HL-LHC BPMs:
Status of the Specifications
Update July 2020

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13/7/2020

Discussion between WP13 (BI) and WP2

- **A new HL-LHC BPM document was drafted:**
  - **Conceptual BPM Specifications for the HL-LHC**
  - **Current version: 2020-06-02**
  - **Authors: R. De Maria, D. Gamba, R. Tomas**

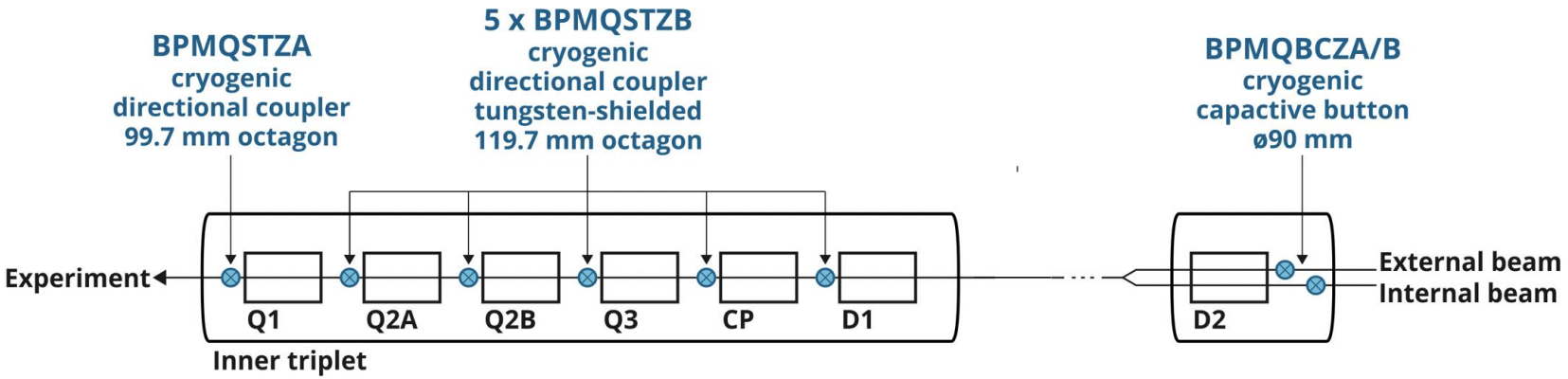
- **Covering:**
  - **HL-LHC beam parameters**
  - **BPM families**
  - **Measurement modes**
  - **HL-LHC Specifications**

Beam Parameters

Particle	Bunch charge		# of bunches		Min. bunch spacing [ns]	Bunch length FWHM [ns]	
	min	max	min	max		min	max
Protons	5e9	2.3e11	1	2760	25	0.7	1.2
Ions	5e9	1.6e10	1	1232	50	0.7	1.2
Pilot (p or ions)	5e9	1e10	1	3	(25)	0.7	1.2

- **Doubled bunch (5/20ns) operation was discussed**
  - **No doubles bunches are foreseen in future!**
  - **The HL-BPM and the LHC BPM consolidation projects can assume the double bunches will not be operated in the HL-LHC!**
- **Bunch length: FWHM = 4 x sigma?**
  - **To be clarified!**
- **Pilot bunches**
  - **Machine setup and optics studies**

BPM Families



Type	Two beams	Operation range (OP) [mm]	Max. range for studies	Bunch spacing [ns]
Arc	no	±9	±18	25
Matching section	no	±12	±24	25
Triplet point 2/8	yes	±14	±27	6
Triplet point 1/5	yes	±29†	±58‡	3.8

