EPFL

FCC-ee Orbit Correction and Polarization

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CHART Swiss Accelerator Research and Technology

FUTURE CIRCULAR COLLIDER

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Introduction

Energy calibration in the FCC-ee

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

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

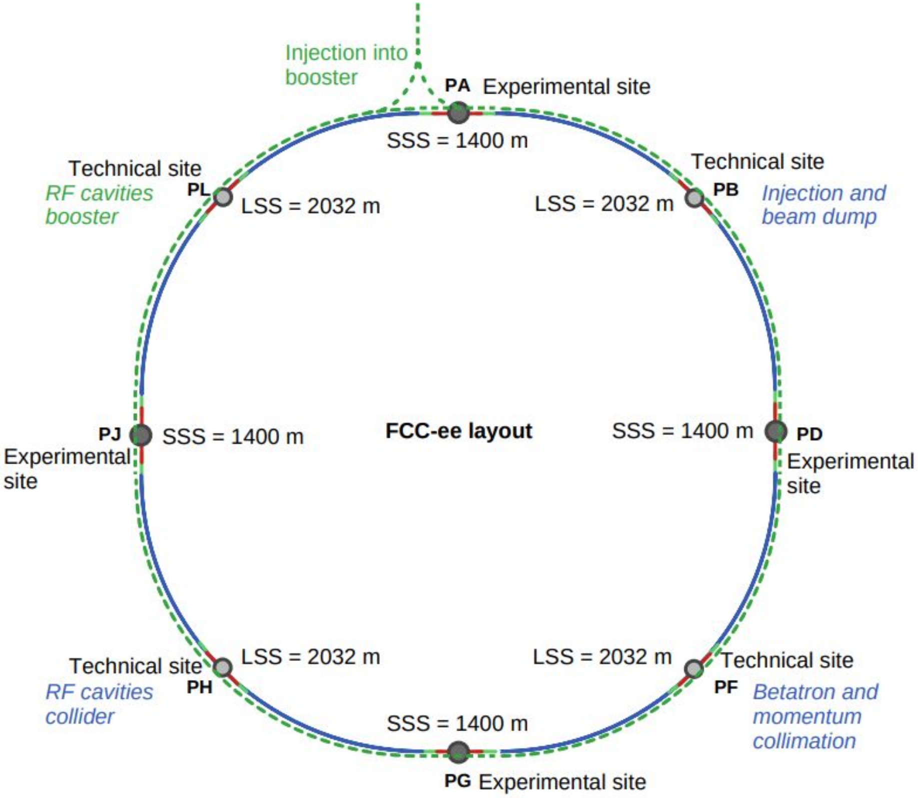
- **High precision COM energy calibration**
- **The current precision targets**

  statistical: 4 keV at Z mass

  systematic: 100 keV at Z mass

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

  ↳ requires a sufficient transverse spin polarization level



Spin polarization

Thomas-BMT equation

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

instantaneous spin precession frequency

$$\Omega = \Omega_0(1 + a\gamma) \quad \Omega_0 = eB_\perp/\gamma mc$$

average spin precession frequency over one turn

$$\langle\Omega\rangle = \Omega_0(1 + a\langle\gamma\rangle)$$

closed orbit spin tune

$$\nu_0 = \frac{\langle\Omega\rangle}{\Omega_0} - 1 = a\langle\gamma\rangle$$

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

perfect flat ring → P ≈ 92.4%

real machine → P < 92.4%

$$\nu' = a\langle\gamma\rangle + \Delta\nu$$

How much?

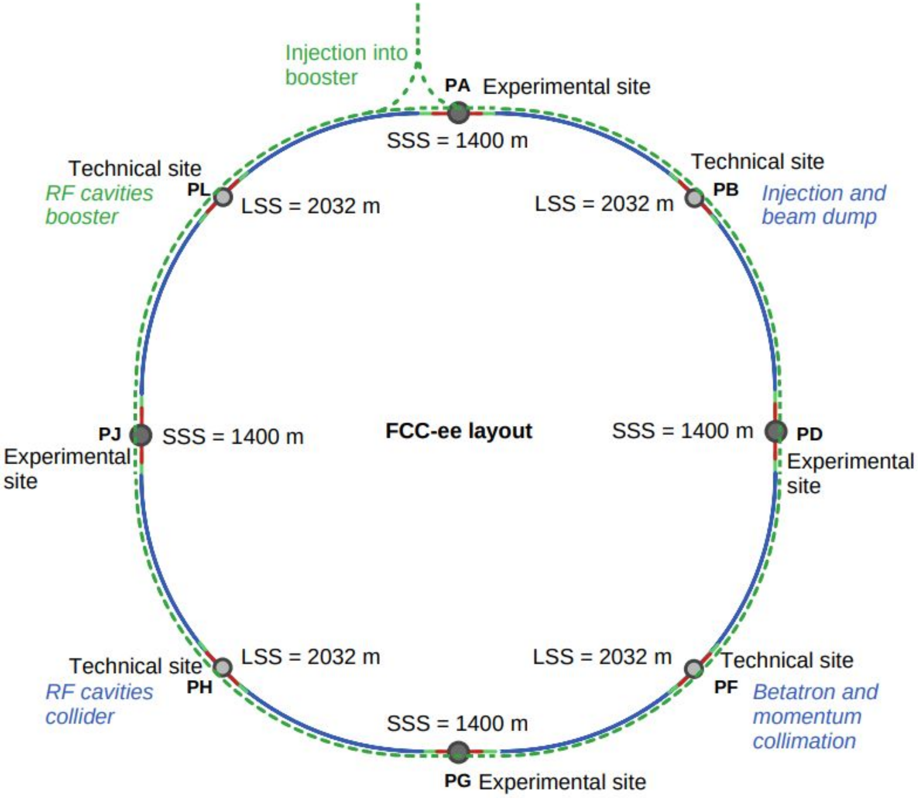
[*] Magnet figures from Maxwell's equations for magnets, A. Wolski, https://cds.cern.ch/record/1333874/files/1103.0713.pdf
[*] Spin polarization theory reference: D. P. Barber, G. Ripken, Sections 2.6.6-2.6.8, Handbook of Accelerator Physics and Engineering, 3rd Edn., World Scientific, Singapore, 2023.

