FCC-ee Orbit Correction and Polarization

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Swiss Accelerator Research and Technology

FUTURE CIRCULAR COLLIDER

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Energy calibration in the FCC-ee

- **Four operation center-of-mass energies**

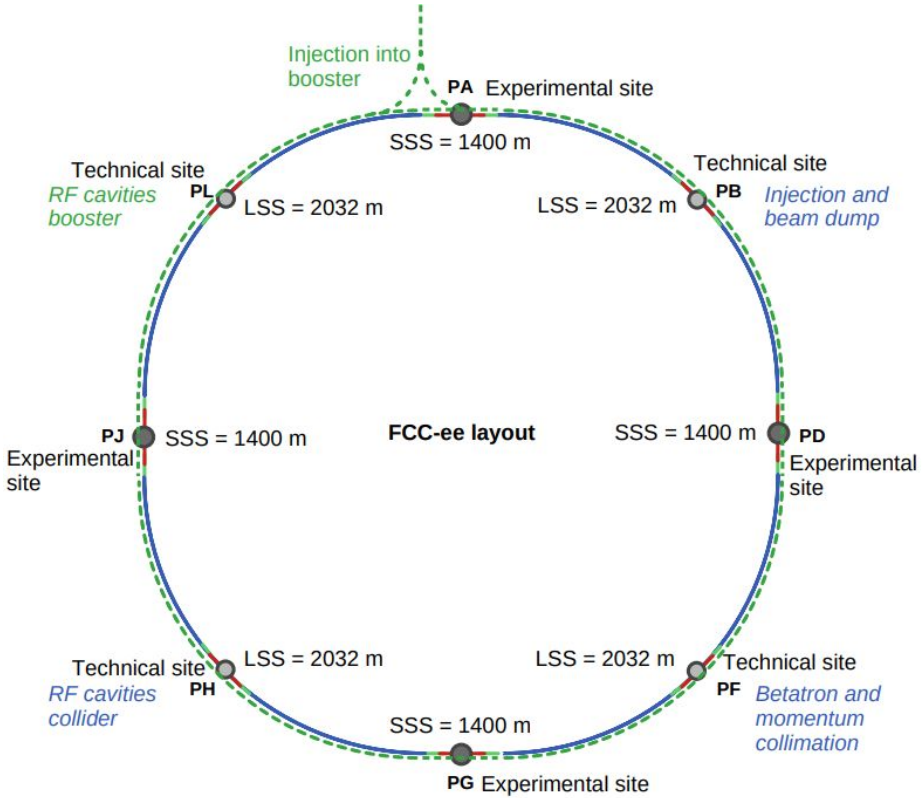
  Z bosons (91 GeV) to top quark pairs (350-365 GeV)

- **High precision COM energy calibration**
- **The current precision targets**

  4 keV at Z mass and 100 keV at W mass

- **Resonant depolarization is the way to achieve this target**

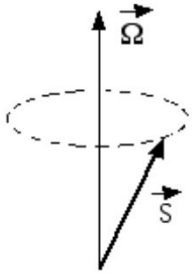
  ↳ requires a sufficient transverse spin polarization level



Spin polarization

Thomas-BMT equation

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{BMT}} \times \vec{S}$$



$$\vec{P} = \frac{\sum_{i=1}^{N} \left\langle \vec{S}_i \right\rangle}{\left| \left\langle \vec{S}_i \right\rangle \right| N}$$

perfect flat ring → P ≈ 92.4% $\nu_0 = a\gamma$

real machine → P < 92.4% $\nu_0 = a\gamma + d\nu_0$

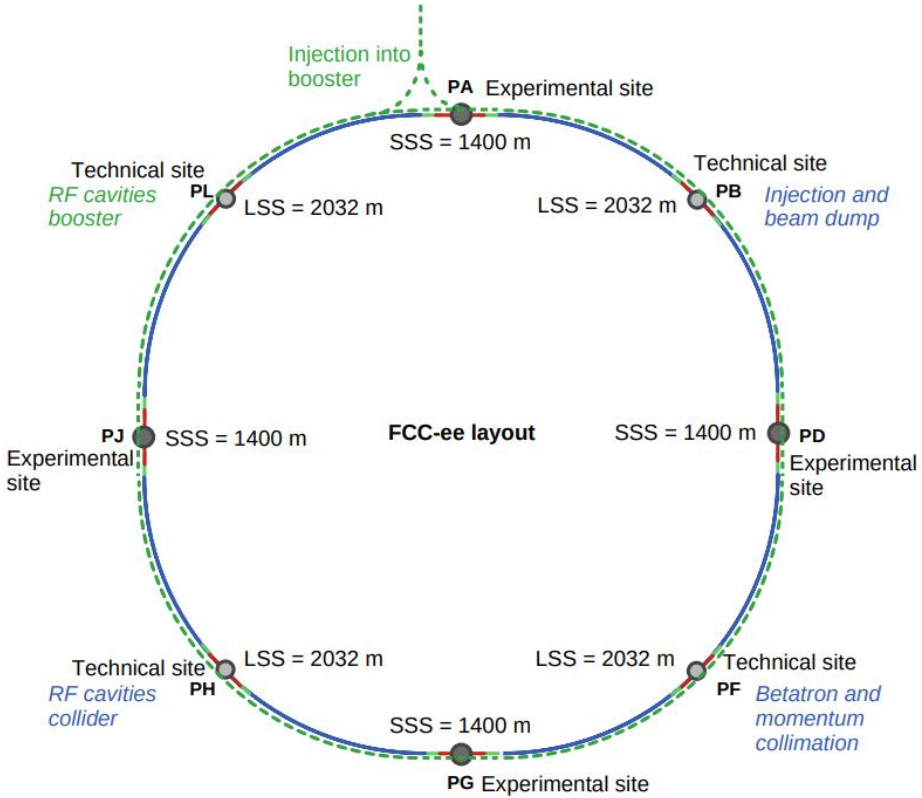
How much?

[*] Magnet figures from Maxwell's equations for magnets, A. Wolski, https://cds.cern.ch/record/1333874/files/1103.0713.pdf
[*] Spin polarization theory reference: D. P. Barber, G. Ripken, Sections 2.6.6-2.6.8, Handbook of Accelerator Physics and Engineering, 3rd Edn., World Scientific, Singapore, 2023.

