BEAM POSITION MONITOR R&D FOR keV ION BEAMS*

S. Naveed#, C.P. Welsch, Cockcroft Institute and University of Liverpool, UK
A. Nosych, CERN, Geneva, Switzerland, Cockcroft Institute and University of Liverpool, UK
L. Søby, CERN, Geneva, Switzerland

Abstract
Beams of cooled antiprotons at keV energies shall be provided by the Ultra-low energy Storage Ring (USR) at the Facility for Low energy Antiproton and Ion Research (FLAIR) and the Extra Low ENergy Antiproton ring (ELENA) at CERN's Antiproton Decelerator (AD) facility. Both storage rings put challenging demands on the beam position monitoring (BPM) system as their capacitive pick-ups should be capable of determining the beam position of beams at low intensities and low velocities, close to the noise level of state-of-the-art electronics. In this contribution we describe the design and anticipated performance of BPMs for low-energy ion beams with a focus on the ELENA orbit measurement systems. We also present the particular challenges encountered in the numerical simulation of pickup response at very low beta values. Finally, we provide an outlook on how the implementation of faster algorithms for the simulation of BPM characteristics could potentially help speed up such studies considerably.

INTRODUCTION

Beams of ions and antiprotons at keV energies and low velocities are useful for both, fundamental and applied research, and also in many technical and industrial fields. The diagnostic of these beams, however, is a challenge because most detectors are either not sensitive enough or too invasive. Here, we discuss the results and limitations of the electromagnetic (EM) analysis of a particular prototype BPM which shall be installed in the ELENA ring as a part of its orbit measurement system.

ELENA is a compact storage ring, only 30.4 m in circumference, which shall slow down antiprotons from 5.3 MeV to 100 keV, cool them via electron cooling, and deliver the cold beam to various experiments via electrostatic beam lines. The total number of extracted antiprotons is estimated to be $\sim 2 \cdot 10^7$. An energy of 100 keV was chosen to meet the beam quality requirements that can be degraded at low energies when extracted through foils separating the ultra-high vacuum environment of trap experiments from the beam lines at a higher pressure. The ring's BPM system is based on 20 cylindrical diagonally cut electrodes mounted inside quadrupole and dipole magnets by ceramic supports, see Fig. 1. The BPMs consist of families of horizontal and vertical electrodes. Difference and sum signals read from the electrodes will be digitized and provide beam position information along the ELENA ring.

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#sehar@liverpool.ac.uk

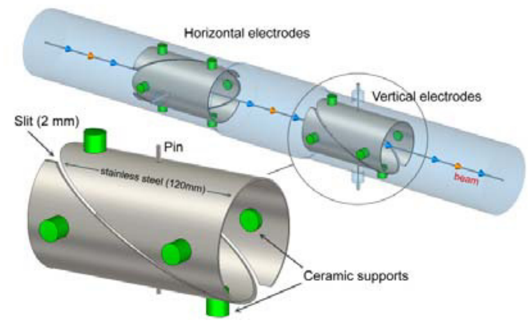

Figure 1: A simplified 3D model of the ELENA BPM.

CHALLENGES IN EM MODELING

In order to understand and optimize the performance of the ELENA BPM, EM simulations were carried out using several different EM solvers of CST Studio Suite [1]. Particular challenges were encountered in building a reasonable mesh of the BPM model and numerical simulation of pickup response at sub-relativistic beam velocities.

The CST Studio meshing algorithm employs hexahedral elements for time domain simulations. Although very powerful, it has limitations to its use, which affect our simulations: the mesh cells containing very thin and curved metallic shapes are treated as single PEC blocks. If two or more such block are adjacent they can cause unwanted electrical connections or perturb the geometrical integrity of the structure. Unless simplifications to the model can be made, the PEC cells must be avoided at the cost of increasing regional mesh density and thus the simulation time. If not properly meshed, the 2 mm gap between the thin curved electrodes of the ELENA BPM is shorted and voltage readings are invalid. Denser meshing of the electrode edges is crucial for accurate simulation of the signals, so that the gap region does not contain any PEC cells. Moreover, the non-symmetric design of the electrodes excludes the possibility of cutting the simulation domain with symmetry planes for faster calculation

In order to have stable simulations of BPM signals, the minimum mesh count of the original mechanical model was estimated to have over 20 million mesh cells. Simulation of a single relativistic Gaussian-type bunch (σ=325 mm, nominal for the ELENA ring) with the Wakefield solver of CST took ~8 h of computation time on a 32-core PC. It is clear that such amount of mesh cells renders quick runs and optimization of any structure unreasonable. However, several simplifications were still possible, which allowed reduction of the mesh count by a factor of 3, which is a reasonable amount to start convergence studies. The original mechanical design of the ELENA BPM envisaged a skew of the electrode pins and feed throughs due to space constraints inside the magnets, see Fig. 2a. Since the approximation of any tilted objects with hexahedral mesh is not recommended, a simplified 3D model of the BPM was built, having all tilted parts (feed throughs and ceramic supports) aligned with the closest coordinate axis, see Fig. 2 (b).

