HL-LHC instrumentation

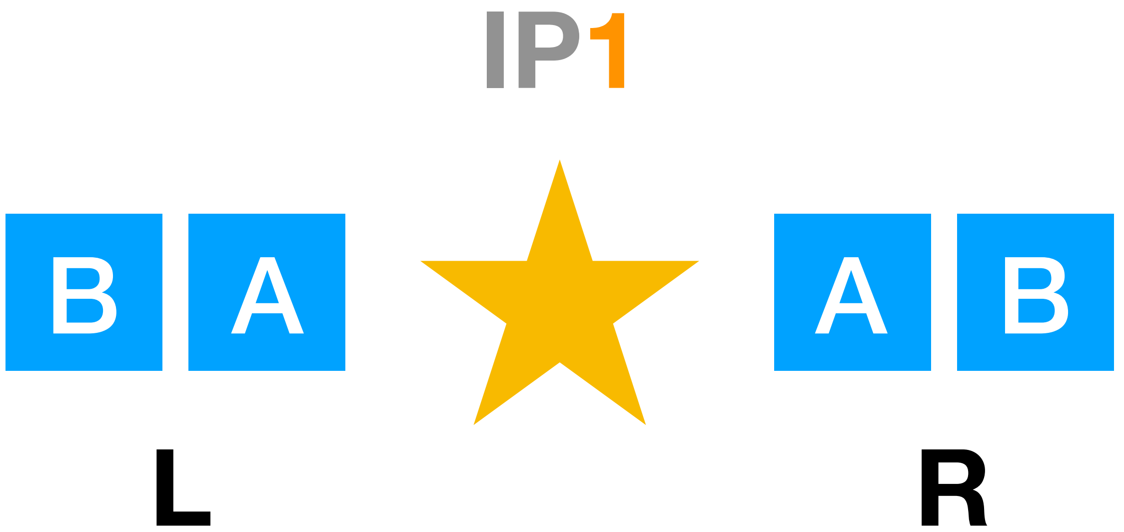
A. Alekou, H. Bartosik

Thanks to A. Boccardi, R. Calaga, M. Carla’, L. Carver, R. De Maria, M. Krupa, T. Lefevre, T. Levens, Y. Papaphilipou, R. Tomas, BI Group

HL-LHC injection optics (v1.4)

- LHC Beam Instrumentation to be used during CC commissioning:
  - Head Tail (HT) monitors
  - Wire Scanners (WS)
  - BPMs (standards and DOROS [higher resolution]), ADT (typically more sensitive and we can have a lot more turns)
  - Beam Synchrotron Radiation Telescope (BSRT), Beam Gas Vertex (BGV), Multi-band Instability Monitor (MIM)

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

Cavity-name anatomy:

ACFCA.AR1.B1

Cavity-name anatomy:

ACFCA.AR1.B1

Beam1/2

Cavity-name anatomy:

ACFCA.AR1.B1

IP1

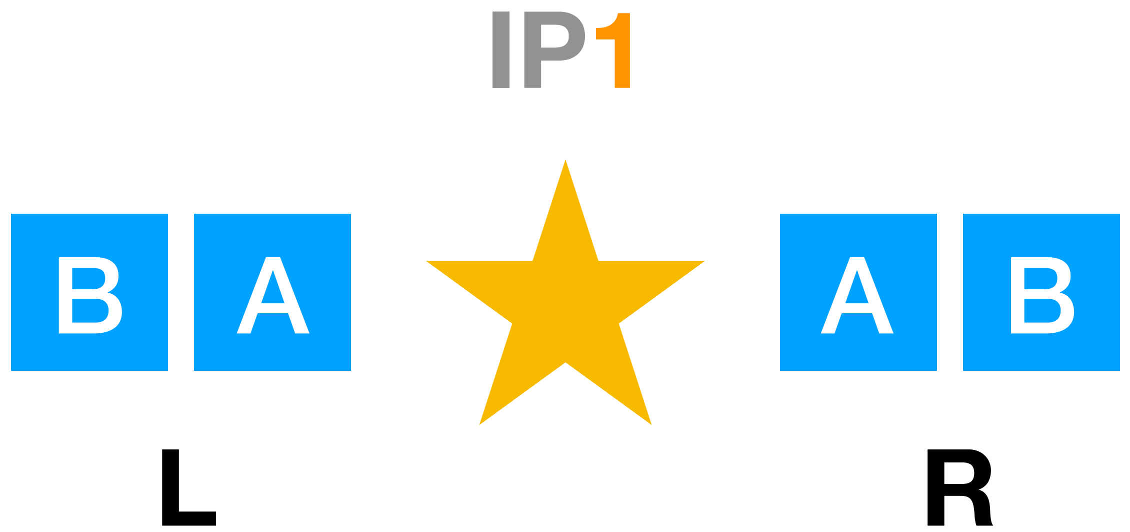
<u>Cavity-name anatomy:</u>

ACFCA.AR1.B1

IP1/IP5

Cavity-name anatomy:

ACFCA.AR1.B1



Cavity-name anatomy:

ACFCA.AR1.B1

L/R wrt IP

Cavity-name anatomy:

ACFCA.AR1.B1

Cavity-name anatomy:

ACFCA.AR1.B1

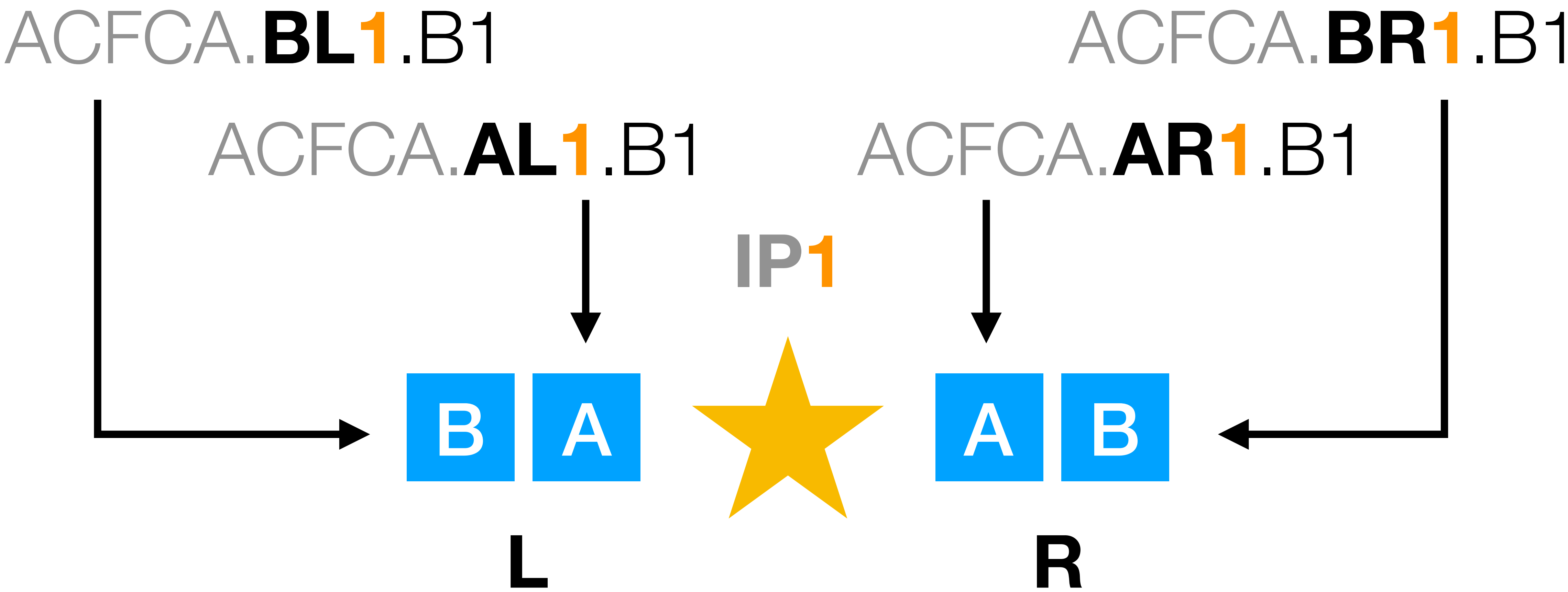
A/B:

A: close to IP

B: further away

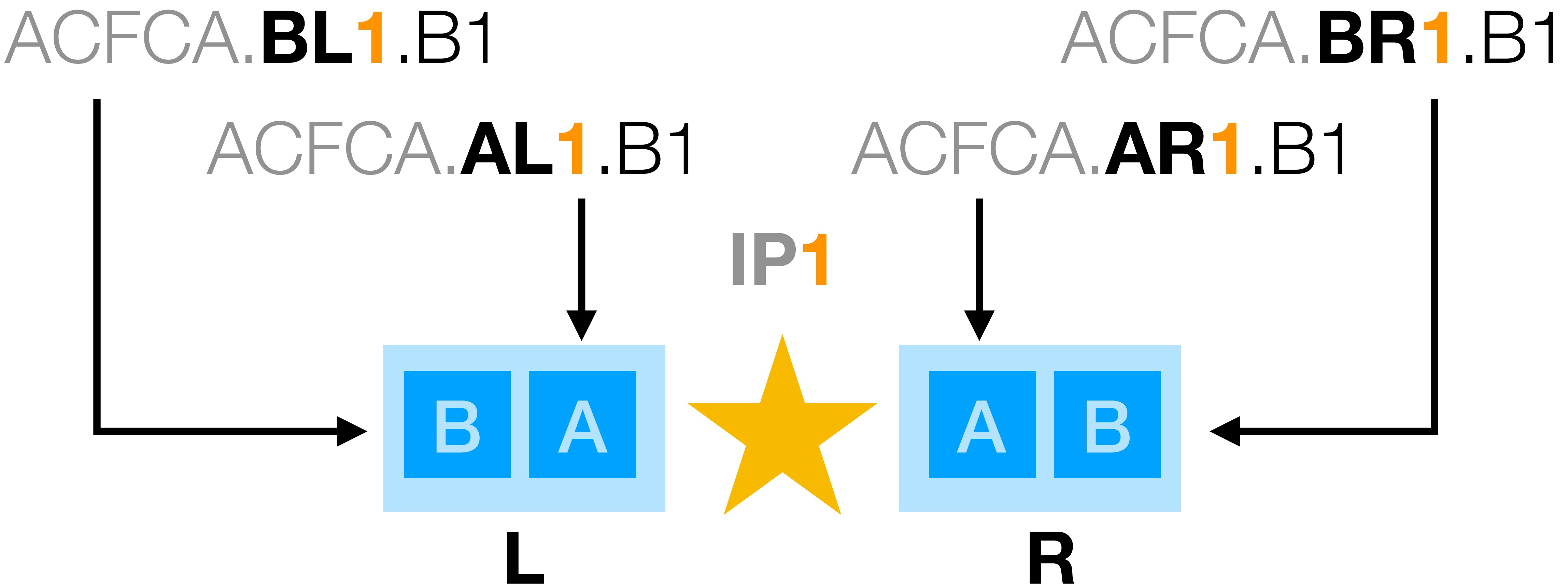
Cavity-name anatomy:

ACFCA.AR1.B1



Cavity-name anatomy:

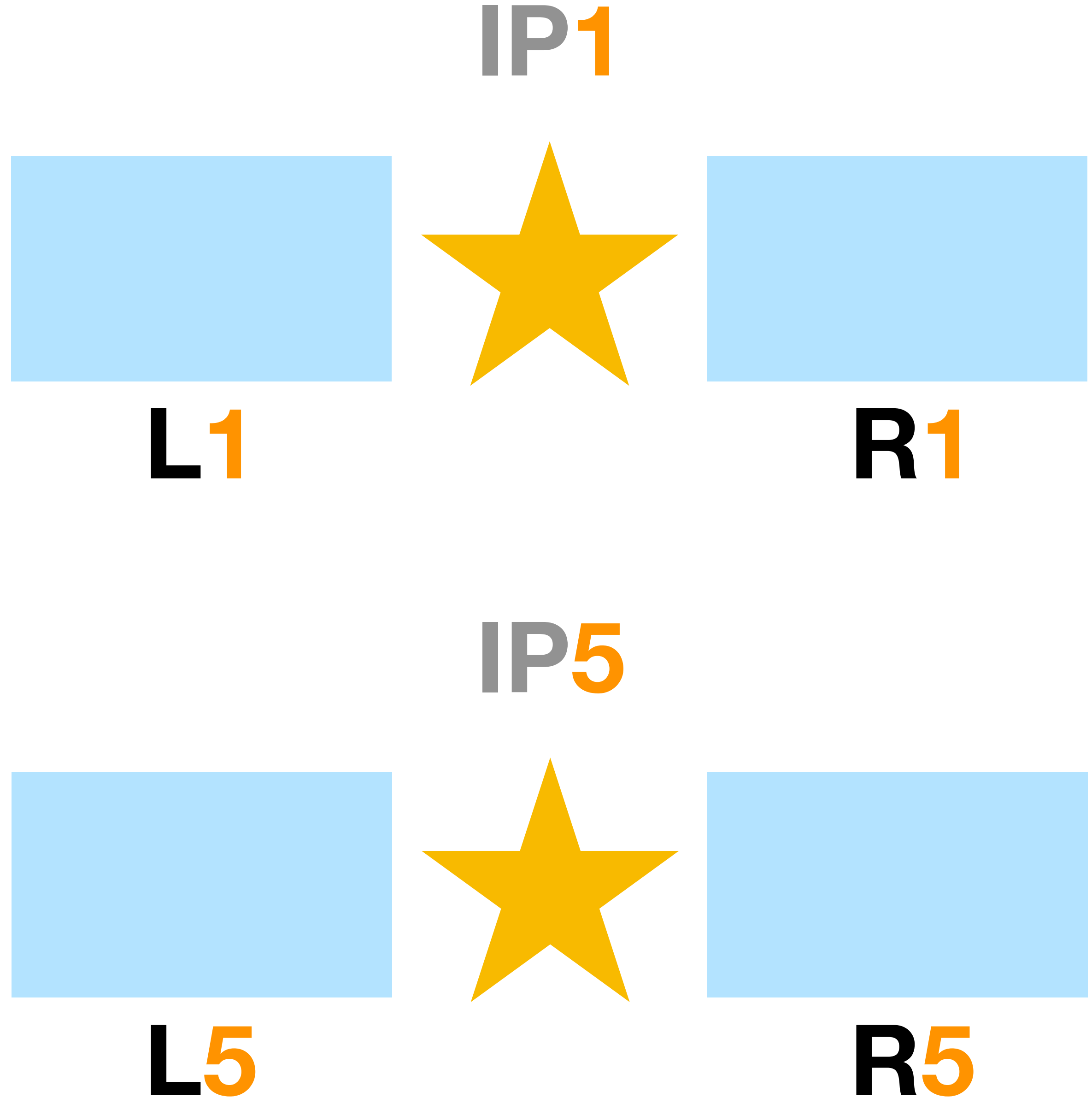
ACFCA.AR1.B1



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

Cavity-name anatomy:

ACFCA.AR1.B1


IP1
L1
R1
IP5
L5
R5

Instrumentation reading

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

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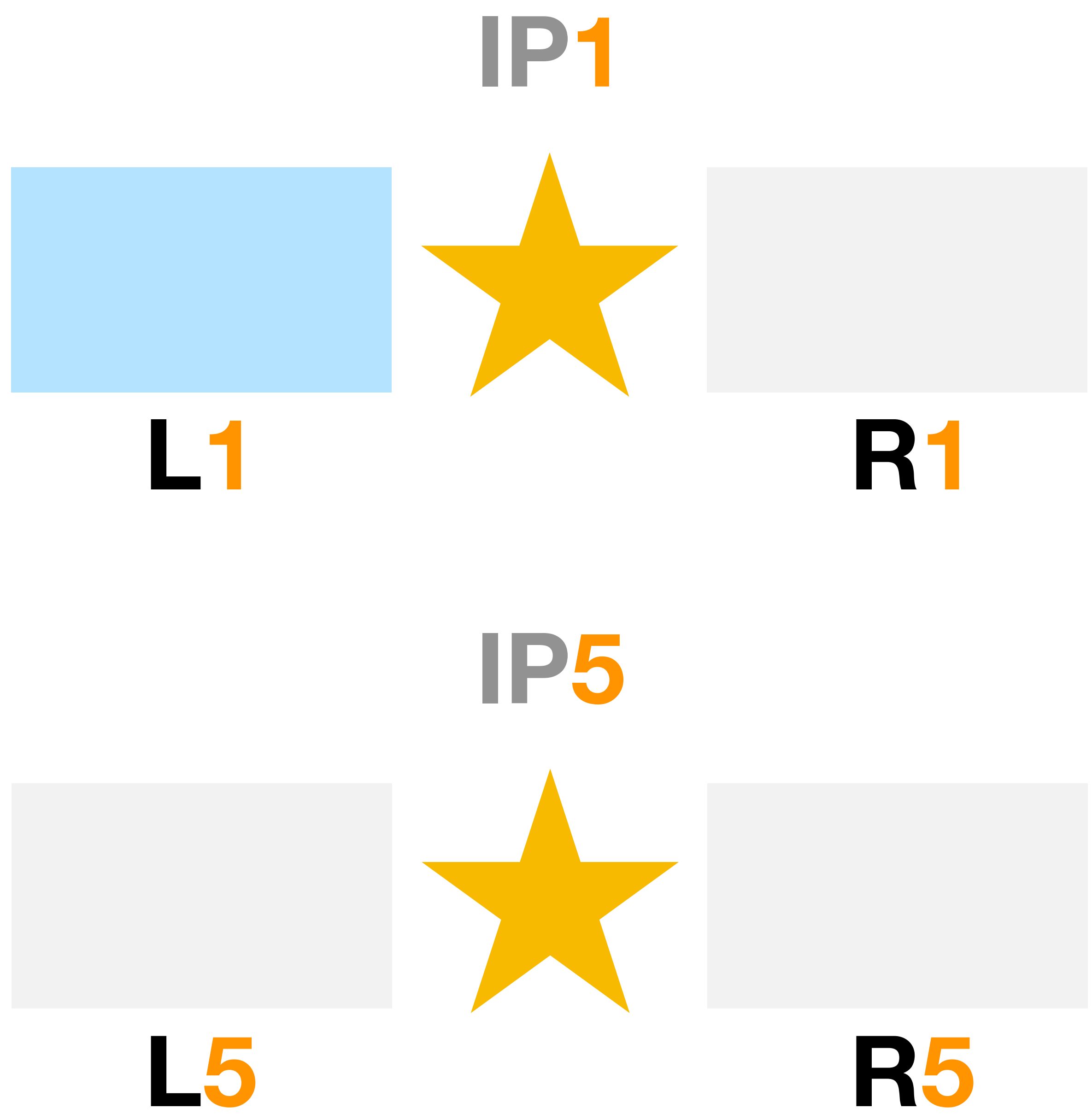
➡ BPM reading, including filtering

Calculating reading when only one set of CCs is ON at a time (V_{set}=2*0.5=1 MV)



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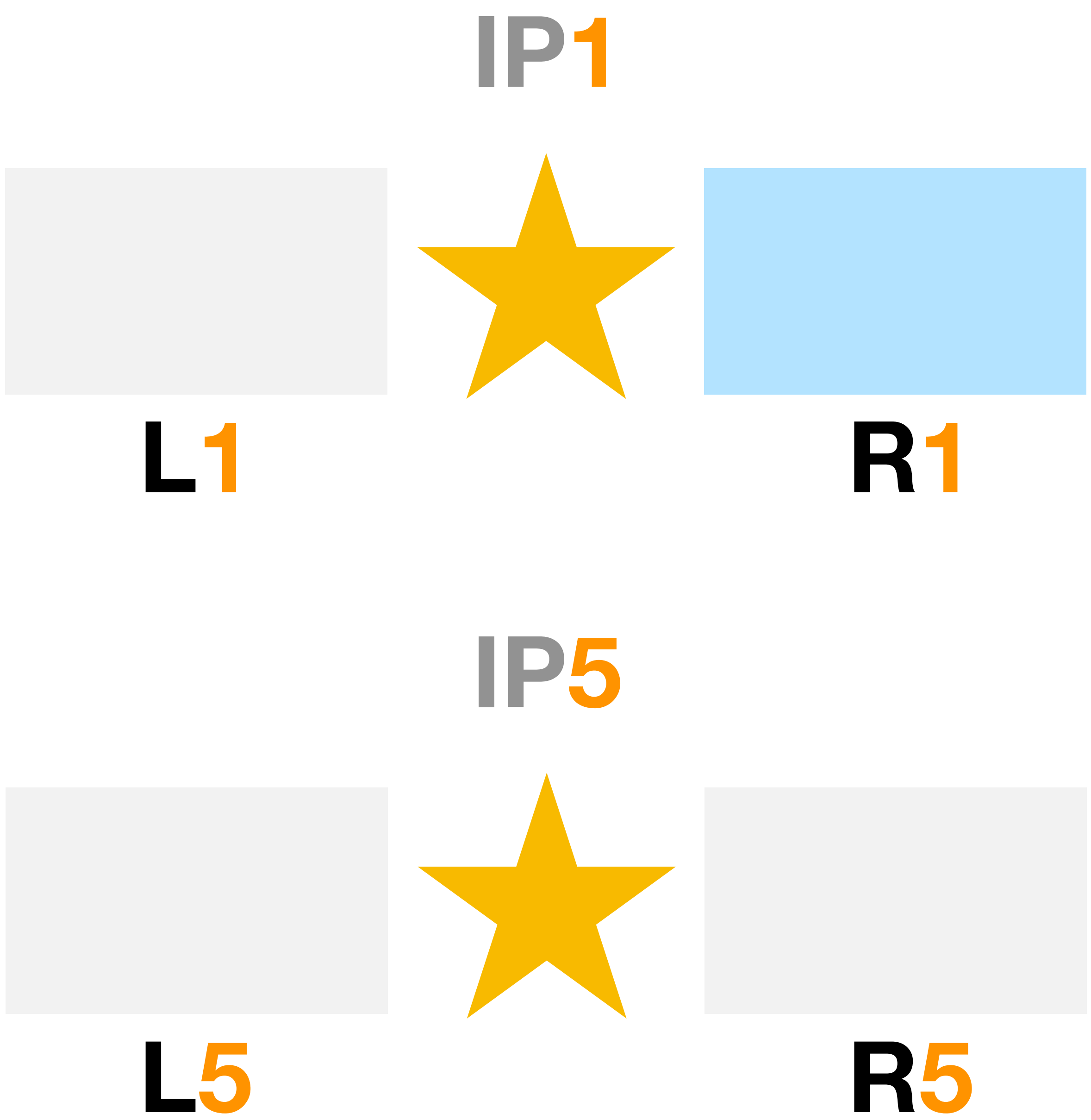