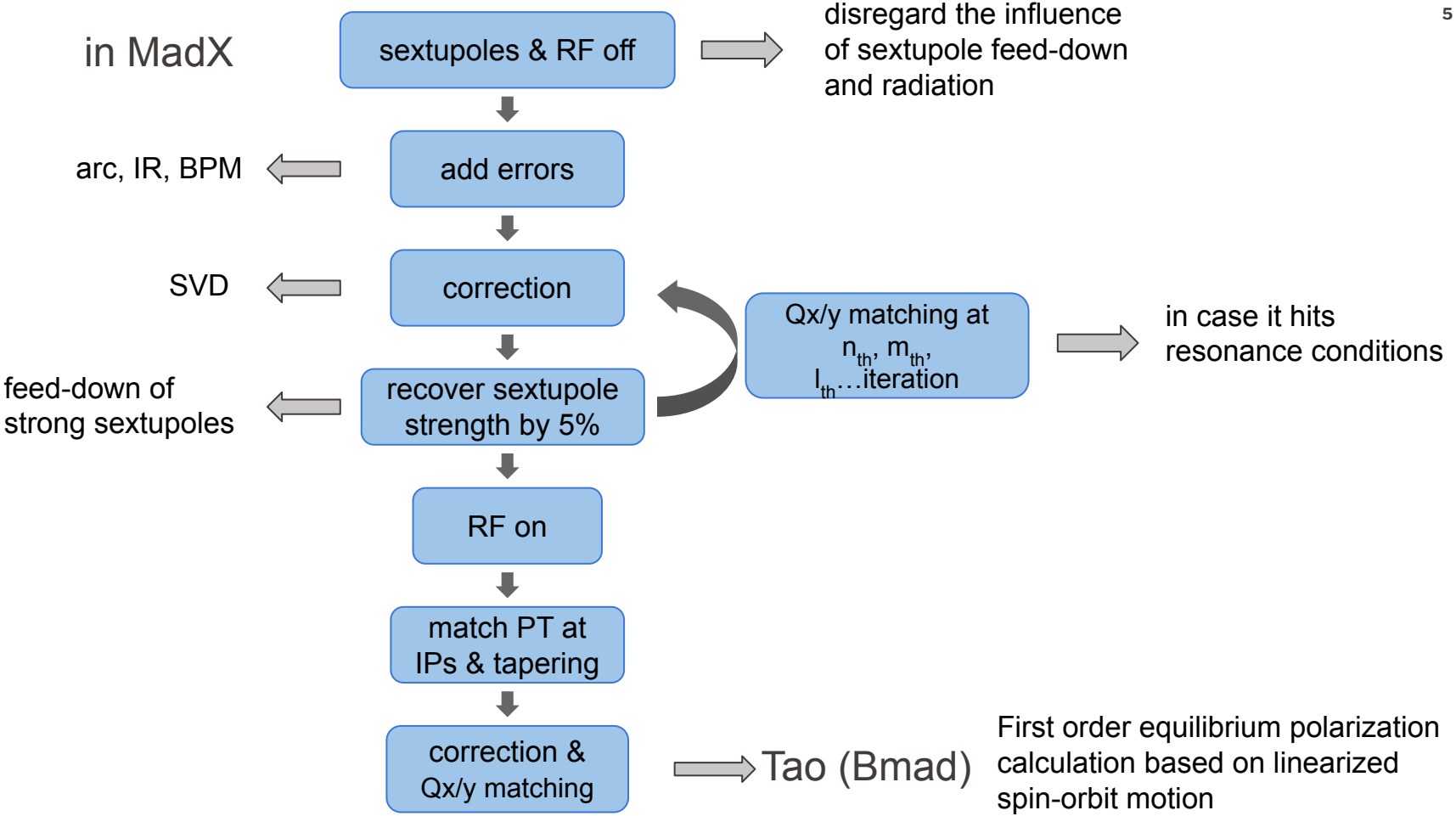
Lattice

- Based on V22 Z lattice
  - 1856 quadrupoles
- Modified by adding
  - 1 BPM & 1 corrector next to each quad

