Orbit Correction for Polarization Studies

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Energy calibration in the FCC-ee

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

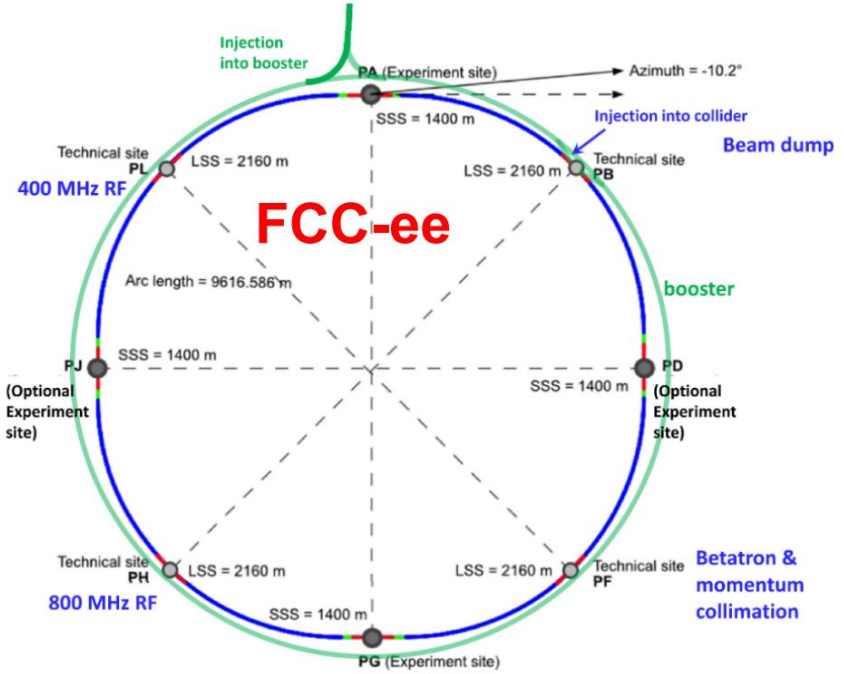
  Z bosons (91 GeV) to top quark pairs (350-365 GeV)

- **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**

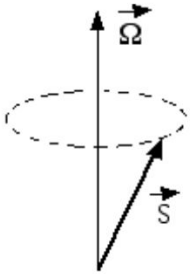
  ↳ requires a sufficient transverse spin polarization level



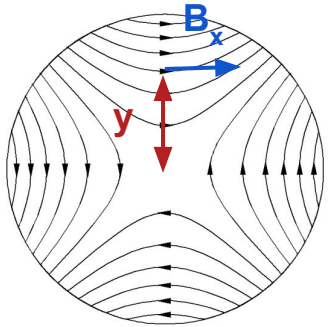
Spin polarization

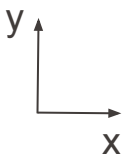
Thomas-BMT equation

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



displacement in quad





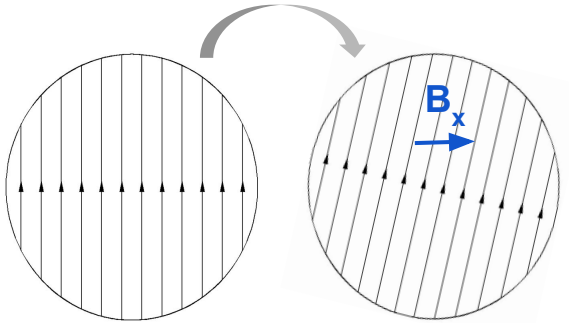
$$\vec{P} = \frac{\sum_{i=1}^{N} \left\langle \vec{S}_i \right\rangle}{\left| \left\langle \vec{S}_i \right\rangle \right| N}$$

perfect flat ring → P ≈ 92.4%

real machine → P < 92.4%

How much?

dipole roll (DPSI)

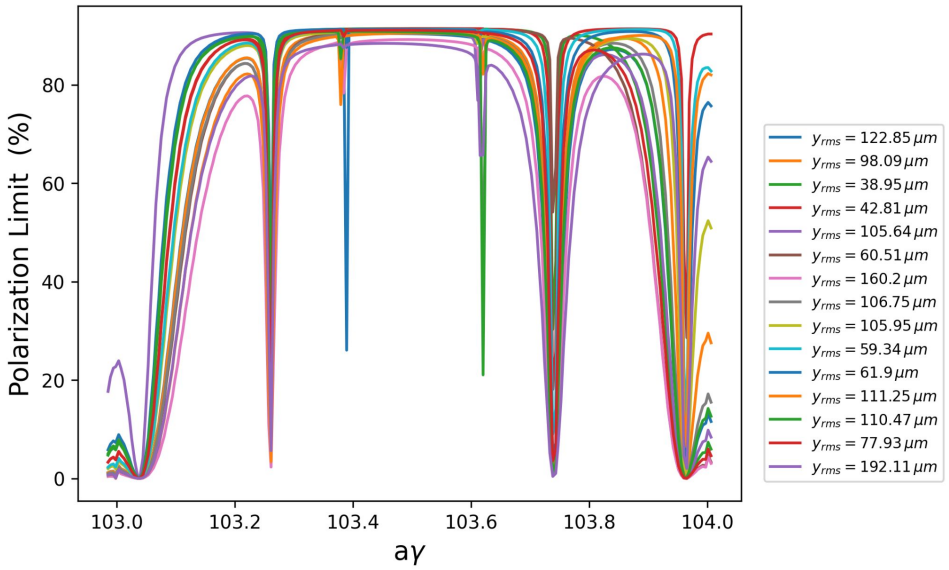


Magnet figures from Maxwell's equations for magnets, A. Wolski, https://cds.cern.ch/record/1333874/files/1103.0713.pdf

Previous machine for polarization study:

clean lattice + small errors + no orbit correction ⇒ high polarization

$\sigma_{dx/dy/ds}$= 120 nm, σ_{angle}=2 urad



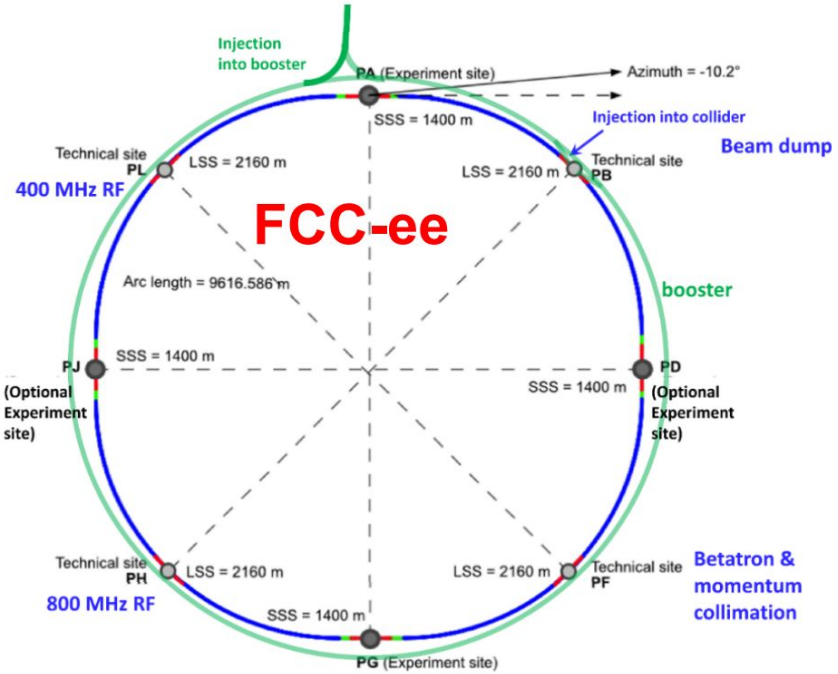
What if:

clean lattice + large errors + orbit correction ⇒ polarization?

