Evaluation of Individual Feedthroughs and Fully Assembled BPMs

Advancements in BPM measurements and simulations

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Outline

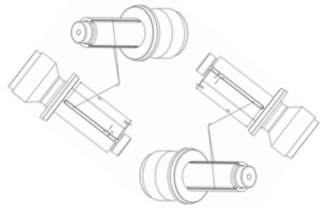
1 Steps to improve BPM measurement accuracy (summary from DEELS 2023 presentation)

2 Measurements of single feedthrough using VNA (Vector Network Analyzer)

- TDR (Time Domain Reflectometry) measurement
- calculated capacitance from TDR trace vs. capacitance measurement vs. simulation
- measurement results: fixed connector and cables
- measurement results: assembling-disassembling holder with feedthrough and connector
- comparing results of measurement of two sets of feedthrough prototypes

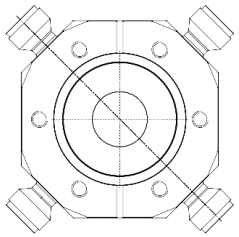
2 Formation of groups of 4 identical feedthroughs out of 30

- using least squares method to find similar TDR traces
- results of group formation



3 Measurements of fully assembled BPMs using VNA and applying Lambertson method

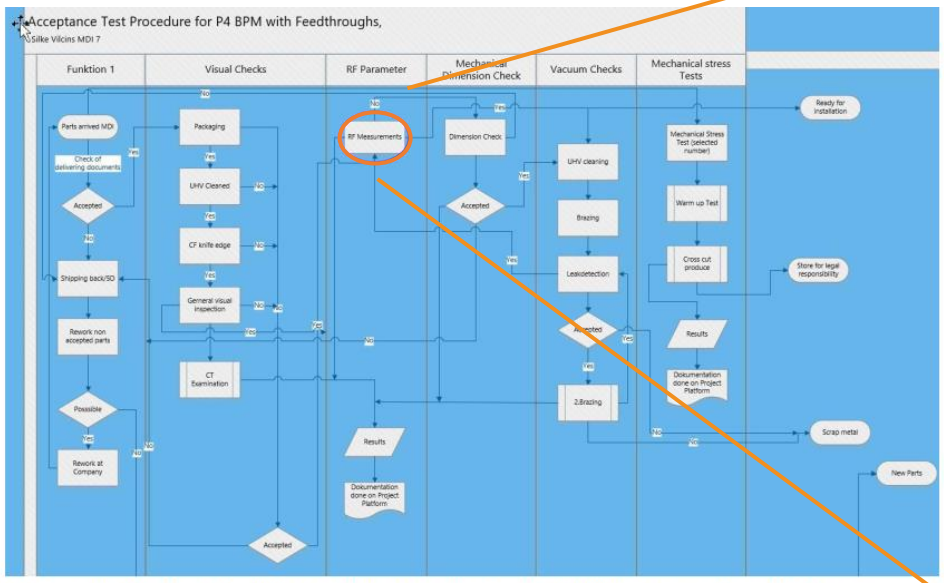
- mechanical measurement of buttons' displacements
- comparison of mechanical measurements with VNA and CST simulations



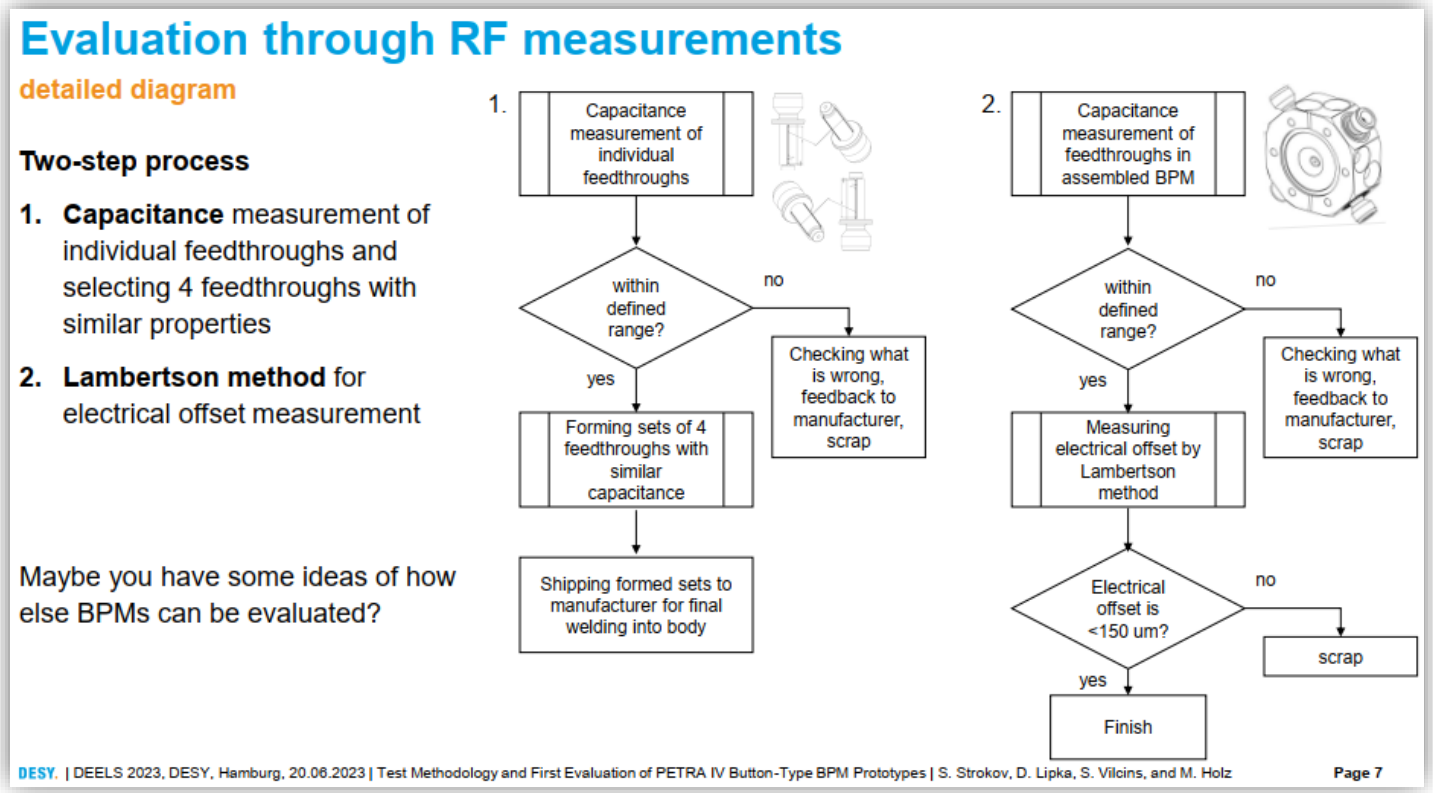
1 Steps to improve measurement accuracy

Summary from DEELS 2023 presentation

- Grouping feedthroughs in sets of 4 and measuring assembled BPM

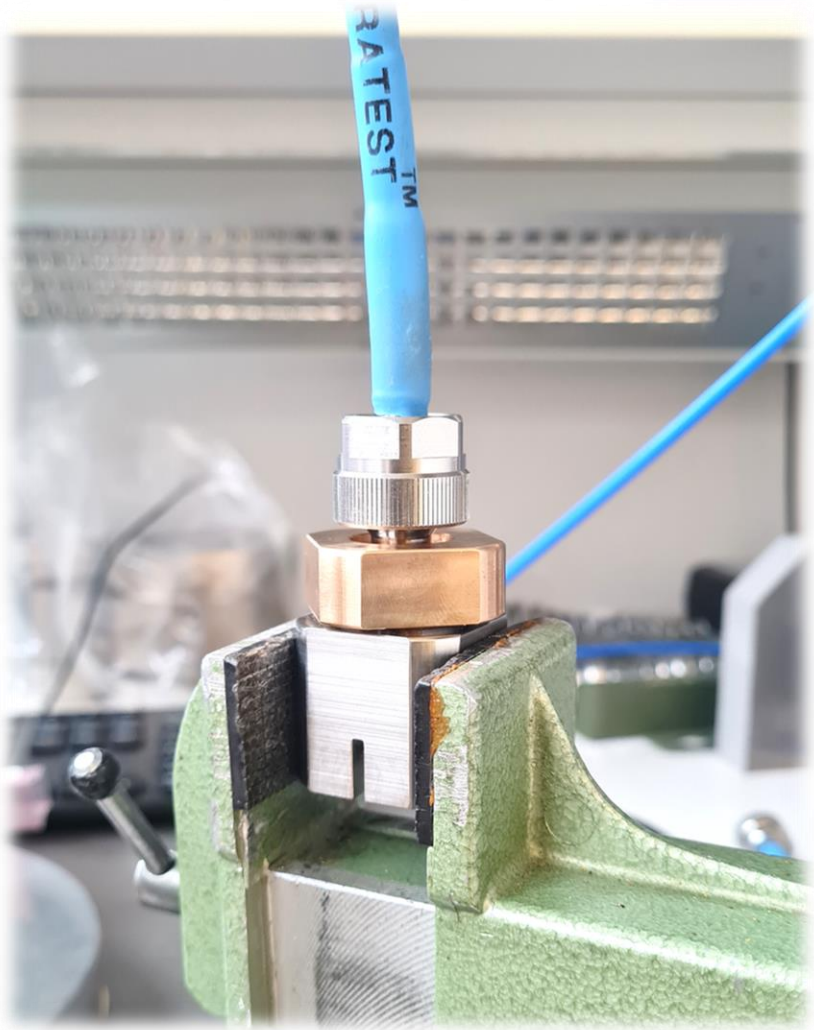


BPM assessment consists of many steps



2 Measurements of single feedthrough using VNA

Measurement setup for TDR (Time Domain Reflectometry)