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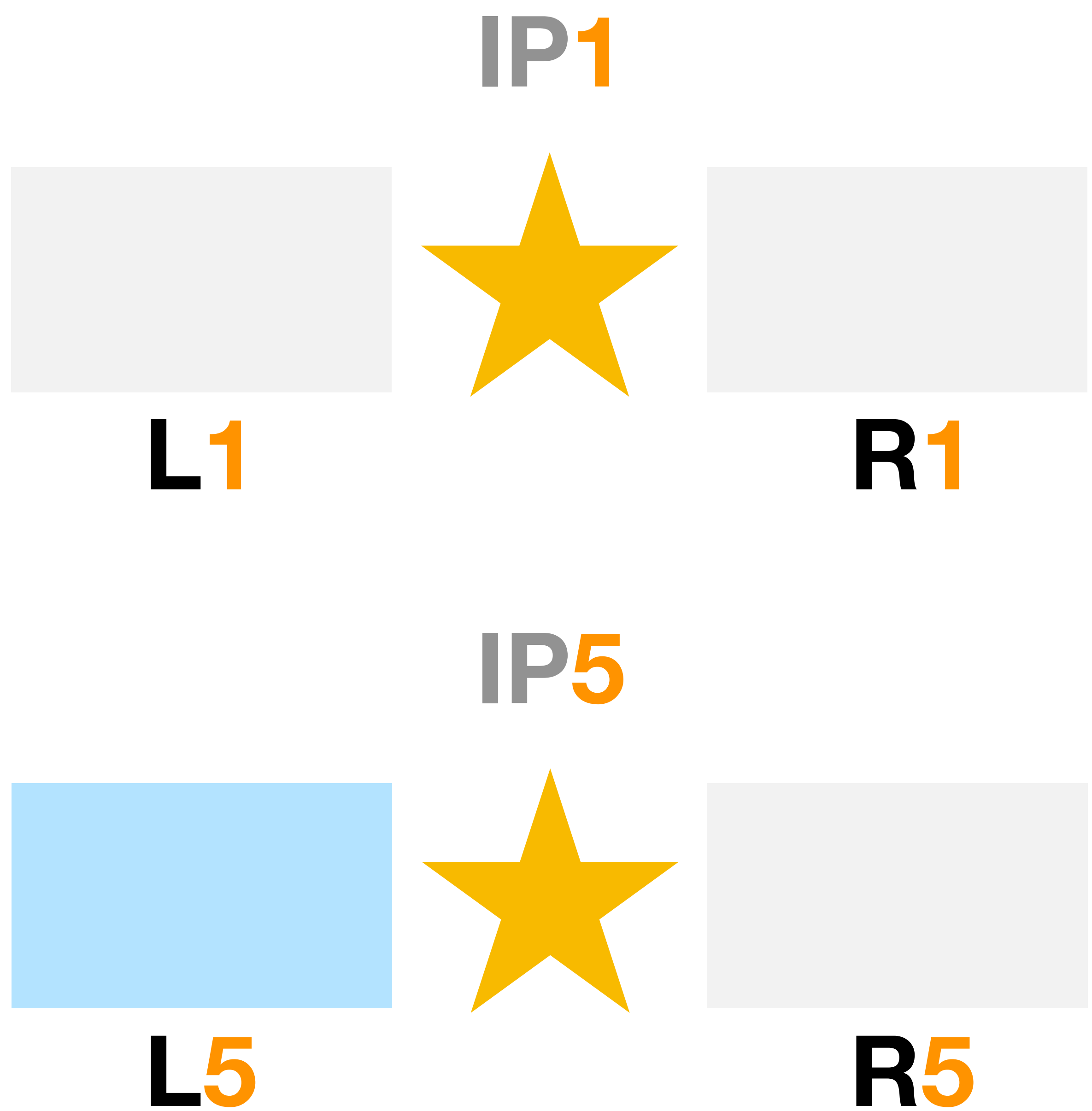

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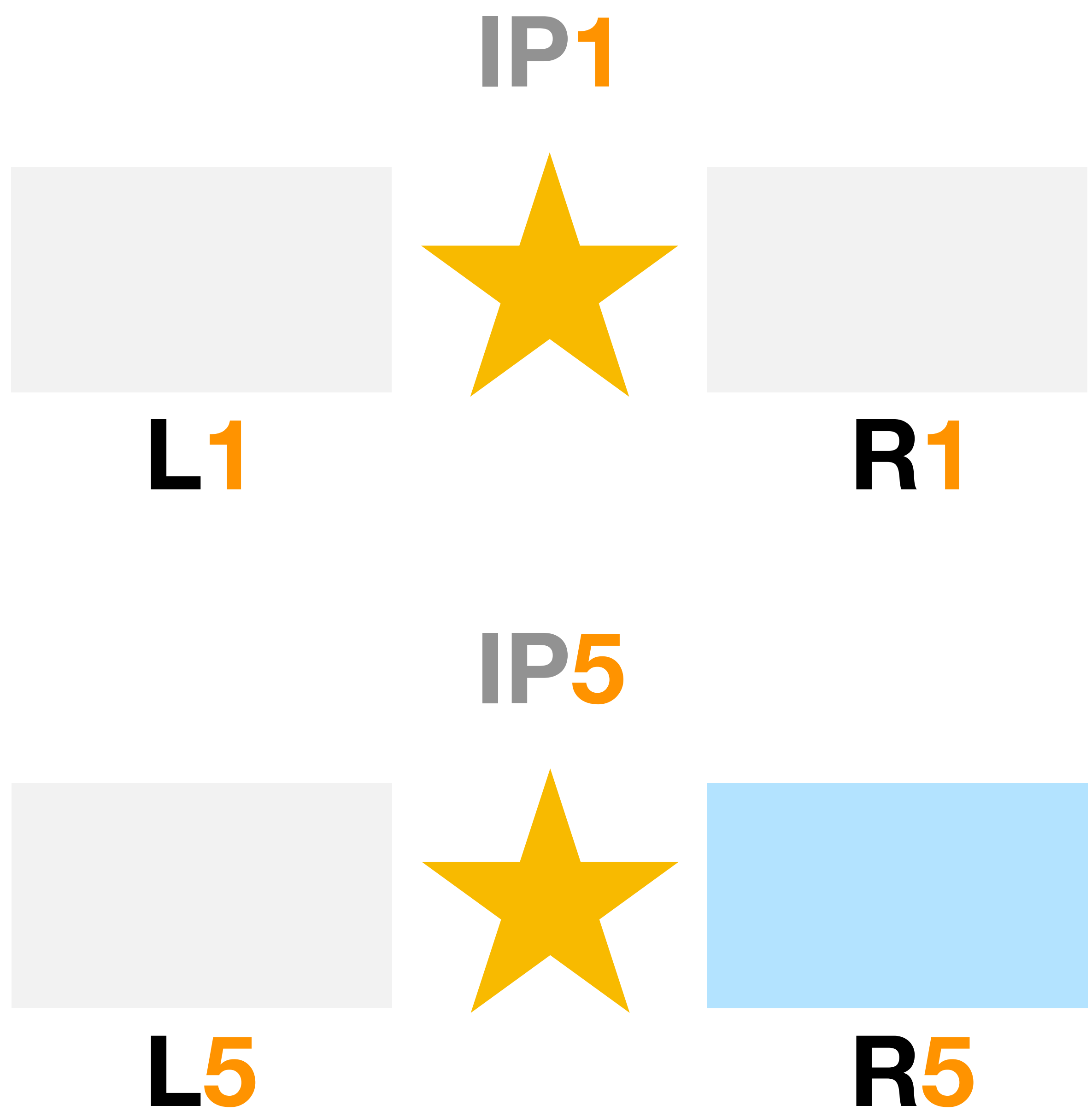

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➡ BPM reading, including filtering

twiss at appendix

HT

- Beam1:

H
- BPLH.7R4.B1

V
- BPLV.A6R4.B1

- Beam2:

H
- BPLH.6R4.B2

V
- BPLV.7R4.B2

IP1: H crossing

IP5: V crossing

HT

- Beam1:
  - H: BPLH.7R4.B1
  - V: BPLV.A6R4.B1
- Beam2:
  - H: BPLH.6R4.B2
  - V: BPLV.7R4.B2

IP1: H crossing

IP5: V crossing

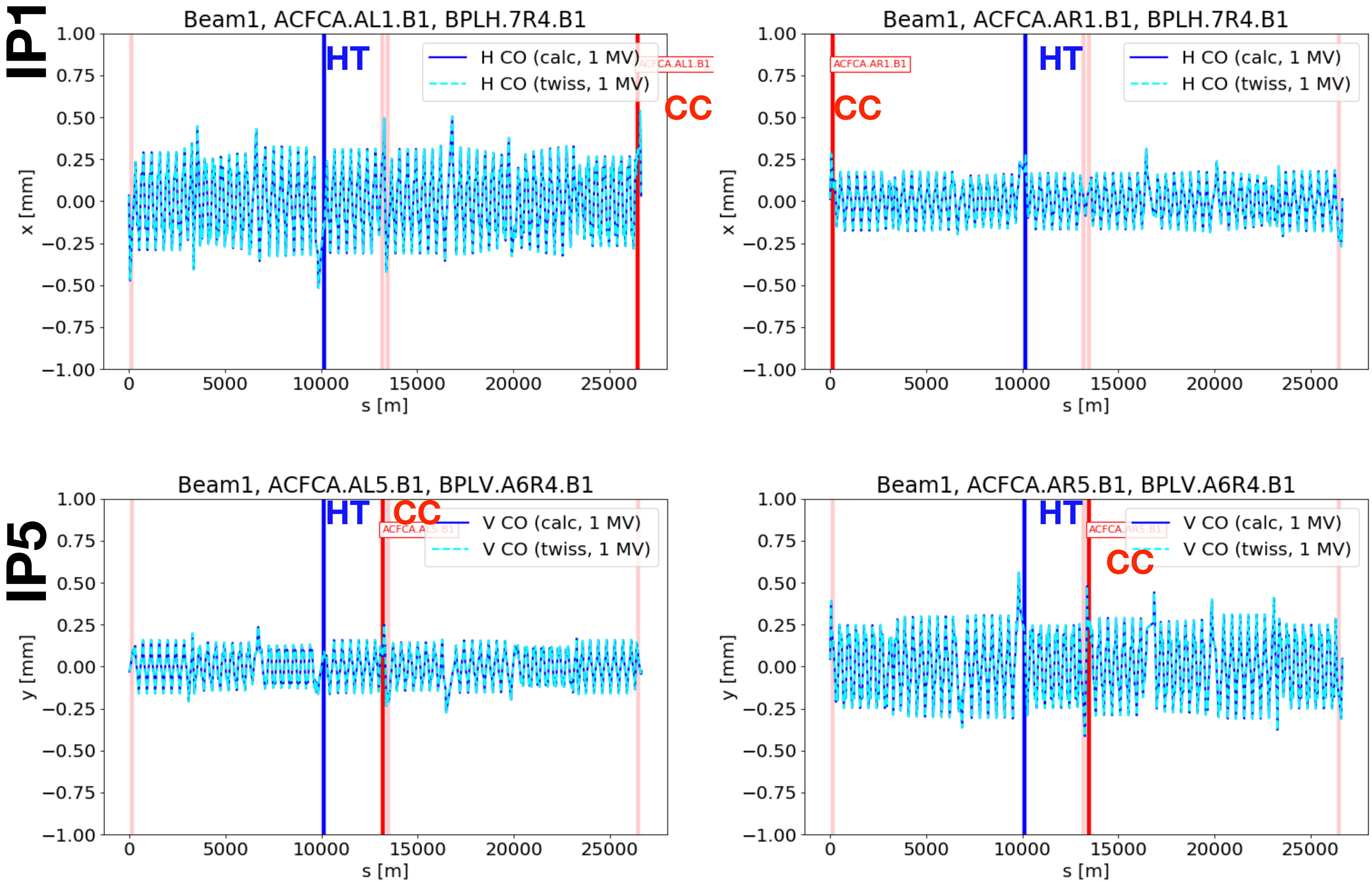
From T. Levens:

- New HT exact configuration not yet decided
- Trying to optimise positions to get largest amplitude of crabbing signal; this might require having multiple pickups, but baseline would still be 1 per plane
- Existing pickups resolution:
  - <100 μm in turn by turn mode
  - For the CC <10 μm (thanks to averaging)
  - Systematics may limit us