    928 Ver. corrector + 928 Hor. corrector
  - sextupole knob to control all sextupole strengths proportionally

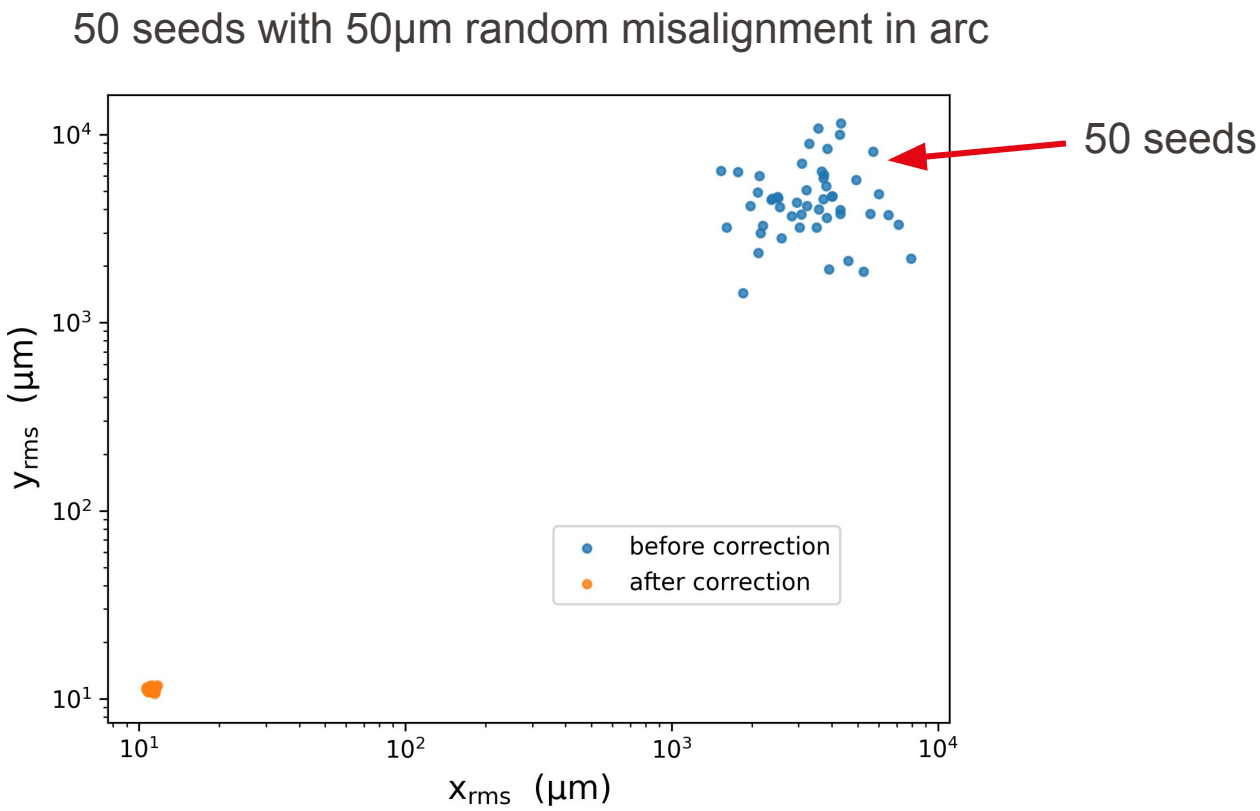


in MadX



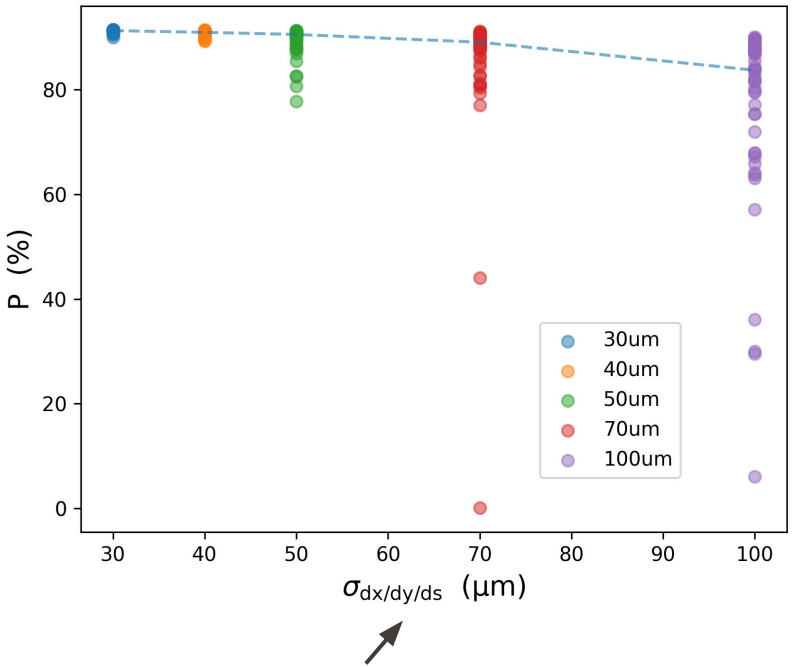
[*] Bmad Home Page https://www.classe.cornell.edu/bmad/

Misalignments in arc

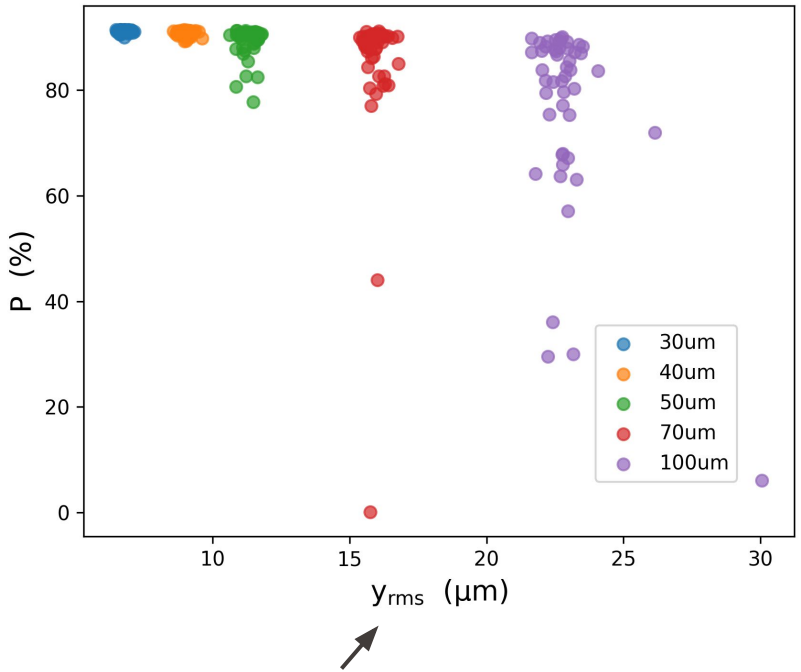


Misalignments in arc

50 seeds for each misalignment scale



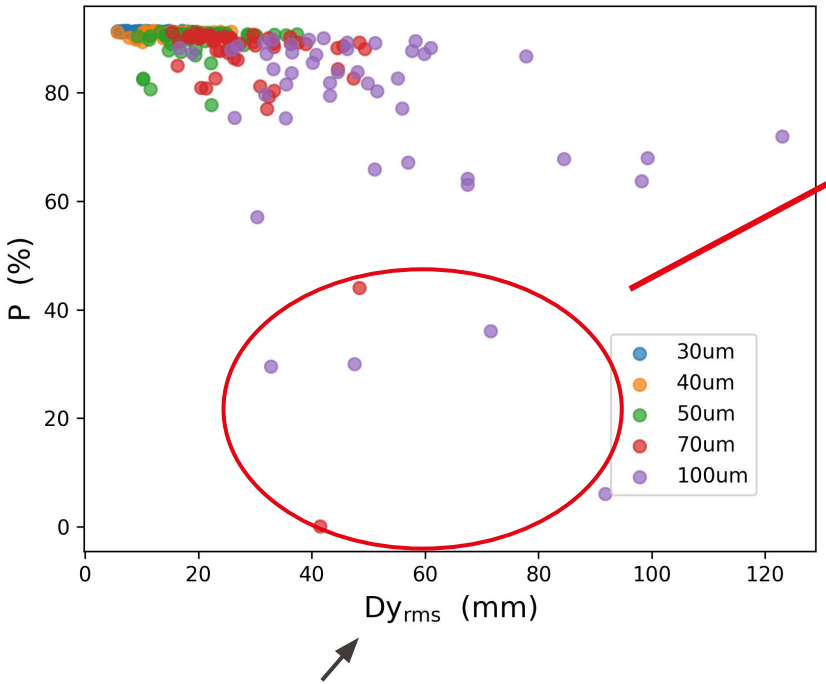
rms misalignments we set



ver. orbit after correction

Misalignments in arc

50 seeds for each misalignment scale



ver. dispersion after correction

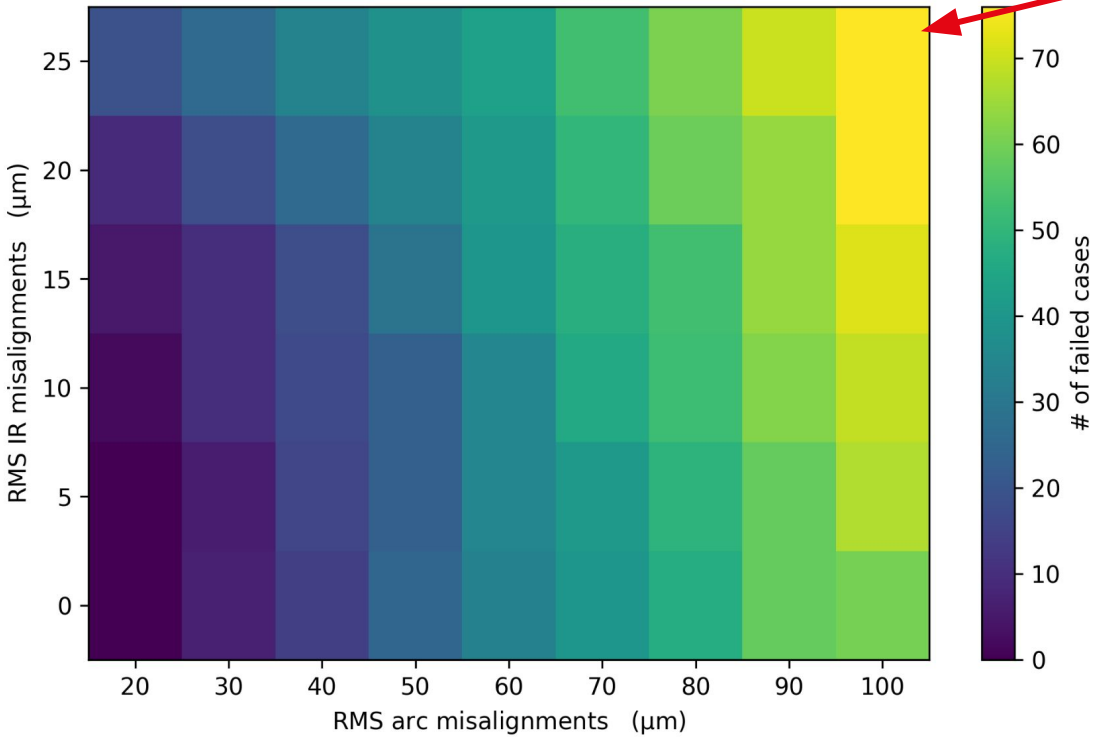
extreme cases may have large dispersion or chromaticity

