HL-LHC instrumentation

A. Alekou, H. Bartosik

Thanks to G. Arduini, A. Boccardi, R. Calaga, M. Carla',
L. Carver, R. De Maria, M. Krupa, T. Levens, Y.
Papaphilipou, F. Roncarolo, R. Tomas, G. Tradd, BI Group

Layout

- Introduction
- Available instruments:
  - BPMs: charge centre with applied filter
  - HT monitors: transverse offset along bunch due to beam crabbing
  - WS/BSRT/BGV monitors: beam-profile change
- Conclusions

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There is 1 pair of CCs on each side of the Interaction Points (IP), per beam (i.e. total of 16 CCs)


IP1
B
A
A
B
L
R

A/B ~1m apart: group together, left set, right set

Instrumentation reading

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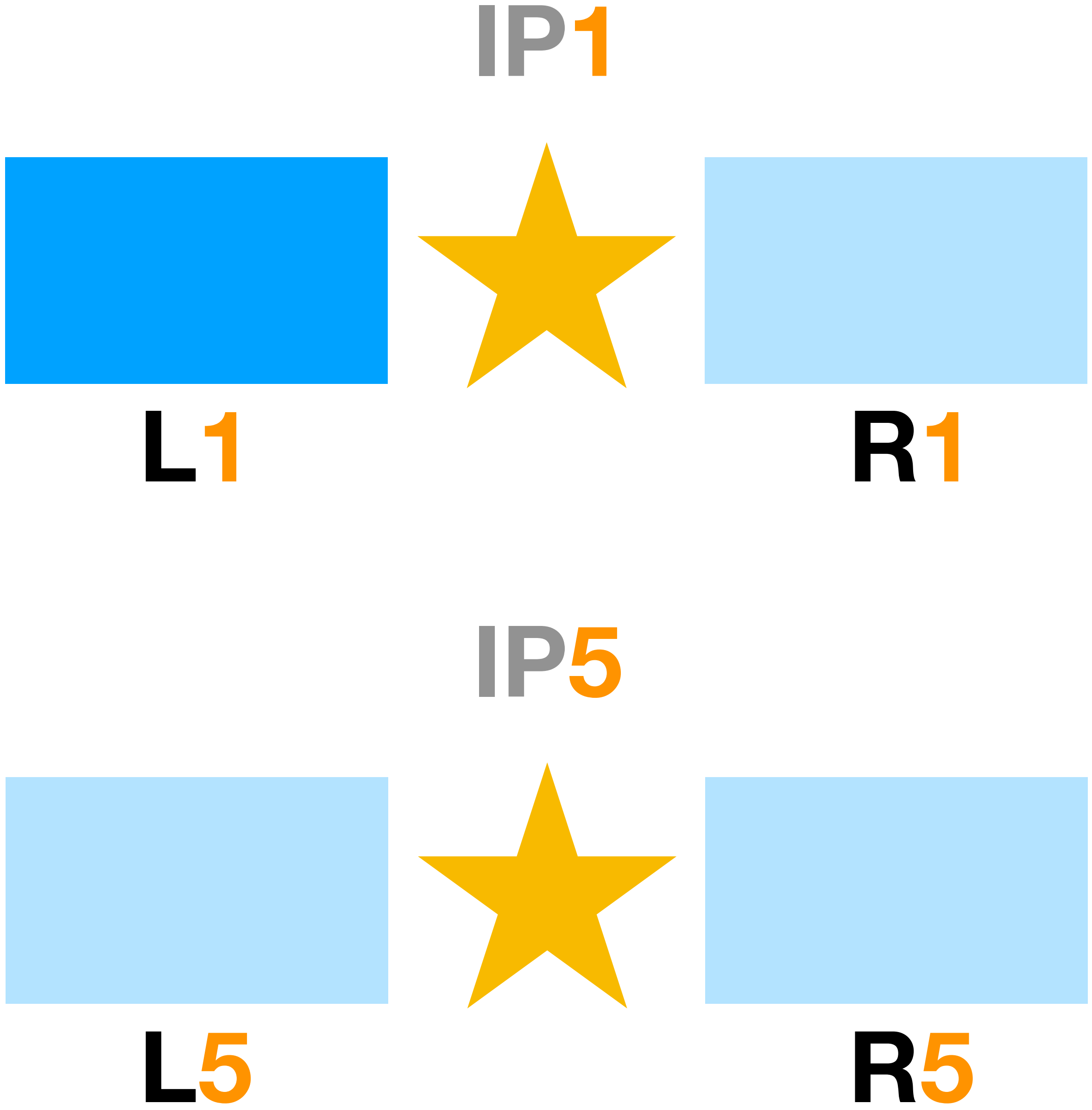
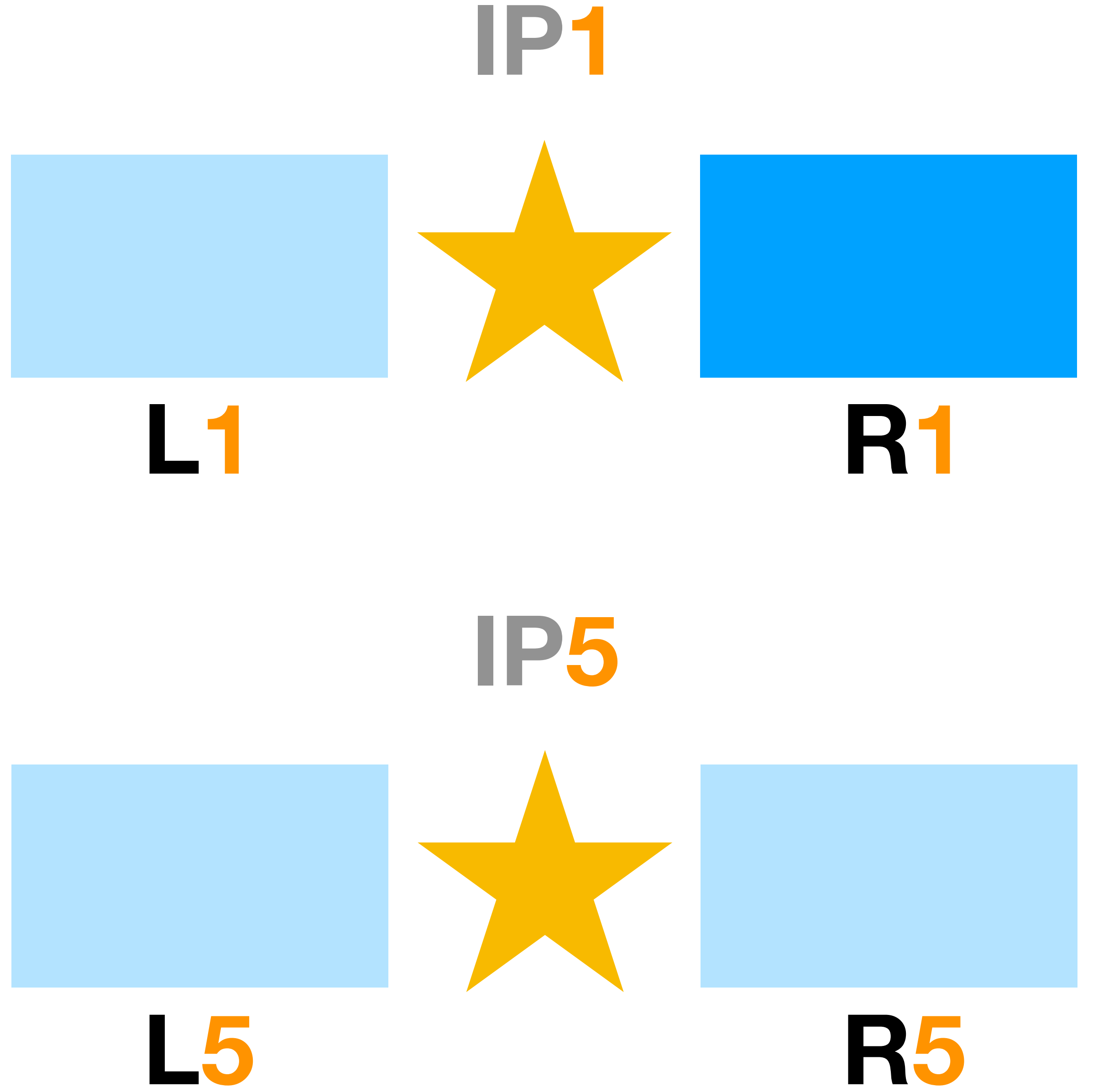
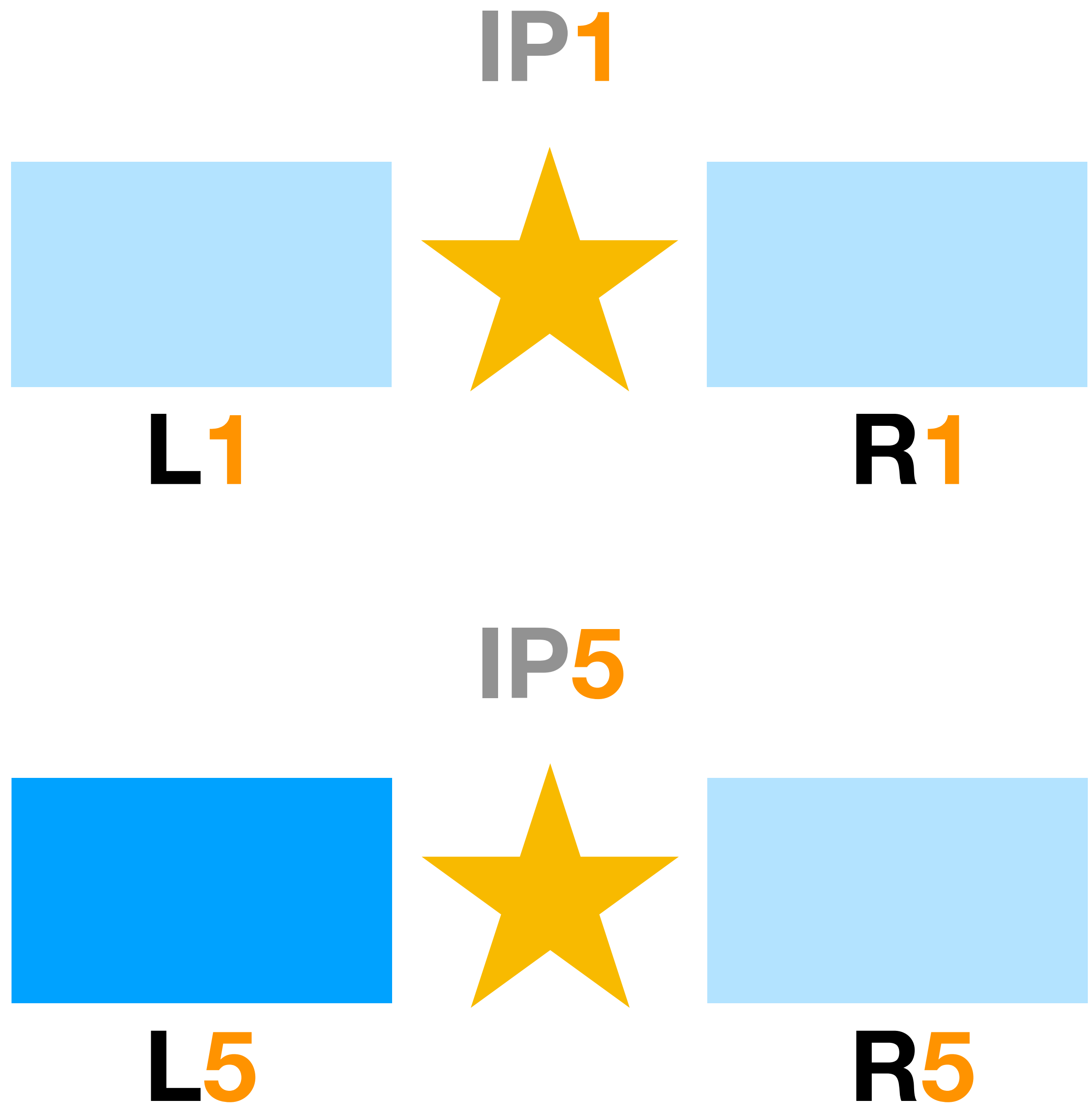
- During CC commissioning, the cavities will be operated one at a time at injection energy, 450 GeV

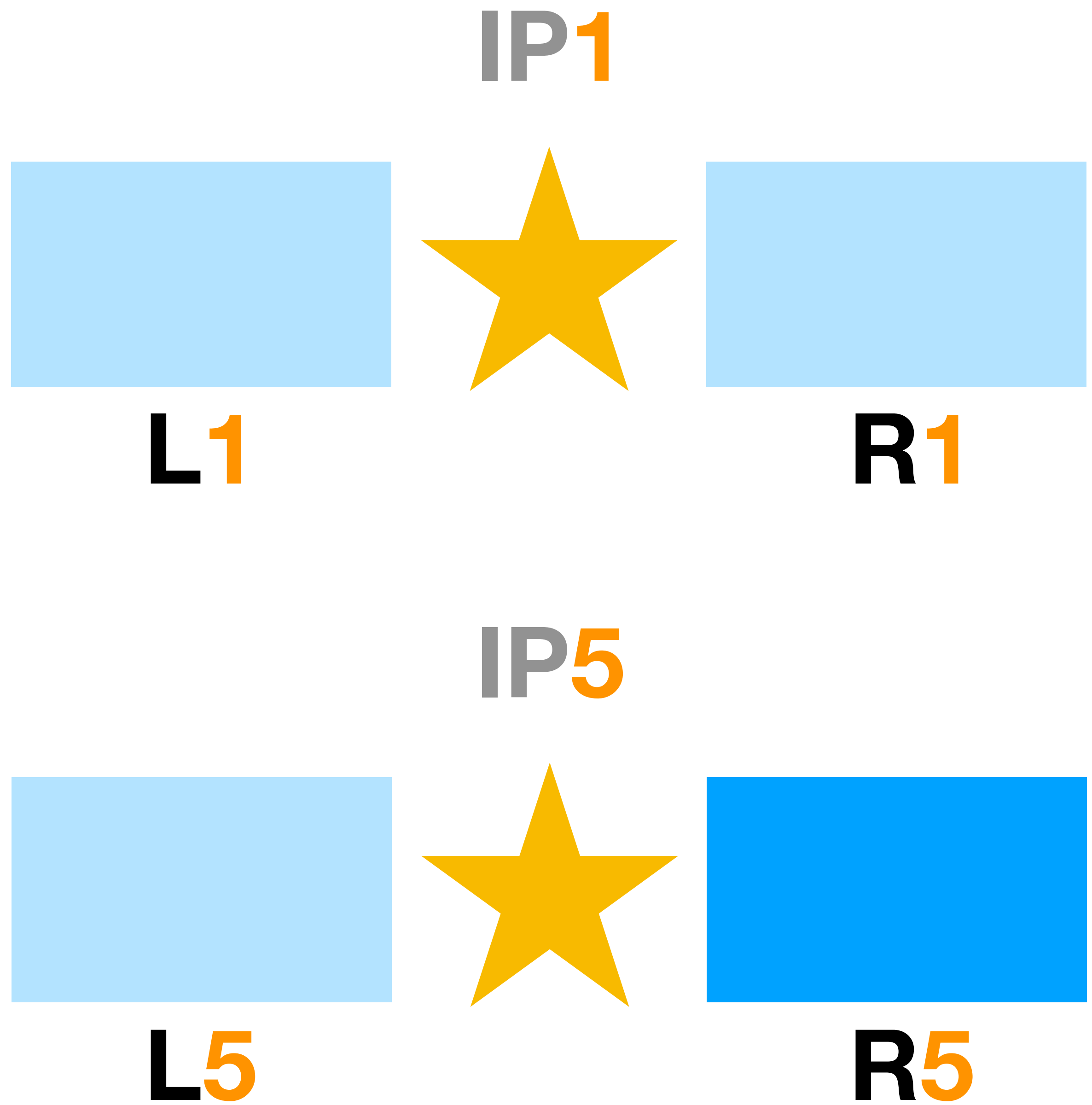
Instrumentation reading

- During CC commissioning, the cavities will be operated one at a time at injection energy, 450 GeV
- Following plots done showing expected instrument reading for 1 combined kick at CC location


IP1
L1
R1
IP5
L5
R5


IP1
L1
R1
IP5
L5
R5


IP1
L1
R1
IP5
L5
R5


IP1
L1
R1
IP5
L5
R5

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Resolution and accuracy

Table 6: Instrumental resolution, independent of bunch intensity. As for the HT monitor, in first approximation the resolution does not depend on intensity, as long as all bunches are of similar intensity and appropriate setup is performed for the circulating intensity [9–13]

Instrument	Resolution	Accuracy
HT [9]	0.1 mm	- *
WS [10]	<10 μm, at least 3 pts/σ	5-10% (beam-size), at least 3 pts/σ
BSRT [11]	min. 10 μm beam-size change	- *
BGV [12]	5% within 1 minute (bunch-by-bunch)	2% in 1 minute (average beam-size)
BPM [13]	100 μm (turn-by-turn) 1 μm (average orbit)	50 μm

*values to be acquired

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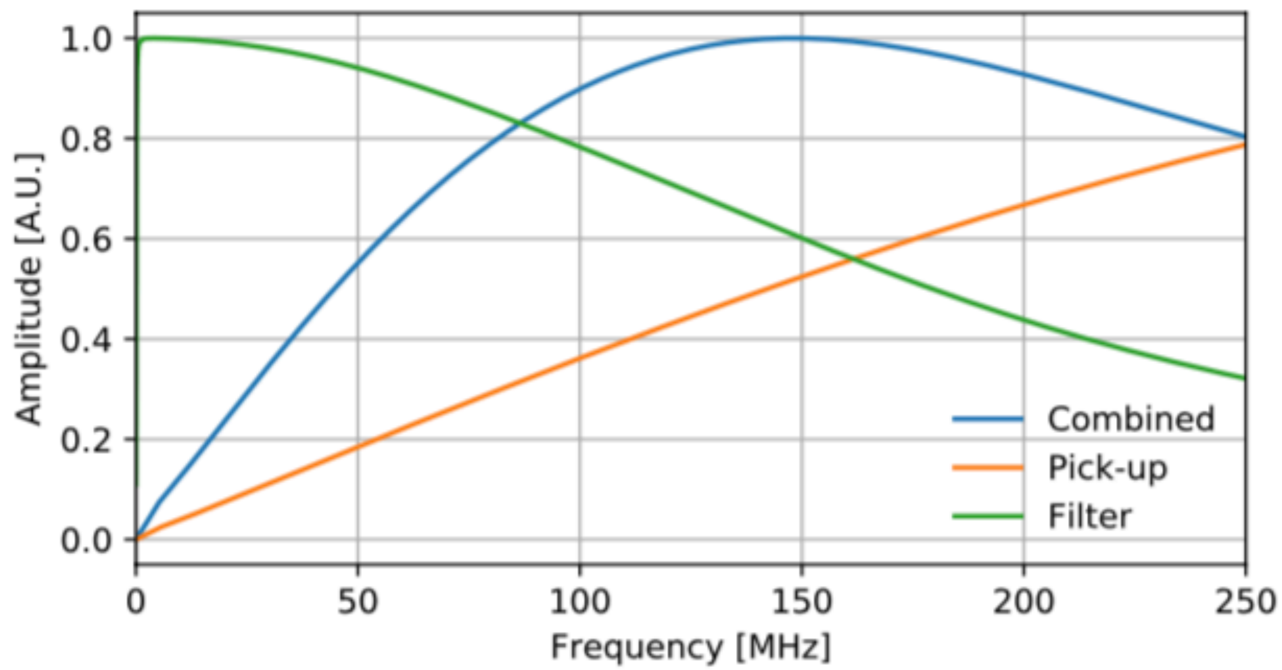
BPM

BPM filtering



M. Carla

- Frequency filtering applied to LHC BPMs (as with SPS BPMs)
- **Effective beam position measured by a BPM:**

$$\bar{X}^2 = \frac{\int |R(\omega) \cdot \mathcal{F}\{I(t) \cdot X(t)\}|^2 d\omega}{\int |R(\omega) \cdot \mathcal{F}\{I(t)\}|^2 d\omega}$$

- R(ω): BPM spectral response (transfer function)
- I(t): bunch longitudinal distribution
- X(t): bunch transverse position slice with a delay t with respect to the bunch centre
- F: Fourier transform operator

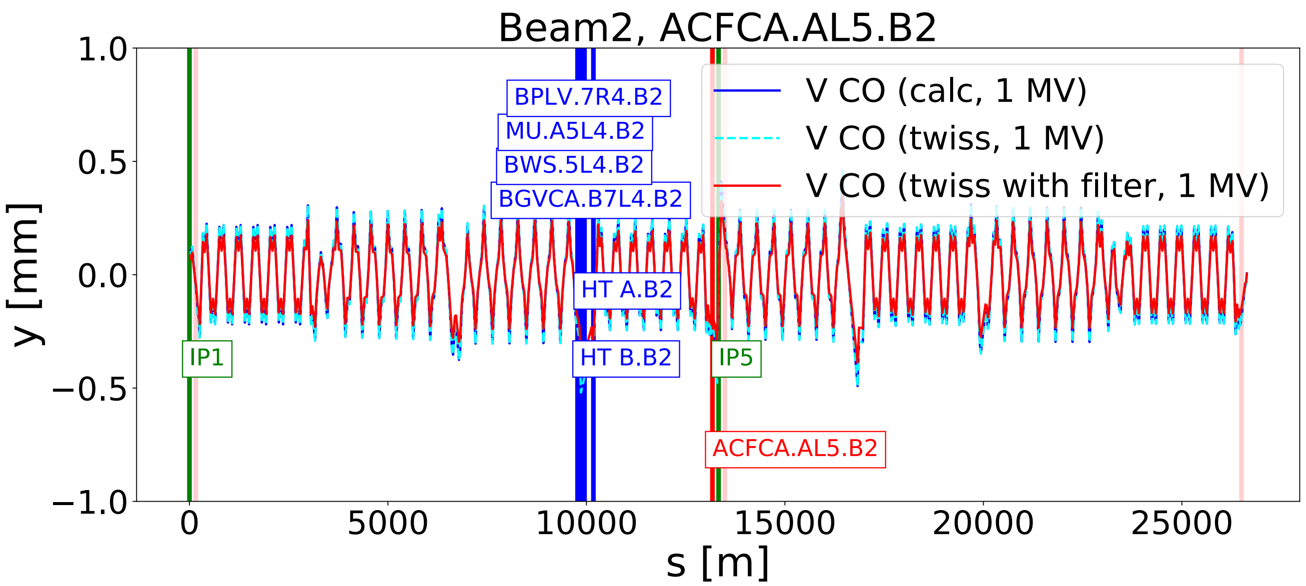
- Strongly depends on longitudinal distribution, I(t)

ACFCA.AL5.B2 set to 1 MV

BPM filtering of
0.790 (inj)
0.797 (col)
for 90° CC-phase

CO, analytical calculation
CO, MAD-X twiss
CO with BPM filter

Injection



ACFCA.AL5.B2 set to 1 MV

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0.797 (col)
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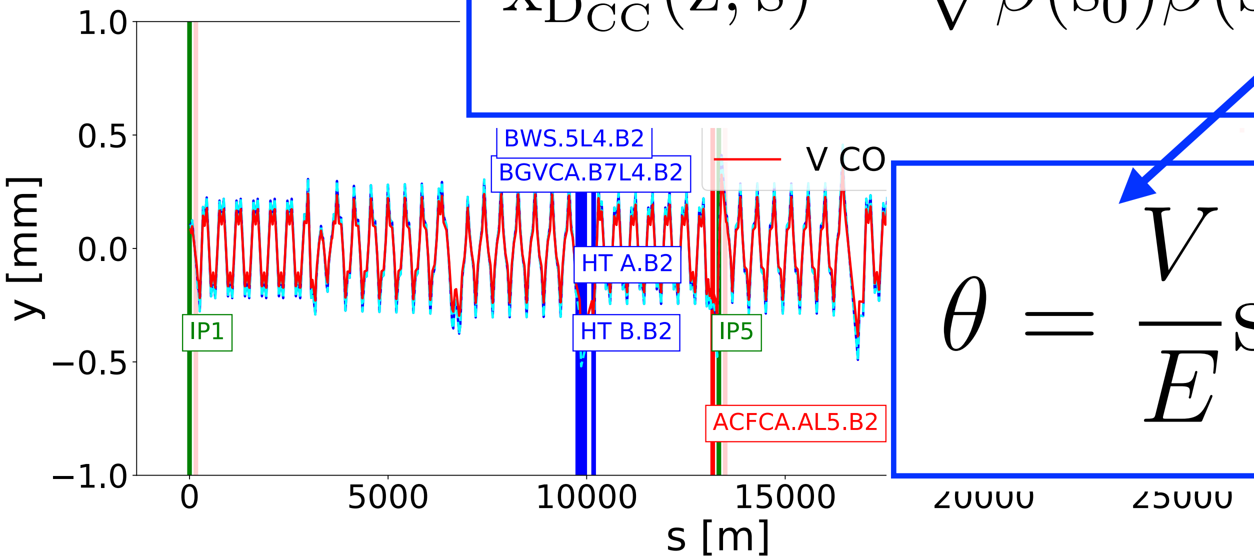
CO with BPM filter

Injection

$$x_{D_{CC}}(z,s) = \sqrt{\beta(s_0)\beta(s)}\frac{\theta}{2\sin\pi Q}\cos\left(\psi(s,s_0) - \pi Q\right)$$

$$\theta = \frac{V}{E}\sin(\kappa z + \phi)$$



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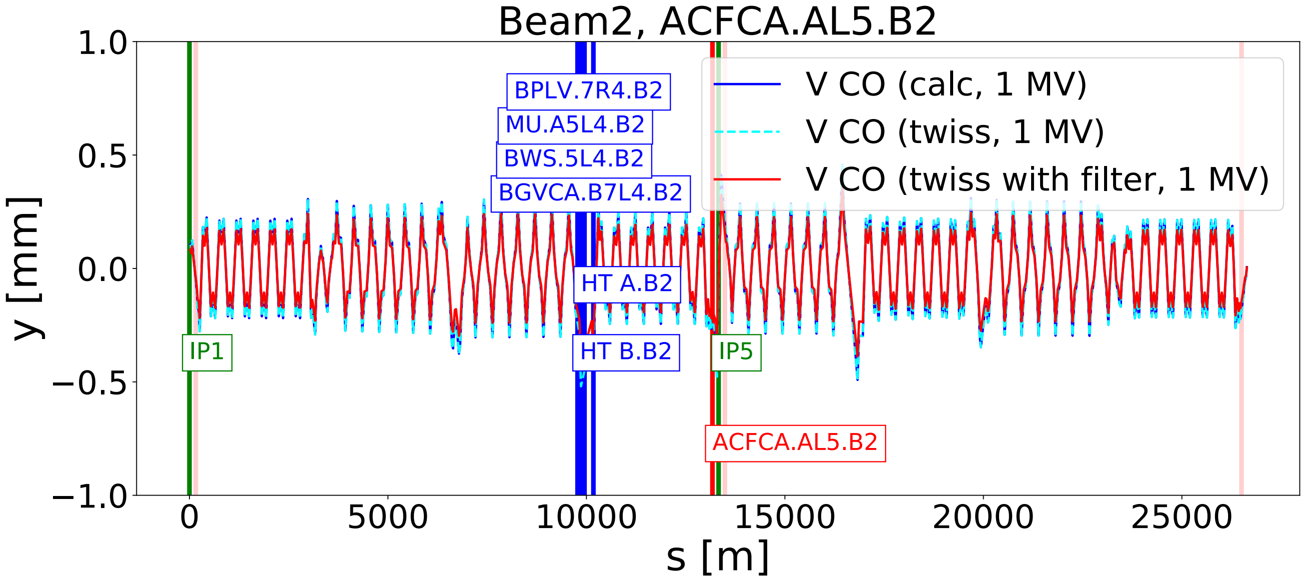

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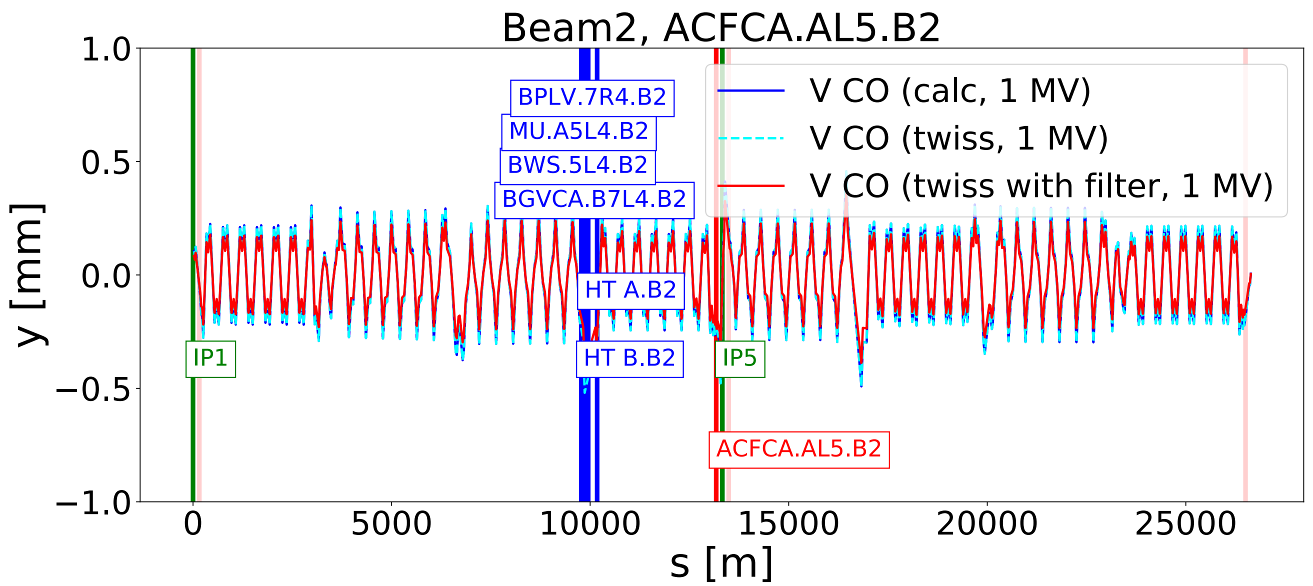