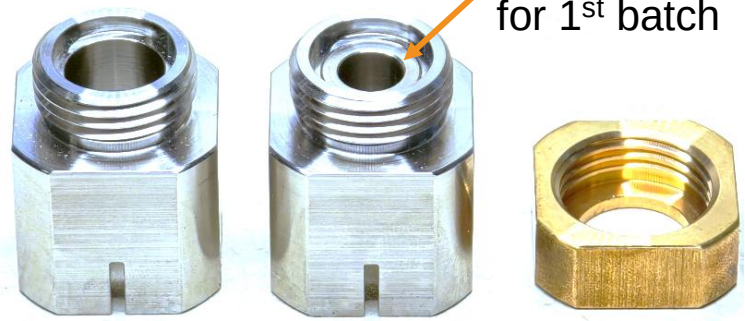


VNA – R&S®ZNB8,
4 ports (used 1), 8.5 GHz

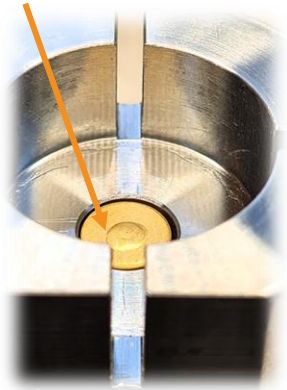
first and second batches
of feedthrough prototypes
(30 feedthroughs in each batch)

holders

cylindrical adaptor
for 1st batch



button of installed
feedthrough



Measurements of single feedthrough using VNA

Steps to understand influence of measurement conditions and tolerances on beam position readings

To understand influence of VNA and measurement condition

- fixed cable and holder with installed feedthrough
- TDR traces were measured and averaged for 1, 10, and 50 consecutive traces
- 10 measurements at each averaging set

To understand influence of manufacturing tolerances

- assembling-disassembling connector and holder with feedthrough before each measurement to reproduce real-life situations
- TDR traces were measured and averaged for 1, 10, and 50 consecutive traces
- for each measurement, the assembly-disassembly process was performed, with 10 measurements taken and averaging applied

Electrical offset calculation from TDR trace

Rise time → capacitance calculation

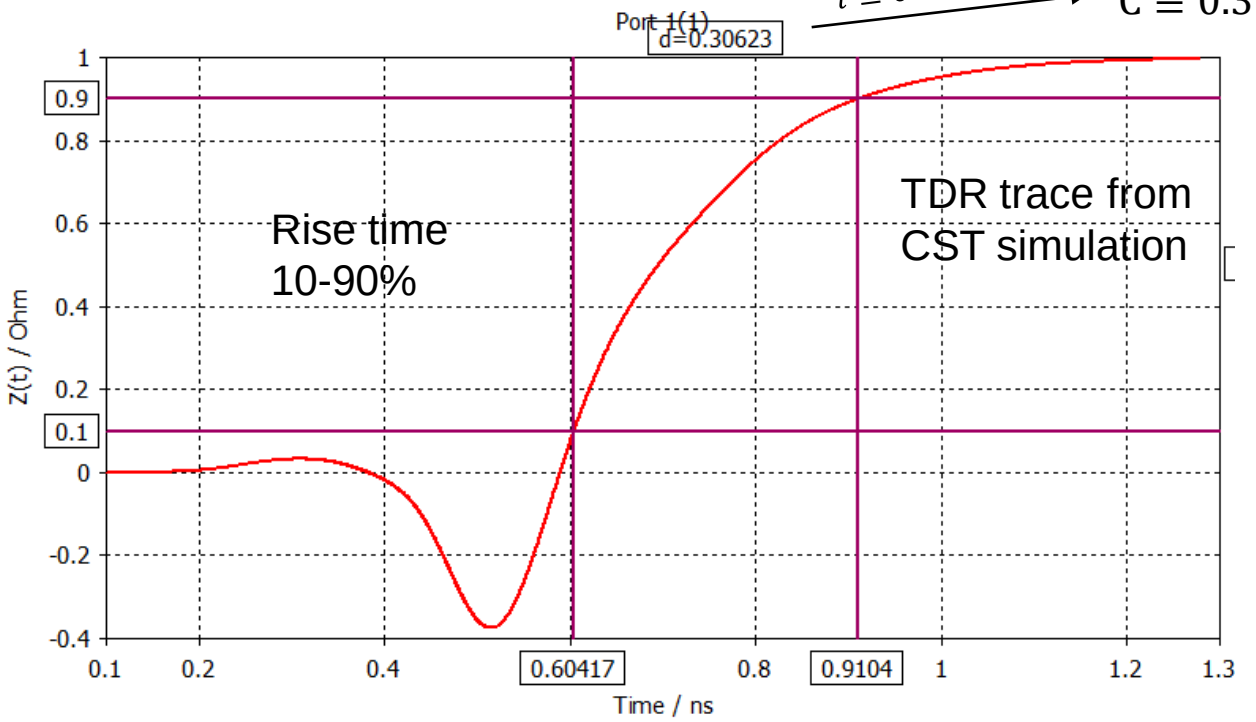
- Electrical offset can be calculated through U_n using Δ/Σ method
- Voltage is inversely proportional to button's capacitance C
- Button's capacitance C can be found from TDR trace
- Monitor constant $K_{x,y}$= 7.2 mm

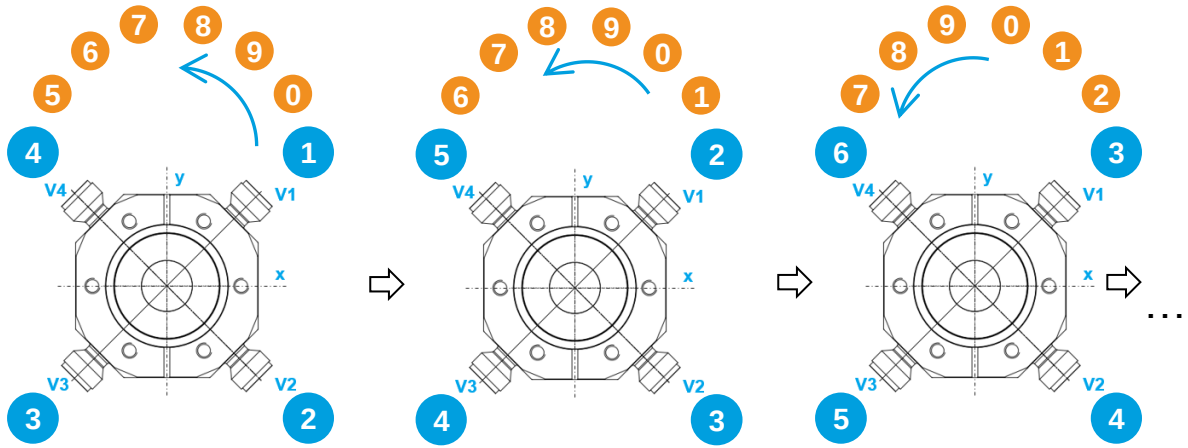
$$Horizontal = K_x \frac{(V1+V2)-(V3+V4)}{V1+V4+V2+V3}$$

