Sorting of the MQXFB: new results

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- Context
- Description of the Pair Calibration
- Sorting results
- Conclusions

Contents

Context

- Based on previous analysis, it was concluded that:
  - The Pair Calibration is very very effective to mitigate the beta-beating.
  - Setup Calibration and Precision errors affect strongly the Pair Calibration from measurement estimation. No benefice from the sorting can be seen during the commissioning if this calibration is used.
  - Nevertheless, the sorting may still show benefice from beam based calibration.

- To illustrate this, three plots are shown:
  - **Prediction:** Showing what the sorting expect based on the Measurement.
  - **Realistic:** Showing what can be expected in reality at the commissioning using the Pair Calibration based on Measurements.
  - **Optimistic:** Showing what can be expected in reality using the best Pair Calibration.

- Between the 3 plots, the sorting results are the same. The goal is to estimate the impact of uncertainty on the prediction.

Context

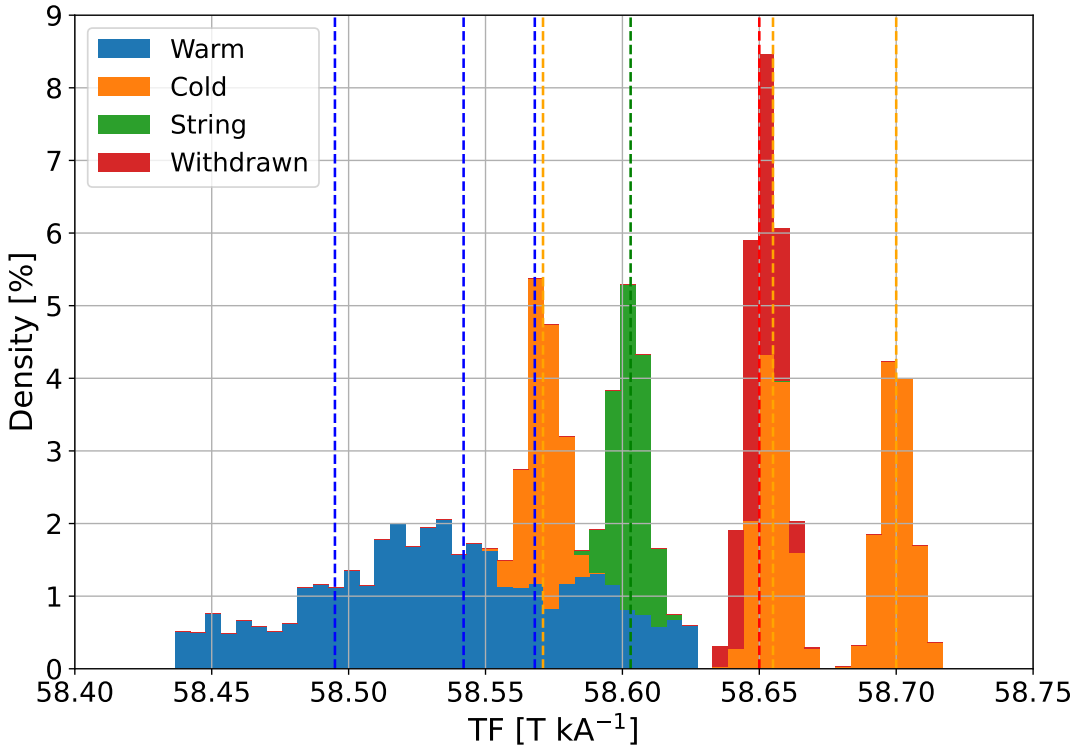
Measurement results transmitted by Lucio

Cold mass	-	**LMQXFB01**	**LMQXFB02**	**LMQXFB03**	**LMQXFB05**	**LMQXFB04**
Magnet	-	MQXFBP2	MQXFBP3	MQXFB02	MQXFB03	MQXFB04
Used for	-	String	String	Withdrawn	Machine	Machine
Central gradient	T m-1 kA-1	-	8.1712	8.1804	8.1556	8.1691
Magnetic length	m	-	7.1720	7.1696	7.1816	7.1801
TF integral	T kA-1	-	58.603	58.650	58.571	58.655
Temperature		Cold	Cold	Cold	Cold	Cold

Cold mass	-	**LMQXFB06**	**LMQXFB07**	**LMQXFB08**	**LMQXFB09**
Magnet	-	MQXFB05	MQXFB06	MQXFB07	MQXFB08
Used for	-	Machine	Machine	Machine	Machine
Central gradient	T m-1 kA-1	8.1772	8.1532	8.1592	8.1638
Magnetic length	m	7.1785	7.1745	7.1750	7.1741
TF integral	T kA-1	58.700	58.495	58.542	58.568
Temperature		Cold	Warm	Warm	Warm

Context

- Lucio reports that 3 types of uncertainty must be considered:
  - **Cold measurement:** a Gaussian ($\sigma = 1u$) cut at 3σ.
  - **Extrapolation from Warm measurement:** a Uniform distribution between $\pm 10u$.
  - **Unknown magnets:** Still not precisely defined, so we used a Gaussian centered around the average of all errors and cut at 3σ ($\sigma = 20/3u$).



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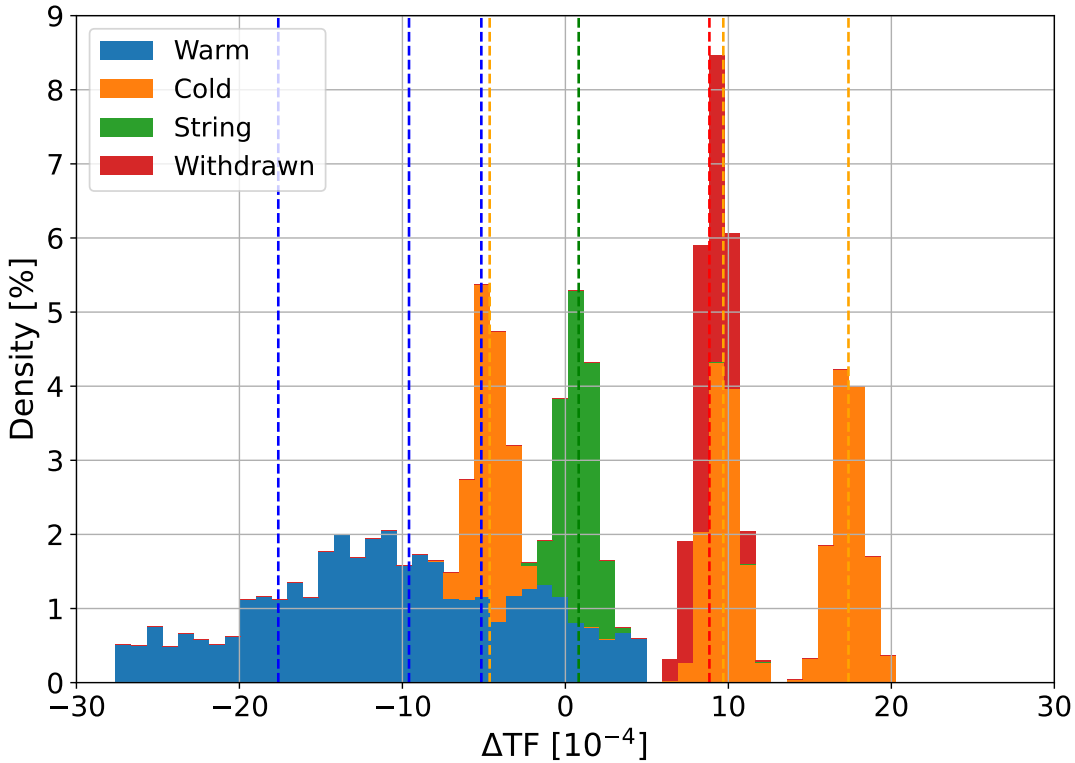

