Non-Destructive Beam Instrumentation for the Cooling Demonstrator

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A cooling demonstrator bunch simulated in G4beamline, rendered in Blender.

Summary

Alongside upstream and downstream experiments in the cooling demonstrator, instrumentation along the beamline is necessary for measurement and tuning of the accelerator during operation. Beam instrumentation must non-destructively measure spatial distribution on the order of millimeters and bunch timing structure on the order of 10 picoseconds. However, a beam in the cooling demonstrator is expected to be very low-intensity, ~ $10^5 - 10^6$ muons per bunch. We examine several conventional beam instrumentation methods and their limitations.

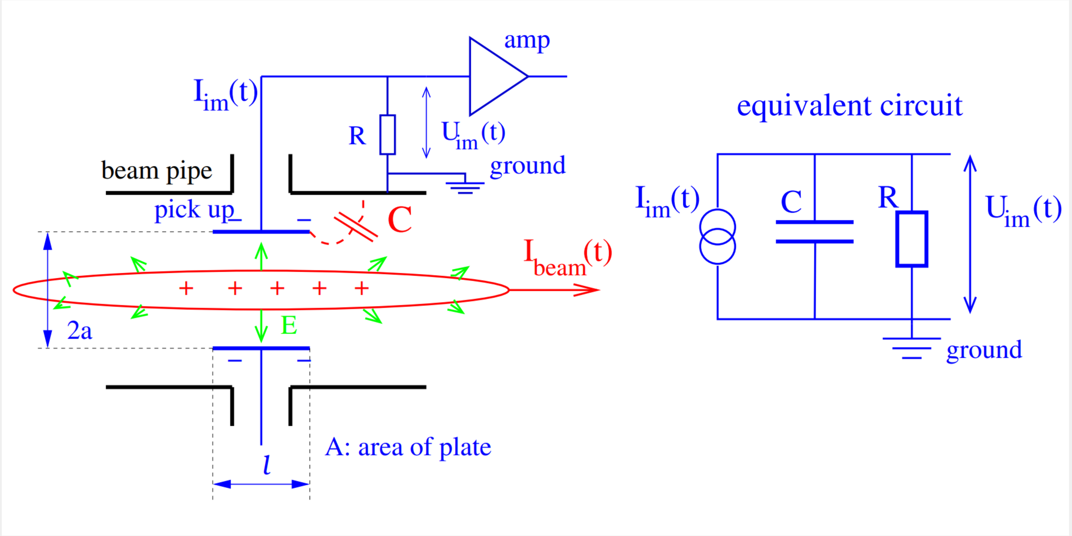

Fig. 1: Scheme of a BPM pick-up electrode and its equivalent circuit, from [1]. The capacitance C comes from the distance between the plate and the beam pipe, and the cable from the plate to an amplifier. The resistance R is largely the resistance of the amplifier. The circuit itself forms a high pass filter, and the coaxial cable that transmits the signal is a low pass filter.

Multi-Wire Monitors

Multi-wire monitors are a grid of thin wires, placed in the beamline to measure the beam profile.

- Poor SNR at intensities below 10^7 particles/bunch
- Wires that are thin enough not to interfere significantly with the beam are liable to burn out

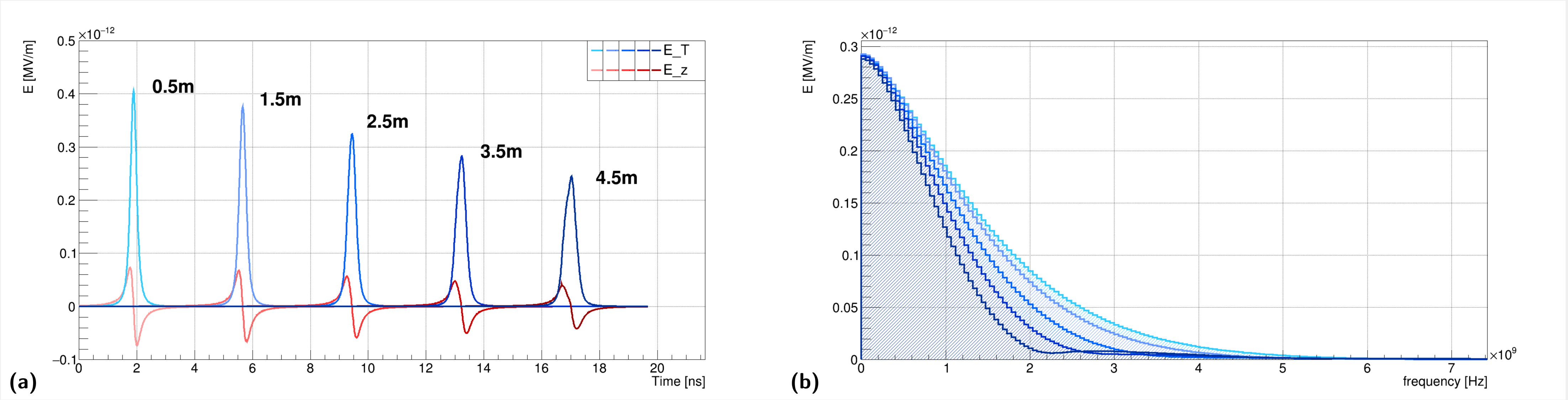

Figure 2: The $E_\perp$ and E_z fields induced by a single bunch passing by, measured 1 mm away from the surface of the beam pipe. The pipe is aluminum and conductive, necessary to allow the calculation of fields in G4beamline collective mode. 1(a) shows $E_\perp$ and E_z, measured 1 mm away from the inside wall of the beam pipe. 1(b) shows the FFT of $E_\perp$. At 6 GHz, the attenuation of a low loss RG58 coaxial cable is 1.532 dB/m (~ 30%/m) [4]. Parameters for the demonstrator bunch structure are from [2].