Beam1

L analytical formula R

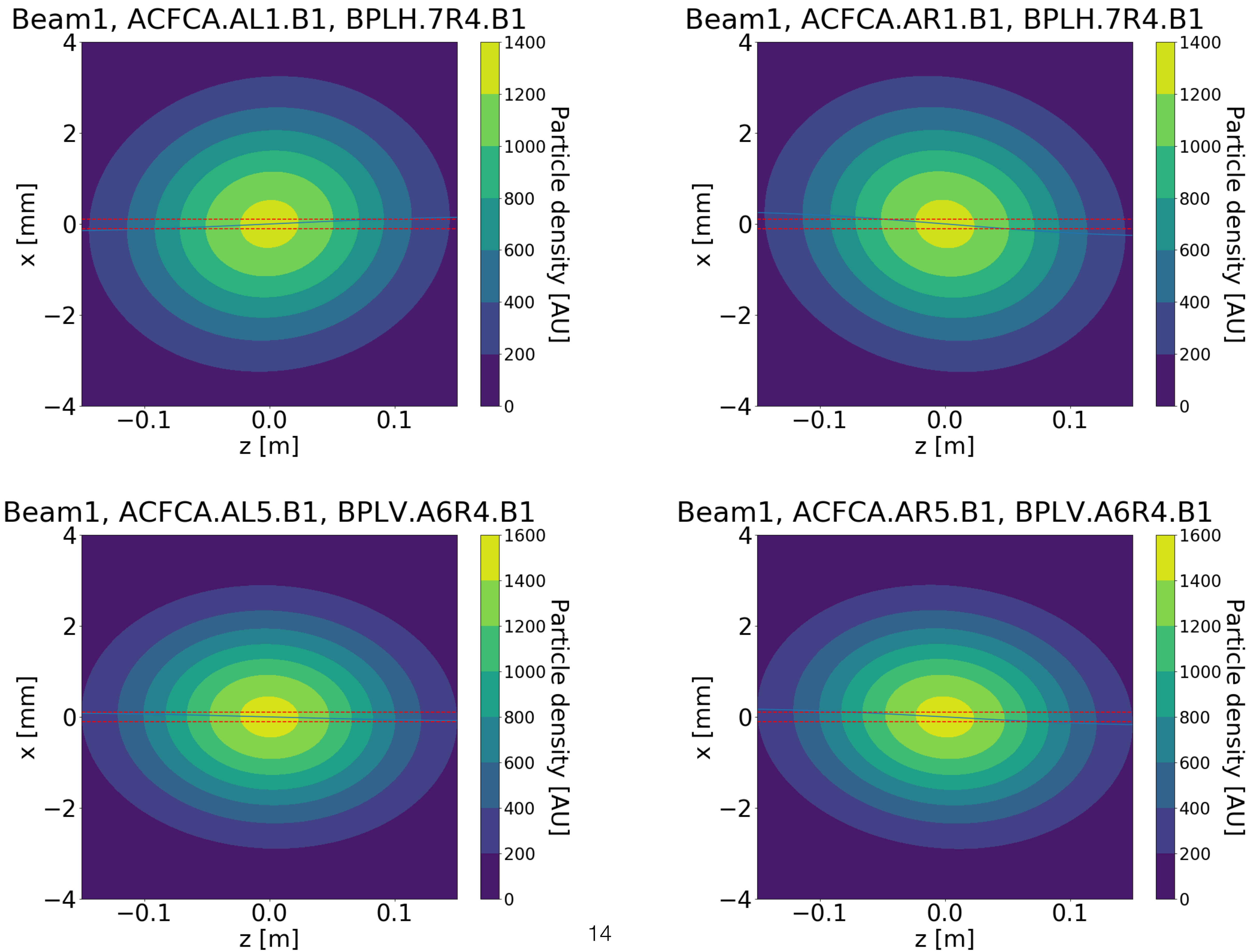
MAD-X twiss



L bunch length: 0.075m R

IP1

IP5



L **bunch length: 0.075m** **R**

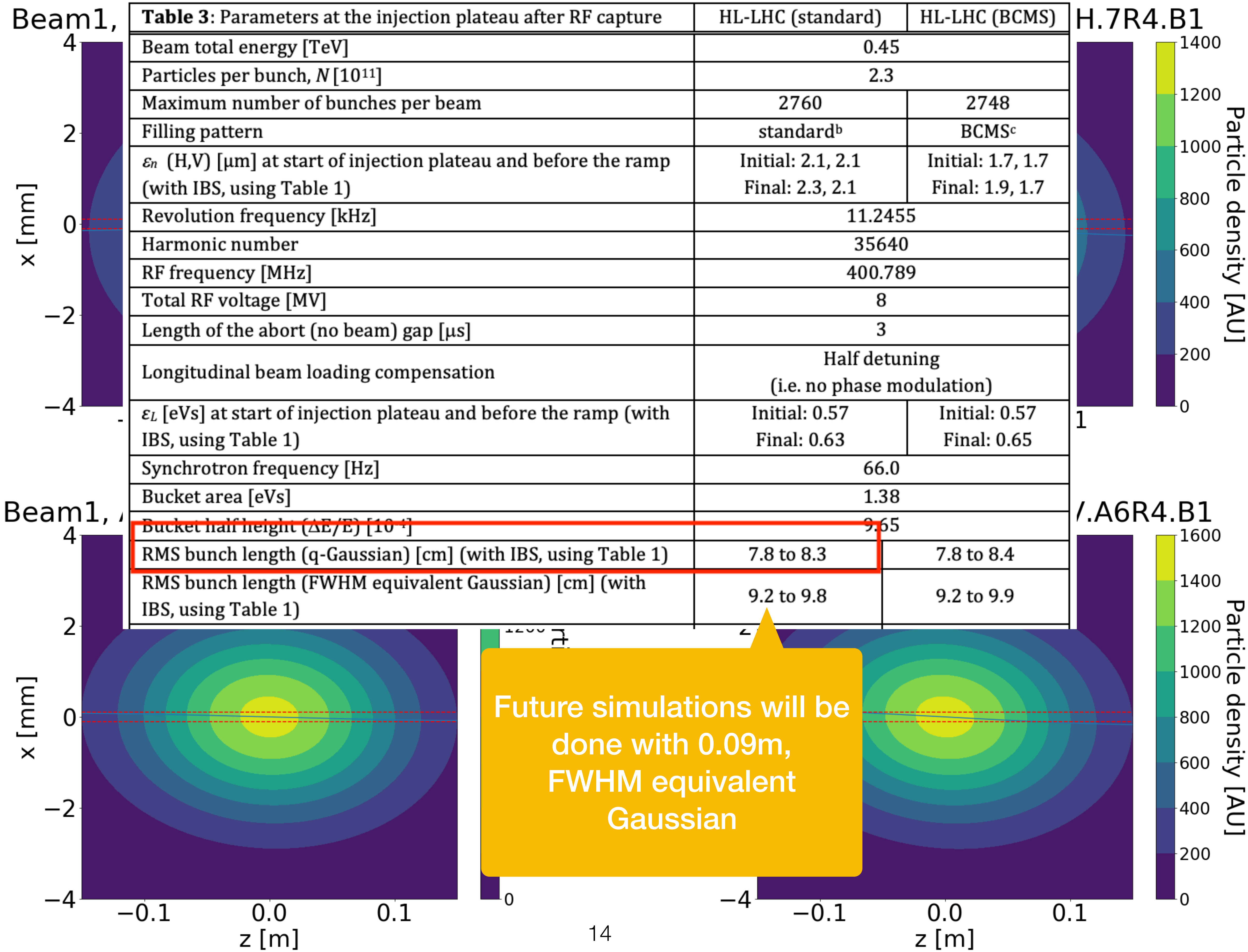
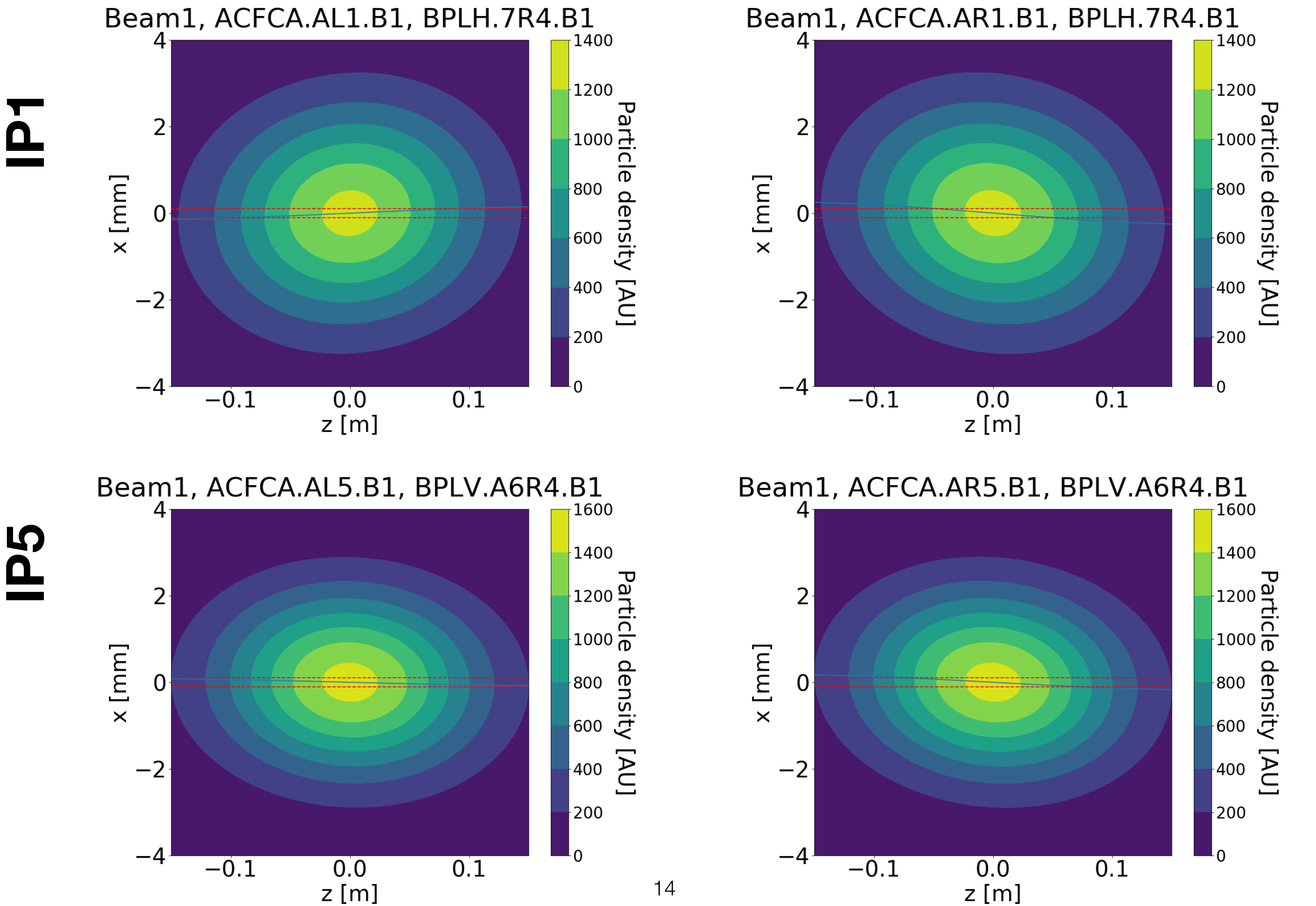
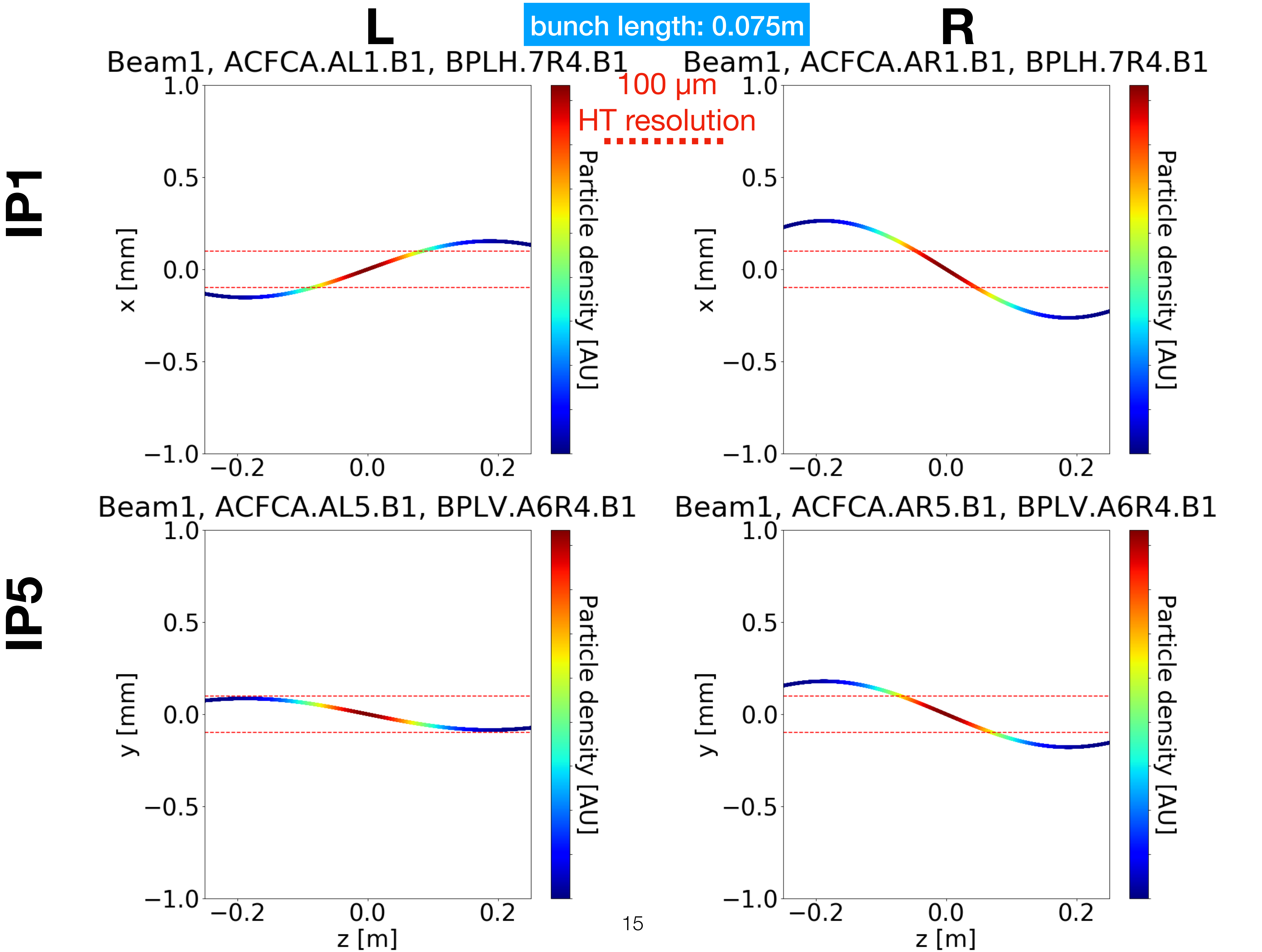


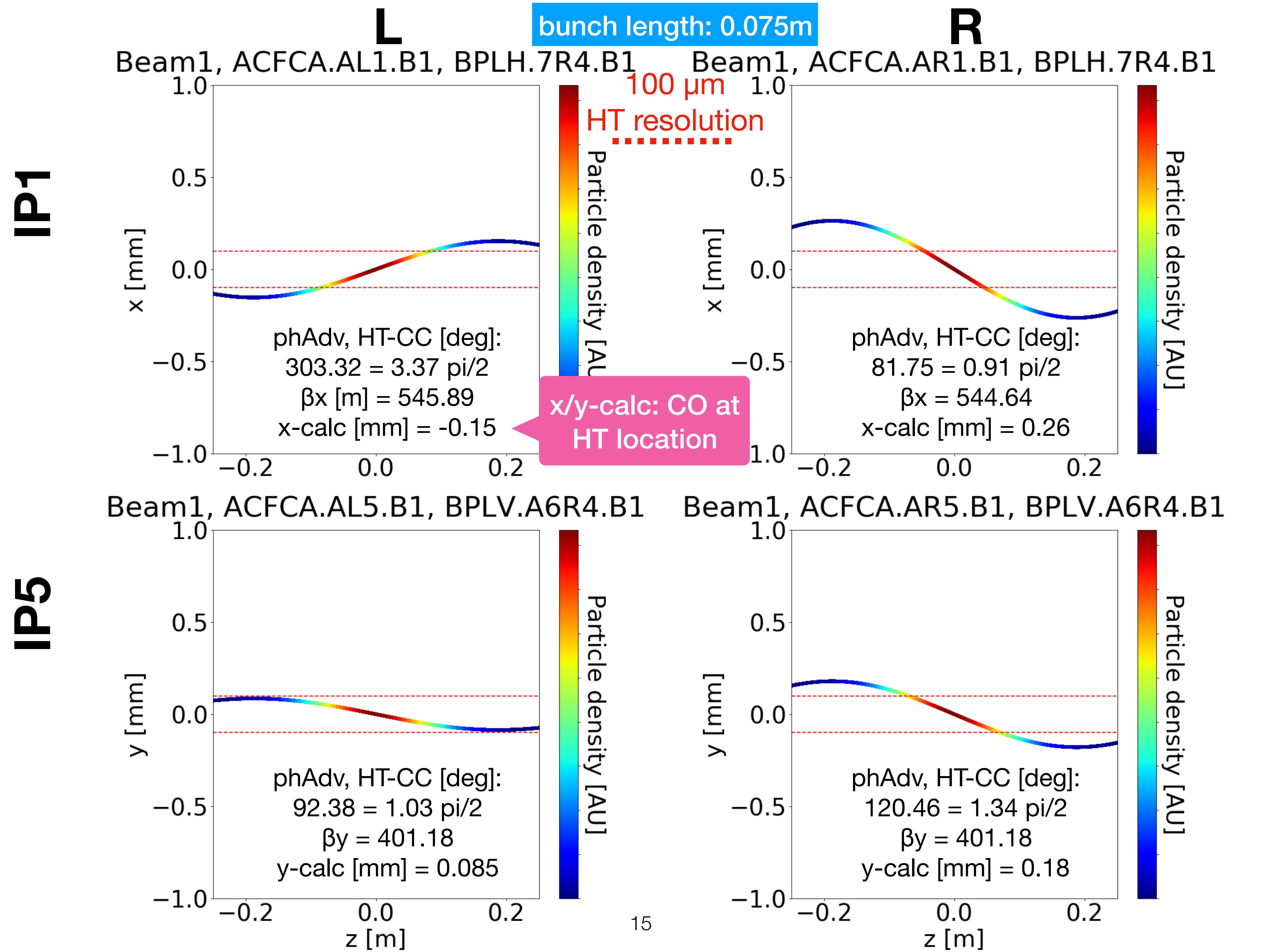
Table 3: Parameters at the injection plateau after RF capture	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	0.45	
Particles per bunch, N [10^{11}]	2.3	
Maximum number of bunches per beam	2760	2748
Filling pattern	standard[b]	BCMS[c]
ε_n (H,V) [μm] at start of injection plateau and before the ramp (with IBS, using Table 1)	Initial: 2.1, 2.1 Final: 2.3, 2.1	Initial: 1.7, 1.7 Final: 1.9, 1.7
Revolution frequency [kHz]	11.2455	
Harmonic number	35640	
RF frequency [MHz]	400.789	
Total RF voltage [MV]	8	
Length of the abort (no beam) gap [μs]	3	
Longitudinal beam loading compensation	Half detuning (i.e. no phase modulation)	
ε_L [eVs] at start of injection plateau and before the ramp (with IBS, using Table 1)	Initial: 0.57 Final: 0.63	Initial: 0.57 Final: 0.65
Synchrotron frequency [Hz]	66.0	
Bucket area [eVs]	1.38	
Bucket half height ($\Delta E/E$) [10^{-4}]	9.65	
RMS bunch length (q-Gaussian) [cm] (with IBS, using Table 1)	7.8 to 8.3	7.8 to 8.4
RMS bunch length (FWHM equivalent Gaussian) [cm] (with IBS, using Table 1)	9.2 to 9.8	9.2 to 9.9

Future simulations will be done with 0.09m, FWHM equivalent Gaussian

L **bunch length: 0.075m** R

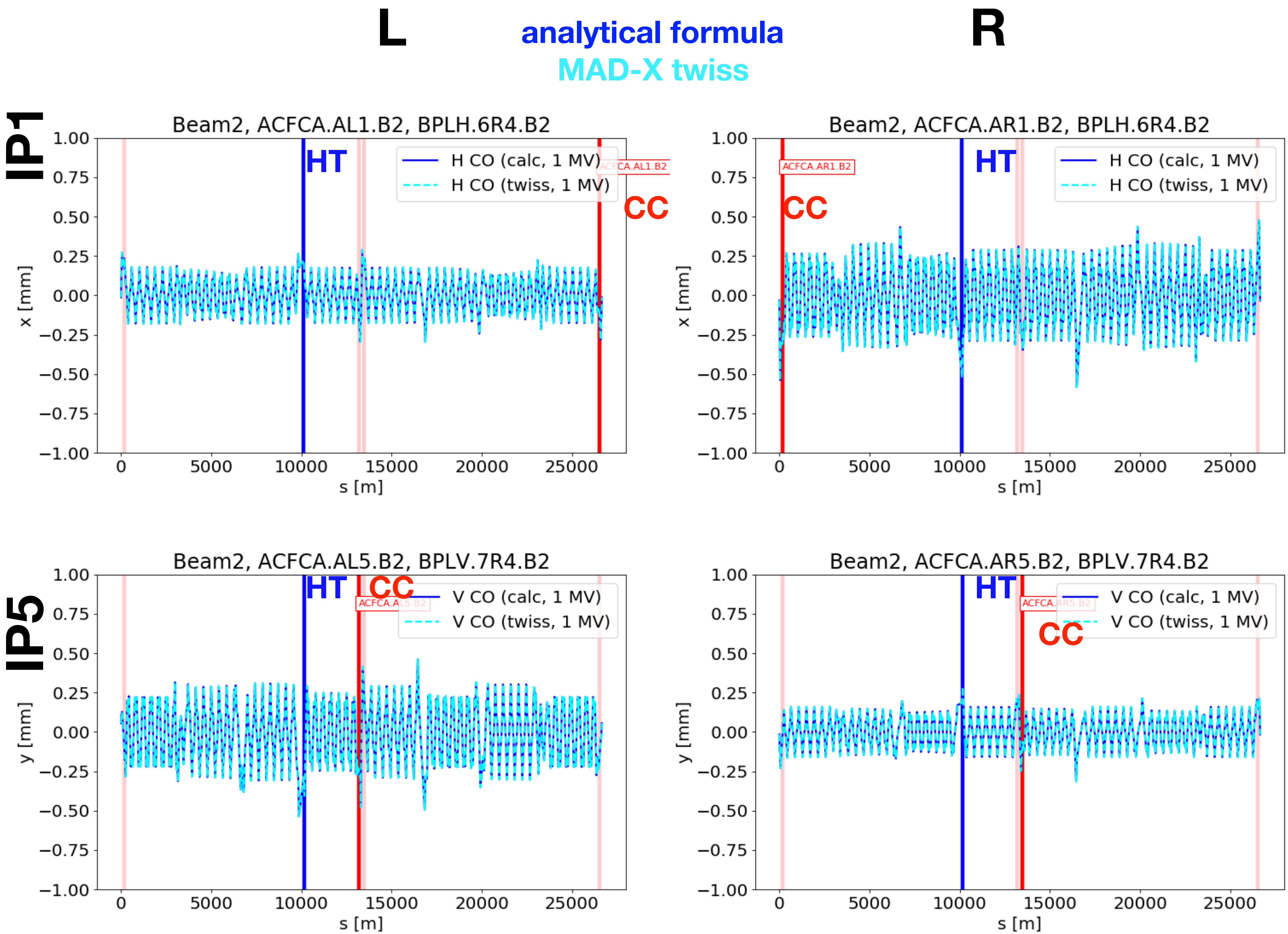



L
bunch length: 0.075m
R
IP1
IP5
Beam1, ACFCA.AL1.B1, BPLH.7R4.B1
Beam1, ACFCA.AR1.B1, BPLH.7R4.B1
100 μm
HT resolution
Beam1, ACFCA.AL5.B1, BPLV.A6R4.B1
Beam1, ACFCA.AR5.B1, BPLV.A6R4.B1
x [mm]
y [mm]
z [m]
Particle density [AU]
1.0
0.5
0.0
−0.5
−1.0
−0.2
0.0
0.2



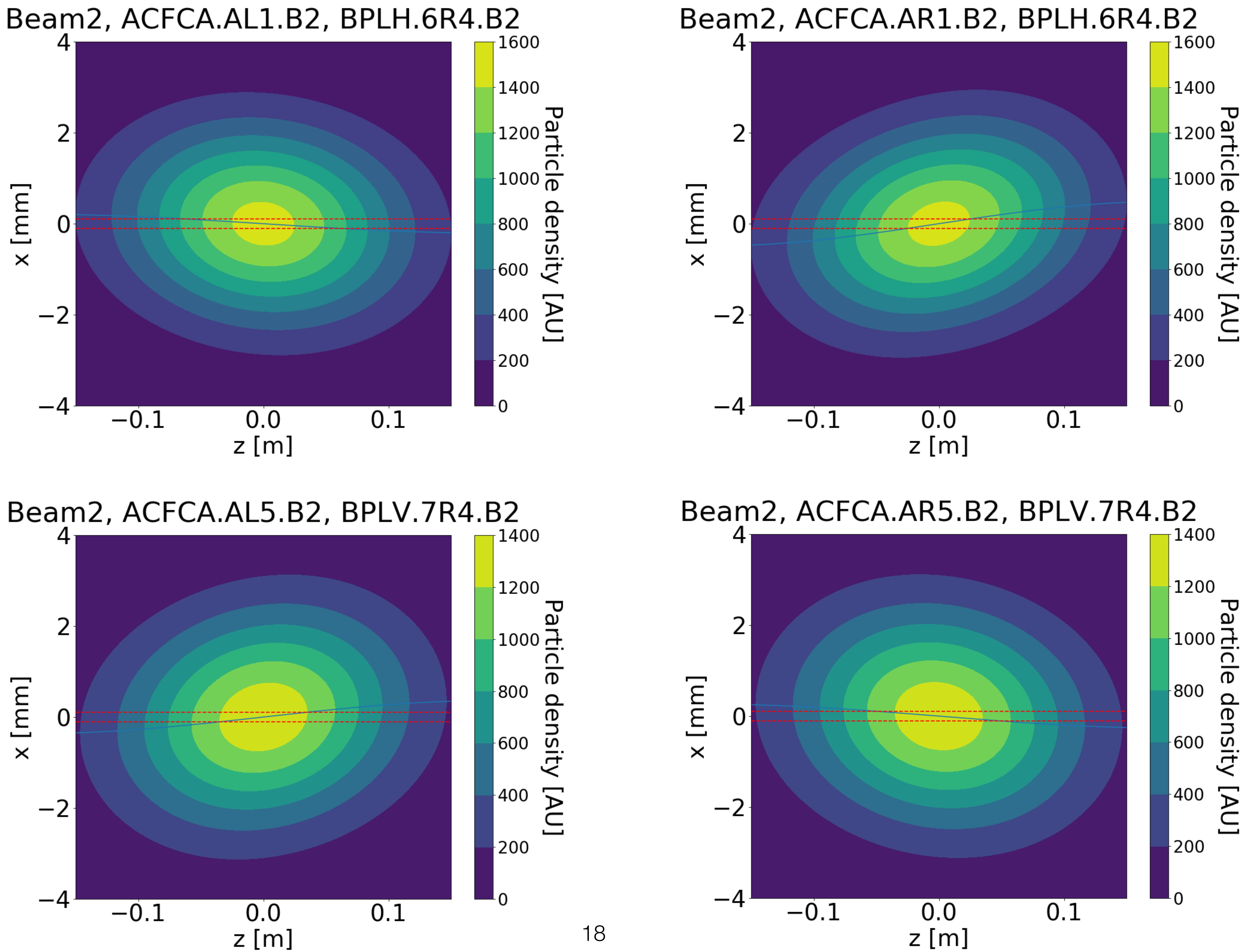
L
bunch length: 0.075m
R
IP1
IP5
Beam1, ACFCA.AL1.B1, BPLH.7R4.B1
Beam1, ACFCA.AR1.B1, BPLH.7R4.B1
100 µm
HT resolution
x [mm]
Particle density [AU]
phAdv, HT-CC [deg]:
303.32 = 3.37 pi/2
βx [m] = 545.89
x-calc [mm] = -0.15
x/y-calc: CO at HT location
phAdv, HT-CC [deg]:
81.75 = 0.91 pi/2
βx = 544.64
x-calc [mm] = 0.26
Beam1, ACFCA.AL5.B1, BPLV.A6R4.B1
Beam1, ACFCA.AR5.B1, BPLV.A6R4.B1
y [mm]
phAdv, HT-CC [deg]:
92.38 = 1.03 pi/2
βy = 401.18
y-calc [mm] = 0.085
phAdv, HT-CC [deg]:
120.46 = 1.34 pi/2
βy = 401.18
y-calc [mm] = 0.18
z [m]