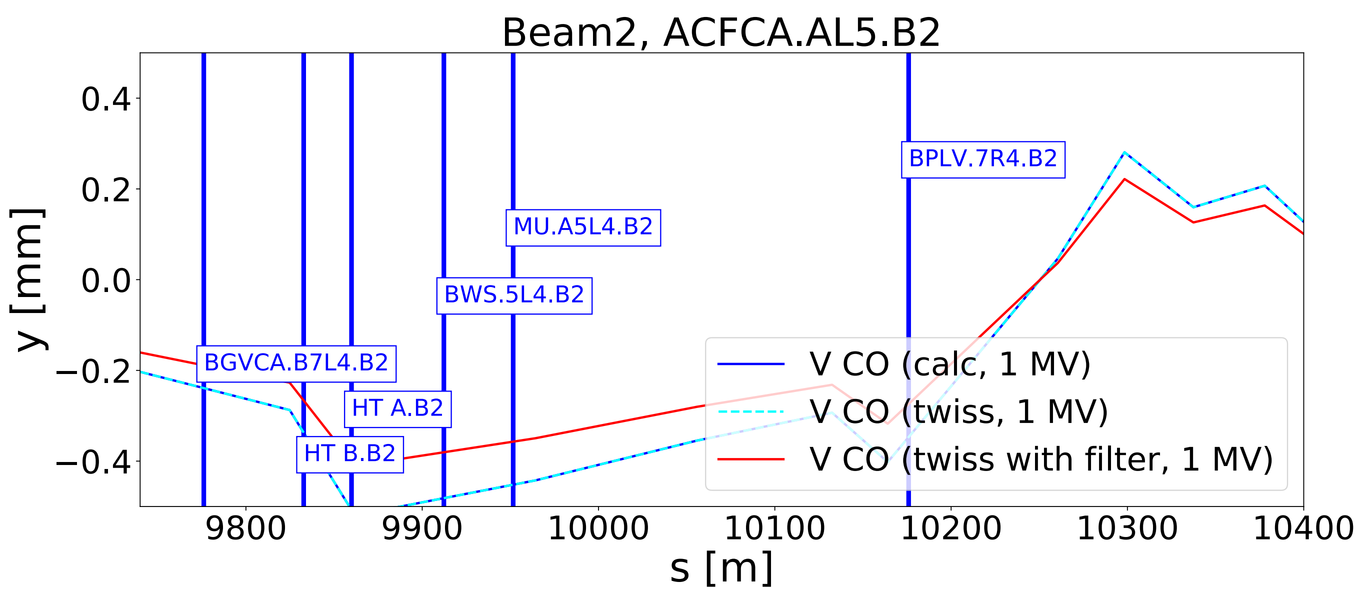

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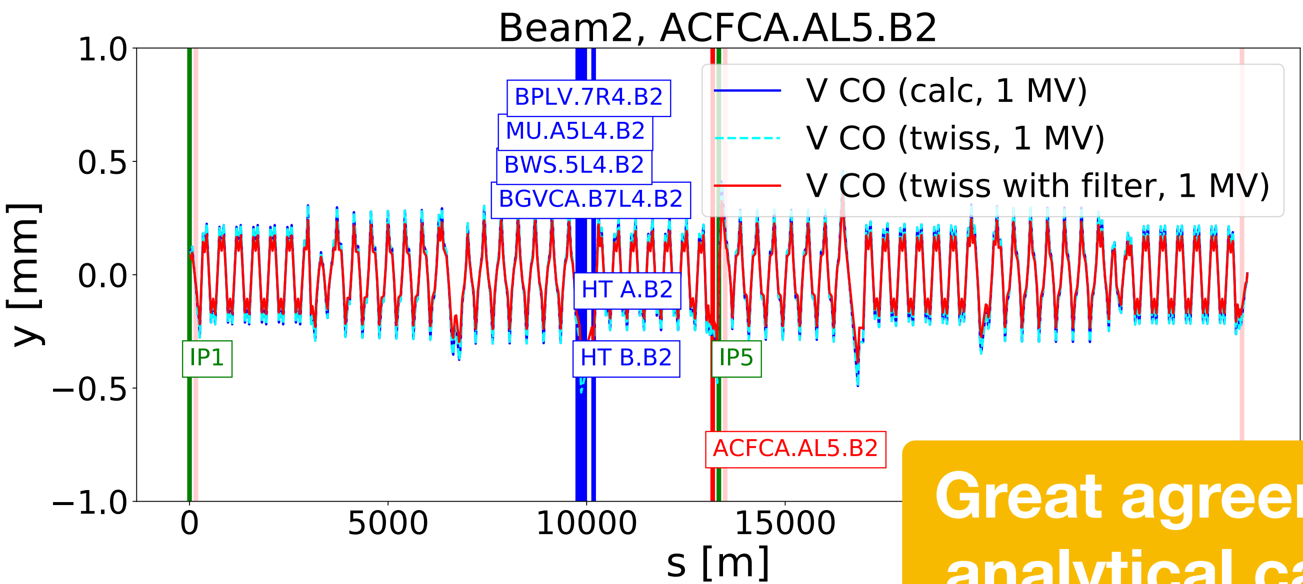
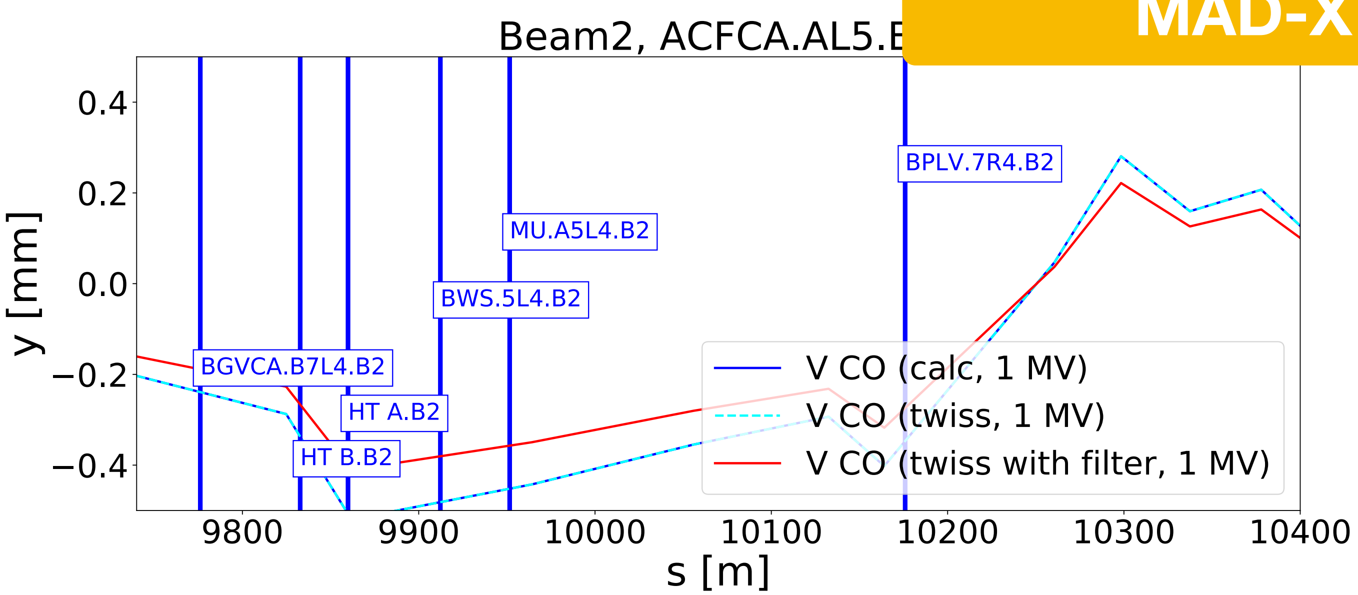


Great agreement between analytical calculation and MAD-X twiss



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BPM filtering of
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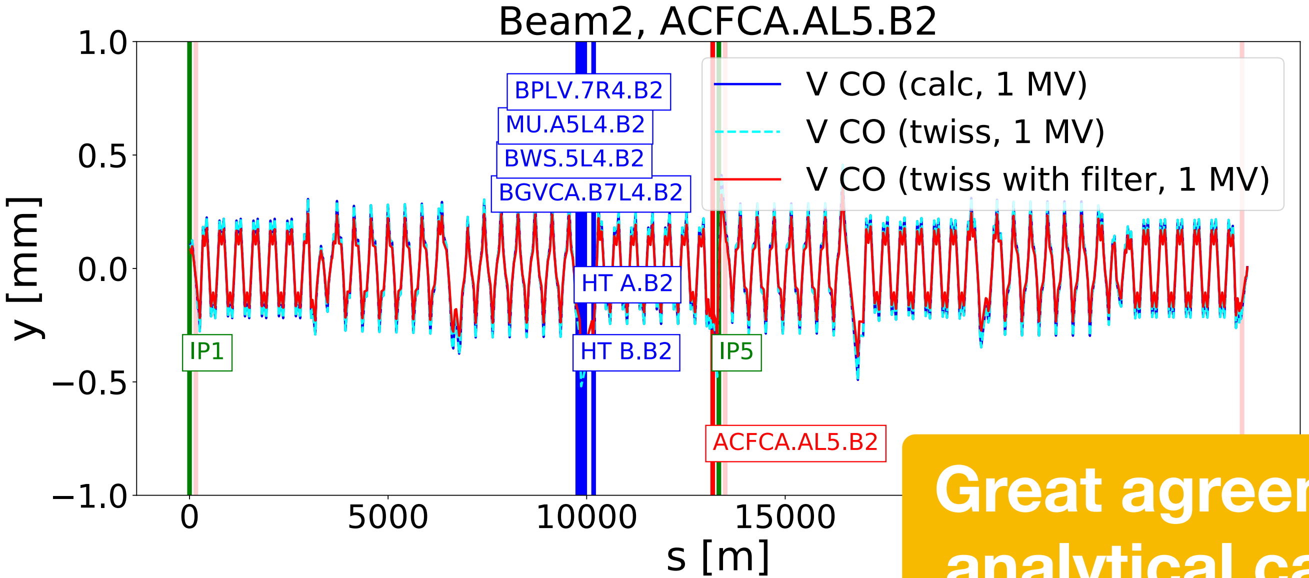
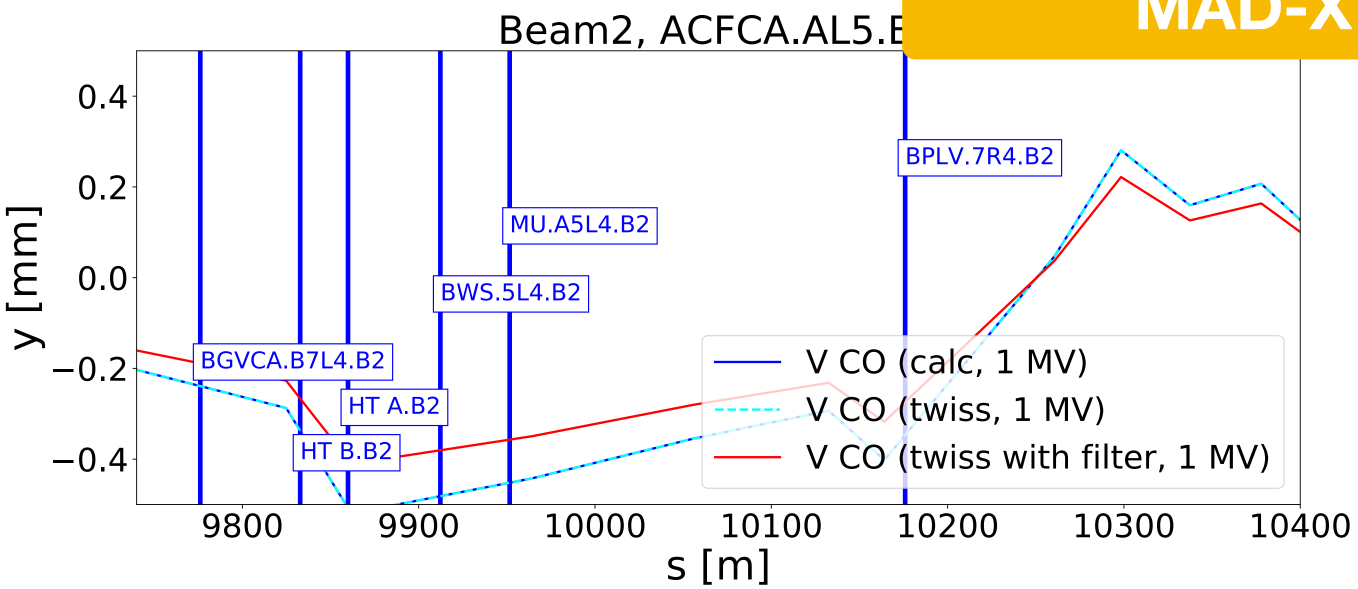
CO with BPM filter

Injection

Collision (β*=15 cm)





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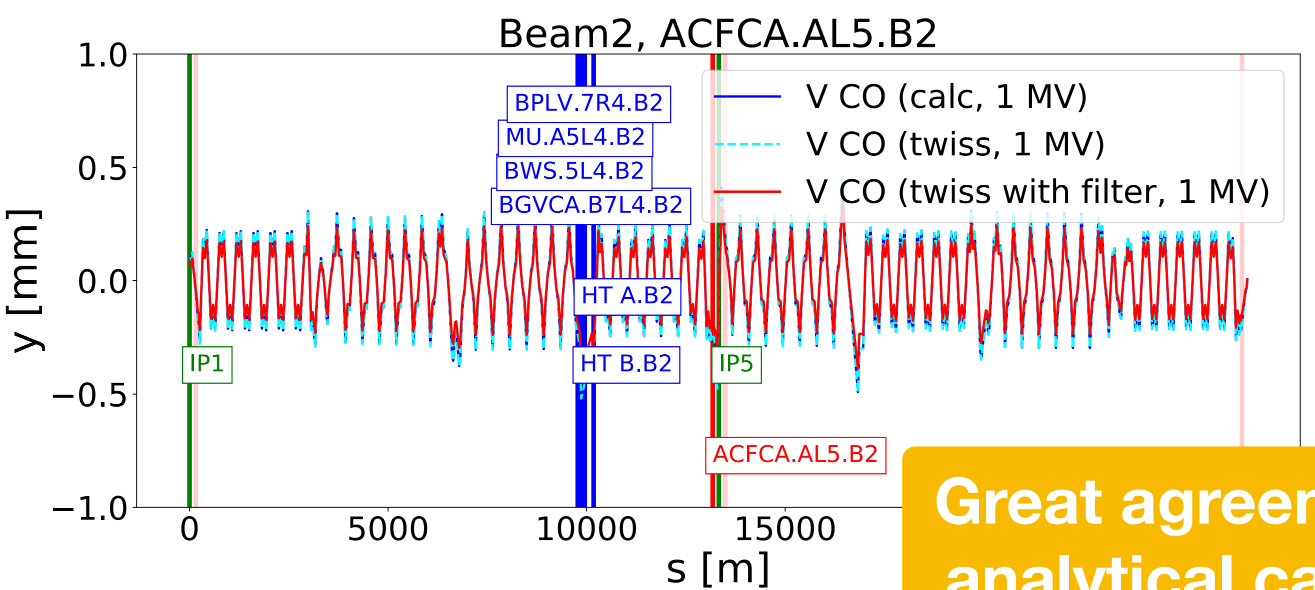

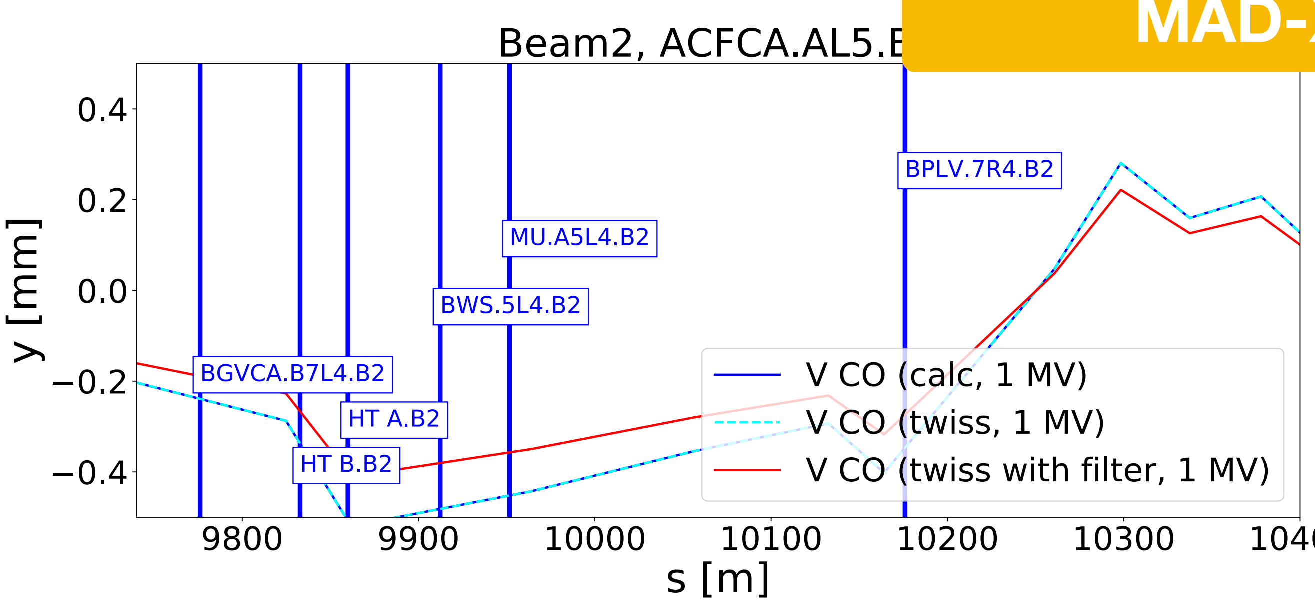

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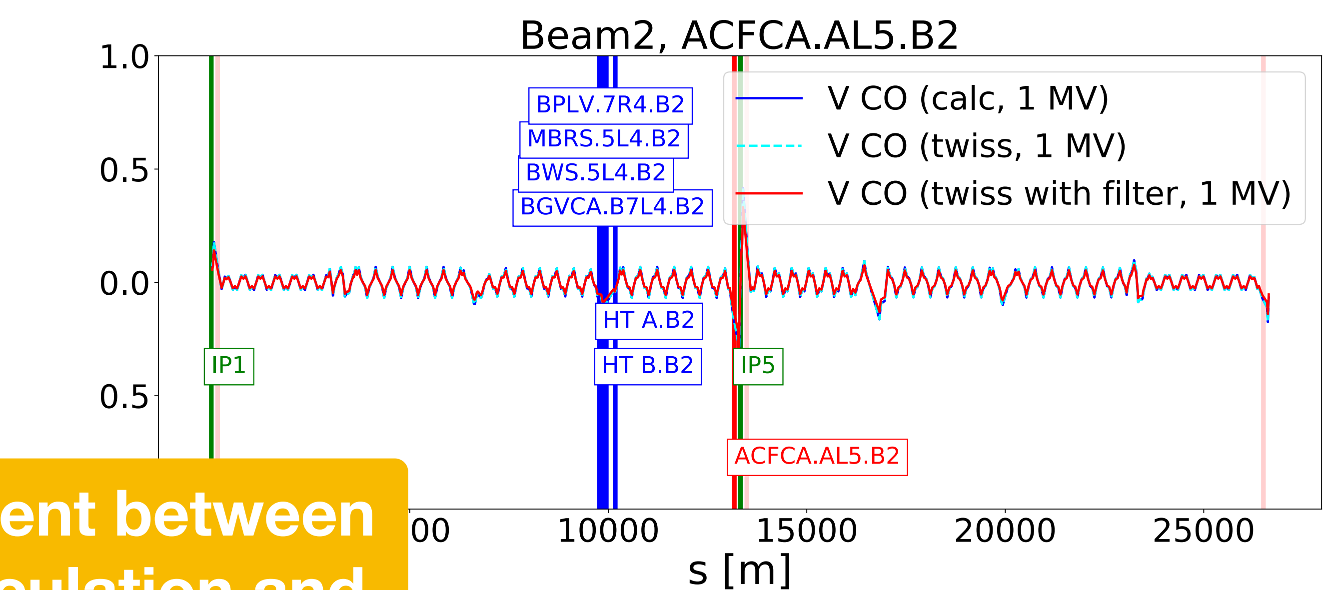
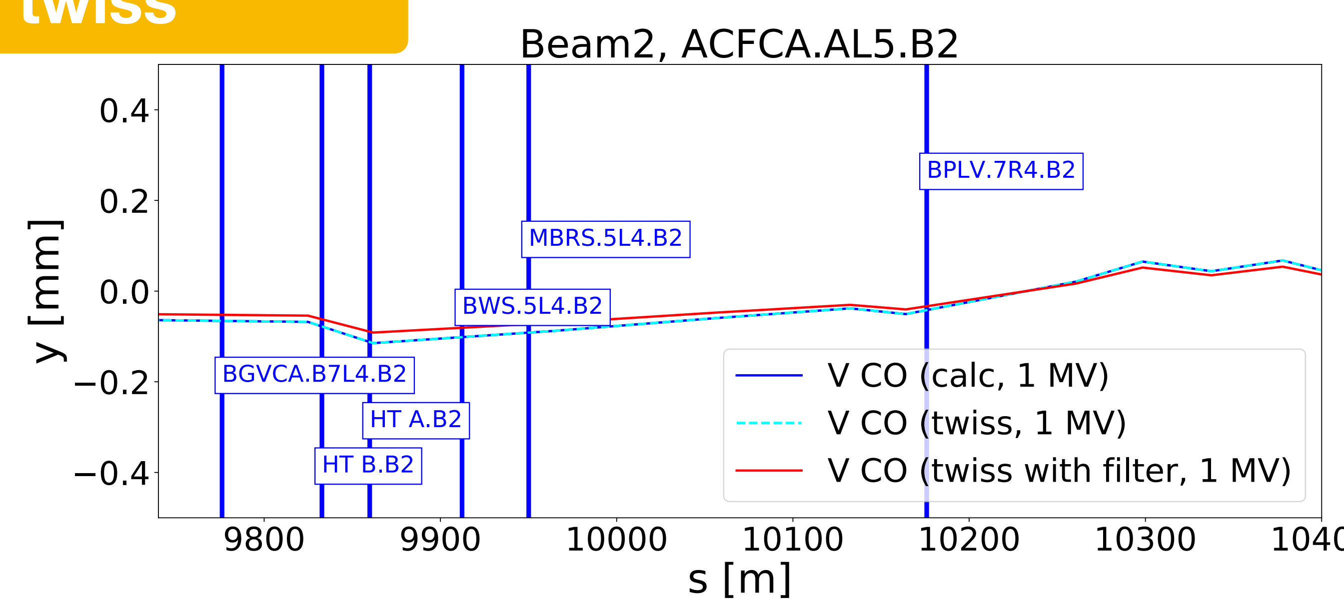




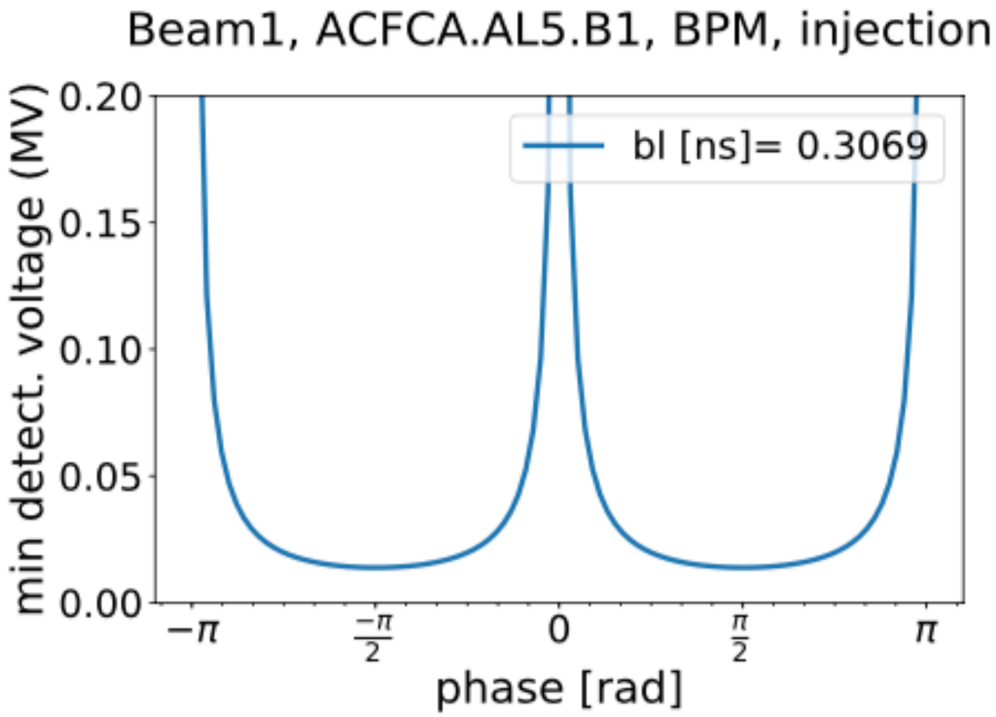
Great agreement between analytical calculation and MAD-X twiss

Minimum detectable voltage by BPMs within 1 μm BPM resolution

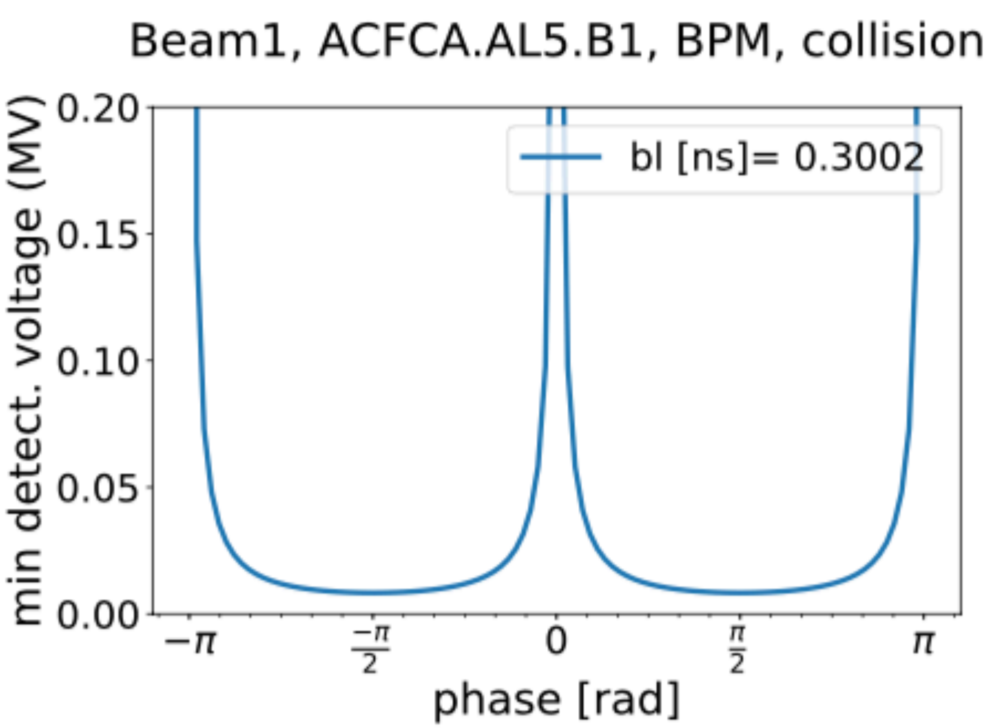
ACFCA.AL5.B1 set to 1 MV

Bunch-length of 9.2 cm (inj) and 9.0 cm (col) assuming FWHM equivalent Gaussian

Injection



Collision



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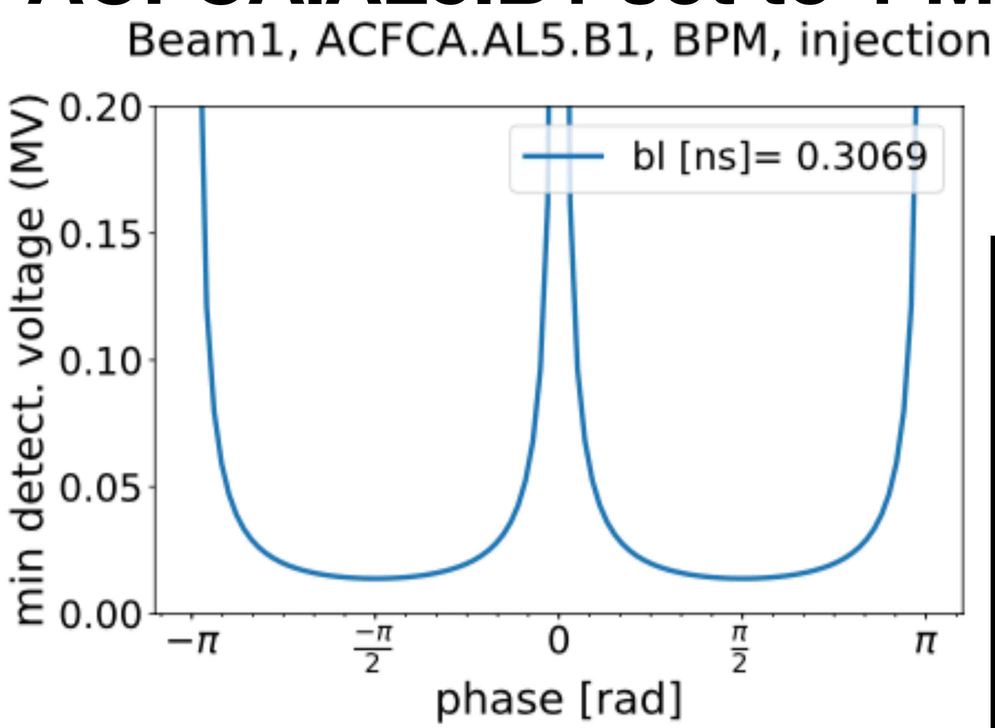


Collision

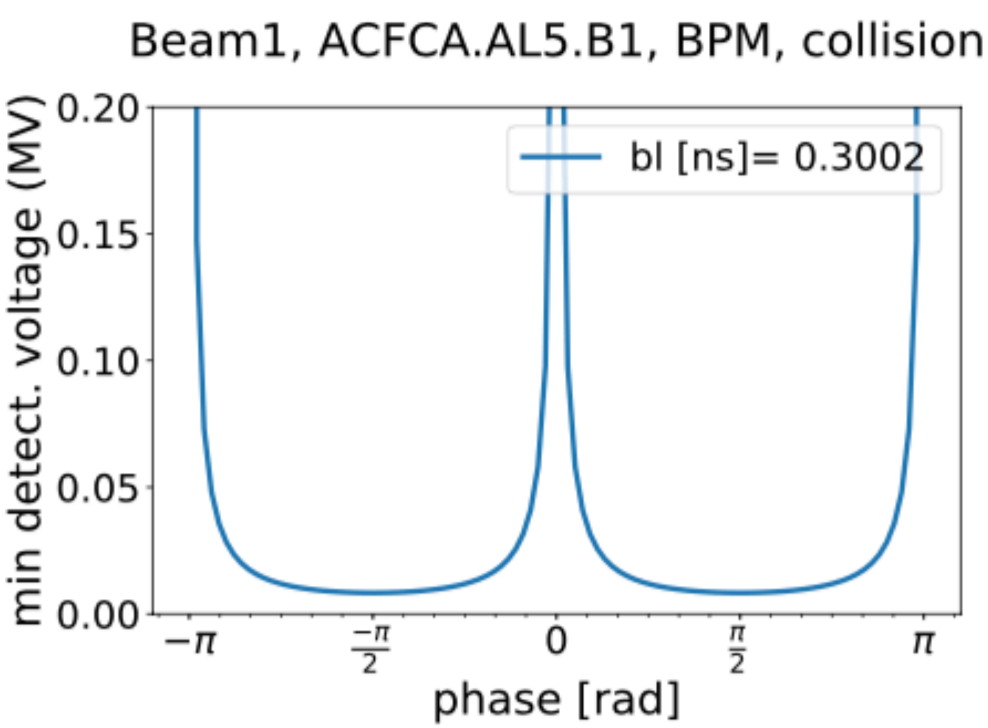


Table 7: Minimum detectable voltage [MV] within the 1 μm BPM resolution for a CC-phase of 90 degrees

Injection	L1	R1	L5	R5
B1:	0.0061	0.0113	0.0138	0.0072
B2:	0.0114	0.0061	0.0071	0.0138
Collision	**L1**	**R1**	**L5**	**R5**
B1:	0.0079	0.0074	0.0083	0.0083
B2:	0.0074	0.0079	0.0083	0.0083

Table 8: Minimum detectable voltage [MV] within the 50 μm BPM accuracy for a CC-phase of 90 degrees

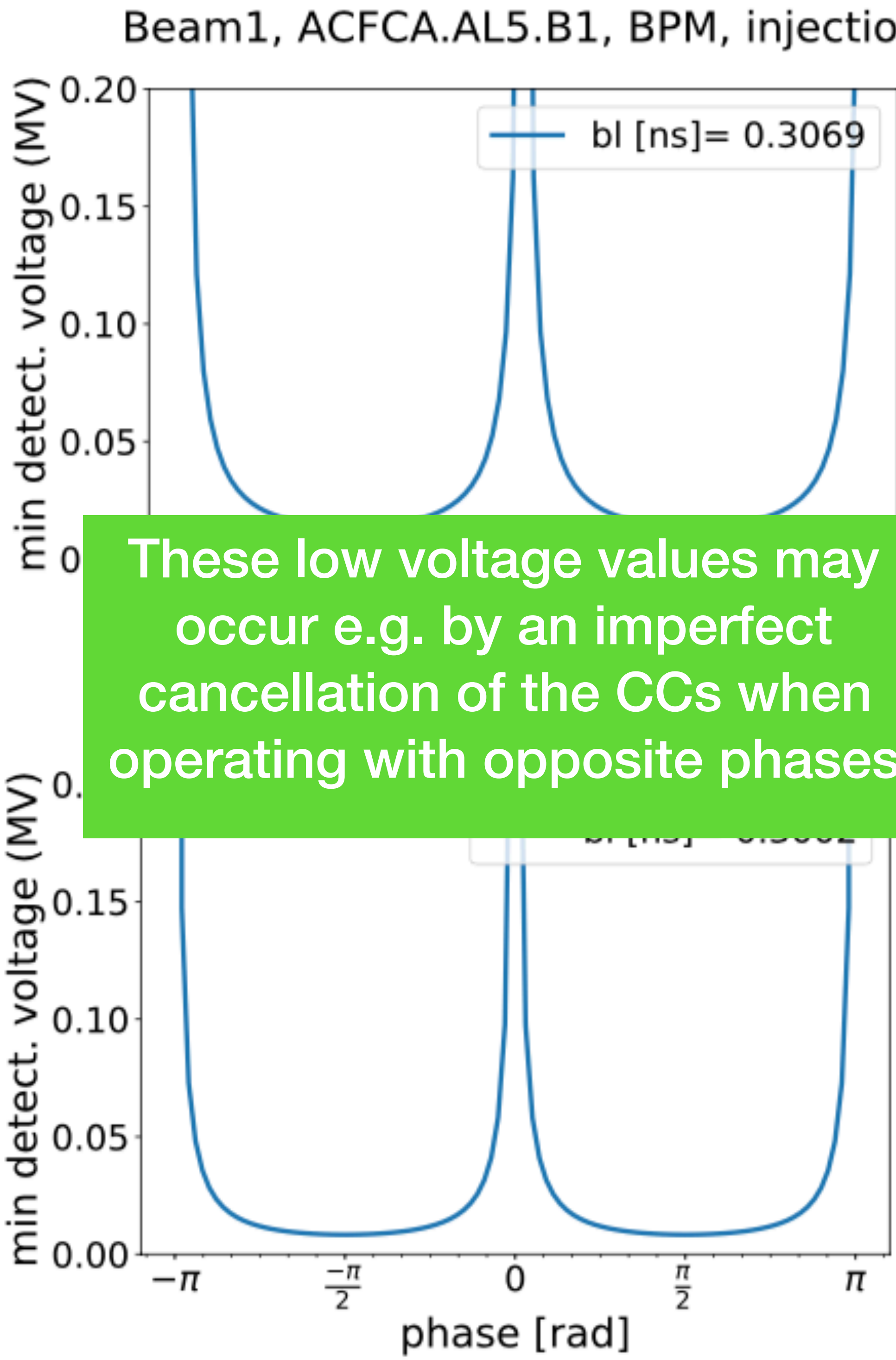
Injection	L1	R1	L5	R5
B1:	0.31	0.57	0.69	0.36
B2:	0.57	0.31	0.36	0.69
Collision	**L1**	**R1**	**L5**	**R5**
B1:	0.40	0.37	0.42	0.42
B2:	0.37	0.40	0.42	0.42

