Beam-based tuning of the beam delivery system (BDS)

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Acknowledgements: Daniel Schulte, Rogelio Tomás, Andrea Latina

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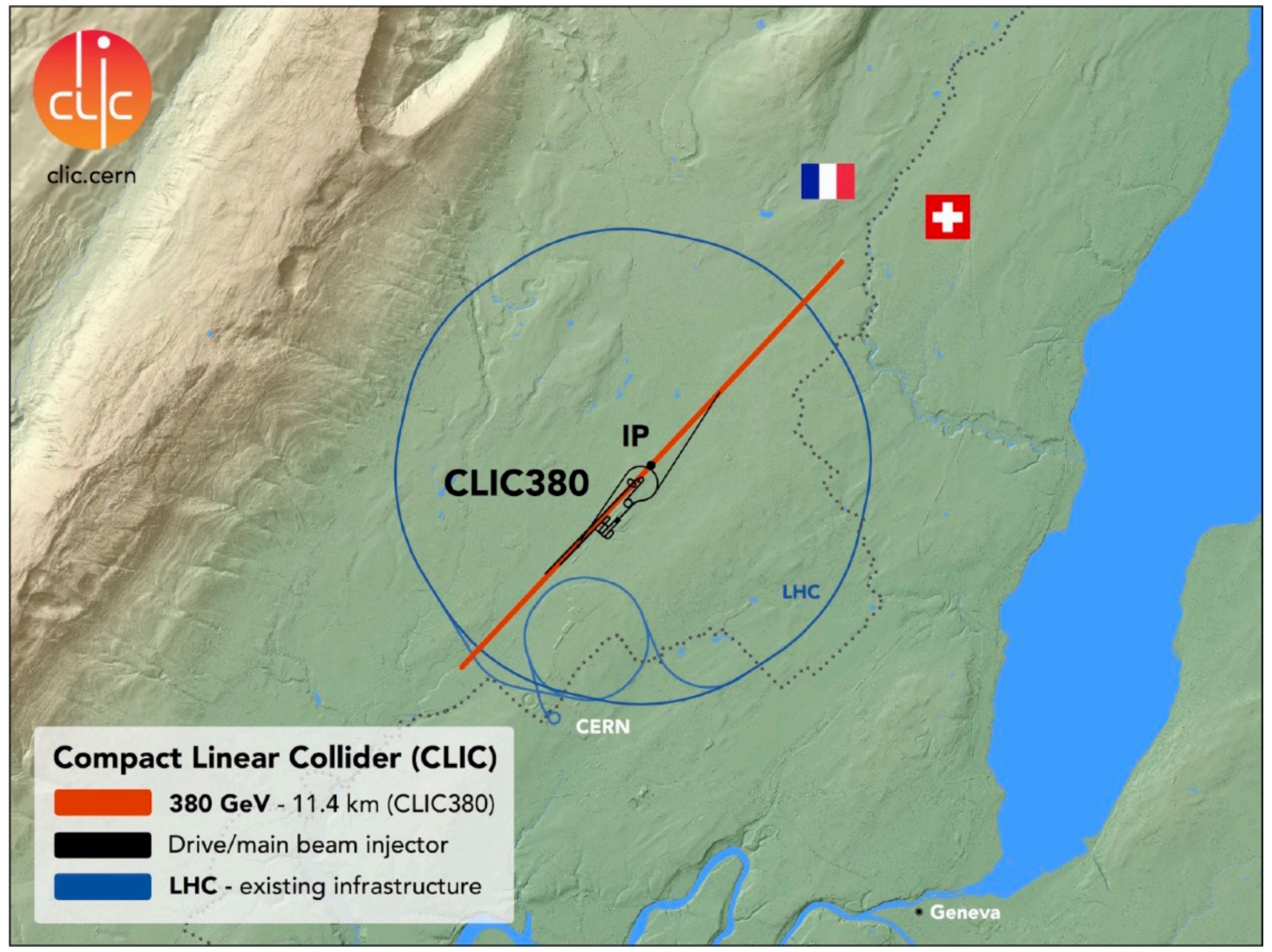
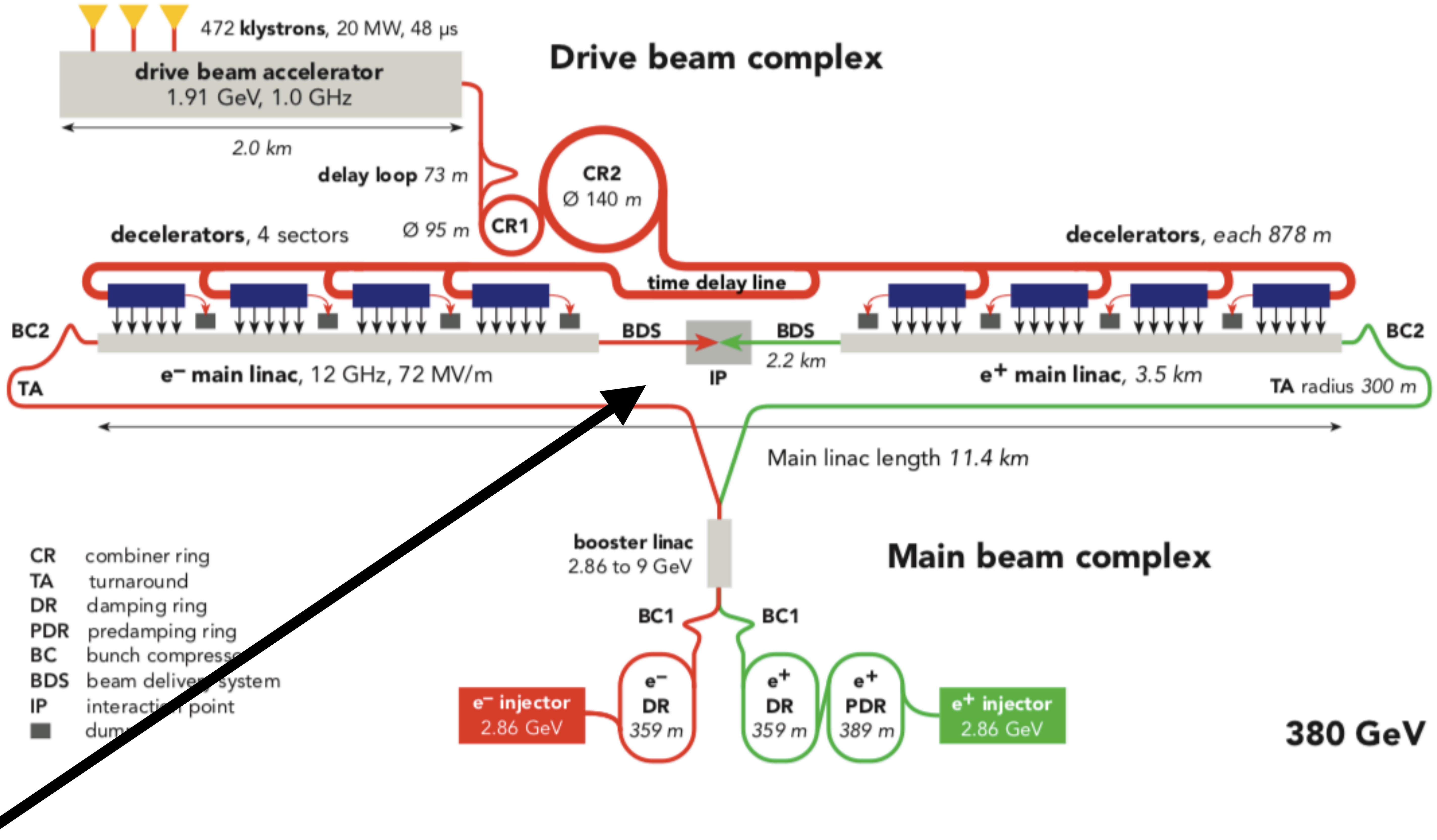
The beam delivery system (BDS)





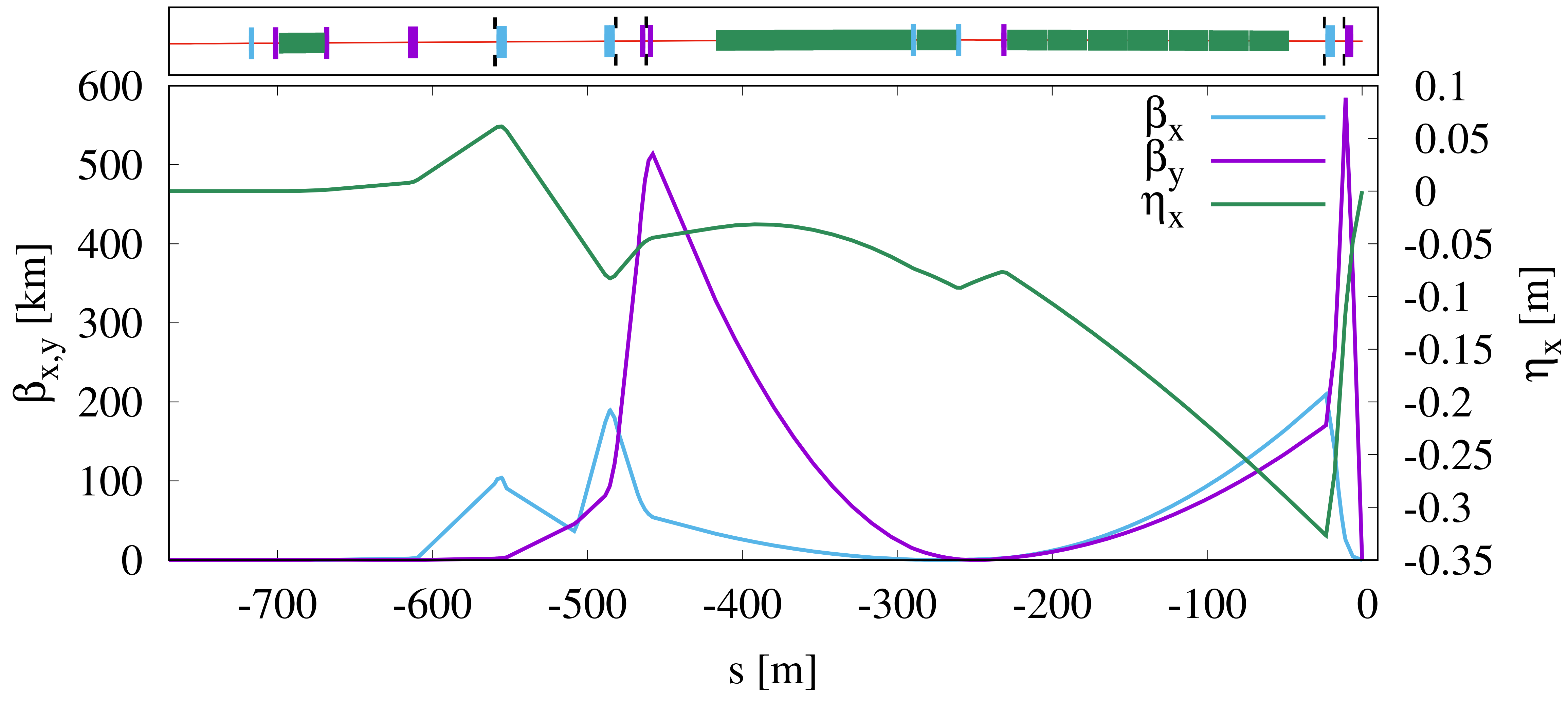
The beam delivery system (BDS) - Last 2.2 km of the main linacs

- Collimation section
- Final-focus system

The 380 GeV CLIC FFS

The final-focus system (FFS):

- Local chromaticity scheme
- L* = 6 m (new baseline)



Norm. emittance (end of linac) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	900 / 20
Norm. emittance (IP) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	950 / 30
Beta function (IP) β_x^*/β_y^*	[mm]	8.2 / 0.1
Target IP beam size σ_x^*/σ_y^*	[nm]	149 / 2.9
Bunch length σ_z	[μm]	70
rms energy spread δ_p	[%]	0.35
Bunch population N_e	[10^9]	5.2
Number of bunches n_b		352
Repetition rate f_{rep}	[Hz]	50
Luminosity $\mathcal{L}_{total}$	[10^{34}cm^{-2}s^{-1}]	1.5
Peak luminosity $\mathcal{L}_{1\%}$	[10^{34}cm^{-2}s^{-1}]	0.9

FFS System in numbers:

- 780 m
- 20 quadrupole magnets
- 22 Beam-position monitors (BPMs)
- 6 sextupole magnets
- 2 octupole magnets