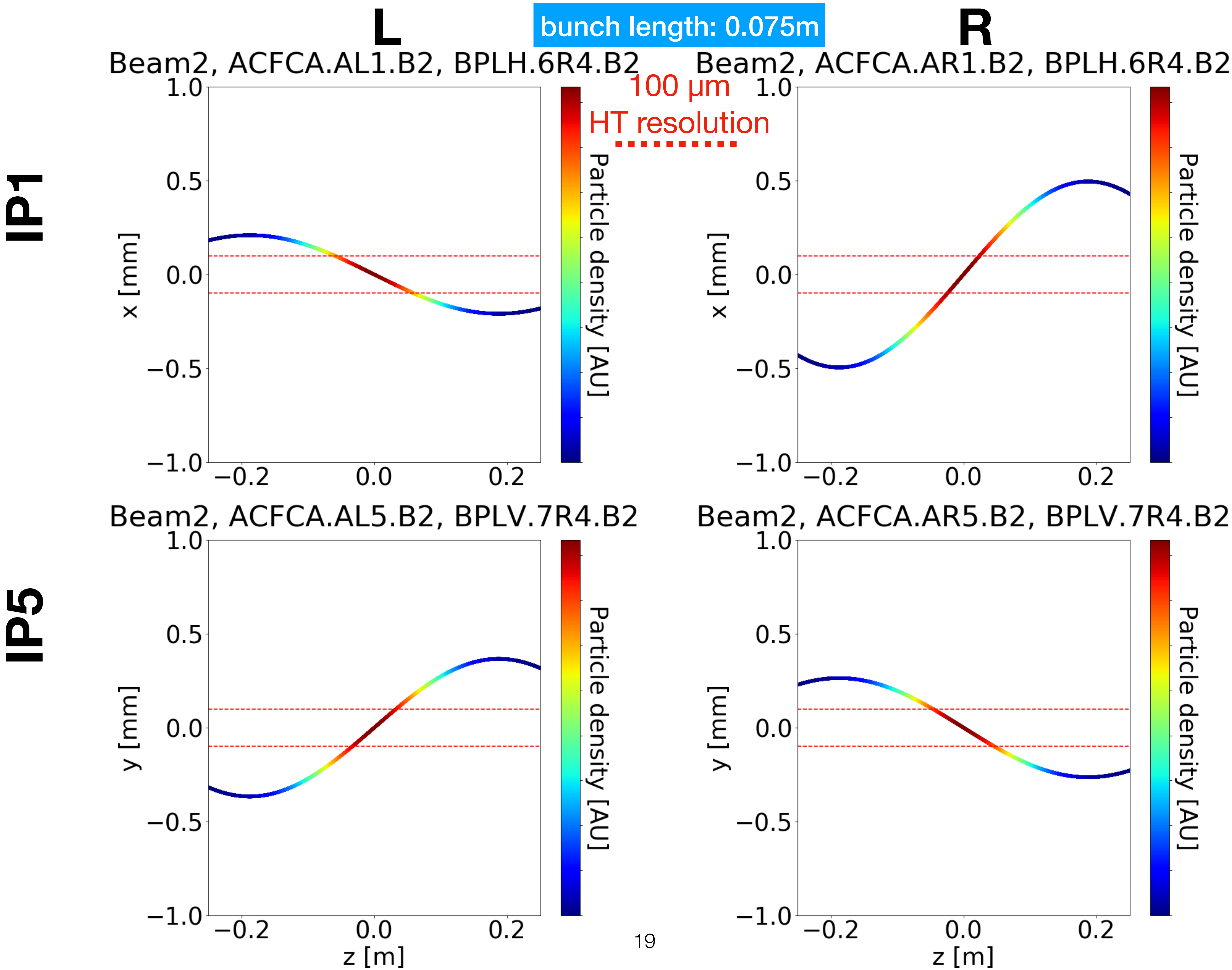
Beam2


L
analytical formula
MAD-X twiss
R
IP1
Beam2, ACFCA.AL1.B2, BPLH.6R4.B2
HT
CC
ACFCA.AL1.B2
H CO (calc, 1 MV)
H CO (twiss, 1 MV)
x [mm]
s [m]
Beam2, ACFCA.AR1.B2, BPLH.6R4.B2
HT
CC
ACFCA.AR1.B2
H CO (calc, 1 MV)
H CO (twiss, 1 MV)
x [mm]
s [m]
IP5
Beam2, ACFCA.AL5.B2, BPLV.7R4.B2
HT
CC
V CO (calc, 1 MV)
V CO (twiss, 1 MV)
y [mm]
s [m]
Beam2, ACFCA.AR5.B2, BPLV.7R4.B2
HT
CC
V CO (calc, 1 MV)
V CO (twiss, 1 MV)
y [mm]
s [m]

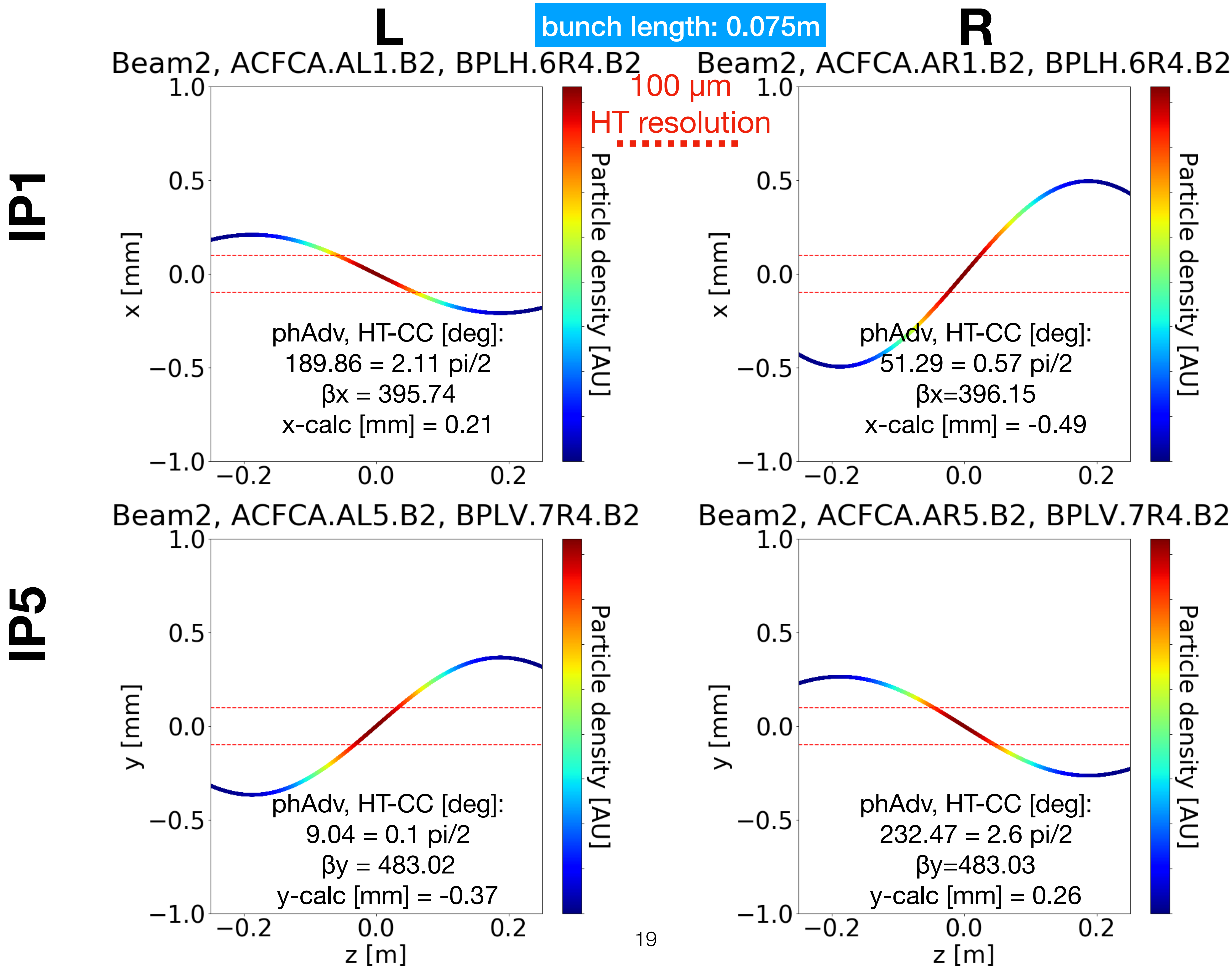
L | bunch length: 0.075m | R

IP1 / IP5





L
bunch length: 0.075m
R
IP1
IP5
Beam2, ACFCA.AL1.B2, BPLH.6R4.B2
Beam2, ACFCA.AR1.B2, BPLH.6R4.B2
100 μm
HT resolution
Beam2, ACFCA.AL5.B2, BPLV.7R4.B2
Beam2, ACFCA.AR5.B2, BPLV.7R4.B2
x [mm]
y [mm]
z [m]
Particle density [AU]
1.0
0.5
0.0
−0.5
−1.0
−0.2
0.0
0.2



L
bunch length: 0.075m
R
IP1
IP5
Beam2, ACFCA.AL1.B2, BPLH.6R4.B2
Beam2, ACFCA.AR1.B2, BPLH.6R4.B2
100 μm
HT resolution
x [mm]
Particle density [AU]
phAdv, HT-CC [deg]:
189.86 = 2.11 pi/2
βx = 395.74
x-calc [mm] = 0.21
phAdv, HT-CC [deg]:
51.29 = 0.57 pi/2
βx=396.15
x-calc [mm] = -0.49
Beam2, ACFCA.AL5.B2, BPLV.7R4.B2
Beam2, ACFCA.AR5.B2, BPLV.7R4.B2
y [mm]
phAdv, HT-CC [deg]:
9.04 = 0.1 pi/2
βy = 483.02
y-calc [mm] = -0.37
phAdv, HT-CC [deg]:
232.47 = 2.6 pi/2
βy=483.03
y-calc [mm] = 0.26
z [m]

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
- V_{CC}=1 MV (total), E_{inj}=450 GeV, θ= 0.00222 mrad

➡ Head Tail (HT) monitor

➡ Wire-scanner (WS)

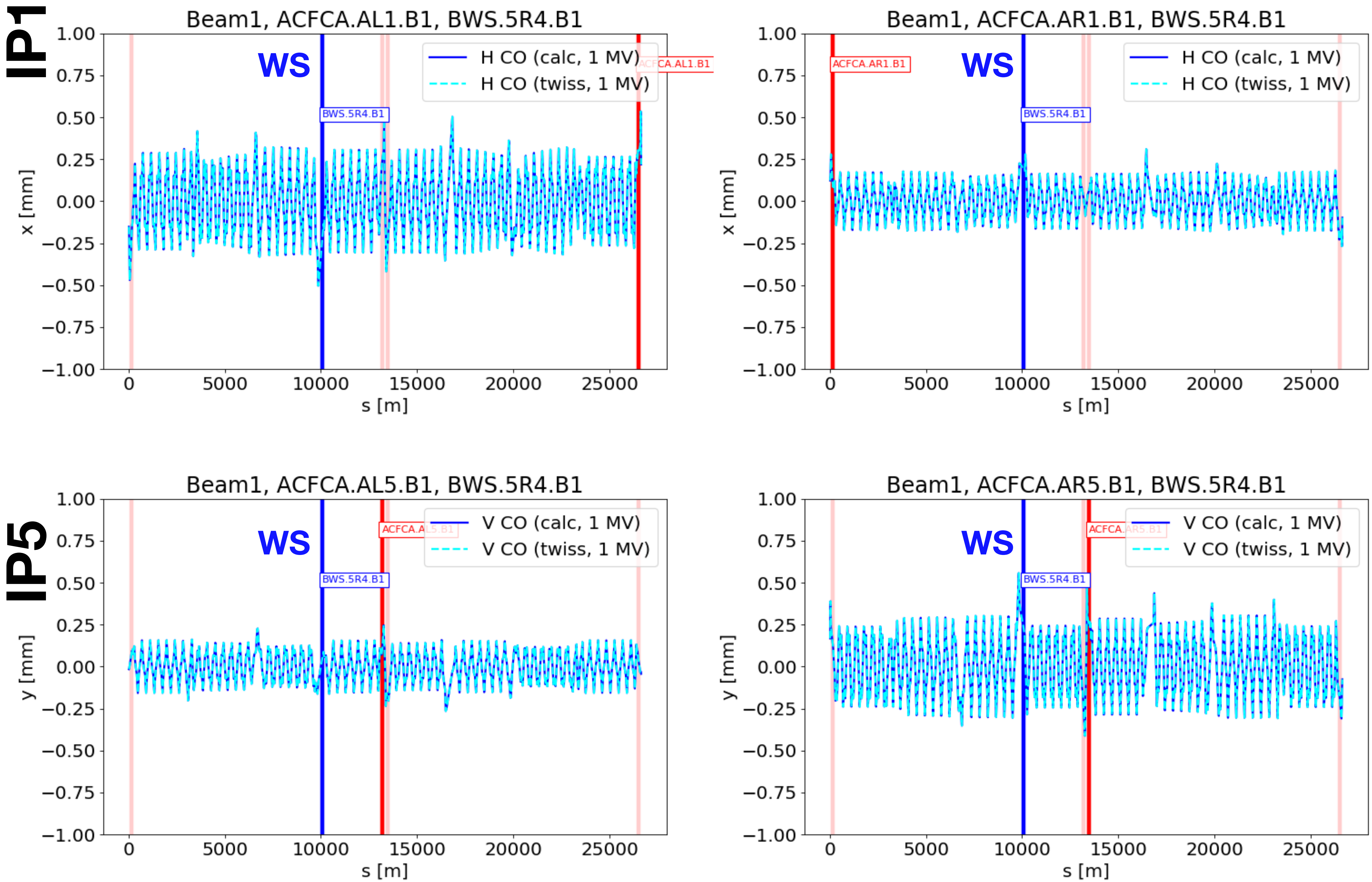
➡ BPM reading, including filtering

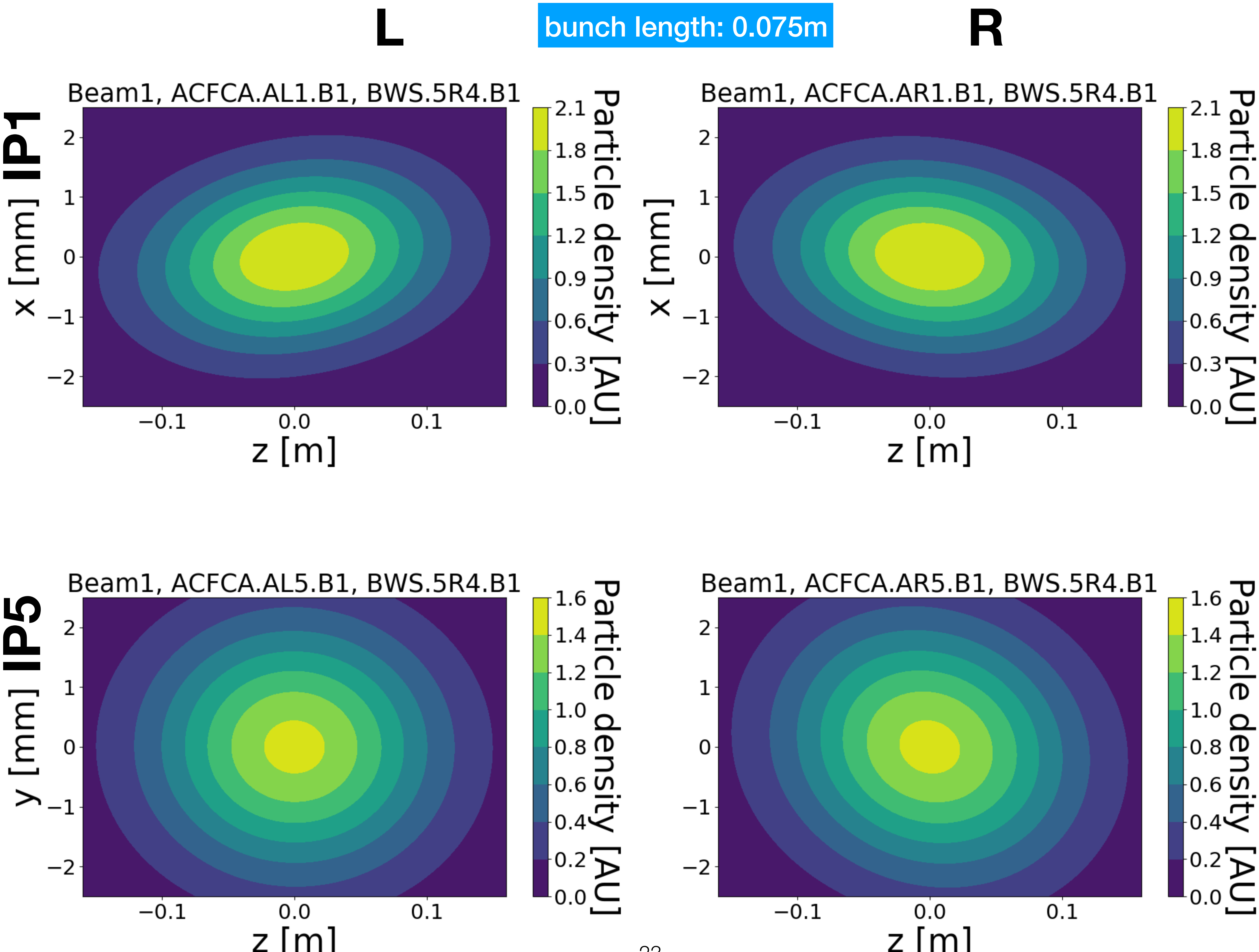
twiss at appendix

Beam1

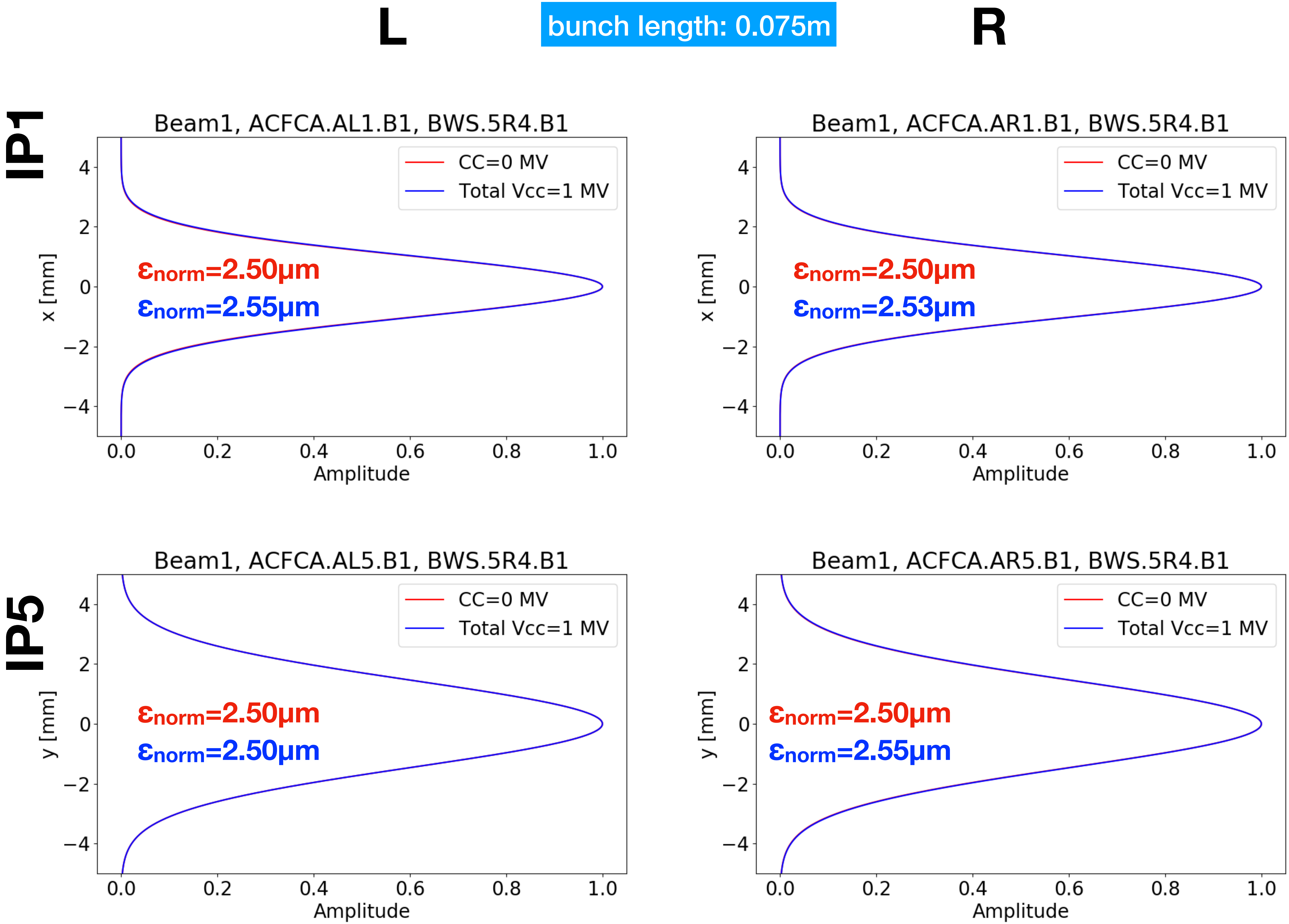
L **analytical formula** **R**

MAD-X twiss




L
bunch length: 0.075m
R
IP1
IP5
Beam1, ACFCA.AL1.B1, BWS.5R4.B1
Beam1, ACFCA.AR1.B1, BWS.5R4.B1
Beam1, ACFCA.AL5.B1, BWS.5R4.B1
Beam1, ACFCA.AR5.B1, BWS.5R4.B1
x [mm]
y [mm]
z [m]
Particle density [AU]
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.1
0.0
0.1
2
1
0
−1
−2