⇒ need nonlinear spin tracking later

Misalignments in arc & IR

same 100 initial seeds for each square on the colormap

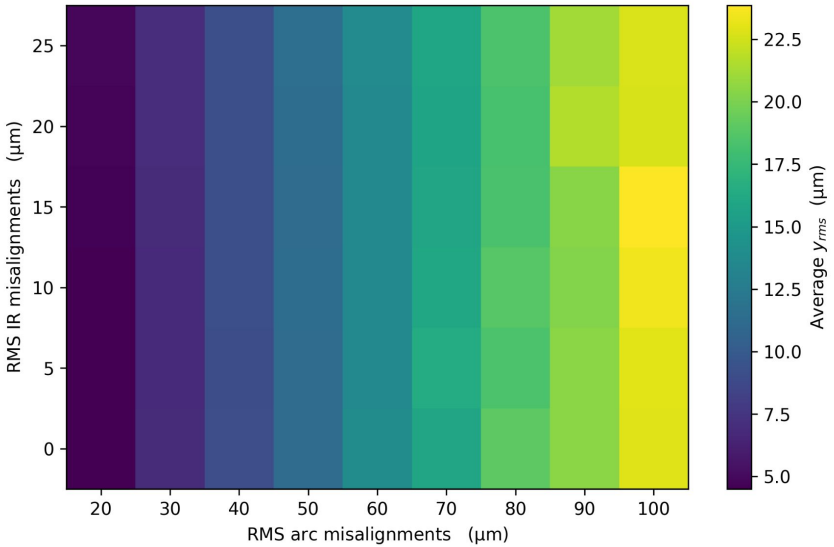
can be further improved



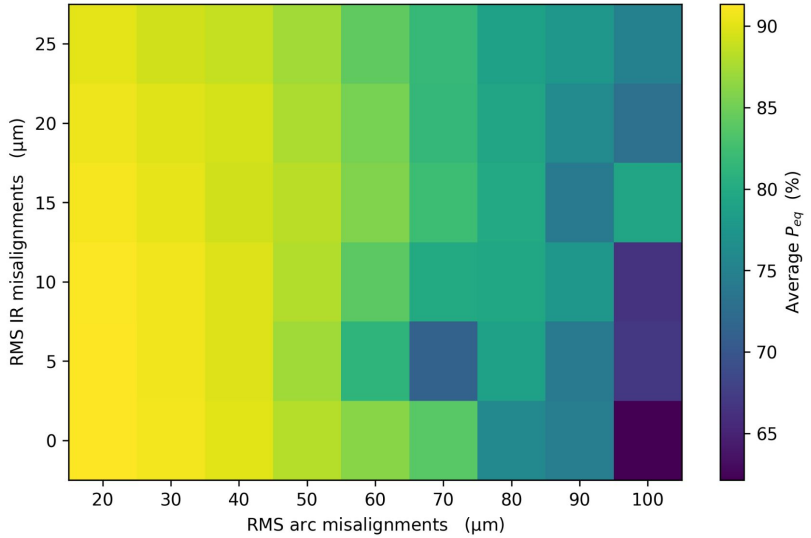
Misalignments in arc & IR

all survived seeds

average y_{rms} (μm)



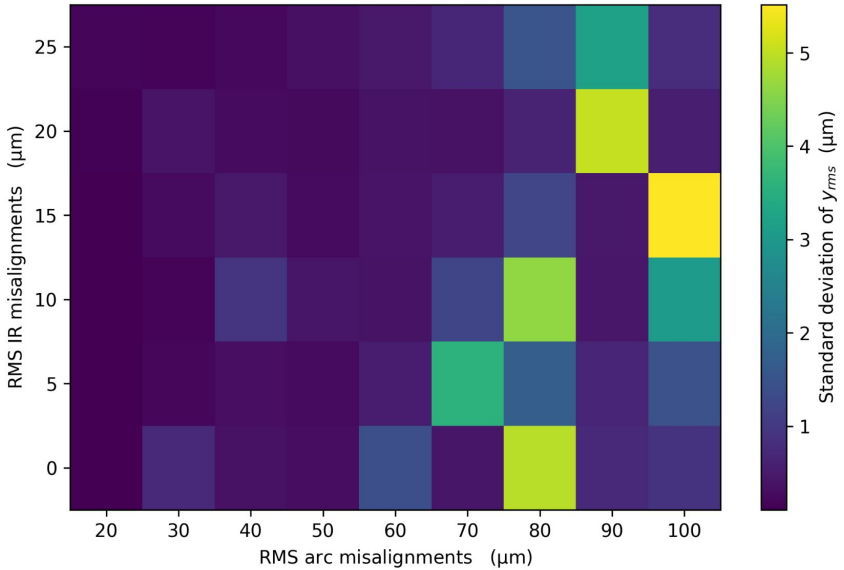
average P_{eq} (%)



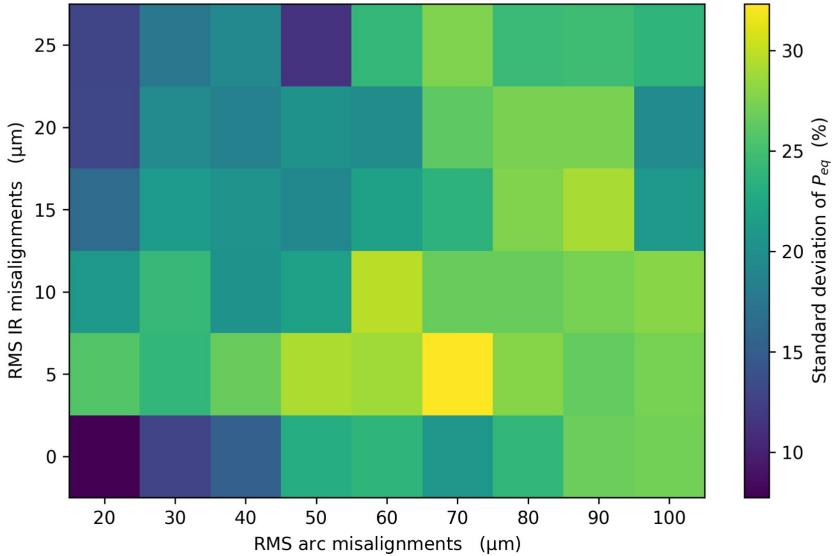
Arc misalignment level dominates the influence to orbit and polarization

Misalignments in arc & IR

standard deviation of y_{rms} (μm)



standard deviation of P_{eq} (%)