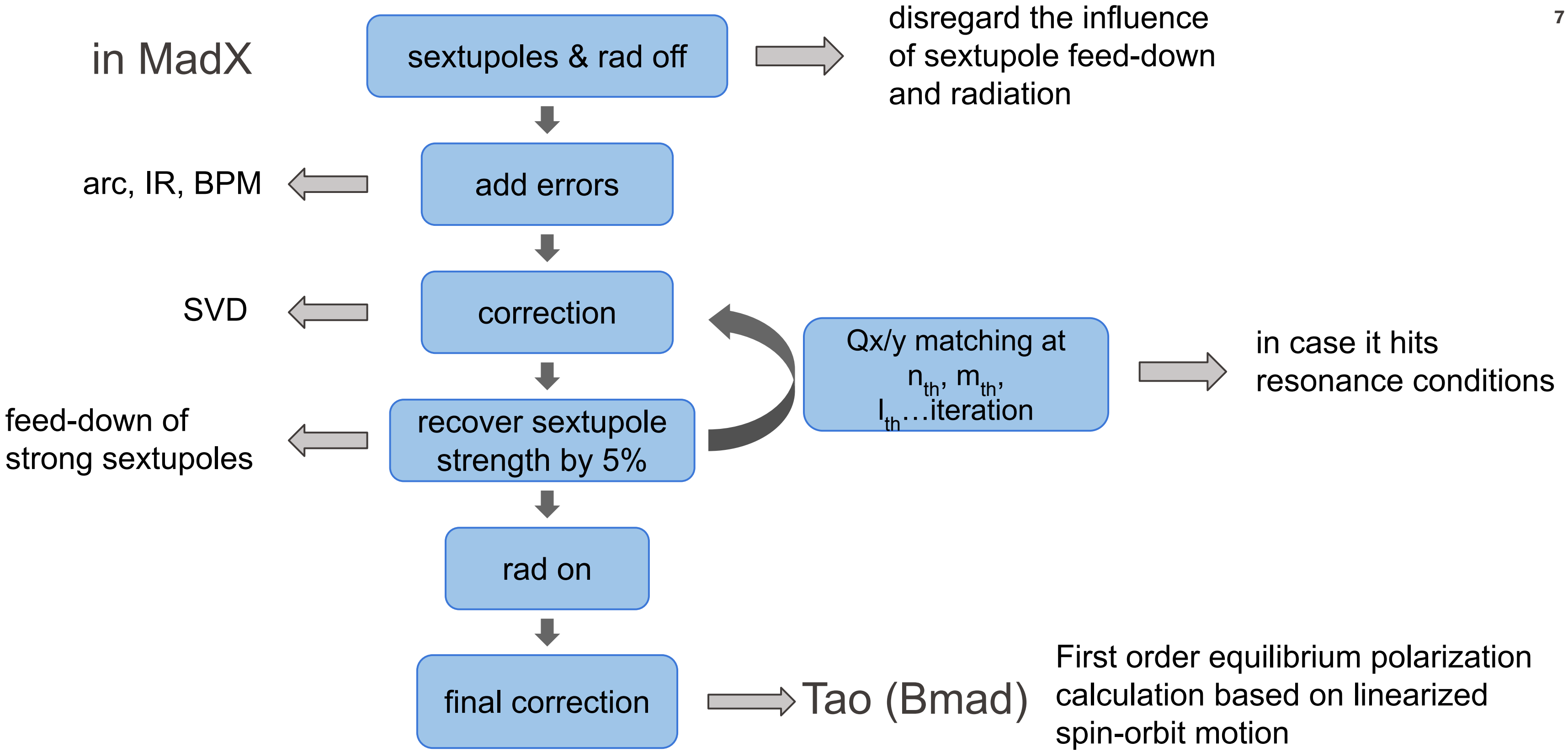
Orbit Correction

Lattice

- Based on FCC-ee Z lattice (at 45.6 GeV)
  - 1856 quadrupoles
  - 4 insertion regions with stronger magnets
- Modified by adding
  - 1 BPM & 1 corrector next to each quad

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





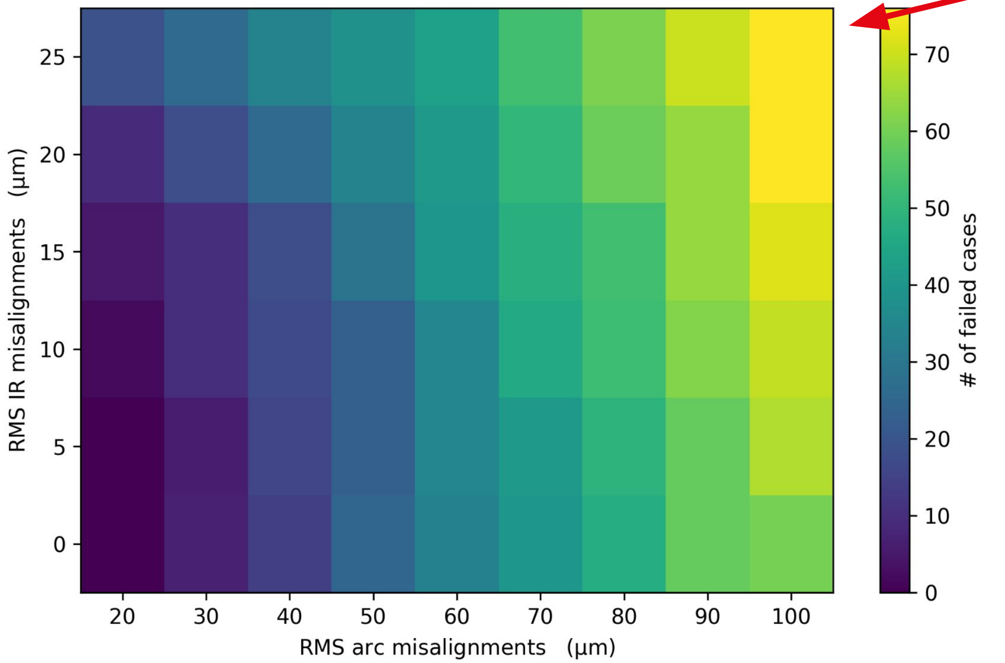
This procedure works for most error seeds, but may not find a stable solution for some seeds.