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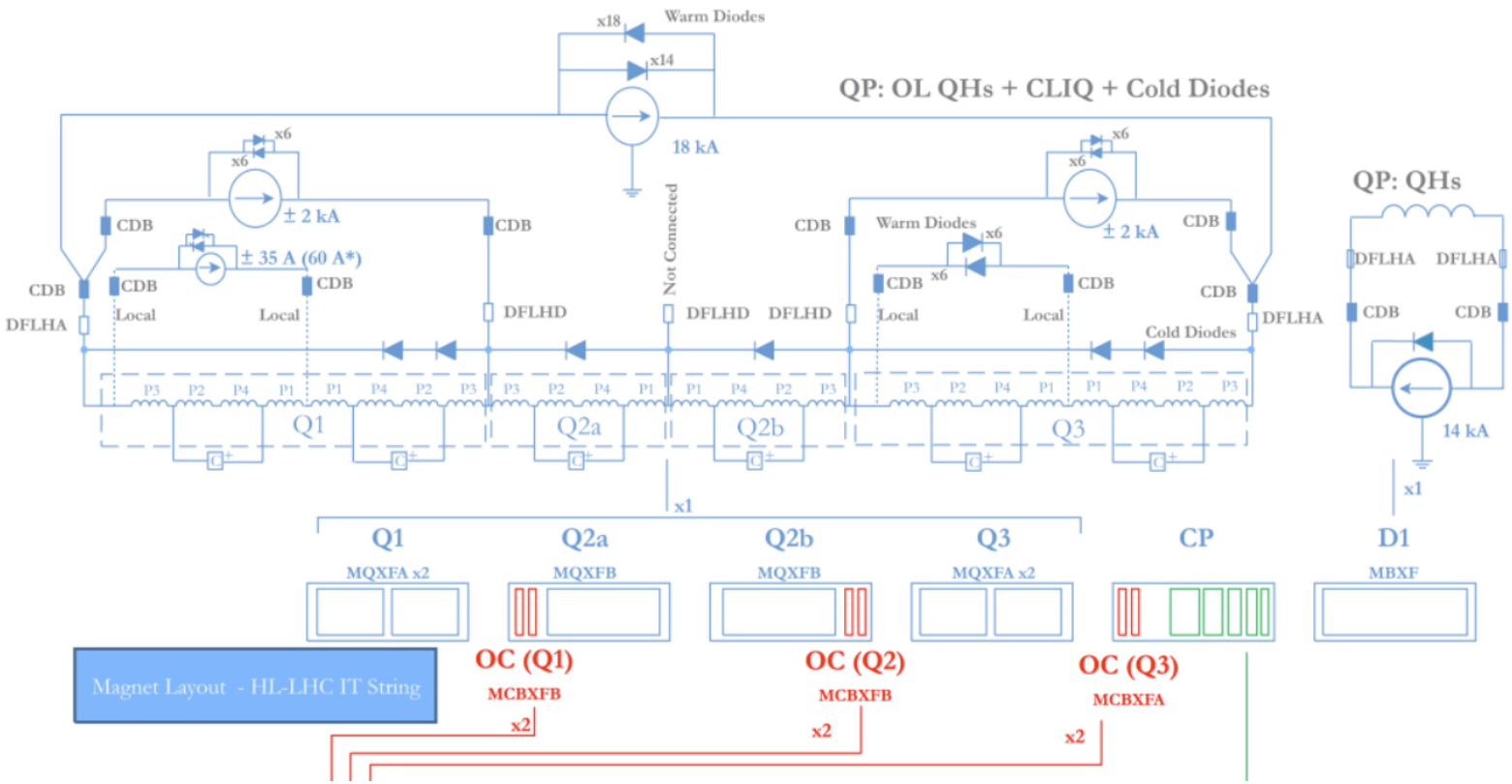
- Three scenarios are presented:
  1. **1st scenario:** The sorting has been performed based on the measurement values from Lucio alone and the two unknown magnets are set to 0. The uncertainty is used to estimate the strength experienced by the beam in reality.
  2. **2nd scenario:** For this sorting, the warm measurement uncertainty are used for the sorting instead.
  3. **3rd scenario:** For this sorting, the warm measurement uncertainty AND that of the unknown ones are used for the sorting instead.

- One constrain has to be considered: MQXFB04 is in B2L5.

Contents

HL-LHC Power Circuit



The Triplet Power Circuit is composed of 3 circuits: one circuit that powers all Triplet in series and one for each pair of Q_1 and Q_3.

Pair Calibration description

- **Expression of β-beating with the Pair Calibration (PC):**

$$\frac{\Delta\beta_z}{\beta_z}(s) = \mp 10^{-4} \sum_i K_{1,Ri}\beta_{z,i} \left(\frac{b_{1,i} - \langle b_1 \rangle_P}{1 + 10^{-4} \langle b_1 \rangle_P} \right) \frac{\cos\left(4|\psi_{z,i}(s)| - 2\pi Q_z\right)}{2\sin(2\pi Q_z)}$$

with the Transfer Function deviation $b_{1,i}$ in $\left[10^{-4}\right]$ and:

$$\langle b_1 \rangle_P = \frac{b_{1,i} + b_{1,j}}{2} \qquad \Delta b_{1,i} = \frac{b_{1,i} - b_{1,j}}{2}$$

for $i, j \in \{A, B\}$ of a same pair.

- The Sorting strategy consists in minimizing the Score function based on this expression of the β-beating:

$$score = \sqrt{\sum_s \left(\frac{\Delta\beta_x}{\beta_x}\right)^2 + \sum_s \left(\frac{\Delta\beta_y}{\beta_y}\right)^2}$$

- In reality, the measurement results provided are not perfect. There are Systemic errors (e_s) like the one from then Measurement settings and Random errors (e_r) like the measure precision.

Pair Calibration errors

- Let's assume the following relation between the measurement ($b_{1,i|M}$), the real deviation ($b_{1,i|R}$) and the errors:

$$b_{1,i|M} = b_{1,i|R} + e_s + e_{r,i}$$

- Then, the strength average between pairs of quadrupoles used for the Pair Calibration would follow:

$$\langle b_1 \rangle_{P|M} = \langle b_1 \rangle_{P|R} + e_s + \langle e_{r,i} \rangle_P$$

- The measurement errors are applied to the real TF deviation from the Pair Calibration based on Measurements:

$$\begin{aligned} b_{1,i|M} - \langle b_1 \rangle_{P|M} &= \Delta b_{1,i|R} + \Delta e_{r,i} \\ b_{1,i|R} - \langle b_1 \rangle_{P|M} &= \Delta b_{1,i|R} - e_s - \langle e_{r,i} \rangle_P \end{aligned}$$

- This is not negligible! It was previously estimated that the TF deviation follows a Gaussian with a sigma from 10/3 to 25/3 units and the Precision error a Gaussian with sigma equal 1 units, i.e. a ratio between 12 and 30%.