bunch length: 0.075m



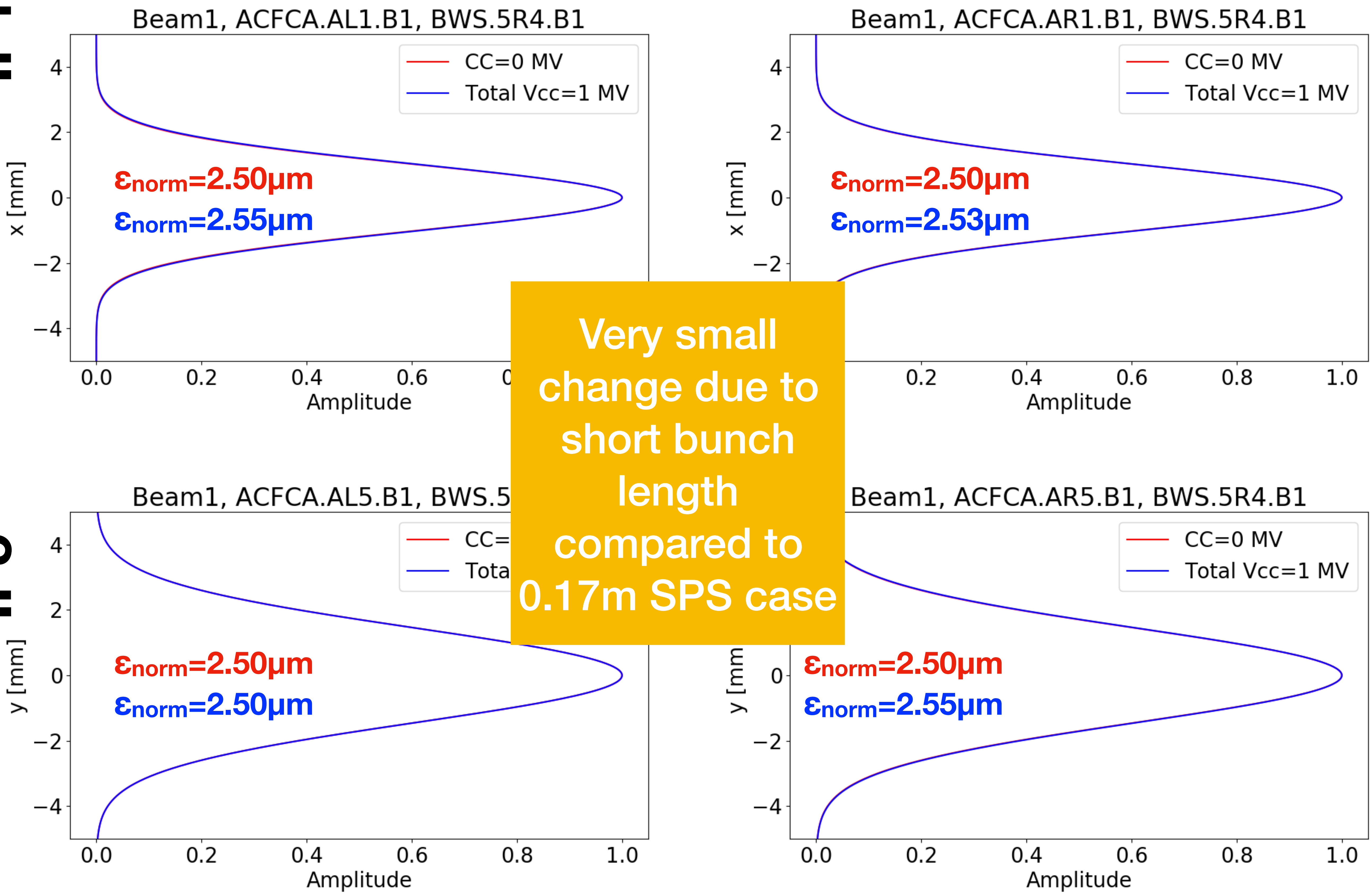
L

bunch length: 0.075m

R

IP1

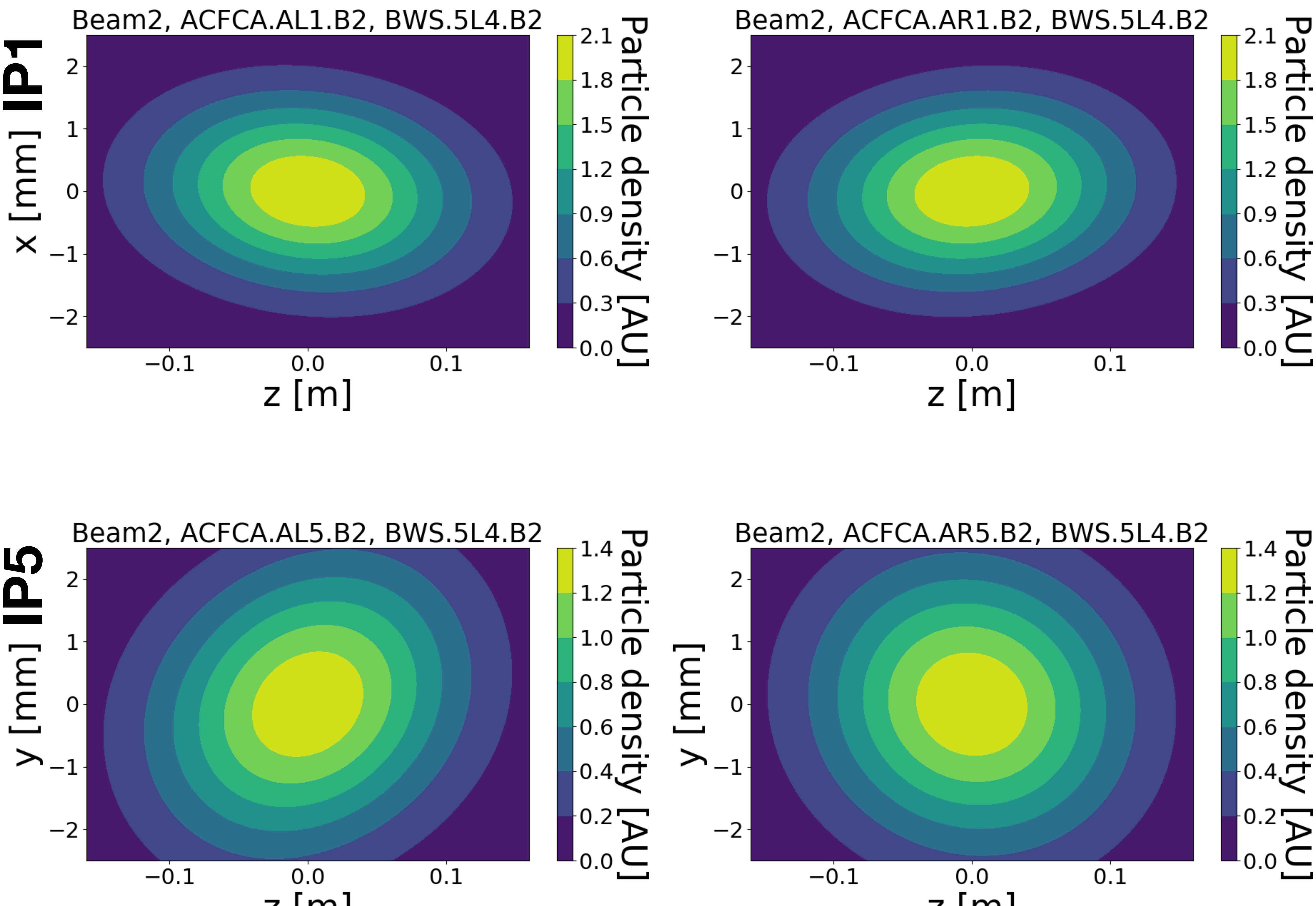
IP5



Very small change due to short bunch length compared to 0.17m SPS case

Beam2

bunch length: 0.075m



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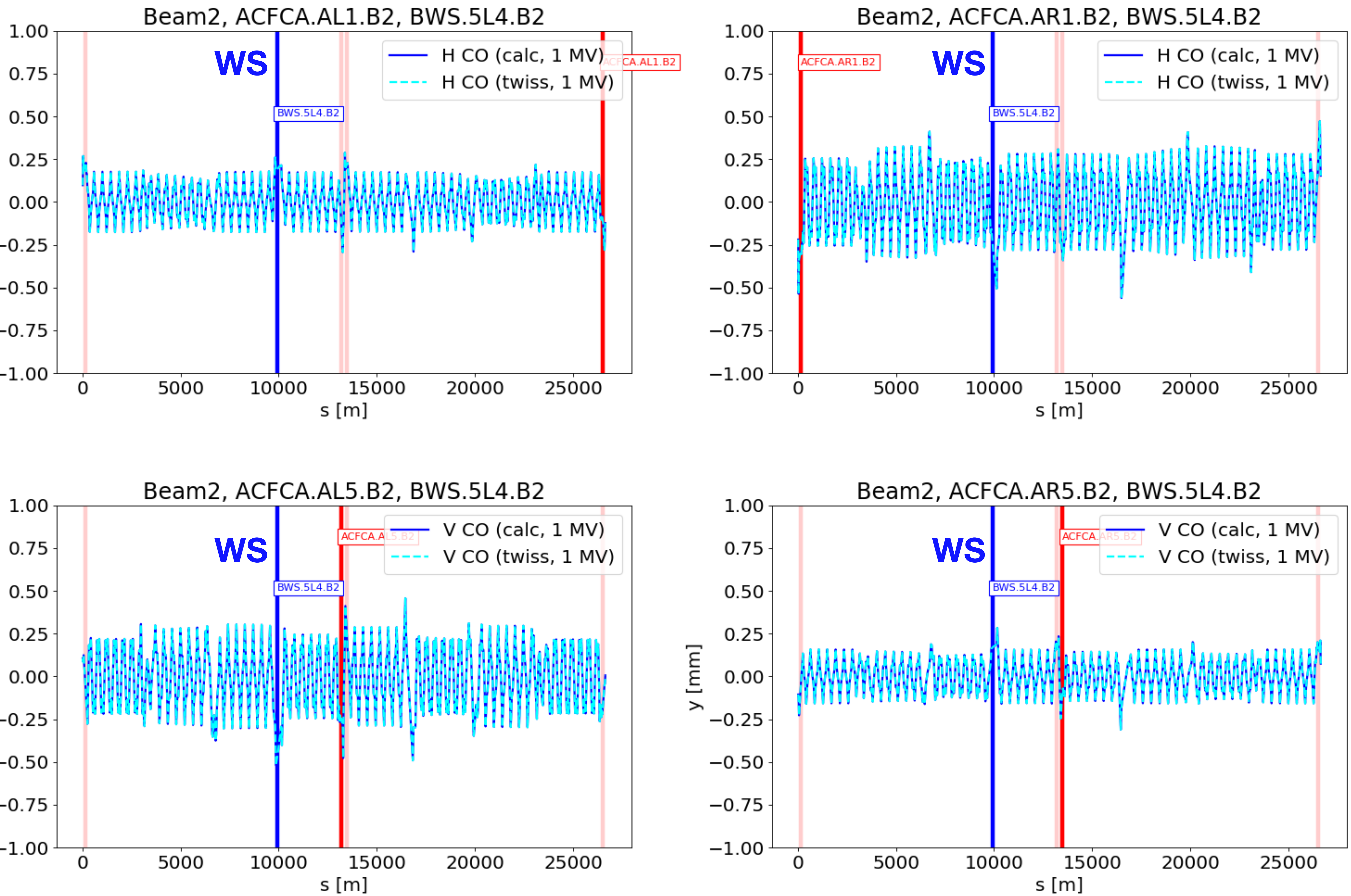
MAD-X twiss

IP1

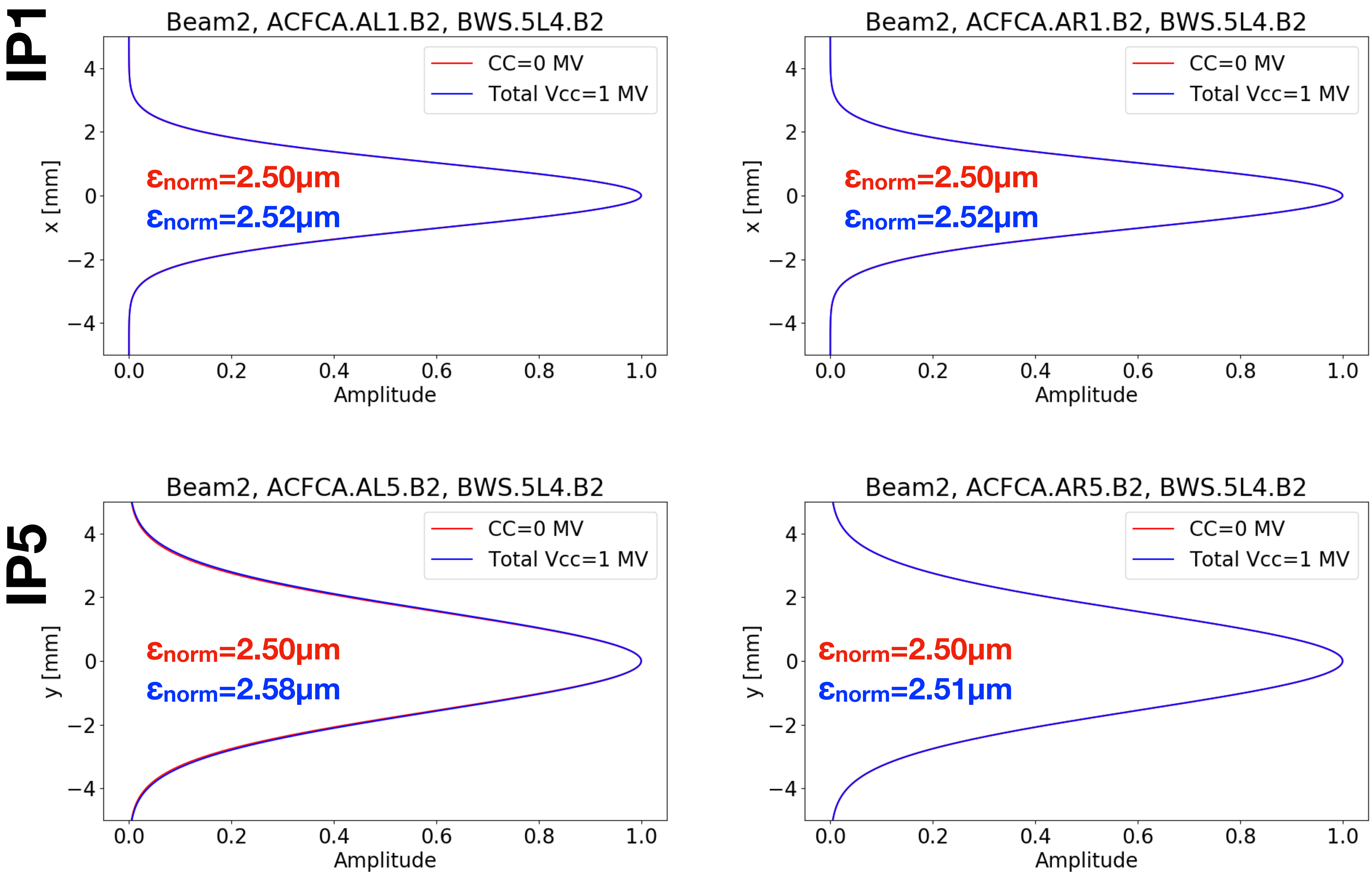
IP5



L

bunch length: 0.075m

R



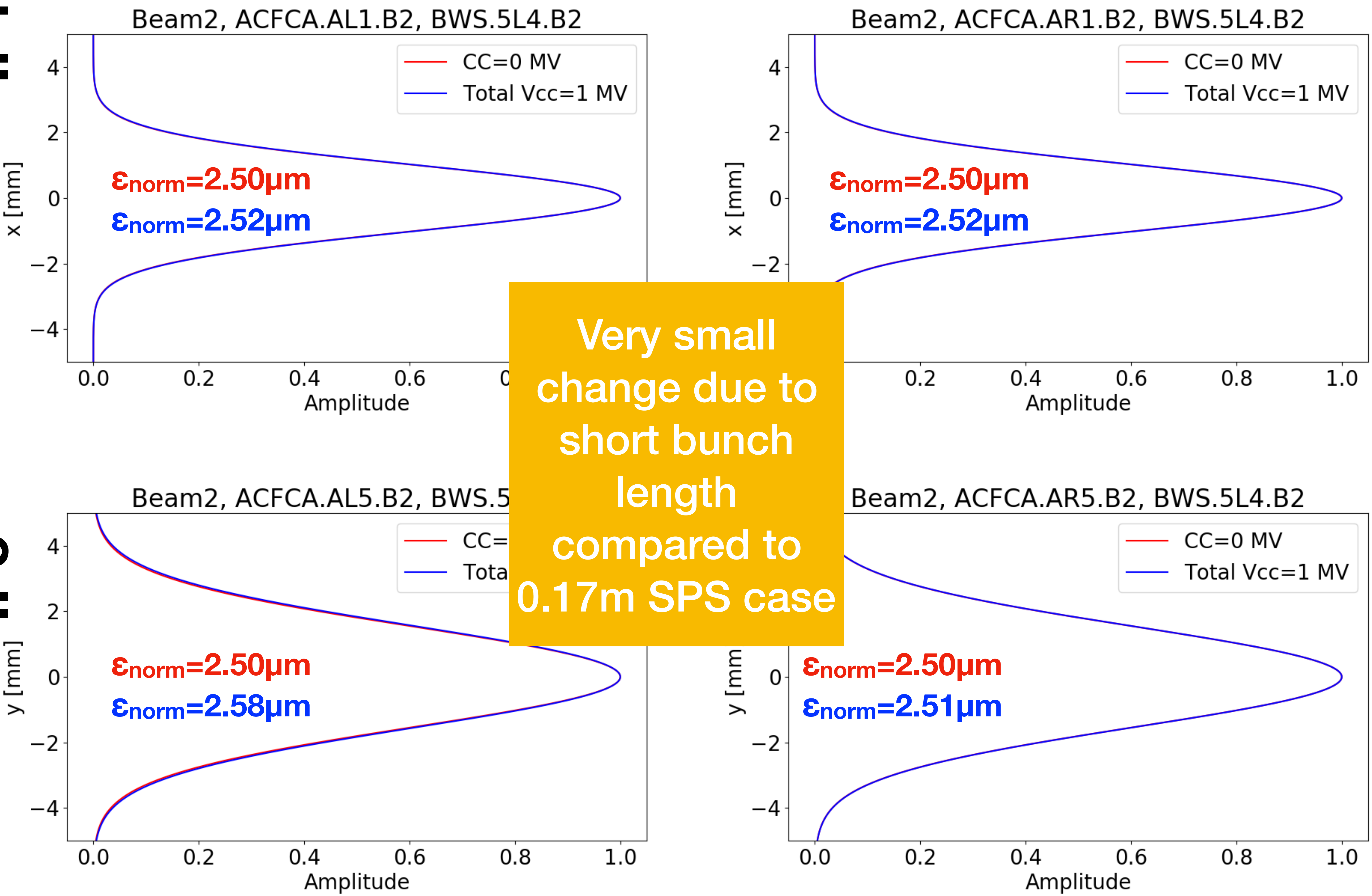
L

bunch length: 0.075m

R

IP1

IP5



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➡BPM reading, including filtering

twiss at appendix

Crab dispersion

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- CC effect: orbit corrector with z-dependent kick