Minimum detectable voltage by BPMs within 1 μm BPM resolution

ACFCA.AL5.B1 set to 1 MV

Injection

Collision



These low voltage values may occur e.g. by an imperfect cancellation of the CCs when operating with opposite phases

Bunch-length of 9.2 cm (inj) and 9.0 cm (col) assuming FWHM equivalent Gaussian

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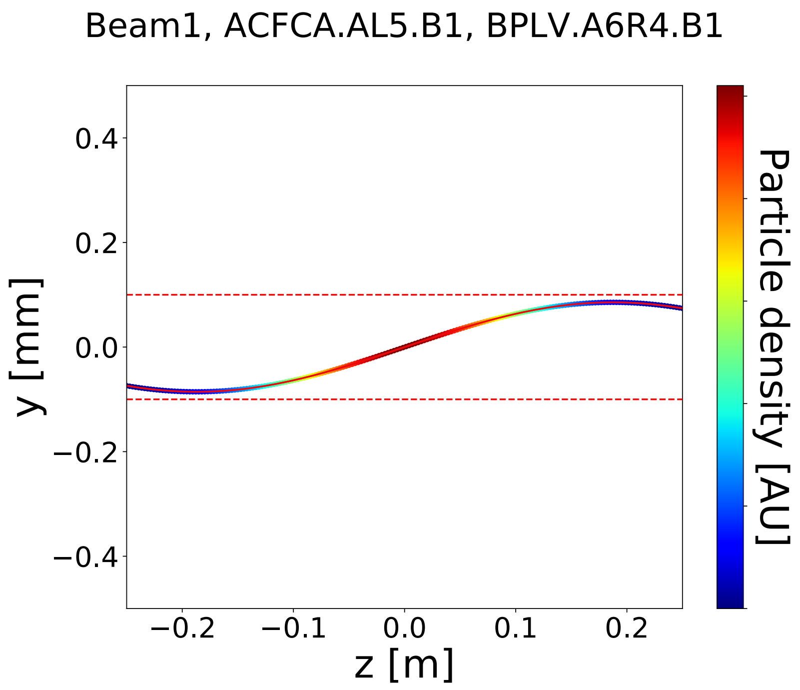
HT

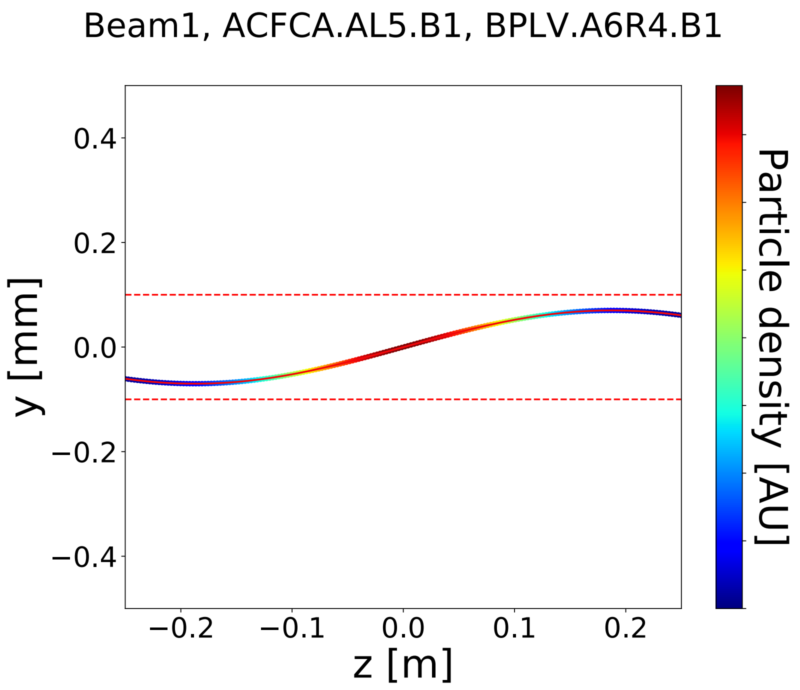
ACFCA.AL5.B1 set to 1 MV

HT resolution: ±0.1 mm

Injection



Collision



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Injection

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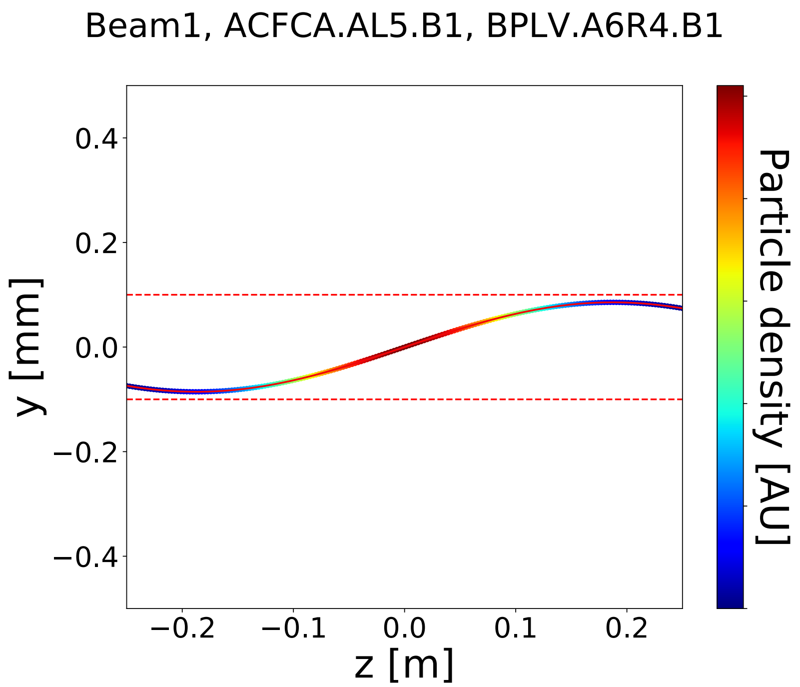
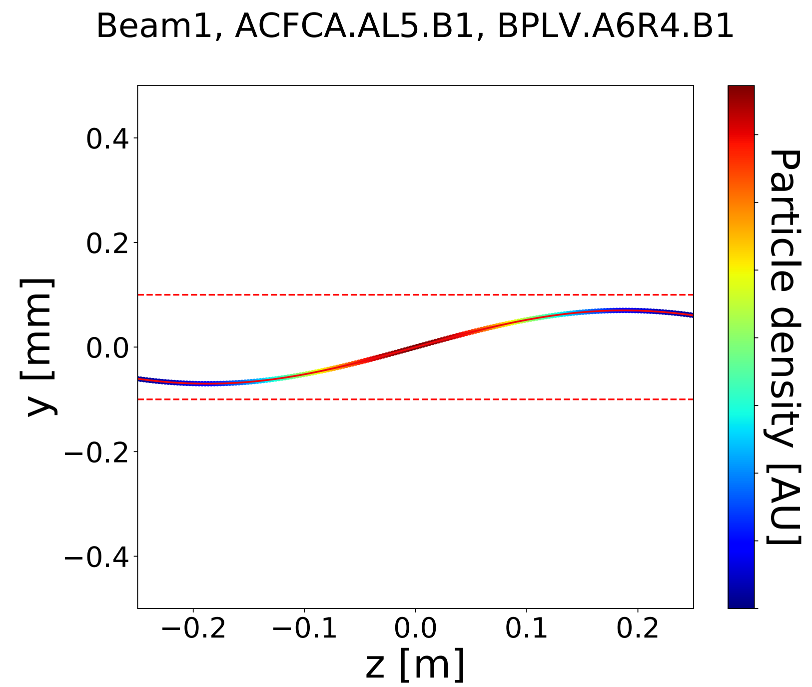


Collision

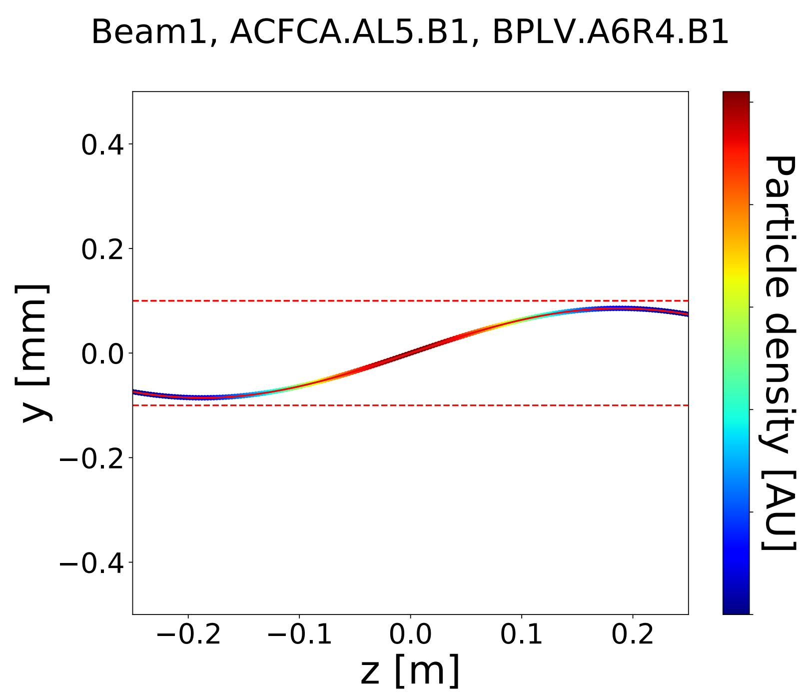


HT resolution: ±0.1 mm

Injection	**L1**	**R1**	**L5**	**R5**
HT - B1	0.15	0.26	0.09	0.18
HT B.B1	0.34	0.14	0.15	0.54
HT A.B1	0.49	0.22	0.1	0.38
HT - B2	0.21	0.50	0.37	0.26
HT B.B2	0.26	0.18	0.32	0.09
HT A.B2	0.19	0.16	0.51	0.16
Collision	**L1**	**R1**	**L5**	**R5**
HT - B1	0.02	0.02	0.07	0.07
HT B.B1	0.07	0.08	0.03	0.03
HT A.B1	0.1	0.11	0.01	0.02
HT - B2	0.11	0.10	0.04	0.05
HT B.B2	0.02	0.02	0.07	0.08
HT A.B2	0.02	0.02	0.11	0.11

ACFCA.AL5.B1 set to 1 MV

Injection



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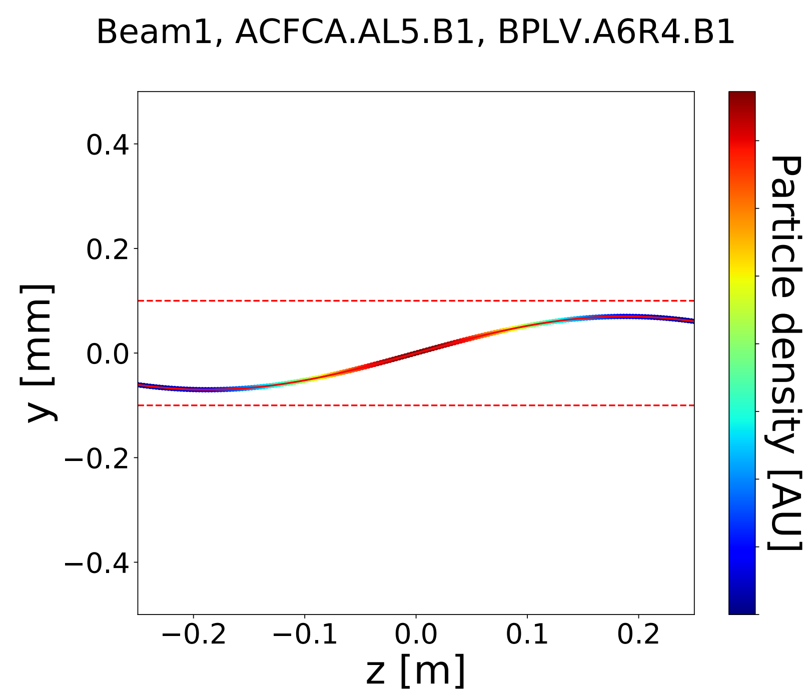

HT resolution: ±0.1 mm

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HT - B1	0.15	0.26	0.09	0.18
HT B.B1	0.34	0.14	0.15	0.54
HT A.B1	0.49	0.22	0.1	0.38
HT - B2	0.21	0.50	0.37	0.26
HT B.B2	0.26	0.18	0.32	0.09
HT A.B2	0.19	0.16	0.51	0.16
Collision	**L1**	**R1**	**L5**	**R5**
HT - B1	0.02	0.02	0.07	0.07
HT B.B1	0.07	0.08	0.03	0.03
HT A.B1	0.1	0.11	0.01	0.02
HT - B2	0.11	0.10	0.04	0.05
HT B.B2	0.02	0.02	0.07	0.08
HT A.B2	0.02	0.02	0.11	0.11

For a 1 MV kick, several cases do not fall within the HT resolution

Expected orbit during operation (closed CC bump), β*=50 cm, β*=15 cm

R. De Maria

Table 10: Expected transverse orbit of particles at ($z = \pm\sigma_z$) at the HT during operating conditions (closed crab cavity bump); the s-location is from IP1.

$\beta^* = 50$ cm	Position [m]	β_x [m]	β_y [m]	x [μm]	y [μm]
HT B - B1	9832.62	184.6	569.1	5.3	10.7
HT A - B1	9859.75	398.5	302.7	9.6	8.7
BPLV.A6R4.B1	10134.76	252.1	401.0	15.6	18.6
BPLH.7R4.B1	10174.96	543.0	51.5	22.8	6.6
HT B - B2	9832.77	467.4	210.2	21.2	2.5
HT A - B2	9859.90	238.0	492.7	15.2	5.6
BPLH.6R4.B2	10134.11	396.3	269.7	8.4	13.9
BPLV.7R4.B2	10175.91	123.6	483.3	2.5	19.4
$\beta^* = 15$ cm	**Position [m]**	**β_x [m]**	**β_y [m]**	**x [μm]**	**y [μm]**
HT B - B1	9832.62	181.3	573.8	2.8	11.0
HT A - B1	9859.75	397.9	303.2	5.2	8.3
BPLV.A6R4.B1	10134.76	243.7	416.9	8.3	9.1
BPLH.7R4.B1	10174.96	482.0	114.0	11.6	4.1
HT B - B2	9832.77	465.0	212.8	11.4	2.7
HT A - B2	9859.90	237.8	493.3	8.2	4.9
BPLH.6R4.B2	10134.11	383.7	277.7	5.2	8.1
BPLV.7R4.B2	10175.91	56.9	556.5	0.7	11.8

Reading 1 or 2 orders of magnitude smaller than HT 100 μm resolution

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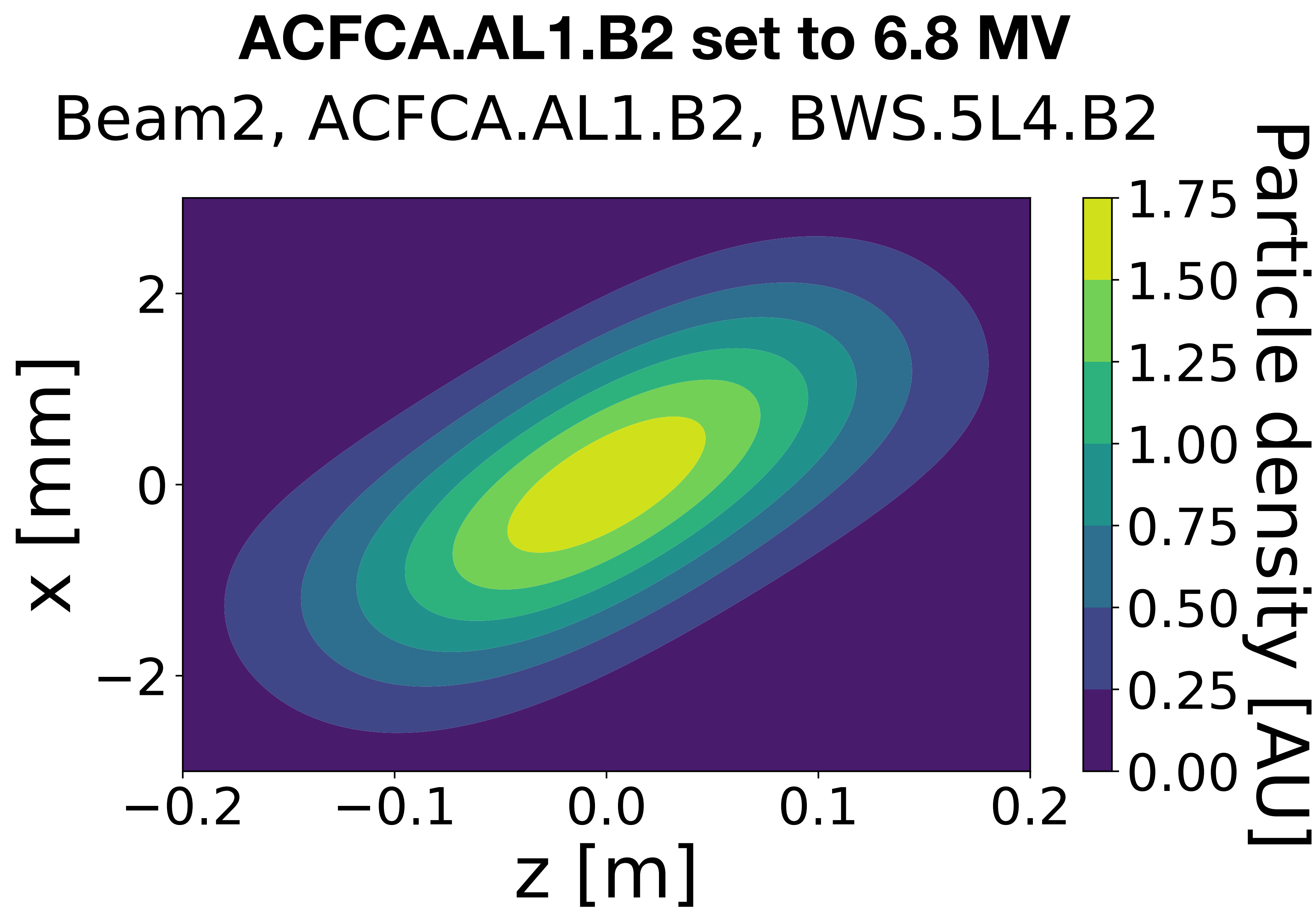
WS/BSRT/BGV

Emittance “change” due to tilting



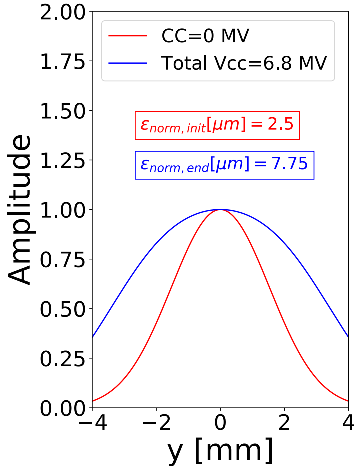
ACFCA.AL5.B2 set to 6.8 MV

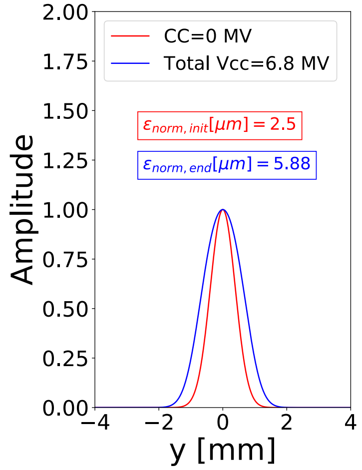
no CC kick

with 6.8 MV kick

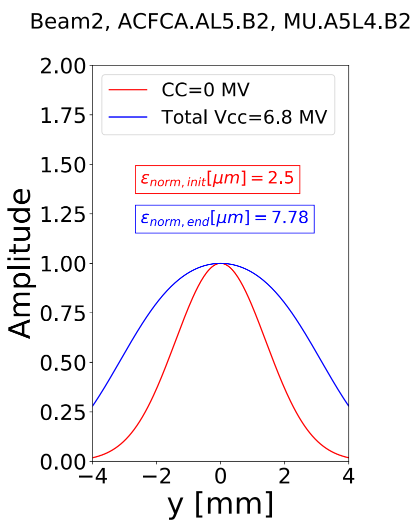
Injection | **Collision**

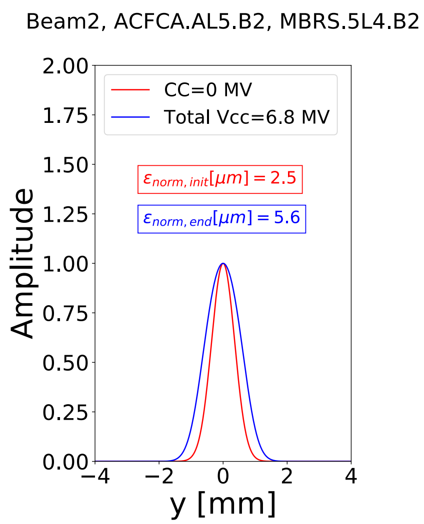
WS



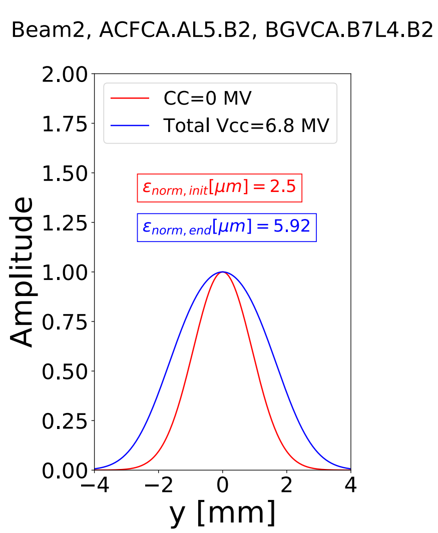


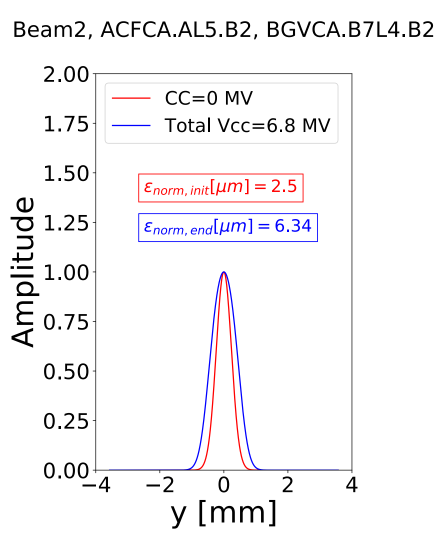
BSRT





BGV





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no CC kick

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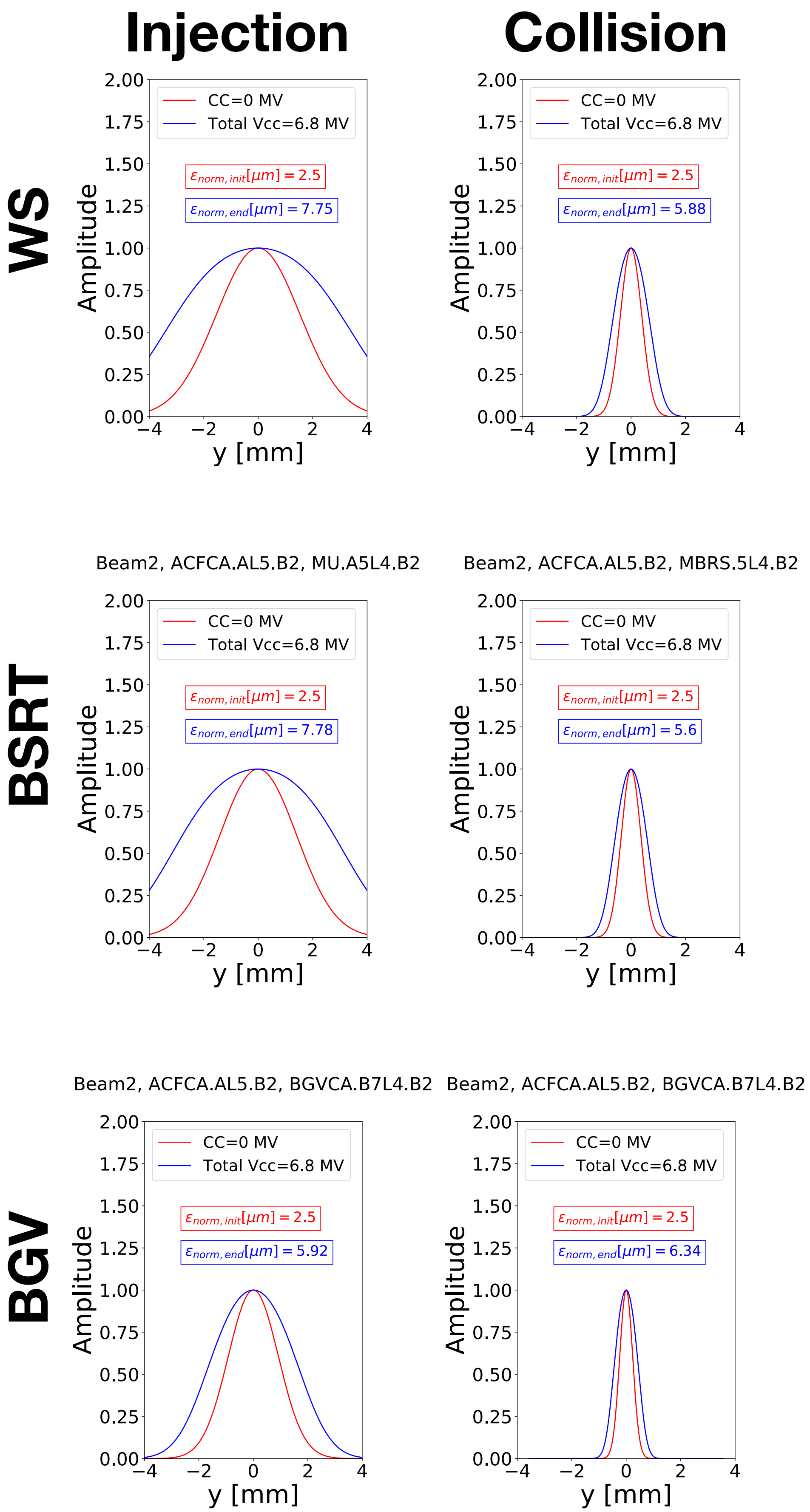

Emittance difference [μm] after a 6.8 MV kick at each of the CC-pairs (init-emit: 2.5μm)

Injection	L1	R1	L5	R5
WS - B1	1.833	1.505	0.065	1.114
WS - B2	1.546	2.313	5.252	0.532
BSRT - B1	3.012	1.588	0.021	1.592
BSRT - B2	1.590	3.563	5.283	0.649
BGV - B2	0.884	0.110	3.418	0.047
Collision	**L1**	**R1**	**L5**	**R5**
WS - B1	0.821	1.065	1.109	1.026
WS - B2	0.994	0.798	3.381	3.446
BSRT - B1	1.312	1.670	0.859	0.785
BSRT - B2	1.792	1.463	3.096	3.174
BGV - B2	0.002	0.006	3.840	3.803

Is beam-size change due to 6.8 MV kick within resolution?

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Injection

Table 12: Checking whether beam-size change is within instrumental resolution at injection

	CC	σ_{init} [μm]	σ_{end} [μm]	σ_{dif} [μm]	σ_{dif} - 10 μm	
WS-B1	L1	1018.56	1341.01	322.44	312.44	
	R1	1012.96	1282.03	269.07	259.07	
	L5	1447.97	1466.64	18.67	8.67	
	R5	1447.83	1740.83	293.00	283.00	
WS-B2	L1	1013.45	1289.24	275.80	265.80	
	R1	1013.24	1405.82	392.59	382.59	
	L5	1534.39	2701.97	1167.58	1157.58	
	R5	1534.53	1689.95	155.42	145.42	
BSRT-B1	L1	1038.82	1542.48	503.66	493.66	
	R1	1035.75	1324.55	288.79	278.79	
	L5	1352.94	1358.68	5.74	-4.26	
	R5	1352.76	1730.65	377.88	367.88	
BSRT-B2	L1	1036.23	1325.36	289.13	279.13	
	R1	1037.46	1615.59	578.13	568.13	
	L5	1413.34	2493.71	1080.36	1070.36	
	R5	1413.52	1586.53	173.00	163.00	
	CC	σ_{init} [μm]	σ_{end} [μm]	σ_{dif} [μm]	0.05*σ_{init}	σ_{dif} [μm]-0.05*σ_{init}
BGV-B1	L1	1324.93	1383.95	59.02	66.25	-7.23
	R1	1314.51	1555.47	240.96	65.73	175.23
	L5	356.01	431.72	75.71	17.80	57.91
	R5	356.08	450.60	94.53	17.80	76.72
BGV-B2	L1	861.16	1001.99	140.83	43.06	97.77
	R1	858.34	877.01	18.67	42.92	-24.25
	L5	920.64	1416.50	495.86	46.03	449.83
	R5	920.53	929.17	8.64	46.03	-37.39

Yes, apart from:
BSRT-B1 for L5, BGV-B1 for L1
BGV-B2 for R1 and R5

Collision

Table 13: Checking whether beam-size change is within instrumental resolution at collision

	CC	σ_{init} [μm]	σ_{end} [μm]	σ_{dif} [μm]	σ_{dif} - 10 μm	
WS-B1	L1	257.29	296.56	39.27	29.27	
	R1	256.61	306.42	49.82	39.82	
	L5	367.04	440.99	73.95	63.95	
	R5	367.04	435.93	68.89	58.89	
WS-B12	L1	256.88	303.70	46.83	36.83	
	R1	256.91	295.09	38.18	28.18	
	L5	389.39	597.26	207.86	197.86	
	R5	389.39	600.54	211.14	201.14	
BSRT-B1	L1	260.49	321.67	61.18	51.18	
	R1	259.82	335.48	75.66	65.66	
	L5	349.21	404.81	55.60	45.60	
	R5	349.21	400.31	51.10	41.10	
BSRT-B2	L1	262.17	343.52	81.35	71.35	
	R1	262.50	330.50	68.00	58.00	
	L5	359.81	538.35	178.54	168.54	
	R5	359.81	542.05	182.24	172.24	
	CC	σ_{init} [μm]	σ_{end} [μm]	σ_{dif} [μm]	0.05*σ_{init}	σ_{dif} [μm]-0.05*σ_{init}
BGV-B1	L1	337.17	338.93	1.76	16.86	-15.09
	R1	336.59	339.89	3.30	16.83	-13.53
	L5	170.50	257.66	87.16	8.52	78.64
	R5	170.49	255.94	85.45	8.52	76.92
BGV-B2	L1	219.32	219.41	0.08	10.97	-10.88
	R1	218.74	218.98	0.24	10.94	-10.69
	L5	237.86	378.78	140.92	11.89	129.03
	R5	237.86	377.69	139.83	11.89	127.94

Yes, apart from:
BGV-B1 and BGV-B2
for L1 and R1

Layout

- Introduction
- Available instruments:
  - BPMs: charge centre with applied filter
  - HT monitors: transverse offset along bunch due to beam crabbing
  - WS/BSRT/BGV monitors: beam-profile change
- Conclusions

Conclusions

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- Overview of available instrumentation and observation estimates for HL-LHC at injection and collision energies

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    - HT monitors at operation-scenario: cannot read beam-leakage

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  - HT monitors: transverse offset along bunch due to beam crabbing;
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    - HT monitors at operation-scenario: cannot read beam-leakage
  - WS/BSRT/BGV monitors: beam-profile change;
    0.0213 μm-5.28 μm (inj) and 0.0019 μm-3.8399 μm (col)
    <u>Outside resolution, injection</u>: BSRT-B1 for L5, BGV-B1 for L1, BGV-B2 for R1 and R5
    <u>Outside resolution, collision</u>: BGV-B1 and BGV-B2 for L1 and R1

Thanks!

