BPM DESIGN STUDIES FOR FCC-ee

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FCC-ee BPM REQUIREMENTS AND CHALLENGES

FCC-ee BPMs

- The FCC arc BPMs, and most other FCC BPMs, will use button pickups.
- Each BPM will measure the transverse position of the centre of charge of each passing bunch, but could also be used to measure bunch intensity and bunch timing.
- Important for commissioning.

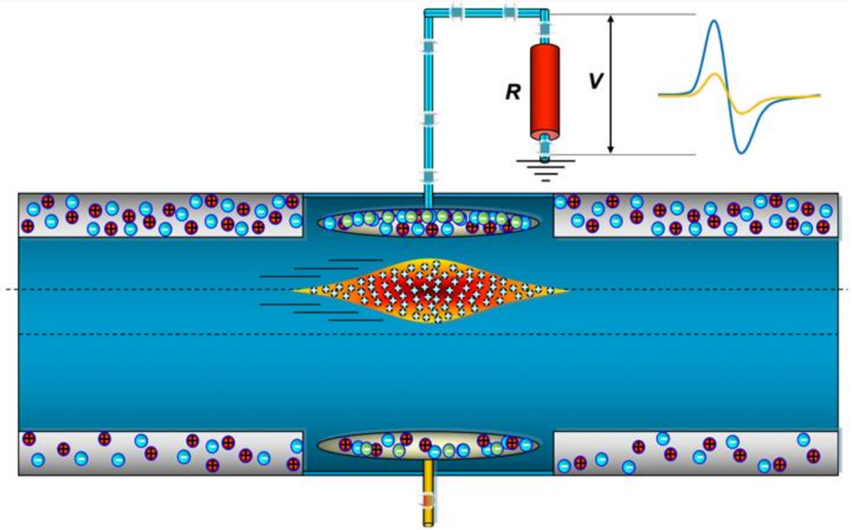


Fig 1: Schematic diagram of a BPM and image current induced as a bunch passes through a beam pipe [1].

What are we optimising for?

- Signal strength should not be limiting factor, due to high beam current (though pilot bunches need to be considered).
- Shall provide orbit, turn-by-turn and bunch-by-bunch measurements.
- Small beam impedance → minimise heating, at the expense of smaller signals and resolution.
- Need to be reliable, rad tolerant electronics.
- Within cost budget.

BPM Parameter	Requirement	Comments
Orbit resolution	0.1 μm	Smaller pipe diameter helps (reduced from 7 to 6 mm)
TxT resolution	< 10 μm	
IP BPM accuracy	**1 μm** (from [2])	Challenging! Could measure BPM offsets by BBA to this level, but not possible for accuracy over large range of beam positions. What is really required?
Arc BPM accuracy	20 μm	No BPMs on sextupoles yet
Min bunch spacing	**25 ns**	Signal processing time needed.

Relevant FCC-ee Beam Parameters

- Lowest bunch charge (at injection) will have to be considered to ensure the BPMs have good enough resolution.
- Largest bunch charge will have to be considered to ensure the impedance and heating are not too great.

Parameter input into the CST simulations

Important for BPM electronics

Parameter	Z	WW	ZH	ttbar
Energy, GeV	45.6	80	120	182.5
Beta	1			
Bunch intensity, 10^11	2.14	1.45	1.15	1.55
Bunch charge, nC	34.3	23.2	18.4	24.8
rms bunch length with SR/BS, mm	5.6/15.5	3.5/5.4	3.4/4.7	1.8/2.2
Number of bunches/beam	11200	1780	440	60
Bunch spacing, ns	25			
Beam current, mA	1270	137	26.7	4.9
Beam pipe radius, mm	30			

Table 2: Relevant beam parameters for beam position monitor design. [11]

From FCCIS workshop discussions. Injection from booster is 1/10 collider bunch pop.

Q: Is 1.84 nC still the expected minimum bunch charge for commissioning/pilot bunch?