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  - Sorting Measurement results without uncertainty (S1)
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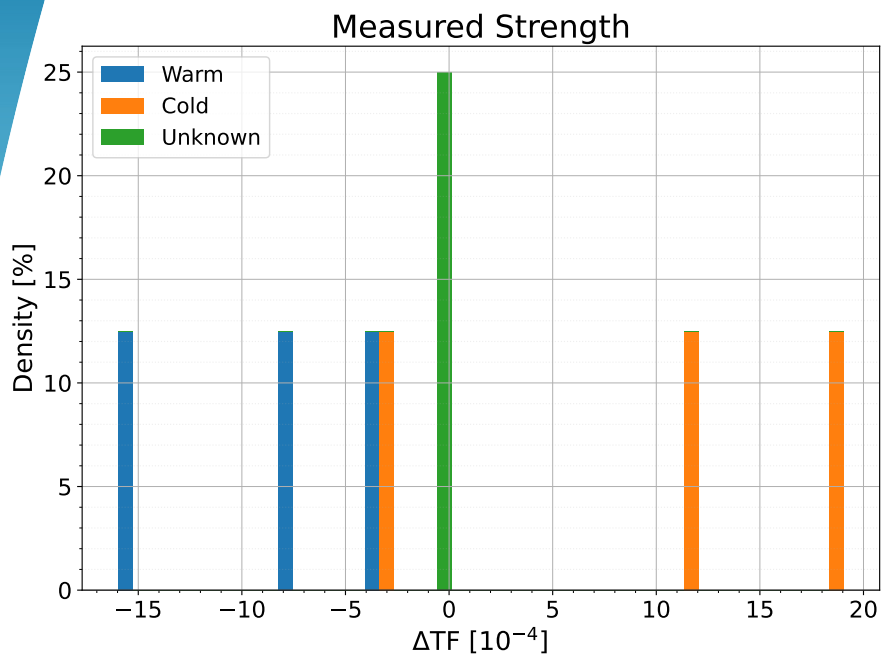
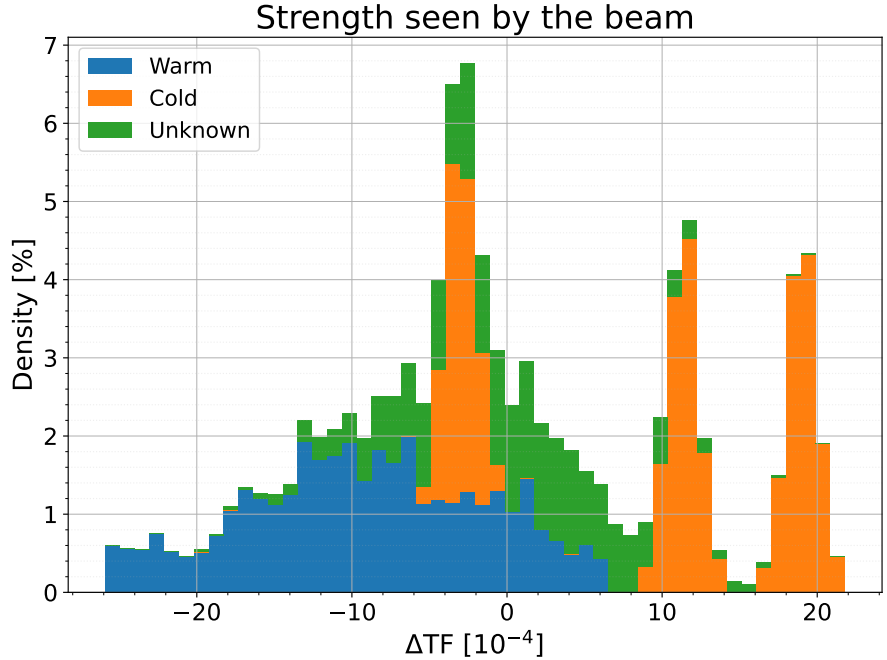
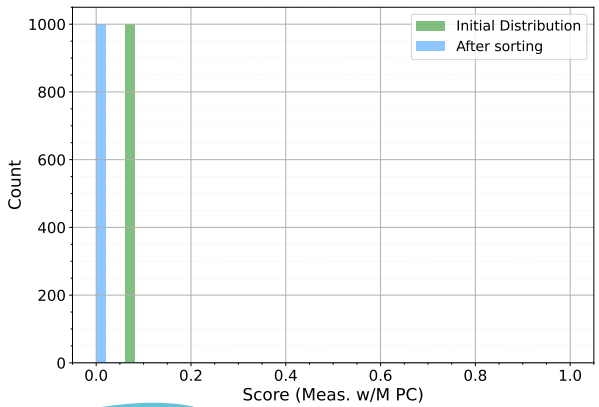
Strength and Score (S1)

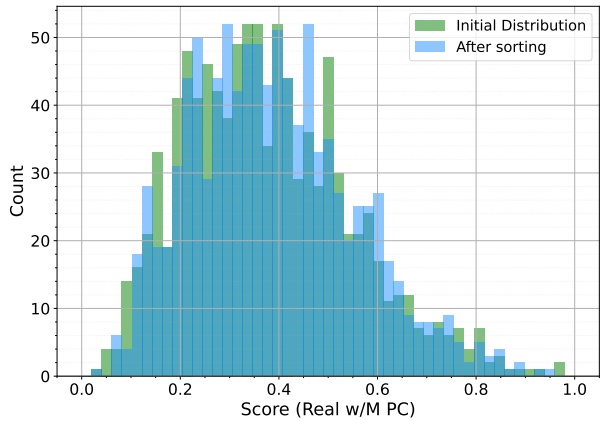




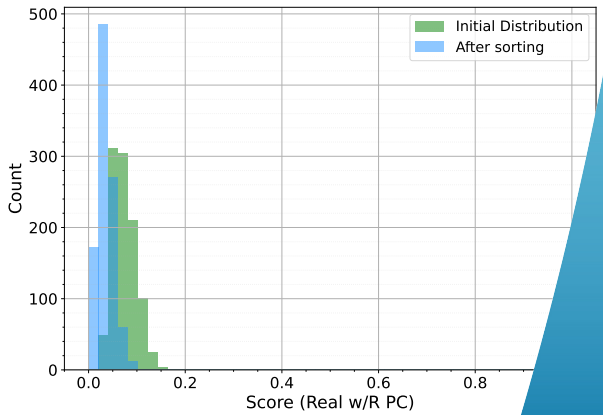
Prediction



Realistic

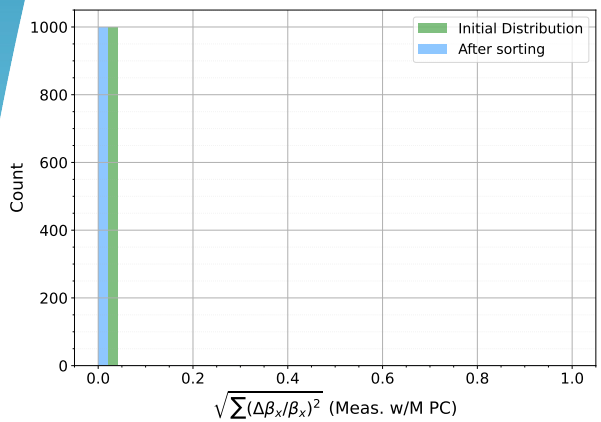


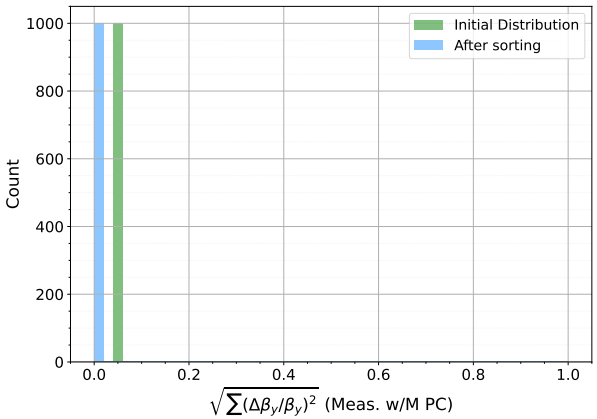
Optimistic



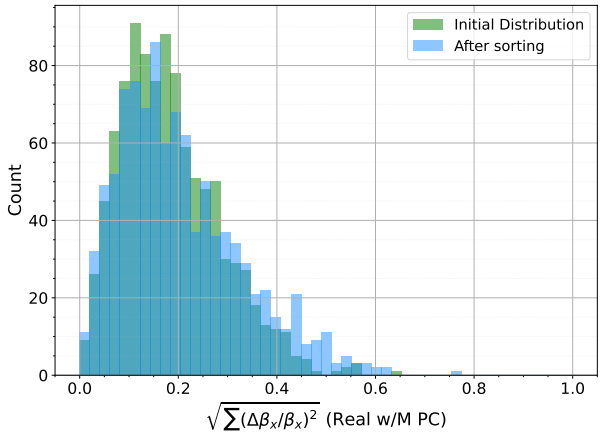
Beta-Beating (S1)