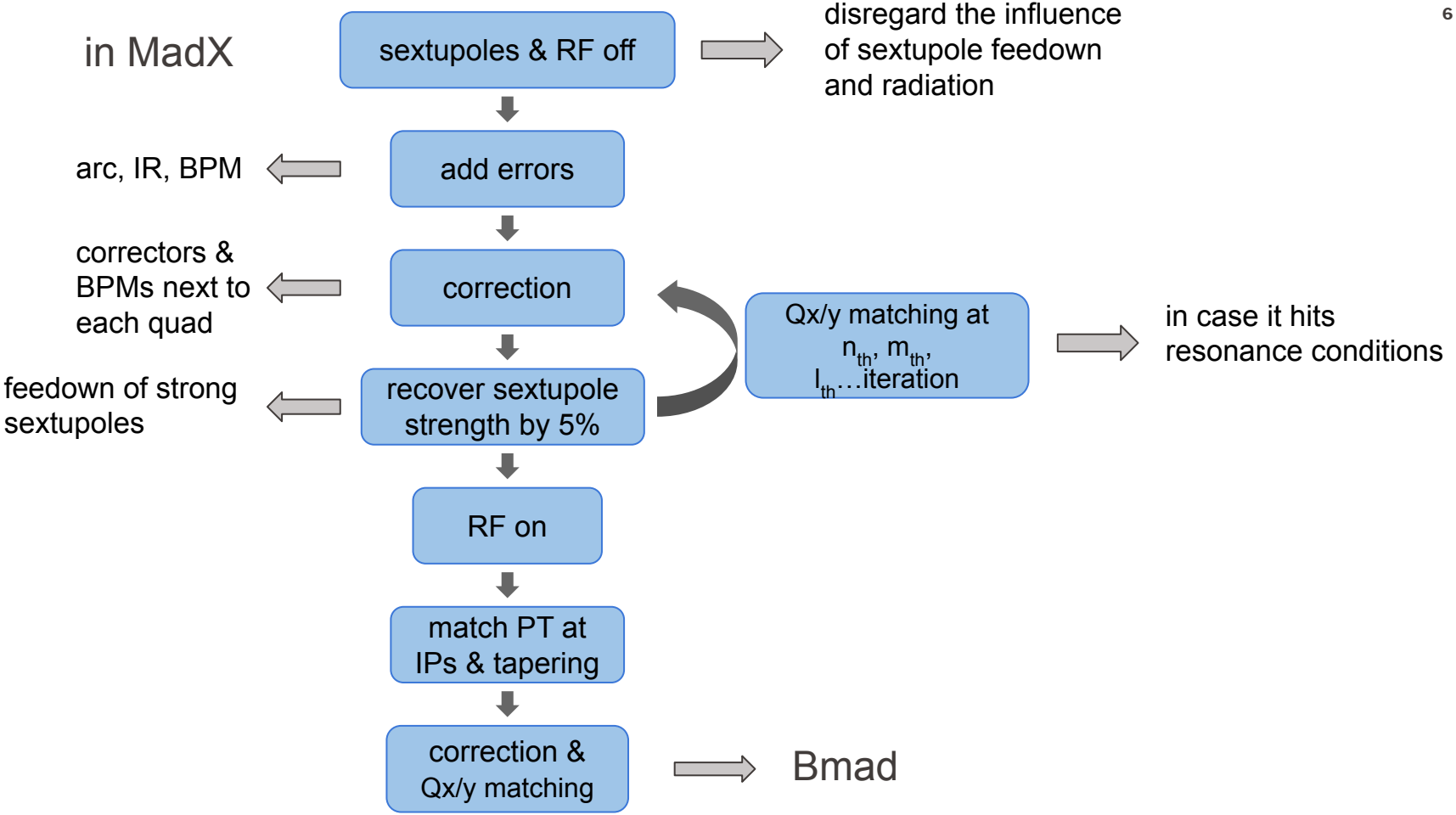
Lattice

- 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



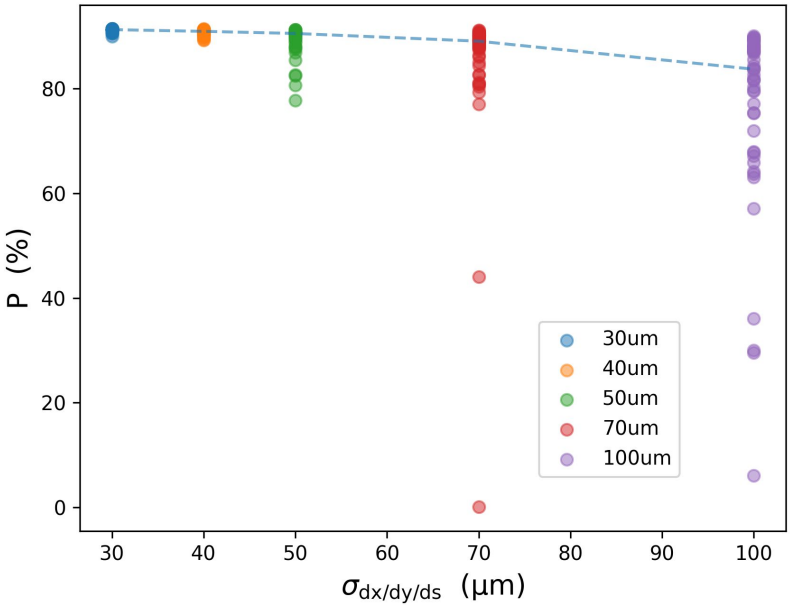
in MadX


sextupoles & RF off
disregard the influence of sextupole feedown and radiation
add errors
arc, IR, BPM
correction
correctors & BPMs next to each quad
recover sextupole strength by 5%
feedown of strong sextupoles
Qx/y matching at n_{th}, m_{th}, l_{th}…iteration
in case it hits resonance conditions
RF on
match PT at IPs & tapering
correction & Qx/y matching
Bmad