Challenges for BPMs in FCCee

- **Size of Collider:** 90.7 km
- **Quantity of BPMs:** ~10’000
- **Performance:** high accuracy and resolution required
- **Radiation tolerance:** high!
- **Alignment and stability**

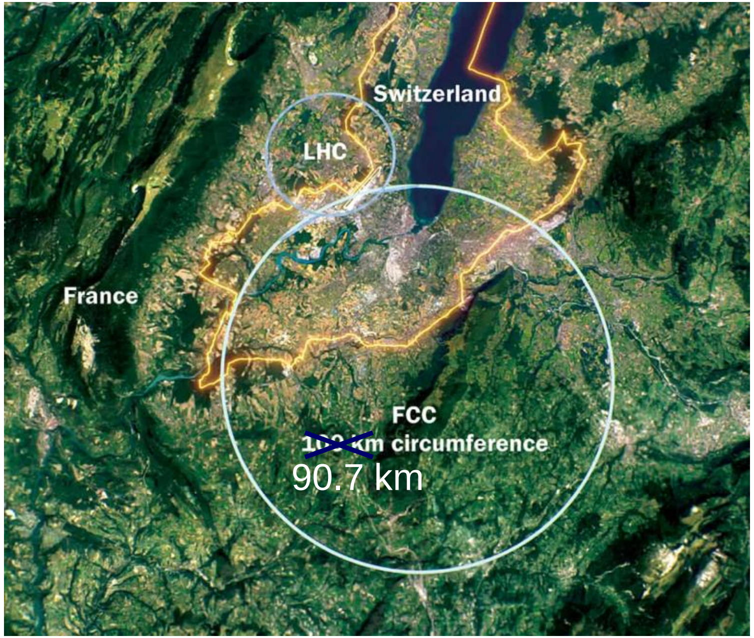


Fig 2: Approximate footprint of FCC compared to LHC [3].

Challenges for BPMs in FCCee

Quantity of BPMs: ~ 10’000 total

- BPMs need minimal beam coupling impedance (and well modelled).
- Minimal heating → minimise energy losses.
- Any small difference in design adds up!
- Resonances → would be beneficial to have a few different BPM button designs of slightly different dimensions to distribute beam resonances on several bands.
- Cost of manufacturing BPMs should be minimised.

Size of Collider: 90.7 km

- Arc BPMs → fast orbit feedback, but large distances cause signal latencies. BPM system could be segmented, but how to do this?
- Large distances make maintenance of the diagnostics more difficult. Need high redundancy.

Challenges for BPMs in FCCee: Performance

Performance of BPMs:

- Precise alignment and stabilization of the BPM pickups
- High accuracy and high resolution (orbit, TxT, BxB).
- Precision (drifts, aging) requirements, which are similar or even more tight than 4th gen sync-light sources.

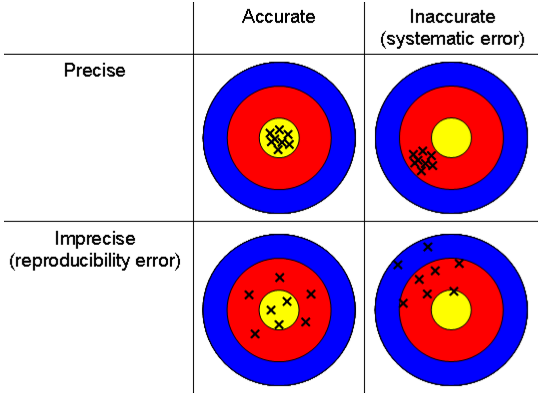


Fig 3: Accuracy vs precision

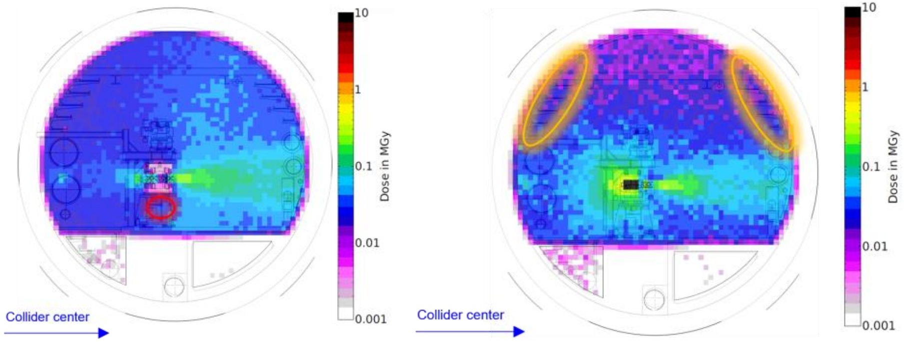
Challenges for BPMs in FCCee: SR

NB: ~ 10 kGy total is space-grade rad-tolerant electronics. Anything more would need to be built specially (like in experiments) – very expensive!