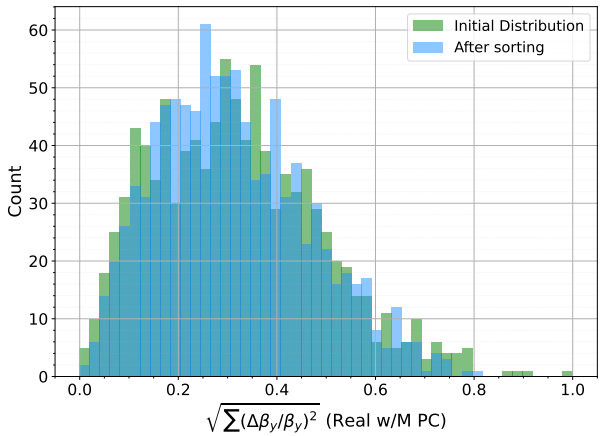
Prediction



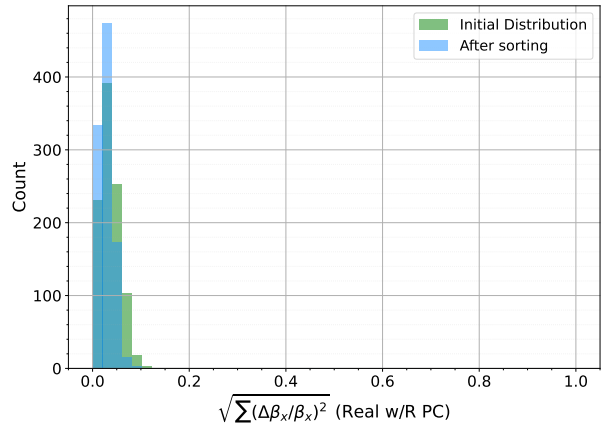


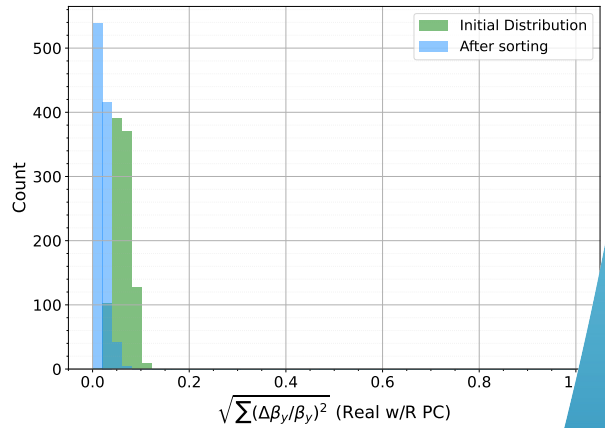
Realistic





Optimistic



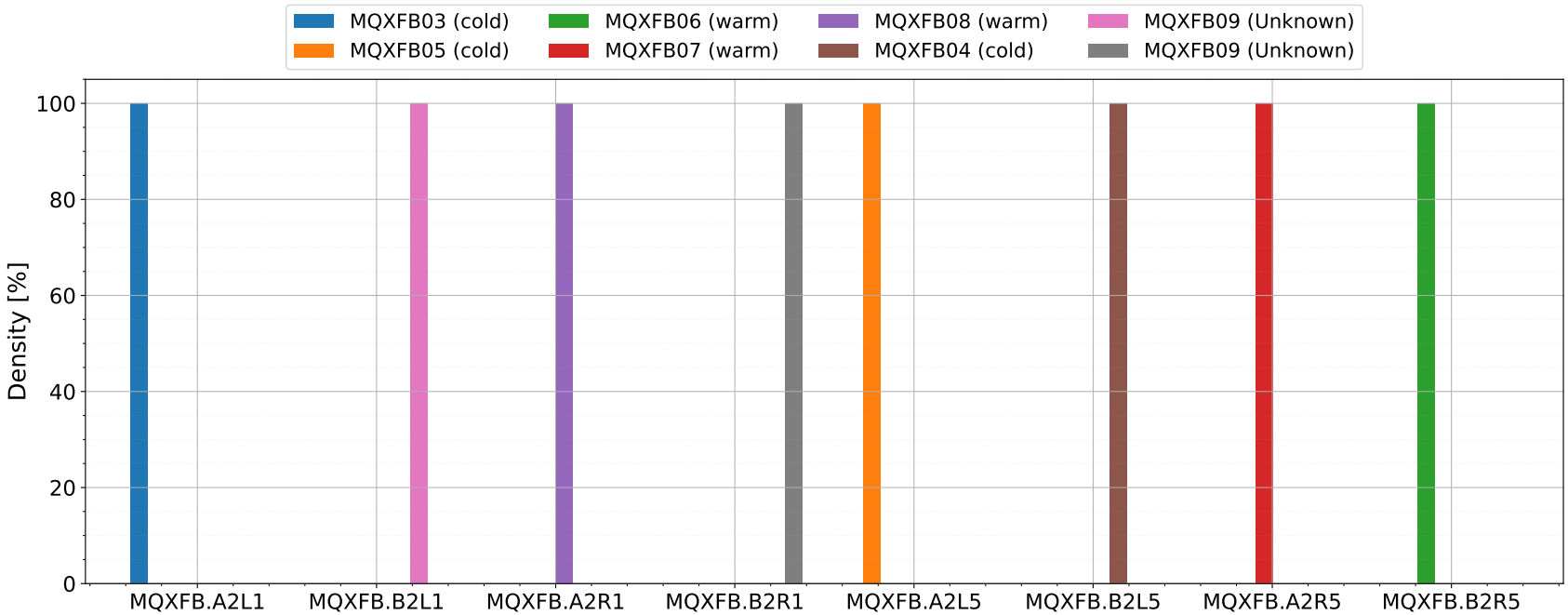


Stats (S1)

Parameter		Min	Avg	Median	Mode	Max	Std
Predicted							
score	ID	0.0672965	0.0672965	0.0672965	0.065	0.0672965	0
	AS	0.0105653	0.0105653	0.0105653	0.015	0.0105653	0
rmsBETX	ID	0.0283151	0.0283151	0.0283151	0.025	0.0283151	0
	AS	0.0080520	0.0080520	0.0080520	0.005	0.0080520	0
rmsBETY	ID	0.0610498	0.0610498	0.0610498	0.065	0.0610498	0
	AS	0.0068404	0.0068404	0.0068404	0.005	0.0068404	0
Realistic							
score	ID	0.0289510	0.3813145	0.3598177	0.395	1.2109220	0.1764917
	AS	0.0265669	0.3884380	0.3735990	0.305	0.9442397	0.1656544
rmsBETX	ID	0.0057470	0.1845494	0.1701233	0.125	0.6410562	0.1011716
	AS	0.0064757	0.2050294	0.1802417	0.145	0.7557660	0.1240252
rmsBETY	ID	0.0081779	0.3201723	0.3063482	0.365	1.0273164	0.1724691
	AS	0.0081802	0.3120563	0.2949768	0.325	0.8118156	0.1533852
Optimistic							
score	ID	0.0296817	0.0731163	0.0696225	0.065	0.1606769	0.0234507
	AS	0.0081799	0.0360735	0.0339352	0.025	0.1256550	0.0160297
rmsBETX	ID	0.0006802	0.0364677	0.0330081	0.025	0.1096799	0.0198925
	AS	0.0007777	0.0285053	0.0268619	0.025	0.0978929	0.0146299
rmsBETY	ID	0.0186855	0.0623220	0.0615055	0.055	0.1174197	0.0169200
	AS	0.0009482	0.0203546	0.0194220	0.015	0.0787792	0.0108328

ID: Initial Distribution;
AS: After sorting;

Position after Sorting (S1)



Only the strength given by Lucio was used for this sorting, and the strength of the two remaining magnets was set as 0.