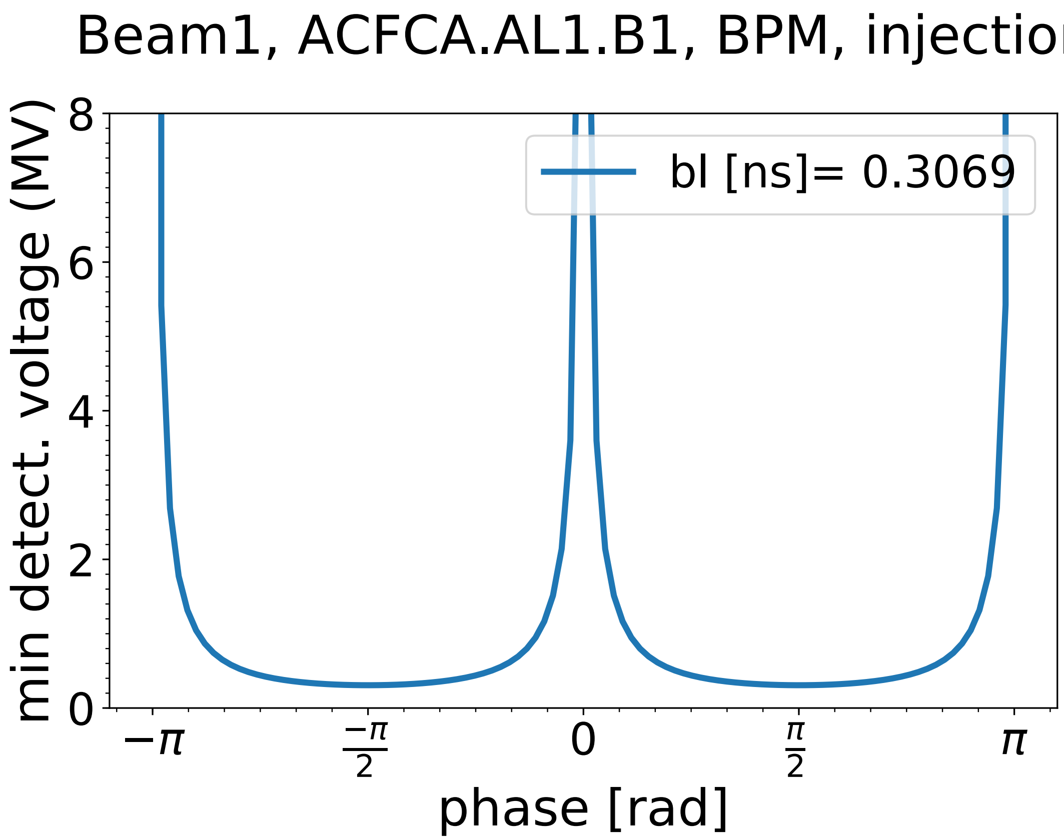
Backup slides

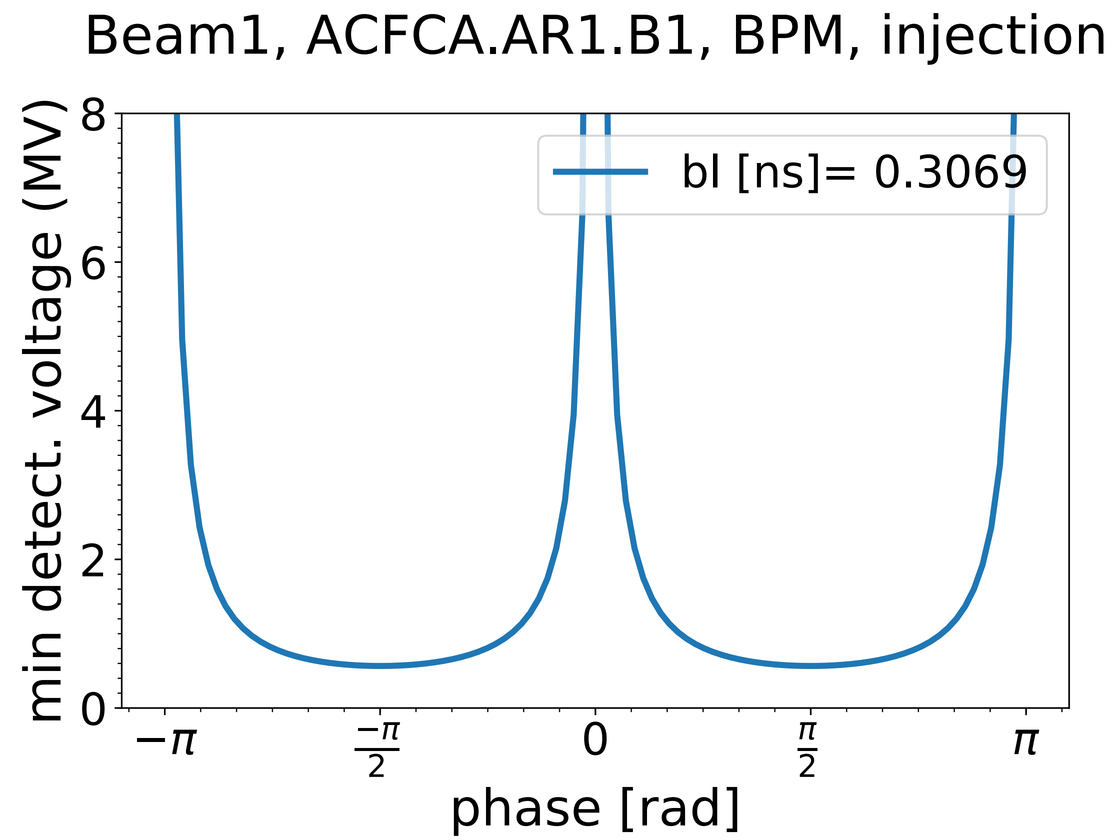
BPM minimum detectable voltage

Injection: B1

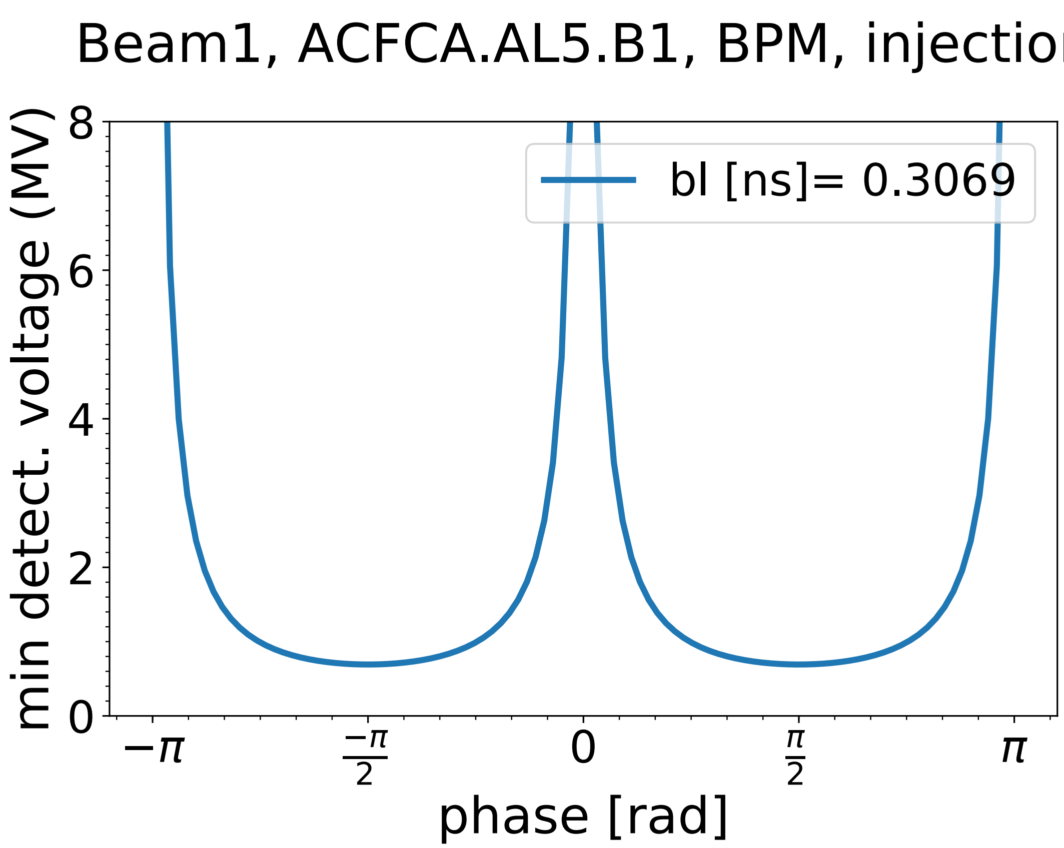
L R

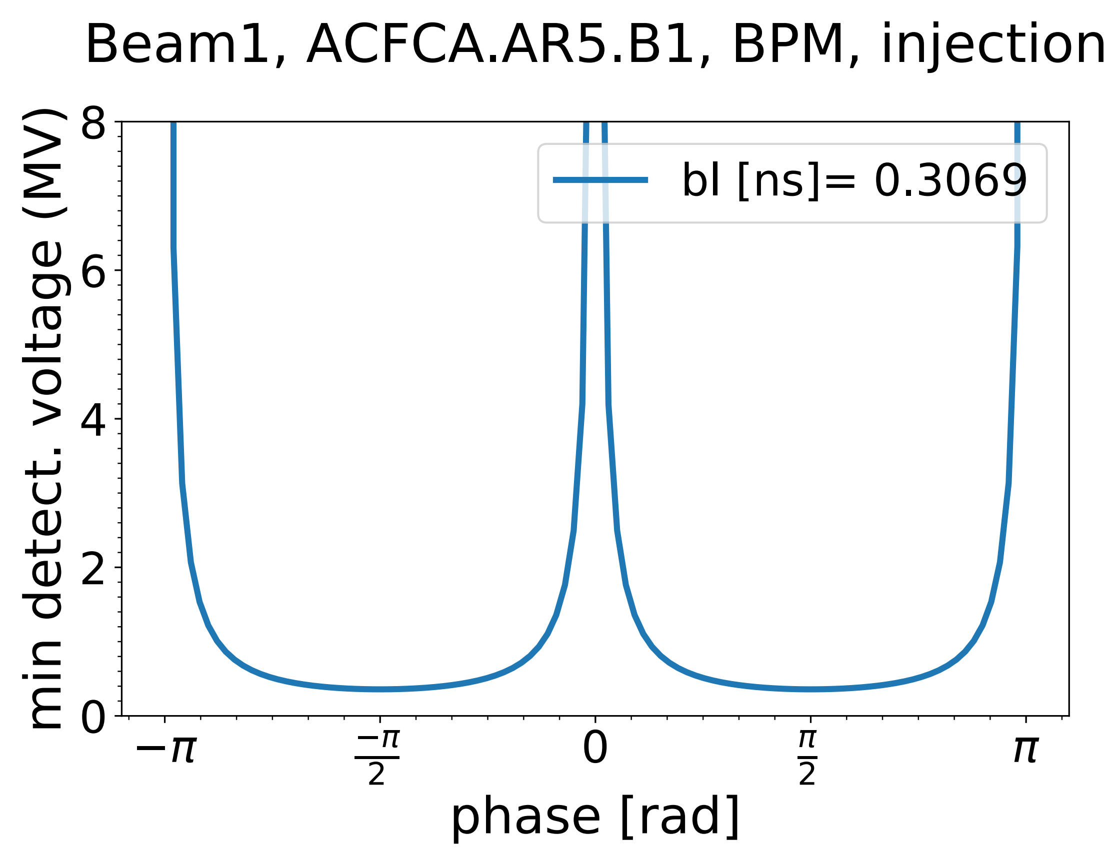
IP1



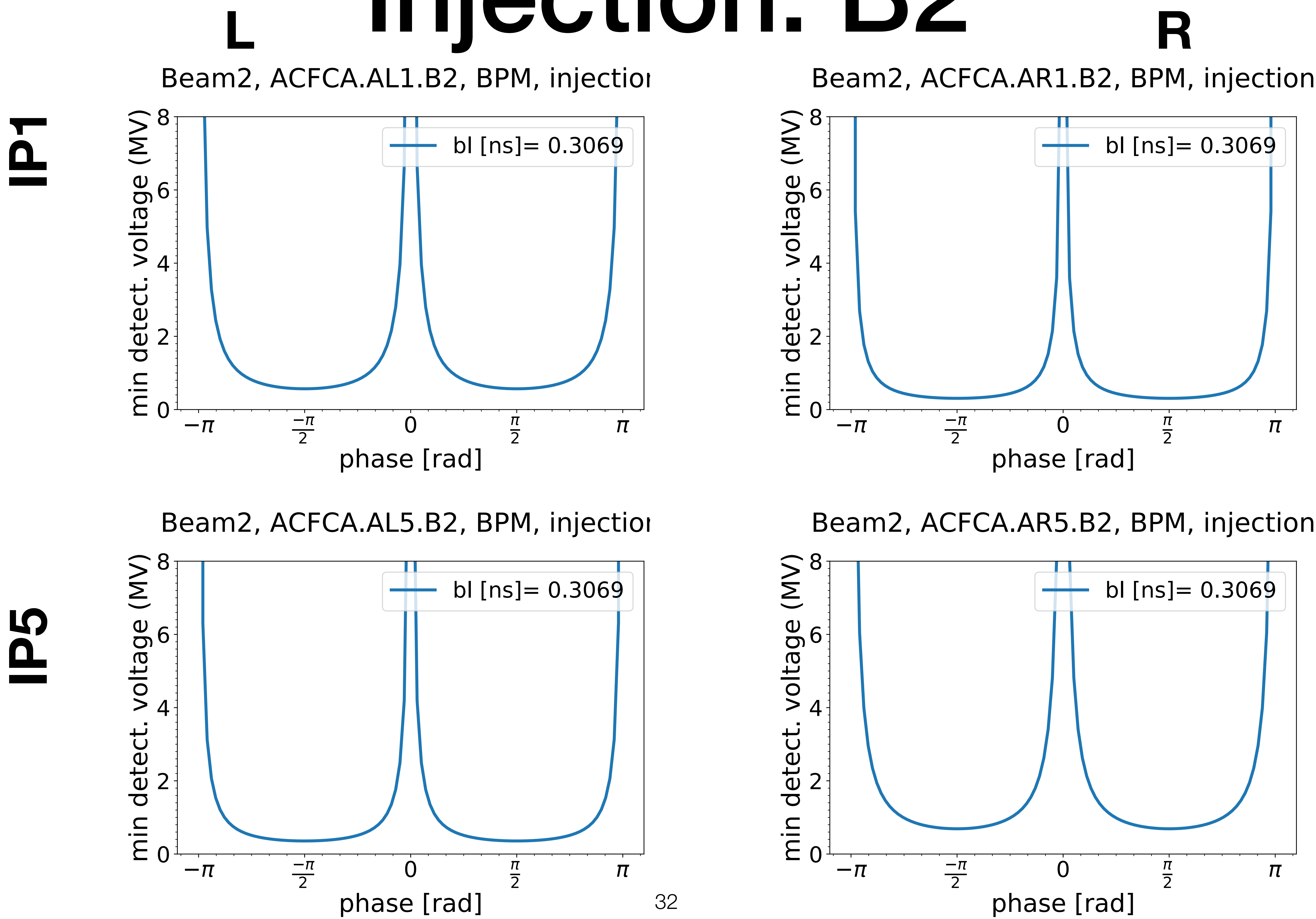


IP5





Injection: B2

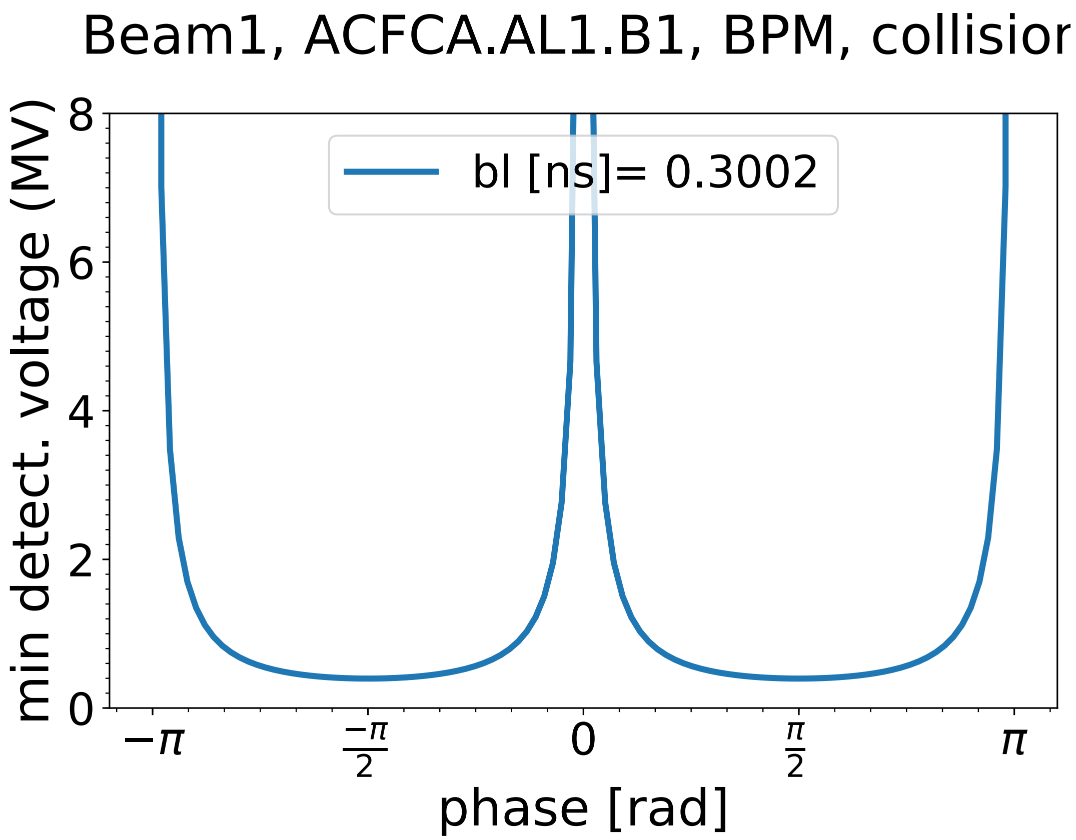


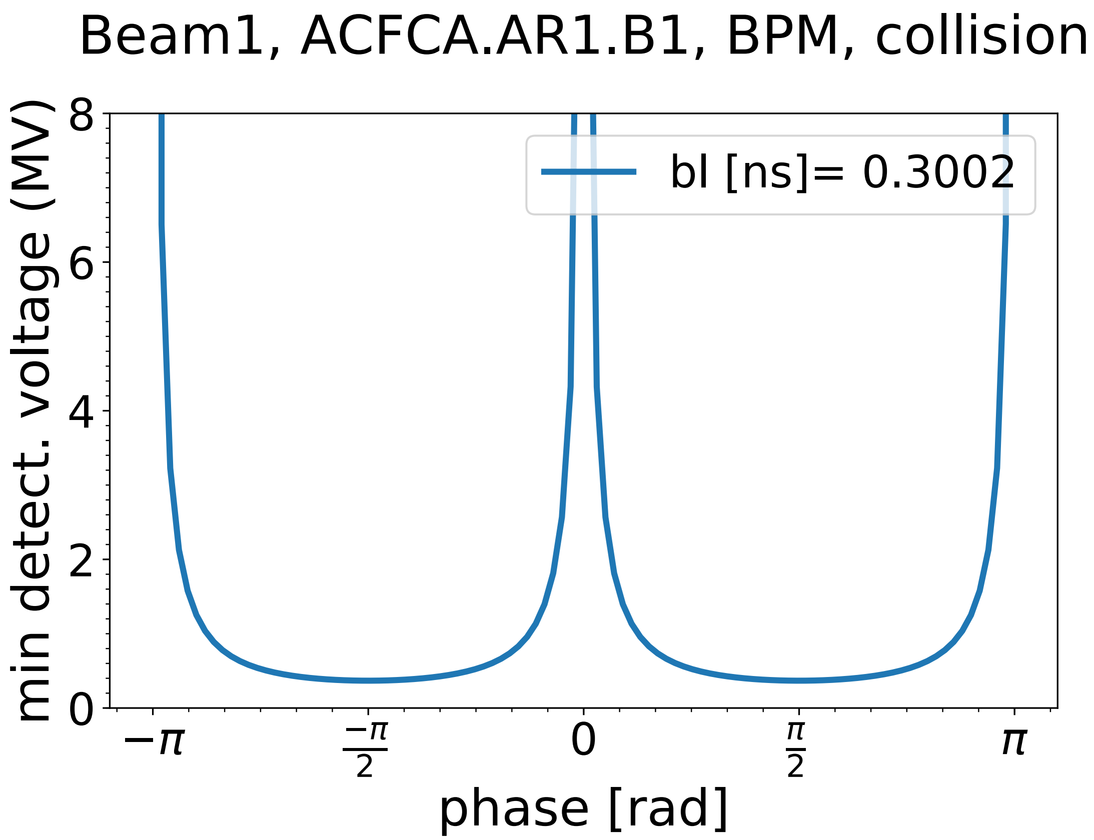
Collision: B1

L

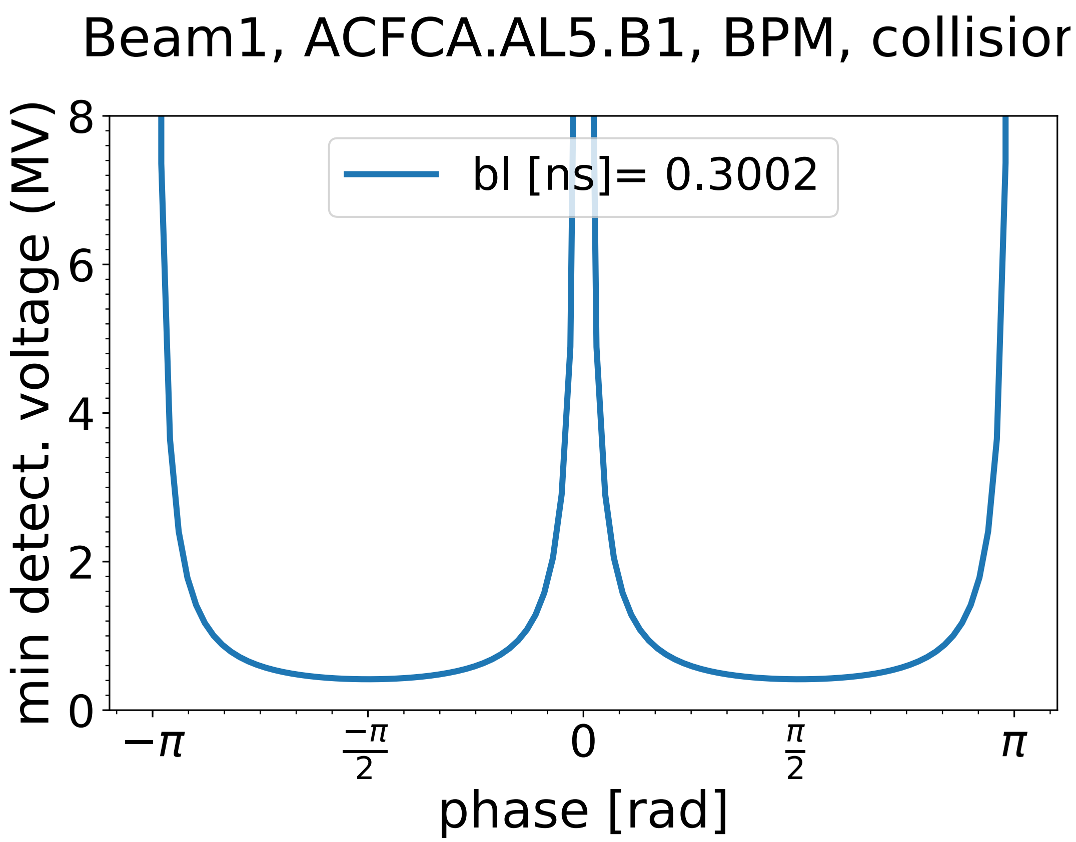
R

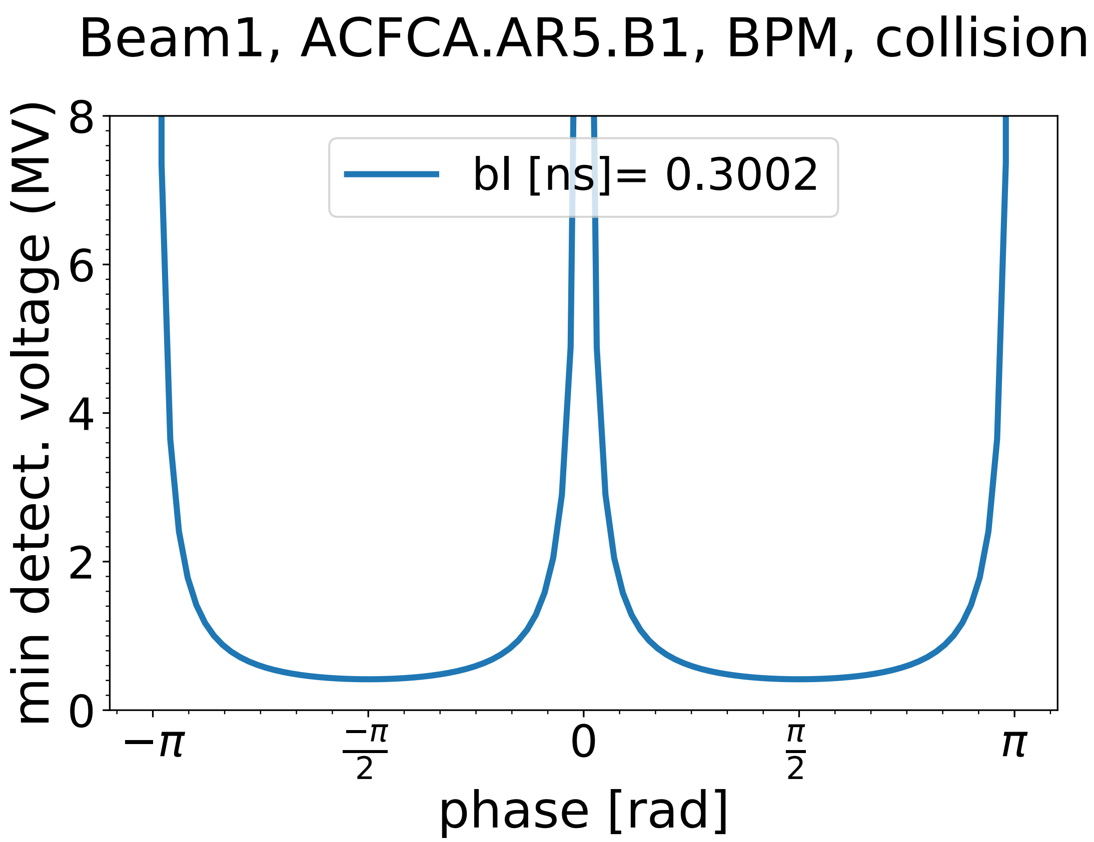
IP1





IP5



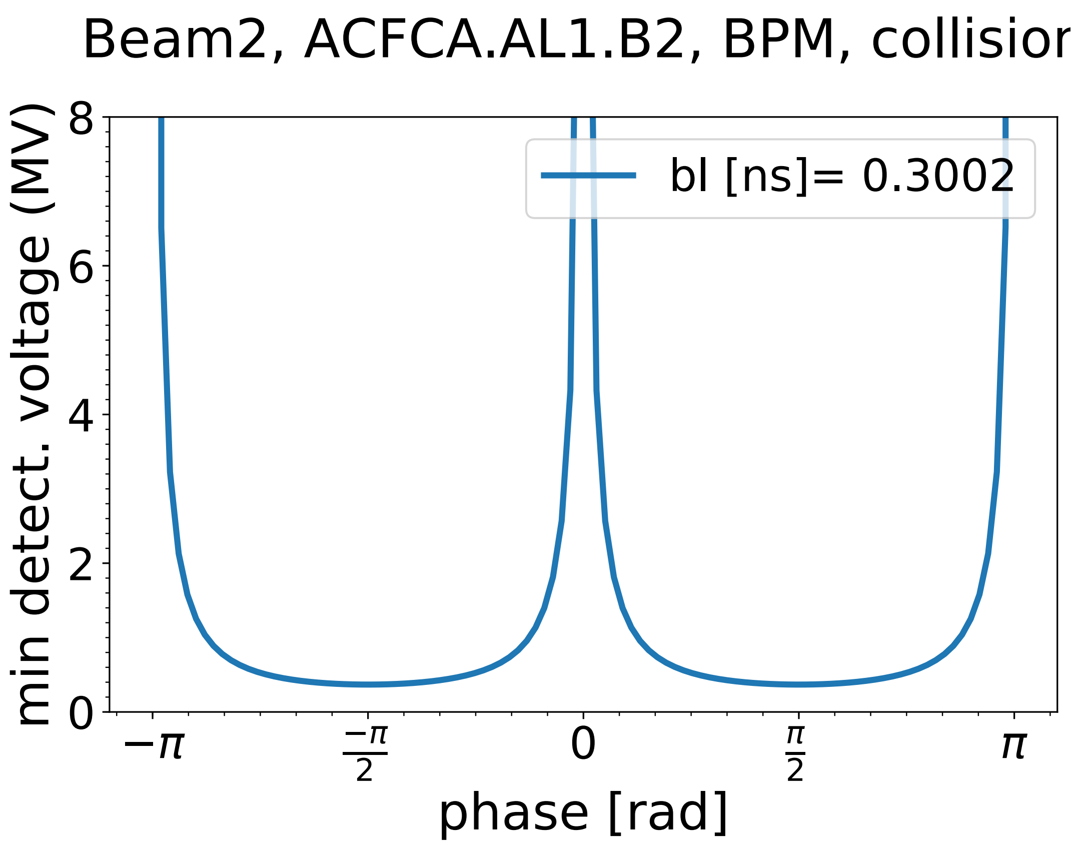


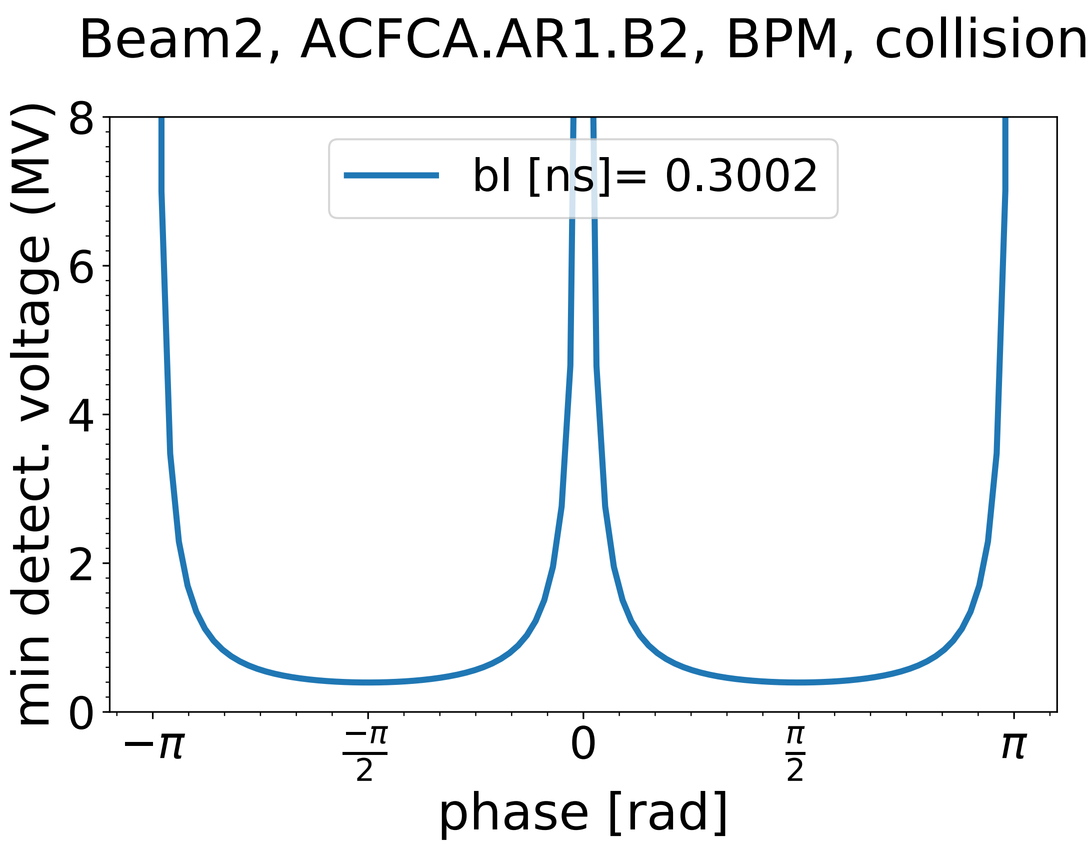
Collision: B2

L

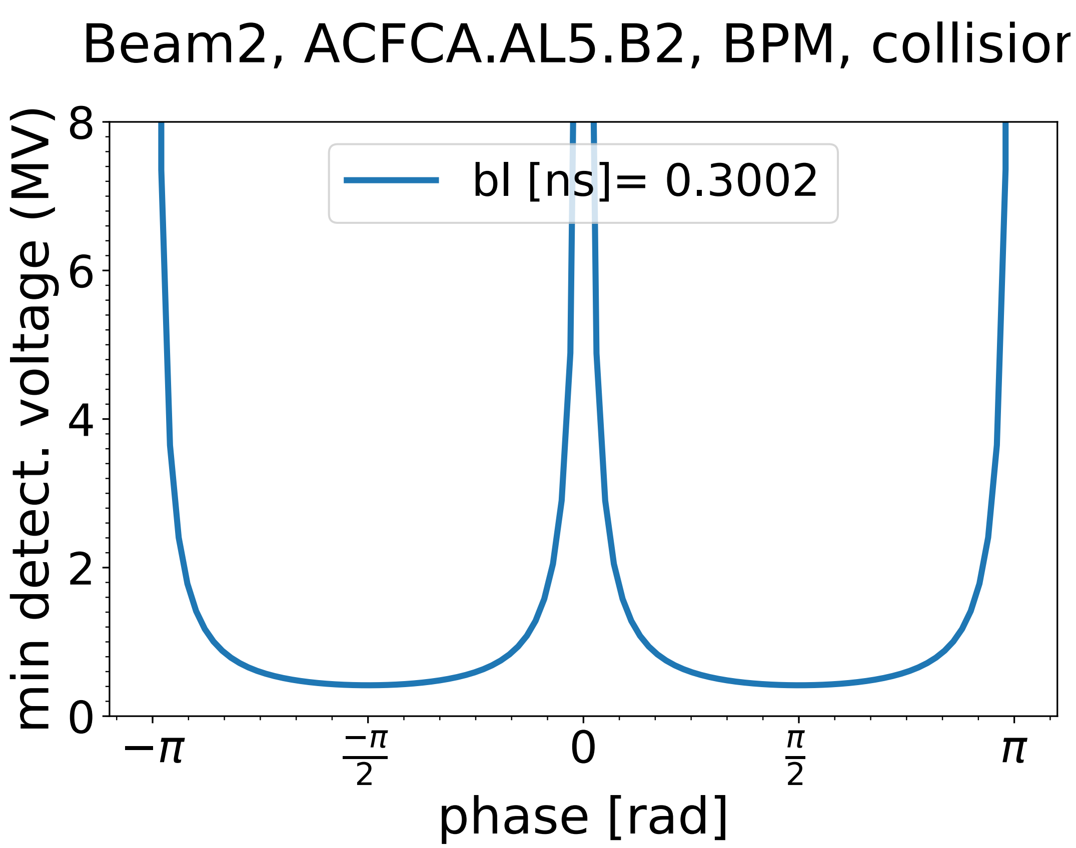
R

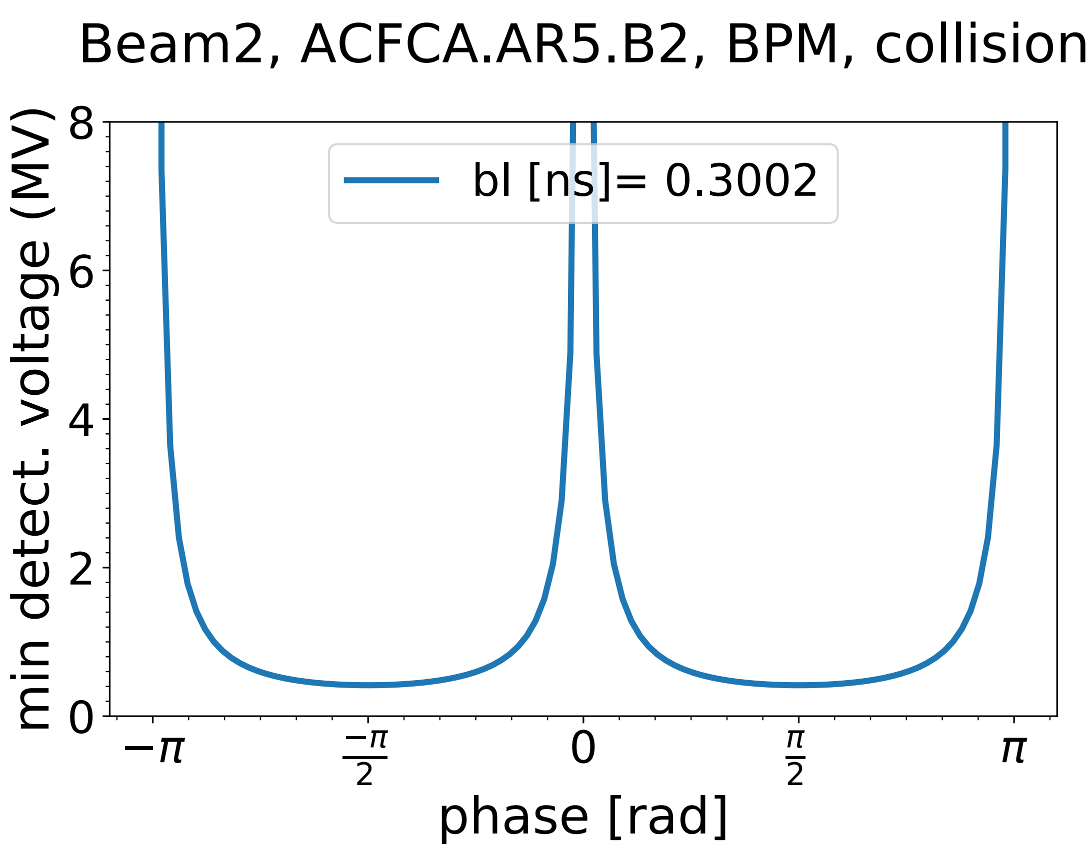
IP1