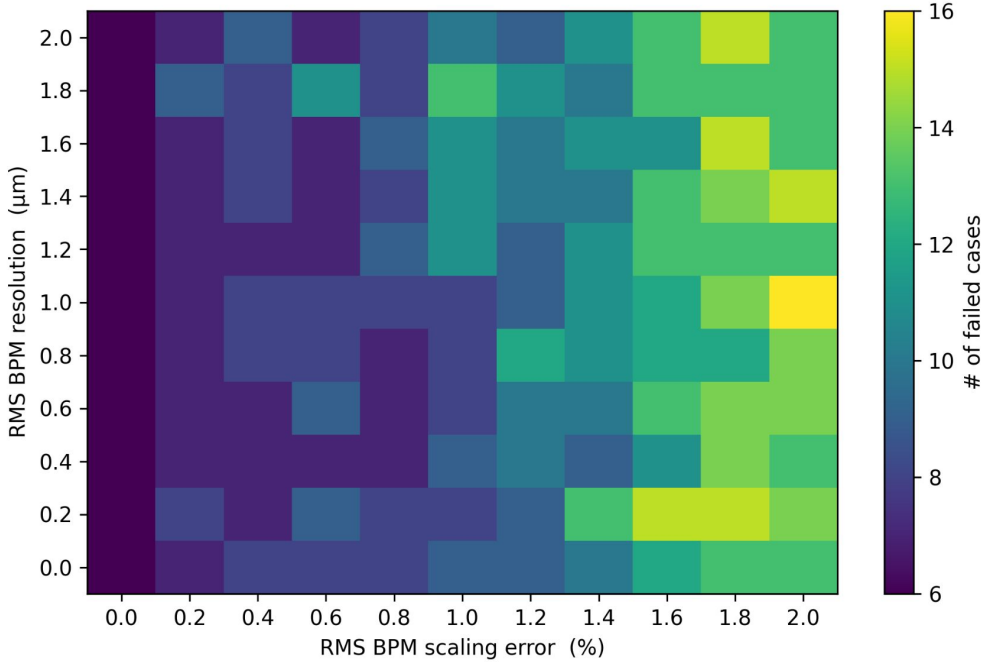
Small variance in final orbits, large variance in P_{eq}

BPM scaling error and resolution

$u_{read}=(1+0.01)u_{real}$ u=x,y read error

same 50 initial seeds for each square on the colormap

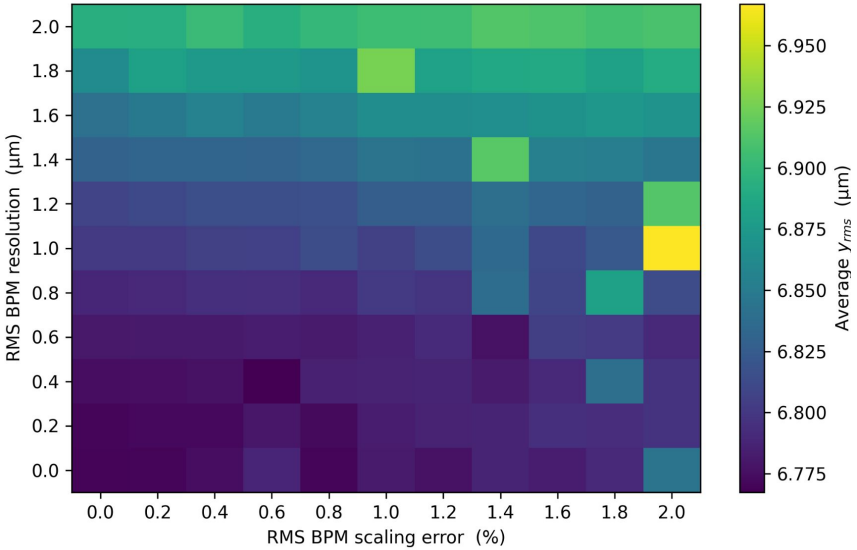
+ 30μm misalign. in arc
+ 10μm misalign. in IR



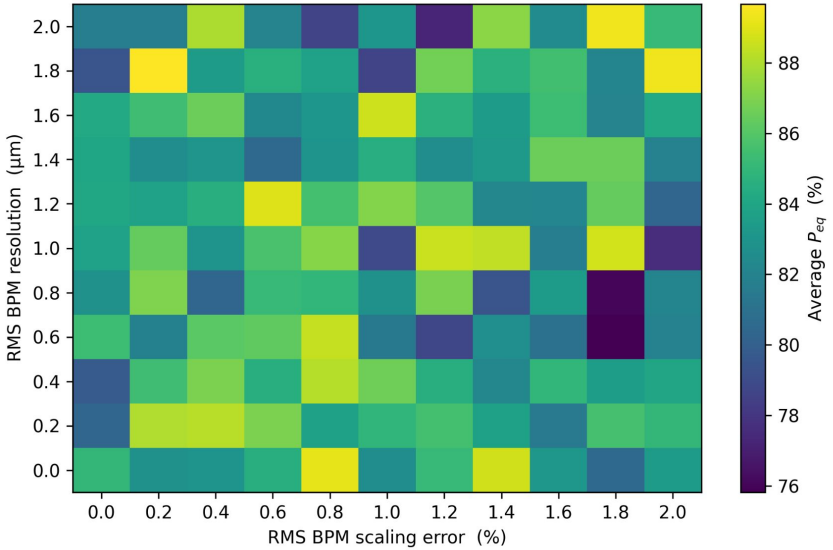
Scaling error dominates the impact for closed orbit searching

BPM scaling error and resolution

average y_{rms} (μm)



average P_{eq} (%)