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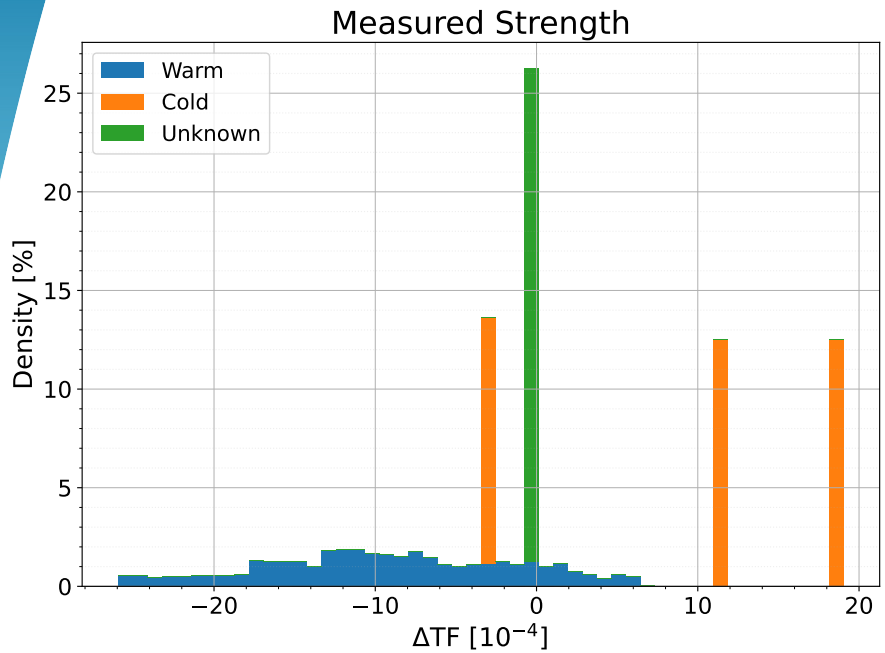
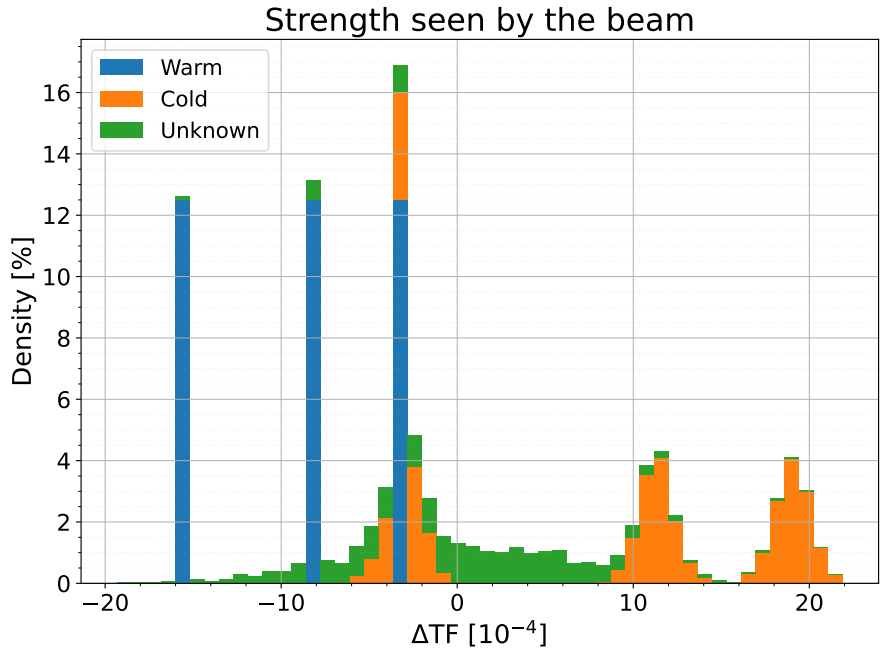
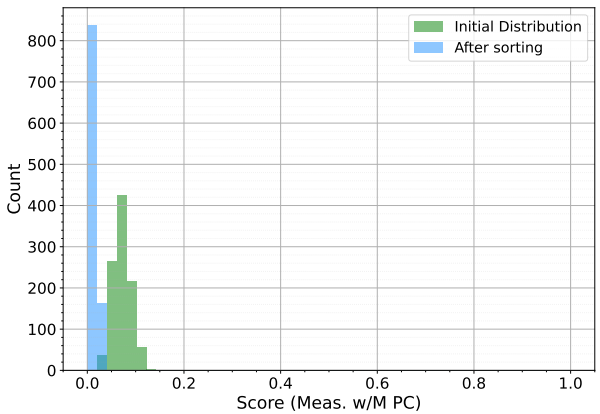
Strength and Score (S2)

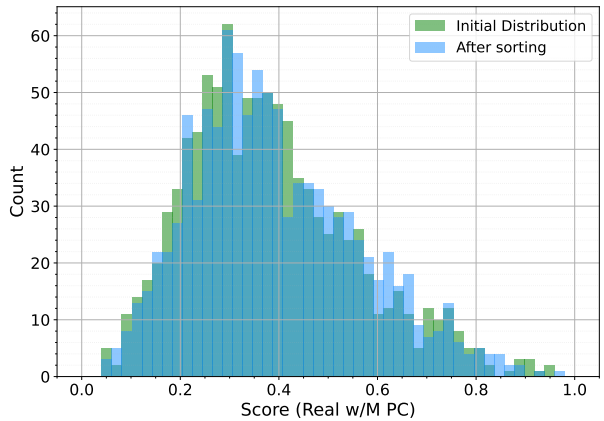




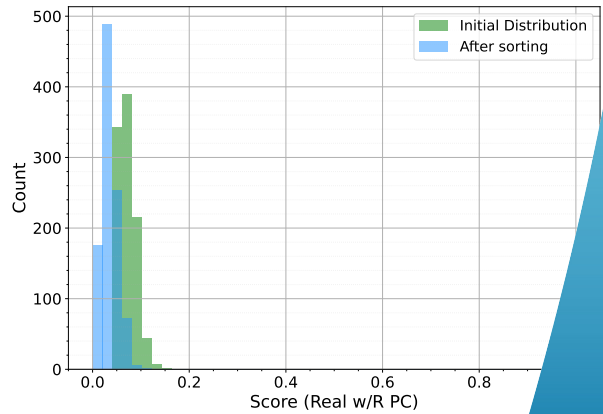
Prediction



Realistic

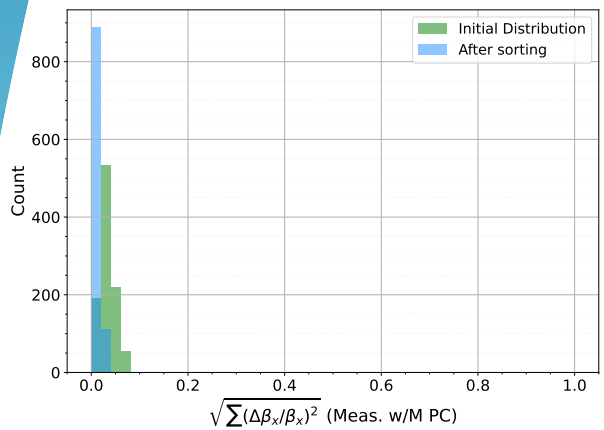


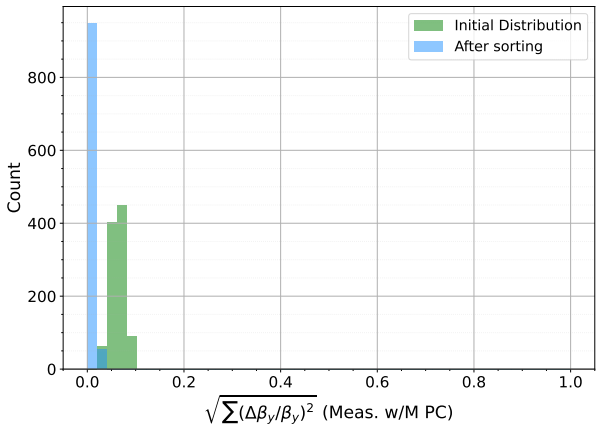
Optimistic



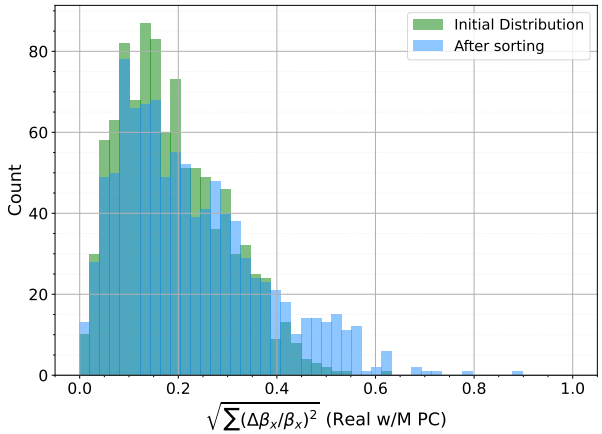
Beta-Beating (S2)