$$Vertical = K_y \frac{(V1+V4)-(V2+V3)}{V1+V4+V2+V3}$$

$$V \sim 1/C \qquad C = \tau/50\ \text{Ohm}$$

$\tau \cong 0.3$ nsec → $C \cong 0.3$ nsec/50 Ohm $\cong$ **6 pF**



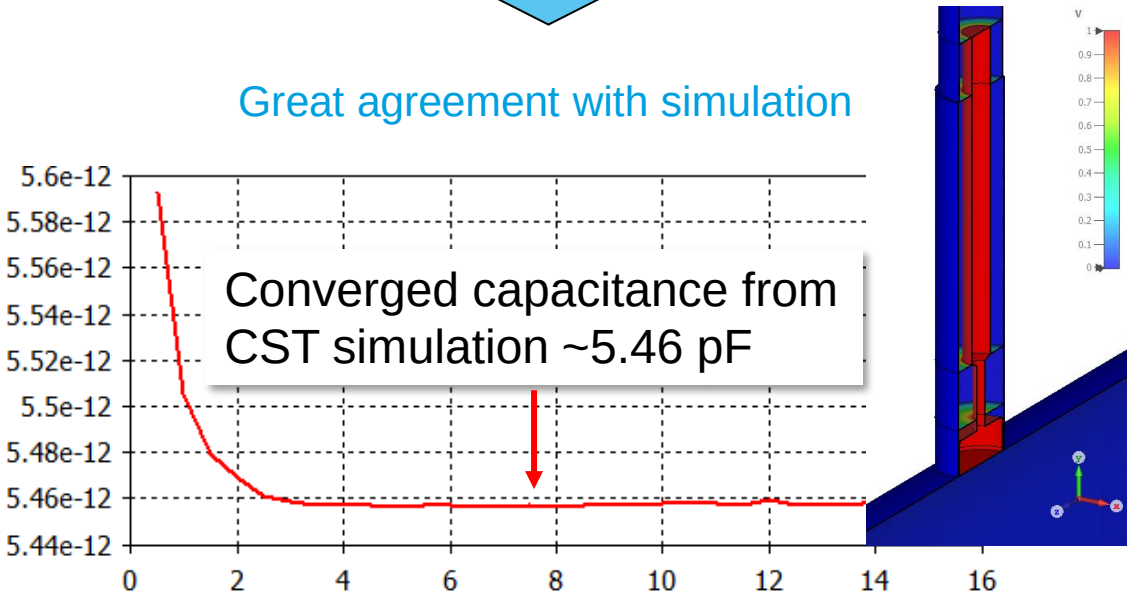


Capacitance measurement

comparison of real measurement with simulation

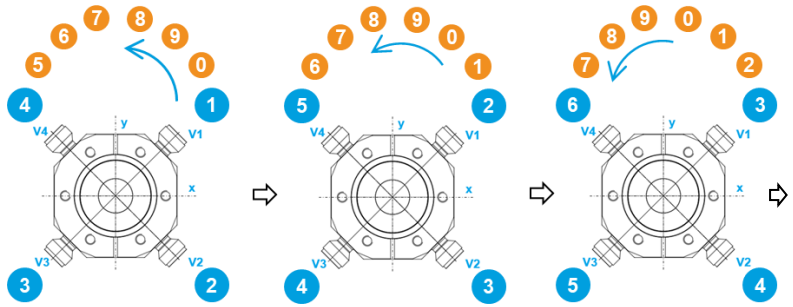
- Feedthrough #203-085
- Capacitance measured by Capacitance Meter is 5.6 pF
- Taking into account capacitance of wires measured separately – 0.1 pF – capacitance of feedthrough is ~**5.5 pF**

Great agreement with simulation



Measurement results

Single feedthrough from 2nd batch

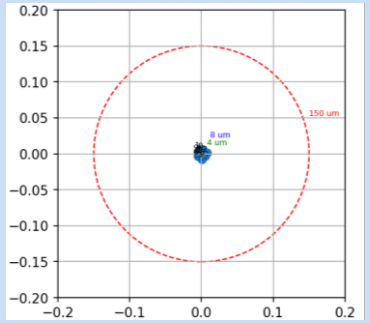
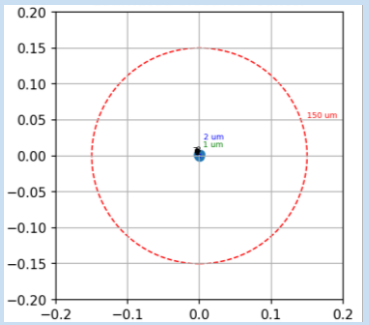
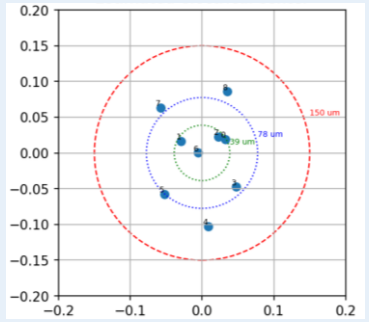
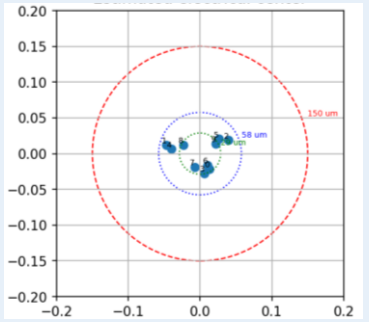


$$Horizontal = K_x \frac{(V1+V2)-(V3+V4)}{V1+V4+V2+V3}$$

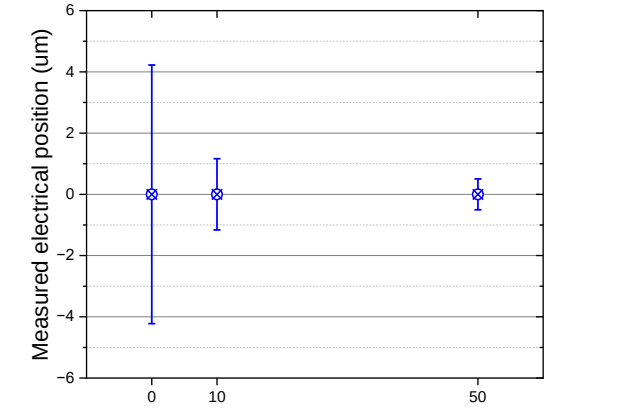
$$Vertical = K_y \frac{(V1+V4)-(V2+V3)}{V1+V4+V2+V3}$$

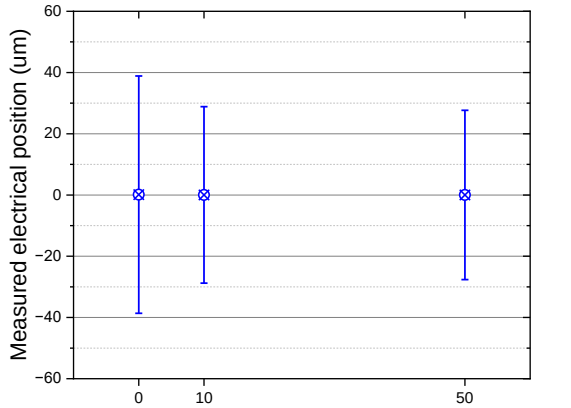
… in total 10 center offsets calculated from 10 measurements of single feedthrough

Each set consists of 10 measurements

# av. traces	1	10	50
Fixed setup **(influence of VNA)**	x = ± 4.223 y = ± 4.313 	x = ± 1.165 y = ± 1.177 	x = ± 0.506 y = ± 0.730
Disassemblin g-assembling **(influence of mechanical tolerances)**	x = ± 38.757 y = ± 59.840 	x = ± 28.823 y = ± 18.644 	x = ± 27.651 y = ± 33.657

- - 150 um – requirement - - 1 sigma (68%) - - 2 sigma (95%)





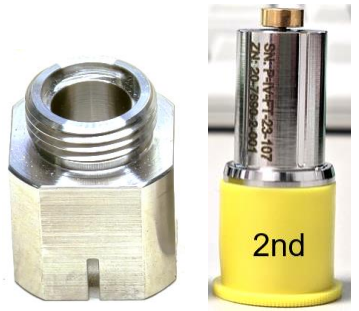
- Averaging over 50 traces is sufficient!
- Influence of VNA is negligible
- Mechanical tolerances restrict magnitude of minimum achievable center offset deviation to ± 30 um

Results of measurements of 30 feedthroughs

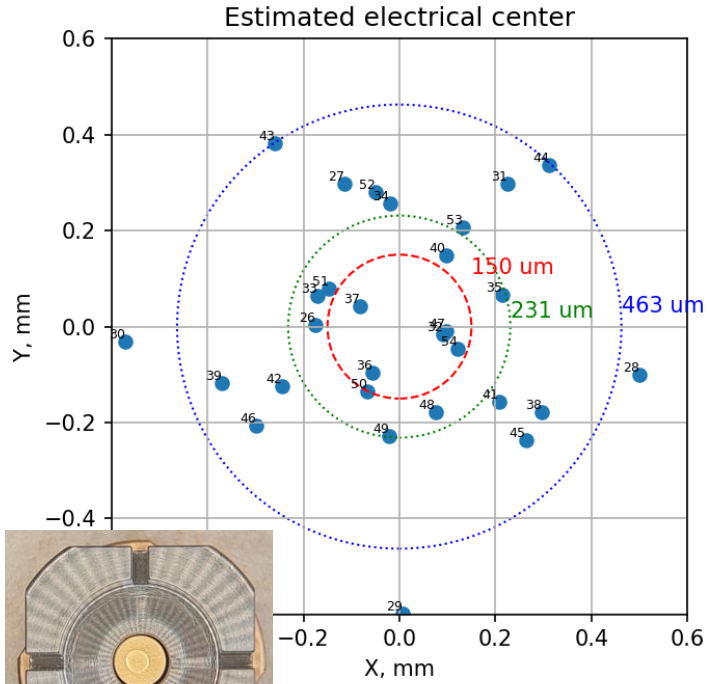
How mechanical tolerances affects deviation

1st batch of
30 feedthroughs
in holder **without**
adaptor

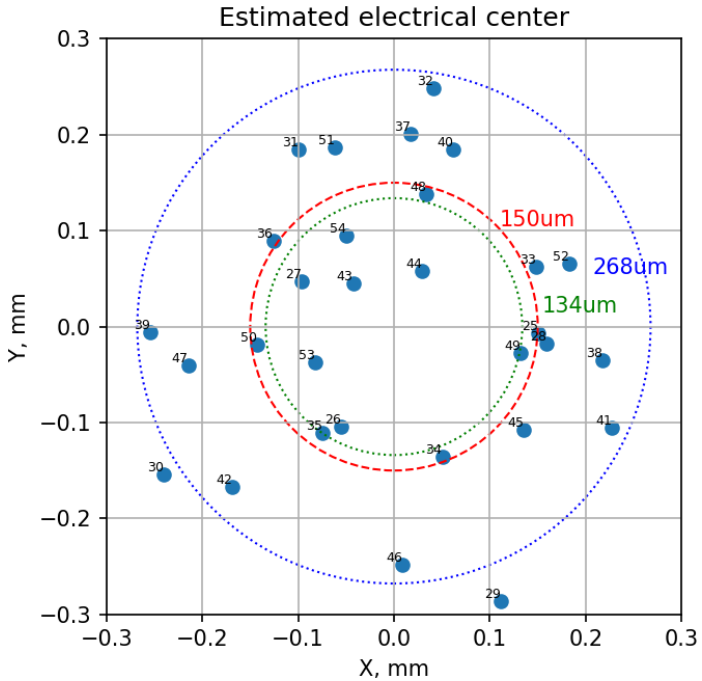
1st batch of
30 feedthroughs
in holder **with**
adaptor