Resolution dominates the impact on orbit

Random impact on P_{eq}

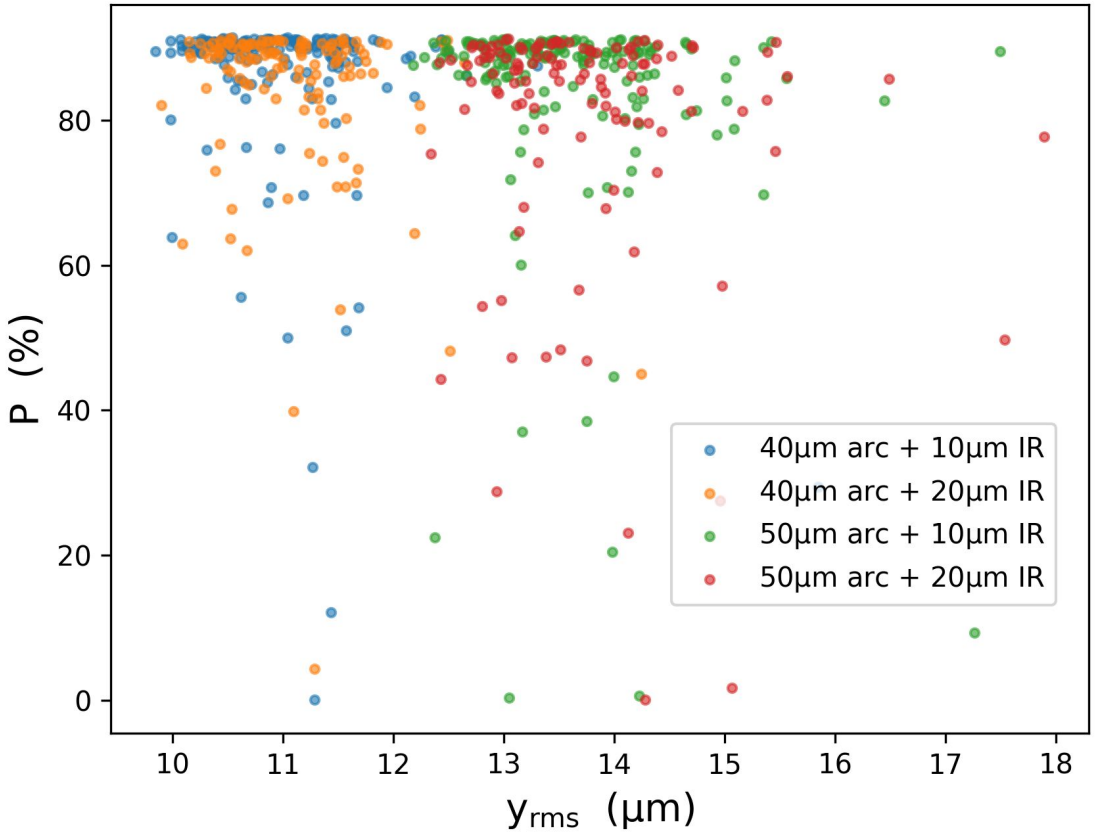
Closed Orbit Searching Result

200 seeds each case

Case	Misalignments (μm)		Failed percentage (%)
	arc	IR	
1	40	10	13.5
2	40	20	36
3	50	10	19
4	50	20	40

+100μrad arc dipole rolls
+ 1% random BPM scaling error + 1μm random BPM resolution + 5% random BPM missing

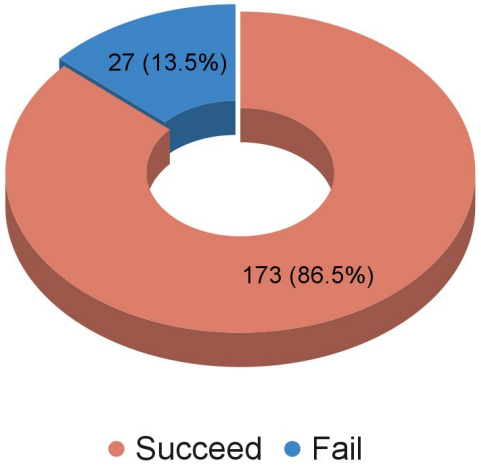
Survivorship bias!



BPM misalignments

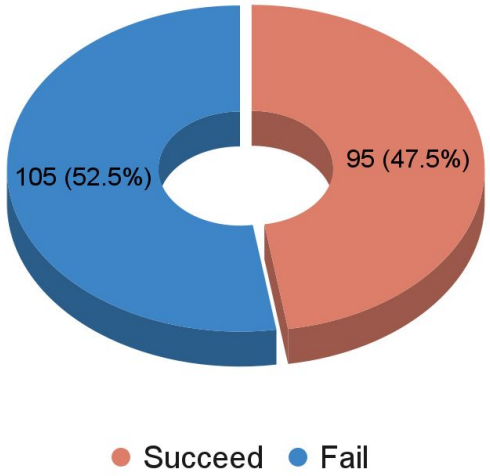
+ 40μm arc misalignment
+ 10μm IR misalignment
+ 100μrad non IR dipole roll (DPSI)
+ 5% random BPM missing + 1% BPM random scaling errors + 1μm BPM random resolution