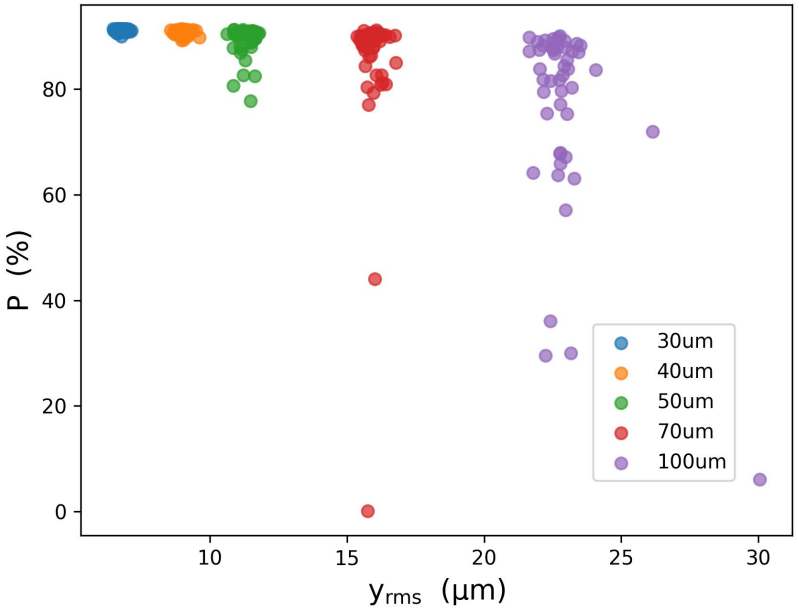
$\sigma_{dx/dy/ds}$ = 30μm for non IR elements (dipoles+quadrupoles+sextupoles)

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	2406.6	8.20	91.412
2	work	1695.2	7.56	91.166
3	work	2953.2	7.41	91.407
4	work	5108.3	7.45	91.301
5	work	3831.1	9.07	90.685
6	work	3124.3	8.26	91.413
7	work	2573.0	6.88	90.685
8	work	2070.8	7.03	91.435
9	work	4298.6	7.65	91.315
10	work	2766.4	7.60	90.937

50 random seeds for each misalignment scale



rms misalignments we set



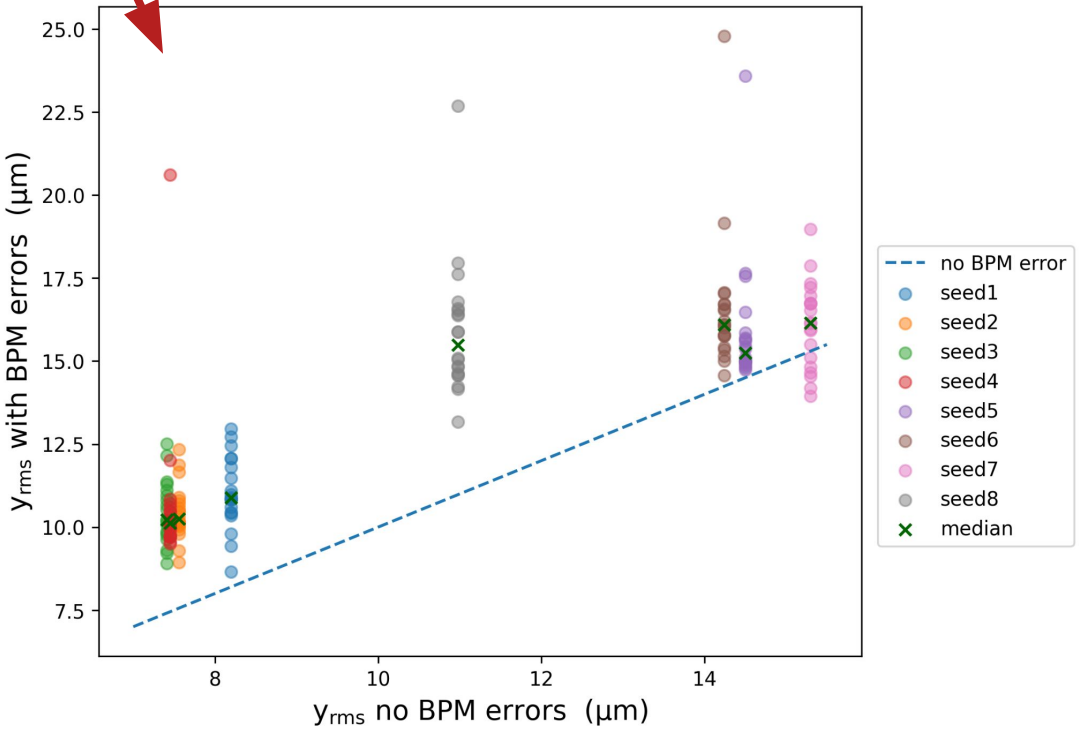
ver. orbit after correction

$\sigma_{dx/dy/ds}$= 30μm (seed 1,2,3,4) and 50μm (seed 5,6,7,8) for non IR elements

+ 10% random BPM missing + 1% rms BPM scaling errors + 1μm rms BPM resolution

20 different BPM missing patterns for each seed

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

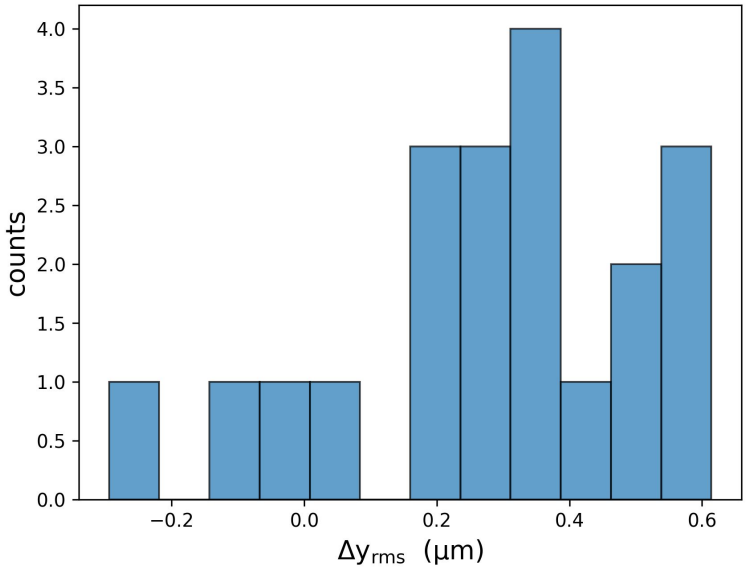


$\sigma_{dx/dy/ds}$ = 30µm for non IR elements

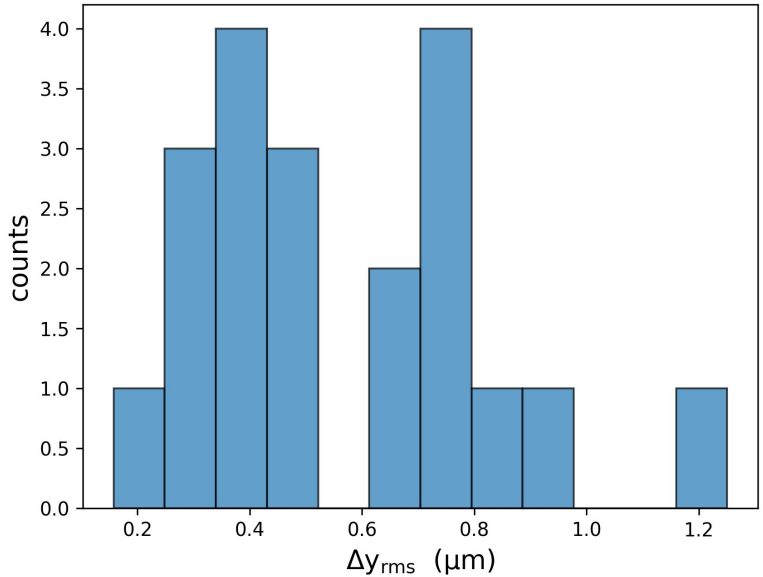
+ 10% random BPM missing + 1% rms BPM scaling errors + 1µm rms BPM resolution