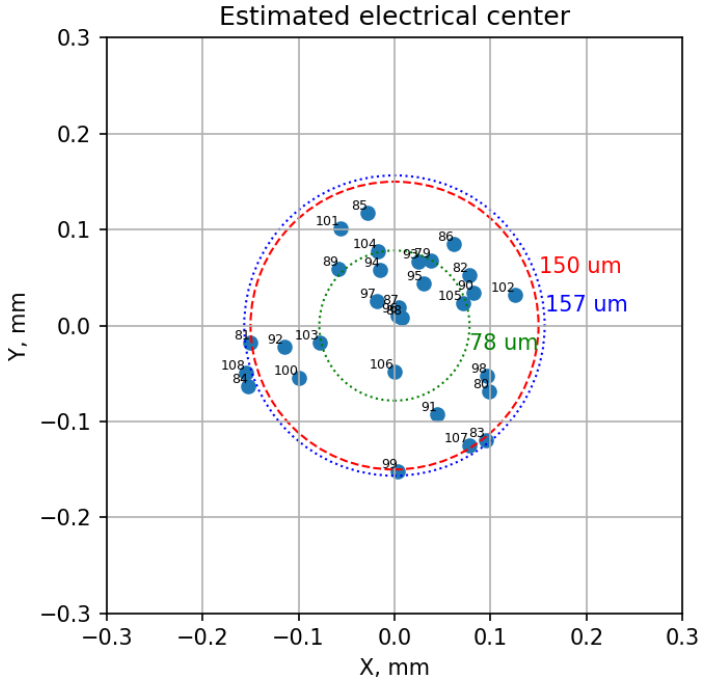
2nd batch of
30 feedthroughs



x = ± 231 um
y = ± 217 um



x = ± 134 um
y = ± 132 um



x = ± 80 um
y = ± 70 um

Summary on measurements of single feedthrough

- Influence of VNA is negligible
- Averaging over 50 traces is sufficient
- Mechanical tolerances restrict minimum achievable center offset deviation to ± 30 um

Formation of groups with 4 similar feedthroughs

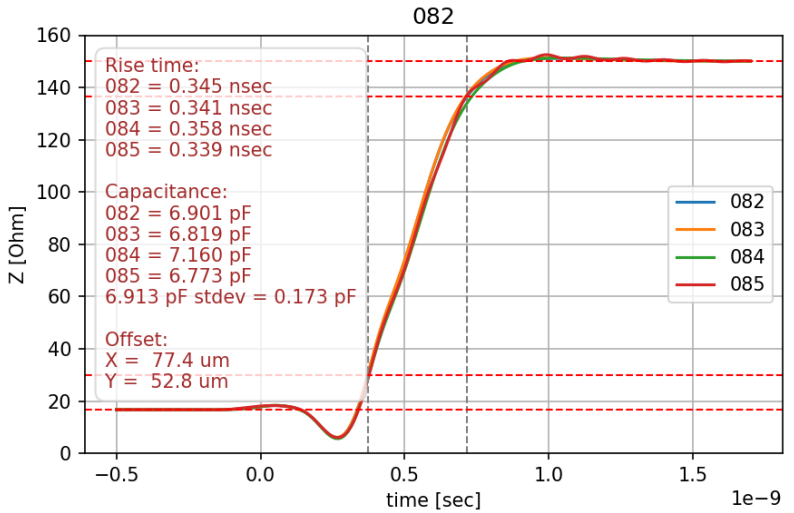
2nd batch of 30 feedthroughs (№№ 23-079 to 23-108)

- least squares method was used to find similar traces
- from 30 feedthroughs, 7 groups of 4 feedthroughs with similar TDR traces can be formed

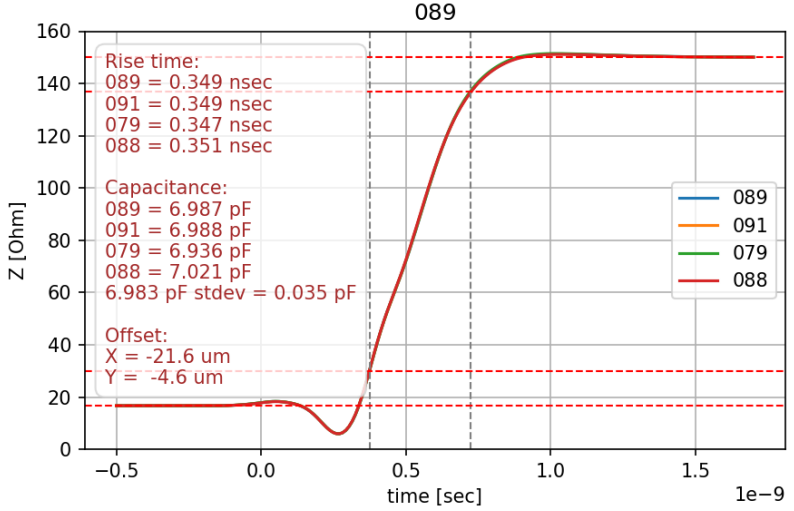
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.
1.	0																													
2.	133	0																												
3.	80	171	0																											
4.	54	21	99	0																										
5.	93	7	164	13	0																									
6.	215	663	258	455	582	0																								
7.	126	468	248	316	386	103	0																							
8.	62	115	230	70	73	425	233	0																						
9.	72	54	56	20	56	412	320	119	0																					
10.	11	125	34	49	97	215	156	101	44	0																				
11.	4	163	60	72	122	172	113	95	77	7	0																			
12.	44	170	16	82	151	198	181	161	44	15	29	0																		
13.	4	150	56	63	112	184	123	89	66	4	1	25	0																	
14.	312	746	240	534	686	45	215	583	437	270	251	207	258	0																
15.	10	91	86	26	61	281	179	45	39	17	20	44	15	371	0															
16.	14	125	39	46	99	218	166	99	36	3	11	12	6	270	13	0														
17.	37	152	11	71	133	211	185	157	42	9	24	3	20	227	41	10	0													
18.	75	202	10	112	189	207	214	222	59	34	53	6	48	190	77	32	10	0												
19.	152	440	77	289	402	78	169	375	217	110	109	67	112	46	191	113	76	53	0											
20.	96	313	40	187	285	117	165	269	123	59	65	22	64	99	113	56	32	16	15	0										
21.	229	480	94	334	457	158	278	471	230	163	178	92	176	74	250	158	108	63	24	33	0									
22.	222	652	224	449	582	6	127	451	389	208	174	176	185	20	284	210	190	176	49	90	111	0								
23.	7	85	69	24	56	278	178	58	39	9	14	40	10	363	4	10	32	70	178	108	240	279	0							
24.	62	37	95	7	32	437	318	76	10	50	78	69	66	499	26	41	65	98	270	166	301	426	30	0						
25.	77	87	24	42	90	364	307	164	8	38	72	26	62	364	54	34	24	31	161	85	169	333	49	32	0					
26.	167	481	104	317	439	59	162	386	241	128	122	81	125	30	204	127	93	71	4	21	30	33	196	291	186	0				
27.	46	306	174	188	235	136	44	117	208	78	45	116	52	260	86	89	114	153	162	134	271	159	85	198	207	165	0			
28.	389	807	254	599	760	108	308	700	476	327	318	241	324	16	447	326	263	205	59	119	57	66	434	561	389	50	354	0		
29.	37	254	68	131	211	105	105	154	105	29	21	24	21	150	51	24	30	39	58	26	106	100	52	116	91	58	64	208	0	
30.	232	511	105	355	483	130	255	473	251	169	181	99	179	51	260	165	114	74	17	33	6	87	249	320	188	18	256	42	103	0

- Table of distances which is used to form groups
- Traces with long distances are used last