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

Misalignments in arc & IR

same 100 initial seeds for each square on the colormap

can be further improved

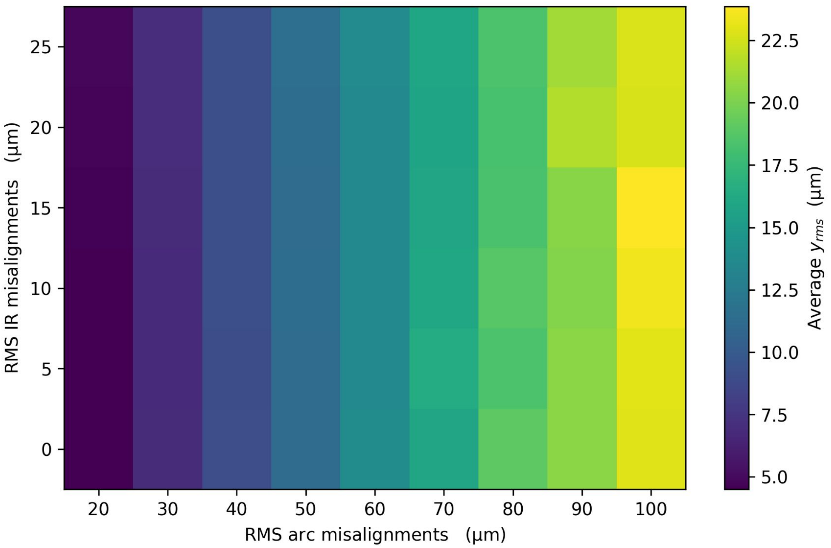


In general, IR misalignments have a bigger impact on closed orbit searching.

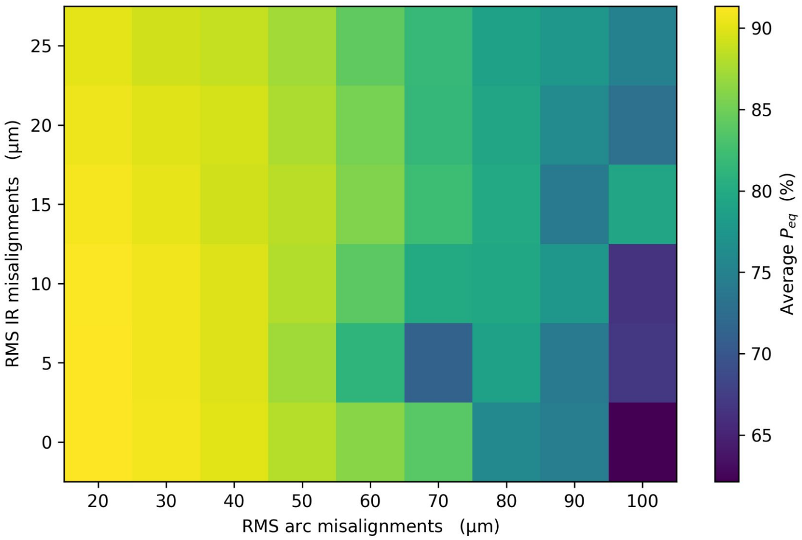
Misalignments in arc & IR

all survived seeds

average y_{rms} (µm)



average P_{eq} (%)



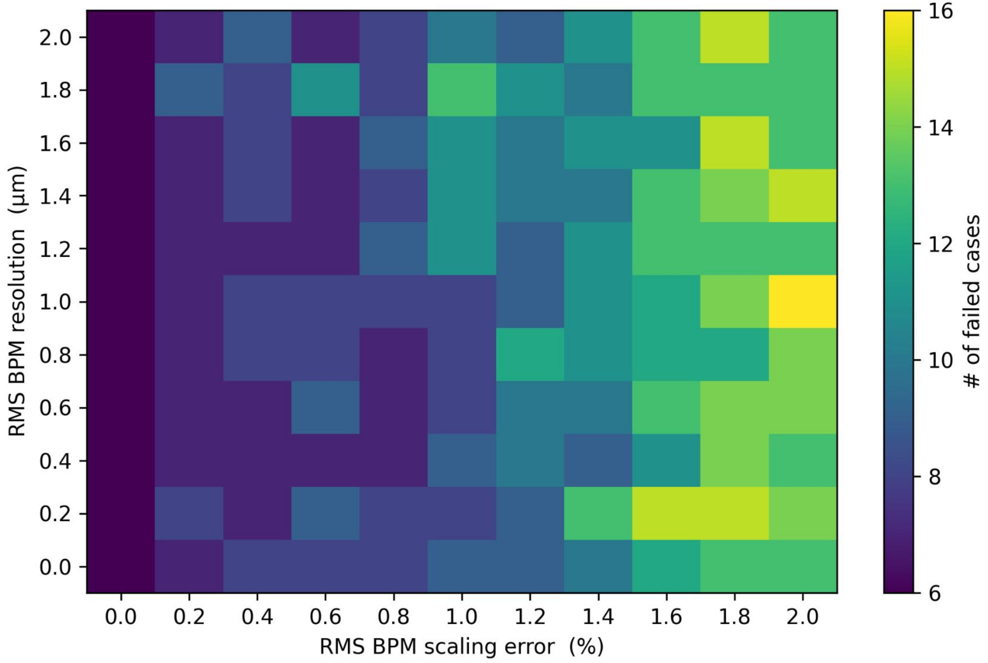
Arc misalignment level dominates the influence to final orbit and polarization

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

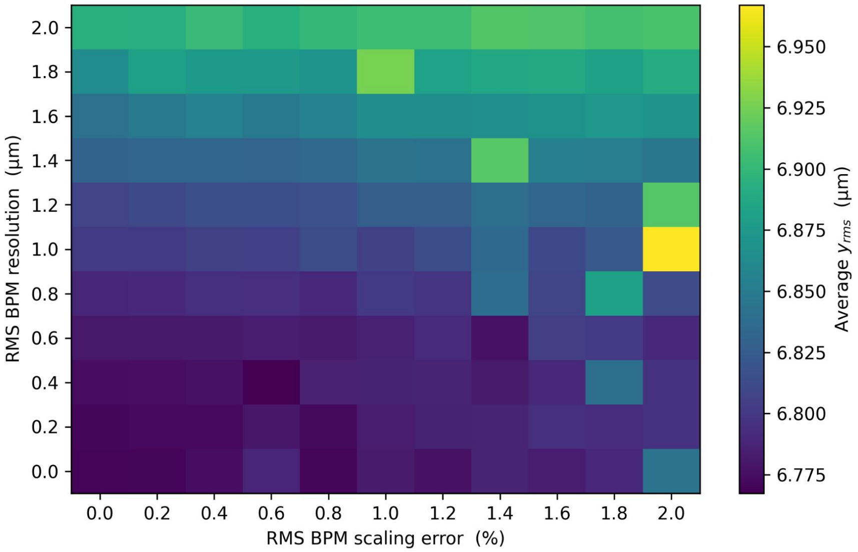
+ 30µm misalign. in arc
+ 10µm misalign. in IR