Parameters	Cooling Demonstrator	G4beamline simulation
Intensity	$\sim 10^5 - 10^6\ \mu$/bunch	$10^6\ \mu+$
Momentum	200 ± 10 MeV	200 ± 10 MeV
Bunch length	~ 100 ps	$\sigma_z = 12.72$ mm (1/2 βc ·100 ps)
Beam spot size	10–20 mm RMS + dispersion	$\sigma_x = \sigma_y = 5$ mm
Beam pipe radius	81.6 mm	81.6 mm

Beam Position Monitors

Beam position monitors measure image charges induced by beam on the instrument's conducting surfaces as it passes.

- Resolutions ~ pA ~ $10^{19} * 10^{-12} = 10^7$ particles. Still measurable with amplifiers, low noise background.
- The capacitive pickup BPM in Fig. 1 can be described by a simple circuit with capacitance C, resistance R. Modeling the passing bunch as a current source I_{beam}, the impedance Z is

$$\frac{1}{Z} = \frac{1}{R} + i\omega C \iff Z = \frac{R}{1+i\omega RC}$$

and thus the transfer function U_{im} is

$$U_{im} = \frac{R}{1+i\omega RC} \cdot I_{im} = \frac{1}{\beta c}\frac{1}{C}\frac{A}{2\pi a}\frac{i\omega RC}{1+i\omega RC} I_{beam} \equiv Z_t(\omega, \beta) \cdot I_{beam}$$

- This equation has the form of a first order high pass filter with cutoff frequency $f_{cut} = \omega_{cut}/2\pi = (2\pi RC)^{-1}$.

Laser Wire Scanners

A tightly focused laser beam is scanned across a (e^+/e^-) beam. An image of the beam is reconstructed from Compton-scattered photons.

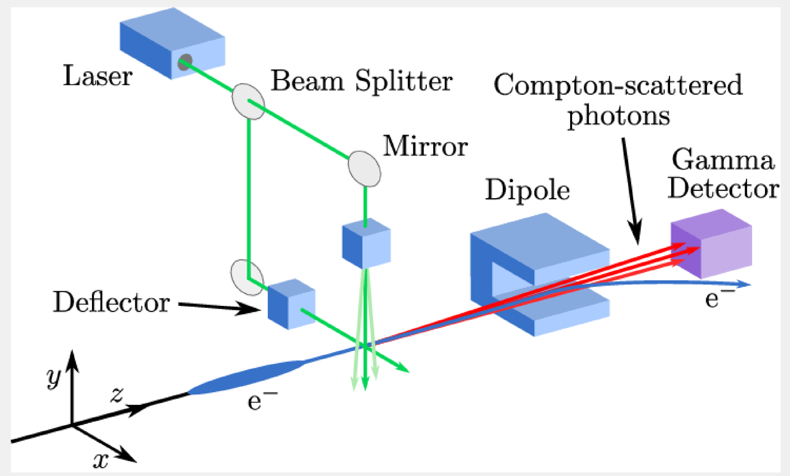

Figure 3: A conceptual schematic of a laser wire scanner, from [3]. Such scanners are used at SLAC, PETRA-III in DESY, and the ATF-II at KEK, and have been proposed for the ILC and CLIC.

- Compton scattering: $\nu_0 h \approx m_e c^2$; for electrons, requires hard x-ray lasers.
- For muons, Compton scattering requires v 200x higher, so a scanner would rely on Thomson scattering ($\nu_0 h << m_e c^2$).
- Thomson cross section is $(m_\mu/m_e)^2 \approx 40{,}000$x smaller for muons than electrons, ~1.5E-5 barn.
- A demonstrator bunch, using parameters of laser wire scanners at PETRA and ATF, would Thomson scatter ~ 5 photons; could increase laser light intensity.
- Differentiate photons scattered by the muon bunch and by background electrons, background photons.

References

[1] P. Forck, P. Kowina, and D. Liakin. "Beam Position Monitors". In: Synchrotron Radiation News 1 (Jan. 2008).

[2] P. B. Jurj, C. Rogers, and I. Ortega. "Beam parameters and functional specifications for Demonstrator and Muon Collider instrumentation". In: Proceedings of the 17th BIFT - Muon Collider. Jan. 2025.

[3] L. J. Nevay, R. Walczak, and L. Corner. "High power fiber laser system for a high repetition rate laserwire". In: Phys. Rev. ST Accel. Beams 17(7 July 2014), p. 072801.

[4] RFI Technology Solutions: Coaxial Attenuation Chart. 2021.