pEDM Beam Position Monitors

Introduction

Moving to the Coincident Beam Scheme (CBS) both simplifies and complicates the task of meeting the physics requirements for the Beam Position Monitors. While stability of absolute position of the two beams relative to the accelerator components remains a concern, the crucial requirement for the CBS is to control the position of the two beams relative to each other.

The two counter-rotating beams exert force on each other unless their centers coincide. For the nominal one year of data acquisition and for the desired 10^{-29}e·cm sensitivity, the permitted integrated vertical offset for the resulting systematic error to be below the EDM signal is ~1pm for magnetic focusing and ~0.1pm for electric focusing. Our preliminary design goal for the BPM system is to achieve a resolution of 1pm in 10^6 seconds of storage time, a few weeks. This corresponds to an average resolution of 1nm with a 1Hz bandwidth or ~10nm with 1 Hz bandwidth per cavity.

With the pickups positioned such that the counter-rotating bunches arrive simultaneously, the signals due to their image currents cancel. The differencing function essential to the position measurement can then accomplished by the pickup itself, rather than in external electronics. In principle this simplifies the task of meeting the physics requirements, having the following virtues:

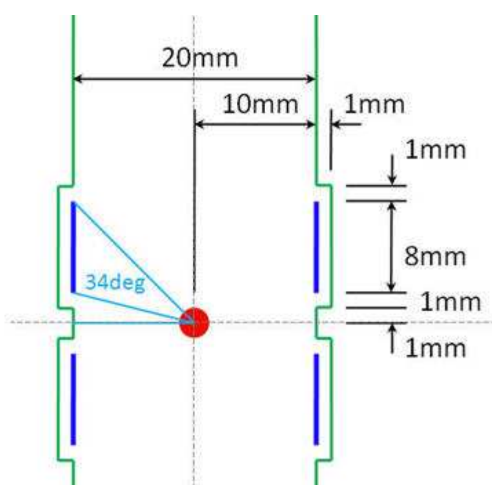
1) The stability requirement for the pickup and the electronics becomes a second order effect, and in principle in the limit of equal beam intensities cancels completely.
2) With orbit feedback on local trim dipoles the measurement becomes a null measurement. The dynamic range of the detection electronics is correspondingly reduced.
3) The longitudinal impedance of the pickup is reduced by the cancellation factor

In the following sections we first look at the simplest possible circumstance for position monitoring, namely the conventional shorted stripline pickup. We analyze the attainable resolution for this configuration with nominal beam parameters. We then consider the possibility of resonating the striplines to simplify the differencing and improve the resolution, and look briefly at possible advantages and disadvantages of resonant cavity pickups. Finally, we outline the proposed R&D program.

Pickup Resolution

A possible stripline geometry is shown to the right. The following parameters are used in the analysis of pickup resolution:

RF frequency	f_{rf} = 90MHz
Number of bunches	N_b = 120
Revolution frequency	f_{rev} = 750KHz
Bunch length	σ = 1nsec
Bunch charge	N = 2×10^8
Stripline length	L = 50cm
Stripline subtended angle	α = 34deg
Stripline impedance	Z = 50ohm



The results of calculations [1] using these parameters are shown below:

$\tau := \frac{L}{2c}$ $\qquad \tau = 8.339 \times 10^{-10}\,s$ $\qquad \phi := \frac{\alpha}{57.3}$ $\qquad \phi = 0.593$

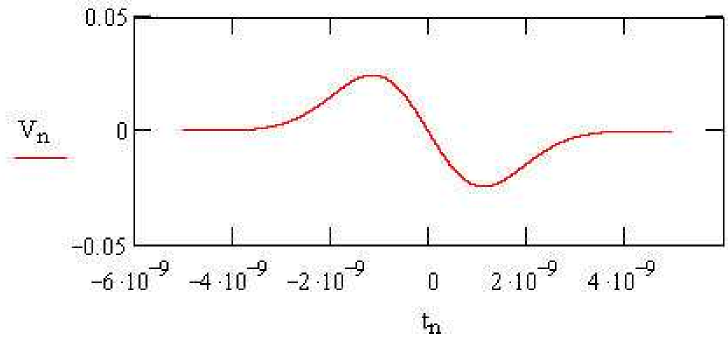
for a single bunch: $\quad n := 1 .. 10000 \qquad t_n := (n - 5000) \cdot psec$