IP5

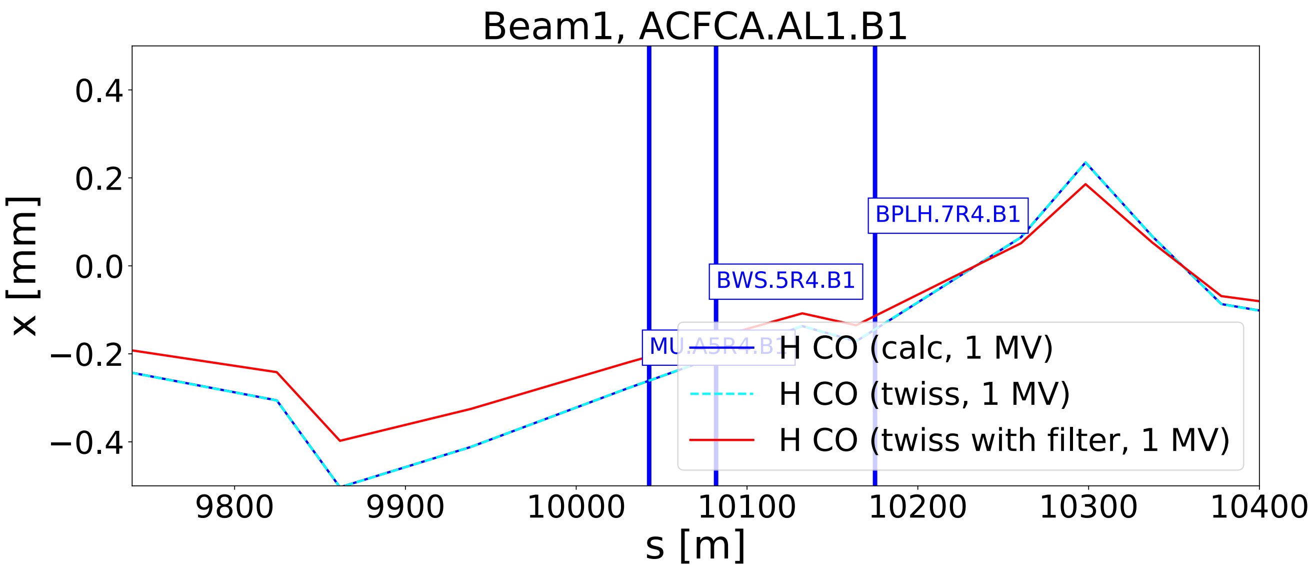


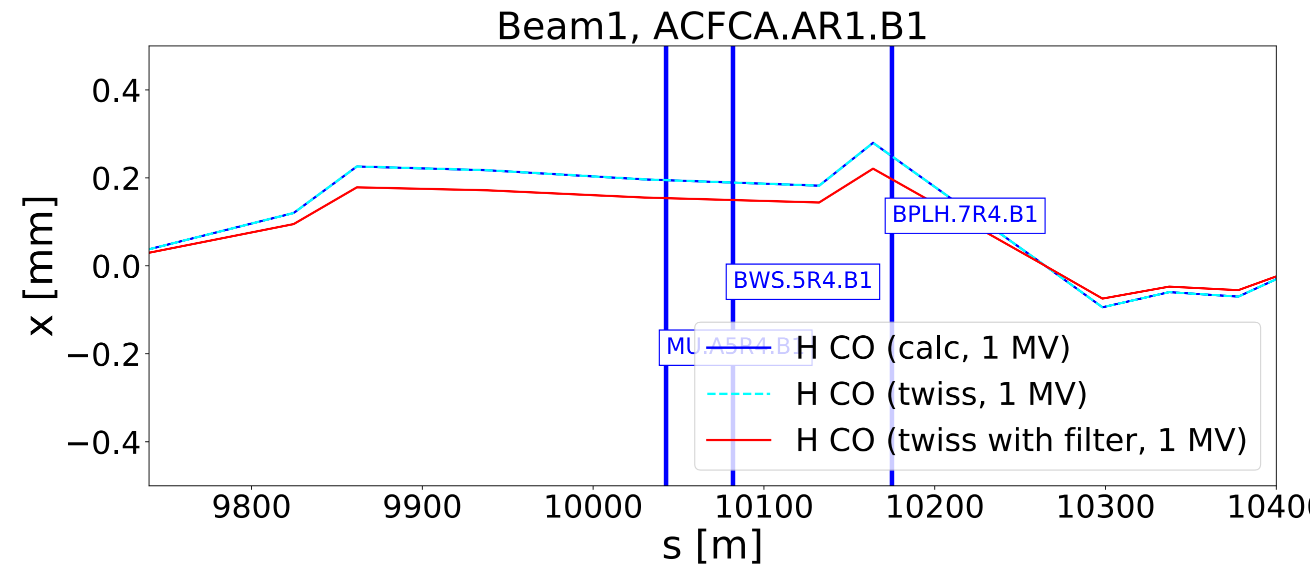


Injection: B1

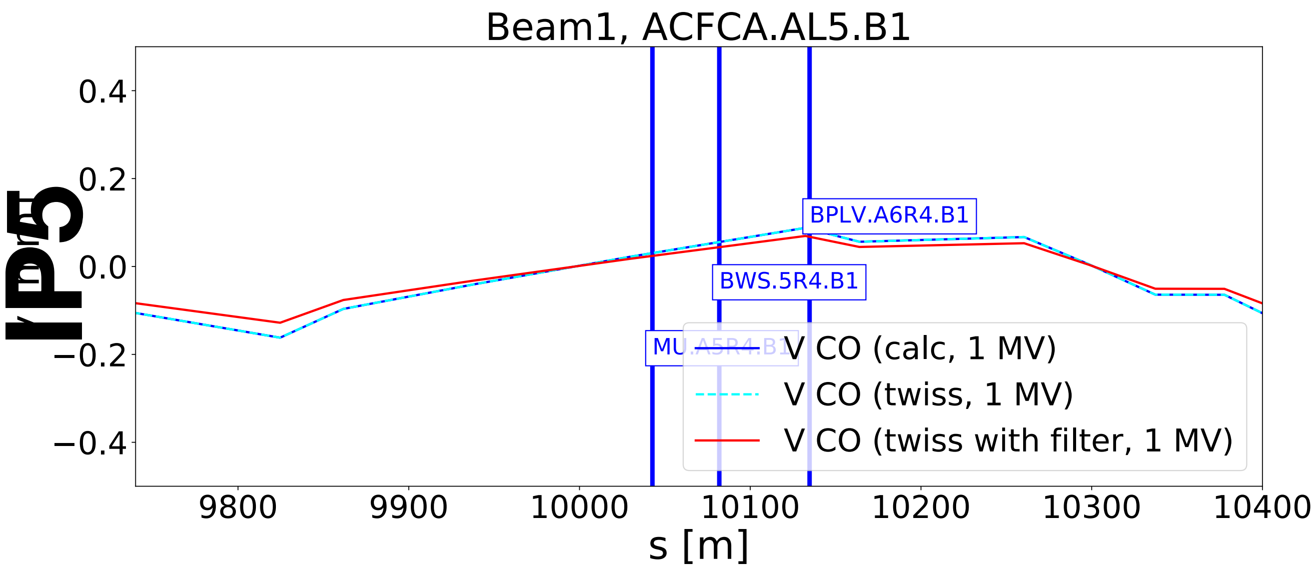
L R

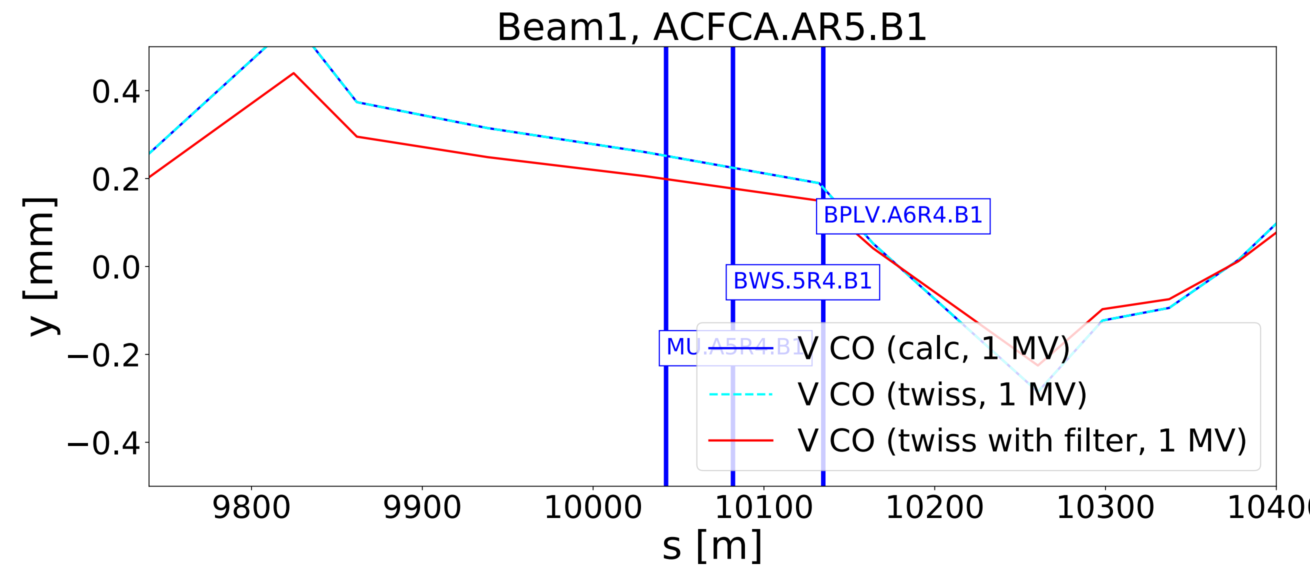
IP1





IP5



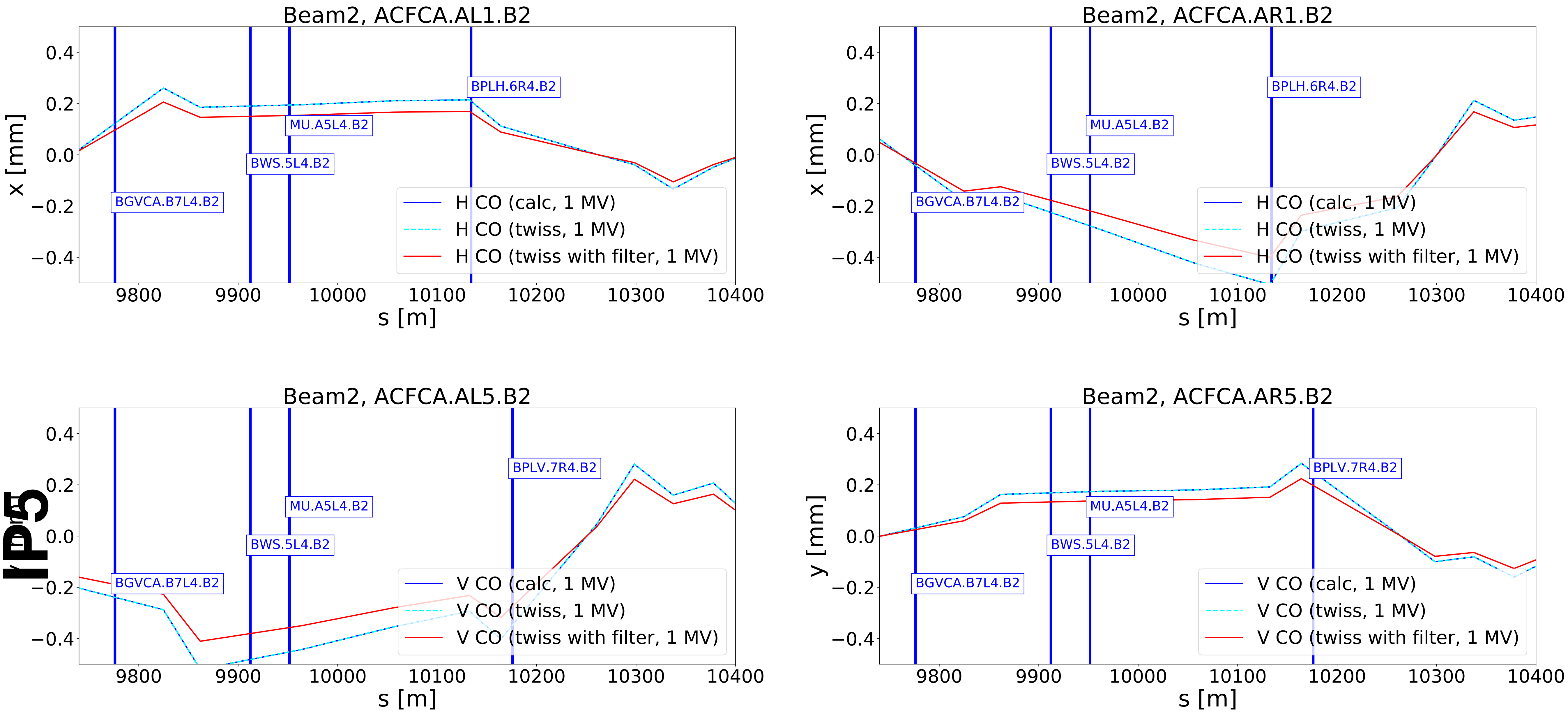


Injection: B2

L R

IP1

IP5



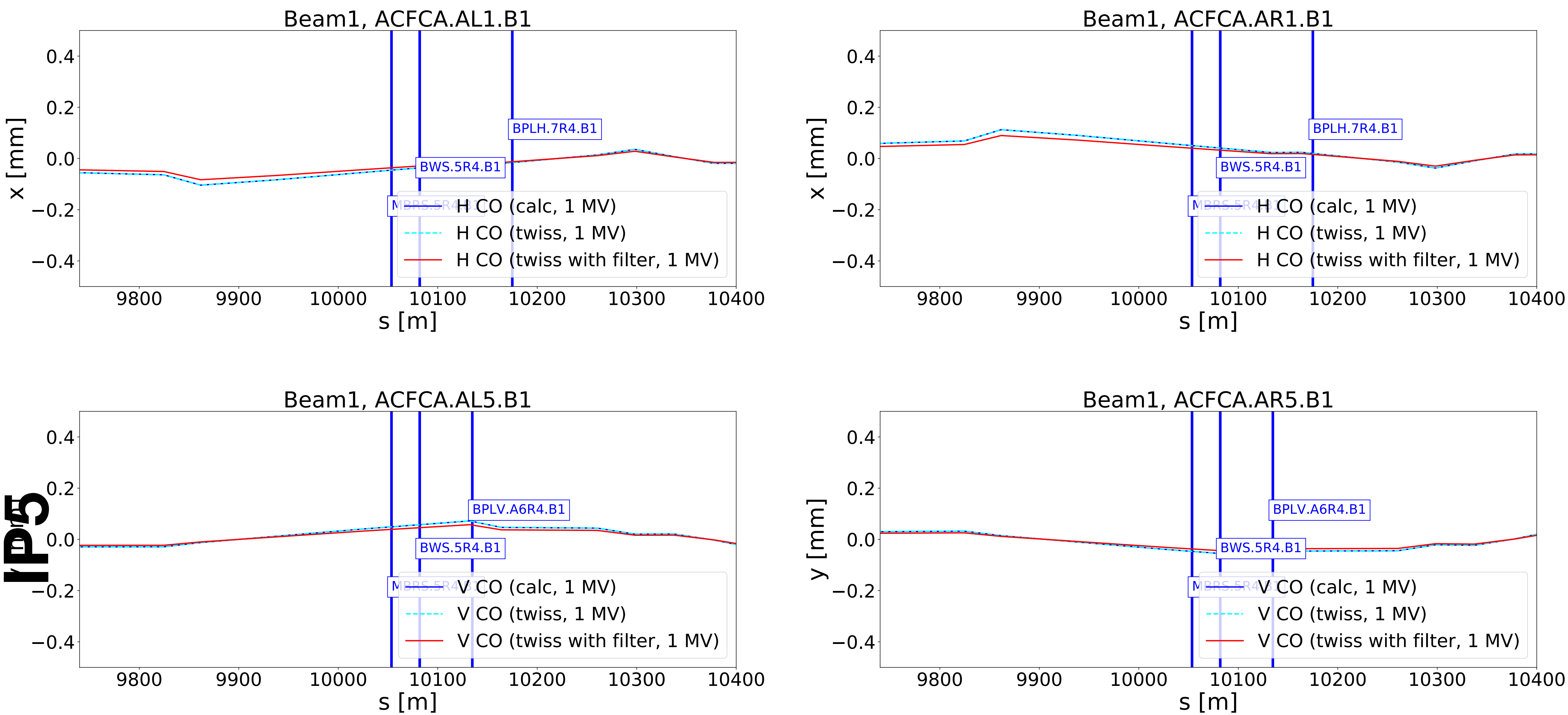
Collision: B1

L

R

IP1

IP5

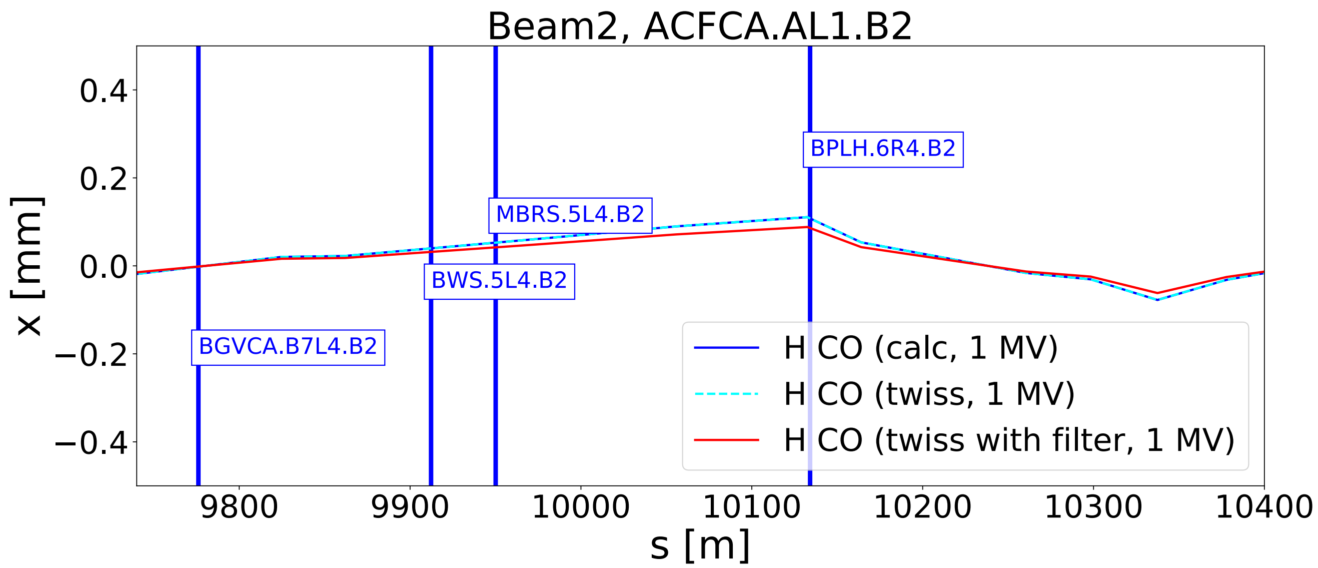


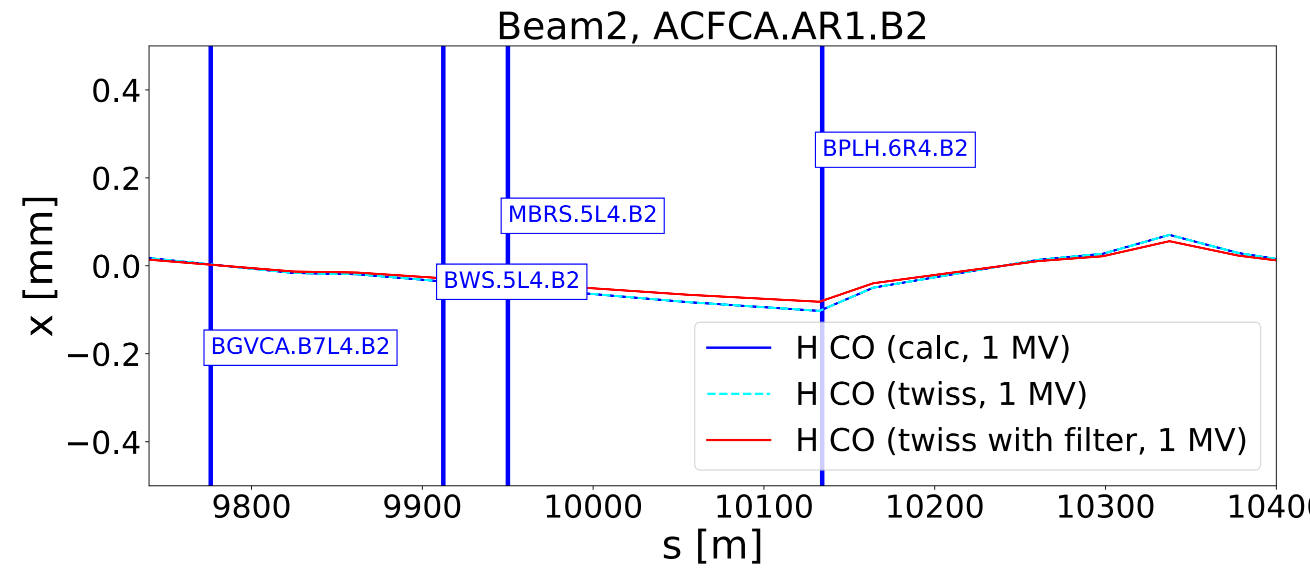
Collision: B2

L

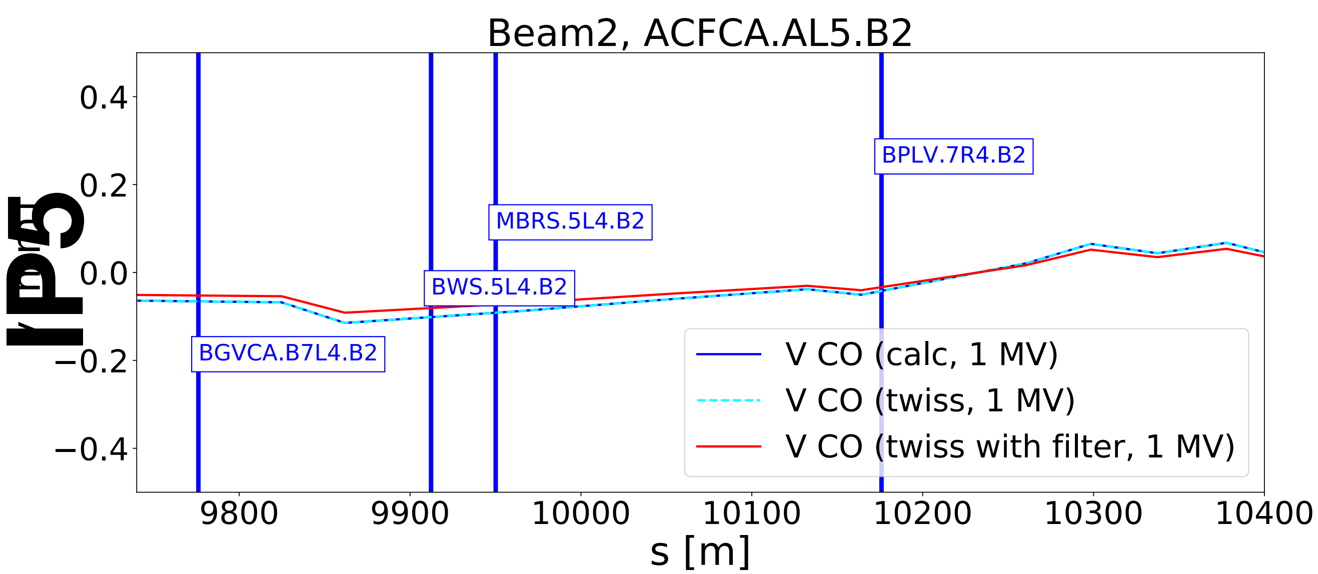
R

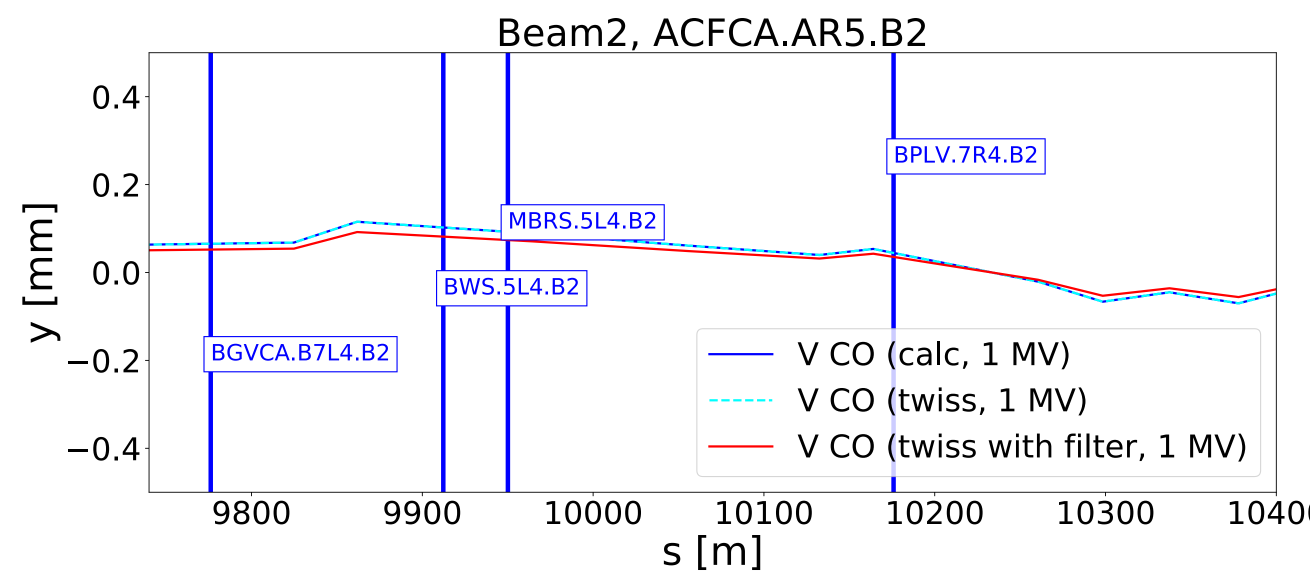
IP1





IP5



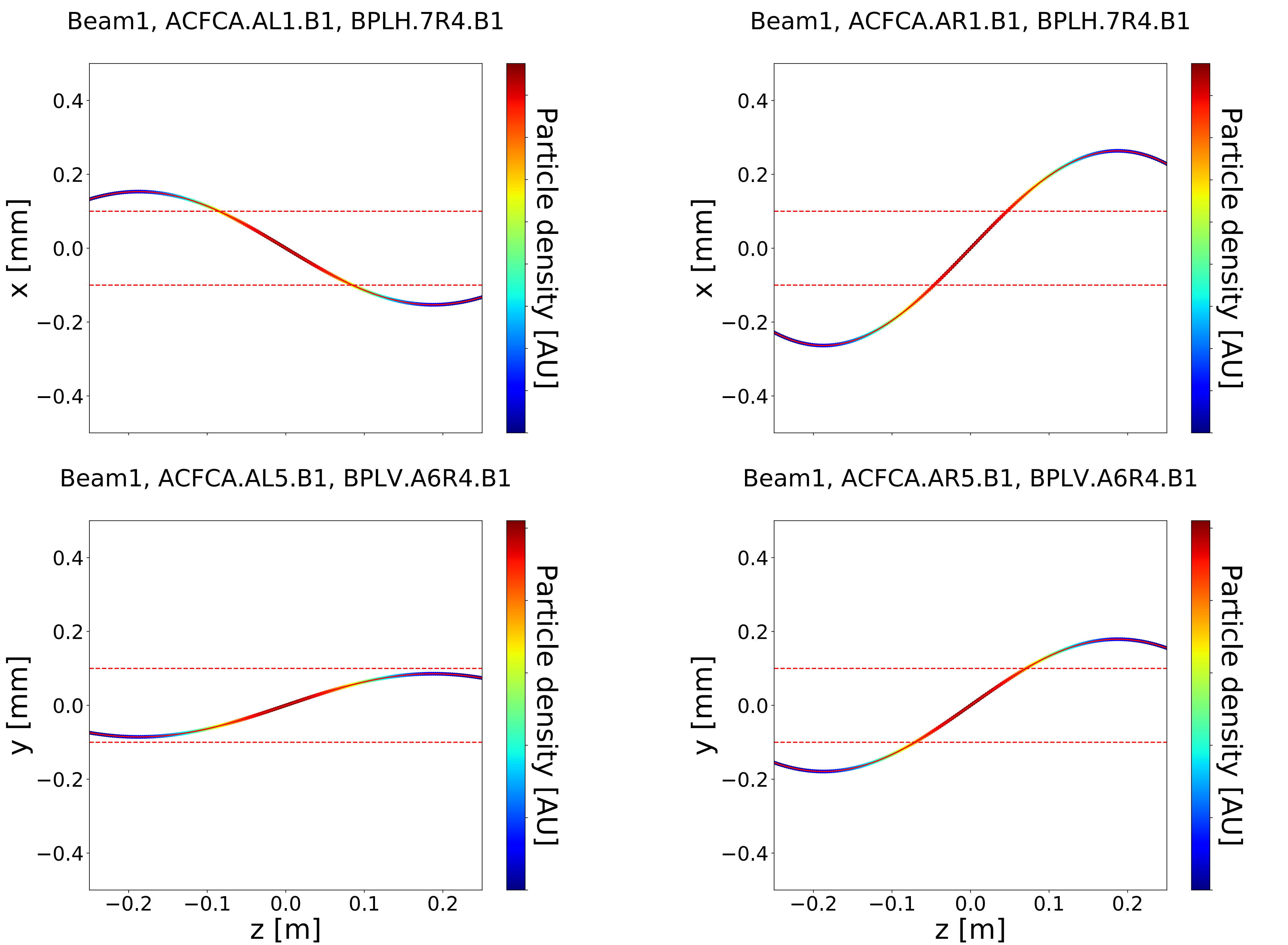


HT

L Injection: B1 R

IP1

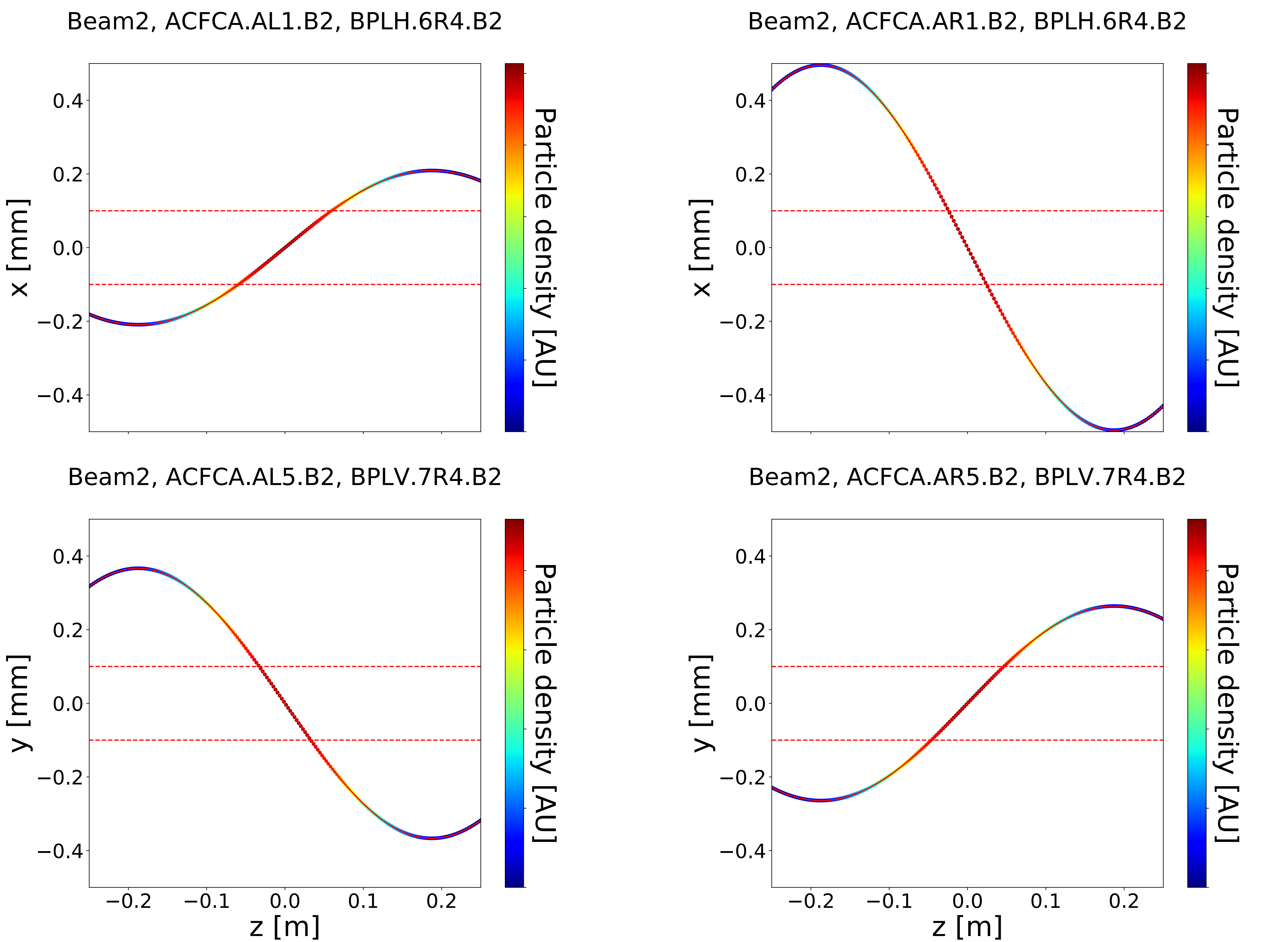
IP5



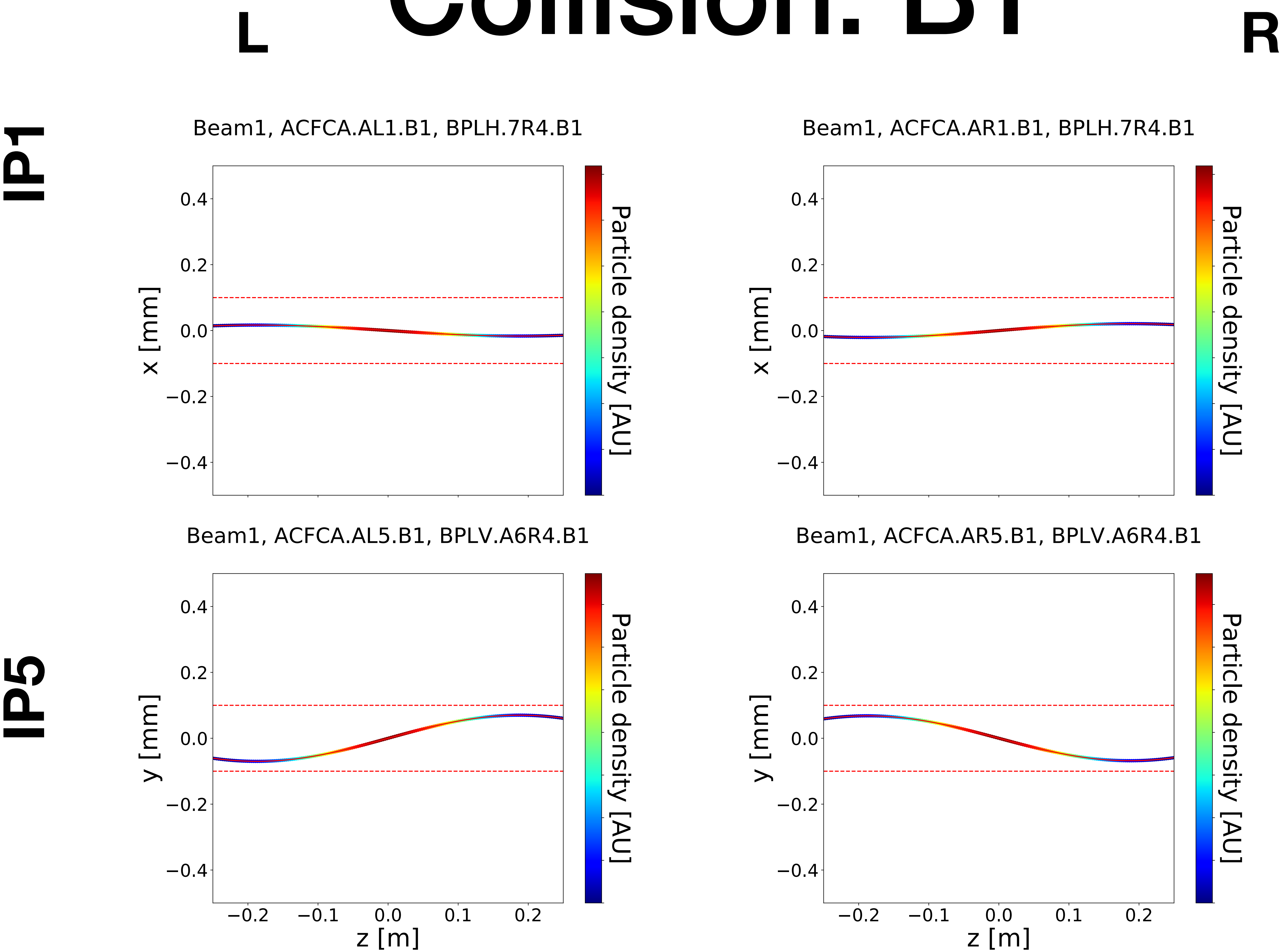