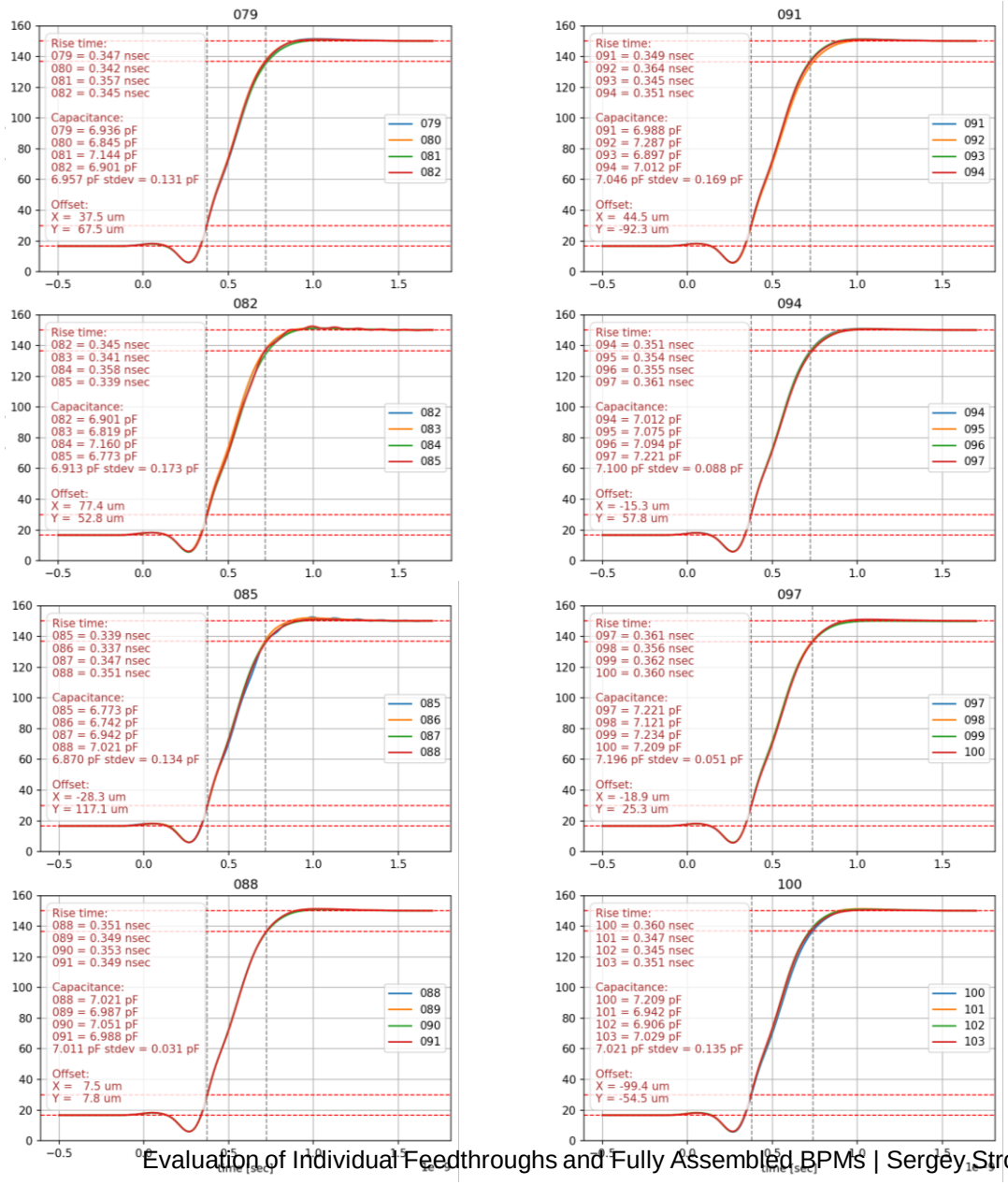
Example of four TDR traces before grouping

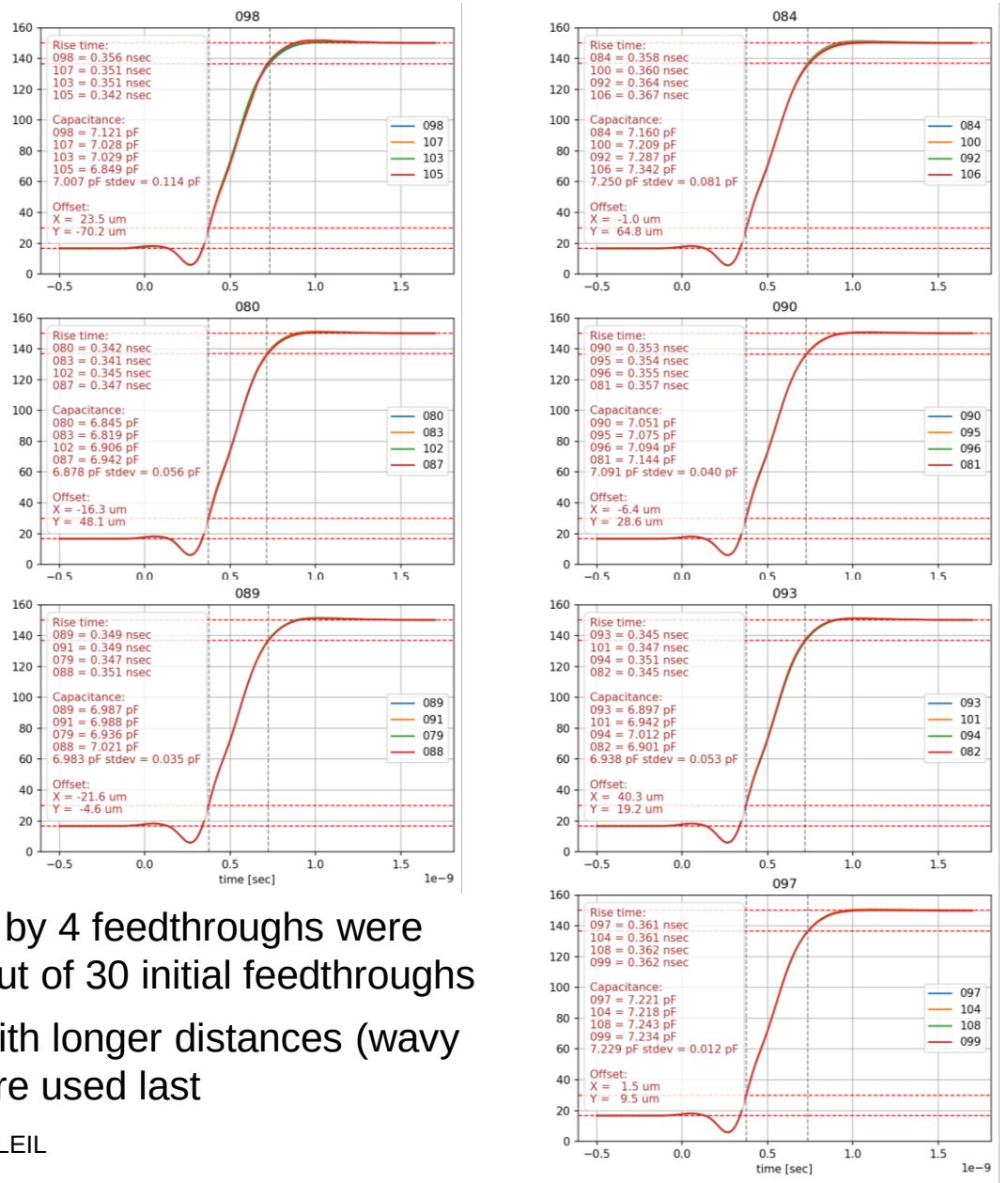


After grouping



More examples before and after grouping

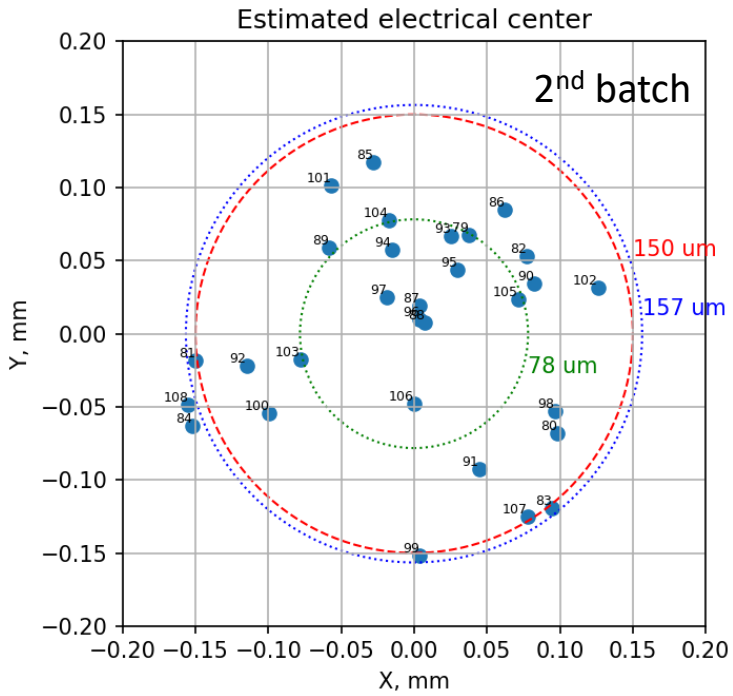


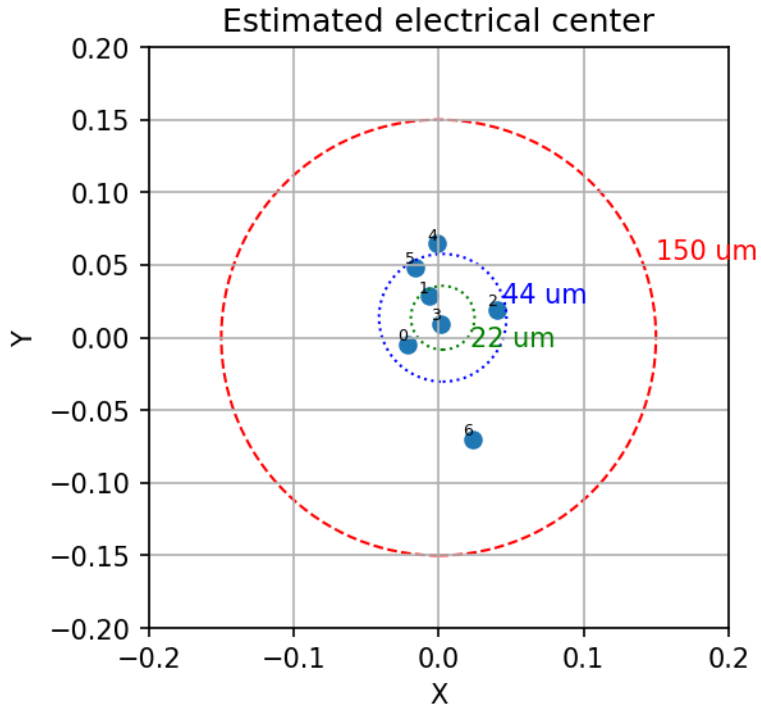


- 7 groups by 4 feedthroughs were formed out of 30 initial feedthroughs
- Traces with longer distances (wavy traces) are used last