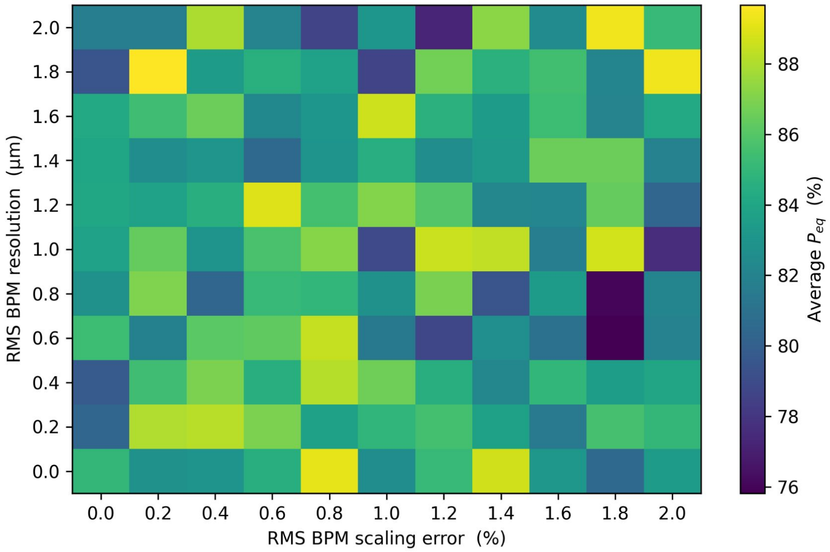
Scaling error dominates the impact for closed orbit searching

BPM scaling error and resolution

average y_{rms} (µm)



average P_{eq} (%)



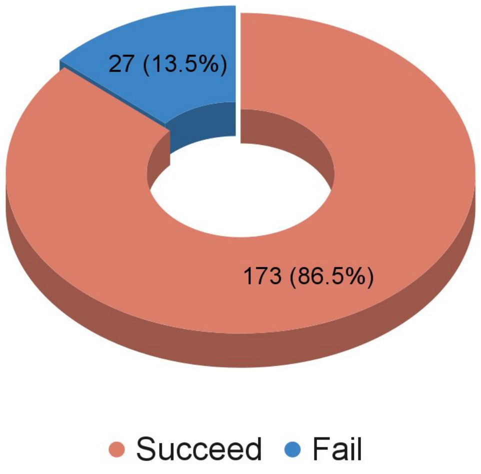
Resolution dominates the impact on orbit

Random impact on P_{eq}

BPM misalignments

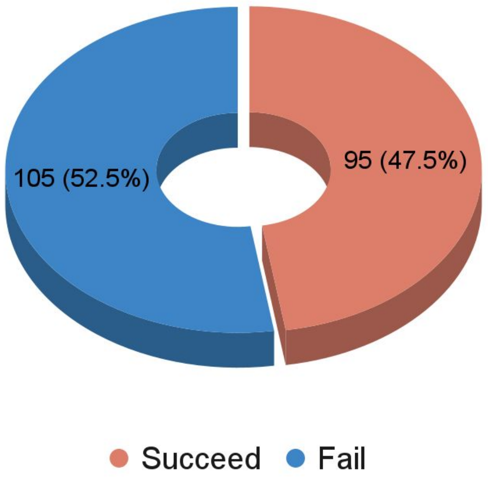
- 40μm arc misalignment
- 10μm IR misalignment
- 100μrad non IR dipole roll (DPSI)
- 5% random BPM missing + 1% BPM random scaling errors + 1μm BPM random resolution

BPM not misaligned



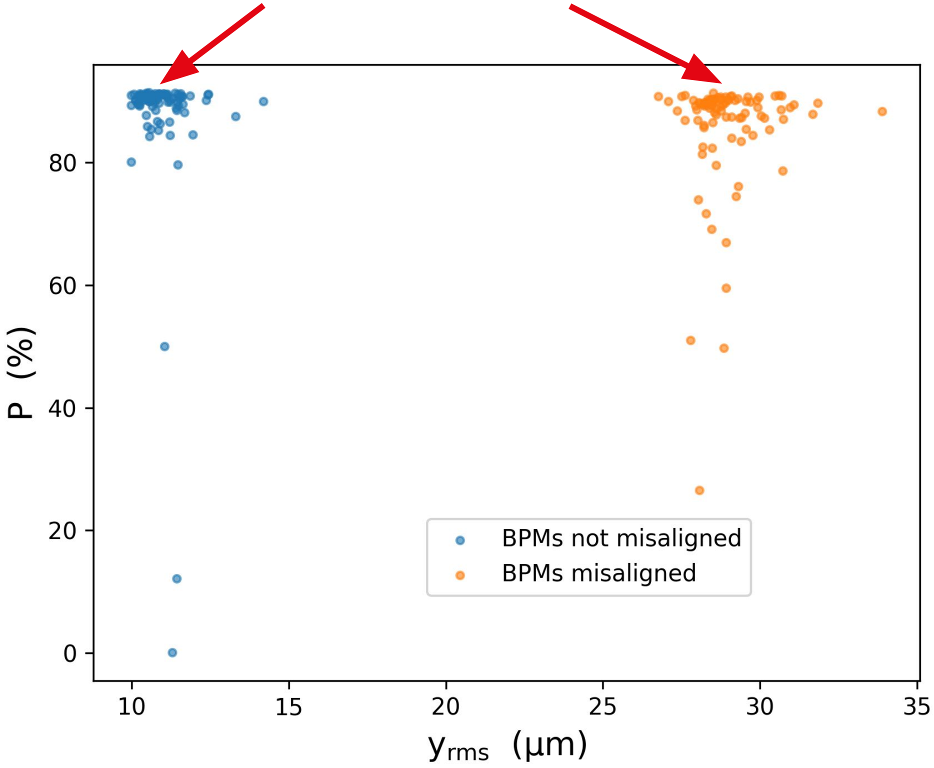
200 same seeds

BPM misaligned **together with quads**



BPM misalignments

same 93 seeds



Big difference in residual orbits, larger variance in polarization

Spin Tune Shift

Average energy estimation

In real machine measurement

spin tune ν' measured by RDP = amplitude dependent spin tune (ADST)+δ_1

= closed orbit spin tune ν_0 + δ_2

= a<γ> + δ_3

Tao (Bmad)

what we want to measure

$$\nu' = a\langle\gamma\rangle + \Delta\nu$$

incorporates the contribution from systematic error

Average energy estimation

Only in perfectly aligned flat lattice

$$\nu_0 = a\langle\gamma\rangle = \frac{a}{m} E_{\text{ave}} \approx \frac{a}{m} \frac{\int E(\theta)\mathrm{d}\theta}{2\pi}$$