Crab dispersion

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- Closed-orbit distortion approach: deviation of crab closed orbit with specific z [1]

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- Closed-orbit distortion approach: deviation of crab closed orbit with specific z [1]

$$x_{D_{cc}}(z, s) = \sqrt{\frac{\beta(s)}{\beta^*}} \cdot \frac{c \cdot \tan(\frac{\theta}{2})}{\omega} \cdot \sin\left(\frac{\omega z}{c}\right) \cdot \frac{\cos(\Delta\varphi_1 - \pi Q)}{\cos(\Delta\varphi_0 - \pi Q)},$$

Crab dispersion

- CC effect: orbit corrector with z-dependent kick

- Closed-orbit distortion approach: deviation of crab closed orbit with specific z [1]

$$x_{D_{cc}}(z, s) = \sqrt{\frac{\beta(s)}{\beta^*}} \cdot \frac{c \cdot \tan(\frac{\theta}{2})}{\omega} \cdot \sin\left(\frac{\omega z}{c}\right) \cdot \frac{\cos(\Delta\varphi_1 - \pi Q)}{\cos(\Delta\varphi_0 - \pi Q)},$$

half crossing angle

longitudinal coordinate of the particle with respect to the bunch centre

CC angular frequency

phase advance between CC and location s

phase advance between CC and IP

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half crossing angle

longitudinal coordinate of the particle with respect to the bunch centre

CC angular frequency

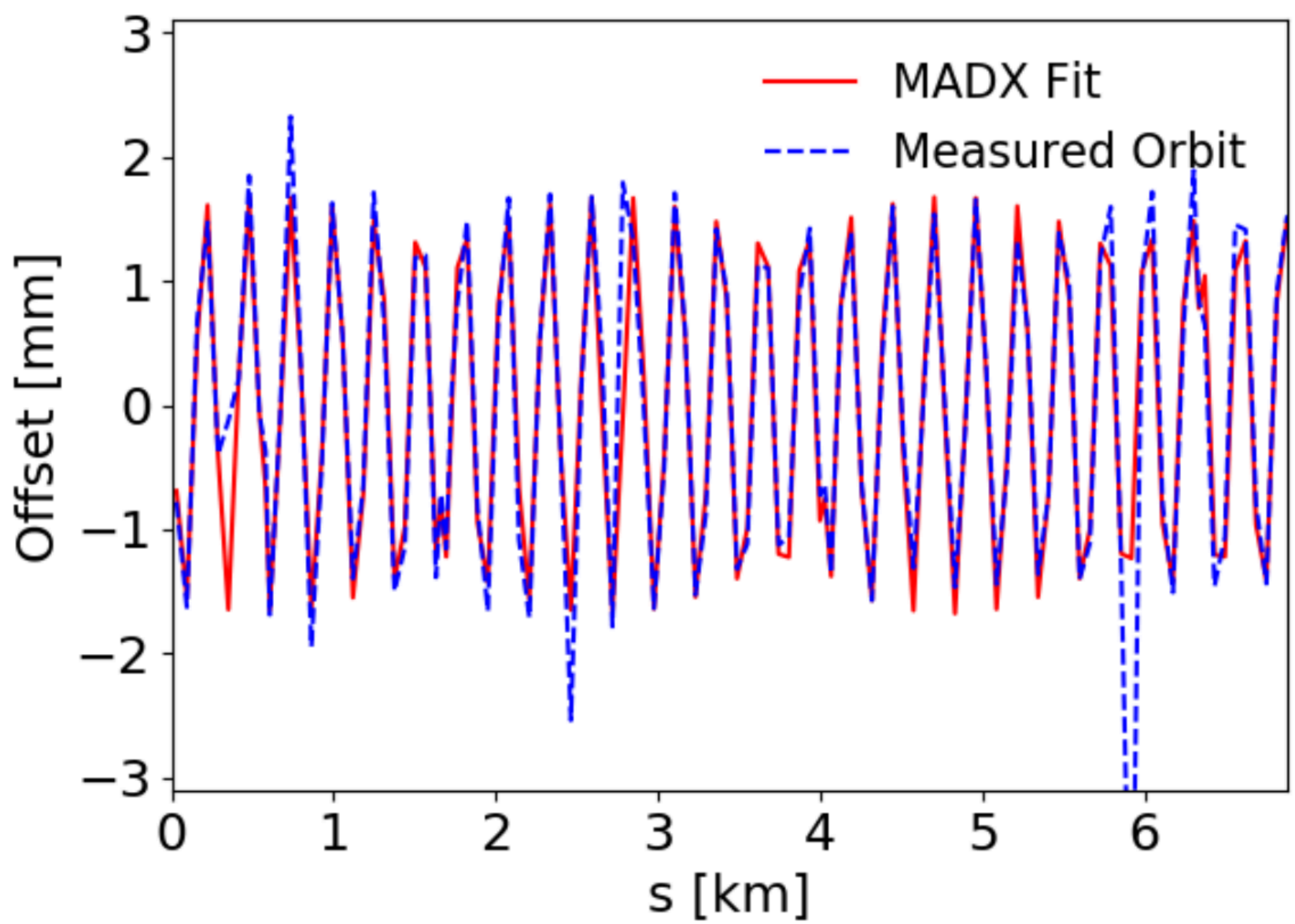
phase advance between CC and location s

phase advance between CC and IP

- Assuming 2 CCs combined to 1 dipole kick, MAD-X gives orbit of particles at crest

Crab dispersion, during SPS tests, May-Nov2018

- Crab dispersion measurement utilises all available BPMs



All available BPMs should be utilised in HL-LHC as well

From L. Carver's presentation

LHC BPMs

- Due to BPM filtering, '*time normalisation'**, BPMs will only see part of the bunch
- Multiply MAD-X BPM reading with a factor to obtain what will be read during measurements
- Assuming bunch length of 0.075 m (0.25ns, RMS), this factor has been calculated*** to be 0.821
- **New pickups:** draft of the installation request
- We currently have these BPMs equipped with DOROS. But this may well change by HL [document from Marek]

Existing LHC BPM system	Resolution**
turn-by-turn	Order of 100μm
average orbit	Order of 1μm
accuracy	Order of 50μm

***From Michal Krupa*

*A. Boccardi: *The zero crossings are used to generate two pulses. The position (amplitude's ratio) is encoded in the time distance between those 2 pulses that are transmitted optically to the surface*)

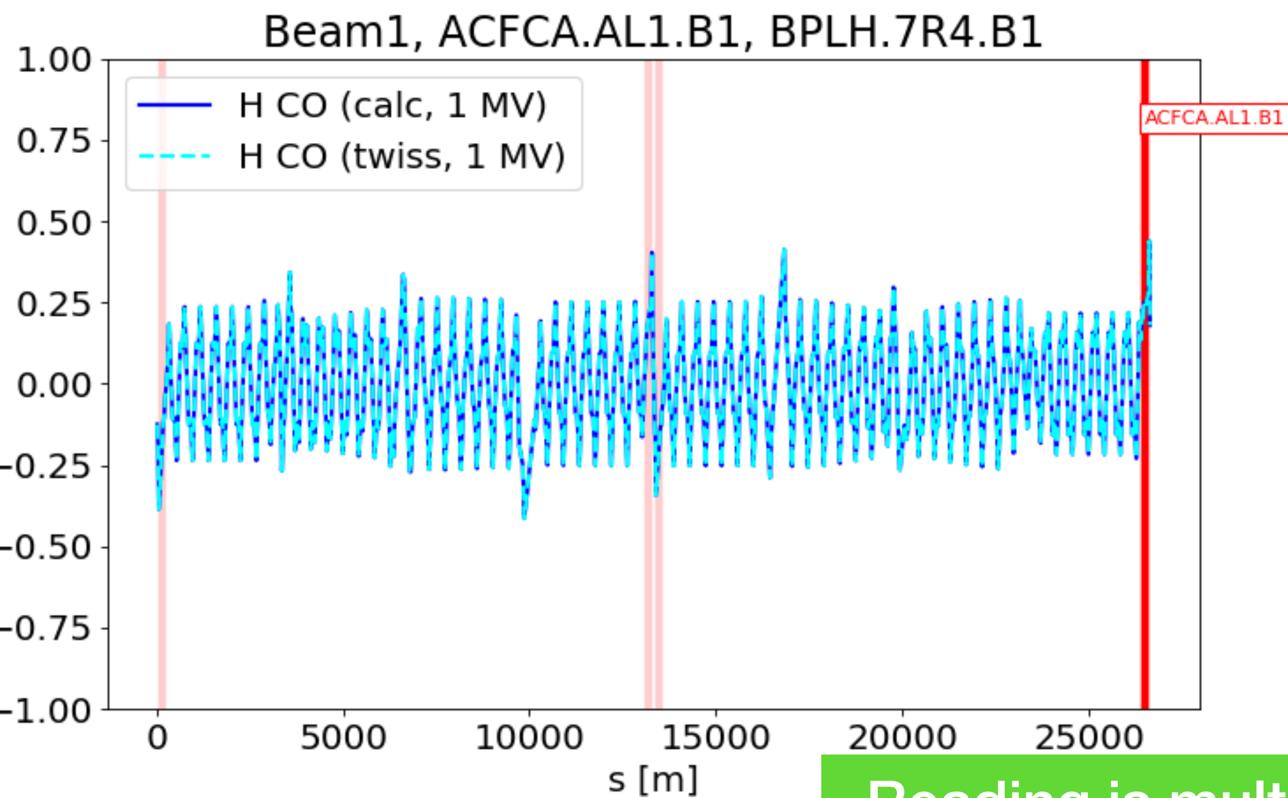
******For code see appendix, thanks to Michele Charla'*

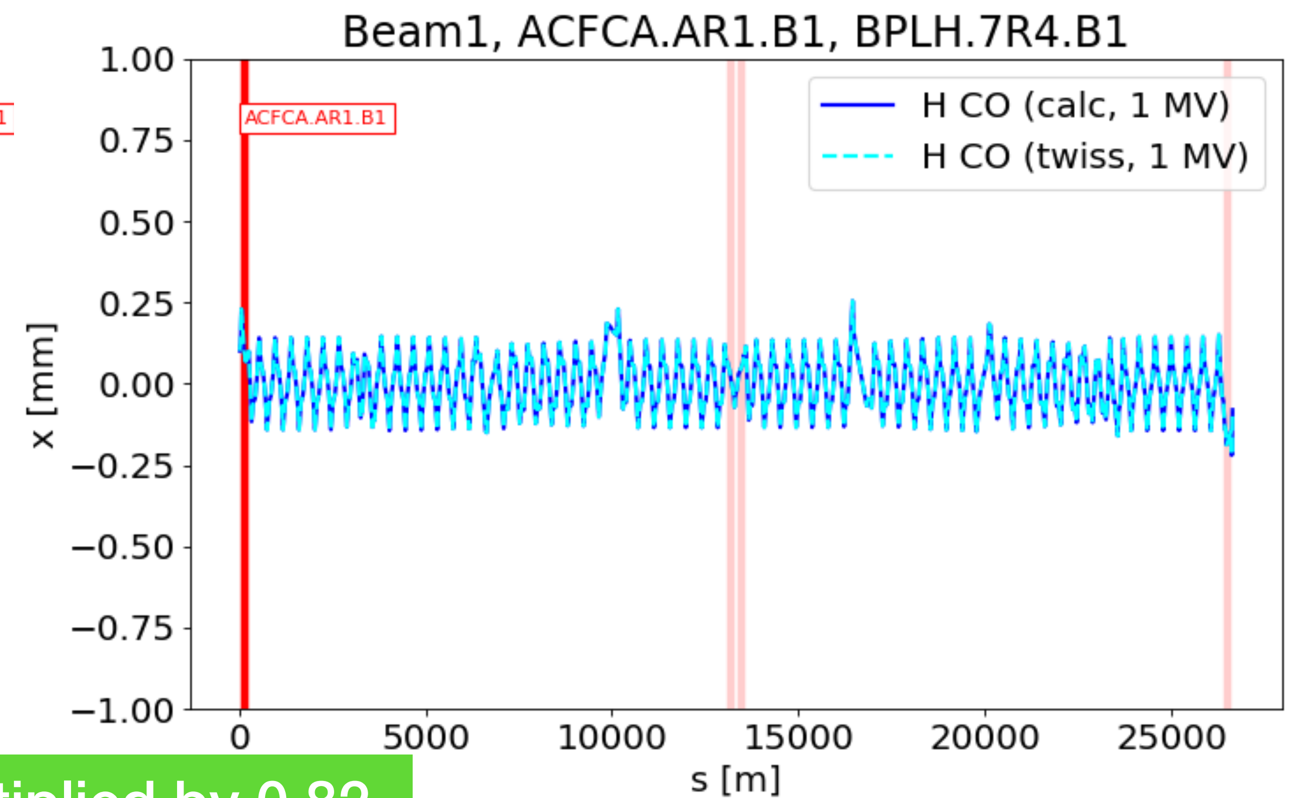
BPM Reading

Beam1

L analytical formula R
MAD-X twiss

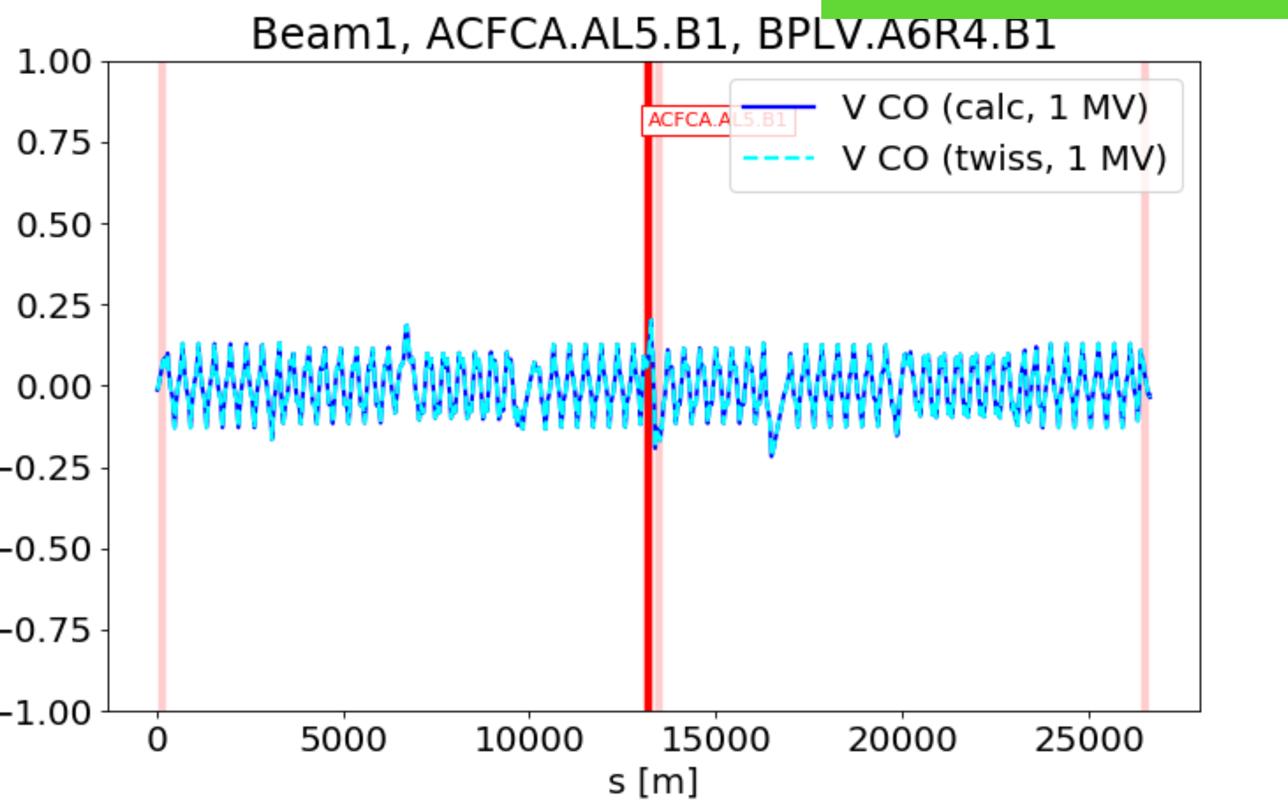
IP1

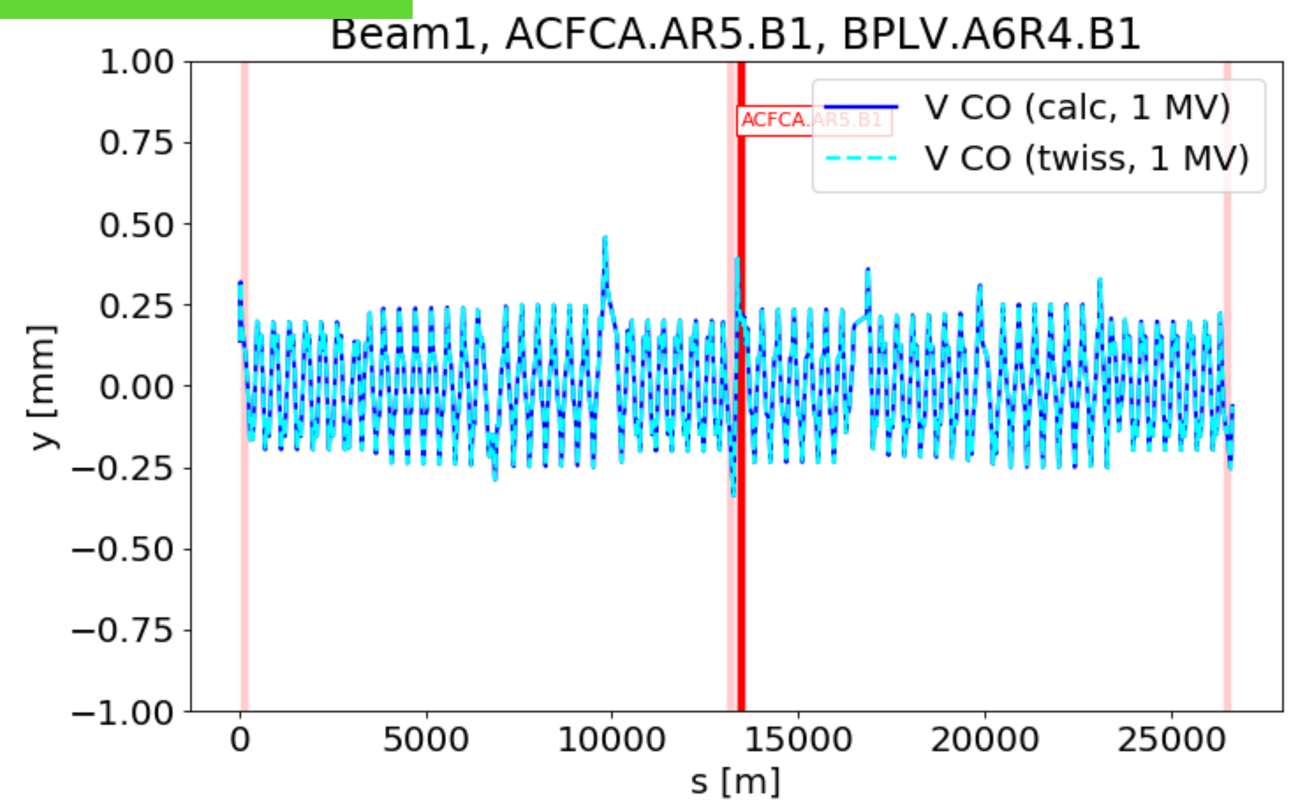




Reading is multiplied by 0.82
Well within the BPM resolution!