Synchrotron radiation power = 50 MW per beam

- Significant synchrotron radiation in the arc sections imposes high requirements on shielding and radiation hardness of BI.
- Electronics should be radiation hard enough to last for at least 10 years.
- Electronics recently built for SPS were built to withstand 0.075 kGy/year [5].

Left: position at MQ. The red circle indicates that shielding is required in this location to reduce the dose to an acceptable level to place electronics there. Goal is 0.5-1 kGy TID.



Right: absorber location. The orange circles indicate that the observed dose levels are 10-30kGy/year → some improvements need to be made to reach the 10kGy/year limit for cables.

Fig 4: FLUKA simulations of the radiation levels in the FCC tunnel [12]

courtesy of B. Humann

Challenges for BPMs in FCCee: SR

Radiation:

- Winglets of beam pipe used to absorb synchrotron radiation.
- Require pickups to be skewed.
- Rad-tolerant optical fibre could be used to transfer signal to centralised acquisition system in alcoves or in central shaft/access point.
- Alcoves are planned every 1.6 km → 300 fibres to each alcove or 2000 fibres to main access gallery.

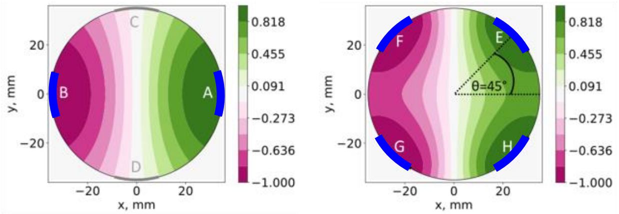


Fig 5: Horizontal position characteristic of BPMs on axis and skewed, modelled in python.

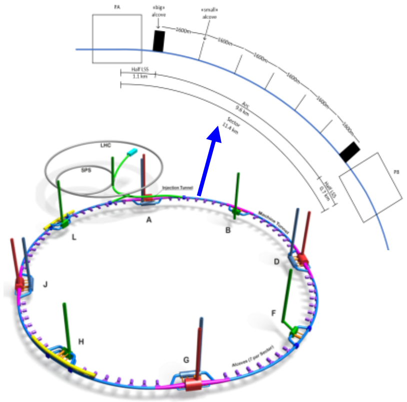


Fig 6: Schematic (not to scale) of FCC layout including alcoves [6]

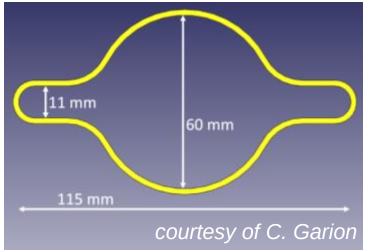


Fig 7: Cross section of beam pipe with winglets.

Alignment and Stability

- BPMs will be BB-aligned with respect to the quadrupoles, so ideally their relative positions should be always conserved. This can be best achieved if the BPMs are rigidly attached to the quads (rigidly = BPMs follow all quad movements) and fully detached from all other force sources.
- This would require bellows on either side of the BPM to be detached from the beam pipe movements.
- **Mechanical position errors:** roll and offsets.
- **Electrical position errors**: any asymmetry (subject to drifts) in the signal path of the BPM electrodes will cause a position error.
- For 20 μm arc BPM accuracy, would need $\sim 10^{-3}$ matching of electronics between channels, including buttons, short cable and read-out electronics.

➔very challenging and expensive for ~10’000 BPMs!

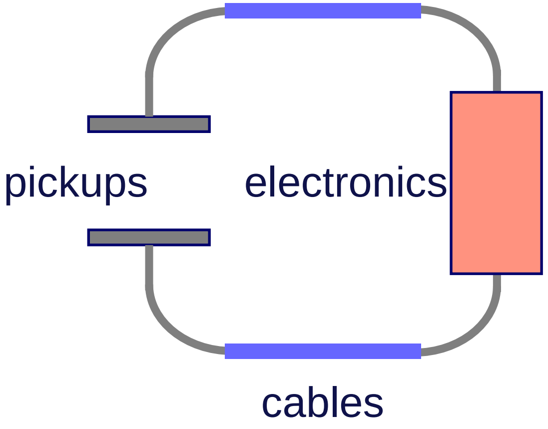


Fig 8: A simple schematic of a BPM system.