What if **+ 100µrad non IR dipole roll (DPSI)** with all other error values unchanged?

seed = 1



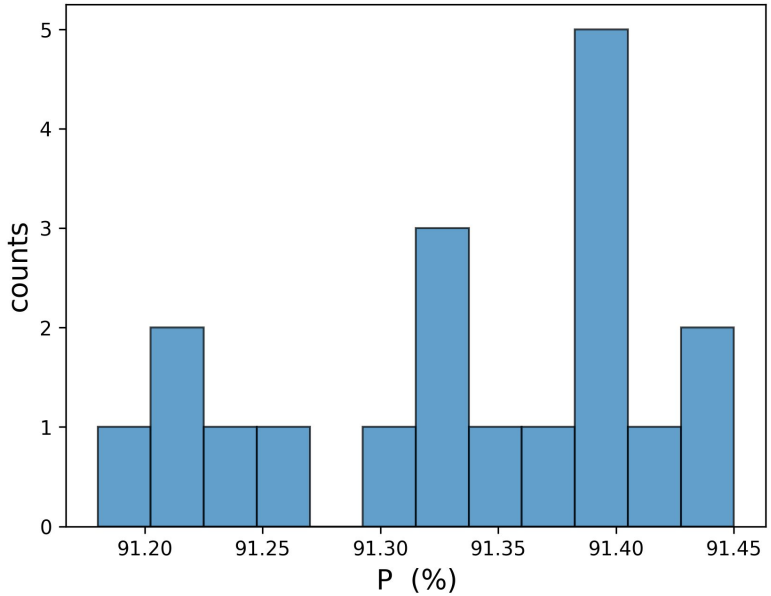
seed = 2

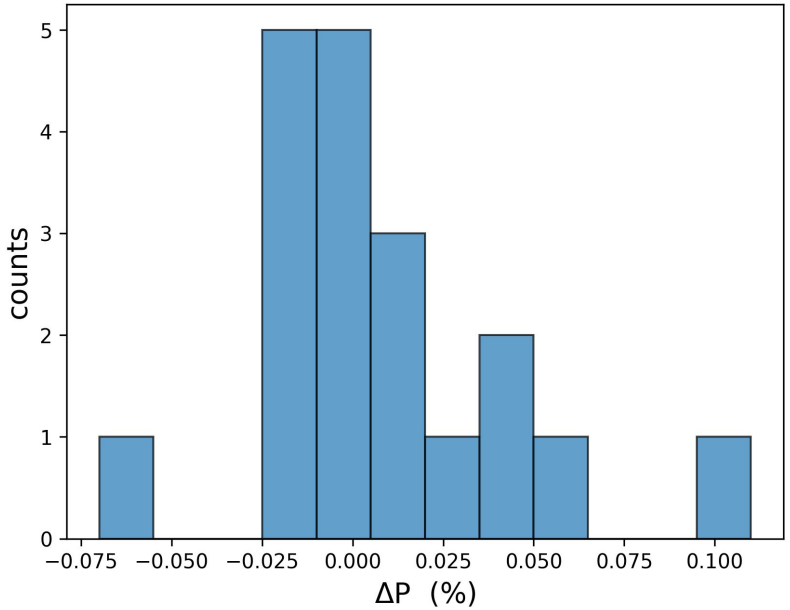


$\sigma_{dx/dy/ds}$ = 30μm for non IR elements + 100μrad non IR dipole roll (DPSI)

+ 10% random BPM missing + 1% rms BPM scaling errors + 1μm rms BPM resolution

The influence to polarization? seed = 1

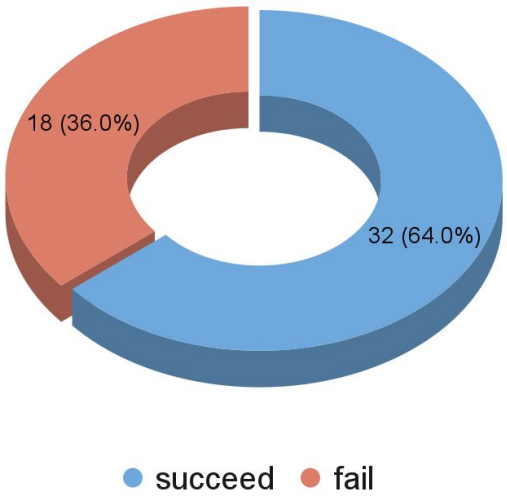




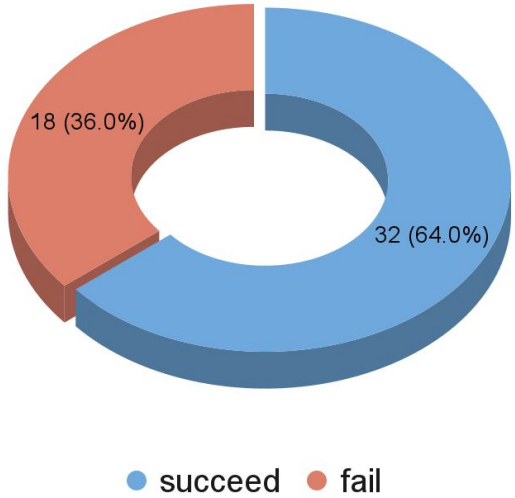
+ 100μrad non IR dipole roll (DPSI)

+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution

$\sigma_{dx/dy/ds}$= 40μm non IR+ 10μm IR



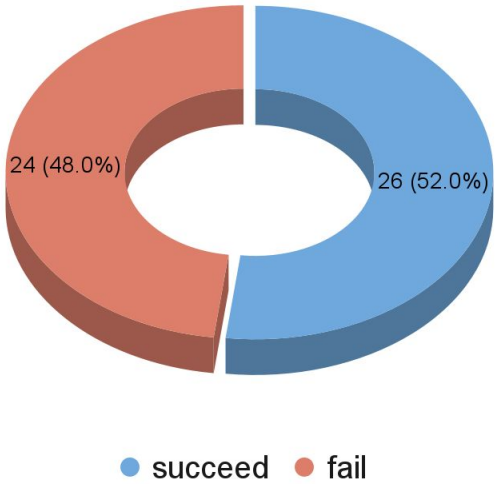
$\sigma_{dx/dy/ds}$= 50μm non IR+ 10μm IR