assume that dθ only happens in bending dipoles

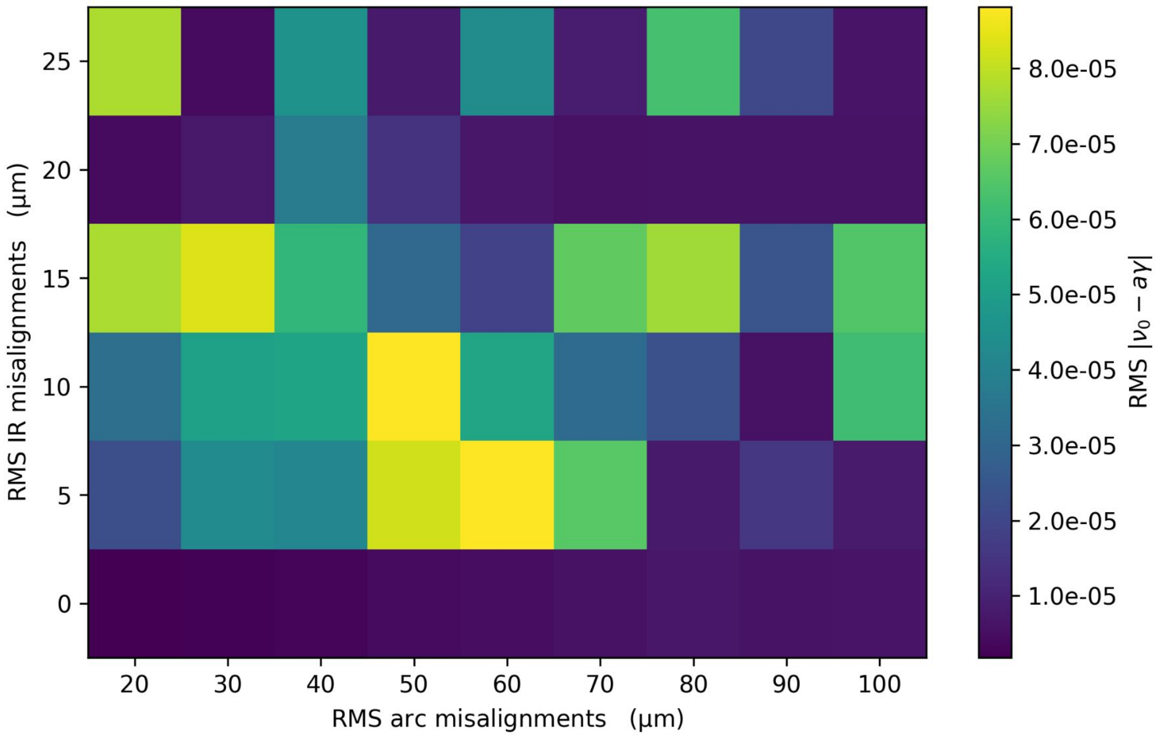
tests in clean lattice at different reference energies

⇒ less than 0.3keV difference

Spin tune shift colormap

100keV error
⇒ 2e-4 shift

| closed orbit spin tune ν_0 – a<γ> |



- adding additional complex factors could easily push it beyond the precision target

Off Z pole scan

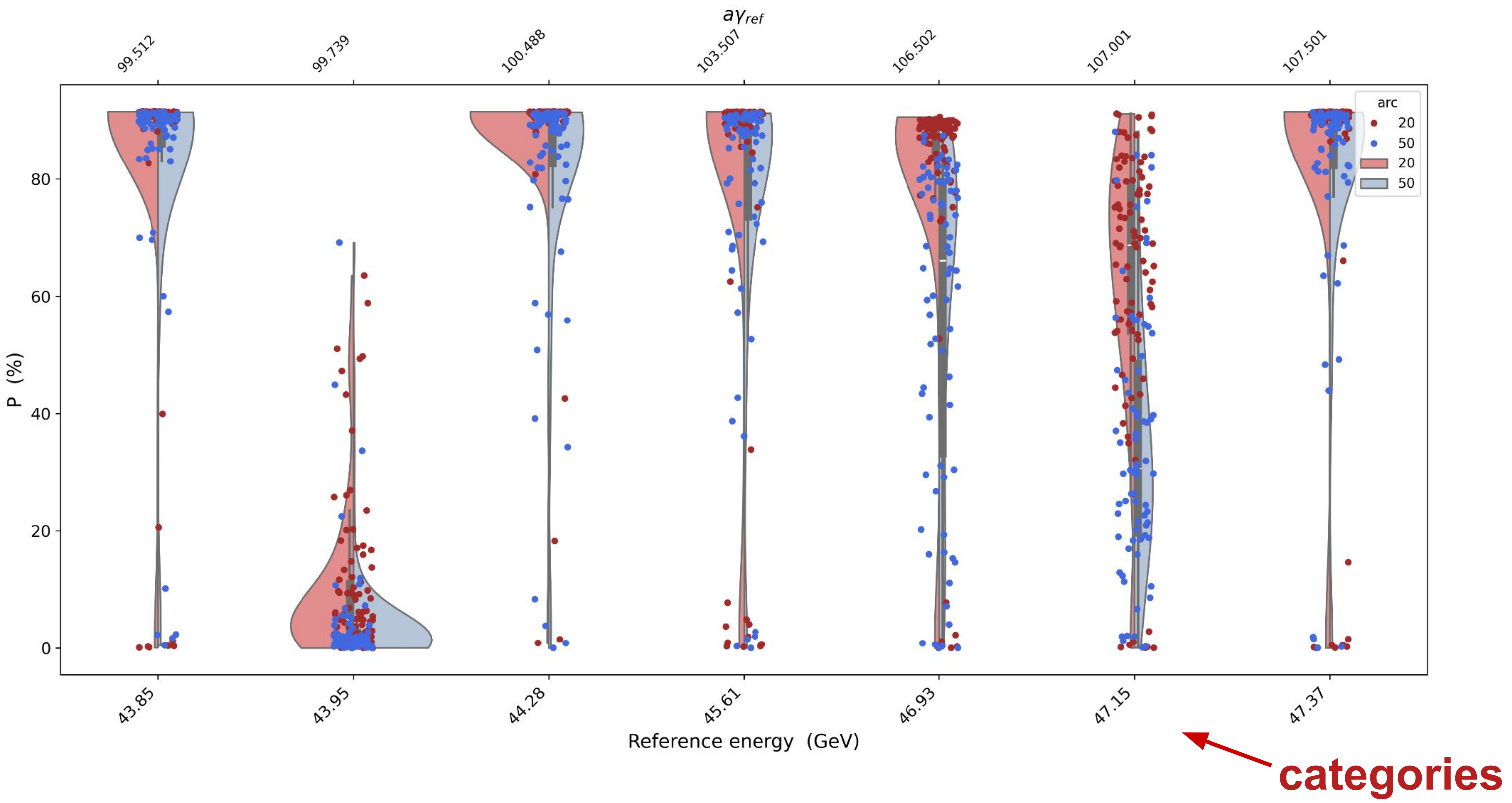
Scan point	$\sqrt{s}$ (GeV)	E_b (GeV)	Spin tune
$\sqrt{s_-}$ A	87.69	43.85	99.5
$\sqrt{s_-}$ Request	87.9	43.95	99.7
$\sqrt{s_-}$ B	88.57	44.28	100.5
$\sqrt{s_0}$	91.21	45.61	103.5
$\sqrt{s_+}$ A	93.86	46.93	106.5
$\sqrt{s_+}$ Request	94.3	47.15	107.0
$\sqrt{s_+}$ B	94.74	47.37	107.5