Tuning of the Final focus system

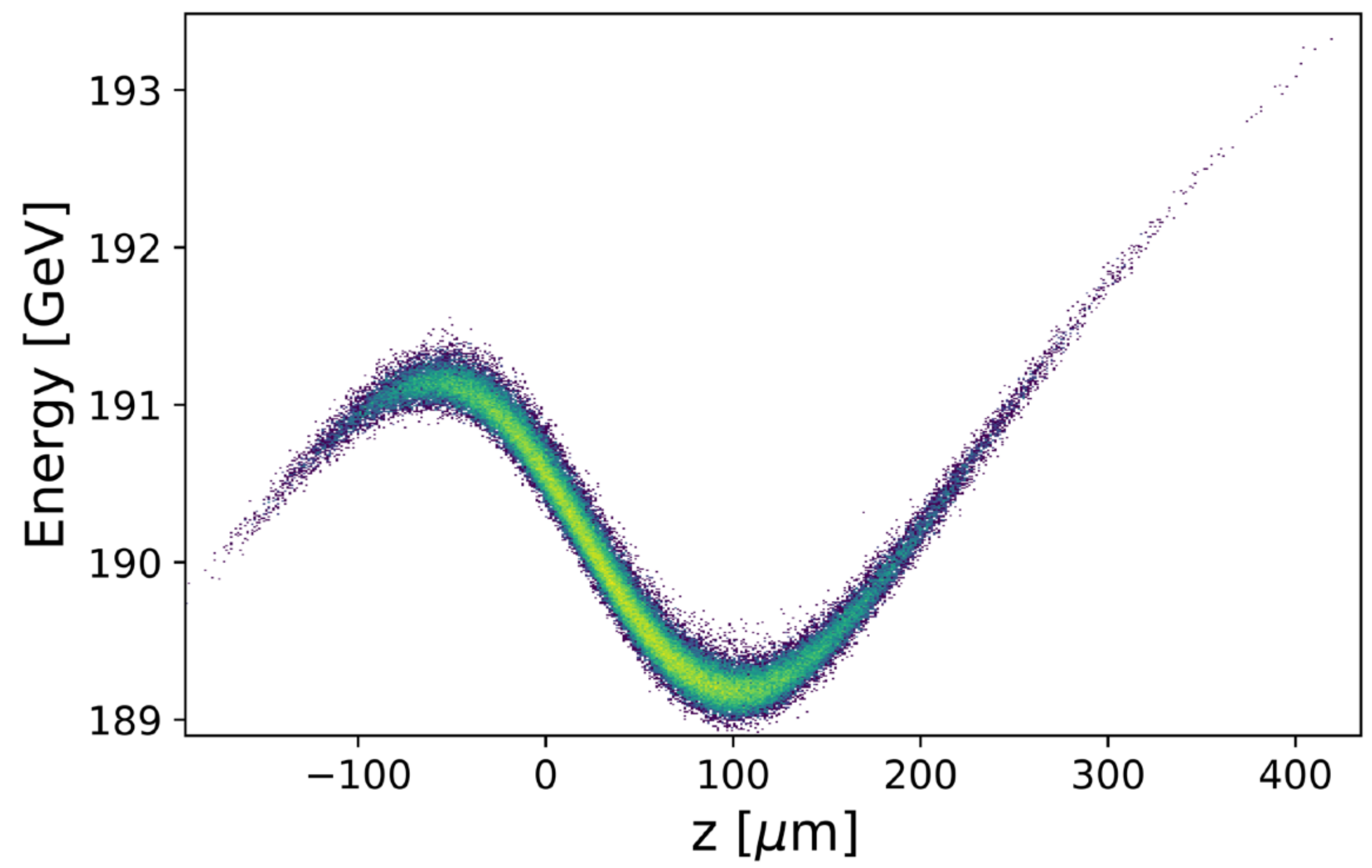
- Tuning = reaching performance for a machine with imperfections
  - Studied extensively for CLIC
  - For 3 TeV machine: two-beam tuning, static and dynamic imperfections (work by E. Marin)
  - Can we improve? Lower the tuning time (number of luminosity measurements)

- Simulation setup
  - Tracking in PLACET
  - GUINEA-PIG for computing the luminosity

- What is new?
  - New method for aligning the sextupoles
  - Using beam from integral simulation (RTML+ML+BDS)

- The challenge
  - Complicated, interleaved system with many effects
  - Stuck in local optima
  - Separate functions and correct subsystems independently

Beam energy profile at end of main linac



Single-beam tuning simulation

1. Beam-based alignment (BBA) with all multipoles switched OFF
2. Pre-alignment of sextupoles by powering them one-by-one
3. Sextupole linear knobs
4. Octupole linear knobs

Static imperfections:

Imperfection	Specified tolerance (rms error)	Elements
Resolution	20 nm	BPMs
Transverse misalignments	10 μm	BPMs, quadrupoles, multipoles
Roll errors	100 μrad	BPMs, quadrupoles, multipoles
Relative strength error	10^{-4}	Quadrupoles, multipoles

Monte Carlo simulations:

- Generate machines with random imperfections
- Tuning goal: 90% of machines to be successfully tuned

Beam-based alignment (BBA)

- Correct the linear part of the system
  - Trajectory and dispersion
  - Multipoles OFF

- Measure the response matrix on the misaligned machine

- Use movement of quadrupoles or dedicated steering magnets

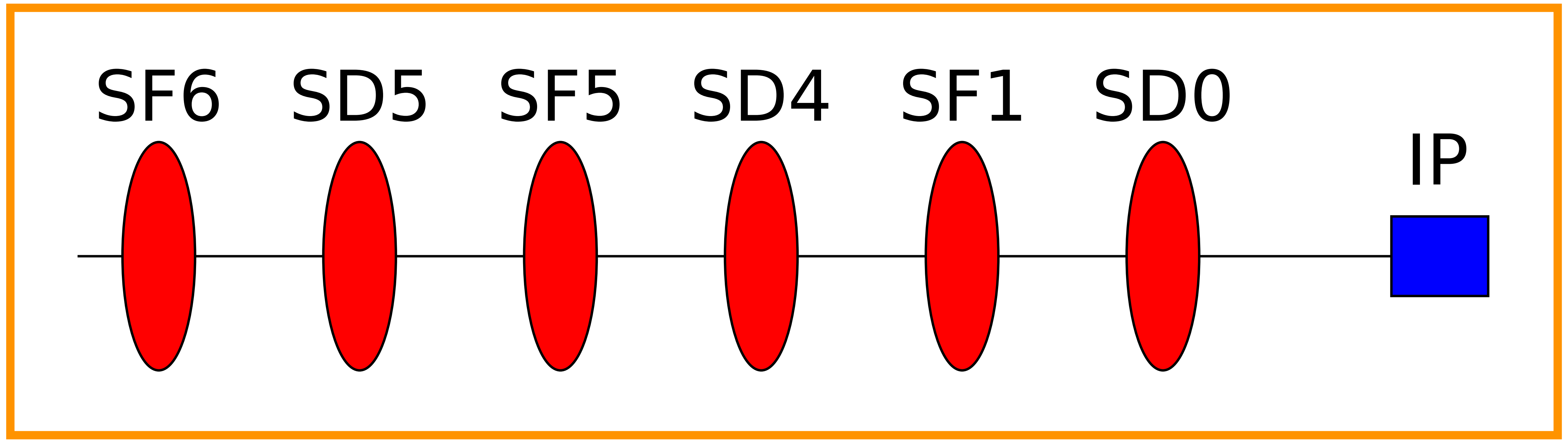
$$\begin{bmatrix} \vec{y}_{\mathrm{traj}} \\ w\vec{y}_{\mathrm{disp}} \\ \vec{0} \end{bmatrix} = \begin{bmatrix} R_{\mathrm{traj}} \\ wR_{\mathrm{disp}} \\ \beta I \end{bmatrix} \begin{bmatrix} \Delta\vec{x} \\ \Delta\vec{y} \end{bmatrix}$$

- Weight on dispersion, beta to condition matrix

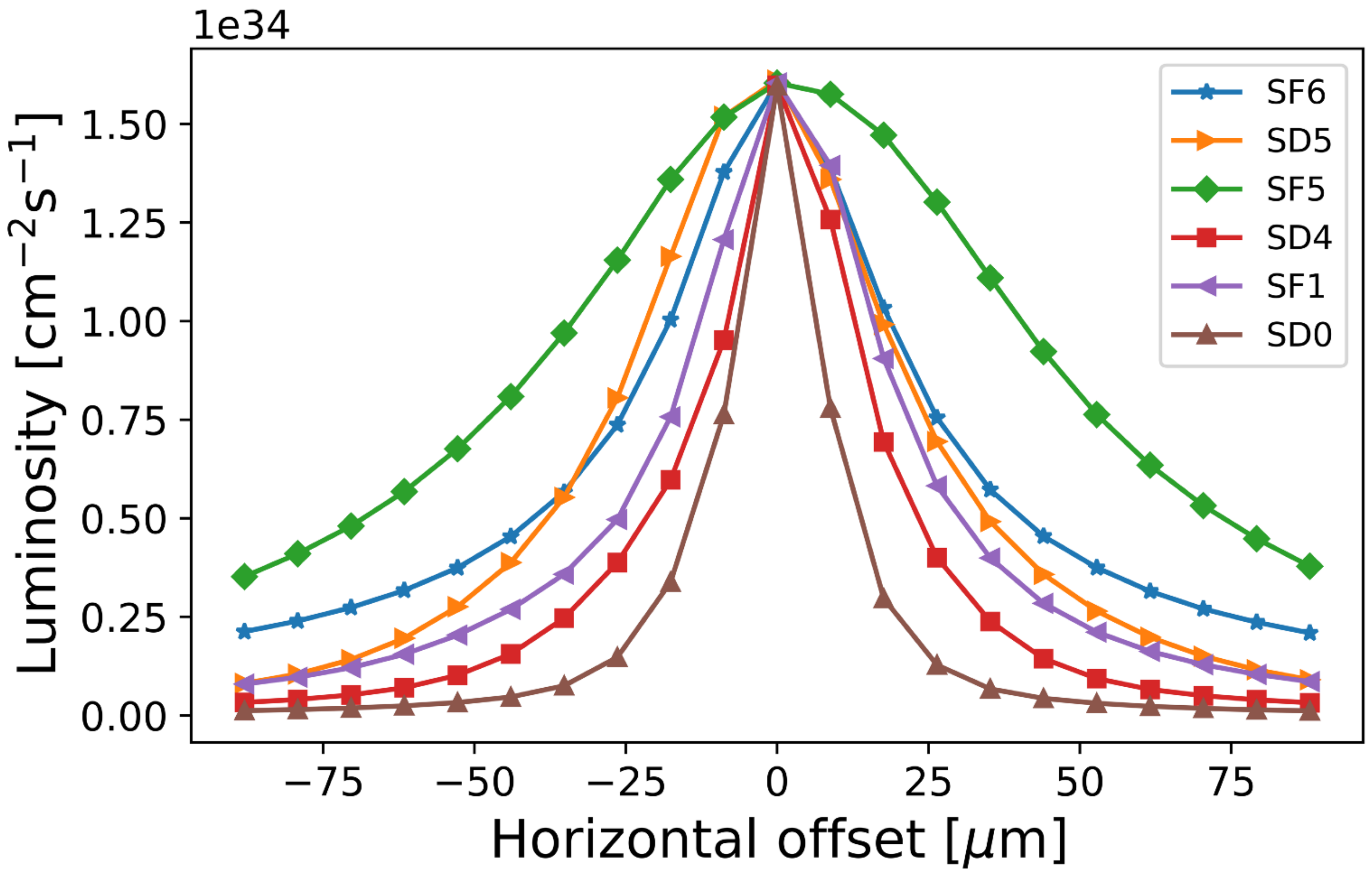
- Invert system to match target trajectory and dispersion

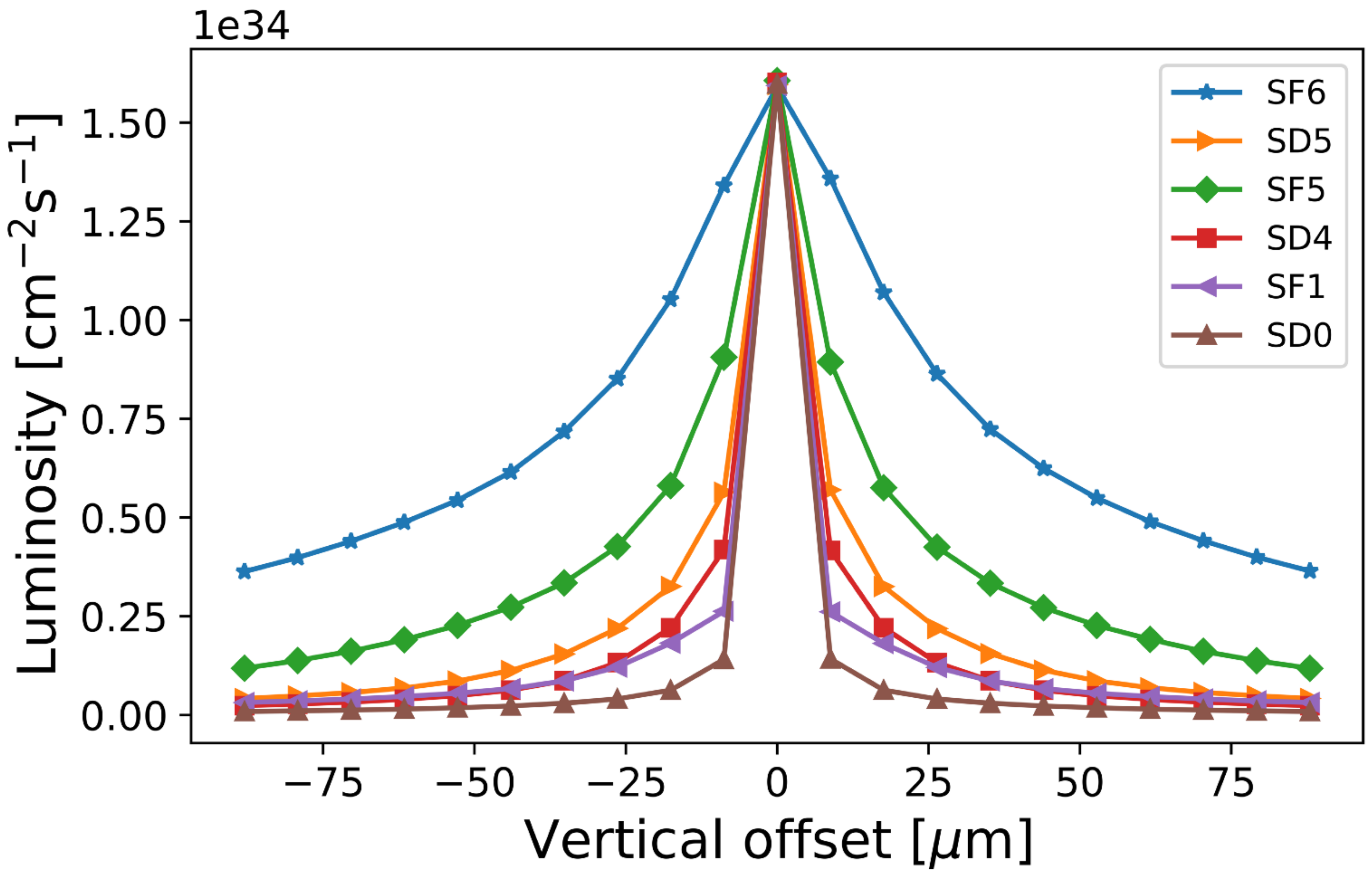
Aligning the sextupoles

- Sextupole transverse offsets
  - Quadrupole and dipole kicks
  - Impacts sextupole knobs tuning
  - Impact on trajectory small
  - difficult to use BBA method