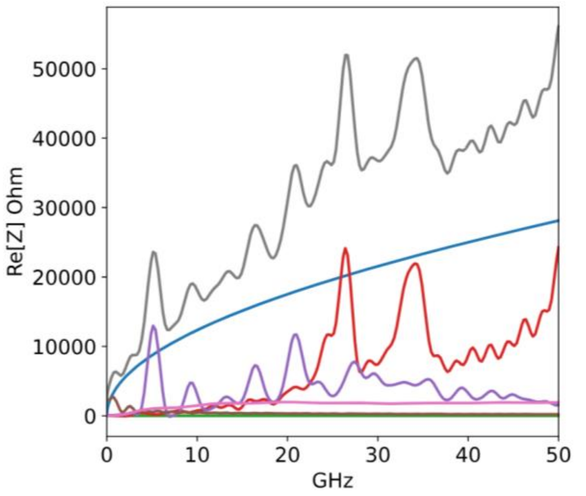
Q: What is the expected temperature range/drift in the tunnel?

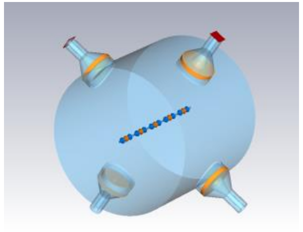
PREVIOUS WORK ON FCC BPMS

Previous Work on BPMs

See ‘FCC-ee single beam collective effects’ talk by M. Migliorati FCC Week 2024. [10]

- Previous work was focused on beam coupling impedance aspects rather than the actual characteristics as a BPM.
- Designs considered similar to 4th generation light-sources (e.g. SIRIUS).
- Previous simulations in CST with a design scaled from DAΦNE have been used to estimate a total loss factor of about 40.1 V/pC for 4000 BPMs in the collider ring [7].
- BPMs will be rigidly fixed to quadrupoles.





Q: Would BPMs be needed on the sextupoles? Is this still under discussion?

Fig 9: Impedance as a function of frequency simulated for different components of FCC-ee.

Courtesy of E. Carideo and M. Migliorati

Low Impedance BPM Button Shapes

- A. Novokhatski at SLAC found in simulation that loss factor was lower for a BPM with elliptical pickups [8].
- A factor 4 decrease in energy loss for an elliptical button with axes ratio 1:24 compared to a round button.
- However, elliptical pickups would incur a greater cost and potentially be more difficult to align precisely.

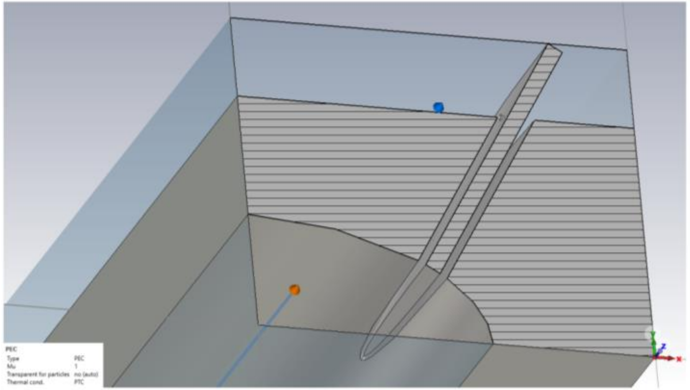


Fig 12: Geometry for the elliptical button with 1:24 axes ratio, simulated in CST [8].

Q: Is this a feasible option cost/alignment-wise?

PRELIMINARY DESIGN STUDIES FOR ARC BPM

Simulations of Simple Button BPM in CST

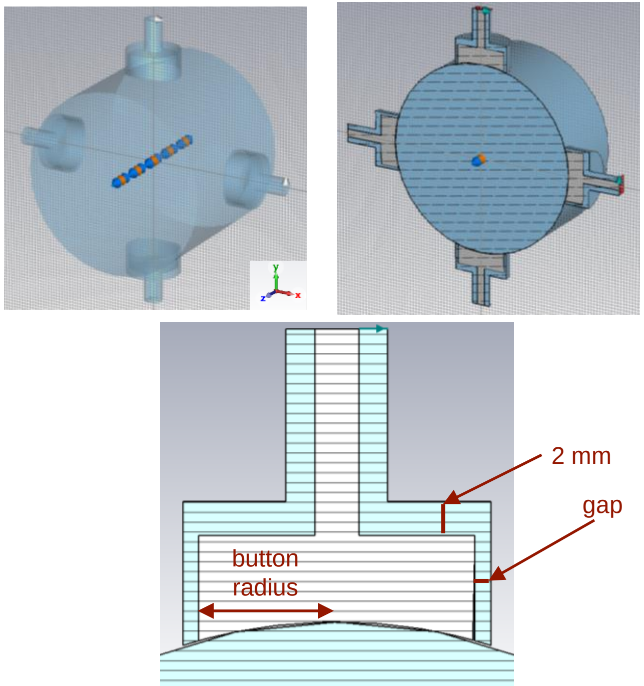


Fig 13: Simple button BPM simulated in CST.

