics

β^* [m]	H	V
Uncorrected	61	72
APJ	39.96	40.5
SbS	38.98	38.7