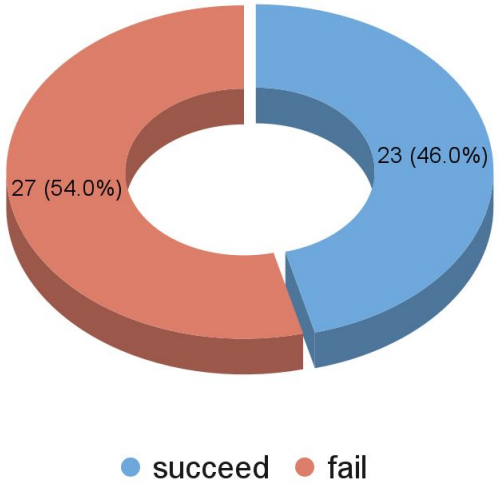
+ 100μrad non IR dipole roll (DPSI)

+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution

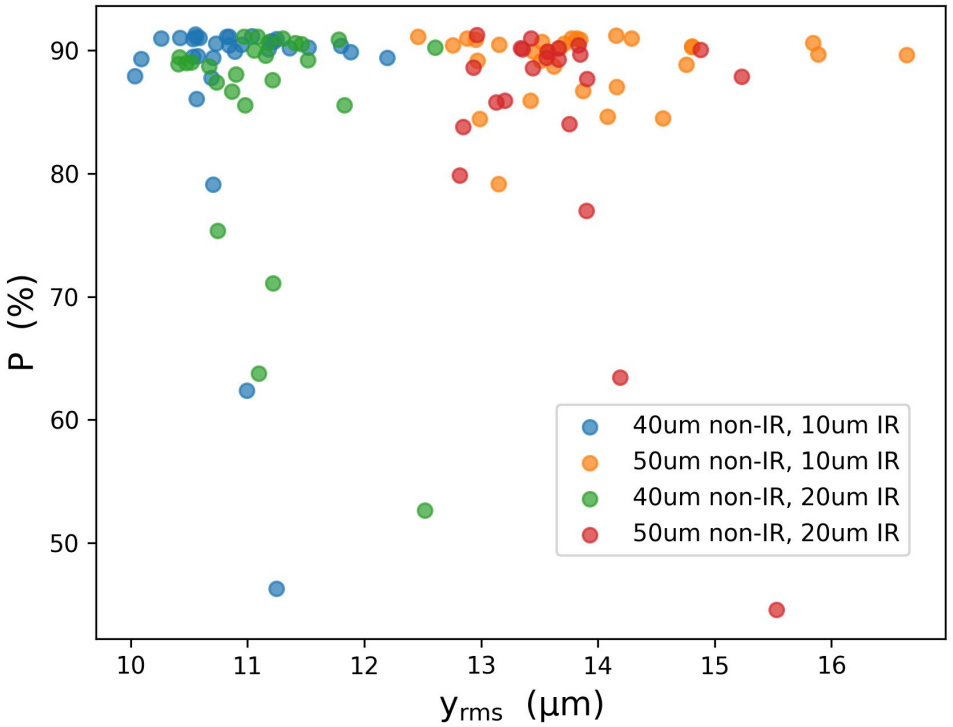
$\sigma_{dx/dy/ds}$= 40μm non IR+ 20μm IR



$\sigma_{dx/dy/ds}$= 50μm non IR+ 20μm IR



Survivorship bias!



Long range alignment errors

Initial Mechanical alignment *

Length scale	Tolerance	Source
6 m	20 to 50 μm	mechanical installation tolerance of components on quad/sext girder
50 m	200 μm	mechanical installation and alignment of girder to girder
200 m	500 μm	mechanical installation

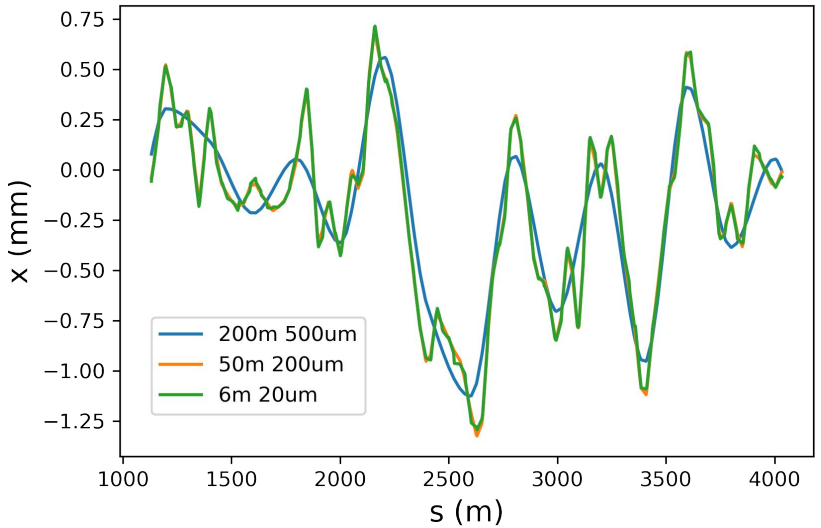
[*] FCC Arc Alignment Requirements, Tor Raubenheimer, FCC IS Workshop, December 5-9, 2022.
https://indico.cern.ch/event/1203316/contributions/5153505/attachments/2561642/4416191/221206%20FCC%20BBA.pdf

Long range alignment errors

For each length scale

- Divide the circumference into grids
- Generate random errors at grids
- Use monotone cubic spline to connect points

Add all spline functions and extract values at every element



[*] Misalignments with short-range and long-range correlations, Michael Hofer
https://indico.cern.ch/event/1325263/contributions/5576644/attachments/2714362/4714173/MH_LRA.pdf

Long range misalignments for non IR, sextupoles off

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	16966.2	99.8	89.92
2	work	13294.3	109.1	90.75
3	work	40886.8	98.2	91.27
4	work	5604.5	102.1	90.85
5	work	13494.4	102.9	90.55
6	work	16843.2	96.6	90.79
7	work	14944.6	104.7	90.25
8	work	17649.9	105.9	90.22
9	work	14362.7	101.1	90.11
10	work	10115.0	101.6	90.43

Long range misalignments for non IR, 10μm rms for IR, sextupoles off

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	19564.1	99.9	89.86
2	work	12407.2	109.2	90.77
3	work	37547.0	98.3	91.26
4	work	7311.7	102.1	90.84
5	work	16286.4	103.0	90.58
6	work	17066.5	96.6	90.80
7	work	14064.3	104.7	90.25
8	work	17649.9	105.9	90.22
9	work	16877.0	101.1	90.11
10	work	11994.2	101.6	90.39

Two models comparison

= 100 µm misalignments in 6 m range

$\sigma_{dx/dy/ds}$ = 100 µm

		Long Range Alignment errors [200m, 500µm], [50m, 200µm], [6m, 20µm] sextupoles off
rms y after correction	~20 to 30 µm	~ 100 µm
Polarization w/o sextupole	~ 86-90%	~ 90%
Polarization w/ sextupole	16% to 90%	under investigation

Further correction methods under development

Conclusion

- High polarization at Z energy can be achieved as long as tight alignment can be made.
- More realistic errors with full correction
- Quantification of the influence of machine errors to polarization remains to be explored.