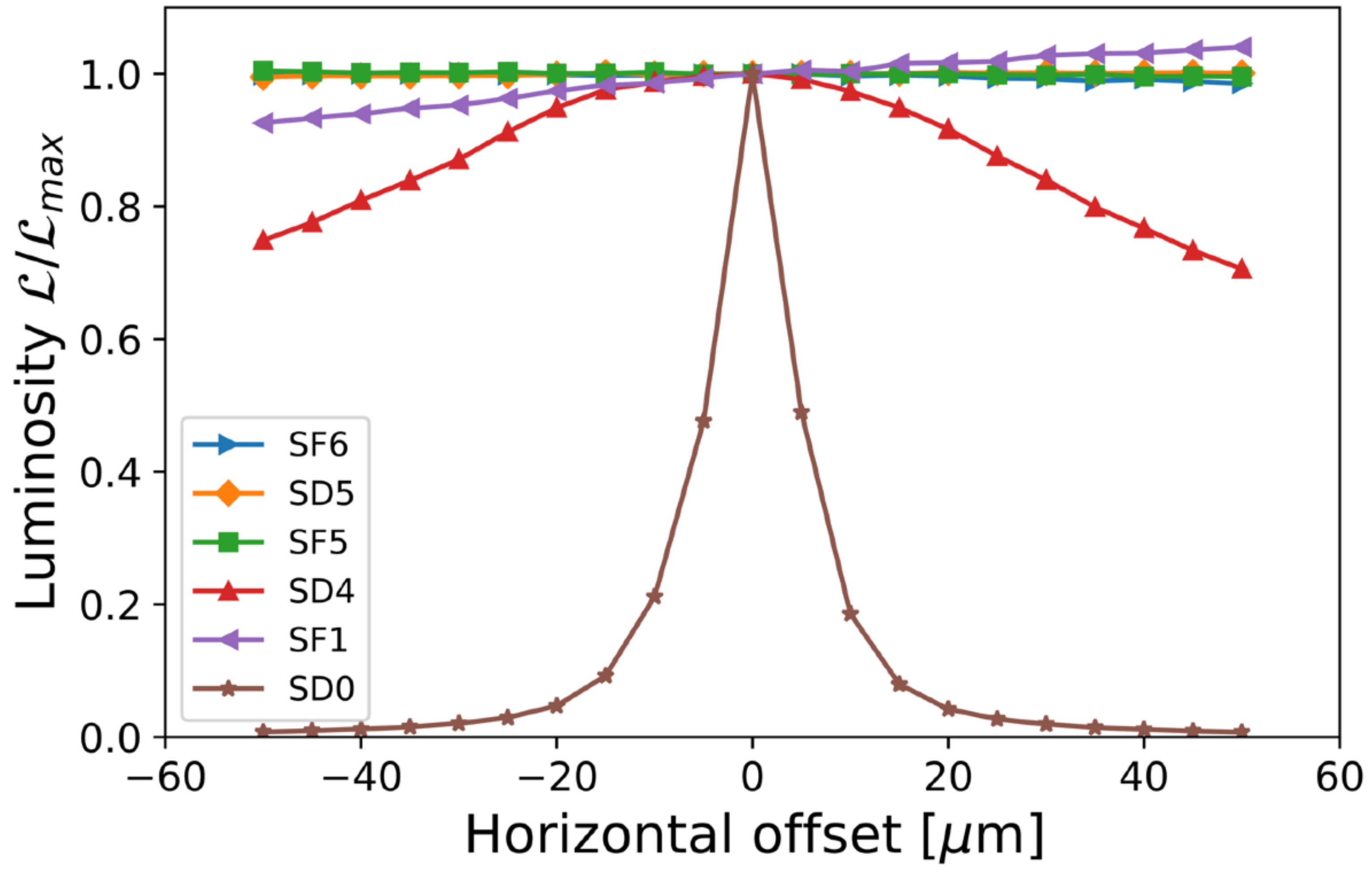
- Luminosity and sextupole offsets (perfect machine)

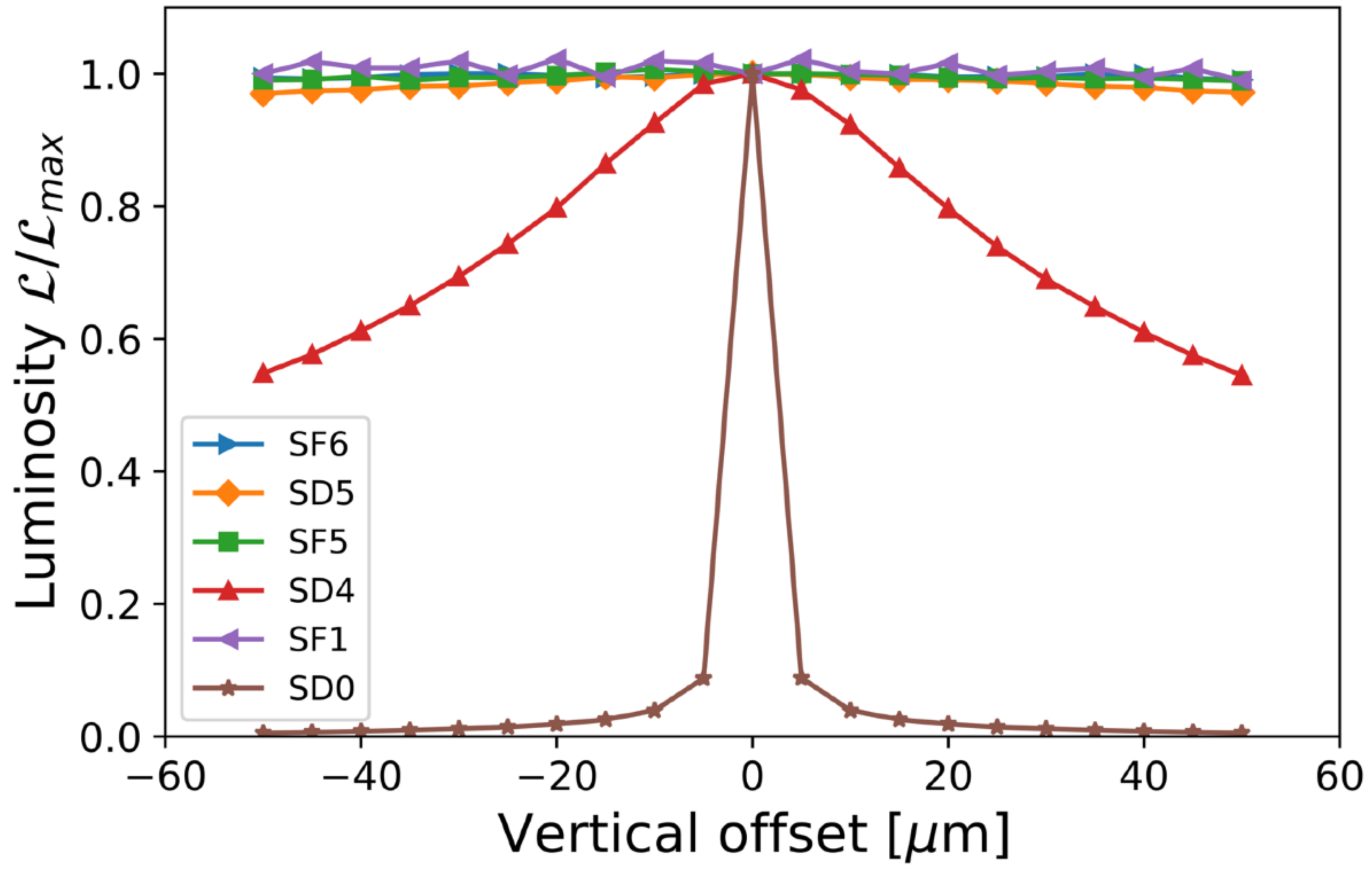


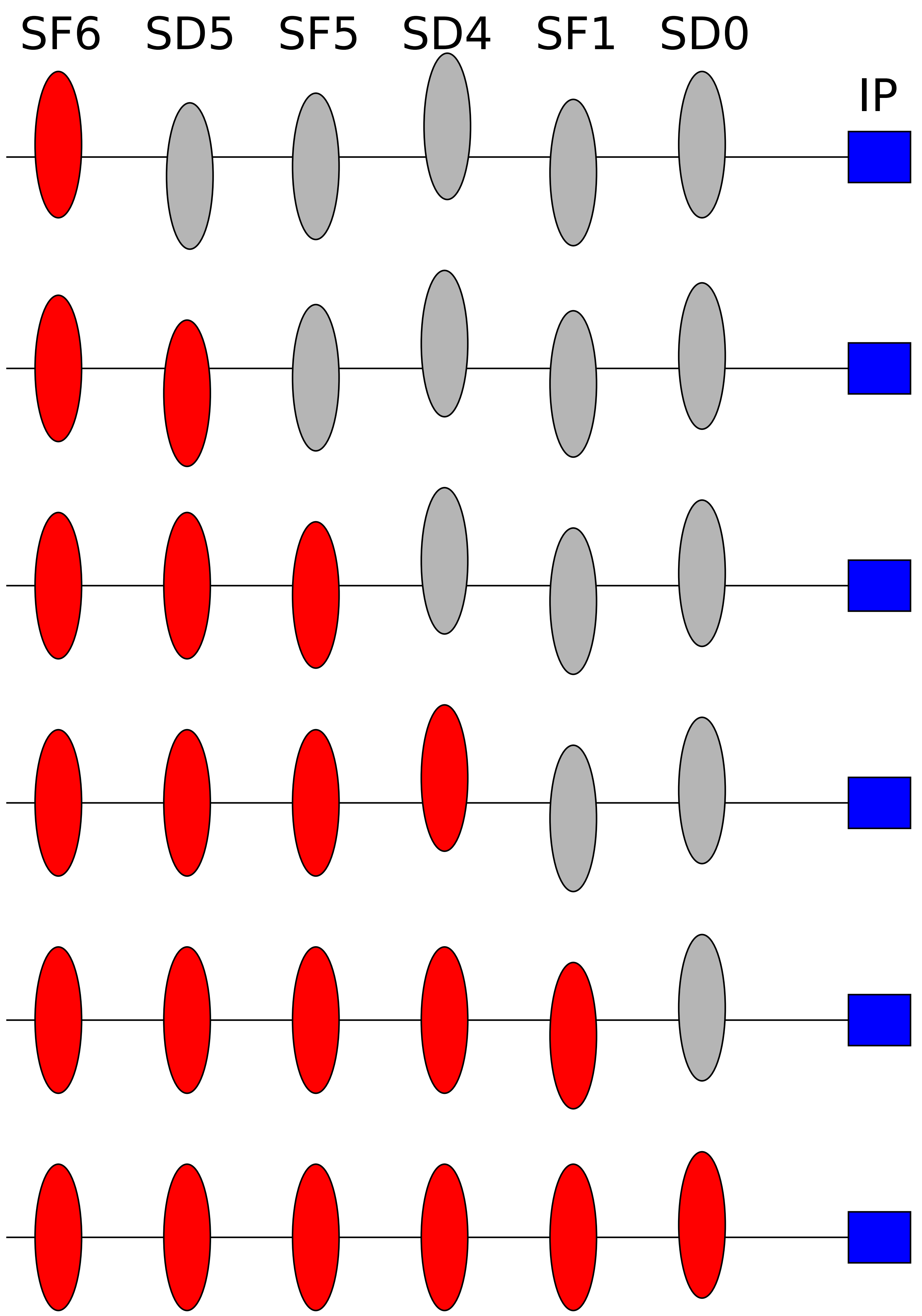


Aligning sextupoles 1-by-1: **downstream**

Relative luminosity change vs offset:







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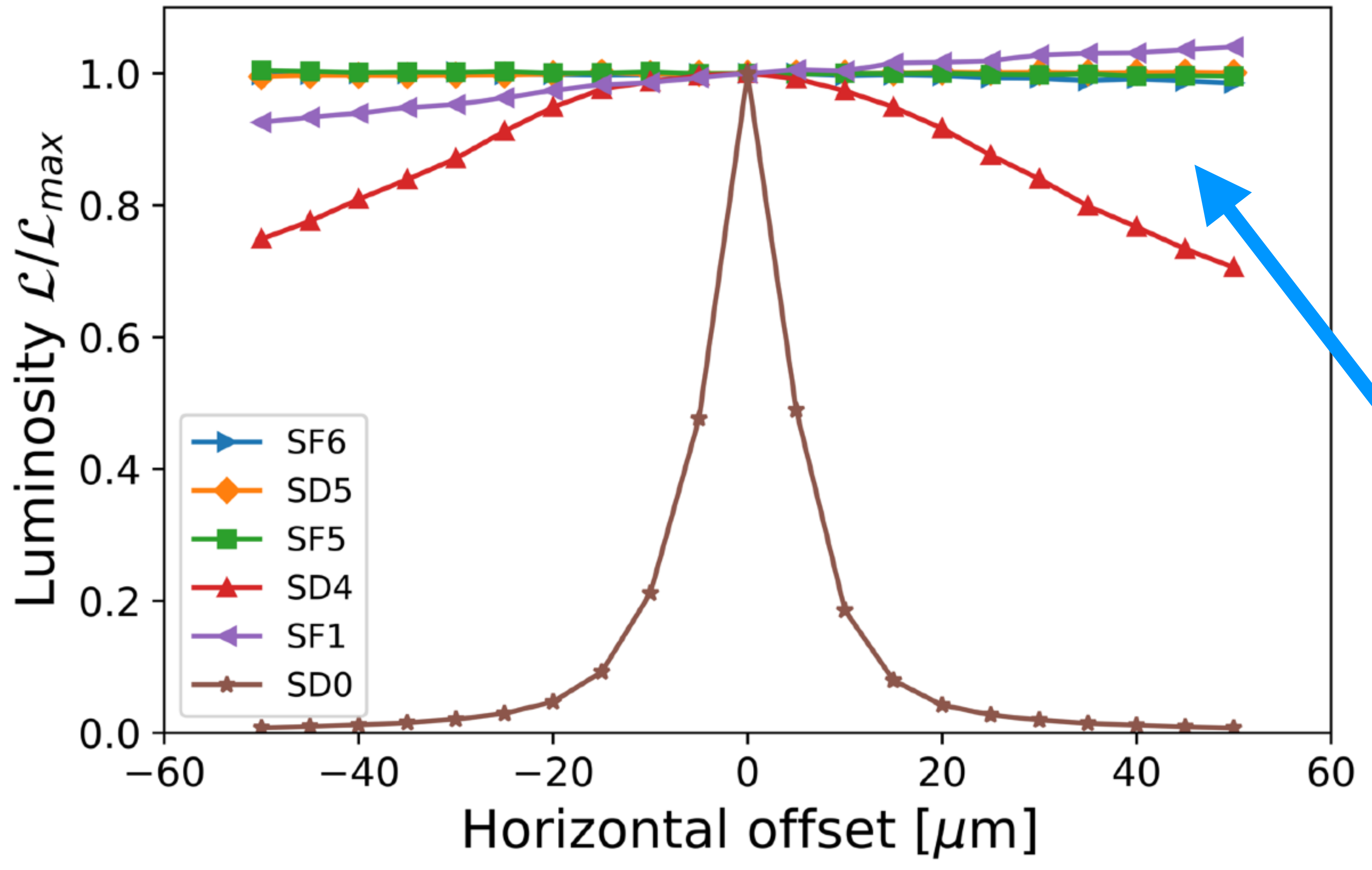
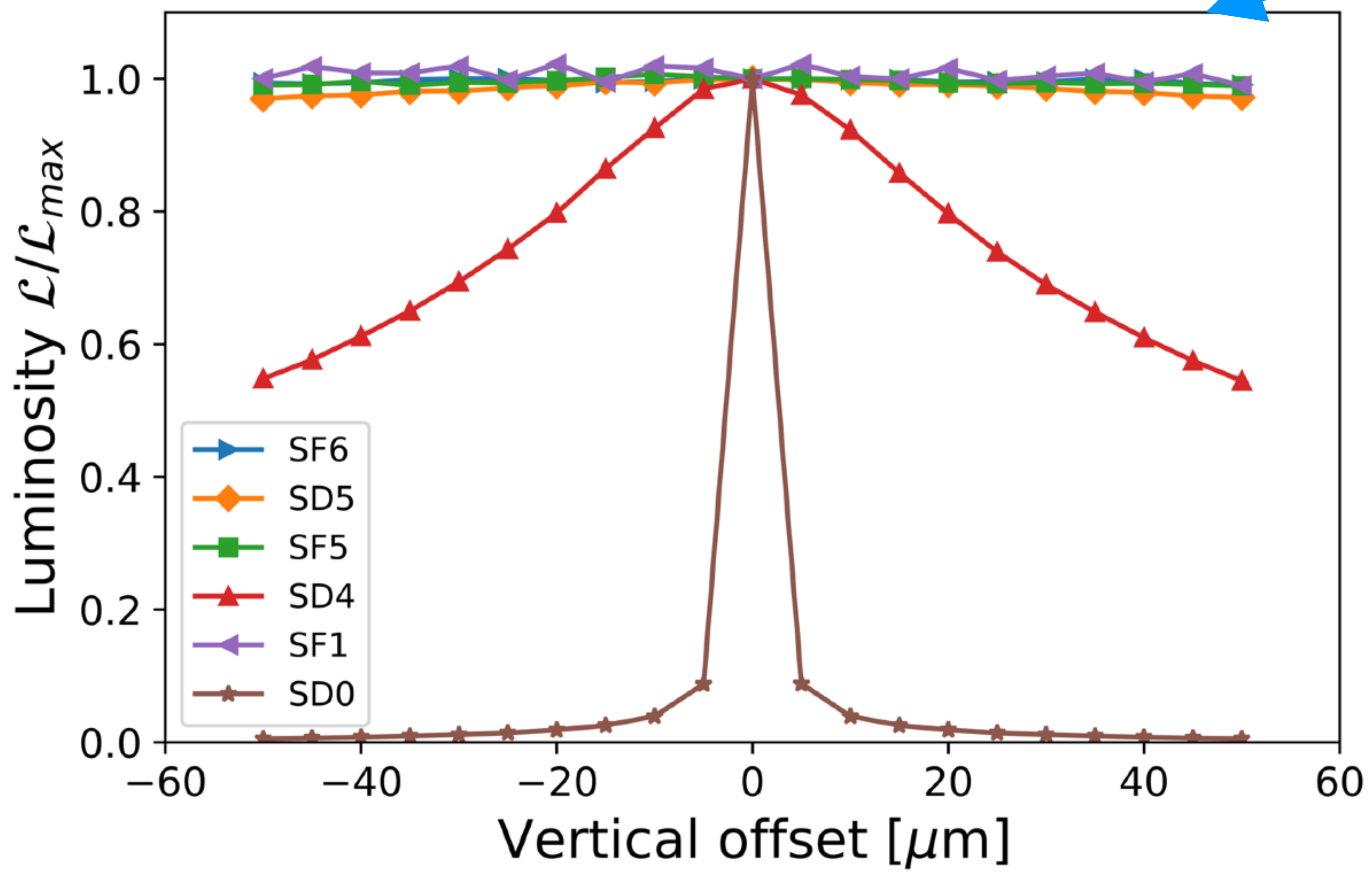
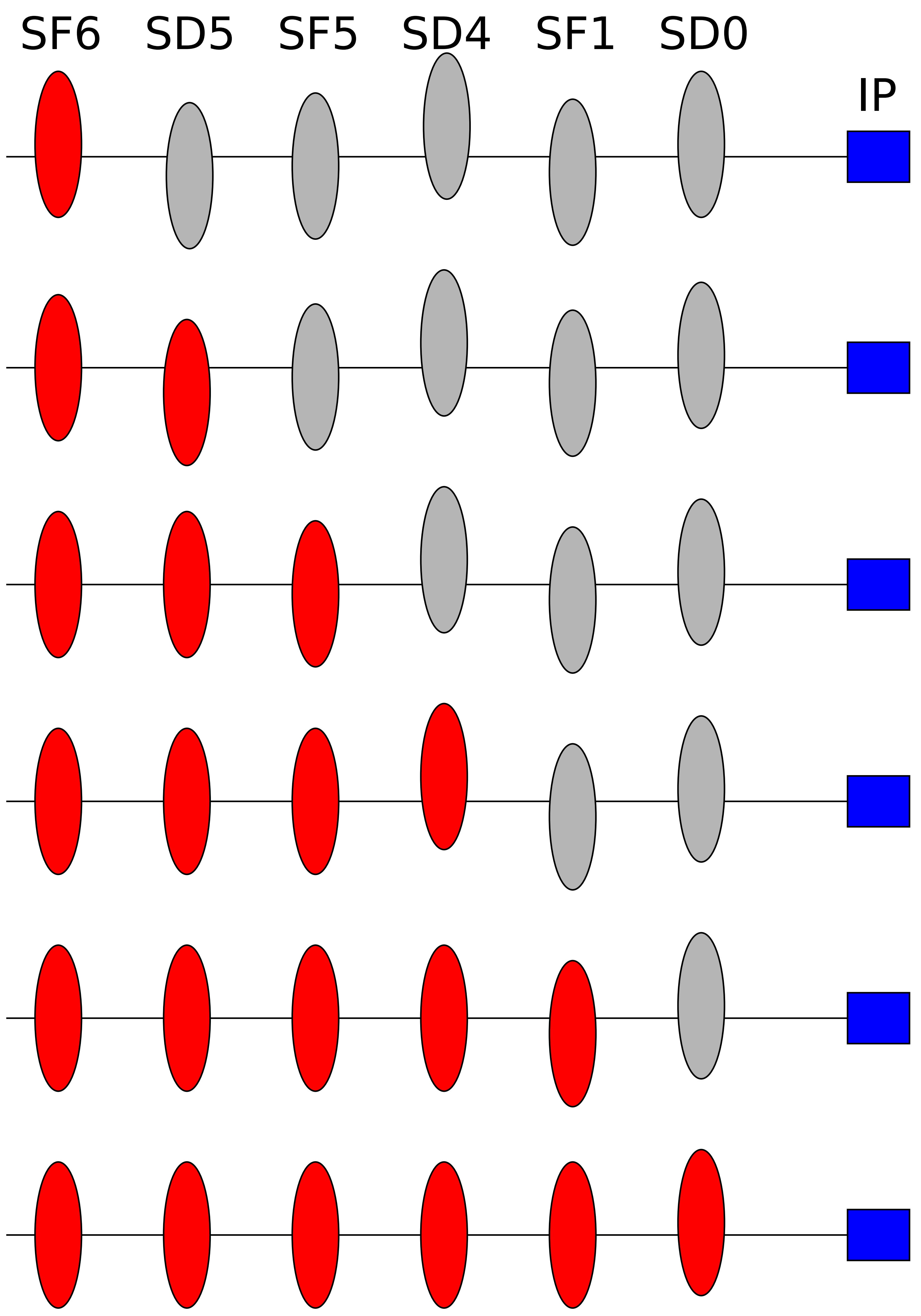