$$V_n := \frac{\phi \cdot Z}{4 \cdot \pi} \cdot \left[e^{\frac{-(t_n + \tau)^2}{2 \cdot \sigma^2}} - e^{\frac{-(t_n - \tau)^2}{2 \cdot \sigma^2}} \right] \cdot \frac{q \cdot N}{\sqrt{2 \cdot \pi} \cdot \sigma}$$

$$P_n := \frac{(V_n)^2}{Z}$$

$$Energy := \sum_n (psec \cdot P_n)$$

$$Energy = 3.236 \times 10^{-14}\,joule$$



for 120 bunches: $\quad \tau_{rev} := 1333 \cdot nsec \qquad N_b := 120$

$P_{ave} := \frac{Energy \cdot N_b}{\tau_{rev}}$ $\qquad P_{ave} = 2.913 \times 10^{-6}\,W$

$P_{dBm} := 10 \cdot \log\left(\frac{P_{ave}}{W}\right) + 30$ $\qquad P_{dBm} = -25.356$

$P_{thermal} := -173$ $\qquad P_{dBm} - P_{thermal} = 147.644$

so S/N with 1Hz BW is ~148dB

Assume we lose ~8dB to various inefficiencies (amplifier noise figure, filters,...)

With 10mm half aperture and S/N of 140dB (ie 1Hz BW), the resolution would be 1nm.

The Bessel factor correction [1] due to the fact that the beam is not fully relativistic is negligible at 90MHz, as is the transit time correction [1] for the gaps at the end of the striplines.

The 1Hz bandwidth resolution remains ~1nm when a second counter-rotating bunch is introduced. The effect of the second bunch is simply, as outlined in the introduction, to reduce the longitudinal impedance and the dynamic range and pickup/electronics stability requirements.

Resonant Striplines

While the above calculations indicate that the magnetic focusing physics requirements for the BPMs can be met, it is potentially useful to gain even better resolution. This opens the possibility of faster machine tuning, as well as improved exploration of whatever unknown systematics that might be present. And perhaps more important, it increases the feasibility of electric focusing, where 0.1pm resolution is needed.

There is substantial experience with resonant stripline pickups in RHIC [2]. Based on that experience, we can state with some confidence that, while it adds some substantial complexity, it is nonetheless straightforward to resonate the stripline pickups. In RHIC the attainable Q was limited to ~100 by the pre-existing design of the vacuum feedthroughs. For the pEDM proposal it is reasonable to expect Q~1000. This will result in resolution improvement of ~30, to better than the 0.1pm required for electric focusing.

Resonant Cavities

It is essential to short the stripline pickup on one end to permit the differencing function to happen within the pickup. The resulting doublets from the counter-rotating bunches have opposite polarity, and cancel in this configuration. However, one result is that the shorted stripline pickups are not symmetric with respect to beam direction. This causes some discomfort when considering the relative position measurement of counter-rotating bunches.

Resonant cavities have the advantage that they can be made symmetric with respect to beam direction. However, they have some potentially significant disadvantages.

If the cavities are made to resonate at the 90MHz bunching frequency, there are many resonant modes that might be excited by the coherent spectrum. This is unlike the resonant stripline, where the only modes are the fundamental and its odd harmonics. With all buckets filled approximately equally the spectrum will be sparse, so that with some attention to mode frequencies this is perhaps not a serious concern.

A larger concern is space. It is not obvious how to fit 90MHz cavities into the available space. One possibility is to design cavities to operate at some higher frequency, say ~1GHz, and to add a ~1GHz cavity to the RF system to permit microbunching at the cavity frequency. The effect of this on the spin coherence time is likely to limit the modulation depth to perhaps 10%, which would result in a 20dB loss of S/N relative to operating at the bunching frequency. An additional 10dB or more will be lost to the combination of Bessel factor and transit time corrections, which become more severe as frequency goes up. And there is further loss as a consequence of the fact that not all buckets will be filled at 1GHz. The end result is that, while the symmetry lost in shorting the striplines could be restored by the cavity approach, it appears this would come at the cost of some added complexity with the second RF system, and without any significant improvement in resolution.

Cost and Manpower

The required level of effort to develop the BPM for the needs of the magic proton EDM ring is estimated to be ~0.5FTE during detailed design and ~1FTE during construction and commissioning. The total time needed for this development is estimated to be about two years. The total cost is estimated to be about $0.45M.

References

[1] Robert Shafer, "Beam Position Monitoring", Robert Shafer, AIP Conf. Proc., V. 249, 601 (1992).

[2] M. Kesselman et al, "Resonant BPM for Continuous Tune Measurements in RHIC", PAC 2001, Chicago.