Appendix

ttbar lattice, $\sigma_{dx/dy/ds}$= 30um for non IR elements

seed number	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%) (the value when away from resonance)
892727030	work	4909.2	17.81	2.54
864141966	work	1680.2	17.56	0.93
726643487	work	2753.8	17.41	0.26

only for the future polarization studies

$\sigma_{dx/dy/ds}$ = 40μm for non IR elements

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	2210.3	9.42	91.046
2	work	4855.4	10.66	90.674
3	work	4014.1	10.61	90.829
4	work	3406.1	10.17	91.244
5	work	2732.8	10.92	89.814
6	work	2615.0	10.51	91.382
7	work	3787.9	8.81	90.326
8	work	3137.4	9.11	88.889
9	work	3451.1	8.89	91.406
10	work	6000.7	10.65	90.132

$\sigma_{dx/dy/ds}$ = 50μm for non IR elements

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	1964.7	14.50	90.825
2	fail at Q matching	4864.2	11.32	90.995
3	work	2715.4	14.24	90.895
4	work	3496.7	15.30	90.039
5	work	10877.2	10.98	90.964
6	work	3244.8	11.24	88.971
7	work	3169.8	13.67	90.951
8	work	5922.6	13.04	68.807
9	work	5659.6	21.95	89.784
10	work	4526.7	13.81	90.750

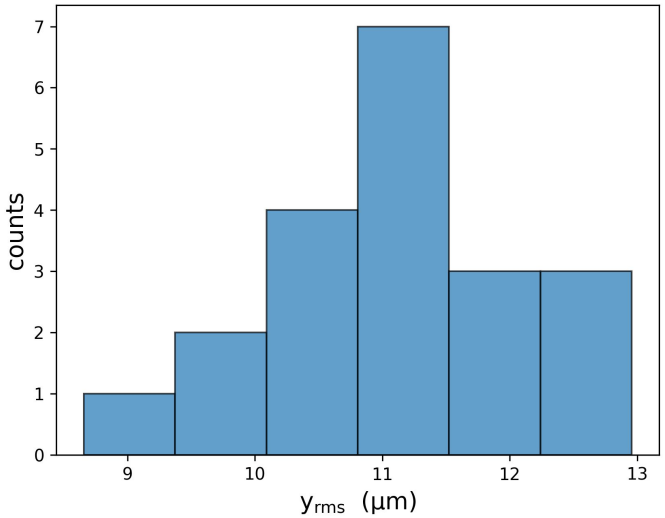
$\sigma_{dx/dy/ds}$ = 100μm for non IR elements

seed	status	y_{rms} before correction (μm)	y_{rms} after correction (μm)	Polarization (%)
1	work	12649.3	34.36	78.898
2	work	9584.2	26.71	87.904
3	work	12177.1	23.01	73.588
4	work	8239.6	21.29	15.781
5	work	8996.3	25.26	90.543
6	work	11860.2	58.58	26.693
7	work	10102.2	42.03	84.835
8	fail at Q matching	7032.0	22.09	0.013 (close to resonance)
9	work	8359.6	22.75	88.419
10	work	11976.8	23.54	89.293

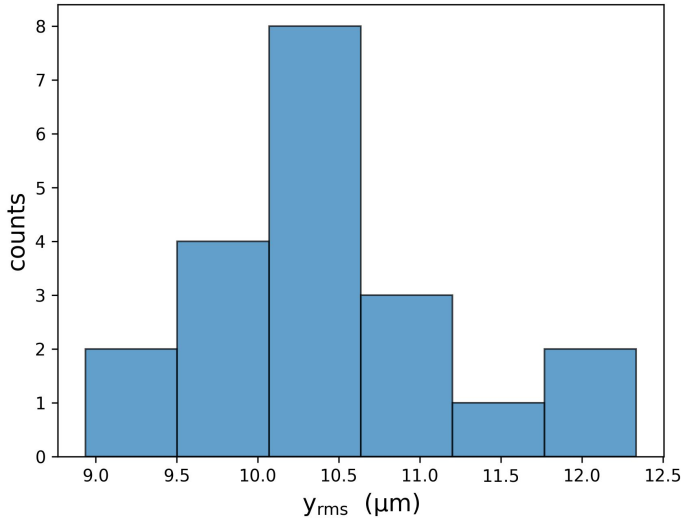
$\sigma_{dx/dy/ds}$ = 30um for non IR elements

+ 10% random BPM missing + 1% BPM scaling errors + 1um BPM resolution (read error)

seed = 892727030, **8.20um**



seed = 690427689, **7.56um**

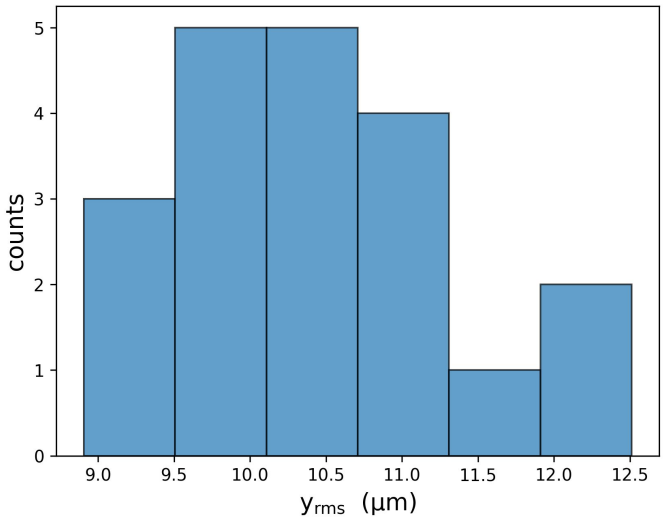


20 different BPM missing patterns

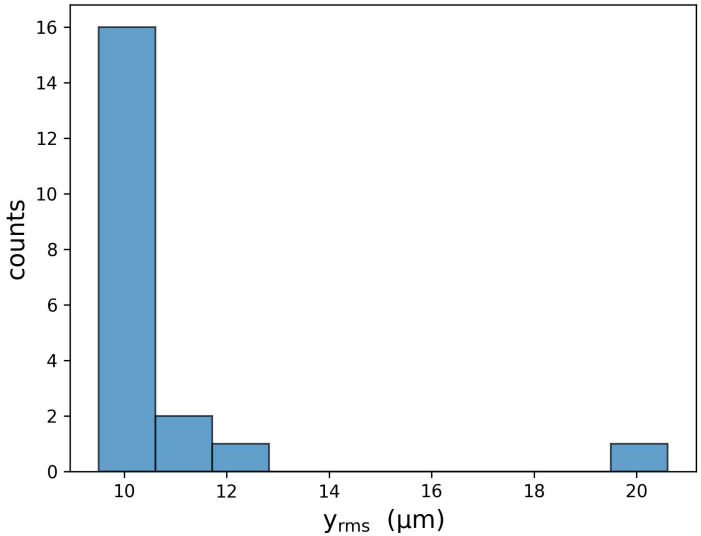
$\sigma_{dx/dy/ds}$ = 30um for non IR elements