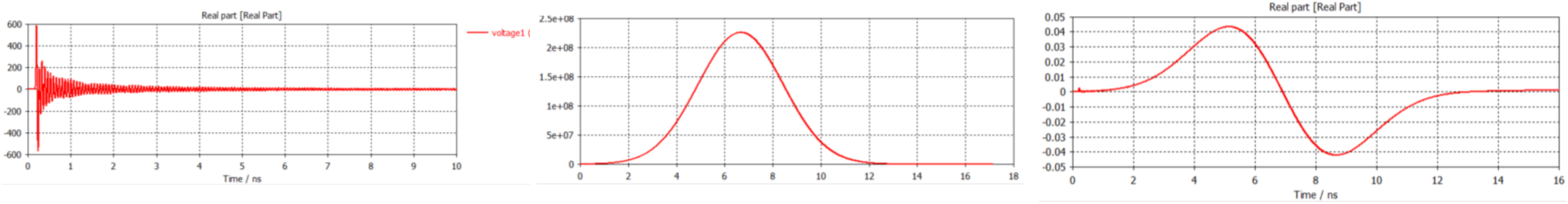
- From simulations, have been analysing resolution and wakeloss factor.

$$\text{resolution} \approx \frac{1}{\sqrt{2}k_{BPM}}\left(\frac{S}{N}\right)^{-1}$$

- k_{BPM} is 2/pipe radius.
- Principle geometric parameters to optimise are the button radius and gap (study ongoing).
- The coax coming out of the button was designed to have an impedance of 50 Ω, and this was verified in CST.

Convolution

- Low pass filter applied in CST post processing.
- Filter makes measurement as insensitive as possible to bunch length and makes the signal long enough to digitise.



Voltage out of pickup + Gaussian filter → Convoluted signal

Fig 14: Signal processing steps in CST post-processing.

Finding suitable geometric parameters – Button Radius

- Resolution calculations so far only take into account estimated thermal noise. Actual resolution will be worse.
- Gap was chosen to be 1 mm for these sims – gap size affects results.
- 8 mm is a good radius value to work with for now – further optimisation studies to come.

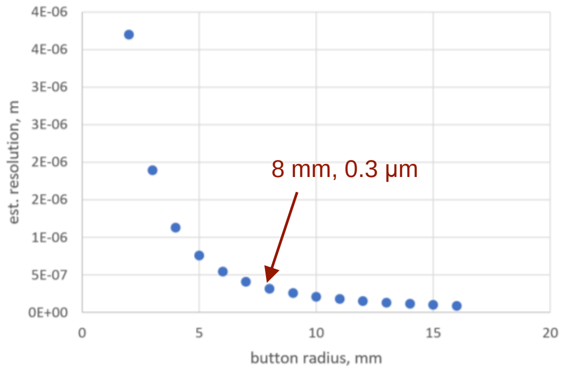


Fig 15: Resolution as a function of button radius.

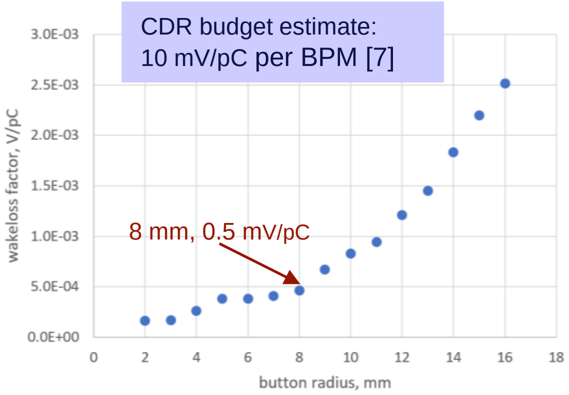


Fig 16: Wakeloss factor as a function of button radius.