BPM not misaligned

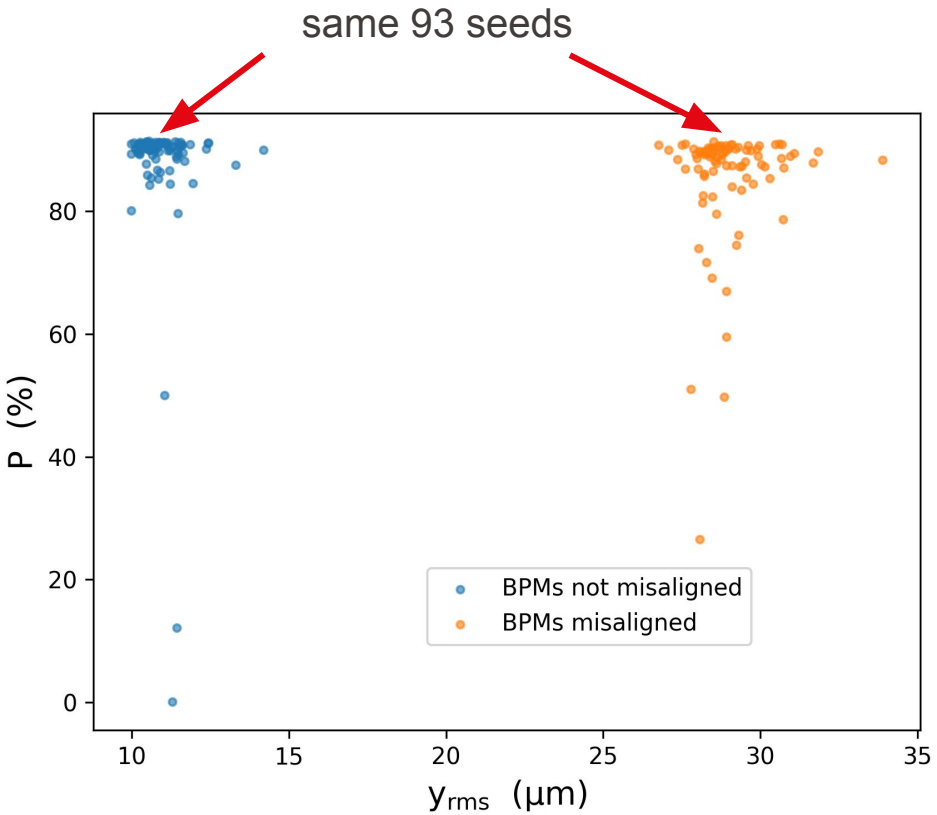


200 random seeds

BPM misaligned **together with quads**

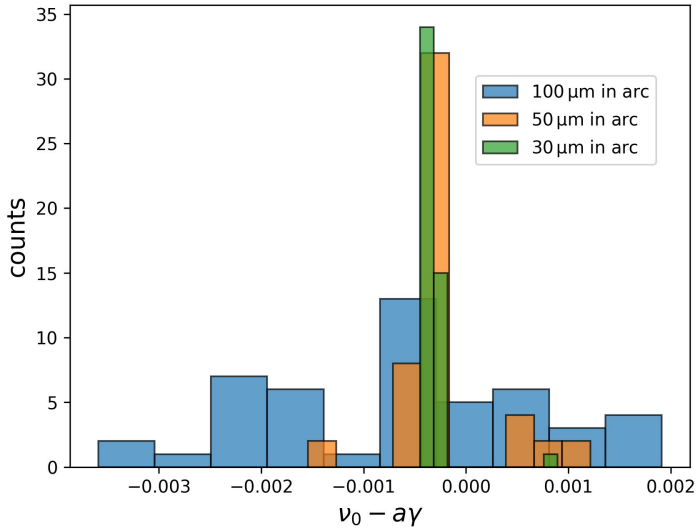


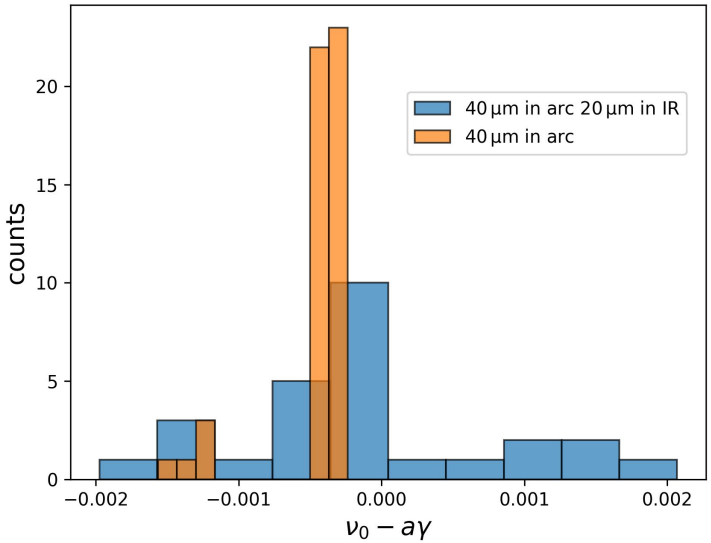
BPM misalignments



Big change in residual orbits, larger variance in polarization

Spin tune shift

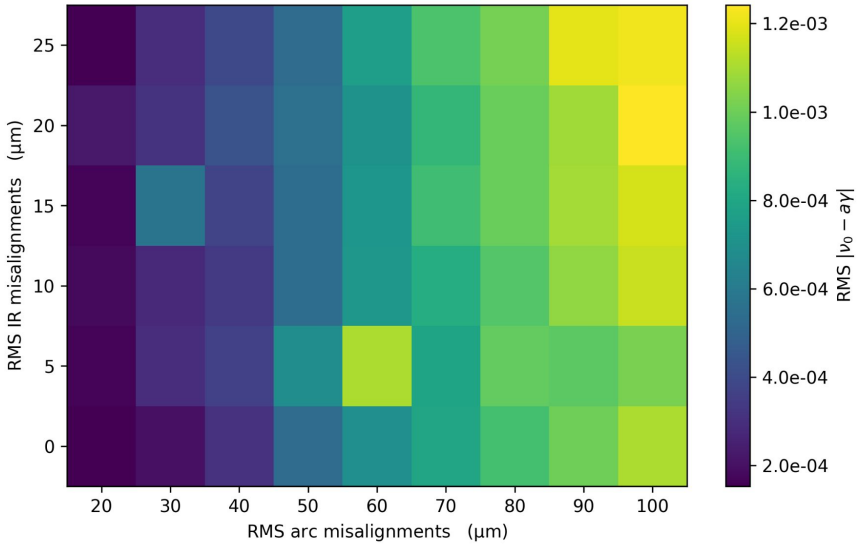


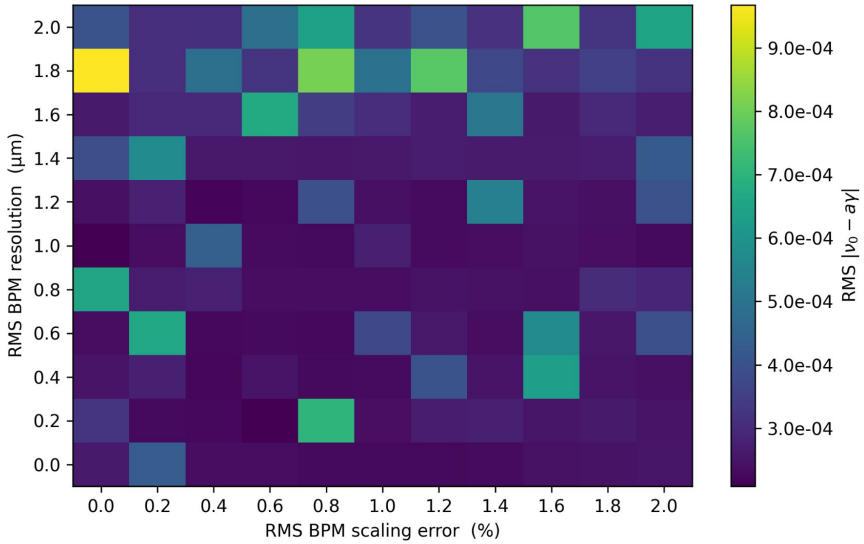


Target: 100 keV systematic error (~2e-4 spin tune shift)

Spin tune shift

Target: ~2e-4





+ 30μm misalign. in arc
+ 10μm misalign. in IR

Conclusion

- Various combinations of machine errors in the lattice have been simulated and tested.
- Orbit and equilibrium polarization are primarily affected by misalignments in arc.
- Closed orbit searching is primarily affected by misalignments in IR.
- Influence of BPM errors has been investigated, among which the BPM misalignments have the most substantial impact
- High polarization at Z energy can be achieved as long as tight alignment can be made.
- Current lattice still falls short of the target for systematic error.

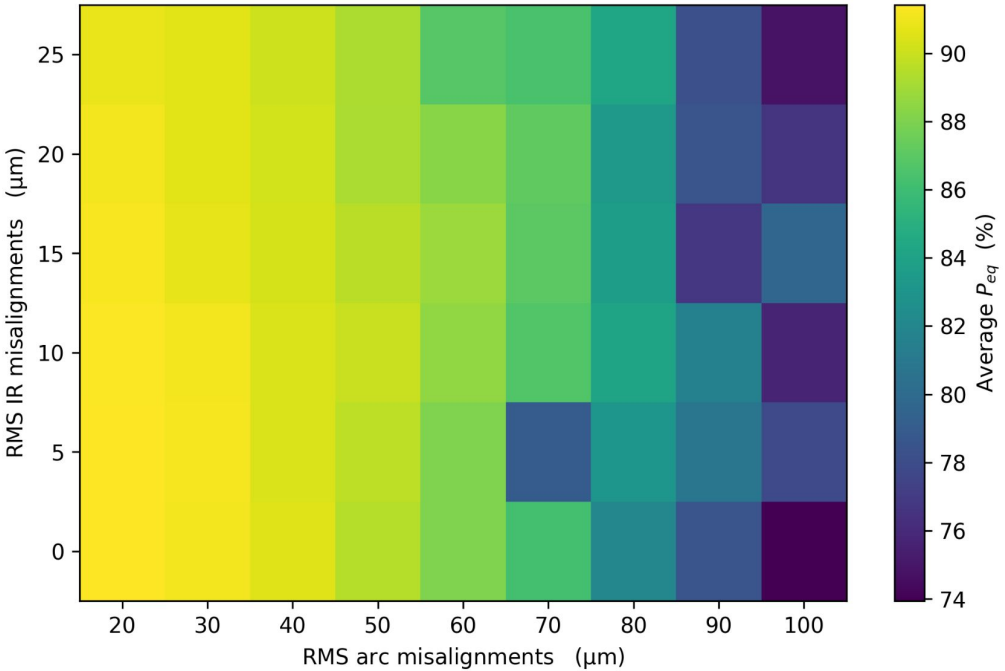
Outlook

- Add phase matching, dispersion correction and chromaticity correction
- Investigate long range alignment errors
- Quantification of the influence of machine errors to polarization remains to be explored.
- Exploration of the origins of systematic errors and devise strategies to mitigate their effects to meet the energy calibration precision target.