L Injection: B2 R

IP1

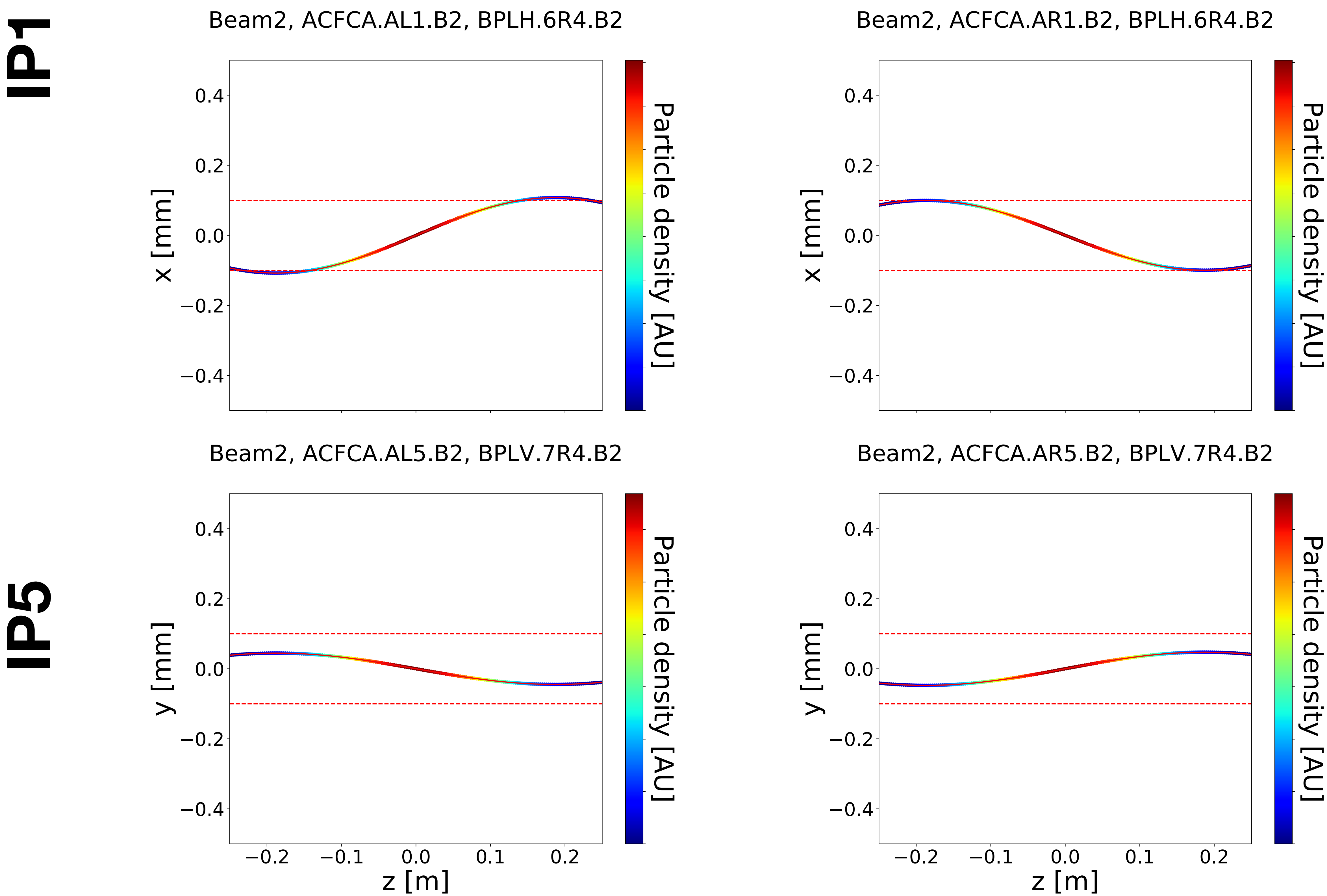
IP5



Collision: B1



L Collision: B2 R



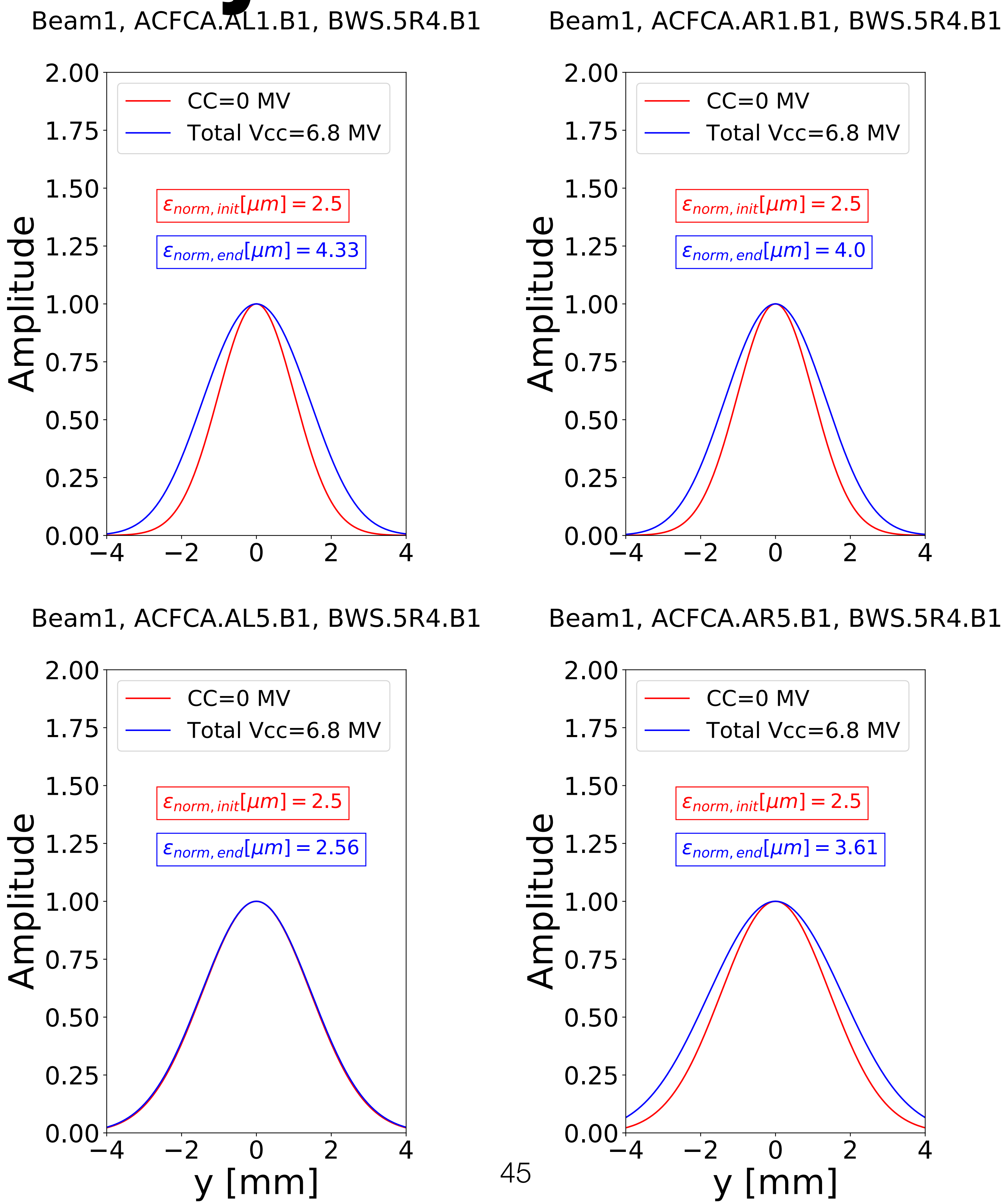
WS

Injection: B1

L R

IP1

IP5

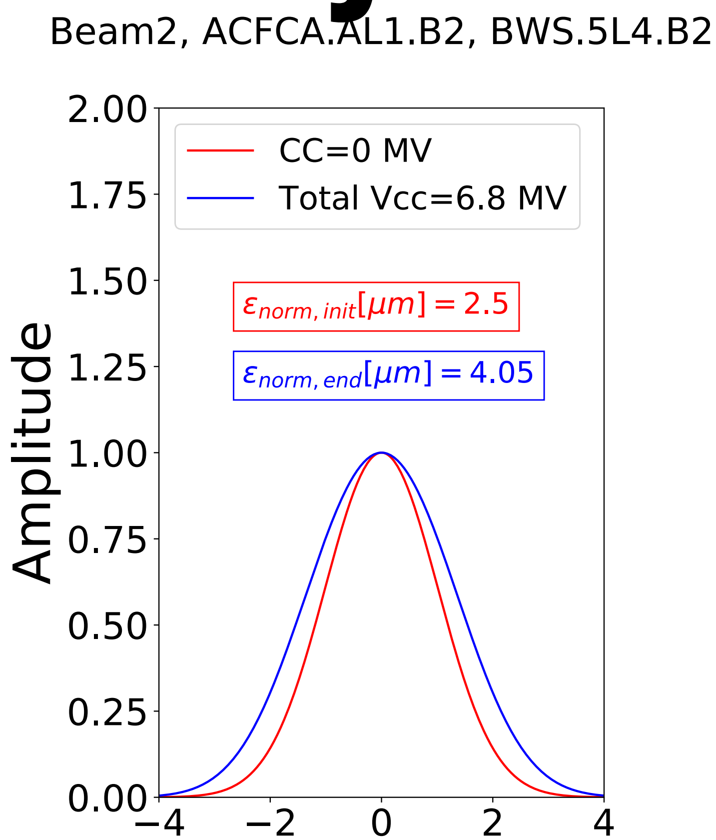


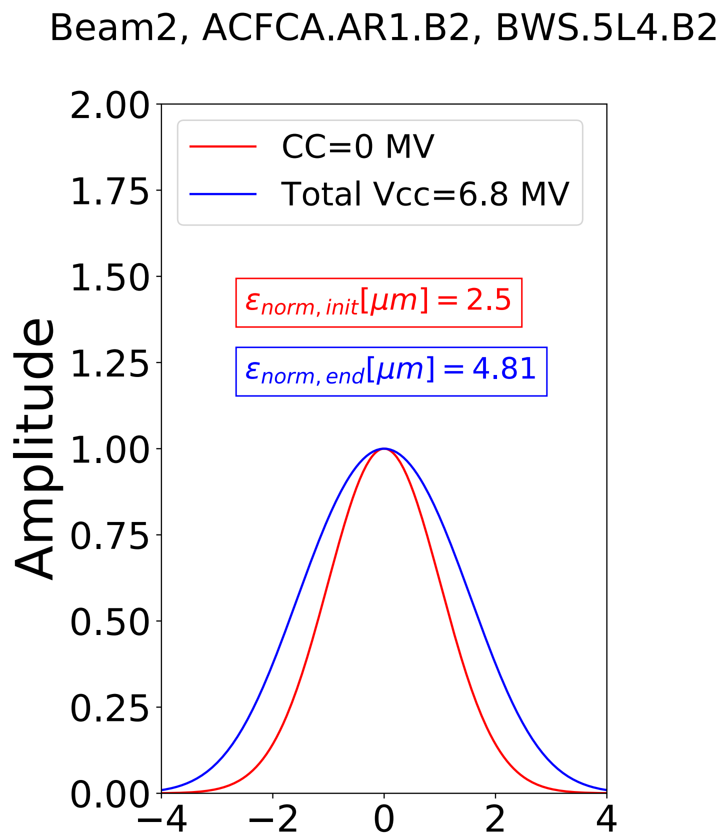
Injection: B2

L

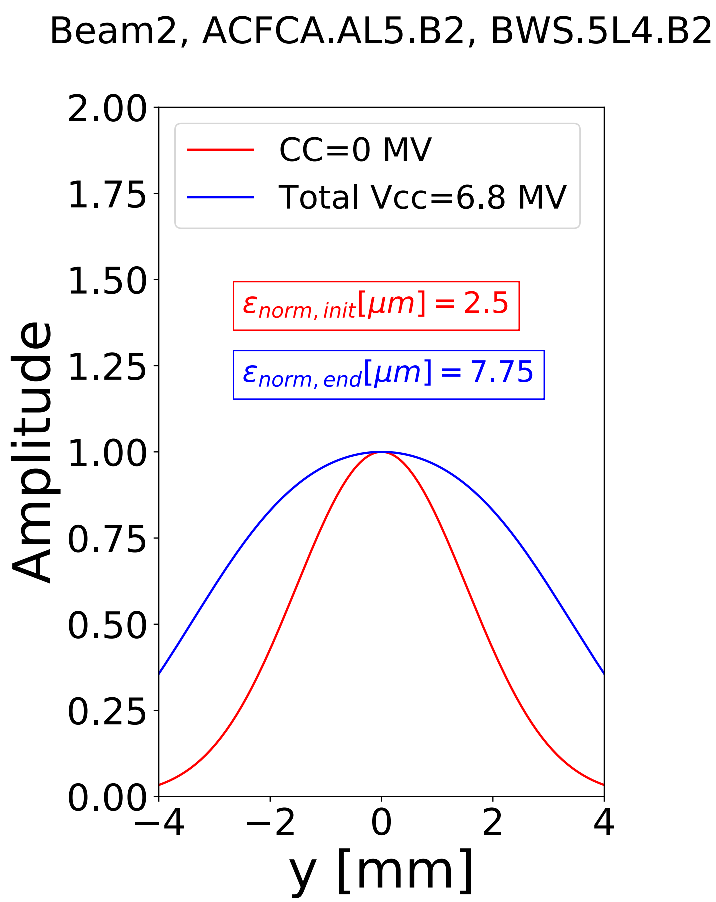
R

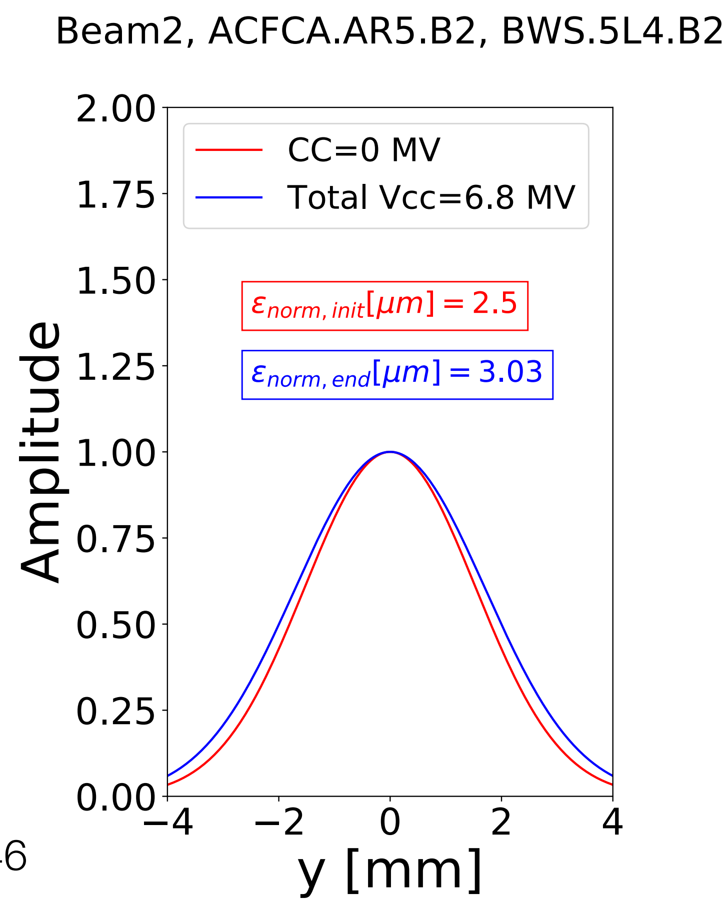
IP1





IP5





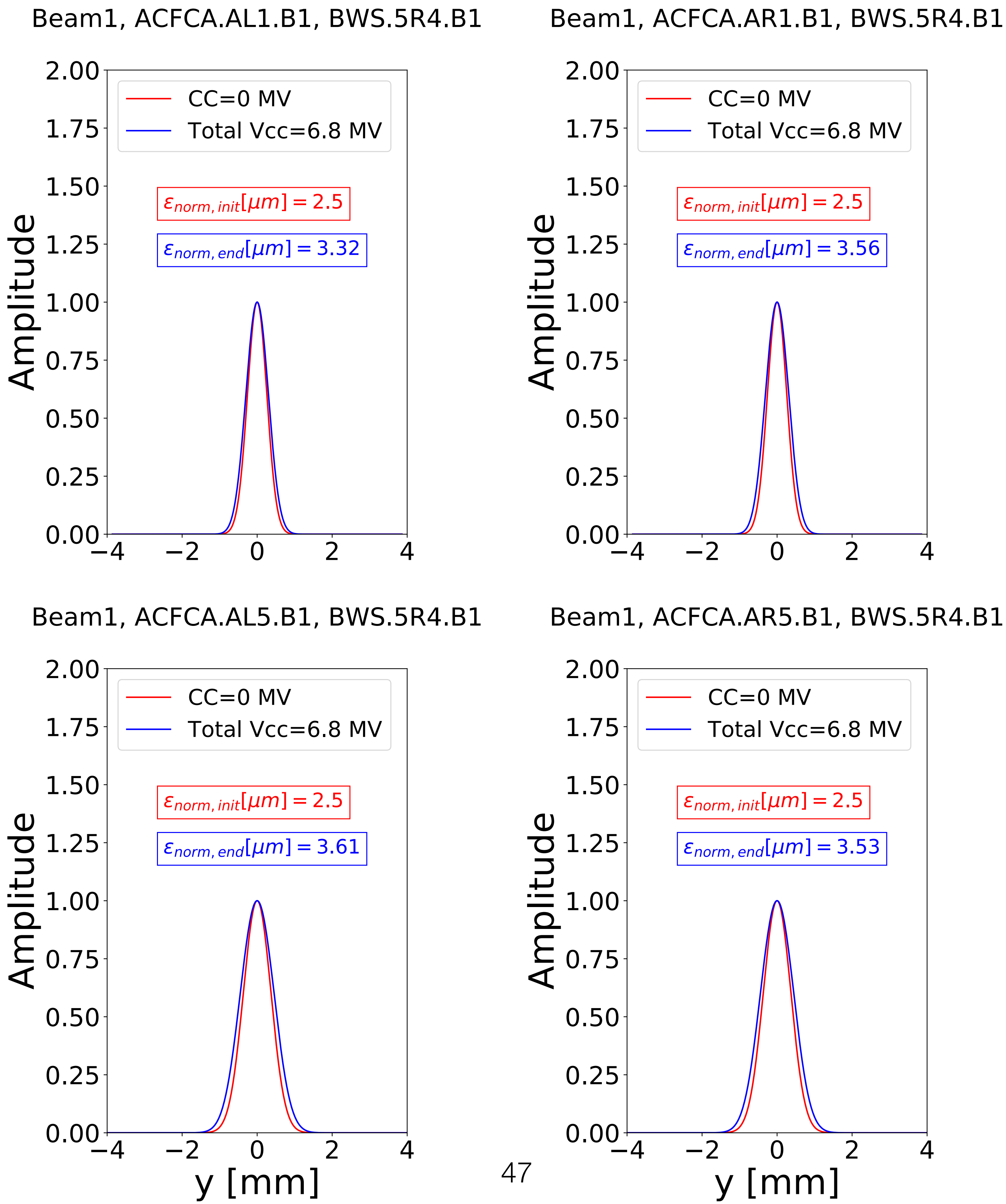
Collision: B1

L

R

IP1

IP5



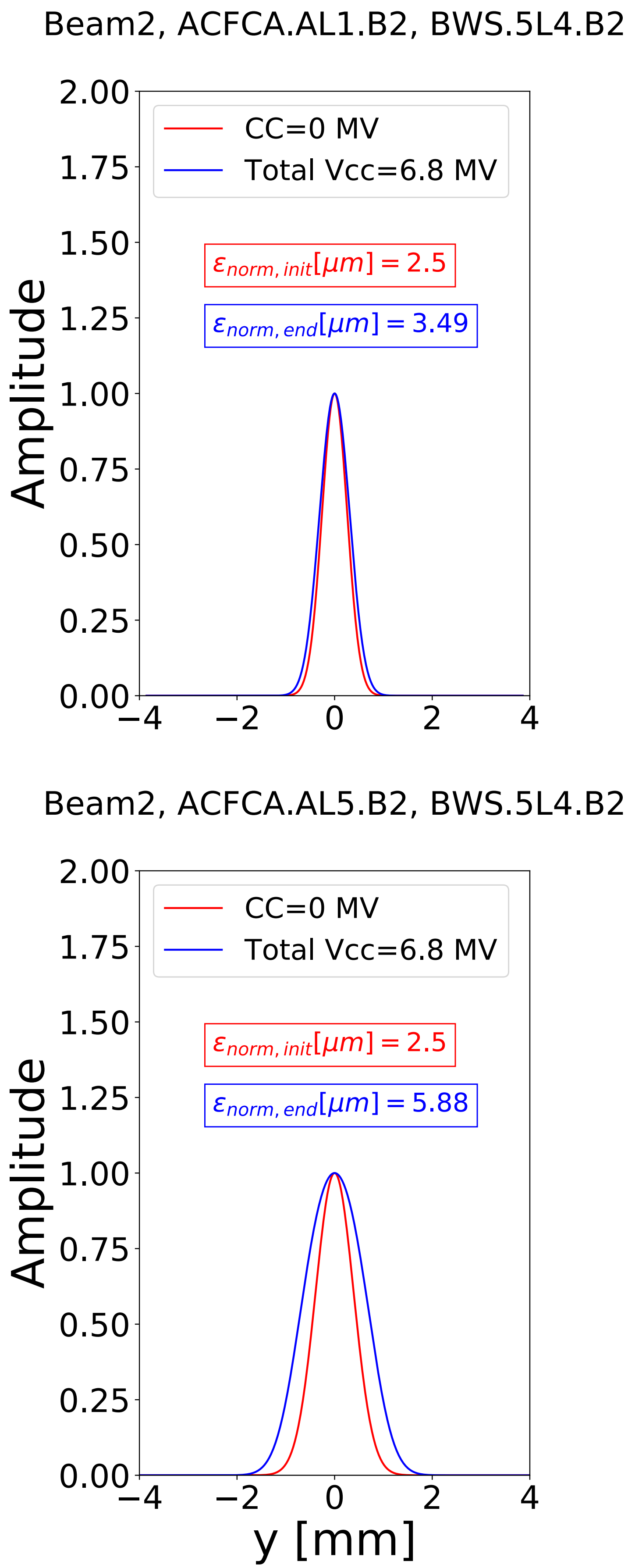
Collision: B2

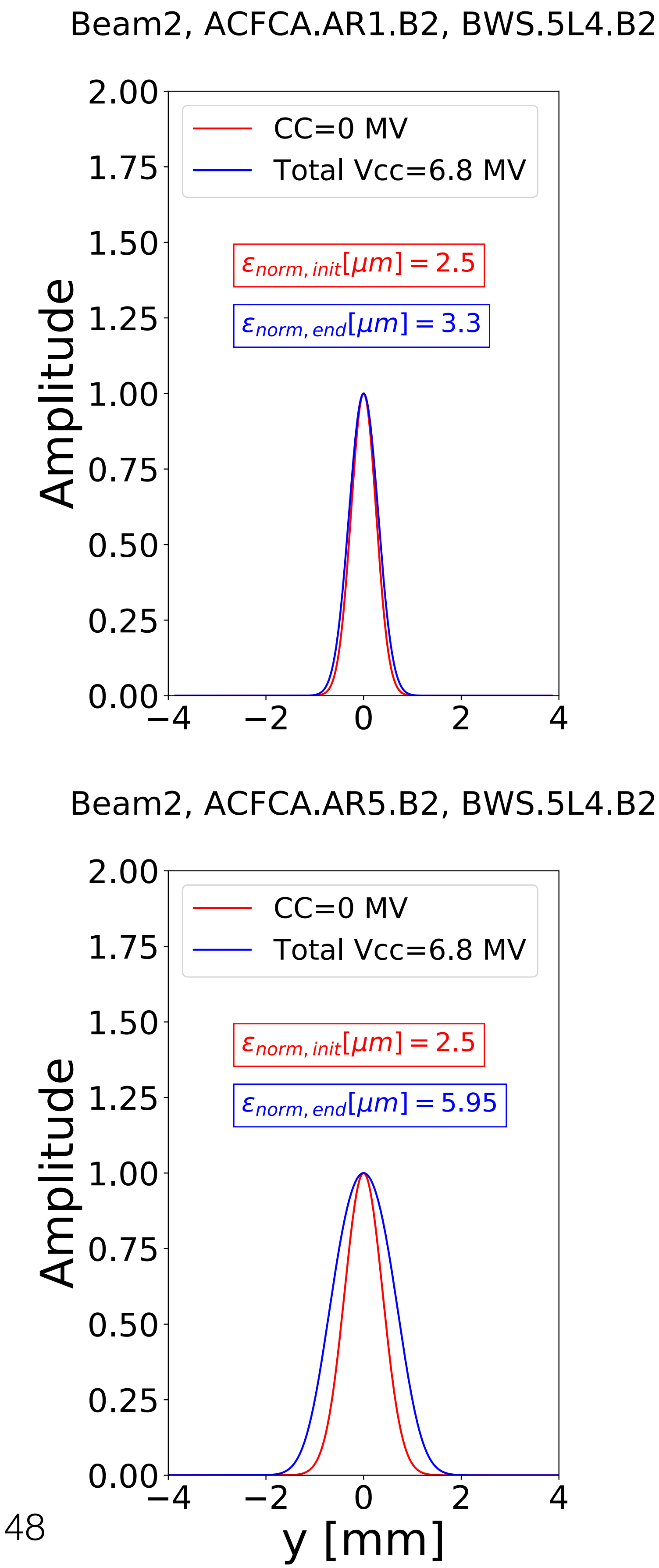
L

R

IP1

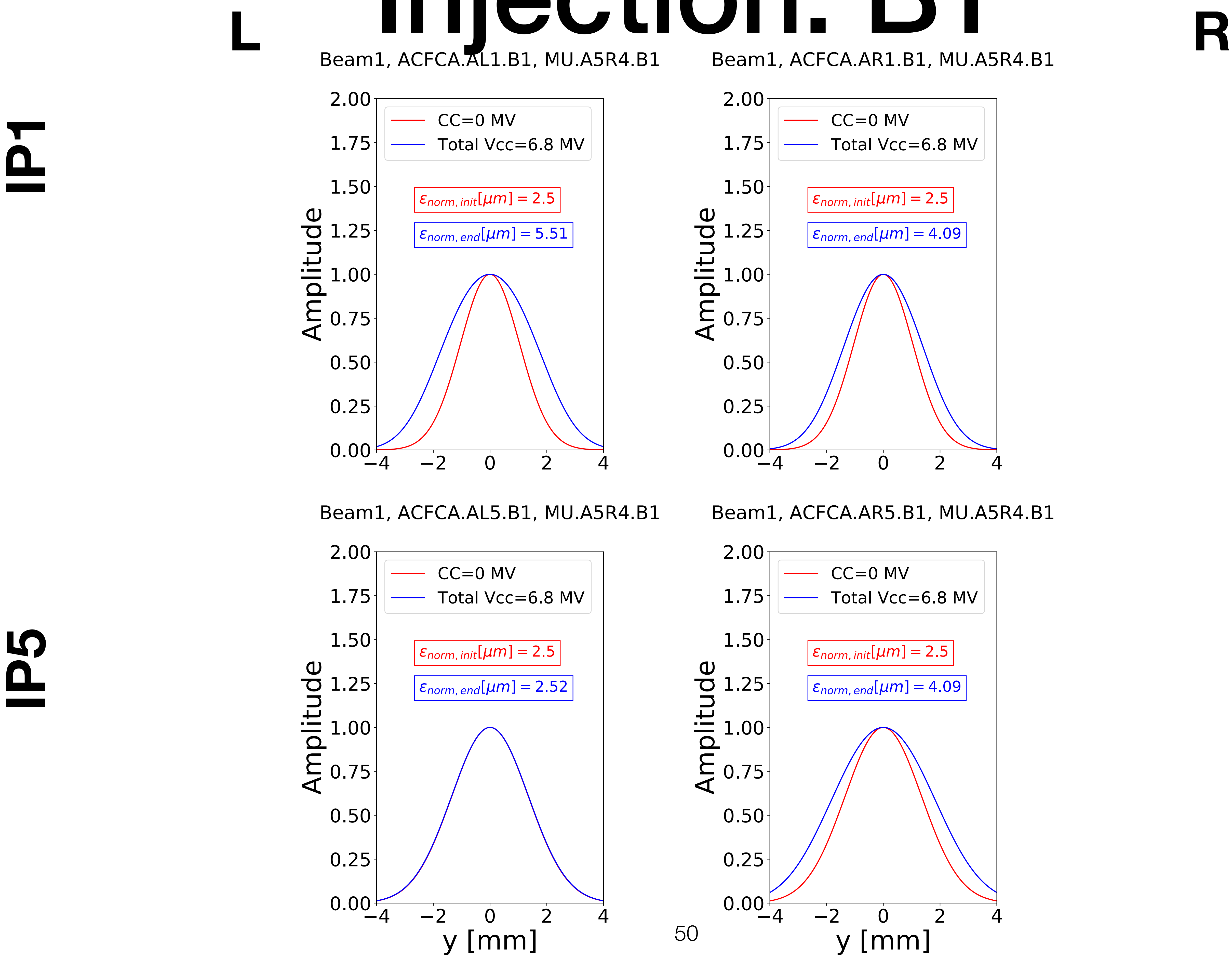
IP5





BSRT

Injection: B1



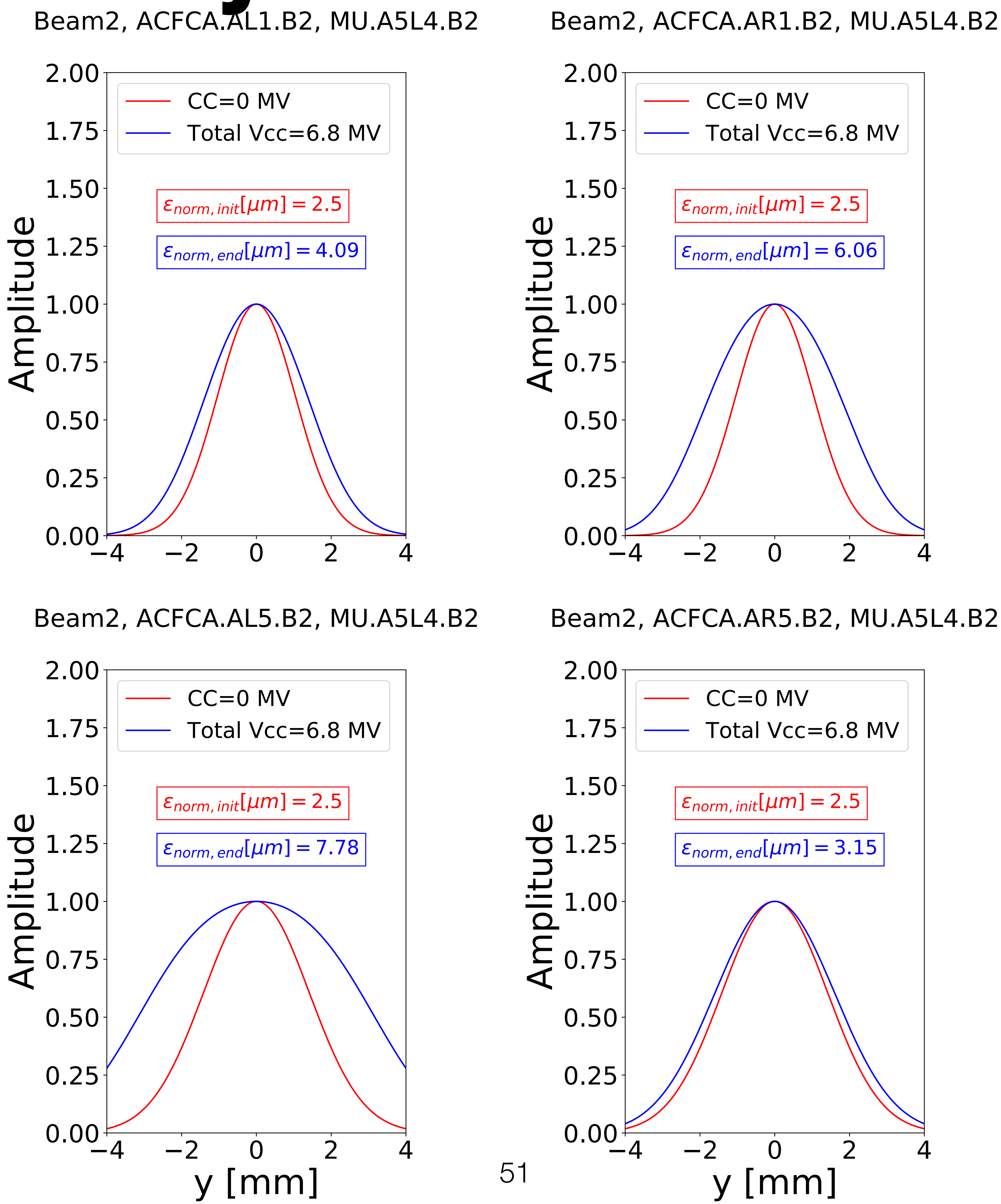