Previous parameters minimum during operation (not commissioning)

Beam params	Bunch charge nC	24
	Sigma, mm	3
	Beta	1
	Max beam frequency, GHz	34.1305
	Max beam f simulated, GHz	35
	Bunch length, mm	3
	Wakelength simulated, mm	5.00E+03
Geometric params	beam pipe radius, mm	30
	pipe length, mm	50
	button length, mm	5
	coax outer radius, mm	2.944
	coax inner radius, mm	1.28
	coax length, mm	10
	gapsize v, mm	2
	phi	0.114
	gap, mm	1

INTERACTION REGION BPMS

Interaction Region BPMs

- Part of the general FCC BPM system, but may also be used for luminosity optimisation, IP luminosity feedback etc.
- Make sure to leave space for diagnostics when designing the interaction regions - please don't forget cables!
- Diagnostics at IR must be reliable and very rad tolerant as no opportunity for access/repair once machine finished – avoid cable connectors.
- High resolution (sub µm) required to allow for optimisation of high luminosities.
- Avoid tapering or altering of the beam pipe cross section near the BPM pickup.

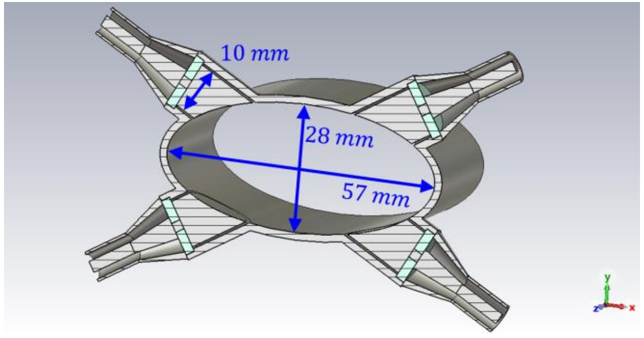


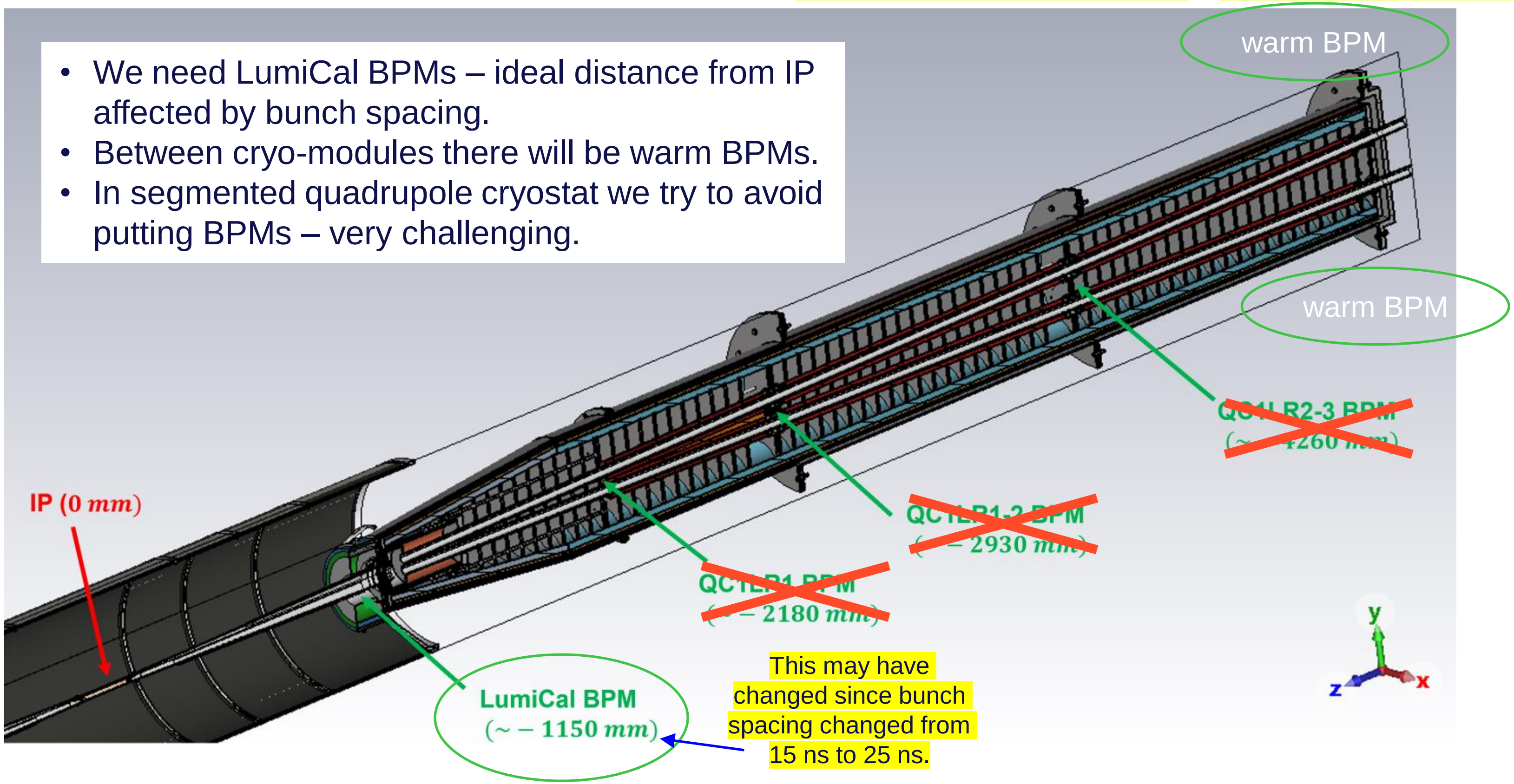
Fig 17: Proposal for LumiCal BPM [9]