IP5





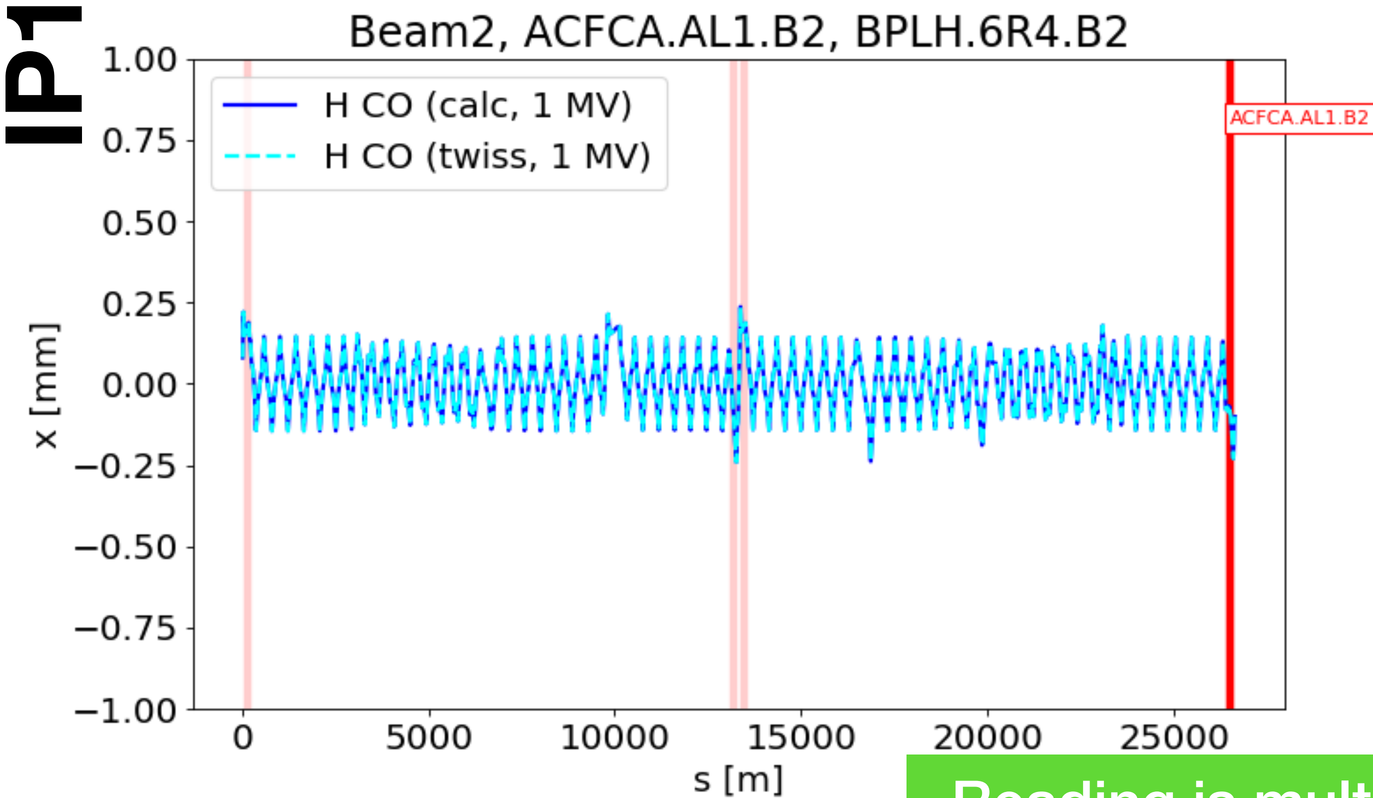
BPM Reading

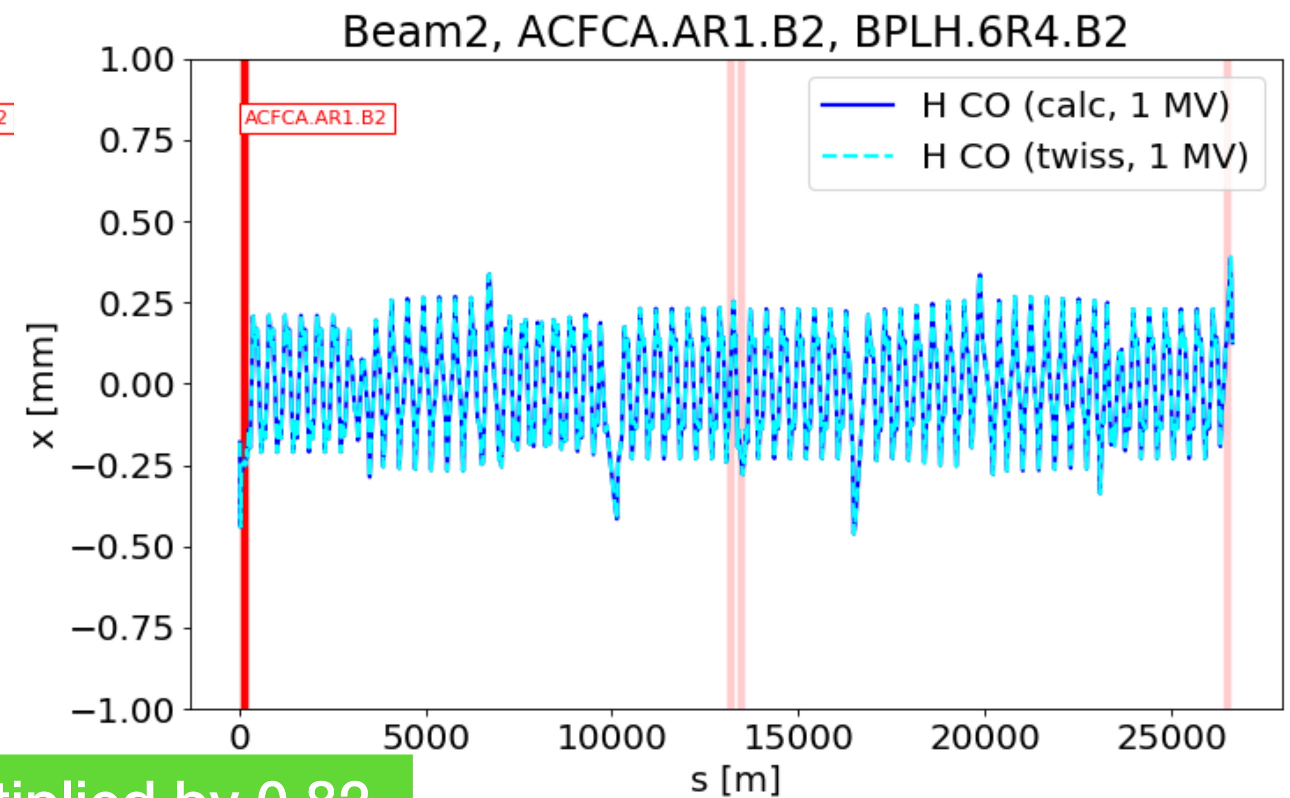
Beam1

L **analytical formula** **R**

MAD-X twiss

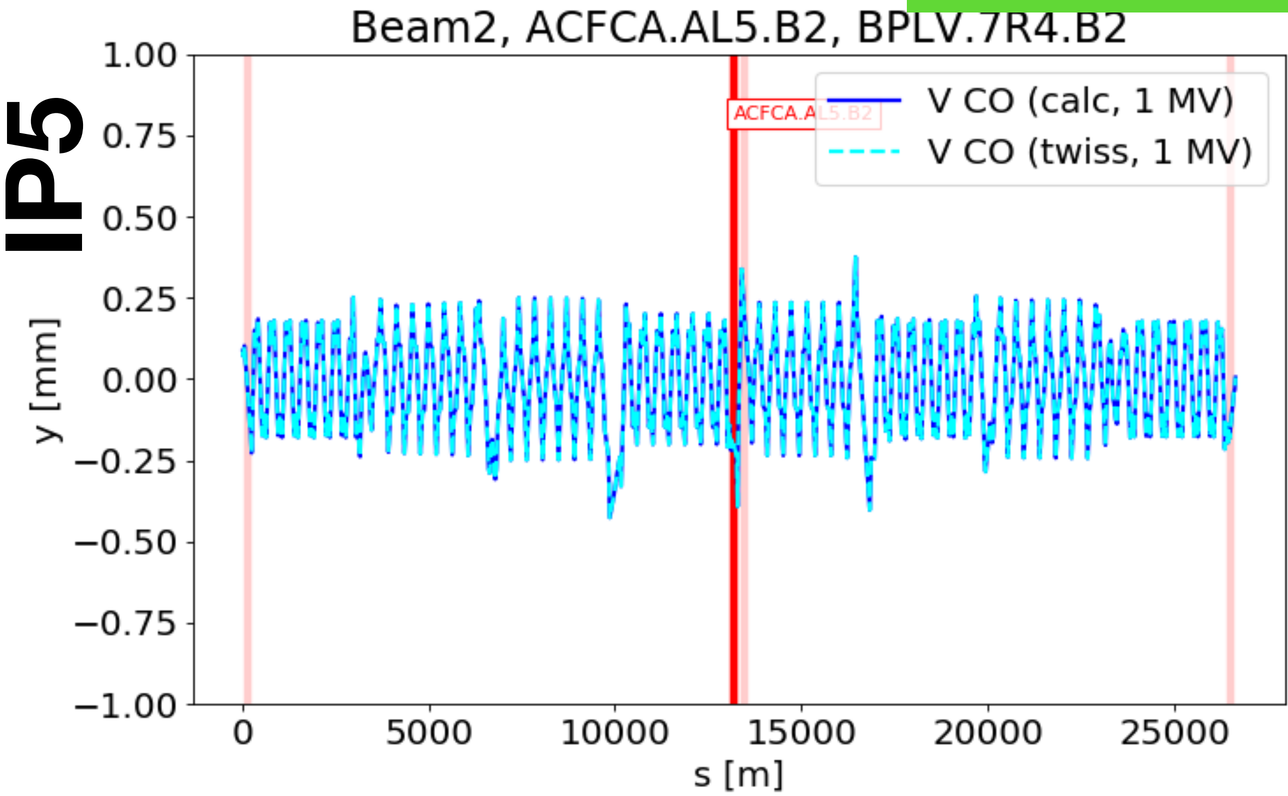
IP1

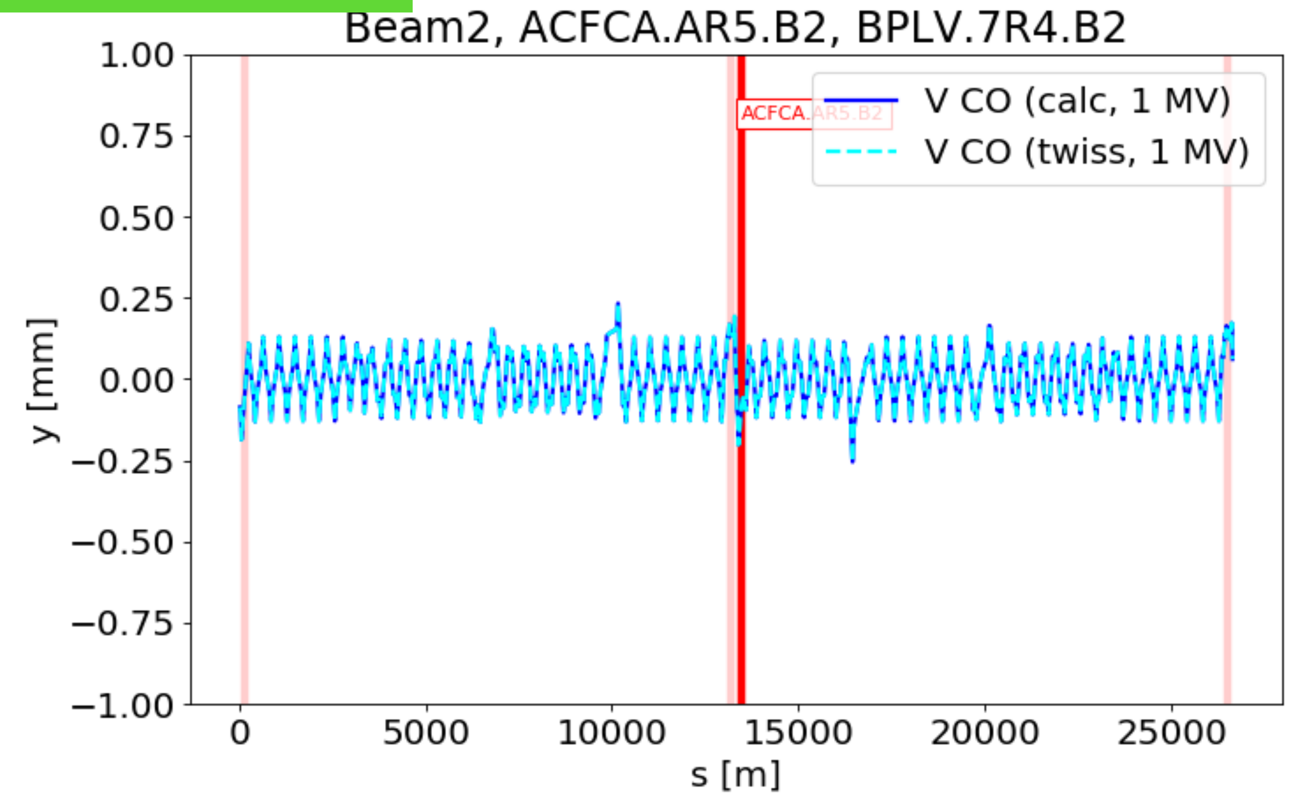




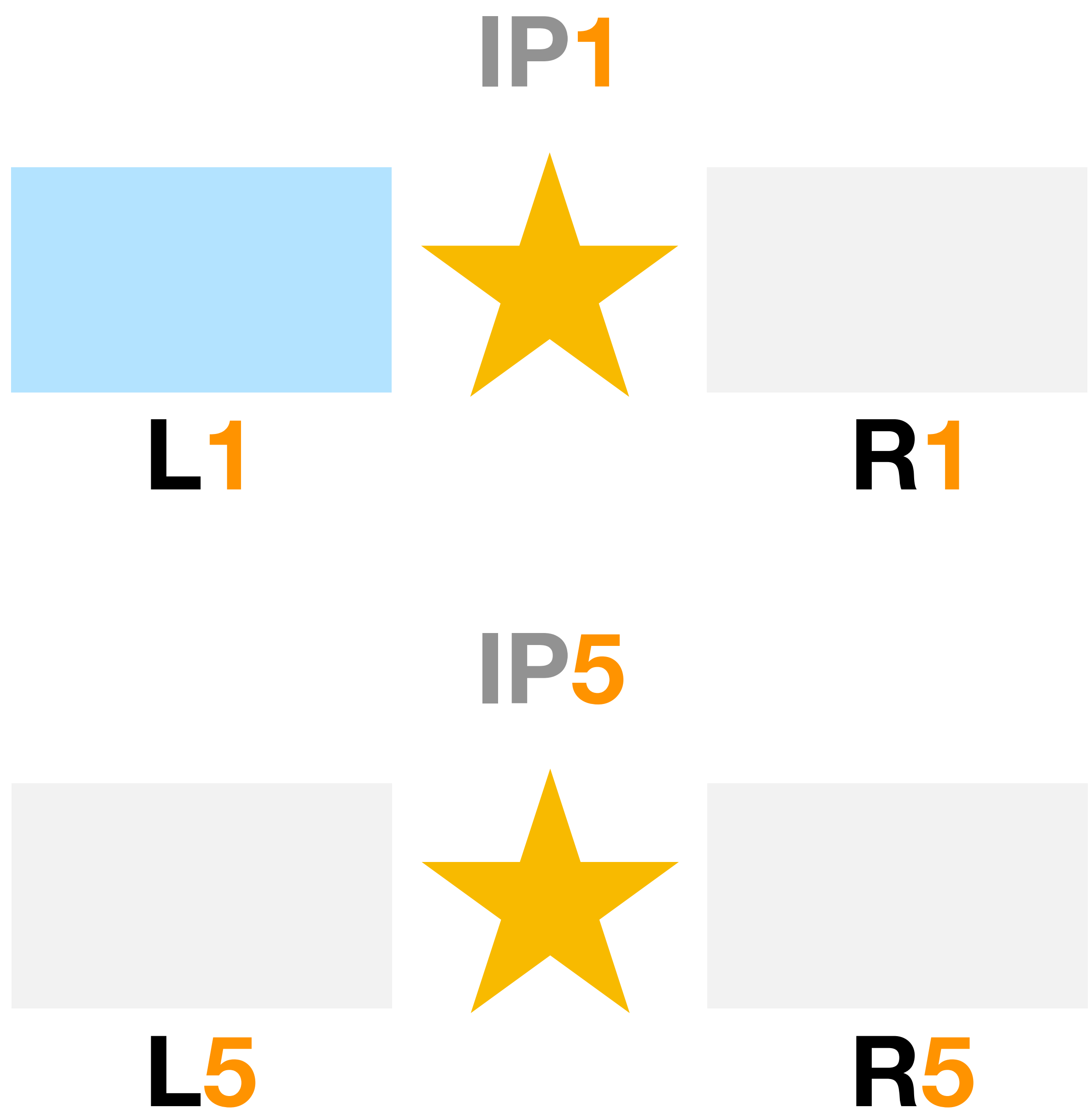
Reading is multiplied by 0.82
Well within the BPM resolution!

IP5





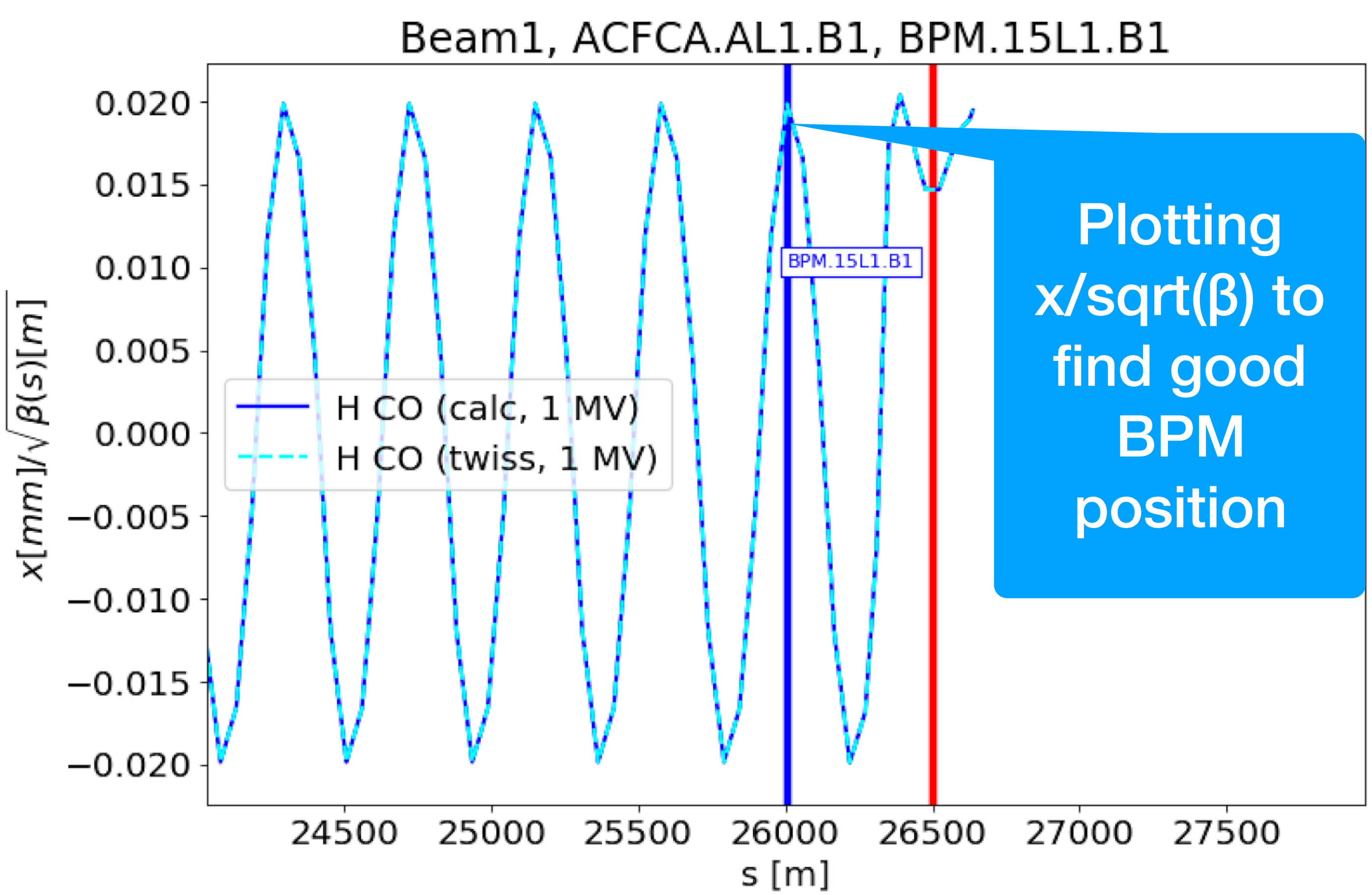
Calculating BPM-phase reading when only one set of CCs is ON (V_{set}=2*0.5=1 MV)