Injection: B2

L

R

IP1

IP5

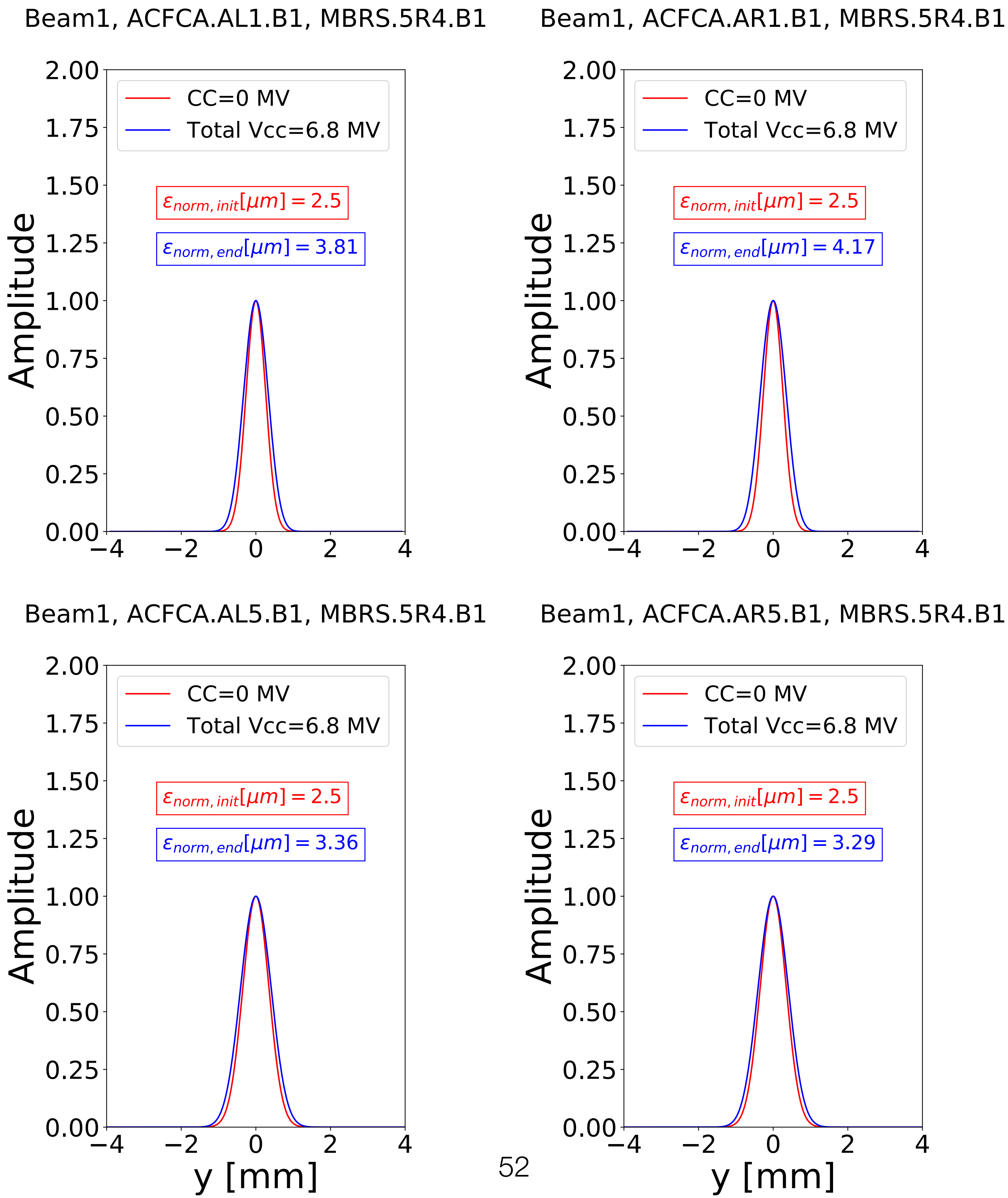


Collision: B1

L R

IP1

IP5



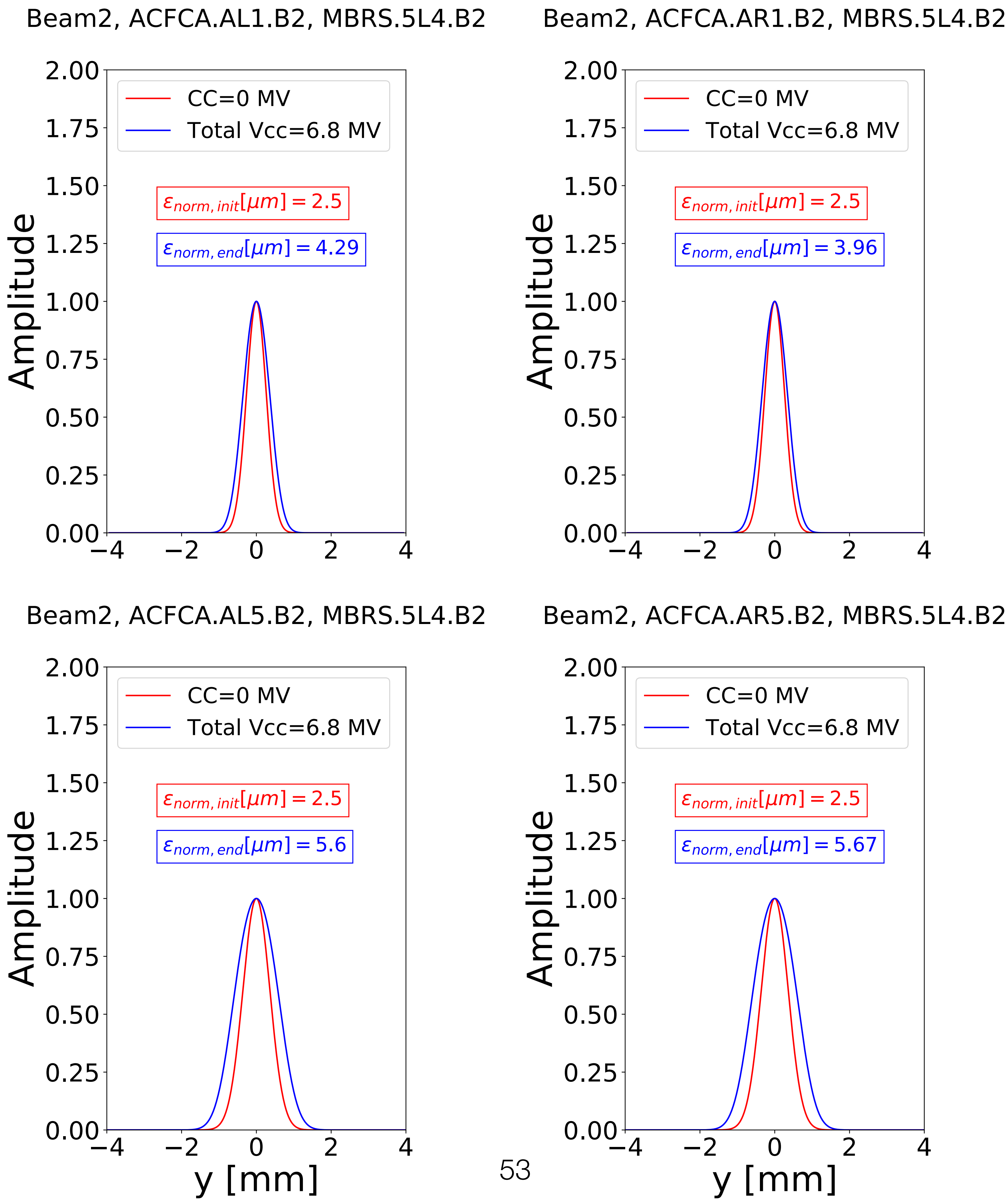
Collision: B2

L

R

IP1

IP5



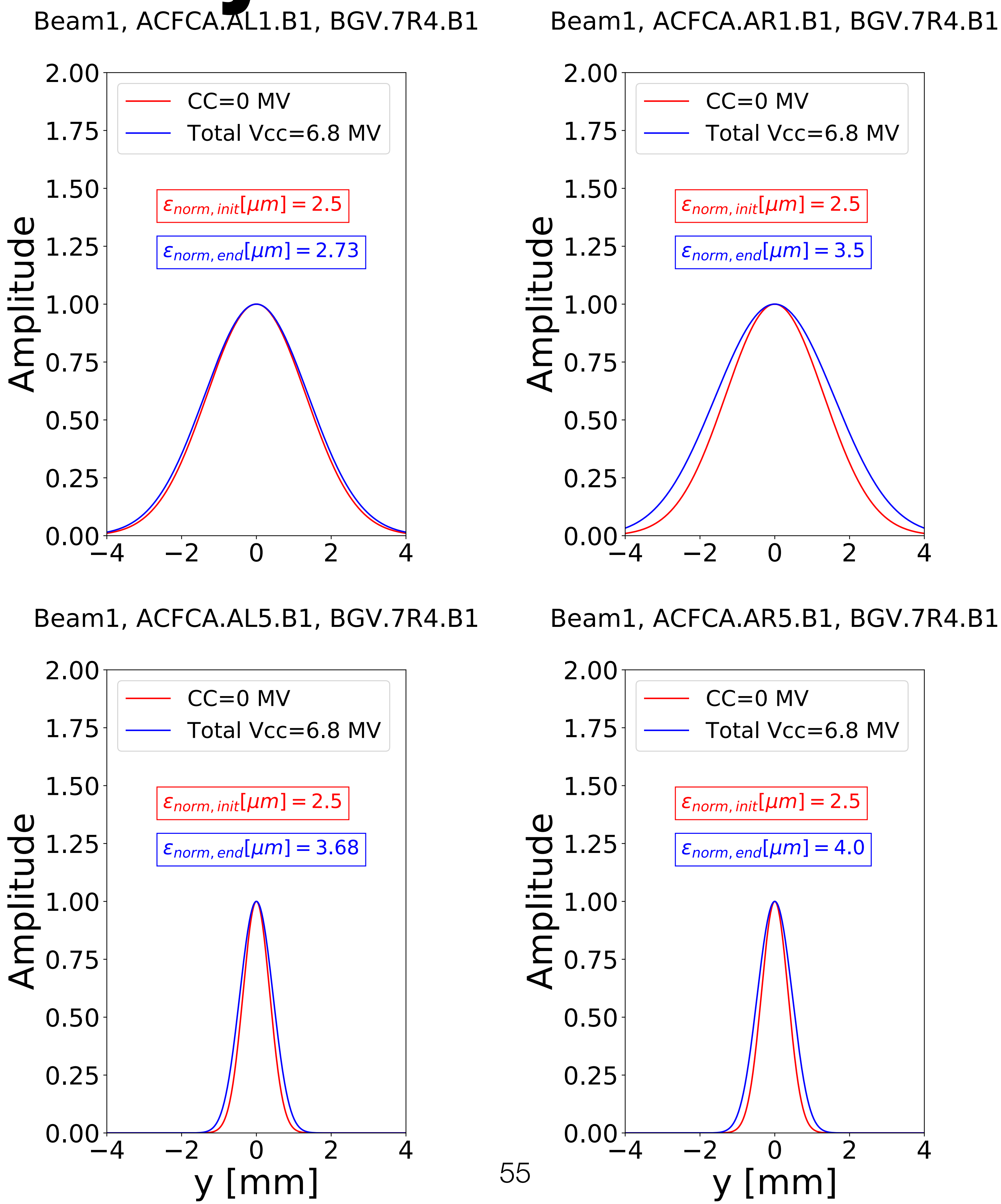
BGV

Injection: B1

L R

IP1

IP5

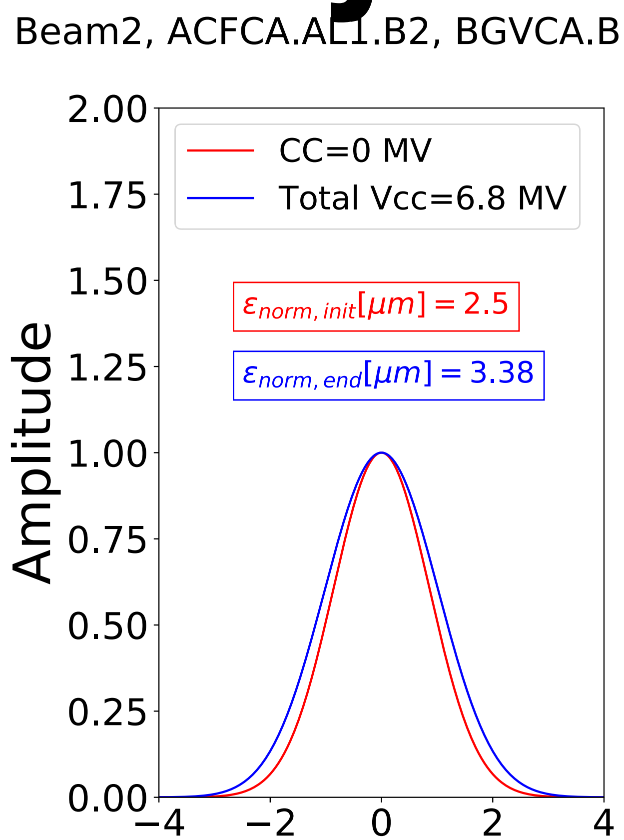


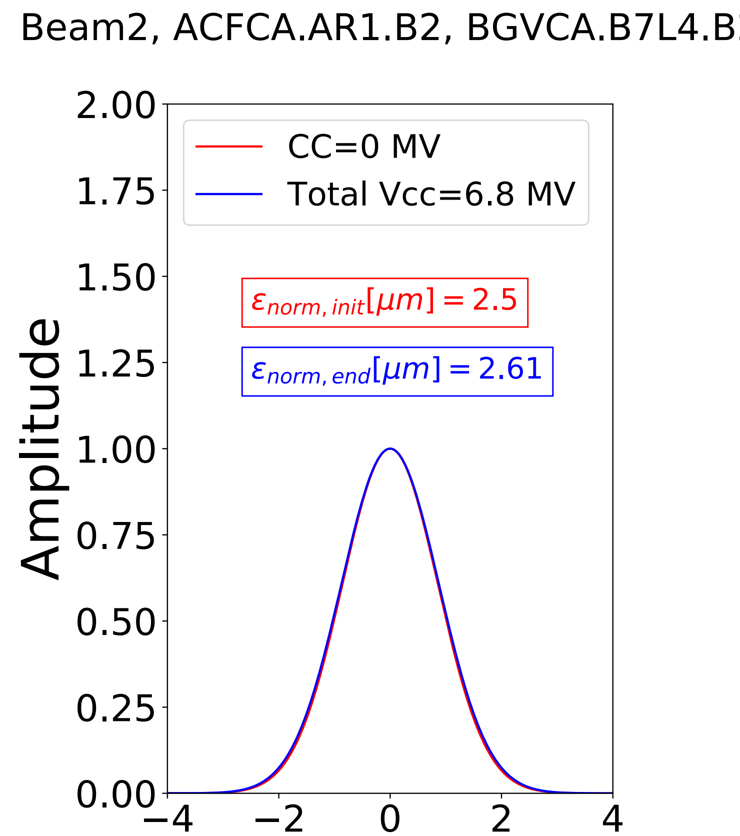
Injection: B2

L

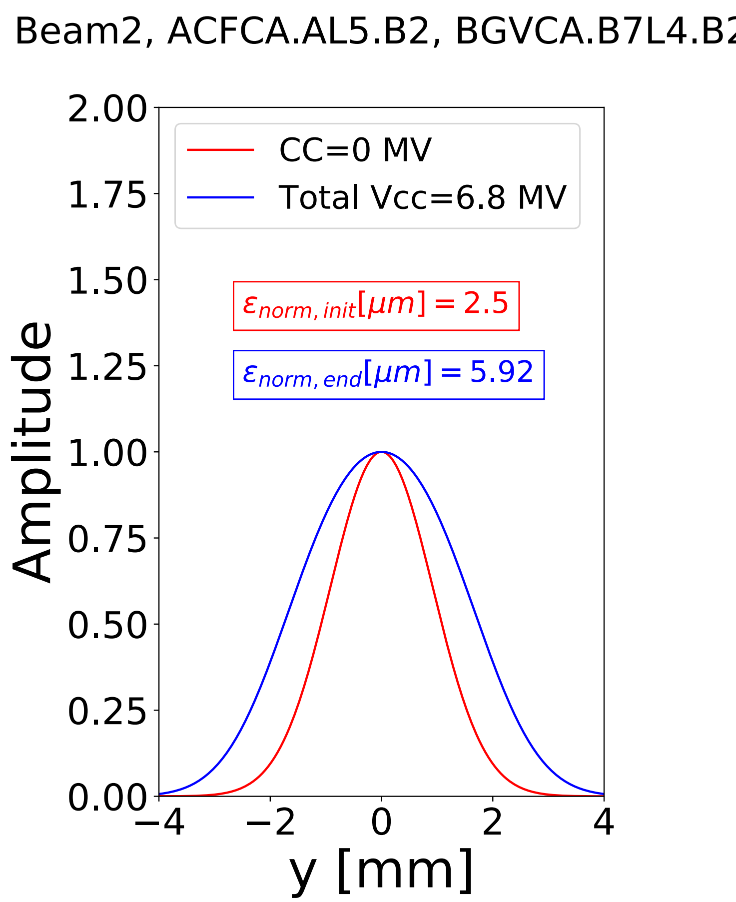
R

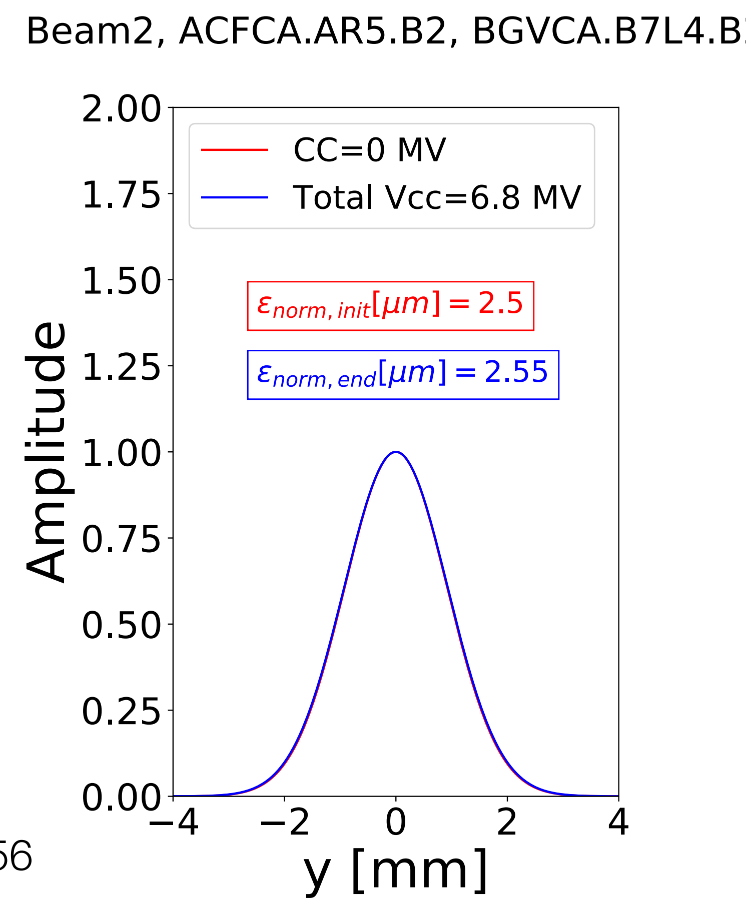
IP1





IP5





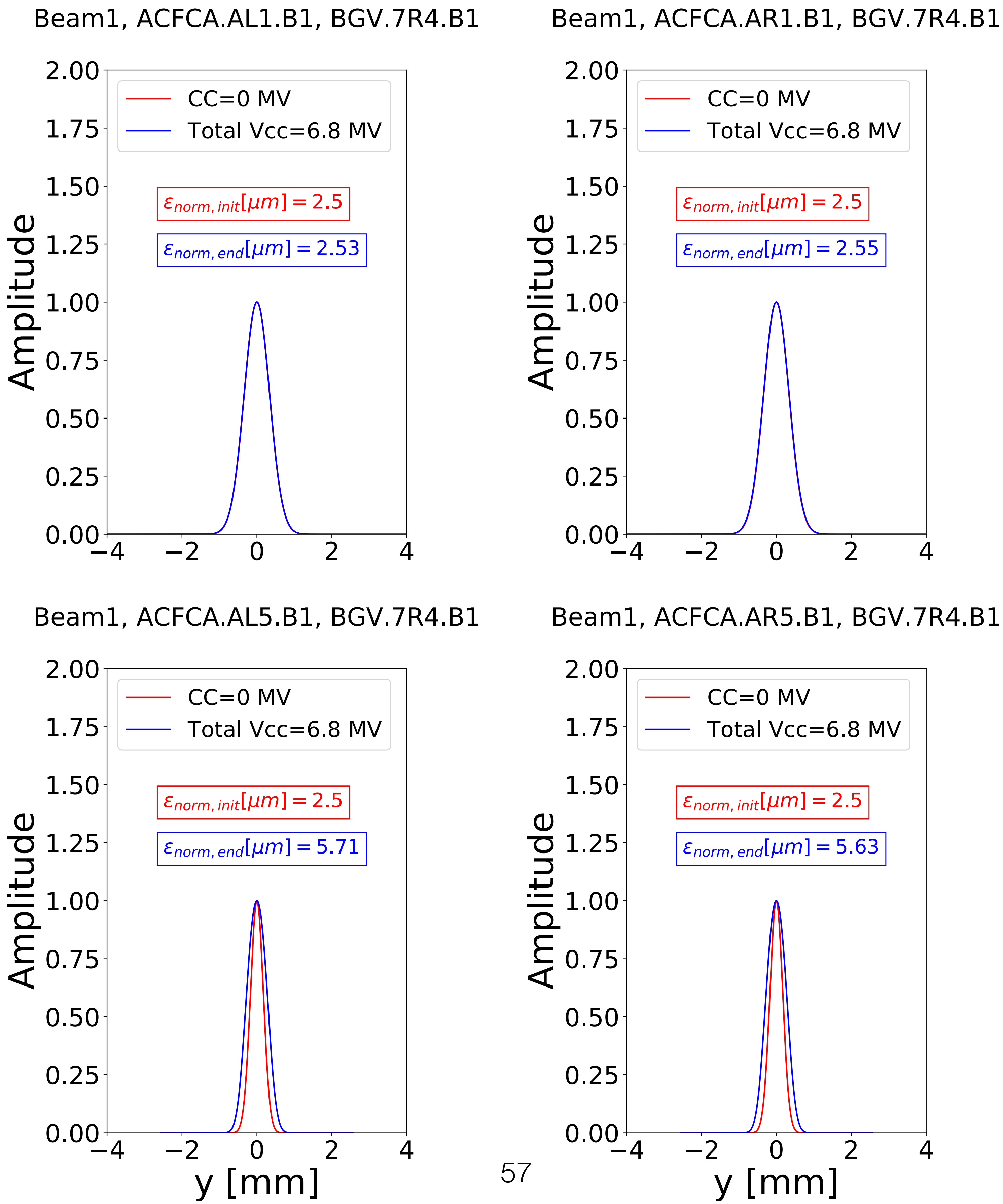
Collision: B1

L

R

IP1

IP5

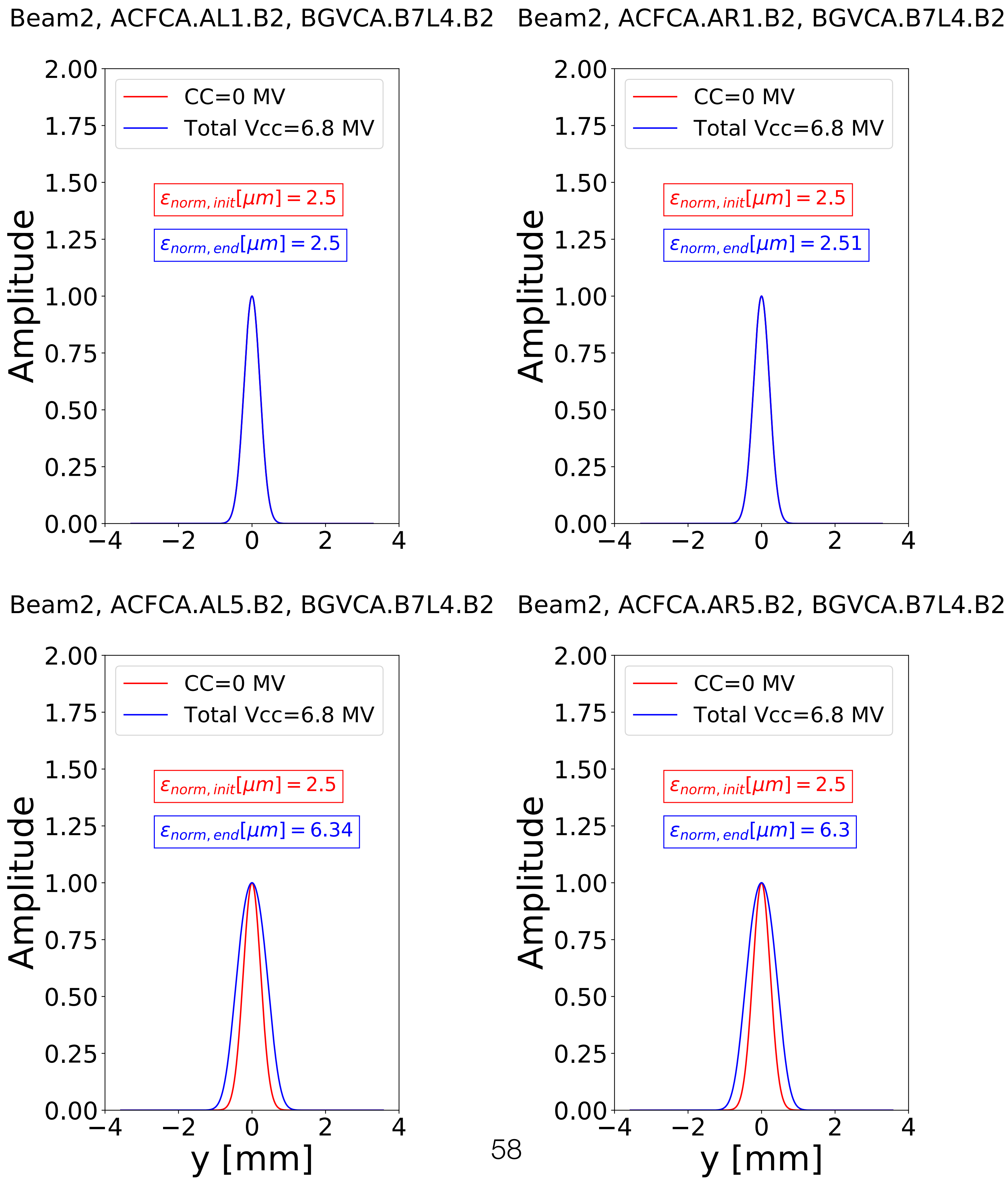


Collision: B2

L R

IP1

IP5



There is 1 pair of CCs on each side of the Interaction Points (IP), per beam (i.e. total of 16 CCs)