+ 10% random BPM missing + 1% BPM scaling errors + 1um BPM resolution (read error)

seed = 688758431, **7.41um**



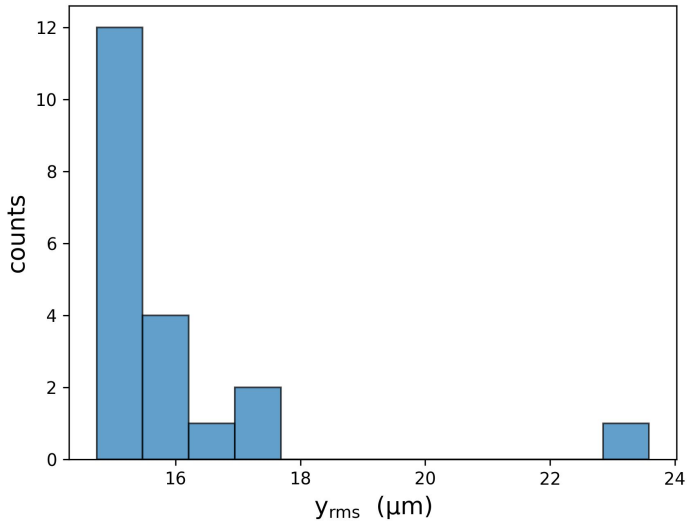
seed = 83627346, **7.45um**



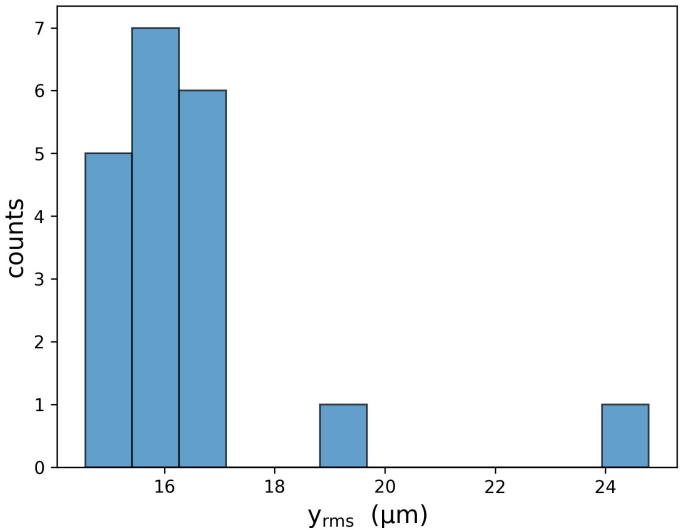
$\sigma_{dx/dy/ds}$ = 50um for non IR elements

+ 10% random BPM missing + 1% BPM scaling errors + 1um BPM resolution (read error)

seed = 429756481, **14.5um**



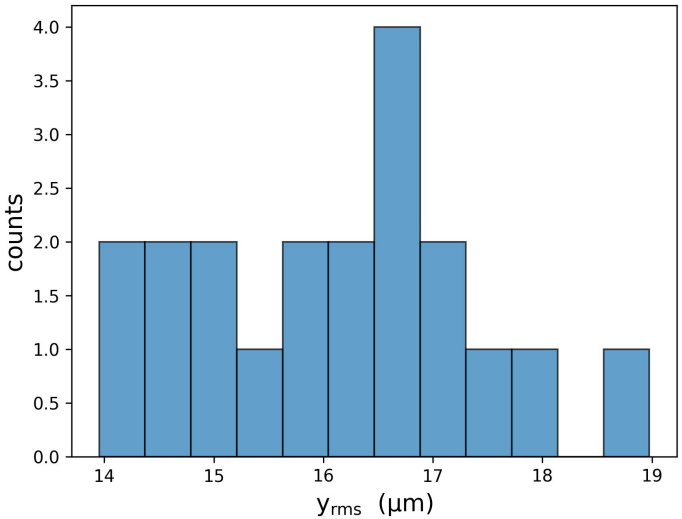
seed = 620990290, **14.24um**



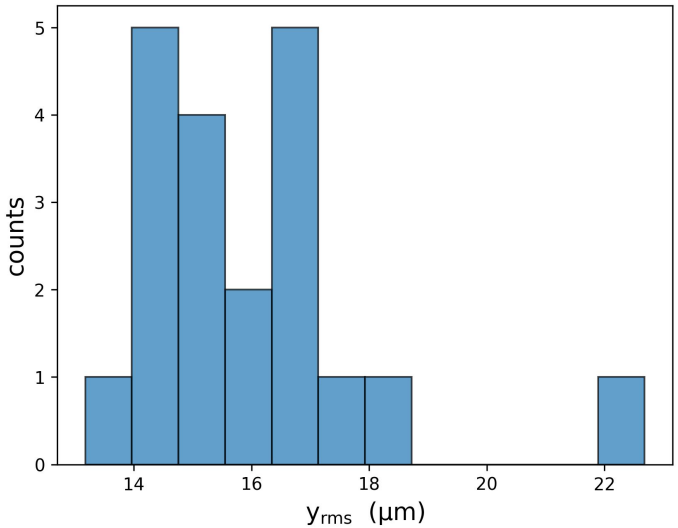
$\sigma_{dx/dy/ds}$ = 50um for non IR elements

+ 10% random BPM missing + 1% BPM scaling errors + 1um BPM resolution (read error)