Centre-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

[*] Polarization and Centre-of-mass Energy Calibration at FCC-ee https://arxiv.org/pdf/1909.12245

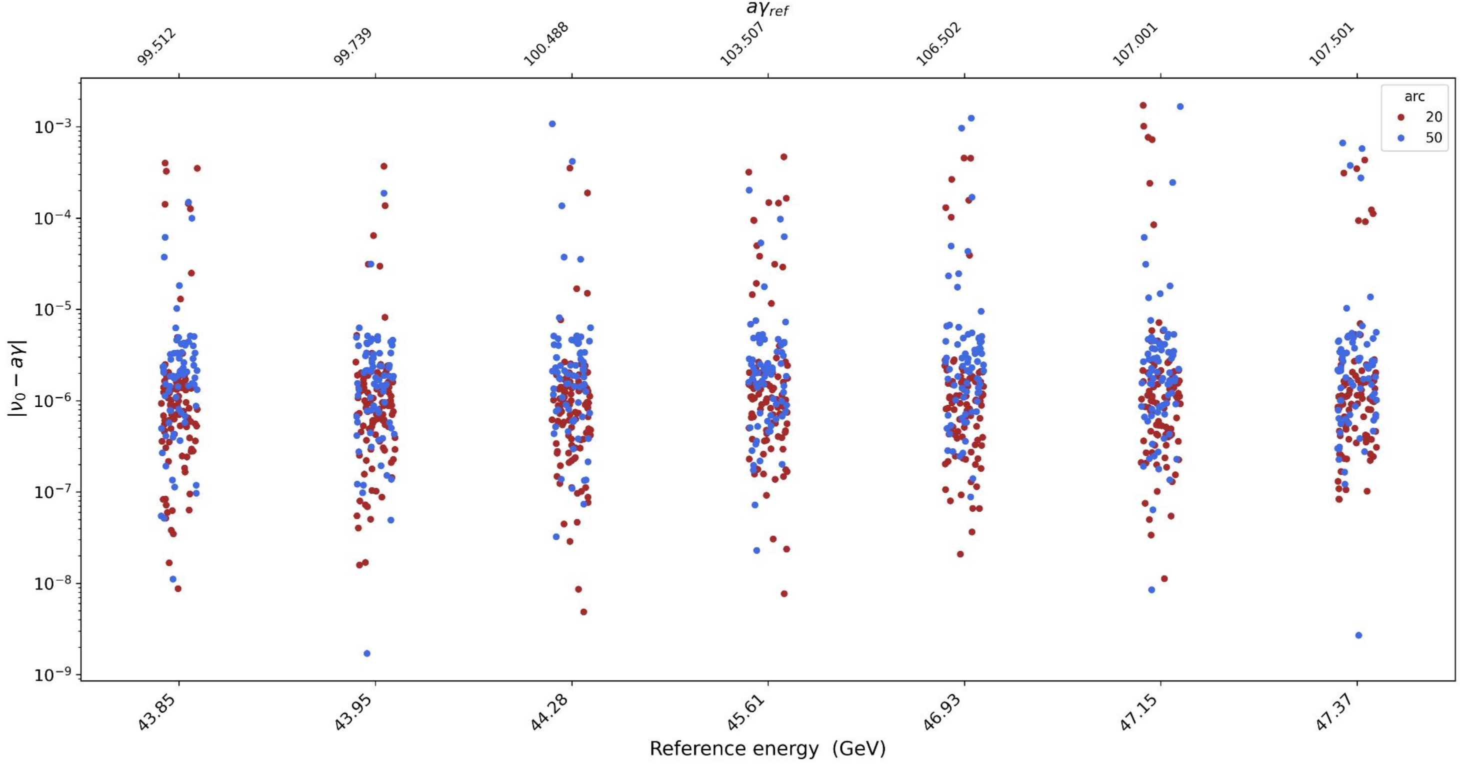
Off Z pole scan

20/50μm in arc, 10μm in IR, the same 100 initial seeds



Off Z pole scan

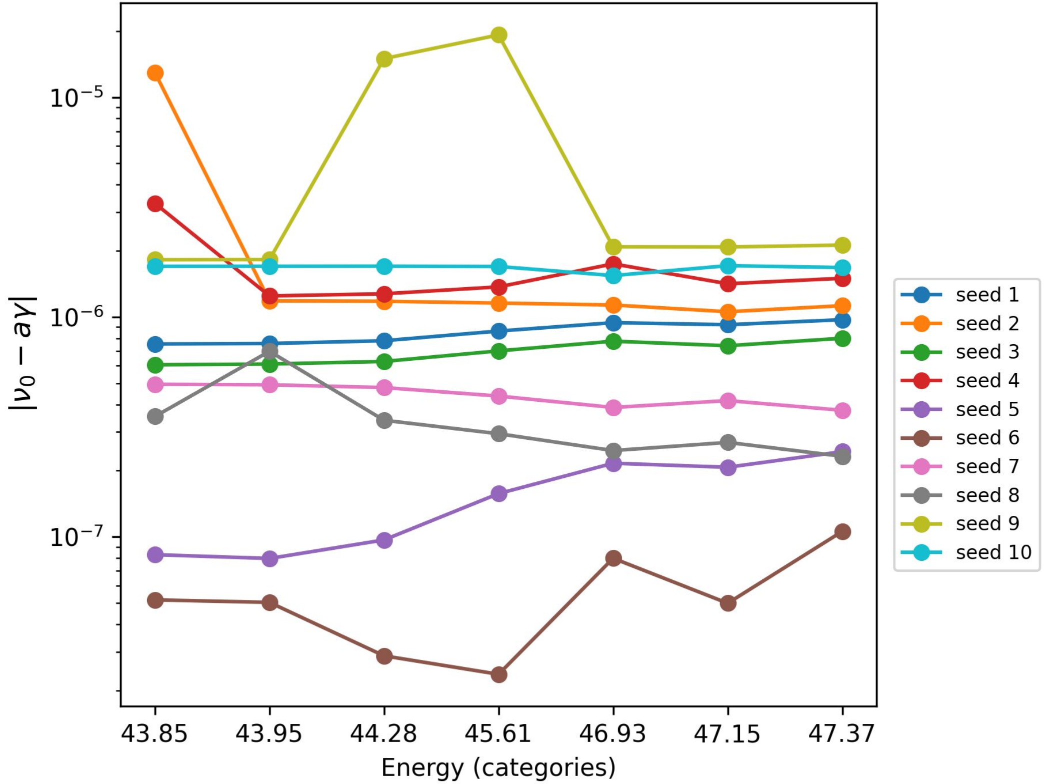
20/50μm in arc
10μm in IR



Absolute value in log scale

Off Z pole scan