Main result

selecting feedthroughs with identical TDR traces





x = ± 80 um
y = ± 70 um

x = ± 22 um
y = ± 44 um

- through group formations, deviation in coordinates X and Y is reduced by factors of approximately 3.5 and 1.5, respectively
- more feedthroughs → higher probability to find identical feedthroughs → smaller spread

Summary on grouping feedthroughs

- Grouping of identical feedthroughs allows to reduce center offset deviation from initial ± 80 um to ± 30 um – limit caused by mechanical tolerances
- more feedthroughs → higher probability to find identical feedthroughs → smaller center offset
- procedure and algorithm of forming groups can still be improved

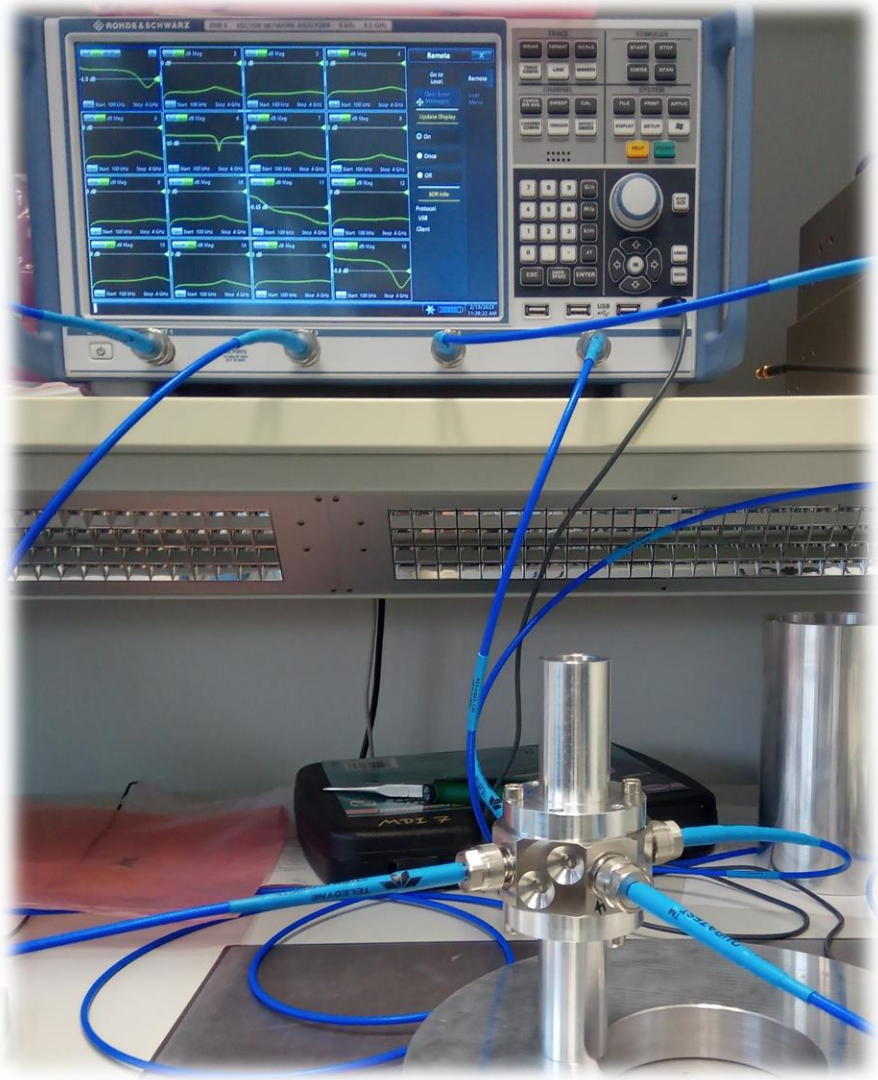
Measurements of fully assembled BPMs

S-parameters (signal transmission) measurements for Lambertson method to find electrical center

R&S®ZNB8,
4 ports used, 8.5 GHz

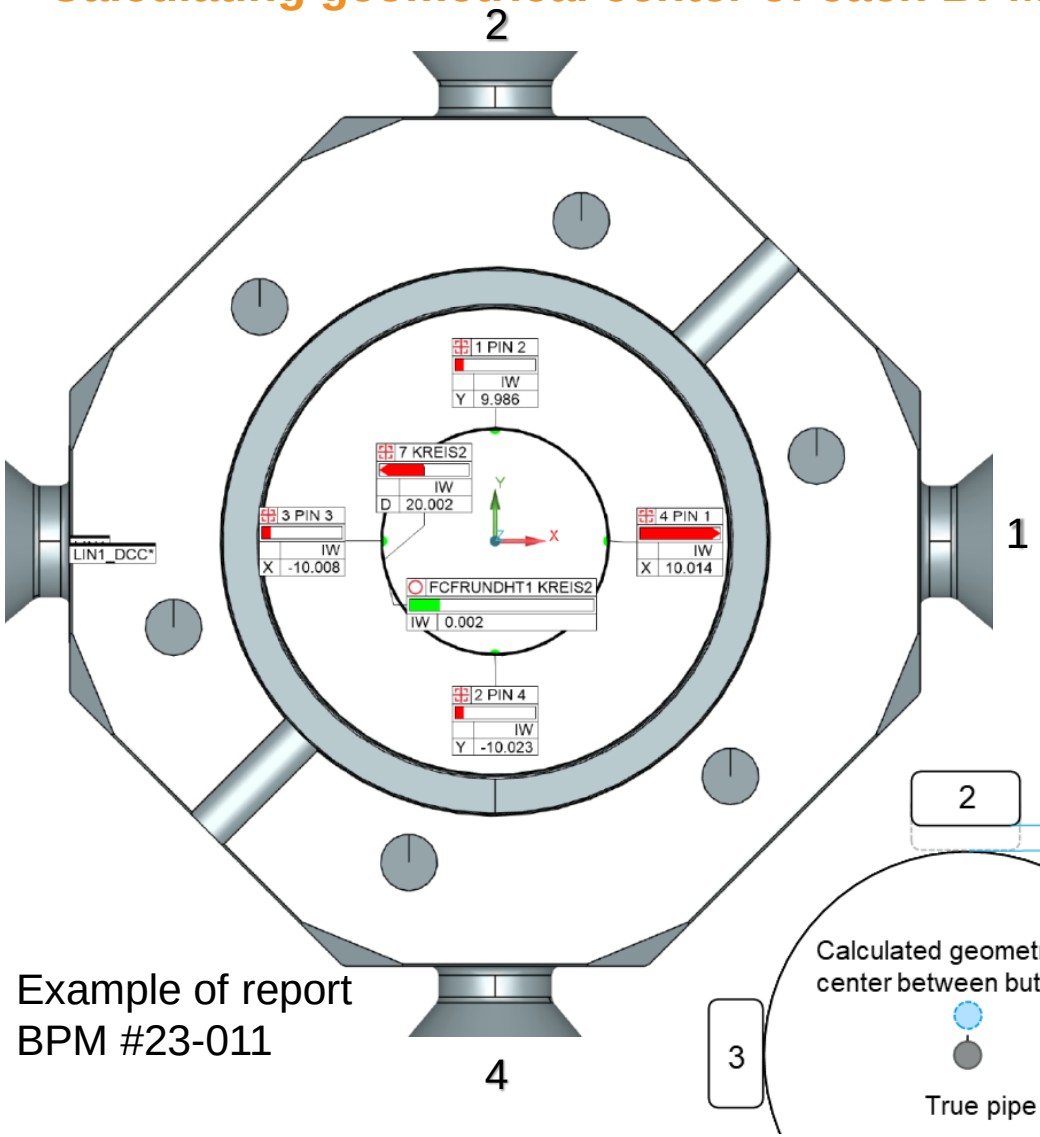
6 fully assembled BPMs

Welded-in feedthroughs were not preliminary checked and grouped in sets of 4



Result of mechanical measurements of buttons' displacements

Calculating geometrical center of each BPM



Example of report
BPM #23-011

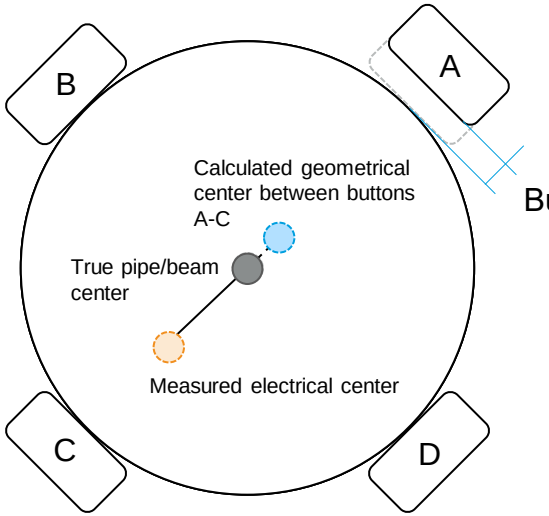
BPM #	23-007	23-008	23-009	23-010	23-011	23-012
Measured position of buttons (mm)						
1	10.021	10.001	10.008	9.984	10.014	10.023
2	10.014	9.996	9.985	10.026	9.986	10.018
3	-10.055	-9.979	-10.007	-9.995	-10.008	-10.012
4	-10.032	-10.013	-9.968	-10.043	-10.023	-10.012
Calculated geometrical center (mm) (0 deg rotated)						
Center X	-0.017	0.011	0.0005	-0.0055	0.003	0.0055
Center Y	-0.009	-0.0085	0.0085	-0.0085	-0.0185	0.003