seed = 44457008, **15.3um**



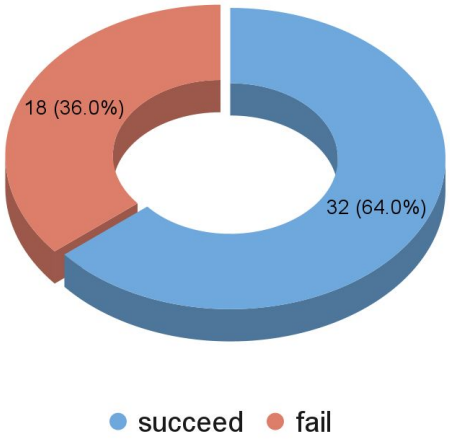
seed = 591903013, **10.98um**

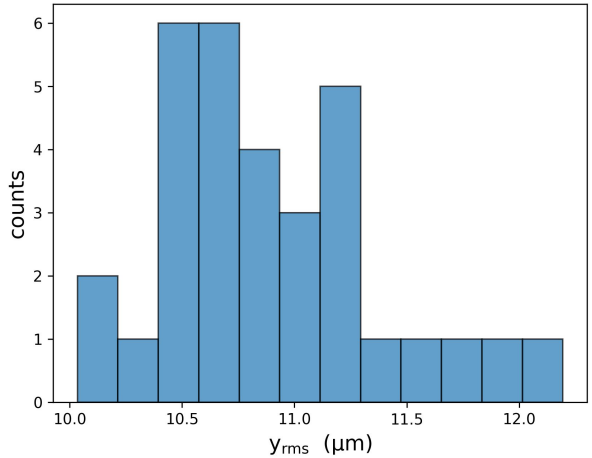


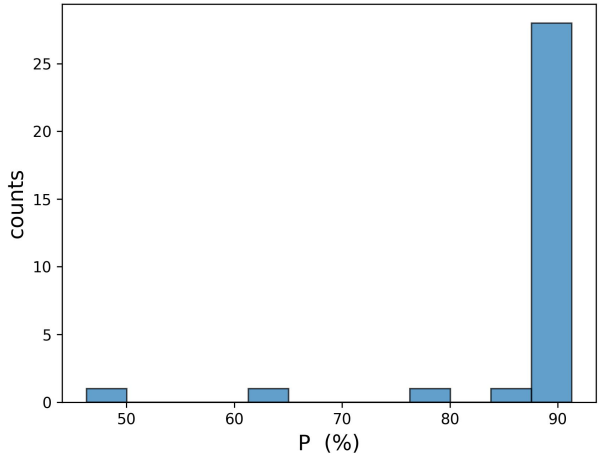
$\sigma_{dx/dy/ds}$ = 40μm for non IR elements + 10μm for IR elements

\+ 100μrad non IR dipole roll (DPSI)

\+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution



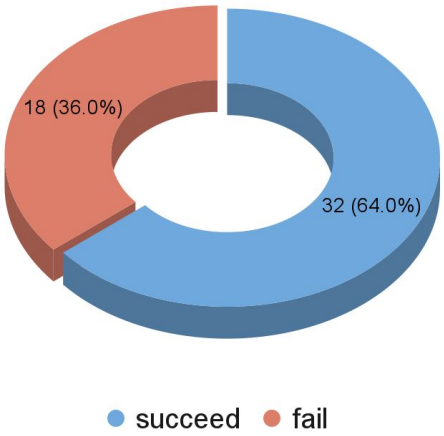


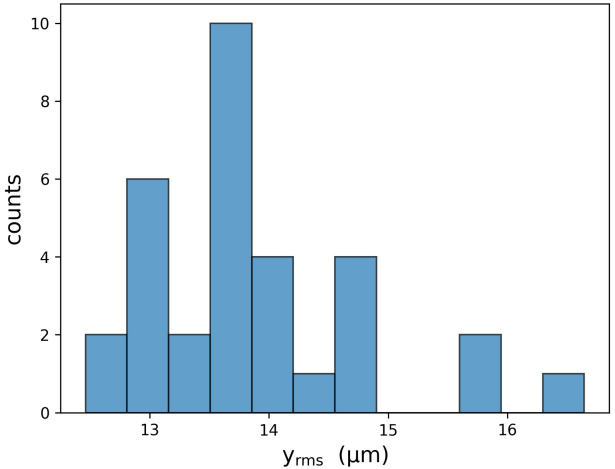


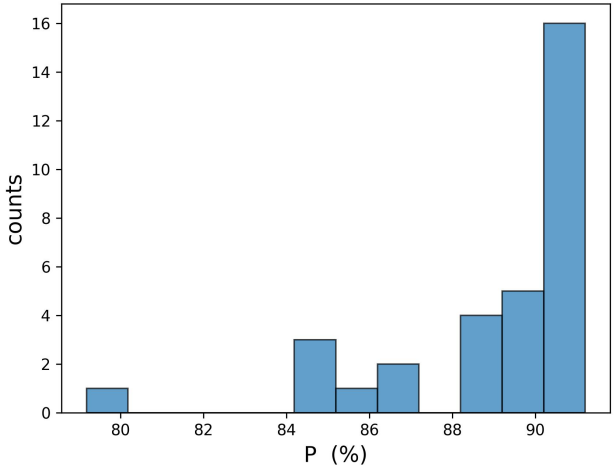
$\sigma_{dx/dy/ds}$ = 50μm for non IR elements + 10μm for IR elements

\+ 100μrad non IR dipole roll (DPSI)

\+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution



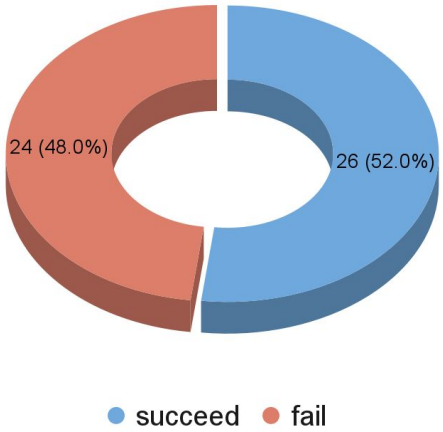


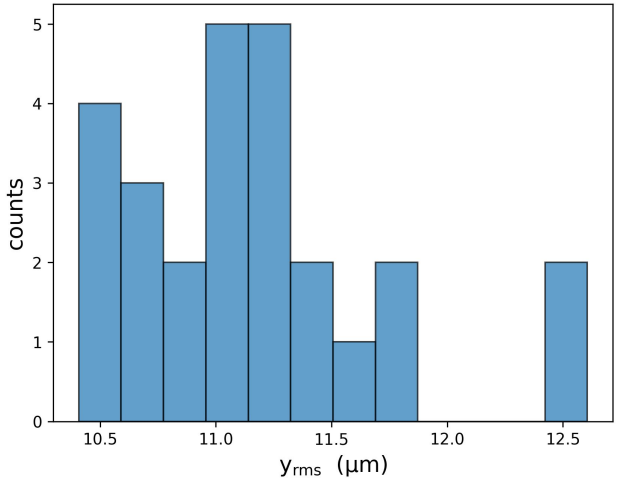


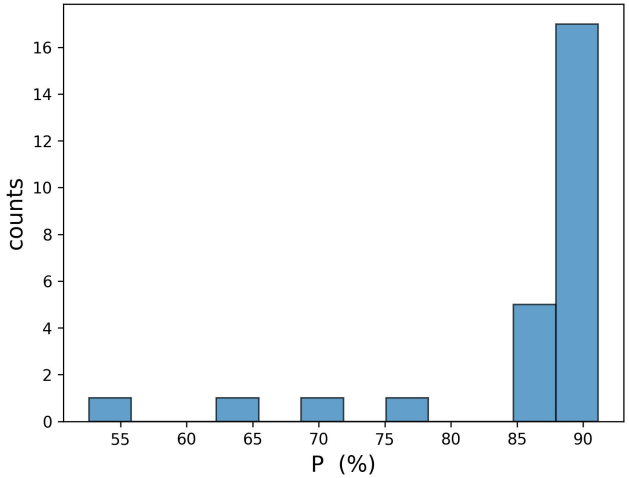
$\sigma_{dx/dy/ds}$ = 40μm for non IR elements + 20μm for IR elements

\+ 100μrad non IR dipole roll (DPSI)

\+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution







$\sigma_{dx/dy/ds}$ = 50μm for non IR elements + 20μm for IR elements

\+ 100μrad non IR dipole roll (DPSI)

\+ 5% random BPM missing + 1% BPM scaling errors + 1μm BPM resolution