20µm in arc
10µm in IR

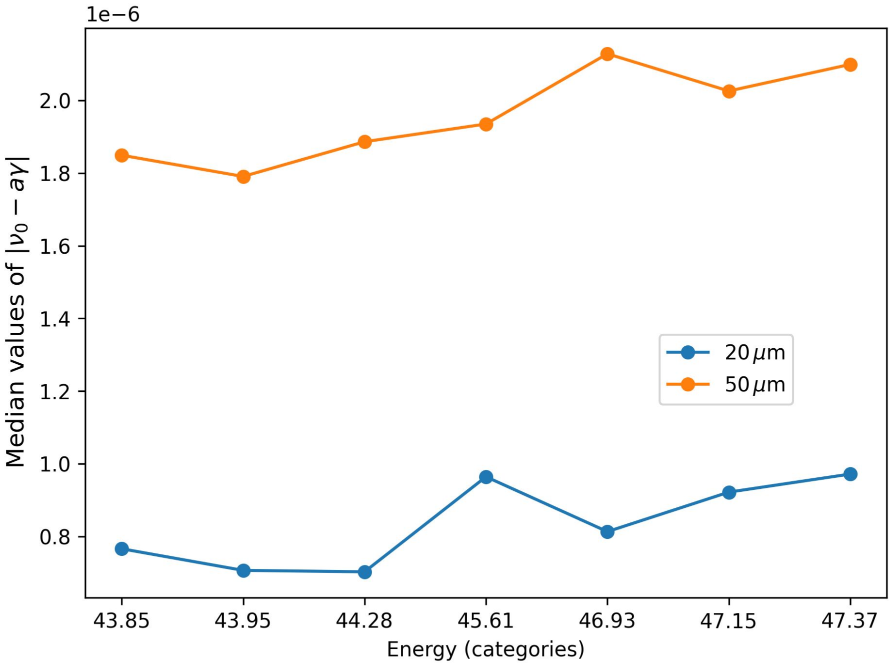


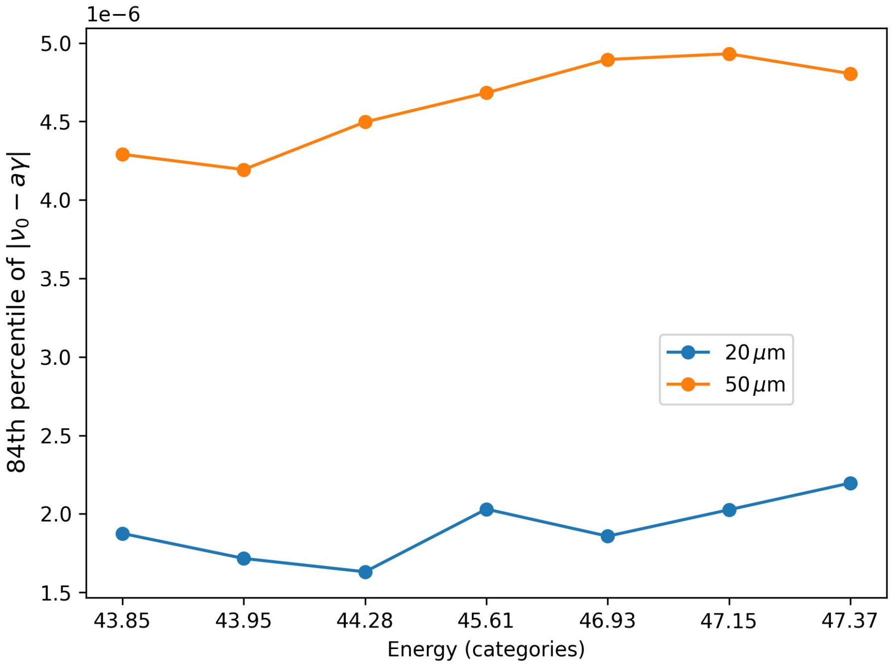
the trend with increasing energy is not clearly apparent

Off Z pole scan

20/50µm in arc
10µm in IR

use all the seeds that survived in all energies and errors





- trends upward overall, the contribution from misalignments to spin tune shift could possibly slightly increase with energies.