Interaction Region BPMs

See ‘Challenges for the IR BPMs’ talk by M. Wendt FCC Week 2023. [9]

STEP drawing file from M. Boscolo and F. Fransesini

- We need LumiCal BPMs – ideal distance from IP affected by bunch spacing.
- Between cryo-modules there will be warm BPMs.
- In segmented quadrupole cryostat we try to avoid putting BPMs – very challenging.



SUMMARY AND CONCLUSIONS

Summary so far

- 8 mm button radius is a good compromise between resolution and wakeloss factor.
- Gap size still under investigation with simulation.
- Simulations suggest wakeloss factor will be a more limiting factor than signal strength, but wakeloss factor can be lower than the estimate in the CDR.

Future plans

Simulations:

- Simulate in beampipe with winglets to check for resonances.
- LHC pickups in FCCee beampipe in CST.
- More realistic button designs for FCC-ee with non-ideal materials etc.
- Different/updated beam parameters.
- Simulate button mechanical tolerances and their implications for alignment and roll. Work to be followed-up in close collaboration with alignment, vacuum and magnet groups for arc cell BPM.

Measurements:

- Tests of eBPM at AWAKE to benchmark against simulation.
- Tests at CLEAR hopefully later this year for further benchmarking of simulations against reality – resolutions calculated are ideal limits, not achievable in practice with the same set up. Tests at CLEAR will use LHC button and pickup from PSI already installed.

Conferences:

- IBIC2024 poster on ‘Preliminary Studies for the Design of a Low Impedance Pick-up for FCC-ee Beam Position Monitors’.

Thank you
for your attention.

References

1. M. Wendt, “A brief introduction to beam position monitors for charged particle accelerators,” IEEE Instrumentation and Measurement Magazine, vol. 24, no. 9, pp. 21–32, Dec. 2021, issn:19410123. doi: 10.1109/MIM.2021.9620043.
2. T. Lefevre, Beam instrumentation for FCC-ee, 2023. [Online]. Available: https : //indico.cern.ch/event/1202105/contributions/5385371/.
3. CERN’s proposed 100 km-circumference “Higgs factory” has lower environmental impact than competing designs, finds study – Physics World. (n.d.). Retrieved May 31, 2024, from https://physicsworld.com/a/cerns-proposed-100-km-circumference-higgs-factory-has-lower-environmental-impact-than-competing-designs-finds-study/
4. G. Kuhlmann, FCC working group transport and handling, Aug. 2023. [Online]. Available:https://indico.cern.ch/event/1316341/
5. A. Boccardi, J. Albertone, M. B. Marin, et al., “COMMISSIONING OF ALPS, THE NEW BEAM POSITION MONITOR SYSTEM OF CERN’S SUPER PROTON SYNCHROTRON,” Proceedings of IBIC2021, pp. 96–99, 2021. doi: 10 . 18429 / JACoW - IBIC2021-MOPP23.
6. K. Hanke, FCCee infrastructure, 2022. [Online]. Available: https://indico.cern.ch/event/1209598/contributions/5092254/.
7. A. Abada, et al., “FCC-ee: The Lepton Collider,” The European Physical Journal Special Topics 2019 228:2, vol. 228, no. 2, pp. 261–623, Jun. 2019, issn: 1951-6401. doi: 10.1140/EPJST/E2019-900045-4.
8. FCC-ee MDI meeting #51 and FCCIS WP2.3 meeting 22 (12 February 2024) · Indico. (n.d.). Retrieved May 31, 2024, from https://indico.cern.ch/event/1376659/
9. M. Wendt and E. Howling, Challenges for the IR BPMs, Jun. 2023. [Online]. Available: https://indico.cern.ch/event/1202105/contributions/5385352/.
10. Migliorati, M. (n.d.). *FCC Week 2024 (10-14 June 2024): FCC-ee single beam collective effects · Indico*. Retrieved June 12, 2024, from https://indico.cern.ch/event/1298458/contributions/5978296/
11. Zimmermann, F. (n.d.). *FCC Week 2024 (10-14 June 2024): FCC Accelerators status · Indico*. Retrieved June 12, 2024, from https://indico.cern.ch/event/1298458/contributions/5975662/
12. Humann, B. (n.d.). *FCC Week 2024 (10-14 June 2024): Radiation environment in the FCC-ee arcs · Indico*. Retrieved June 12, 2024, from https://indico.cern.ch/event/1298458/contributions/5977744/