Averaged position of 24 feedthrough buttons
10.00929 ± 0.020361 mm **$\pm$ 20 um (1 σ)**

Averaged calculated center offset (X and Y combined)
-0.002958 ± 0.009647 mm

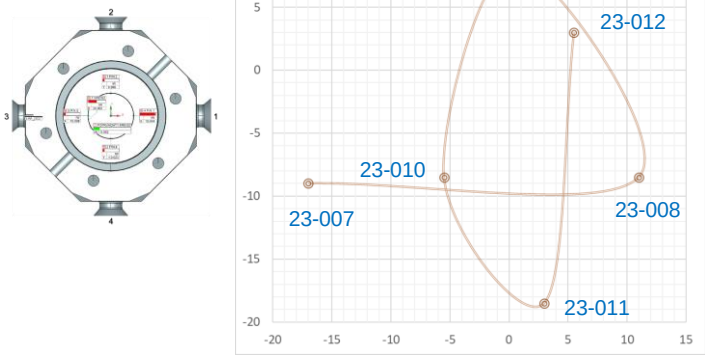
Relation between geometrical and electrical centers

1. Geometric center is opposite to electric

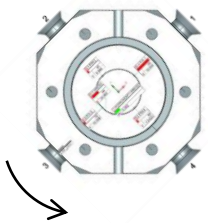


- Lambertson and Δ/Σ methods reflects electrical offset which is opposite to geometrical offset
- To compare electrical and geometrical offsets, geometrical offset should be rotated by 225 degrees and adjusted by a multiplication factor, which will be explained on following slide

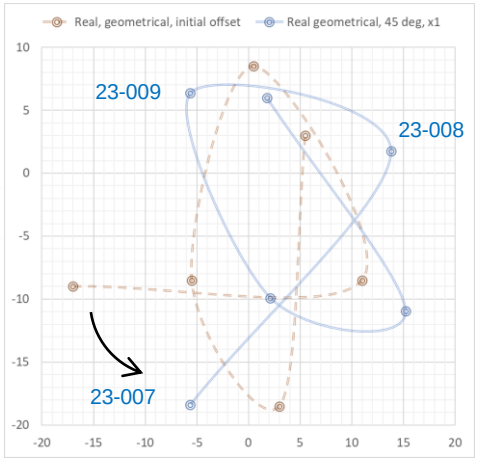
1. Mechanically measured offsets of each BPM, [um]



CCW rotation by 45 deg

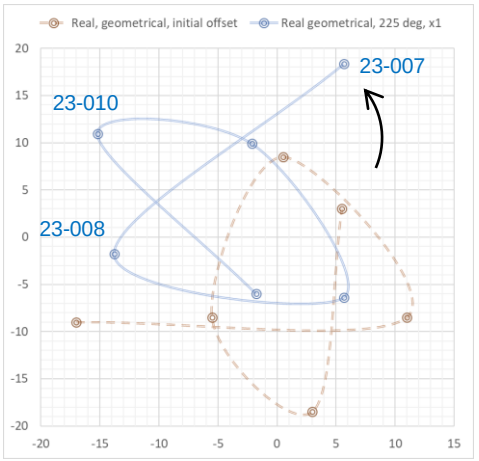


2. After rotation by 45 deg, [um]



CCW rotation by 180 deg

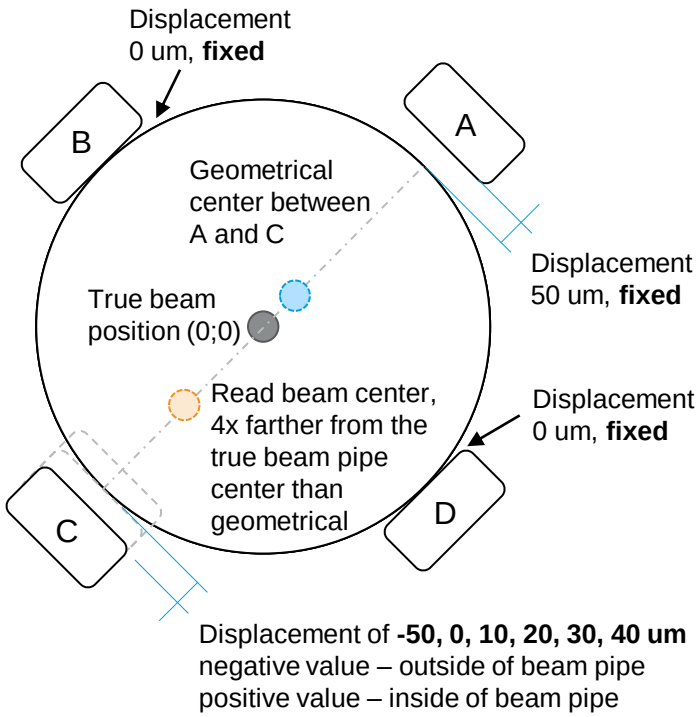
3. 180 deg rotation applied resulting in total rotation of 225 deg from initial data, [um]