Thank you!

Appendix

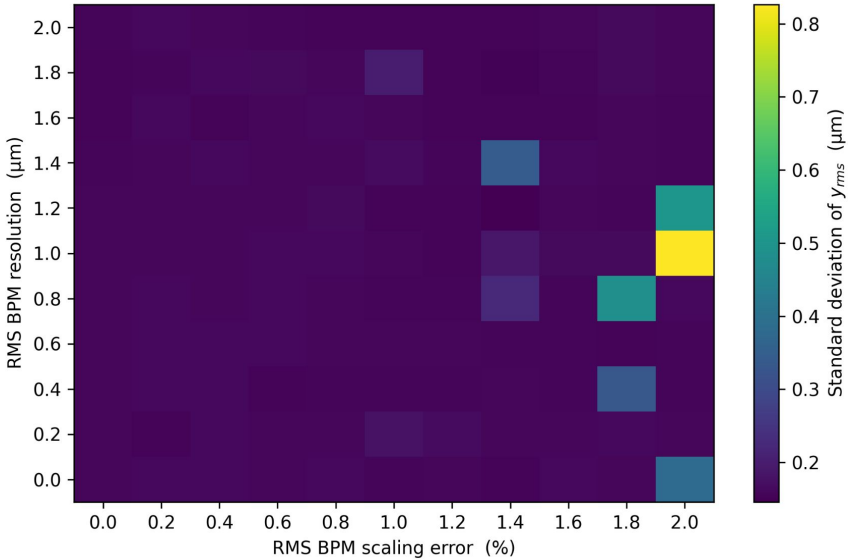
Misalignments in arc & IR



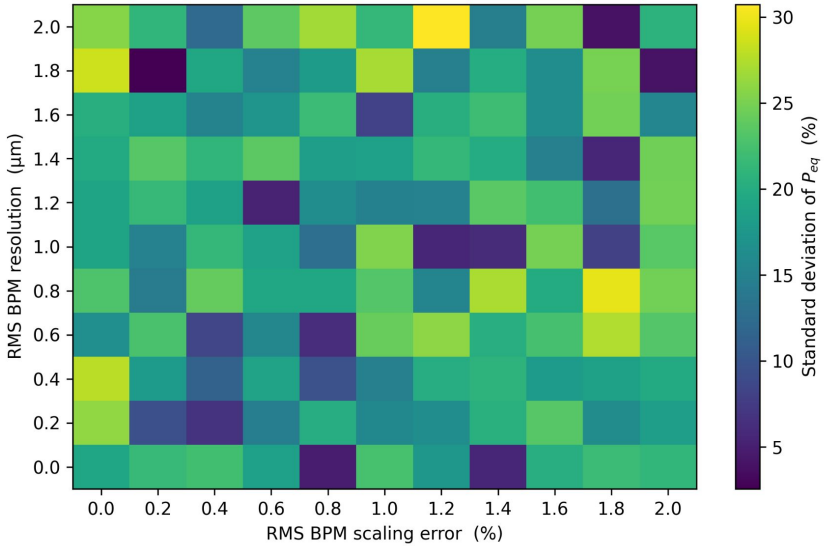
Using the seeds that survived in all scenarios

BPM scaling error and resolution

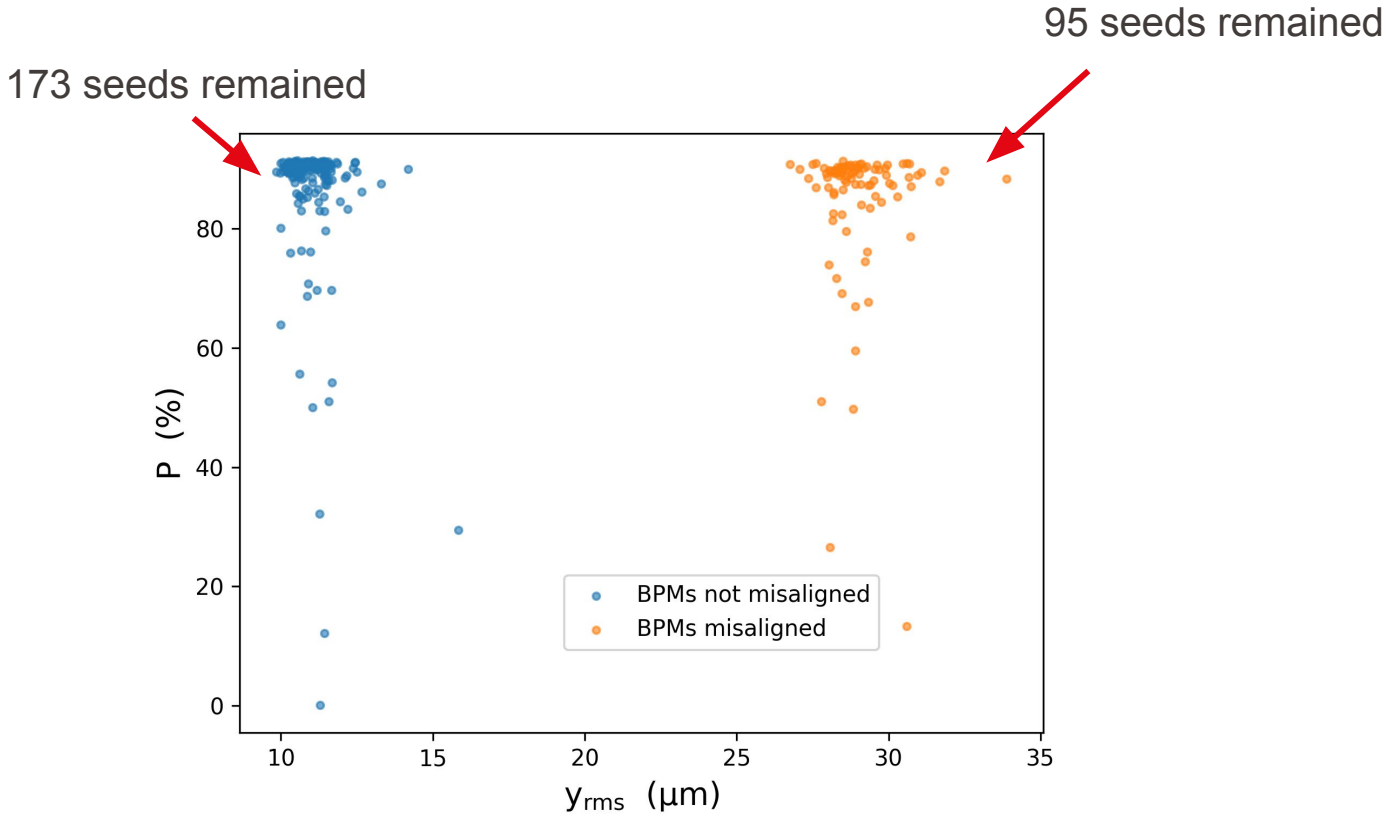
standard deviation of y_{rms} (µm)



standard deviation of P_{eq} (%)



BPM misalignments



Big change in residual orbits