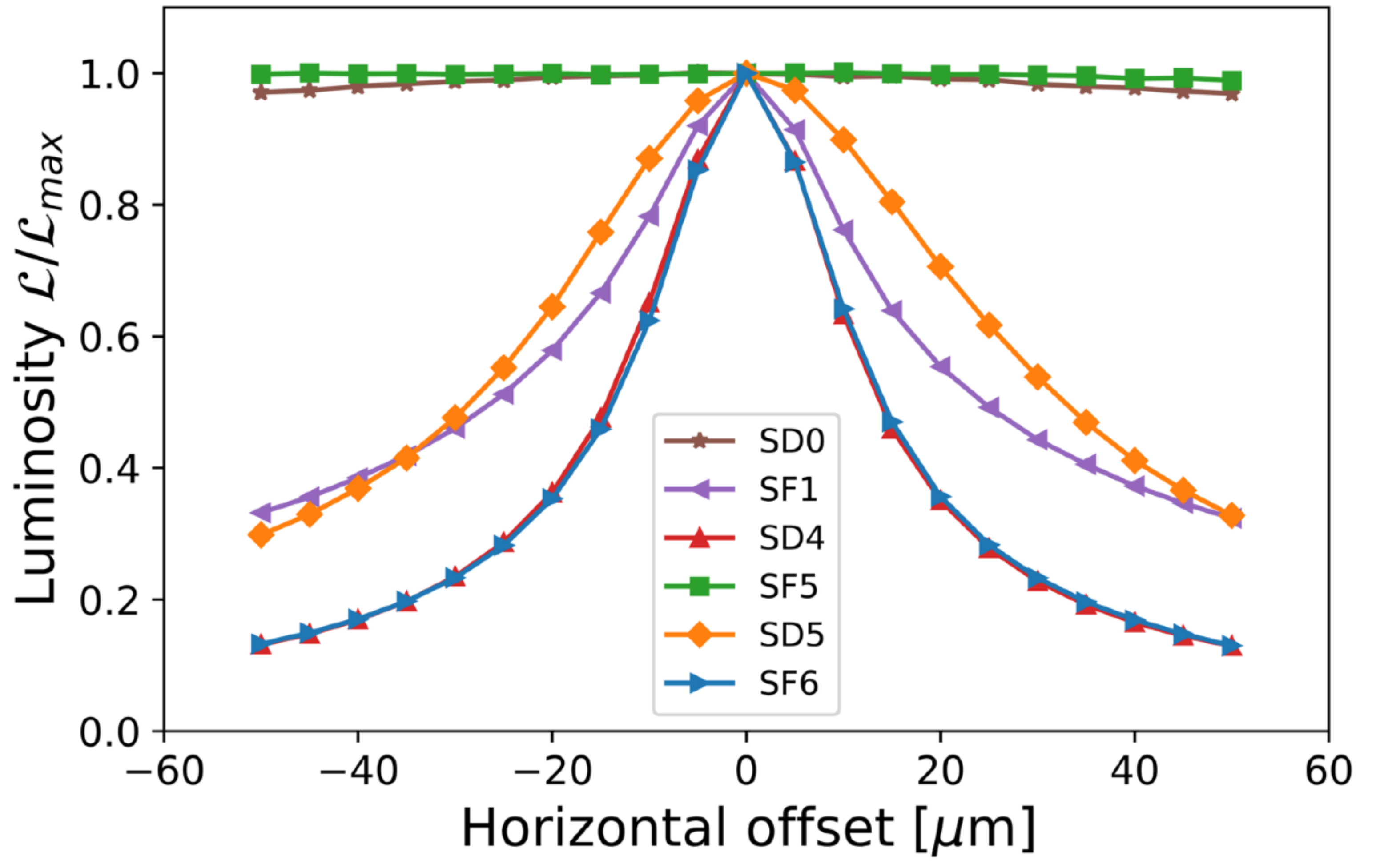


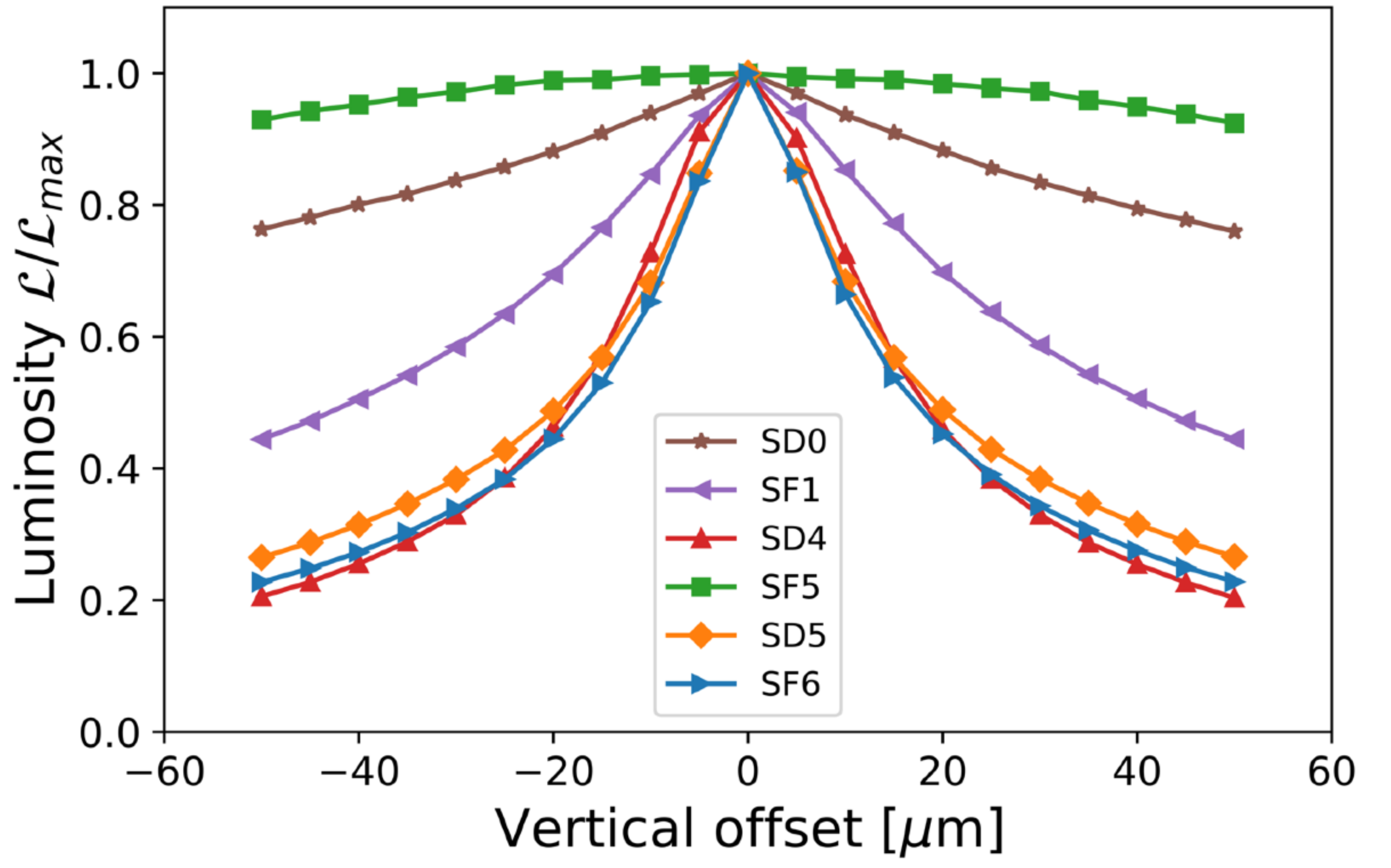
No sensitivity for 4 of the sextupoles

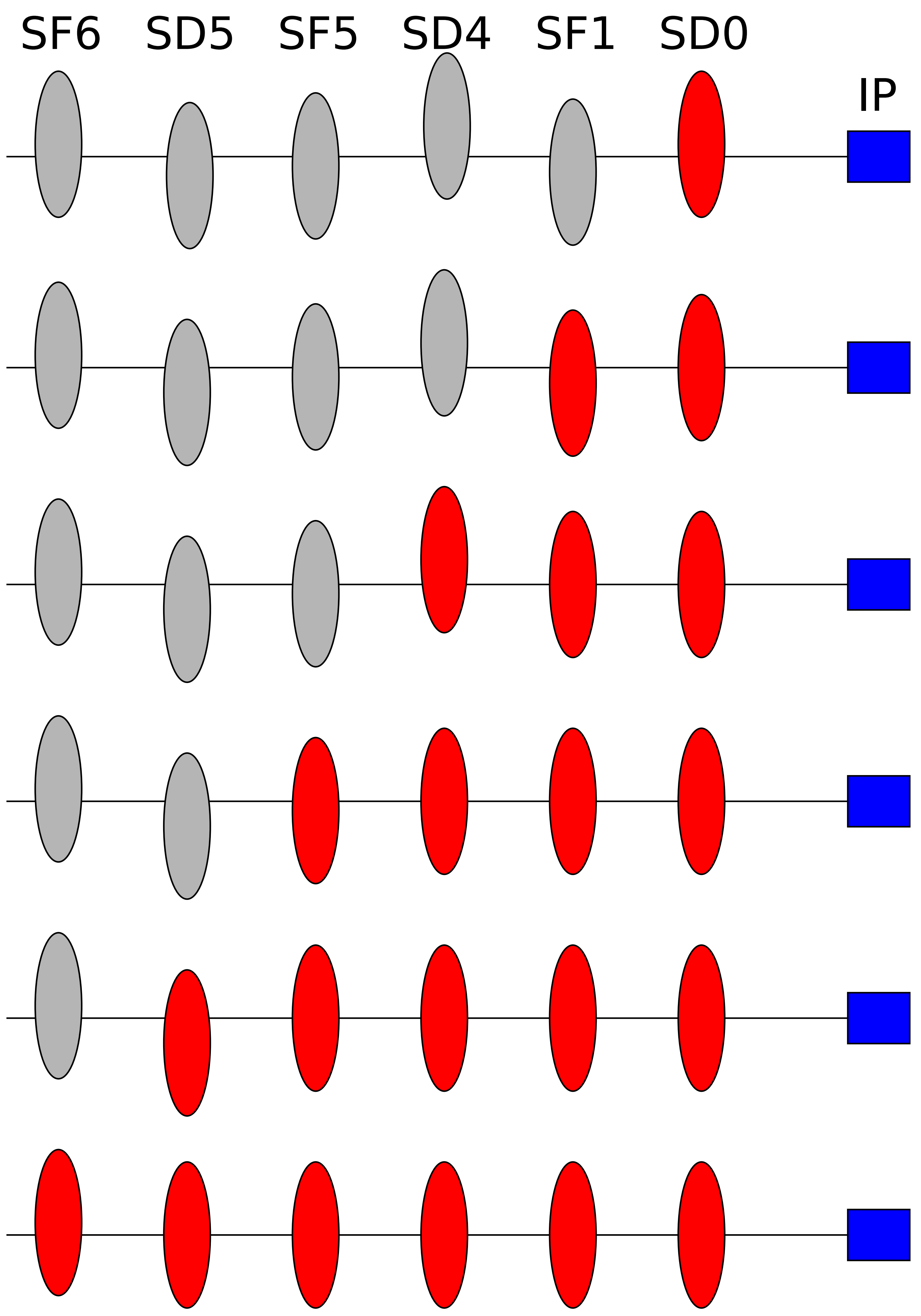


Aligning sextupoles 1-by-1: **upstream**

Relative luminosity change vs offset:

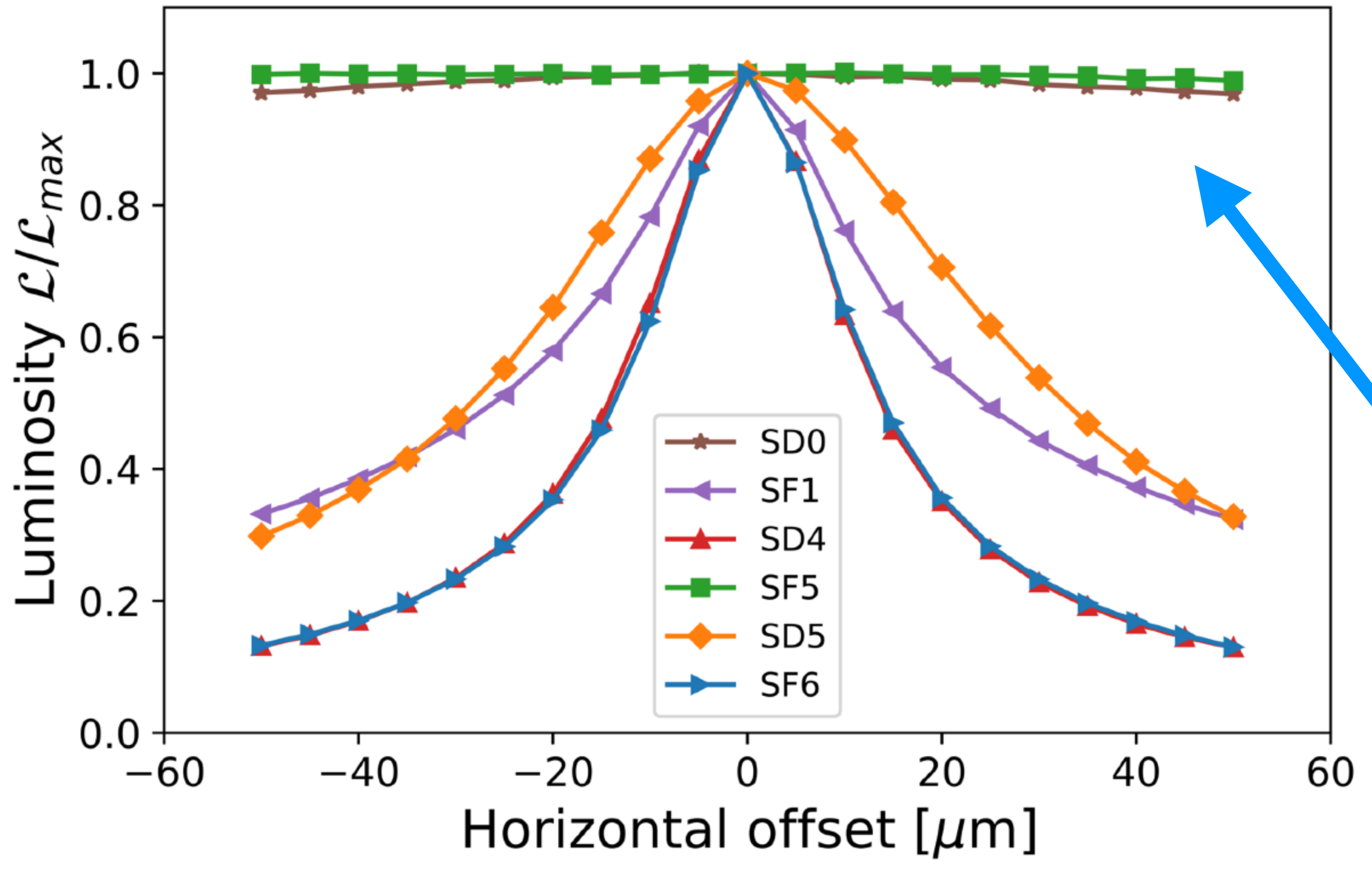


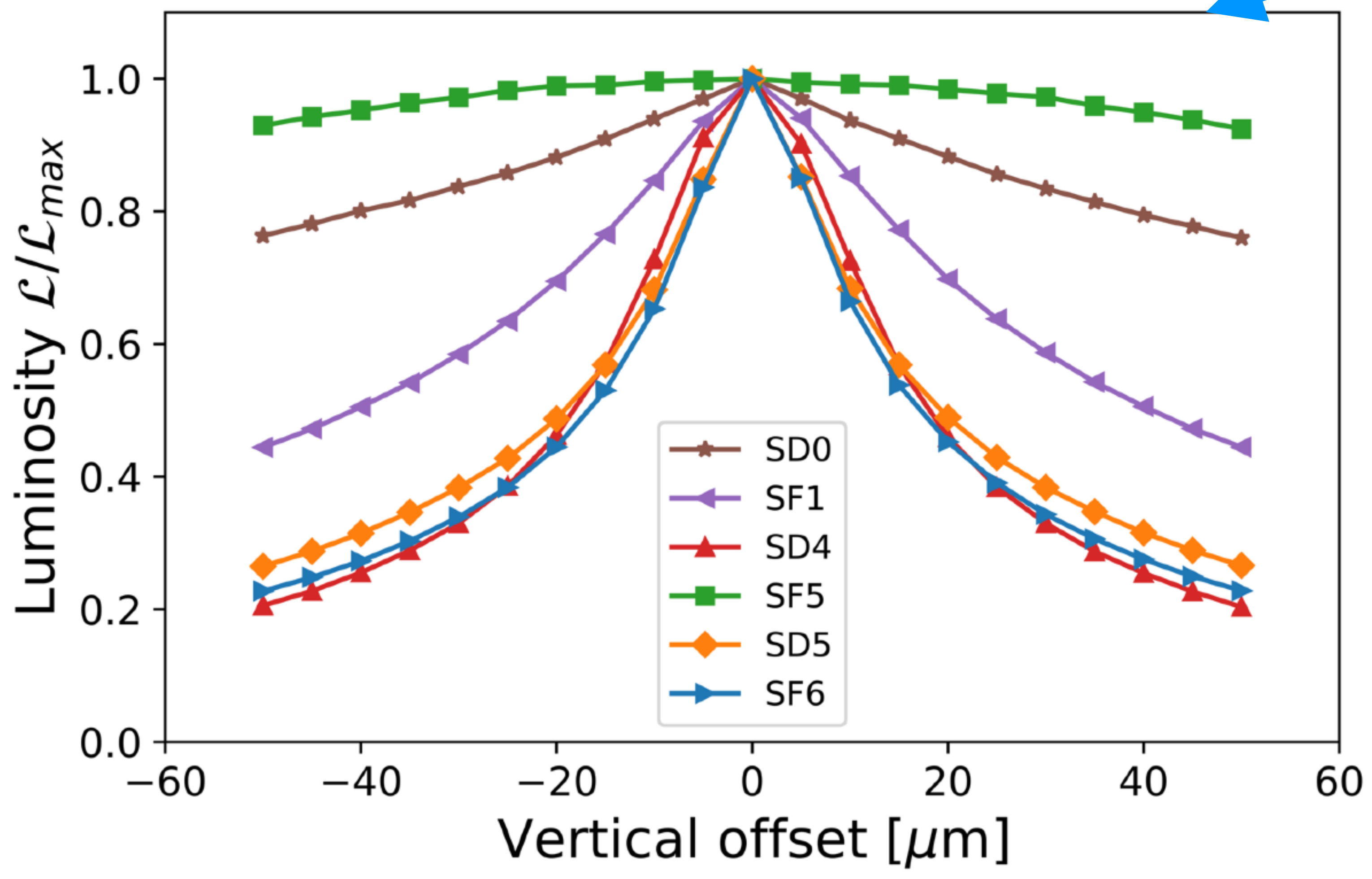




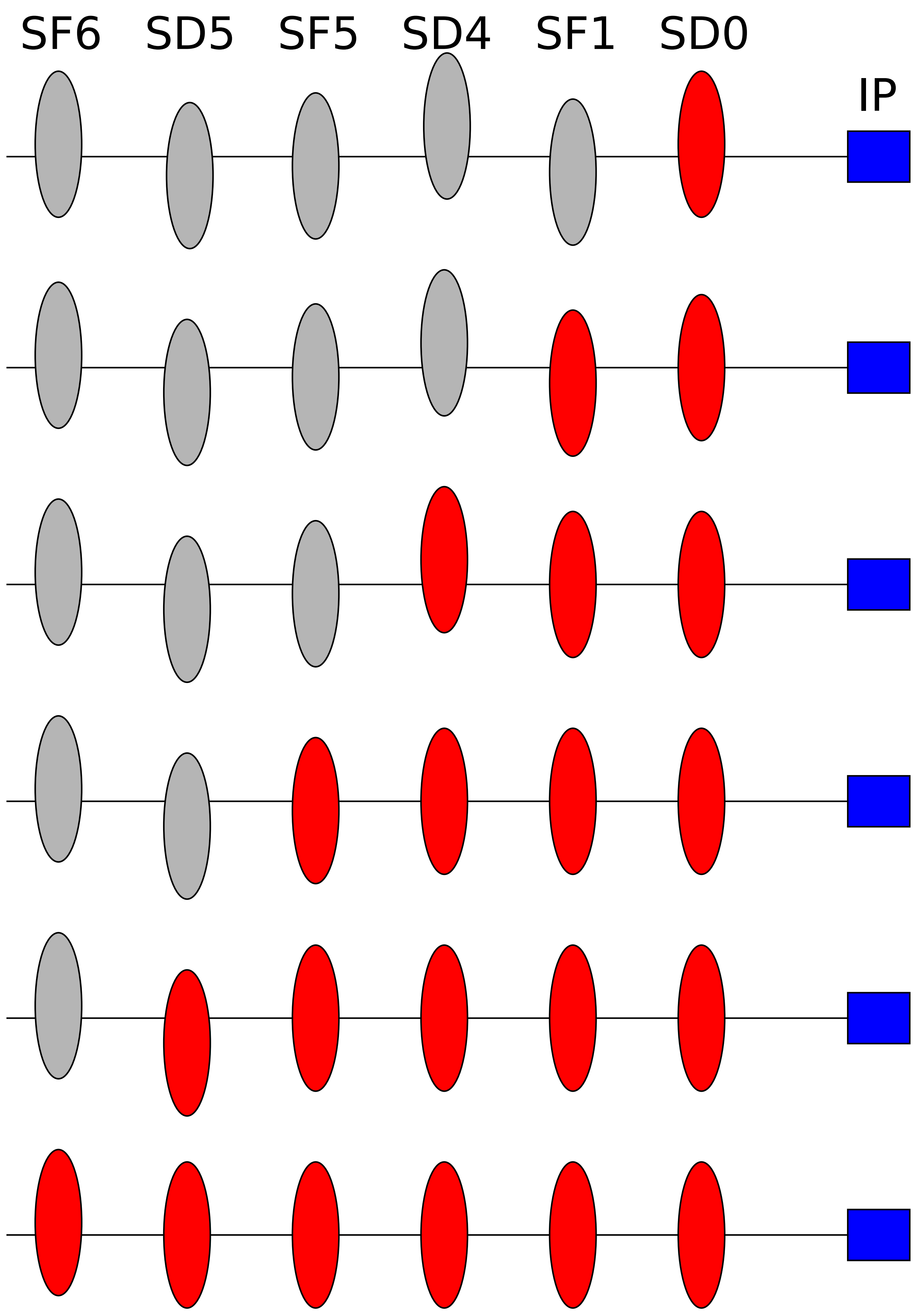
Aligning sextupoles 1-by-1: **upstream**

Relative luminosity change vs offset:



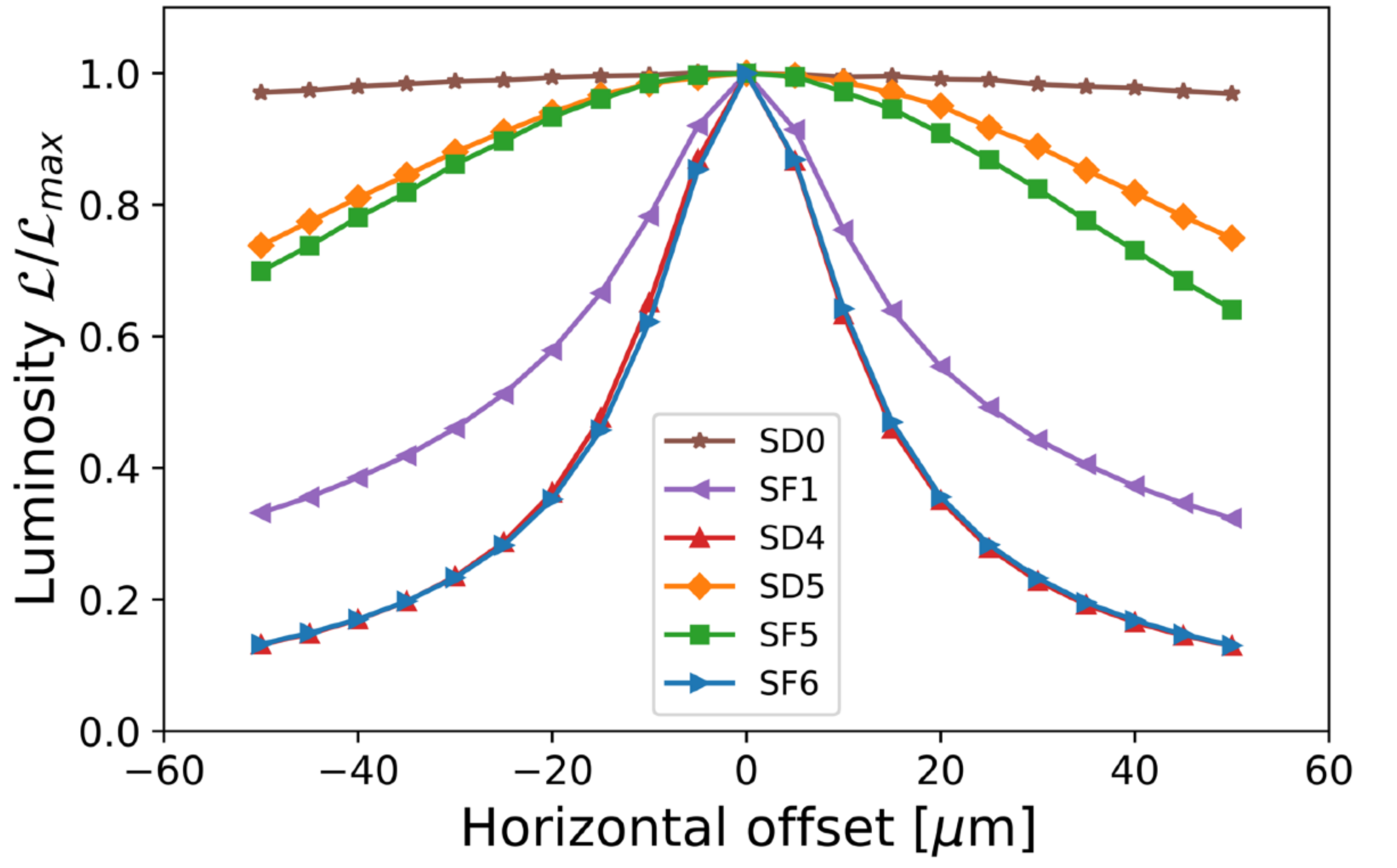


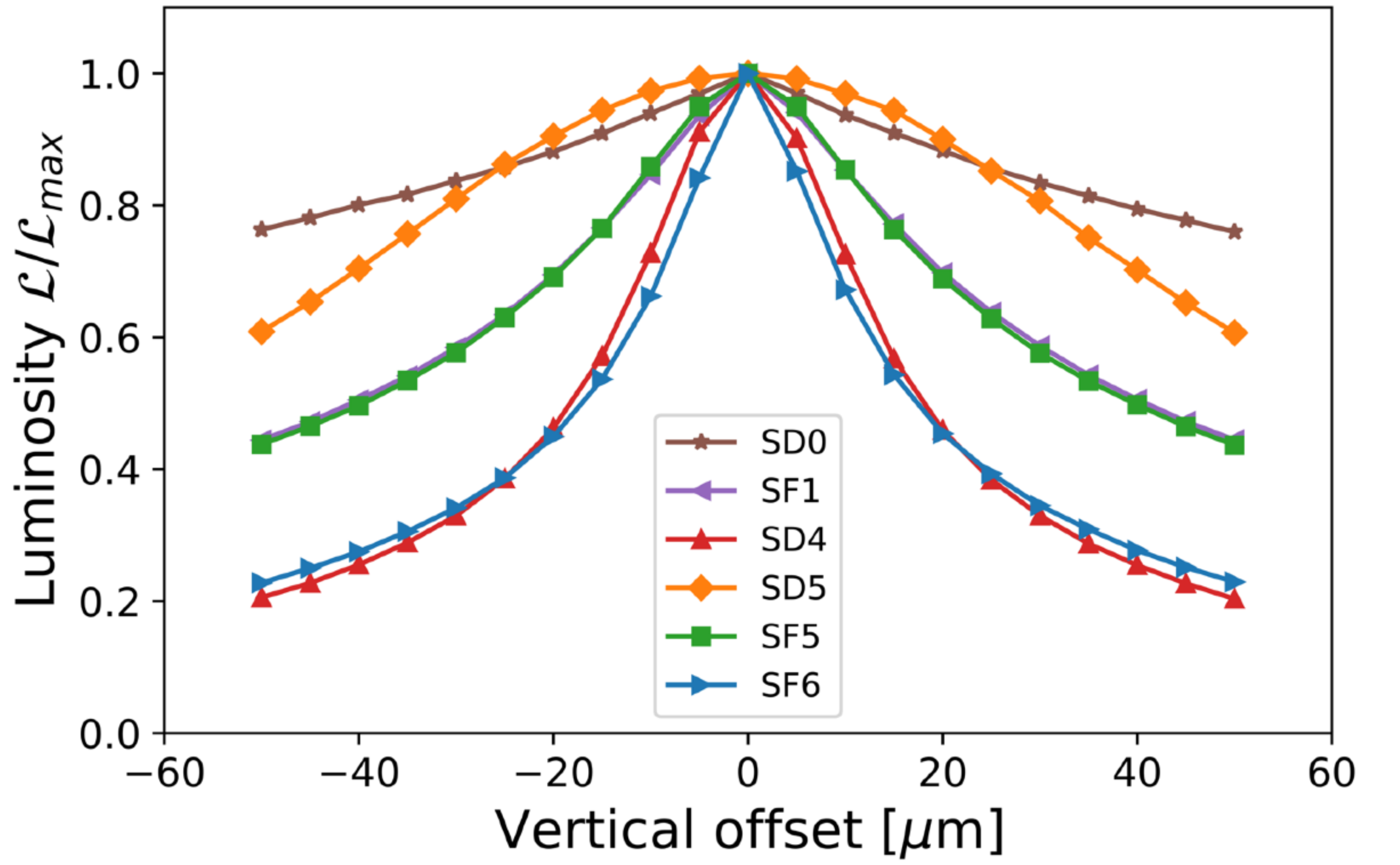
Improved sensitivity

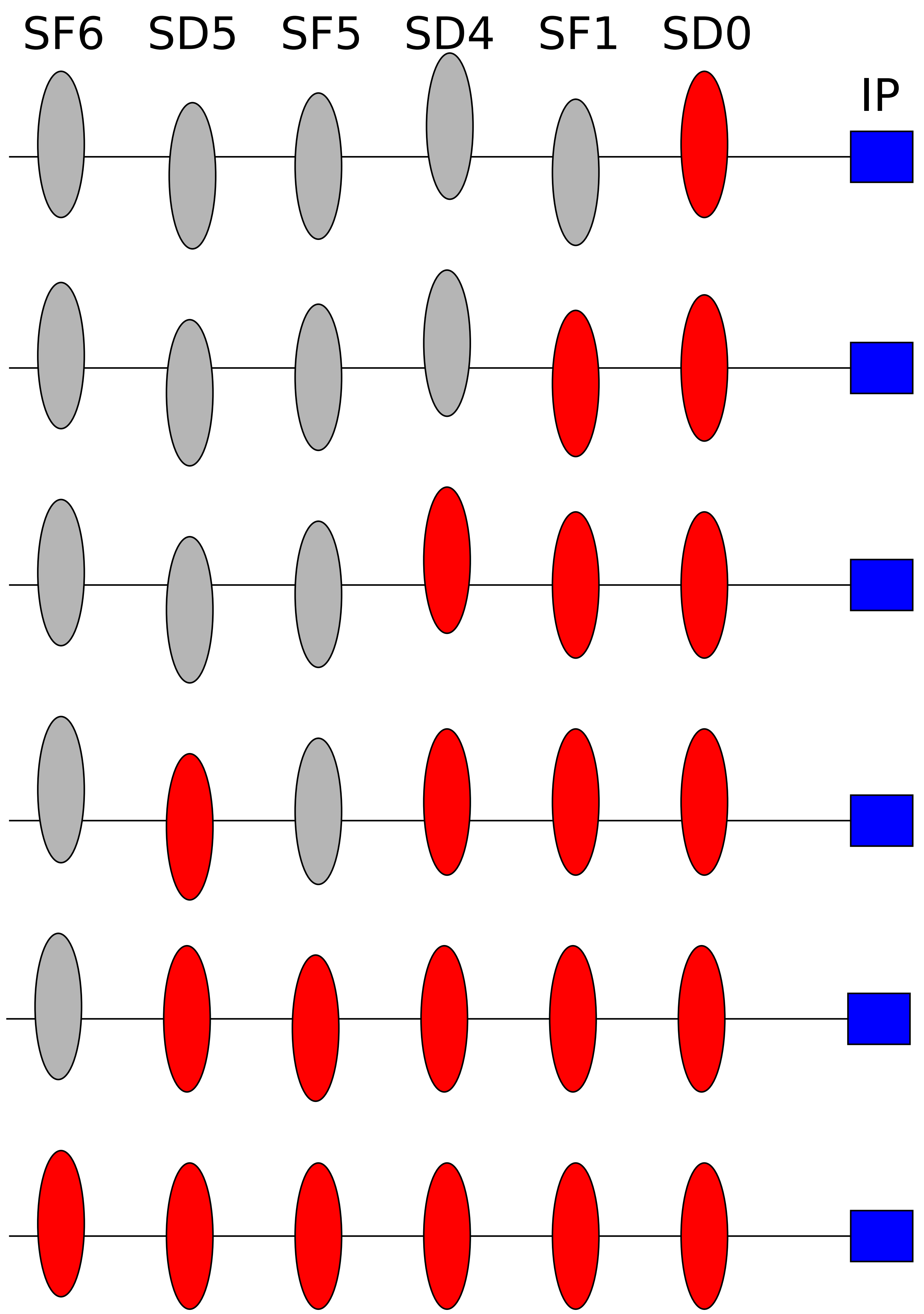


Aligning sextupoles 1-by-1: **optimum**

Relative luminosity change vs offset:

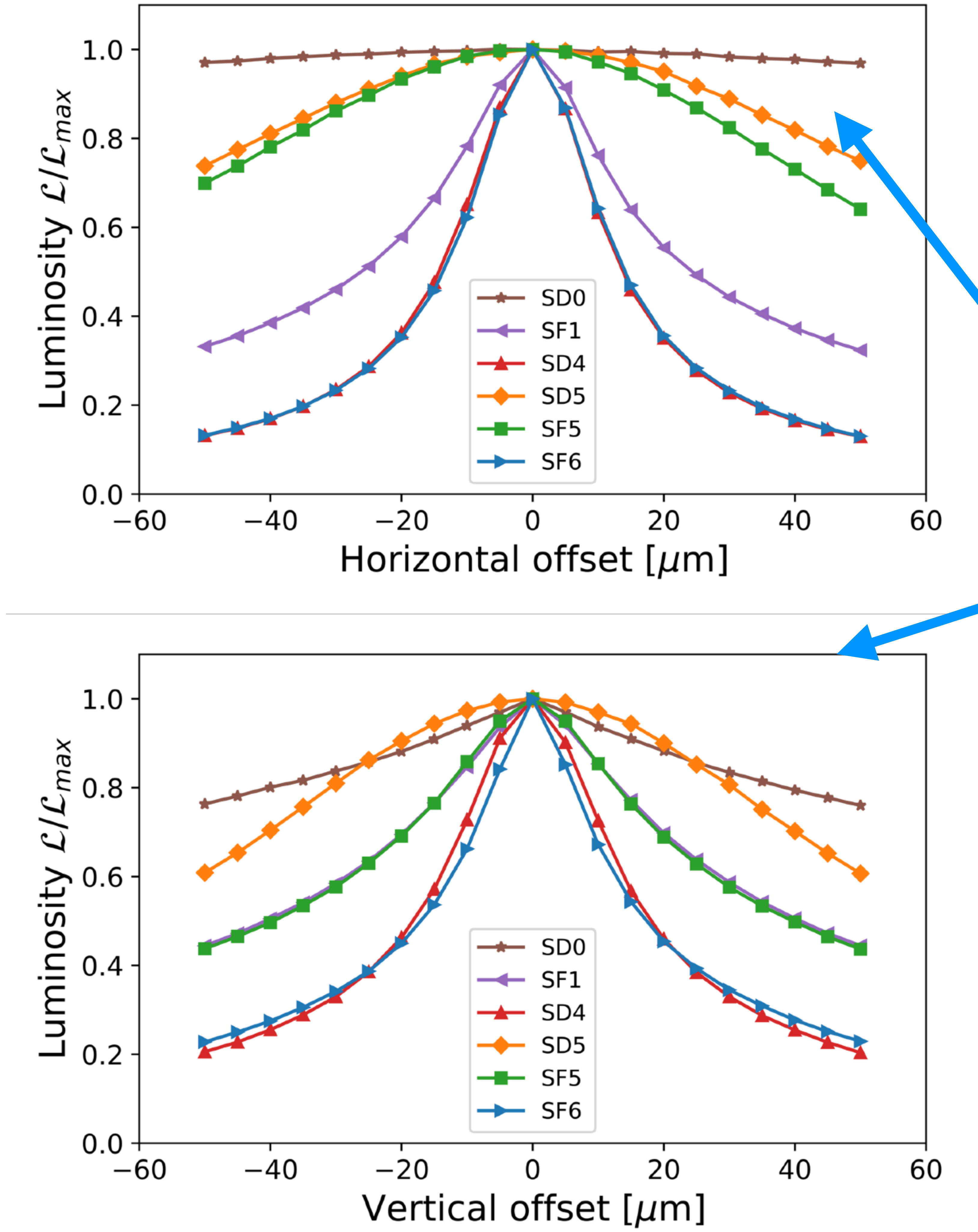




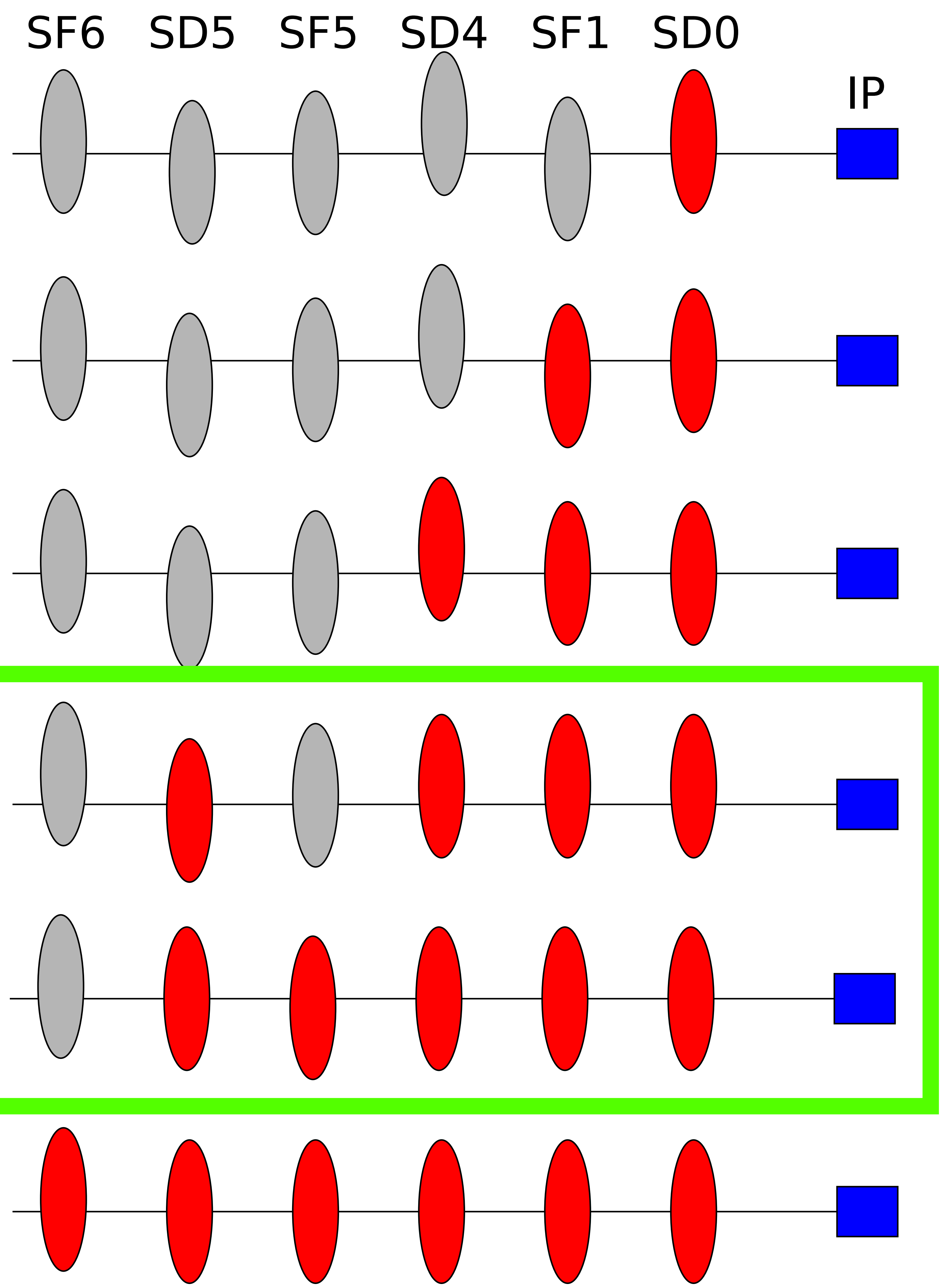


Aligning sextupoles 1-by-1: **optimum**

Relative luminosity change vs offset:



Further improved sensitivity by swapping order of SF5 and SD5



Sextupole knobs - 1st order

- Transverse movement of sextupoles

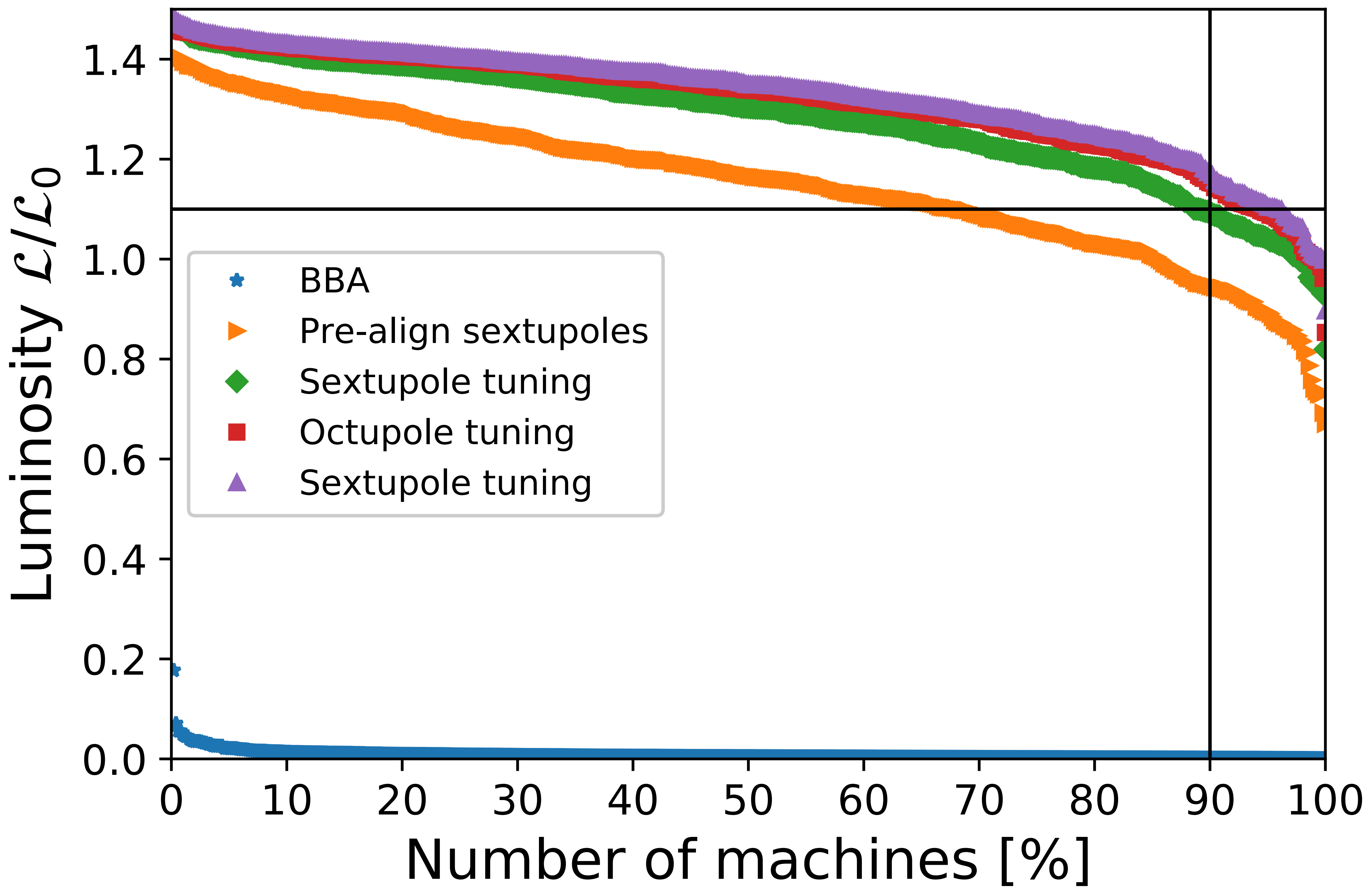
- The response matrix of 2nd order moments
  - SVD to find orthogonal 'knobs' (vectors from matrix V)