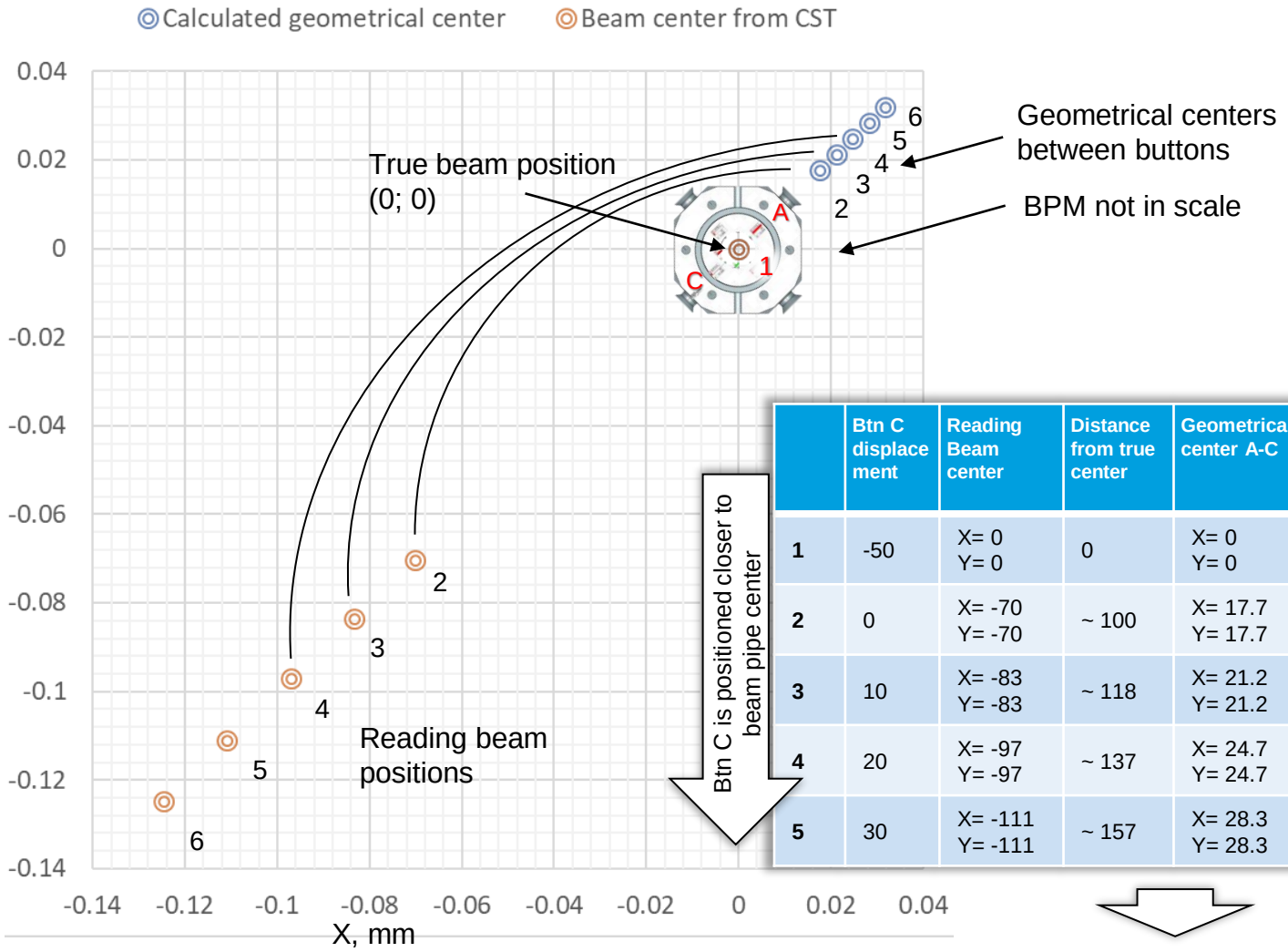


Relation between geometrical and electrical offset

2. Multiplication factor

Initial condition for CST simulation



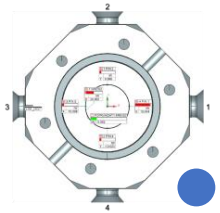


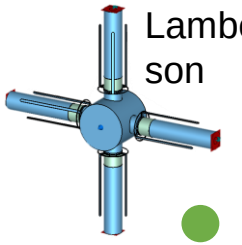
	Btn C displacement	Reading Beam center	Distance from true center	Geometrical center A-C	Distance from true center	Ratio Electrical/Geometrical center
1	-50	X= 0 Y= 0	0	X= 0 Y= 0	0	-
2	0	X= -70 Y= -70	~ 100	X= 17.7 Y= 17.7	25	~ 100/25 = 4
3	10	X= -83 Y= -83	~ 118	X= 21.2 Y= 21.2	30	~ 118/30 = 4
4	20	X= -97 Y= -97	~ 137	X= 24.7 Y= 24.7	35	~ 137/35 = 4
5	30	X= -111 Y= -111	~ 157	X= 28.3 Y= 28.3	40	~ 157/40 = 4

To compare geometrical and electrical centers, multiplication factor of ~ **4** should be applied to geometrical center

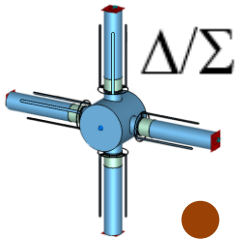
Center offsets from CST simulations, mechanical and RF measurement data

CST – Lambertson method (HF solver), Δ/Σ method (WF solver)

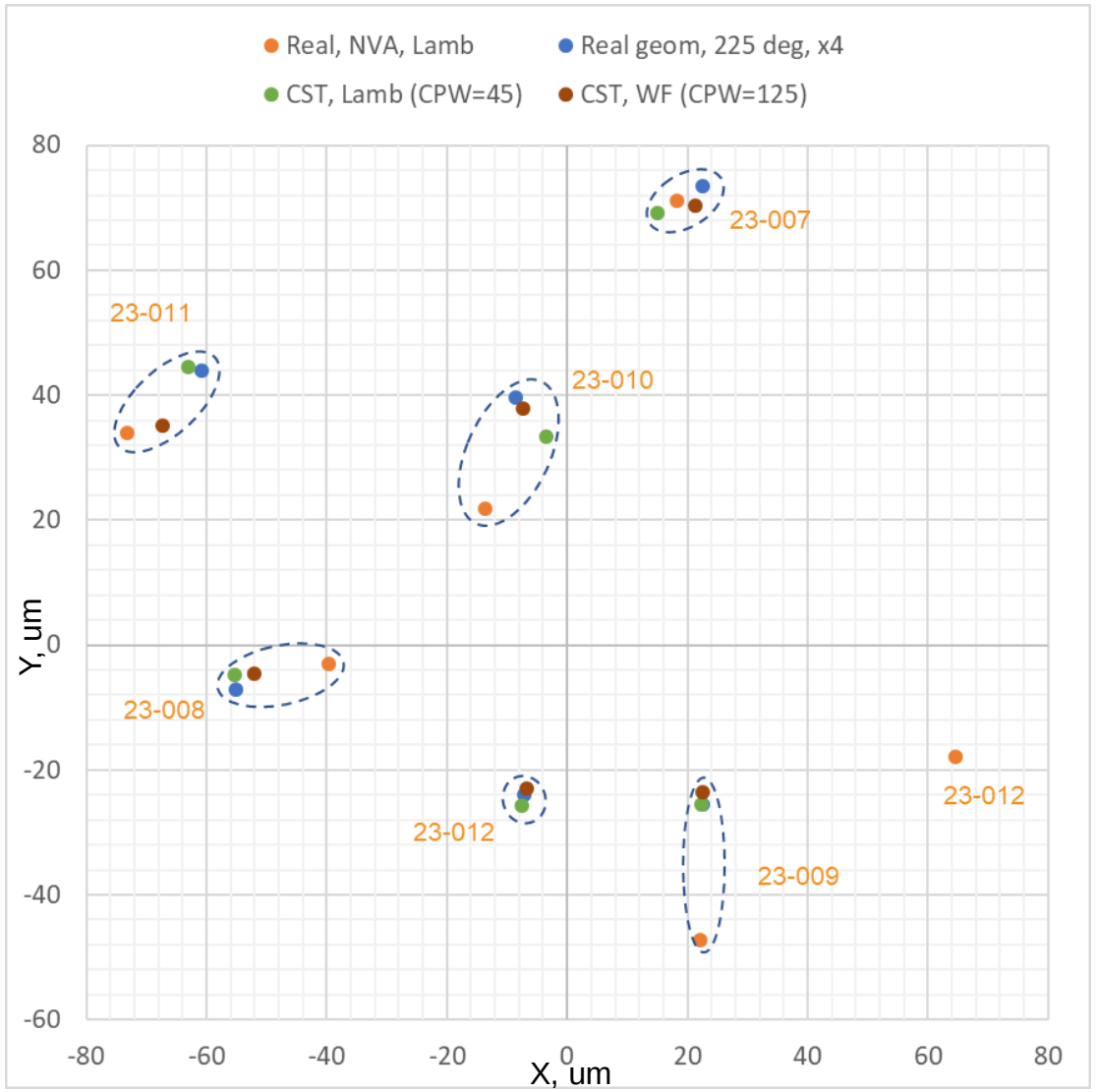




Lambert
son



Δ/Σ



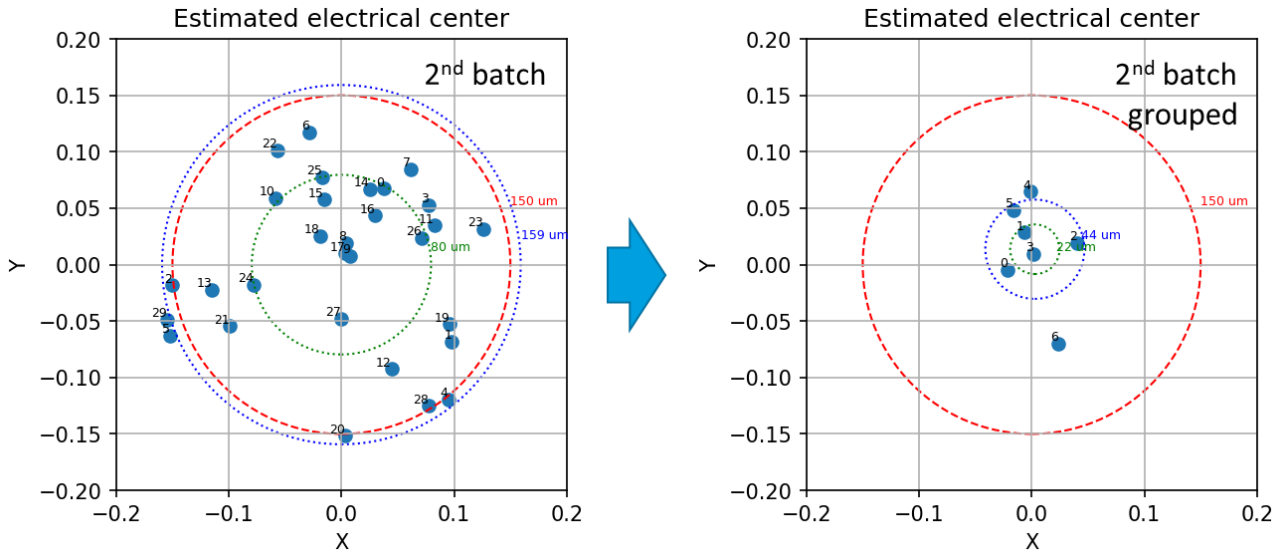
- Measured mechanical button displacements were used to set buttons positions in CST simulations
- CST simulations were performed using HF and WF solvers to calculate electrical center offset, applying Lambertson and Δ/Σ methods, respectively
- There is good agreement between mechanically measured offsets, offset measured from real BPM by VNA with Lambertson method and offsets obtained from CST simulations

Summary

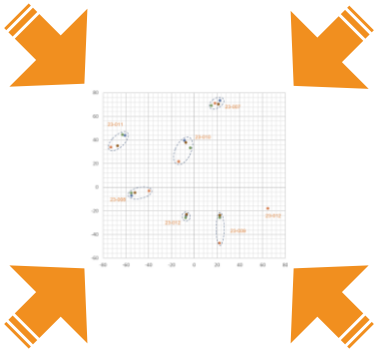
- 6 prototype BPMs manufactured without preliminary feedthrough selection process show electrical offset of less than 80 um < required 150 um
- accuracy of BPMs can be further improved by preliminary grouping feedthroughs in sets of 4 with similar TDR traces
- next step will be development of BPM test stand where we can use preselected feedthroughs to further reduce center offset of assembled BPM

randomly chosen feedthroughs

after forming groups of similar feedthroughs



next step is to further reduce center offset



Thank you