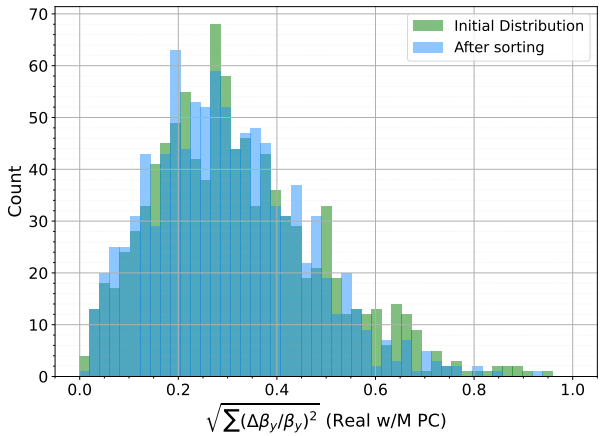
Prediction



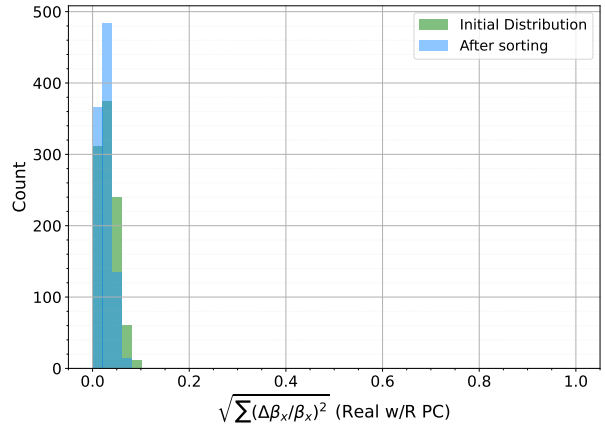


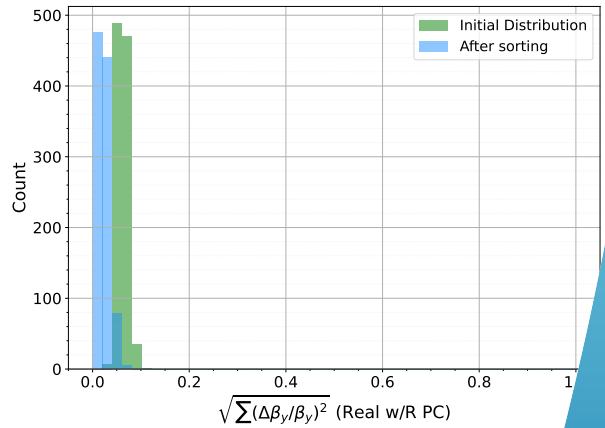
Realistic





Optimistic



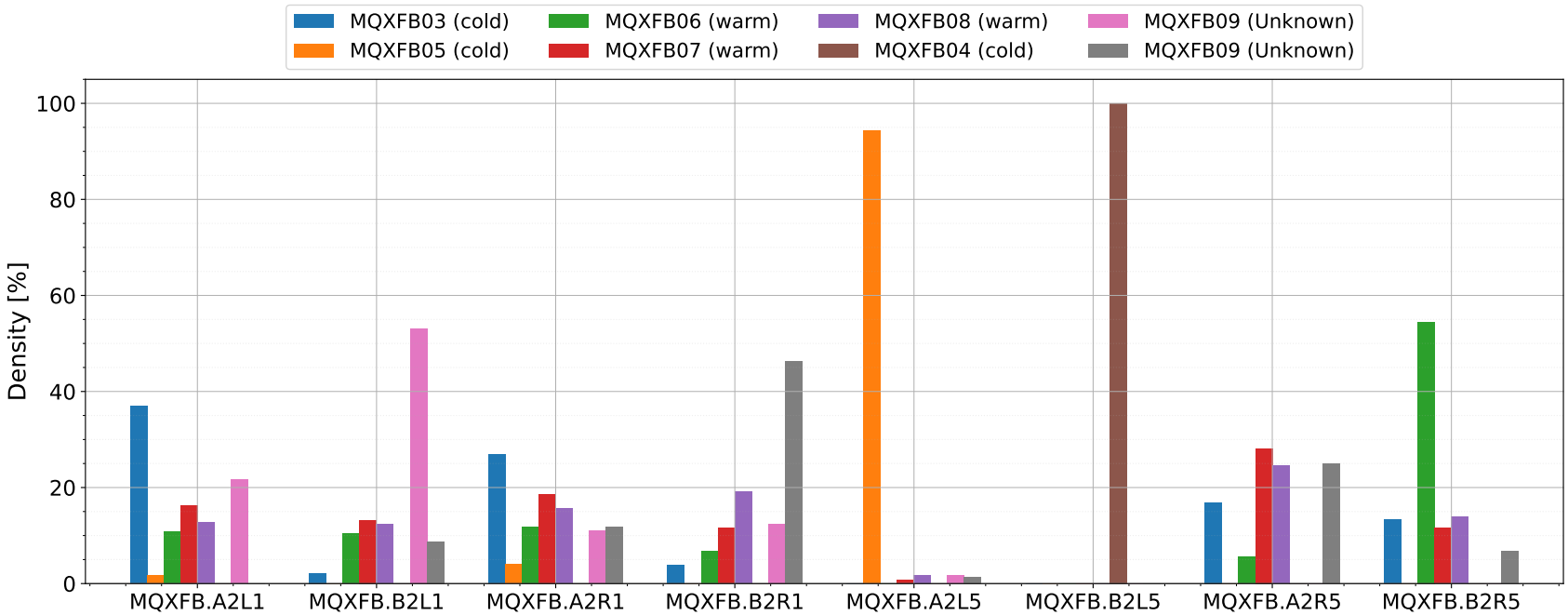


Stats (S2)

Parameter		Min	Avg	Median	Mode	Max	Std
Predicted							
score	ID	0.0342554	0.0710595	0.0701845	0.075	0.1252596	0.0184147
	AS	0.0099701	0.0151785	0.0127900	0.015	0.0364655	0.0059931
rmsBETX	ID	0.0063627	0.0332393	0.0310615	0.025	0.0772557	0.0145787
	AS	0.0002118	0.0102398	0.0085348	0.005	0.0328528	0.0071152
rmsBETY	ID	0.0246985	0.0623282	0.0623718	0.065	0.0985978	0.0136513
	AS	0.0003039	0.0090668	0.0086758	0.005	0.0309326	0.0053494
Realistic							
score	ID	0.0446363	0.3834320	0.3592895	0.285	1.0877348	0.1723165
	AS	0.0442043	0.3944221	0.3670832	0.315	1.0472385	0.1722848
rmsBETX	ID	0.0090215	0.1881524	0.1701510	0.095	0.6136934	0.1060783
	AS	0.0059865	0.2254952	0.1961146	0.095	0.8894450	0.1444173
rmsBETY	ID	0.0089291	0.3188296	0.2942604	0.285	0.9450656	0.1685431
	AS	0.0062022	0.3009043	0.2847756	0.195	0.9373903	0.1516676
Optimistic							
score	ID	0.0431379	0.0712815	0.0678259	0.055	0.1444196	0.0175577
	AS	0.0096305	0.0357021	0.0323937	0.025	0.1053177	0.0160808
rmsBETX	ID	0.0068027	0.0329061	0.0294858	0.015	0.1021769	0.0181508
	AS	0.0021208	0.0265223	0.0242916	0.025	0.0819432	0.0131664
rmsBETY	ID	0.0363211	0.0622127	0.0614038	0.055	0.1020633	0.0103268
	AS	0.0004960	0.0224878	0.0212093	0.015	0.0797280	0.0122778

ID: Initial Distribution;
AS: After sorting;

Position after Sorting (S2)



The uncertainty for the measurements at warm temperature have been used for this sorting. The strength of the two unknown magnets was set as 0.