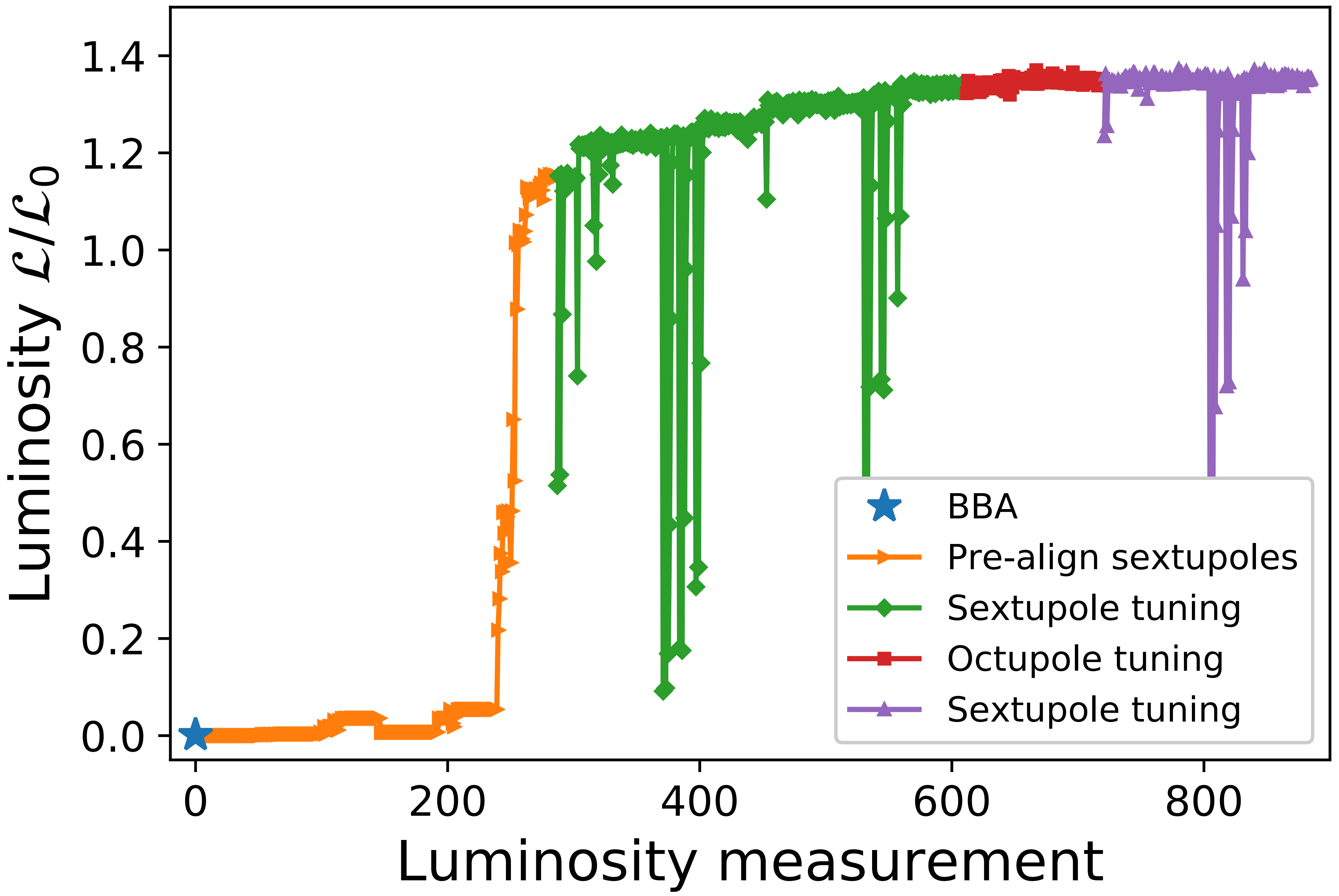
$$U\lambda V^T = \begin{bmatrix} \frac{\partial \sigma_{xx}}{\partial X_1} & \cdots & \frac{\partial \sigma_{xx}}{\partial X_6} & \frac{\partial \sigma_{xx}}{\partial Y_1} & \cdots & \frac{\partial \sigma_{xx}}{\partial Y_6} \\ \frac{\partial \sigma_{xx'}}{\partial X_1} & \cdots & \frac{\partial \sigma_{xx'}}{\partial X_6} & \frac{\partial \sigma_{xx'}}{\partial Y_1} & \cdots & \frac{\partial \sigma_{xx'}}{\partial Y_6} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial \sigma_{zz}}{\partial X_1} & \cdots & \frac{\partial \sigma_{zz}}{\partial X_6} & \frac{\partial \sigma_{zz}}{\partial Y_1} & \cdots & \frac{\partial \sigma_{zz}}{\partial Y_6} \end{bmatrix}$$

- Each knob is scanned over some range and luminosity is maximized

- Similarly for the octupoles

Tuning results





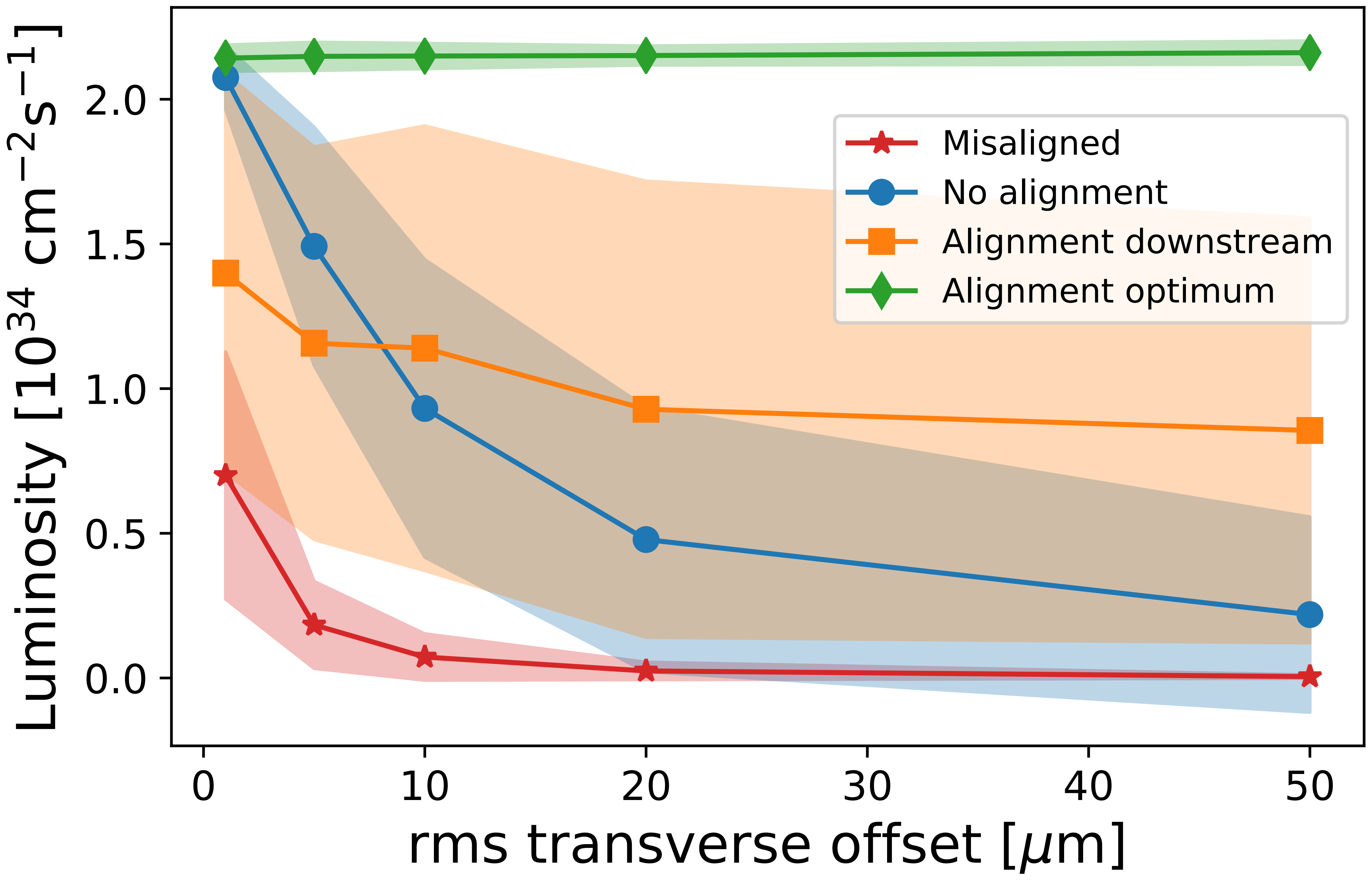
500 machines, randomly distributed imperfections

- Left: 95% of machines reach goal of 110% of L_0
- Right: Luminosity evolution for the median machine

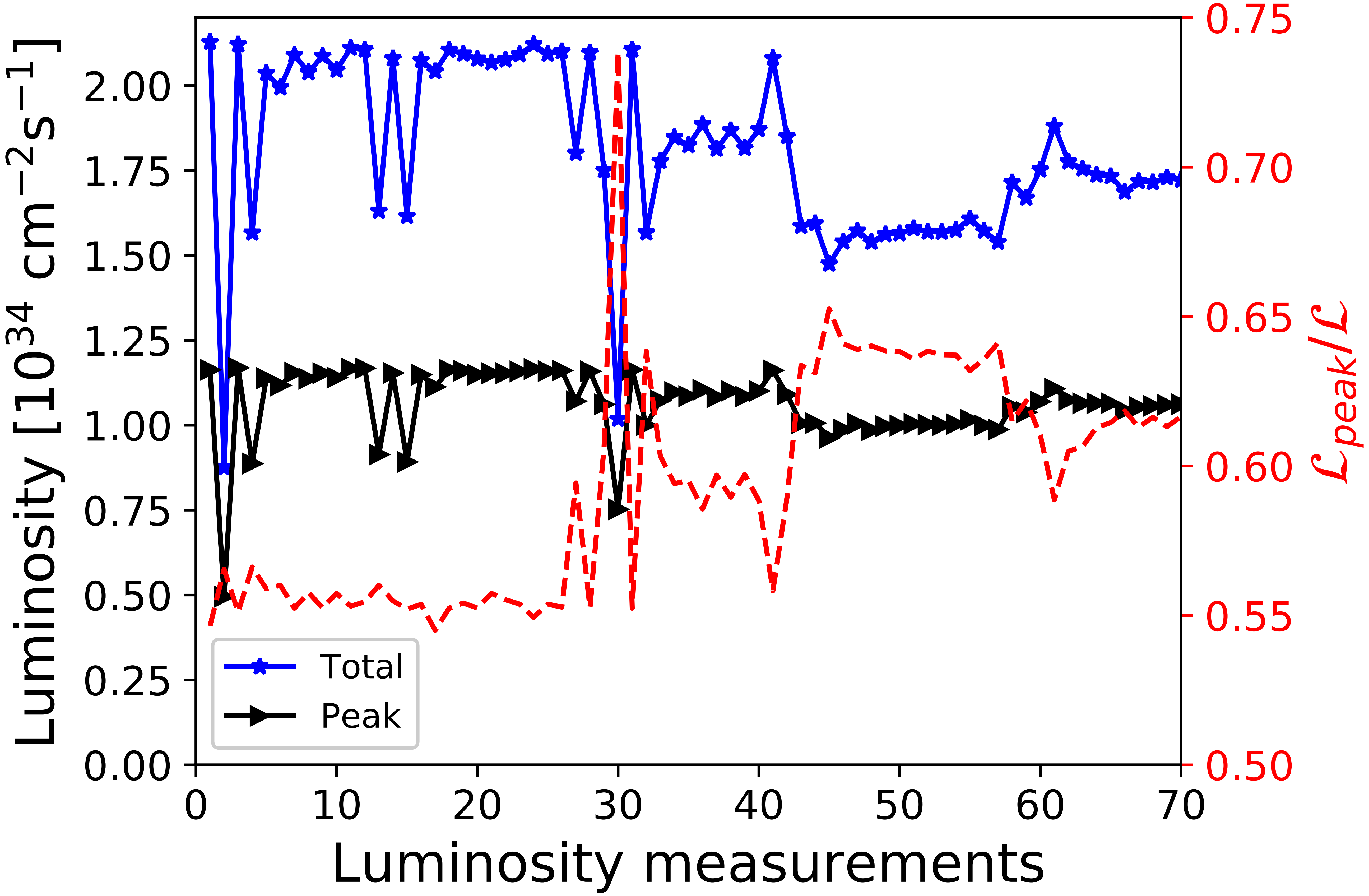
Importance of the sextupole alignment

Perfect lattice, only offset sextupoles

- Compare three methods
    - 1) Sextupole knobs only
    - 2) Alignment downstream + sextupole knobs
    - 3) Alignment optimum order + sextupole knobs
- Random sextupole offsets:
    - rms = 1, 5, 10, 20 and 50 μm
- Average over 10 machines:
- Big impact on tuning efficiency of the sextupole knobs
- Alignment downstream order is far less robust



Tuning of luminosity spectrum



- Tuning only for total luminosity
- Luminosity spectrum
  - Goal: $L_{peak}/L = 0.60$
- Sextupole knobs with new cost function
- Improve the spectrum at the cost of a reduction in total luminosity

Conclusions

- New method for sextupole alignment
  - Align sextupoles one-by-one and optimize for luminosity
  - Order matters
  - Robust and effective, good starting point for the sextupole knobs

- Tuning results
  - 95% of machines reach tuning goal.
  - Can tolerate larger initial misalignments
  - Substantial improvement on the number of luminosity measurements

- Future work
  - Two-beam tuning, including dynamic imperfections
  - Using different beam-beam signals for tuning
  - Experimental test at ATF2?

- For more information:

  J. Ogren, A. Latina, R. Tomas and D. Schulte, *Tuning of the CLIC 380 GeV Final-Focus System with Static Imperfections*, CERN-ACC-2018-0055, CLIC-Note-1141.