Open Questions

- Minimum bunch population during commissioning.
- Radiation levels in the tunnel, shielding.
- BPMs on sextupoles?
- Alignment: tunnel temperature drift, other drifts.
- Heating/impedance budget
- IR BPM resolutions, positions
- Redundancy

LHC alignment tolerances

- For reference, the alignment tolerances for the BPMs attached to the magnets in the LHC.

LHC BPM **offset** alignment tolerance	0.2 mm RMS (~ ±1 mm)
LHC BPM **roll** alignment tolerance	1 mrad RMS (~ ±5 mrad)

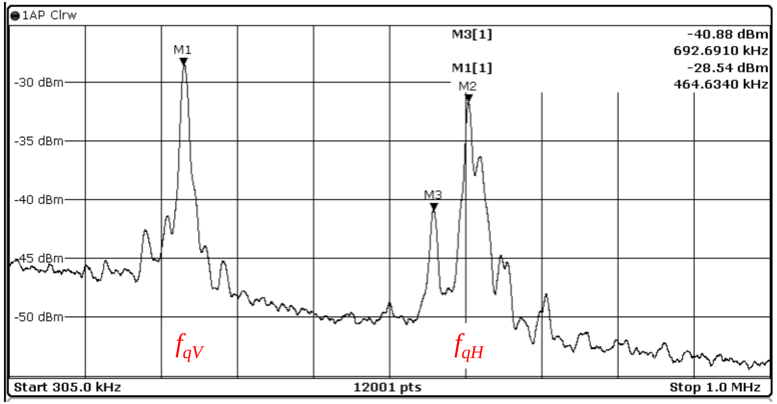
- Values are relative to the magnetic axis of the magnet to which the BPM is attached.
- Tolerances for HL-LHC are very similar.
- Some LHC BPMs are out of spec and LHC still runs, but higher reliability needed for FCC-ee.

Michal Krupa

Tune Measurement

- The BPM system will be used for various non-orbit applications, like instability monitoring, optics and tune measurements.
- As the LHC experience shows, a dedicated system for tune measurement optimised for sensitivity can operate with no explicit beam excitation and therefore deliver tune information all the time “with no cost” [12]
- An ongoing R&D for developing a similar system for the FCC:
  - A base-band tune (BBQ) system prototype optimised for short electron bunches installed on SOLARIS light source in Krakow.
  - First tune signals with no excitation have been already observed.
  - A tune feedback system is being considered in a near future.
  - Further optimisation will continue, with the focus on performance. Optimisation for radiation will follow, once the expected radiation doses are better known and hopefully are reduced by stoppers, shielding or other means.

Courtesy of M. Gasior



Curtesy of M. Szczepaniak, SOLARIS

- First tune observations in October 2023
- Beam signals from a dedicated stripline pick-up
- 1.5 m coaxial cables used as low-pass filters to stretch the short beam pulses and adapt them for the diode detectors
- Some 50 V peak signals on the detectors with ≈ 5 nC bunches
- In the FFC higher signals can be expected, potentially increasing further the system sensitivity