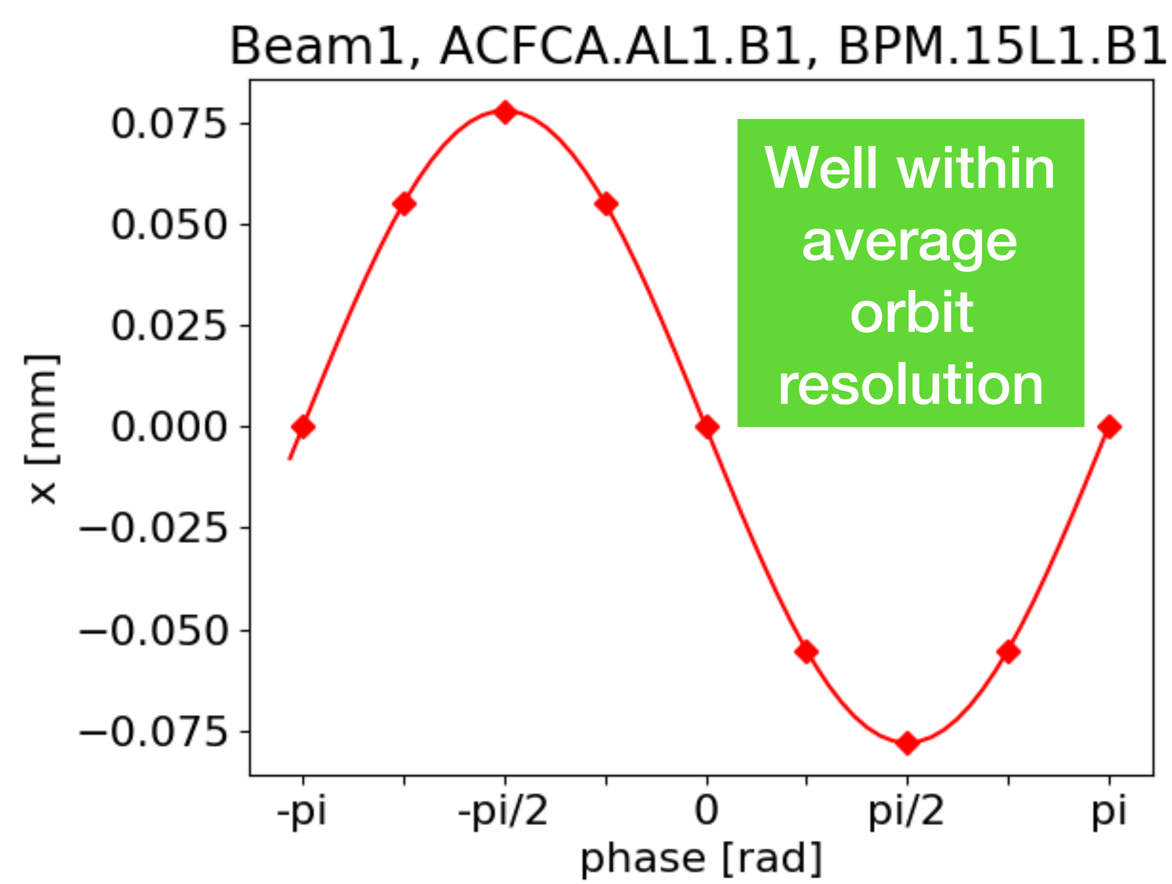


BPM reading with CC-phase

Existing LHC BPM system	Resolution*
turn-by-turn	Order of 100μm
average orbit	Order of 1μm
accuracy	Order of 50μm

**From Michal Krupa*

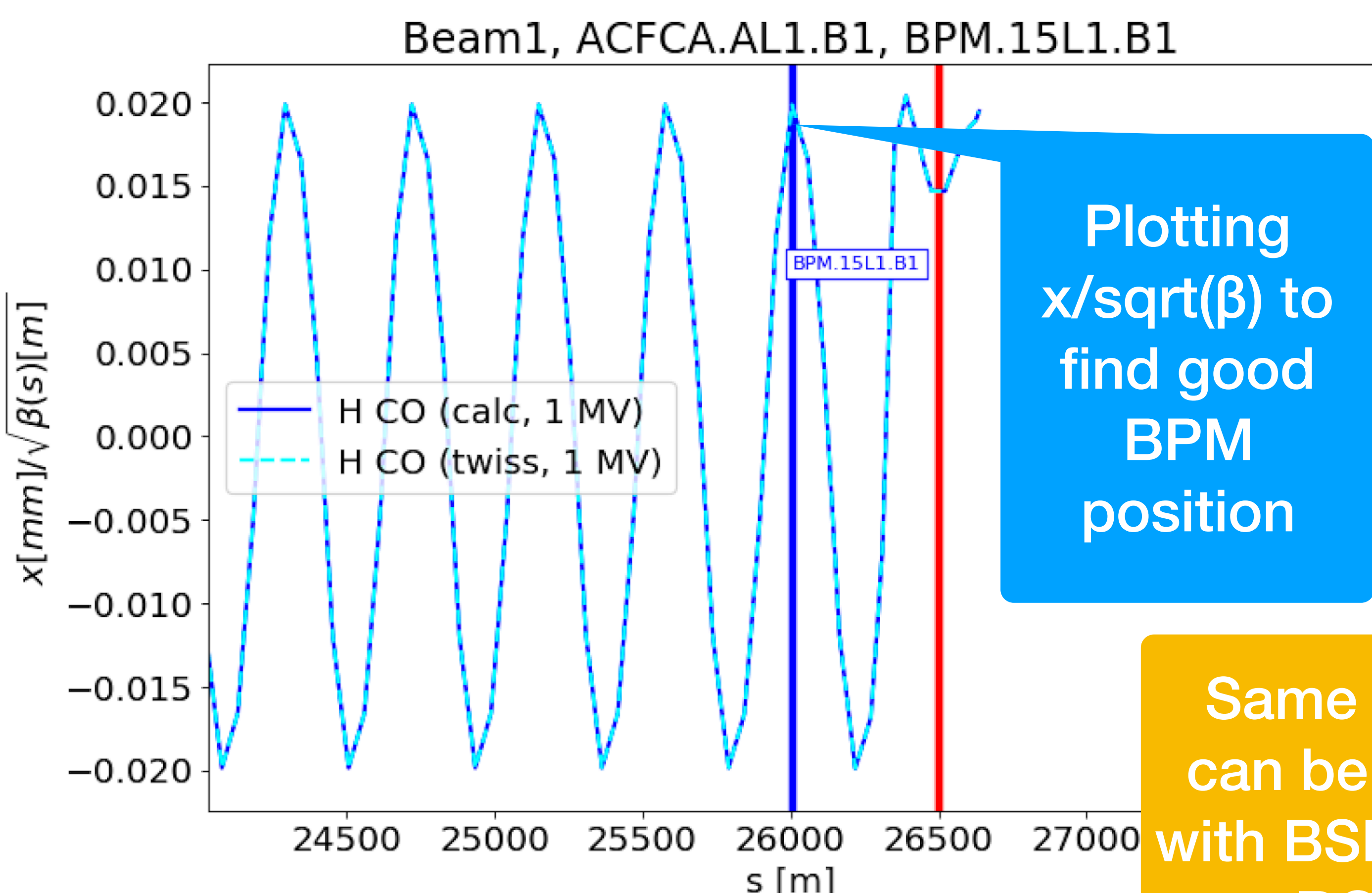


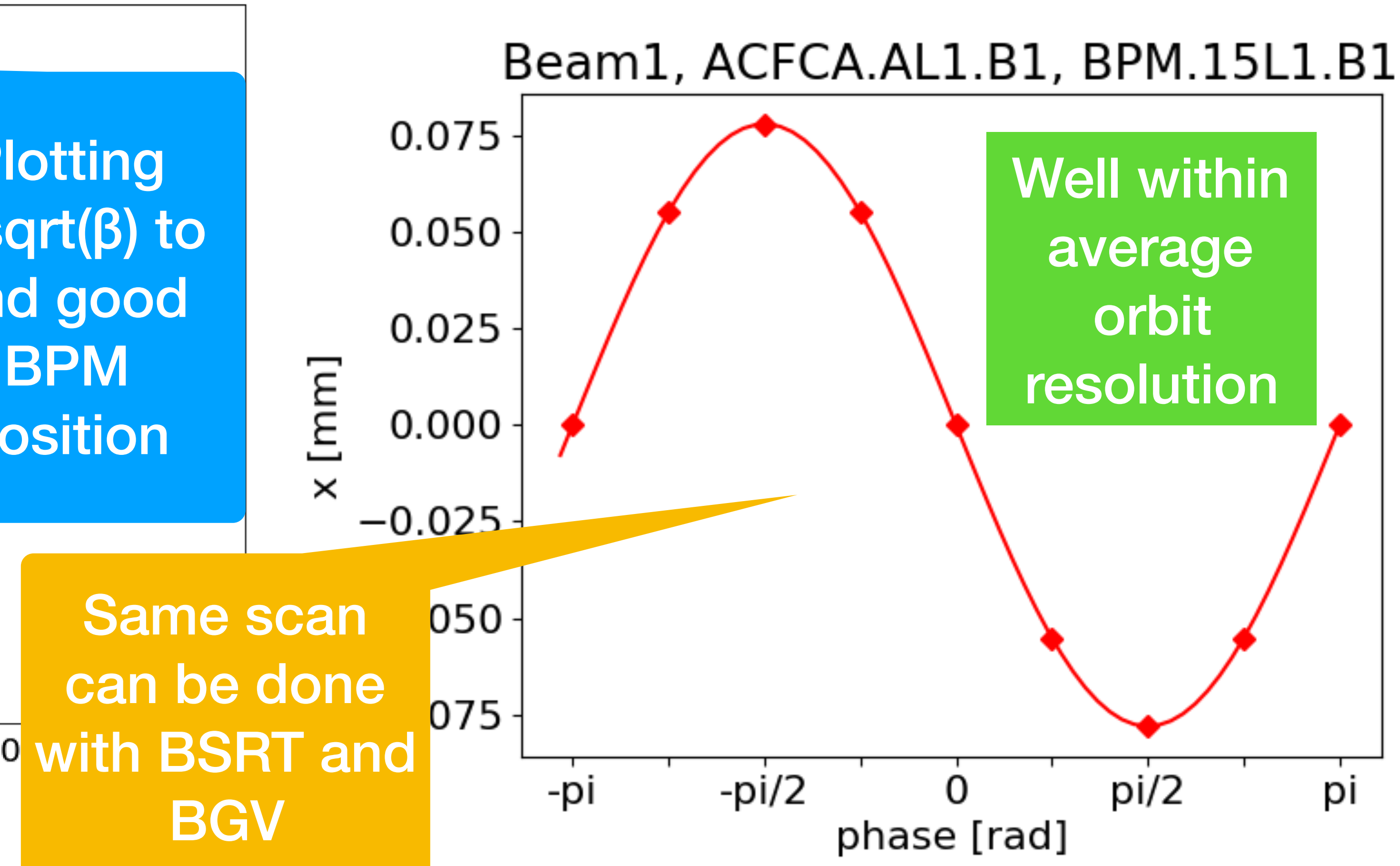


BPM reading with CC-phase

Existing LHC BPM system	Resolution*
turn-by-turn	Order of 100μm
average orbit	Order of 1μm
accuracy	Order of 50μm

**From Michal Krupa*





Next steps

- Study reading at BSRT and BGV for different CC phase
- Simulations will be performed for 9 cm bunch-length (assuming q-Gaussian bunches [link]) and for ramping, squeeze, and flat top optics
- Study minimum detectable non-closure when crab-bump is closed with available instrumentation (to be done at collision energy)
  - Possible instrument: existing LHC BPMs, 0.8 factor suppressed reading (filtering)
  - Can we have **2** HT monitors/beam/plane, 90deg phase-advance?
- Study smaller emittance; it would enhance crabbing effect

Appendix

Beam1

CCs

NAME	S	BETX	BETY	ALFX	ALFY	MUX	MUY	MUX [deg]	MUY [deg]
ACFCA.AR1 .B1	154.817	82.90706	279.5391	1.1402	-0.4697	0.32193	0.29135	2.02274	12.7092
ACFCA.BR1 .B1	155.867	80.54316	280.5304	1.1111	-0.4743	0.32398	0.29195	2.03562	12.7902
ACFCA.BL5 .B1	13169.602	283.7912	72.54292	0.4940	-1.0096	30.6811	29.6248	192.775	1211.24
ACFCA.AL5 .B1	13170.652	282.7585	74.69381	0.4894	-1.0388	30.6817	29.6271	192.779	1211.26
ACFCA.AR5 .B1	13484.106	82.76328	279.4378	1.1404	-0.4699	31.2973	30.2478	196.646	1235.56
ACFCA.BR5 .B1	13485.156	80.39898	280.4294	1.11127	-0.4744	31.2993	30.2484	196.659	1235.64
ACFCA.BL1 .B1	26499.196	283.2258	72.56884	0.49111	-1.0103	61.9758	59.9633	389.405	2446.70
ACFCA.AL1 .B1	26500.246	282.1993	74.72125	0.4865	-1.0395	61.9763	59.9656	389.409	2446.72

HT WS

NAME	S	BETX	BETY	ALFX	ALFY	MUX	MUY	MUX [deg]	MUY [deg]
BPLH. 7R4.B1	10174.9570	544.9718	51.52153	5.429	1.08101	23.5490	22.3391	147.962	140.360
BPLV.A6R4 .B1	10134.7570	253.0857	401.1932	-4.6406	7.33674	23.5341	22.2874	147.869	140.036
BWS. 5R4.B1	10081.8810	197.6089	402.2346	0.01327	-0.7261	23.4927	22.2682	147.609	139.915

Beam2

CCs

NAME	S	BETX	BETY	ALFX	ALFY	MUX	MUY	MUX [deg]	MUY [deg]
ACFCA.AR1.B2	158.637	283.2259	74.70318	-0.4882	1.0386	0.29376	0.32943	1.84574	2.06986
ACFCA.BR1.B2	159.687	284.2560	72.55276	-0.4928	1.0094	0.29434	0.3317	1.84939	2.08413
ACFCA.BL5.B2	13173.7269	80.80629	280.3141	-1.1166	0.4721	30.6973	29.6853	192.877	186.518
ACFCA.AL5.B2	13174.7769	83.18196	279.3275	-1.1458	0.4675	30.6994	29.6859	192.890	186.522
ACFCA.AR5.B2	13488.2309	282.8328	74.85547	-0.4845	1.0405	31.3145	30.3065	196.755	190.421
ACFCA.BR5.B2	13489.2809	283.8552	72.70092	-0.4891	1.0113	31.3151	30.3088	196.758	190.435
ACFCA.BL1.B2	26503.0162	80.57439	280.3297	-1.1151	0.4741	61.9464	60.0030	29.2210	17.0102
ACFCA.AL1.B2	26504.0662	82.94689	279.3388	-1.1443	0.4695	61.9485	60.0036	29.2339	17.0139

HT WS

NAME	S	BETX	BETY	ALFX	ALFY	MUX	MUY	MUX [deg]	MUY [deg]
BPLH.6R4.B2	10134.1093	395.7512	269.4649	5.31322	-3.8972	23.4211	22.6449	147.159	142.282
BPLV.7R4.B2	10175.9093	123.4477	483.0553	0.18321	5.46555	23.4559	22.6608	147.378	142.382
BWS.5L4.B2	9912.28138	196.9343	451.7253	-0.0139	0.95339	23.2878	22.5265	146.321	141.538

How do the LHC BPMs work*

- LHC BPMs work differently wrt SPS MOPOS
- LHC BPMs first approximation: average over bunch distribution
- BPM measures [int I(s) * X(s) ds] / [int I(s) ds] ; int: integral, I(s): bunch intensity (depends on longitudinal position s), X(s): transverse bunch position (depends on s)
- This would be completely true if the low pass filter cut-off frequency was 0MHz, instead it is 70MHz. Still not too far from 0MHz wrt to 400MHz of CC

**thanks to M. Carla' for discussion*

BPM filter reduction factor

From Michele Carla':

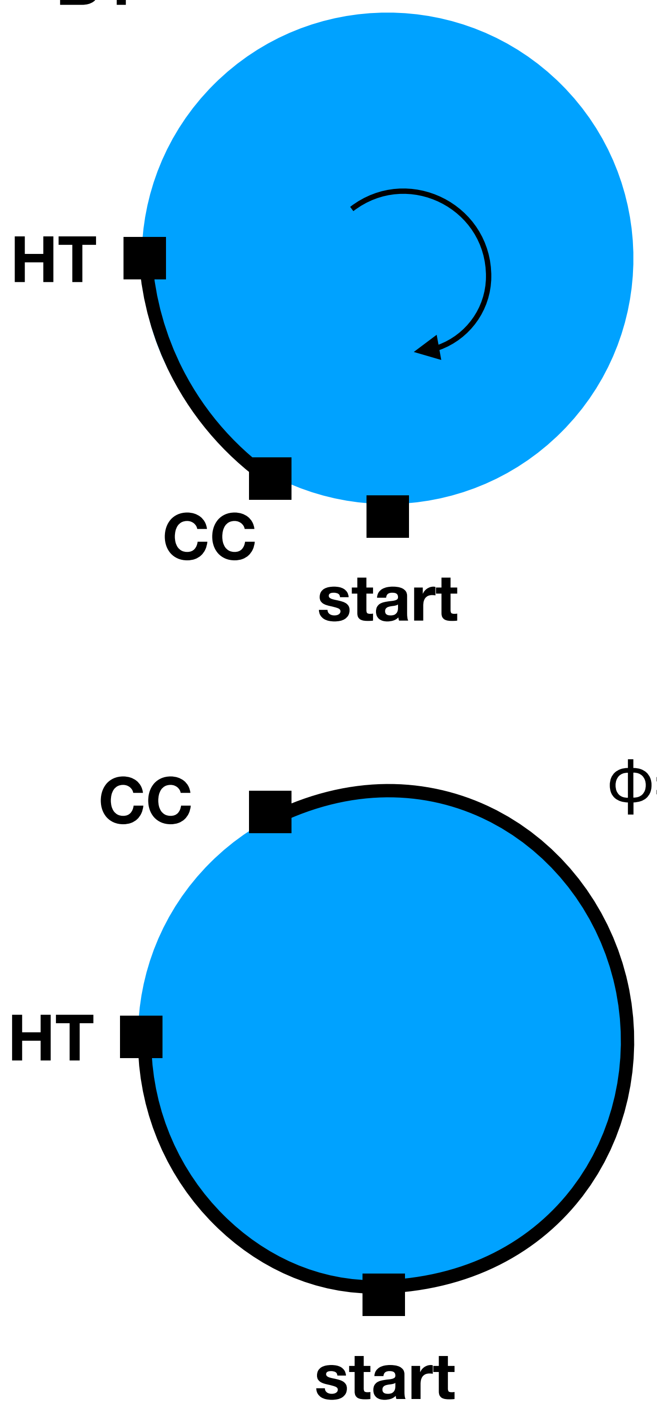
- Simple example with CC on crest, bunch length of “BL"ns (4 sigma)
- Position of proton in middle of bunch, therefore perfectly on-crest
- Assuming the BPM is averaging over the entire bunch.

```
bunch_length = BL/4 #ns
cc_freq = 0.4      #GHz

count = 1000

s = np.linspace(-4.*bunch_length, 4.*bunch_length, count)
I = np.exp(-s*s / (2 * bunch_length * bunch_length))
X = np.cos(s * cc_freq * 2 * np.pi)

print np.sum(I * X) / np.sum(I)
```

I(s) : bunch intensity (depends on the longitudinal position s)
X(s) : transverse bunch position (depends on s)

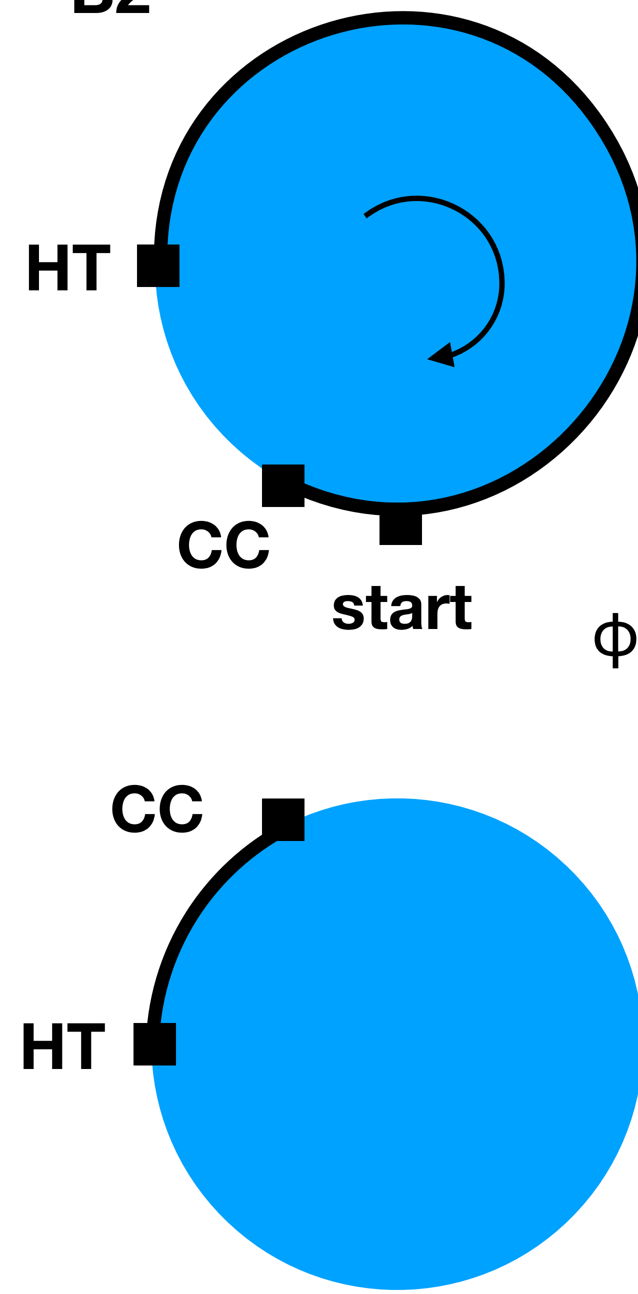
Phase advance calculation

B1



if sHT>sCC:
ϕ=ϕHT-ϕCC
else:
ϕ=ϕQ-(ϕCC-ϕHT)

B2



if sHT>sCC:
ϕ=ϕQ-(-(ϕCC-ϕHT))
else:
-(ϕHT-ϕCC)