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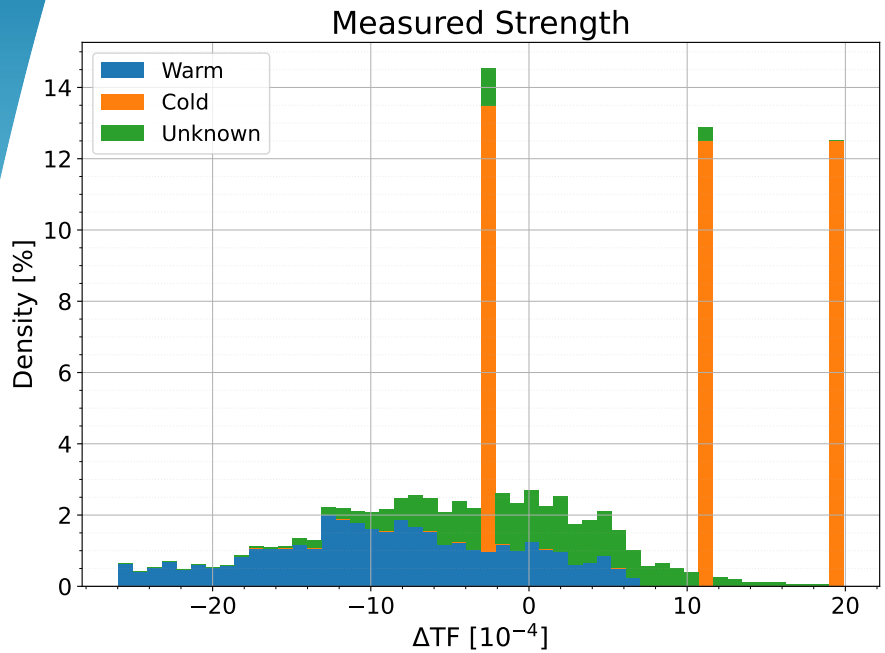
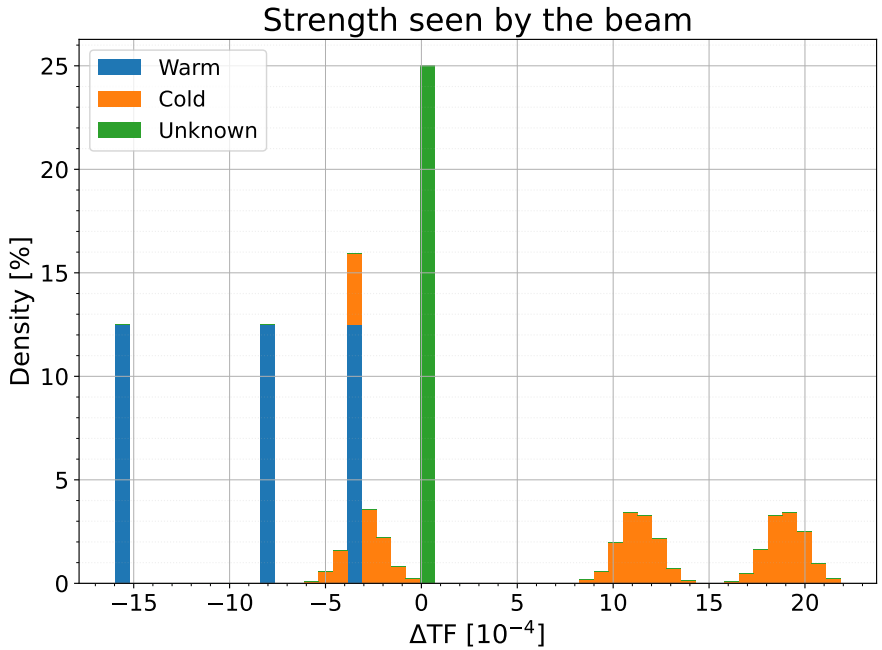
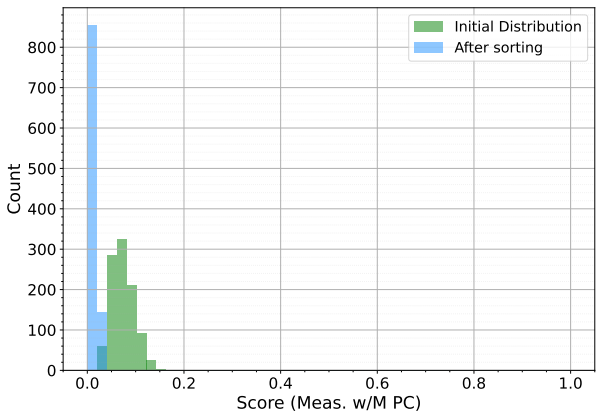
Strength and Score (S3)

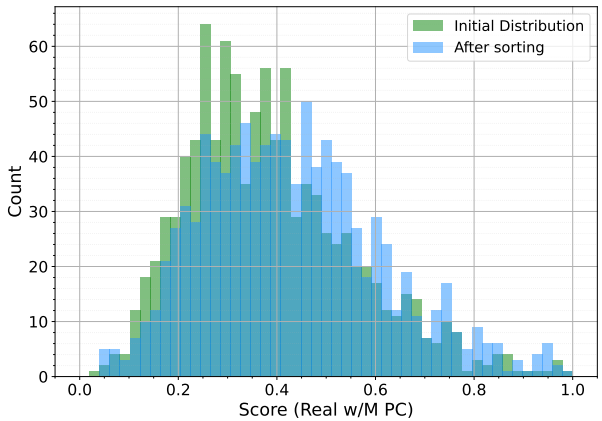




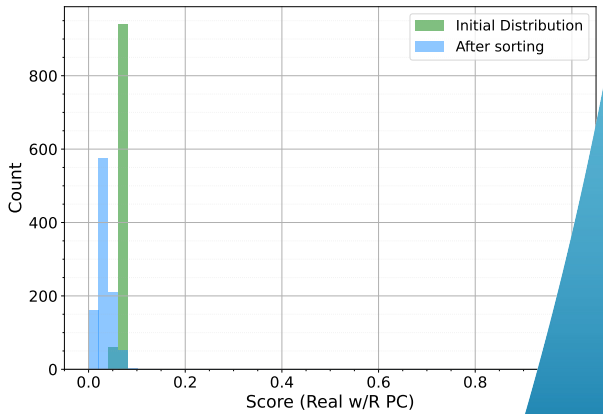
Prediction



Realistic

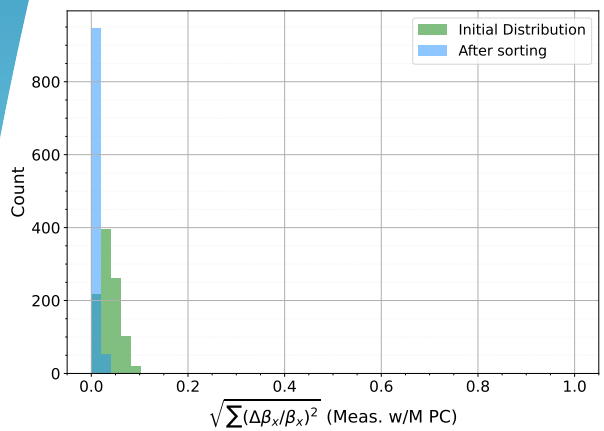


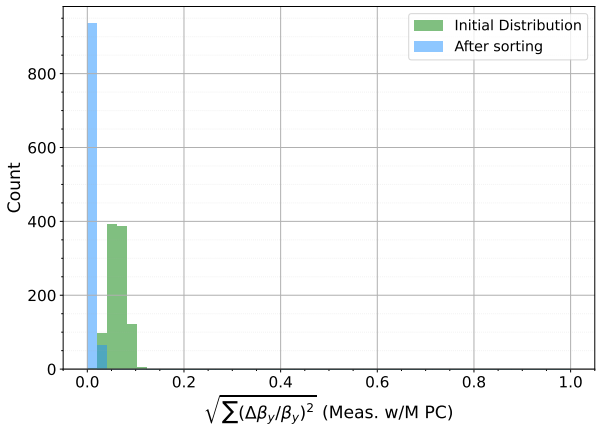
Optimistic



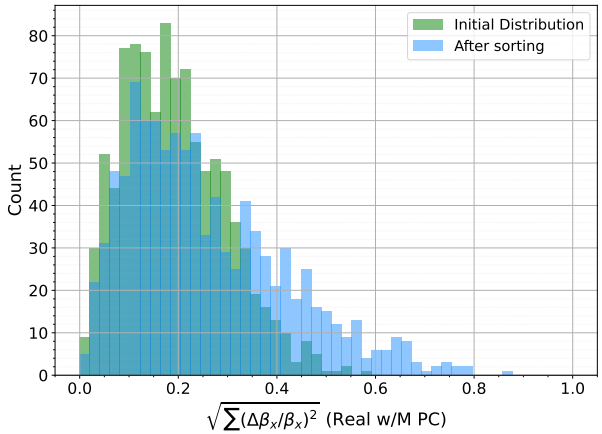
Beta-Beating (S3)