† For BPMQSTZA: ±25 mm

‡ For BPMQSTZA: ±50 mm

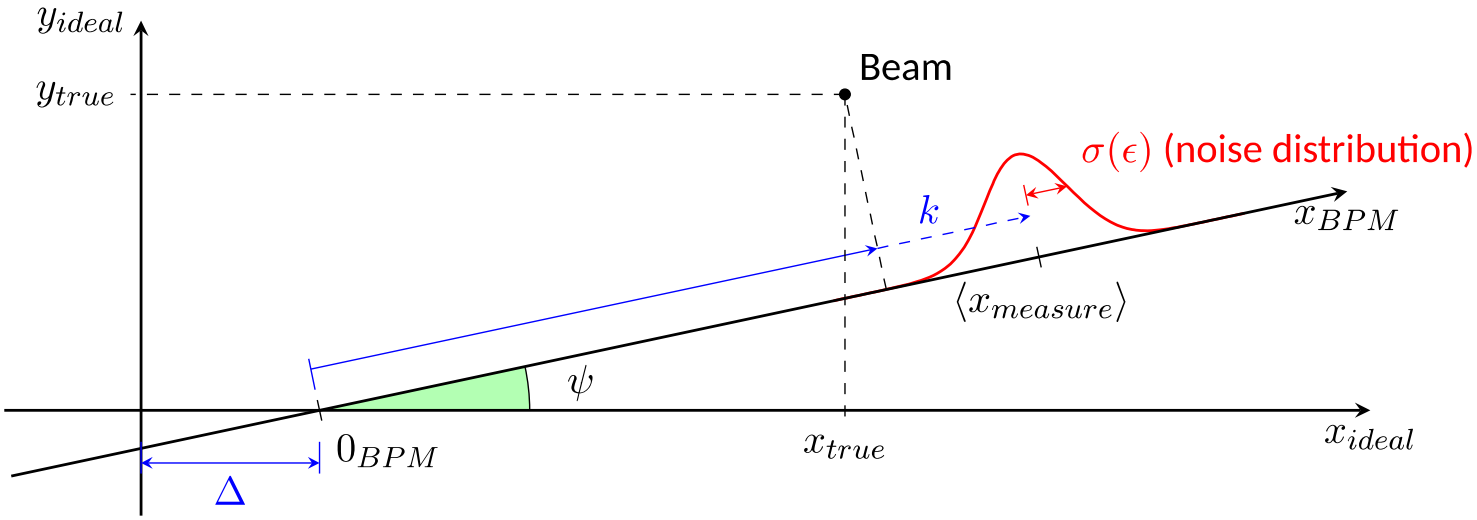
Measurement Modes

- **Bunch-by-bunch, turn-by-turn for beam orbit Trajectories and oscillations (TR)**
- **High resolution averaged Closed Orbit (CO)**

Reproducibility timescale	Usage	Class
Bunch-by-bunch	Optics measurement and correction, steering at injection	TF
Stable Beam (~10 h)	Keep orbit during optic changes, IP position stabilization	CO
Fill to flll (~24 h)	Find collisions after a refill, ensure machine reproducibility	CO

Measurement	Frequency	Quantity
Orbit mode (CO)	25 Hz	Continuous
Trajectory mode (TR)	~0.1 Hz	1-3 pilots, 20 k turns, on demand

Errors of a single BPM Measurement



$$|x_{measure} - x_{true}| \leq |\Delta| + |k|X + |\psi|Y + \max_{x\in[-X,X],y\in[-Y,Y]} \left(\sum_{k=2}^{\infty} \sum_{j\leq k} \alpha_{k,j}\, x_{true}^{k-j}\, y_{rue}^{j} \right) + 2\sigma(\varepsilon)$$

Uncertainties:
Δ: offset
k: calibration error
ψ: tilt
$\alpha_{k,j}$: non-linearities
ε: noise

with X and Y being the applicable ranges of the measurement

Long term BPM Measurement Stability

$$x_{measure}(t) = x_{true}(t) + x_{error}(t, I_b, T, \dots)$$

Timescale	Arc and MS BPMs	Triplet BPMs	
		Point 1/5	Point 2/8
Stable beam (~10 h)	±20 µm	±2 µm	±10 µm
Fill to fill (~24 h)	±28 µm	±28 µm	±28 µm

- **Long term stability in orbit mode**
  - **For luminosity production runs**
  - **Assuming a factor 2 between RMS and peak values**

BPM Errors

Goal	Arc BPMs	Triplet BPMs	
		Point 1/5	Point 2/8
Offset	±100 µm	±30 µm	±30 µm
$\langle x_{B1} \rangle$ - $\langle x_{B2} \rangle$	n.a.	±40 µm	±40 µm
Calibration error (k)	3 %	6 %	4 %
Noise (ε)	±100 µm	±30 µm	±100 µm

- **Offset**
  - **Valid for all types of beams**
- **B1-B2 accuracy**
  - **Position difference for crossing and separation: ±1 %**
- **Calibration error**
  - **Single pilot bunch between two calibrations**

Specification Summary

Goal	Tolerance LHC	Tolerance HL-LHC
Calibration error	±4 %	±3 % (TR, Arc) ±1.6 % (TR, P 1/5) ±4 % (TR, P 2/8)
Roll	±2 mrad (Arc) ±1 mrad (Triplet)	±2 mrad (CO, Arc) ±1 mrad (CO, P 1/2/5/8)
Offset	±100 µm (Arc) ±30 µm (Triplet)	±100 µm (CO, Arc) ±30 µm (CO, P 1/2/5/8)
Non-linearity	±200 µm over ±4 mm (CO) ±500 µm over OP range (CO)	±200 µm over ±4 mm (TR tbc) ±500 µm over OP range (TR tbc)
2 x Std(x_{error})	±20 µm (CO, Arc) ±10 µm (CO, Triplet)	±20 µm (CO, 10 h, Arc) ±10 µm (CO, 10 h, P 2/8) ±2 µm (CO, 10 h, P 1/5) ±28 µm (CO, 24 h, Arc) ±28 µm (CO, 24 h, P 1/2/5/8)
⟨B1⟩ - ⟨B2⟩	±30 µm (CO, Triplet)	±40 µm (CO, P 1/2/5/8)
Noise	n.a.	±100 µm (TR, Arc) ±100 µm (TR, P 2/8) ±30 µm (TR, P 1/5)
Resolution	±50 µm (TR) ±5 µm (CO)	±50 µm (TR, Arc) ±15 µm (TR, P 1/5) ±5 µm (CO, Arc) ±1 µm (CO, P 1/2/5/8)

Discussion

- **Thanks to WP2 (APB and CO) for providing detailed BPM specifications!**
- **Some difficult to be achieve specifications may need follow up discussion, e.g.**
  - **Long term accuracy P 1/5**
  - **Bunch-by-bunch resolution pilot bunch**
  - **Maximum operation range P 1/2/5/8 BPMs**
  - **Bunch length**
- **Some discussion has already started, e.g.**
  - **Difference noise vs. resolution**
  - **BPM offsets**