Conclusion

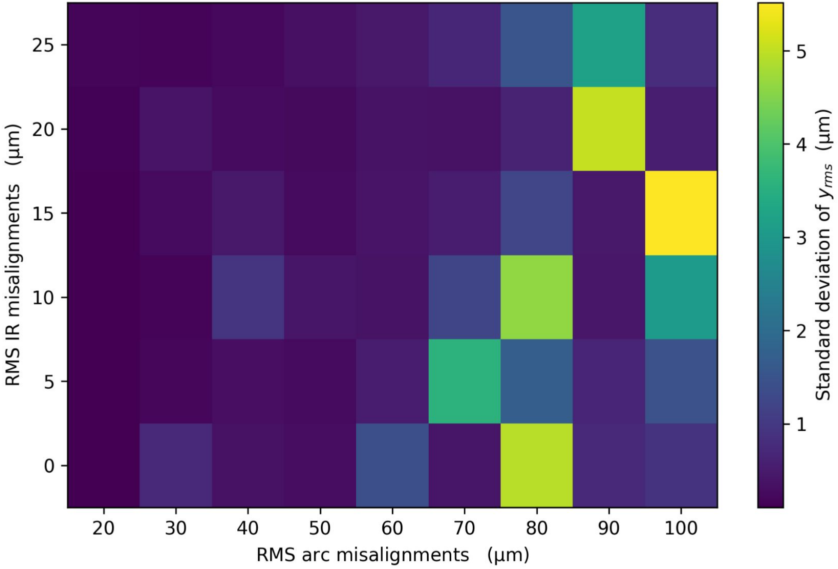
- Orbit and equilibrium polarization are primarily affected by misalignments in arc.
- Closed orbit searching is mainly affected by misalignments in IR.
- Influence of BPM errors has been investigated, among which the BPM misalignments have the most substantial impact
- High polarization at Z energy can be achieved as long as tight alignment can be made.
- It’s promising to be on track to meet the target for systematic error, though additional factors need to be further considered.

Thank you!

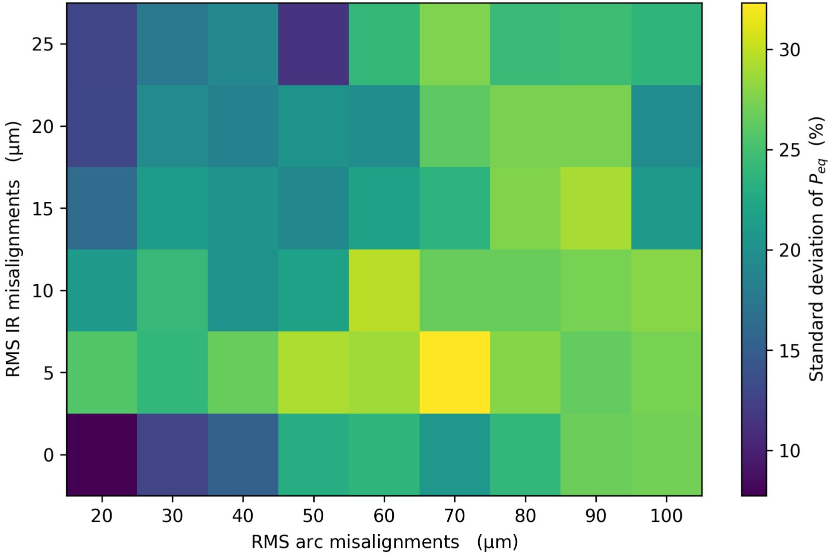
Appendix

Misalignments in arc & IR

standard deviation of y_{rms} (µm)

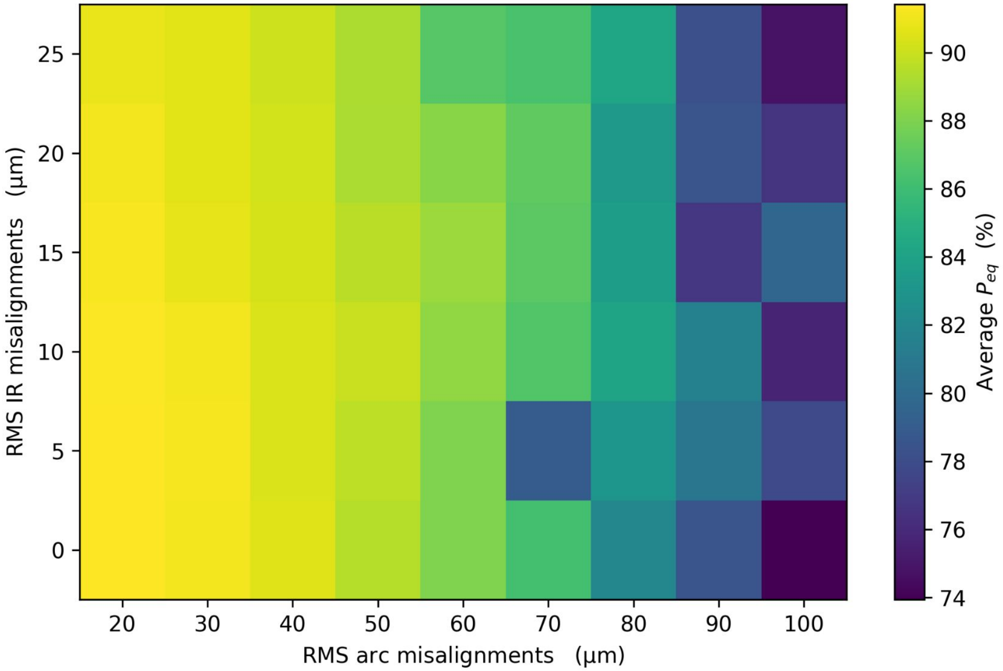


standard deviation of P_{eq} (%)



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

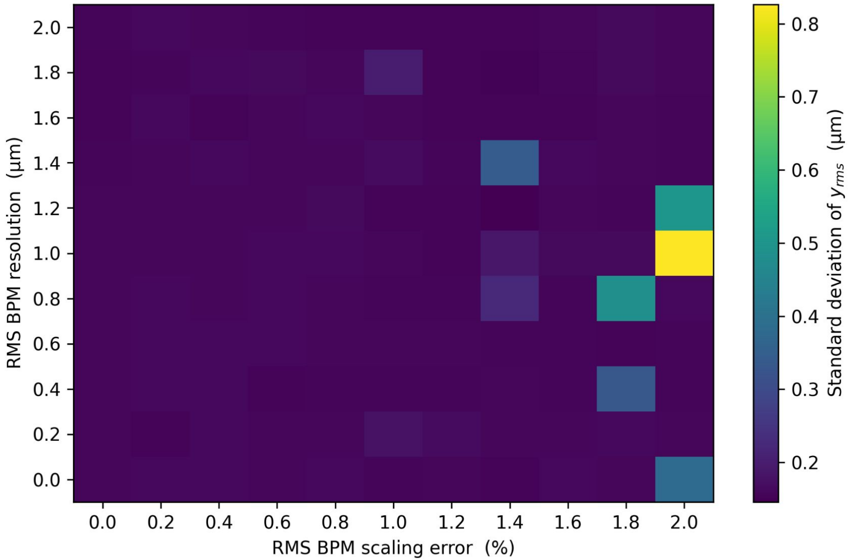
Misalignments in arc & IR



Using the seeds that survived in all scenarios

BPM scaling error and resolution

standard deviation of y_{rms} (µm)



standard deviation of P_{eq} (%)