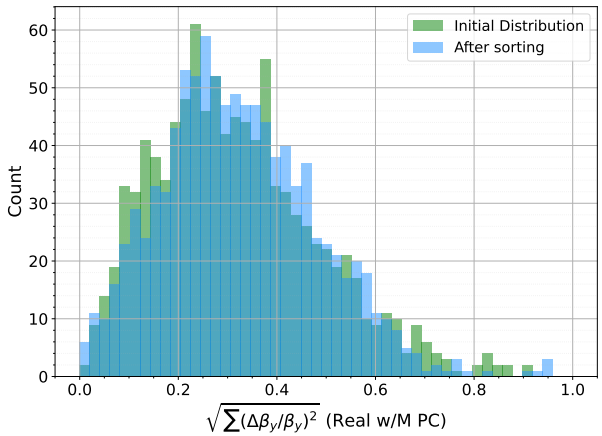
Prediction



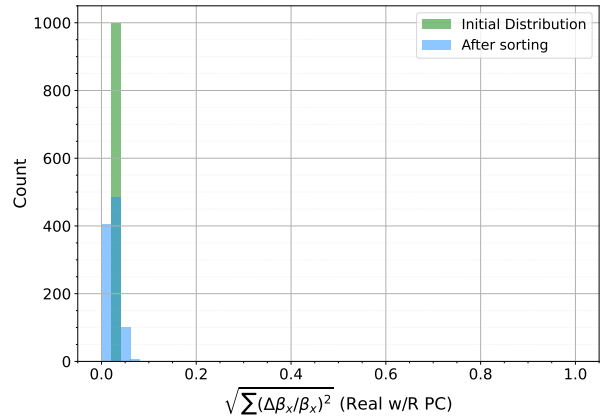


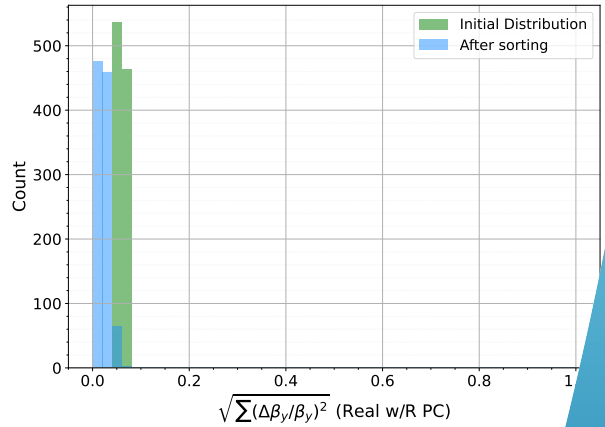
Realistic





Optimistic



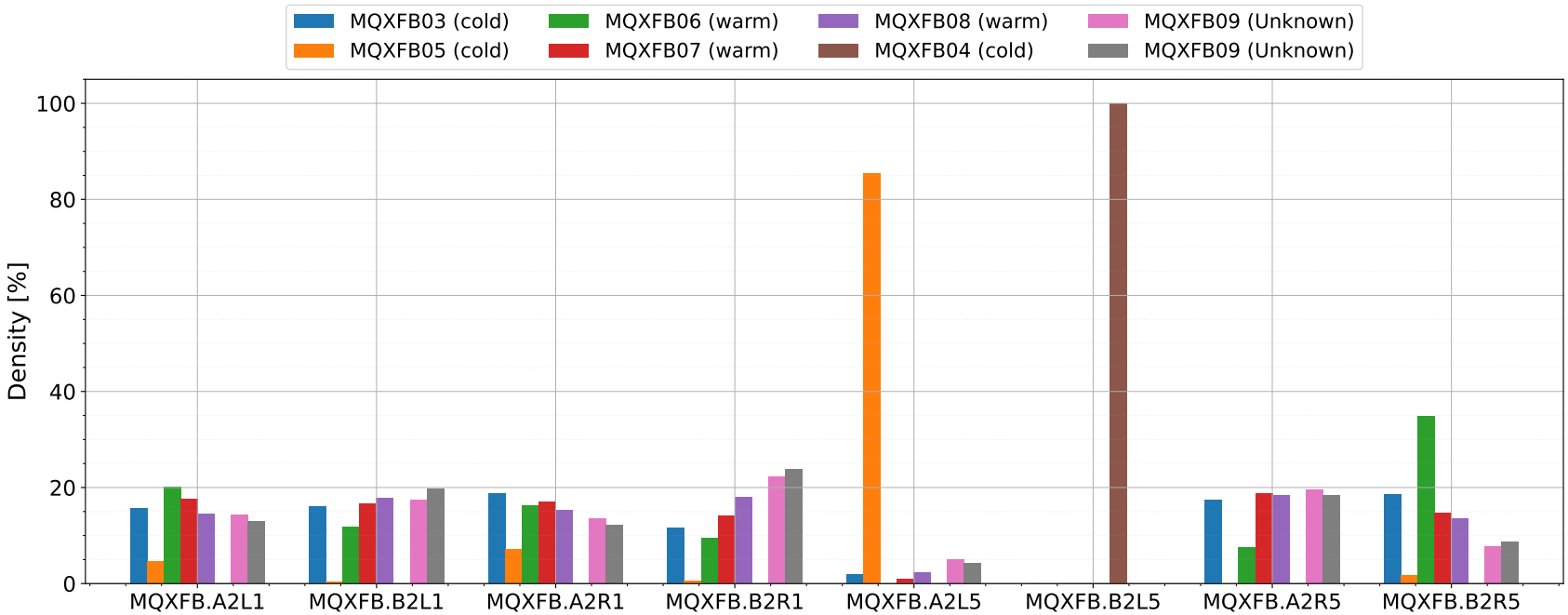


Stats (S3)

Parameter		Min	Avg	Median	Mode	Max	Std
Predicted							
score	ID	0.0336119	0.0729847	0.0703988	0.065	0.1466382	0.0228393
	AS	0.0084254	0.0148416	0.0129017	0.015	0.0358310	0.0052023
rmsBETX	ID	0.0018045	0.0370415	0.0347549	0.025	0.1059947	0.0195380
	AS	0.0004018	0.0095640	0.0086134	0.005	0.0349139	0.0057876
rmsBETY	ID	0.0158698	0.0618563	0.0618913	0.055	0.1059195	0.0163825
	AS	0.0002964	0.0097560	0.0089064	0.005	0.0317829	0.0052146
Realistic							
score	ID	0.0335637	0.3859491	0.3614834	0.265	1.0479970	0.1699616
	AS	0.0470085	0.4338052	0.4174718	0.455	1.1439279	0.1856545
rmsBETX	ID	0.0028048	0.1927872	0.1815210	0.095	0.5884796	0.1030829
	AS	0.0050395	0.2580092	0.2231202	0.225	0.8646619	0.1603754
rmsBETY	ID	0.0061866	0.3197370	0.3014577	0.325	0.9047772	0.1667901
	AS	0.0116521	0.3247934	0.3092194	0.255	0.9524587	0.1577174
Optimistic							
score	ID	0.0547134	0.0671220	0.0671794	0.065	0.0803521	0.0038532
	AS	0.0104040	0.0340062	0.0316740	0.035	0.0942427	0.0145397
rmsBETX	ID	0.0218256	0.0282293	0.0282163	0.025	0.0352537	0.0020183
	AS	0.0003557	0.0243231	0.0234783	0.025	0.0687233	0.0124684
rmsBETY	ID	0.0501717	0.0608953	0.0609825	0.065	0.0722056	0.0033172
	AS	0.0004006	0.0221602	0.0211642	0.015	0.0644887	0.0113873

ID: Initial Distribution;
AS: After sorting;

Position after Sorting (S3)



For this sorting, uncertainties for the measurements at warm temperatures and for unknown magnets have been used.

Contents

Conclusions

- The uncertainties for cold measurements are well adapted for a good quality of the sorting.
- The uncertainties for the warm measurements and the observed systematic shift with respect to the cold measurements, introduce a strong bias in the prediction of the sorting performance.
- Similarly, the fact that two magnets remain unknown introduces strong uncertainties in the estimate of the TF error. This also hinders the performance of the sorting.
- Given the previous considerations, the available data allows for proposing one pairing of MQXFB05 and MQXFB04 in A2L5 and B2L5, respectively.
- As soon as TF measured at cold are made available, they will be considered for sorting. However, the schedule of hardware preparation might impose constraints that prevent sorting.

Thank you.

Extra: Pair Calibration demonstration

$$
\begin{aligned}
K_{1,i} &= K_{1,Ri}\left(1+10^{-4}b_{1,i}\right) \\
&= K_{1,Ri}\left(1+10^{-4}\left[\langle b_1\rangle_P+\Delta b_{1,i}\right]\right) \\
&= K_{1,Ri}\left(1+10^{-4}\langle b_1\rangle_P\right)\left(1+10^{-4}\frac{\Delta b_{1,i}}{1+10^{-4}\langle b_1\rangle_P}\right) \\
&= K'_{1,Ri}\left(1+10^{-4}\frac{\Delta b_{1,i}}{1+10^{-4}\langle b_1\rangle_P}\right)
\end{aligned}
$$

with:

$$
\langle b_1\rangle_P=\frac{b_{1,i}+b_{1,j}}{2} \quad \text{and} \quad \Delta b_{1,i}=\frac{b_{1,i}-b_{1,j}}{2}
$$

for $i,j\in\{A,B\}$ of a same pair.