IP1

Cavity-name anatomy:

ACFCA.AR1.B1

<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1

Beam1/2

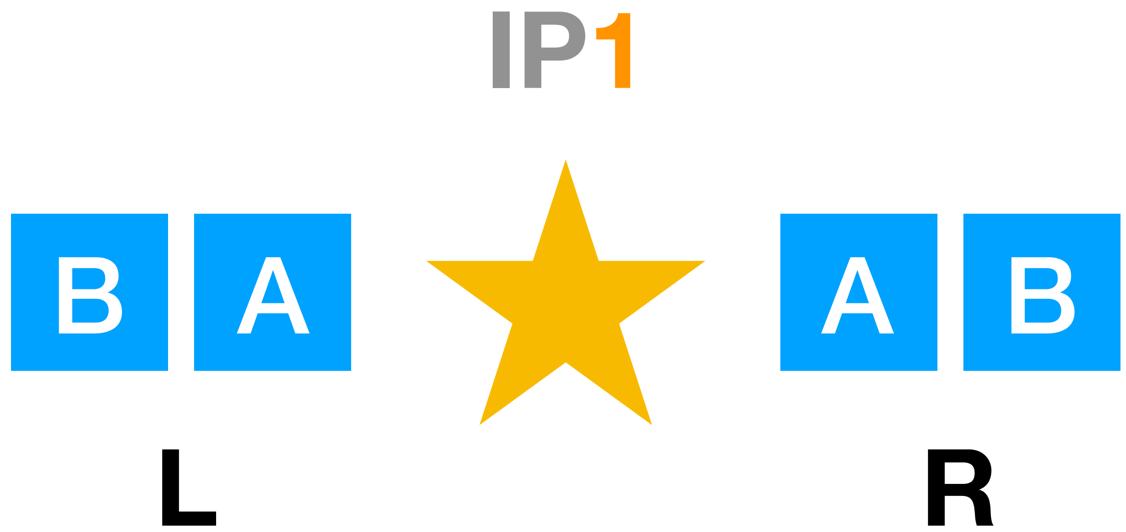
<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1

Cavity-name anatomy:

ACFCA.AR1.B1

IP1/IP5



<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1

Cavity-name anatomy:

ACFCA.AR1.B1

L/R wrt IP

Cavity-name anatomy:

ACFCA.AR1.B1

<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1

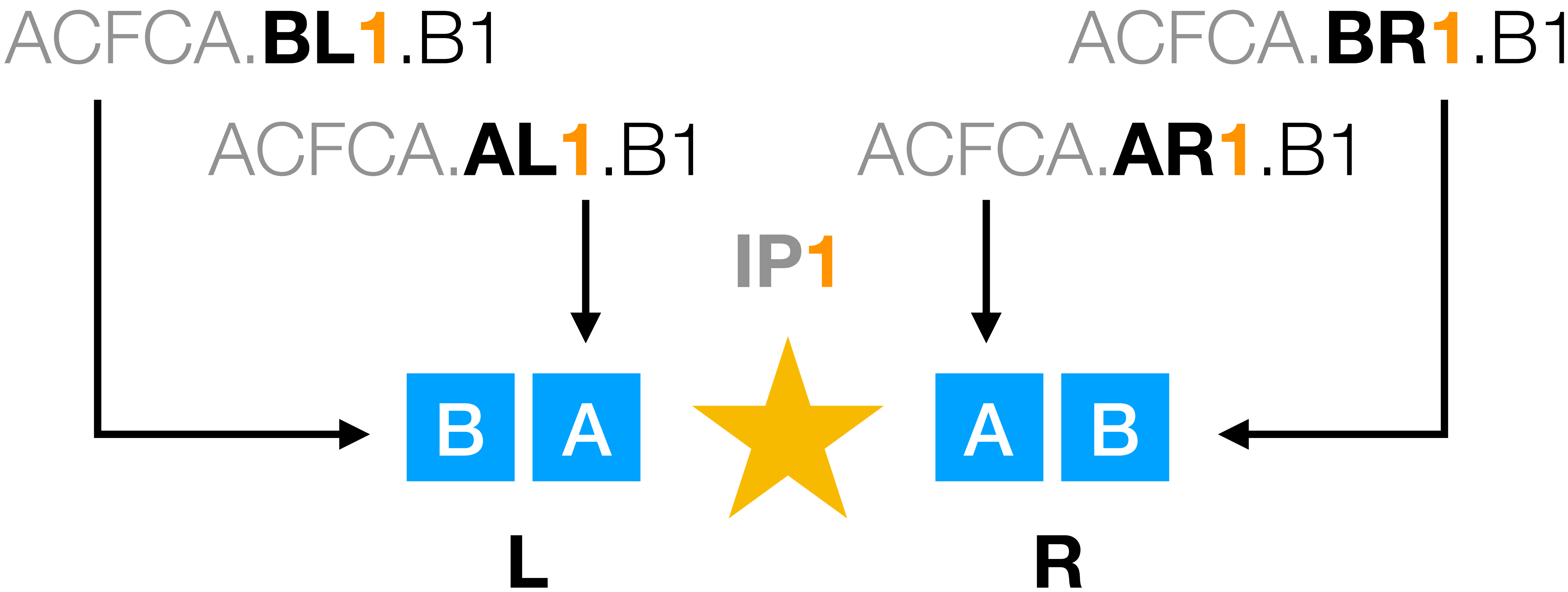
A/B:

A: close to IP

B: further away

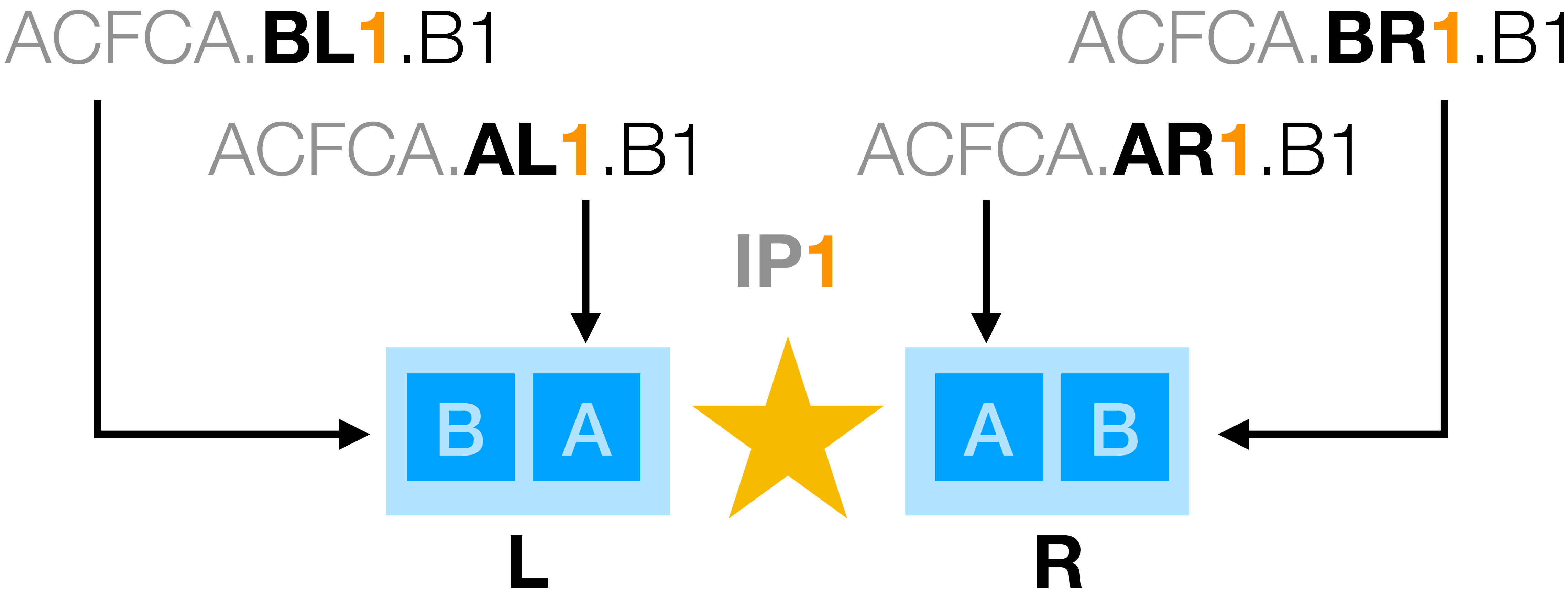
<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1



<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1



A/B ~1m apart: group together, left set, right set

Cavity-name anatomy:

ACFCA.AR1.B1

Table 2: Twiss parameters at the IP-, CC- and detector-location for Beam1, injection energy. The last two columns show the relative phase advance from IP1 (top) and IP5 (bottom); BSRT: MU.A5R4.B1, WS: BWS.5R4.B1, HT-H: BPLH.7R4.B1, HT-V: BPLV.A6R4.B1, additional HT-H: BQKH.B6L4.B1, additional HT-V: BQKV.6L4.B1

Name	s [m]	β_x [m]	β_y [m]	μ_x [2π]	μ_y [2π]	$d\mu_x$ [$\pi/2$]	$d\mu_y$ [$\pi/2$]
IP1	0.0	6.02	6.0	0.0	0.0	0.0 0.1	0.0 0.17
IP5	13329.29	6.02	6.0	30.98	29.96	0.9 0.0	0.83 0.0
ACFCA.AR1.B1	154.82	82.91	279.53	0.32	0.29	0.29 0.38	0.17 0.34
ACFCA.BR1.B1	155.87	80.55	280.52	0.32	0.29	0.3 0.39	0.17 0.34
ACFCA.BL5.B1	13169.6	283.77	72.55	30.68	29.62	0.72 0.82	0.5 0.67
ACFCA.AL5.B1	13170.65	282.74	74.7	30.68	29.63	0.73 0.82	0.51 0.68
ACFCA.AR5.B1	13484.11	82.77	279.43	31.3	30.25	0.19 0.29	0.99 0.17
ACFCA.BR5.B1	13485.16	80.4	280.43	31.3	30.25	0.2 0.29	0.99 0.17
ACFCA.BL1.B1	26499.2	283.21	72.57	61.98	59.96	0.9 0.0	0.85 0.03
ACFCA.AL1.B1	26500.25	282.18	74.72	61.98	59.97	0.91 0.0	0.86 0.04
MU.A5R4.B1	10042.71	206.43	351.16	23.46	22.25	0.85 0.94	0.01 0.18
BWS.5R4.B1	10081.88	197.61	402.23	23.49	22.27	0.97 0.07	0.07 0.25
BPLV.A6R4.B1	10134.76	253.08	401.18	23.53	22.29	0.14 0.23	0.15 0.32
BPLH.7R4.B1	10174.96	544.96	51.52	23.55	22.34	0.2 0.29	0.36 0.53
BQKV.6L4.B1	9832.62	184.13	569.0	23.34	22.14	0.37 0.47	0.56 0.73
BQKH.B6L4.B1	9859.75	397.67	302.68	23.36	22.15	0.44 0.54	0.6 0.77

Table 3: Twiss parameters at the IP-, CC- and detector-location for Beam1, collision energy. The last two columns show the relative phase advance from IP1 (top) and IP5 (bottom); BSRT: MBRS.5R4.B1, WS: BWS.5R4.B1, HT-H: BPLH.7R4.B1, HT-V: BPLV.A6R4.B1, optional HT-H: BQKH.B6L4.B1, optional HT-V: BQKV.6L4.B1

Name	s [m]	β_x [m]	β_y [m]	μ_x [2π]	μ_y [2π]	$d\mu_x$ [$\pi/2$]	$d\mu_y$ [$\pi/2$]
IP1	0.0	0.15	0.15	0.0	0.0	0.0 0.28	0.0 0.04
IP5	13329.29	0.15	0.15	30.93	29.99	0.72 0.0	0.96 0.0
ACFCA.AR1.B1	154.82	4256.24	3821.01	0.25	0.25	0.01 0.28	0.01 0.05
ACFCA.BR1.B1	155.87	4133.64	3779.74	0.25	0.25	0.01 0.28	0.01 0.05
ACFCA.BL5.B1	13169.6	3631.61	3702.45	30.68	29.74	0.71 0.99	0.95 0.99
ACFCA.AL5.B1	13170.65	3672.05	3818.54	30.68	29.74	0.71 0.99	0.95 0.99
ACFCA.AR5.B1	13484.11	4256.24	3821.03	31.18	30.24	0.73 0.01	0.96 0.01
ACFCA.BR5.B1	13485.16	4133.64	3779.76	31.18	30.24	0.73 0.01	0.96 0.01
ACFCA.BL1.B1	26499.2	3631.6	3702.43	62.06	60.07	0.23 0.51	0.27 0.32
ACFCA.AL1.B1	26500.25	3672.05	3818.52	62.06	60.07	0.23 0.51	0.27 0.32
MBRS.5R4.B1	10053.51	201.97	363.9	23.55	22.41	0.19 0.47	0.64 0.69
BWS.5R4.B1	10081.88	197.01	402.01	23.57	22.42	0.29 0.56	0.69 0.73
BPLV.A6R4.B1	10134.76	243.71	416.95	23.61	22.44	0.45 0.73	0.77 0.81
BPLH.7R4.B1	10174.96	481.96	114.03	23.63	22.47	0.52 0.8	0.9 0.94
BQKV.6L4.B1	9832.62	181.35	573.77	23.42	22.29	0.69 0.97	0.17 0.22
BQKH.B6L4.B1	9859.75	397.9	303.19	23.44	22.3	0.75 0.03	0.21 0.26

Table 4: Twiss parameters at the IP-, CC- and detector-location for Beam2, injection energy. The last two columns show the relative phase advance from IP1 (top) and IP5 (bottom); BGV: BGVCA.B7L4.B2, WS: BWS.5L4.B2, BSRT: MU.A5L4.B2, HT-H: BPLH.6R4.B2, HT-V: BPLV.7R4.B2, HT-H/V-optional: the optional HT monitors installed in B1

Name	s [m]	β_x [m]	β_y [m]	μ_x [2π]	μ_y [2π]	$d\mu_x$ [$\pi/2$]	$d\mu_y$ [$\pi/2$]
IP1	0.0	6.0	6.0	0.0	0.0	0.0 0.91	0.0 0.09
IP5	13329.59	6.0	5.99	31.02	29.98	0.09 0.0	0.91 0.0
ACFCA.AR1.B2	158.64	283.24	74.7	0.29	0.33	0.17 0.09	0.32 0.41
ACFCA.BR1.B2	159.69	284.27	72.55	0.29	0.33	0.18 0.09	0.33 0.42
ACFCA.BL5.B2	13173.73	80.81	280.3	30.7	29.69	0.79 0.7	0.74 0.83
ACFCA.AL5.B2	13174.78	83.19	279.31	30.7	29.69	0.8 0.71	0.74 0.84
ACFCA.AR5.B2	13488.23	282.84	74.86	31.31	30.31	0.26 0.17	0.23 0.32
ACFCA.BR5.B2	13489.28	283.86	72.7	31.32	30.31	0.26 0.18	0.24 0.33
ACFCA.BL1.B2	26503.02	80.58	280.31	61.95	60.0	0.79 0.7	0.01 0.1
ACFCA.AL1.B2	26504.07	82.95	279.32	61.95	60.0	0.79 0.71	0.01 0.11
BGVCA.B7L4.B2	9776.11	142.28	162.57	23.2	22.44	0.81 0.72	0.77 0.86
BWS.5L4.B2	9912.28	196.94	451.74	23.29	22.53	0.15 0.07	0.11 0.2
MU.A5L4.B2	9951.6	205.88	383.3	23.32	22.54	0.28 0.19	0.17 0.26
BPLH.6R4.B2	10134.11	395.72	269.45	23.42	22.64	0.68 0.6	0.58 0.67
BPLV.7R4.B2	10175.91	123.44	483.03	23.46	22.66	0.82 0.74	0.64 0.74
HT-V-optional	9832.62	469.38	208.75	23.23	22.5	0.93 0.85	0.99 0.08
HT-H-optional	9859.75	239.32	489.97	23.25	22.51	0.99 0.9	0.04 0.13

Table 5: Twiss parameters at the IP-, CC- and detector-location for Beam2, collision energy. The last two columns show the relative phase advance from IP1 (top) and IP5 (bottom); BGV: BGVCA.B7L4.B2, WS: BWS.5L4.B2, BSRT: MBRS.5L4.B2, HT-H: BPLH.6R4.B2, HT-V: BPLV.7R4.B2, HT-H/V-optional: the optional HT monitors installed in B1

Name	s [m]	β_x [m]	β_y [m]	μ_x [2π]	μ_y [2π]	$d\mu_x$ [$\pi/2$]	$d\mu_y$ [$\pi/2$]
IP1	0.0	0.15	0.15	0.0	0.0	0.0 0.86	0.0 0.2
IP5	13329.59	0.15	0.15	31.03	29.95	0.14 0.0	0.8 0.0
ACFCA.AR1.B2	158.64	3672.55	3818.29	0.25	0.25	0.01 0.87	0.01 0.21
ACFCA.BR1.B2	159.69	3632.1	3702.21	0.25	0.25	0.01 0.87	0.01 0.21
ACFCA.BL5.B2	13173.73	4134.1	3779.62	30.78	29.7	0.13 0.99	0.79 0.99
ACFCA.AL5.B2	13174.78	4256.72	3820.89	30.78	29.7	0.13 0.99	0.79 0.99
ACFCA.AR5.B2	13488.23	3672.45	3818.38	31.29	30.2	0.15 0.01	0.81 0.01
ACFCA.BR5.B2	13489.28	3631.99	3702.29	31.29	30.2	0.15 0.01	0.81 0.01
ACFCA.BL1.B2	26503.02	4134.21	3779.53	62.06	60.07	0.23 0.1	0.27 0.47
ACFCA.AL1.B2	26504.07	4256.84	3820.79	62.06	60.07	0.23 0.1	0.27 0.47
BGVCA.B7L4.B2	9776.11	143.18	168.84	23.15	22.51	0.6 0.46	0.05 0.25
BWS.5L4.B2	9912.28	196.95	452.53	23.24	22.6	0.95 0.81	0.38 0.59
MBRS.5L4.B2	9950.1	205.38	386.38	23.27	22.61	0.07 0.93	0.44 0.64
BPLH.6R4.B2	10134.11	383.65	277.71	23.37	22.71	0.48 0.34	0.86 0.06
BPLV.7R4.B2	10175.91	56.95	556.46	23.42	22.73	0.69 0.56	0.91 0.12
HT-V-optional	9832.62	466.51	211.6	23.18	22.57	0.73 0.59	0.26 0.47
HT-H-optional	9859.75	238.88	491.32	23.19	22.58	0.78 0.64	0.32 0.52

Injection

			multFactor[mm]	dmu	sigma_init_2	sigma_end_2	betaGamma	beta	emit_norm_init	emit_norm_end	emit_norm_dif_1e6
BWS.5R4.B1	L1	B1	-1.381019299	241.7994903	1.04E-06	1.80E-06	479.6039771	199.0310643	2.50E-06	4.33E-06	1.833356605
BWS.5R4.B1	L5	B1	0.394025134	46.23687488	2.10E-06	2.15E-06	479.6039771	402.2219135	2.50E-06	2.56E-06	0.064867889
BWS.5R4.B1	R1	B1	1.254868647	145.5851719	1.03E-06	1.64E-06	479.6039771	196.8467932	2.50E-06	4.00E-06	1.504552812
BWS.5R4.B1	R5	B1	1.561742247	50.1371523	2.10E-06	3.03E-06	479.6039771	402.1438692	2.50E-06	3.61E-06	1.114234411
BWS.5L4.B2	L1	B2	1.271136495	242.9139941	1.03E-06	1.66E-06	479.6039771	197.0357491	2.50E-06	4.05E-06	1.545844221
BWS.5L4.B2	L5	B2	-3.346156232	44.98410096	2.35E-06	7.30E-06	479.6039771	451.6622624	2.50E-06	7.75E-06	5.252269506
BWS.5L4.B2	R1	B2	-1.526463487	144.4845842	1.03E-06	1.98E-06	479.6039771	196.9541142	2.50E-06	4.81E-06	2.312598106
BWS.5L4.B2	R5	B2	1.169007262	48.8833824	2.35E-06	2.86E-06	479.6039771	451.7484454	2.50E-06	3.03E-06	0.532043517
MU.A5R4.B1	L1	B1	-1.763221334	241.9936999	1.08E-06	2.38E-06	479.6039771	207.0249714	2.50E-06	5.51E-06	3.011886529
MU.A5R4.B1	L5	B1	0.211343028	46.34130242	1.83E-06	1.85E-06	479.6039771	351.1562673	2.50E-06	2.52E-06	0.021271637
MU.A5R4.B1	R1	B1	1.315378474	145.3892886	1.07E-06	1.75E-06	479.6039771	205.8051829	2.50E-06	4.09E-06	1.588468132
MU.A5R4.B1	R5	B1	1.719626259	50.24160353	1.83E-06	3.00E-06	479.6039771	351.065615	2.50E-06	4.09E-06	1.591779081
MU.A5L4.B2	L1	B2	1.316470879	242.7175885	1.07E-06	1.76E-06	479.6039771	205.9943777	2.50E-06	4.09E-06	1.589727904
MU.A5L4.B2	L5	B2	-3.090289899	44.88945988	2.00E-06	6.22E-06	479.6039771	383.2122412	2.50E-06	7.78E-06	5.28278174
MU.A5L4.B2	R1	B2	-1.899248566	144.6807946	1.08E-06	2.61E-06	479.6039771	206.4846034	2.50E-06	6.06E-06	3.562583309
MU.A5L4.B2	R5	B2	1.183858387	48.78876254	2.00E-06	2.52E-06	479.6039771	383.3104531	2.50E-06	3.15E-06	0.649411218
BGV.7R4.B1	L1	B1	-0.669692905	241.3982266	1.76E-06	1.92E-06	479.6039771	336.7676402	2.50E-06	2.73E-06	0.227686503
BGV.7R4.B1	L5	B1	0.393792161	45.11913415	1.27E-07	1.86E-07	479.6039771	24.31454677	2.50E-06	3.68E-06	1.17637549
BGV.7R4.B1	R1	B1	1.348766505	145.9921723	1.73E-06	2.42E-06	479.6039771	331.4908826	2.50E-06	3.50E-06	1.000541336
BGV.7R4.B1	R5	B1	-0.440972513	49.01960163	1.27E-07	2.03E-07	479.6039771	24.32376759	2.50E-06	4.00E-06	1.50350758
BGVCA.B7L4.B2	L1	B2	0.834190005	243.4551856	7.42E-07	1.00E-06	479.6039771	142.2700498	2.50E-06	3.38E-06	0.884510426
BGVCA.B7L4.B2	L5	B2	-1.654286397	45.51556246	8.48E-07	2.01E-06	479.6039771	162.6001708	2.50E-06	5.92E-06	3.418245264
BGVCA.B7L4.B2	R1	B2	-0.303342528	143.9412885	7.37E-07	7.69E-07	479.6039771	141.3382922	2.50E-06	2.61E-06	0.109949115
BGVCA.B7L4.B2	R5	B2	0.213792284	49.41485456	8.47E-07	8.63E-07	479.6039771	162.5632564	2.50E-06	2.55E-06	0.047157786

Collision

			multFactor[mm]	dmu	sigma_init_2	sigma_end_2	betaGamma	beta	emit_norm_init	emit_norm_end	emit_norm_dif_1e6
BWS.5R4.B1	L1	B1	-0.243717856	241.8151461	6.62E-08	8.79E-08	7460.52246	197.551845	2.50E-06	3.32E-06	0.821368695
BWS.5R4.B1	L5	B1	0.400000857	45.96260281	1.35E-07	1.94E-07	7460.52246	402.0265555	2.50E-06	3.61E-06	1.1088226
BWS.5R4.B1	R1	B1	0.274446309	146.5222094	6.58E-08	9.39E-08	7460.52246	196.5022048	2.50E-06	3.56E-06	1.064909156
BWS.5R4.B1	R5	B1	-0.385906844	49.12810593	1.35E-07	1.90E-07	7460.52246	402.0230509	2.50E-06	3.53E-06	1.026540096
BWS.5L4.B2	L1	B2	0.266123728	243.9290168	6.60E-08	9.22E-08	7460.52246	196.9135615	2.50E-06	3.49E-06	0.994510878
BWS.5L4.B2	L5	B2	-0.705780307	44.61979375	1.52E-07	3.57E-07	7460.52246	452.4888702	2.50E-06	5.88E-06	3.381452584
BWS.5L4.B2	R1	B2	-0.240122779	144.4174246	6.60E-08	8.71E-08	7460.52246	196.9637664	2.50E-06	3.30E-06	0.798348603
BWS.5L4.B2	R5	B2	0.711851664	47.78530524	1.52E-07	3.61E-07	7460.52246	452.4906972	2.50E-06	5.95E-06	3.44618622
MBRS.5R4.B1	L1	B1	-0.306908604	241.9574591	6.79E-08	1.03E-07	7460.52246	202.4981842	2.50E-06	3.81E-06	1.312255763
MBRS.5R4.B1	L5	B1	0.337890693	46.03683633	1.22E-07	1.64E-07	7460.52246	363.9154672	2.50E-06	3.36E-06	0.8593994
MBRS.5R4.B1	R1	B1	0.341784421	146.3791429	6.75E-08	1.13E-07	7460.52246	201.4557137	2.50E-06	4.17E-06	1.668048144
MBRS.5R4.B1	R5	B1	-0.323841239	49.20234009	1.22E-07	1.60E-07	7460.52246	363.9123709	2.50E-06	3.29E-06	0.785145749
MBRS.5L4.B2	L1	B2	0.356374469	243.7397135	6.87E-08	1.18E-07	7460.52246	205.1156171	2.50E-06	4.29E-06	1.792252222
MBRS.5L4.B2	L5	B2	-0.626752953	44.52922015	1.29E-07	2.90E-07	7460.52246	386.342994	2.50E-06	5.60E-06	3.096518023
MBRS.5L4.B2	R1	B2	-0.325160736	144.6064621	6.89E-08	1.09E-07	7460.52246	205.6335155	2.50E-06	3.96E-06	1.463017541
MBRS.5L4.B2	R5	B2	0.633764548	47.69473204	1.29E-07	2.94E-07	7460.52246	386.3447951	2.50E-06	5.67E-06	3.173767146
BGV.7R4.B1	L1	B1	-0.059149075	241.3961712	1.14E-07	1.15E-07	7460.52246	339.2465551	2.50E-06	2.53E-06	0.026225494
BGV.7R4.B1	L5	B1	0.301833044	45.41125482	2.91E-08	6.64E-08	7460.52246	86.74675825	2.50E-06	5.71E-06	3.209565136
BGV.7R4.B1	R1	B1	0.080788245	146.9431384	1.13E-07	1.16E-07	7460.52246	338.0864331	2.50E-06	2.55E-06	0.049216684
BGV.7R4.B1	R5	B1	-0.298591011	48.57675384	2.91E-08	6.55E-08	7460.52246	86.74635772	2.50E-06	5.63E-06	3.133706047
BGVCA.B7L4.B2	L1	B2	-0.010465563	244.4701445	4.81E-08	4.81E-08	7460.52246	143.550427	2.50E-06	2.50E-06	0.001935012
BGVCA.B7L4.B2	L5	B2	-0.4565846	45.14124035	5.66E-08	1.43E-07	7460.52246	168.8394481	2.50E-06	6.34E-06	3.839850259
BGVCA.B7L4.B2	R1	B2	0.017698371	143.8747642	4.78E-08	4.80E-08	7460.52246	142.784886	2.50E-06	2.51E-06	0.005565764
BGVCA.B7L4.B2	R5	B2	0.454614084	48.30675105	5.66E-08	1.43E-07	7460.52246	168.8392327	2.50E-06	6.30E-06	3.803263854

CC commissioning

1. During the CC commissioning setup, 1-12 pilot bunches will be used. The crabbing for different bunch intensities will be read using BPMs and the HT monitor. Since during the 2018 SPS experiments the intensity was quickly increased from 2E10 ppb to the nominal one, it is expected that the nominal intensity will be used if the BPMs are shown to respond better at those values. The following procedure is expected to be followed:
2. Pilot beams with nominal intensity will be used at injection energy while the CCs are OFF. The injection oscillations, damper setting, and the overall orbit will be studied. The same topics can be studied with the CCs ON. During the 2018 SPS experiments it was shown that when the CCs were OFF the beam circulated without any issues. Additionally, the interlock will be checked for CC and main RF synchronisation, cavity trip, excess phase-change, etc.
3. The closed orbit will be scanned using the interaction region (IR) BPMs to bring the circulating beam as close as possible to the assumed mechanical centre.
4. The crabbing of the bunch induced from each CC pair starting from 1 MV will be measured using the HT monitors. The 1 MV is a safe value with respect to the machine protection and at the same time it gives a decent signal at injection (a different voltage may be used at collision energy).
5. Using the BPMs and the HT monitor a phase-scan routine will be performed to determine the crabbing-slope and deflection. In the SPS the HT cycle-by-cycle reading was used. The CC frequency will follow the main RF so in principle the synchronisation should be still present. An interlock is foreseen to dump the beam when the CCs and main RF are no longer synchronised (this interlock may be masked during commissioning).

CC commissioning

6. The WS, BSRT and BGV monitors will be used as a complementary information to show the change of the bream-size due to crabbing.
7. In order to find the electrical centres at the injection ramp, we need at least 1-batch; 4-batches would be preferable to make a ± 5 mm orbit offset in steps of 0.5 mm and record induced voltage per two-cavity module. The way to do this is still to be devised as the orbit in the other cavities will be perturbed, unless the optics can create a closed bump in the crab region.
8. At injection energies, the voltage will be ramped in both crabbing and deflecting phase per two-cavity module to the nominal 3.4 MV. The beam loading, transparency, etc will be checked
9. In order to check what mode is more practical for operations, the energy ramp will be checked using pilot beams with the CCs OFF (the nominal operational scenario is with the CCs ON with ~1 MV in anti-phase or smaller).
10. Most of the above steps will be repeated with collision optics (2 nominal beams should be enough). The electrical centre can be projected from the injection measurements.
11. The collision optimisation will be studied, including how to do vernier scans with CCs.