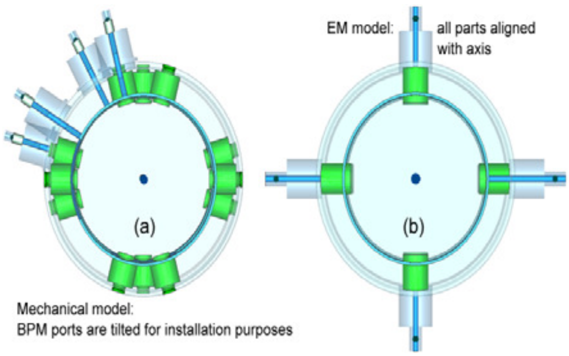

Figure 2: Transverse cross-sections, highlighting the difference in the mechanical and EM design.

Due to symmetry between horizontal and vertical orientation of the electrode plates, the structure was reduced to only two horizontal electrodes. In addition, the two-electrode geometry was benchmarked against a single horizontal electrode to speed up the simulation at low-beta, see Fig. 4. The mesh count of the two-electrode BPM had estimated 4 million, while a single-electrode required less than 1M elements. This simplified model allowed calculation of the signal linearity and expected output voltage as function of beam energy, the signal shape as function of beam position and shape, the pickup bandwidth and electrode capacitance, as well as the longitudinal coupling impedance and the effects from wake fields for relativistic and sub-relativistic beam velocities.

Beam-related EM simulations of low-energy instrumentation in time domain are quite different from simulating beams travelling at the speed of light [1-2]. For relativistic beams with a beta value above 0.999 the field excited by the bunch can be determined by solving a 2D electrostatic problem, which requires a very small amount of memory only. But the conventional time domain solvers become inefficient when the simulated bunch is significantly slower than the speed of light. If beta was chosen to be less than 0.999 a full 3D electrostatic problem must be solved at each time step before the wake-simulation is started. This is necessary to imprint the Eigenfield of the moving charge at the calculation domain's boundaries. Depending on the beta value and the maximum stable time step of the wake field simulation, this can be a very time- and memory consuming operation.

RESULTS FROM EM SIMULATIONS

The electrode capacitance of 17.35 pF was calculated with the Electrostatic solver of CST taking into account the coupling between electrode pairs. The Particle In Cell (PIC) solver of CST was then used to excite the structure with a bunch train consisting of 1 to 3 bunches with $\beta \leq 1$ to study the signal shape and sensitivity of the electrodes to beam position. The transient pass of a bunched beam was simulated by pencil-type bunches of nominal parameters anticipated in the ELENA ring.

To extend the pick-up bandwidth to lower frequencies, the discrete voltage monitors were loaded with 1 MOhm and were used to read the signals from BPM feed throughs. Signal linearity of horizontal electrodes to beam displacement in X and Y axis is shown in Fig. 3. It was found to be very linear up to large axial displacements from the central orbit and will be a very good basis for precision position determination.

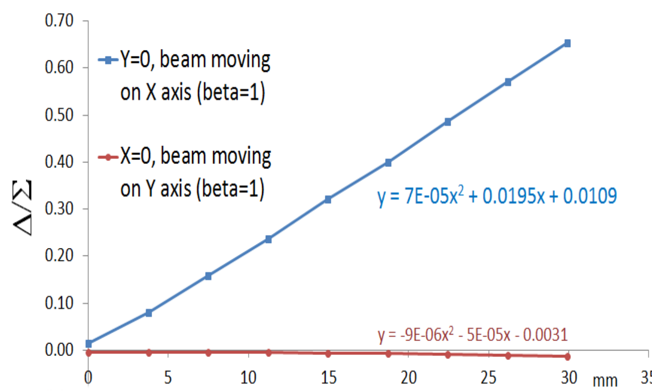

Figure 3: Signal linearity of horizontal electrodes to beam displacement in X and Y axis.

The voltage-time signals are shown in Fig. 4 on the next page as function of β in one-or two-electrode geometry. The peak amplitude for the two-electrode setup is 7.8 mV, while a single electrode reads 7 mV for the same beta. The difference of 0.8 is considered as a coupling contribution from the second electrode if it is present. Note that the peak amplitude remains constant for all β, while the signal length changes according bunch velocity, thus shifting to low-frequency spectrum.

The Wakefield solver of CST was used to estimate the longitudinal coupling impedance and wake fields of the BPM. Fig. 5 displays the longitudinal wake potential with respect to the bunch velocity.

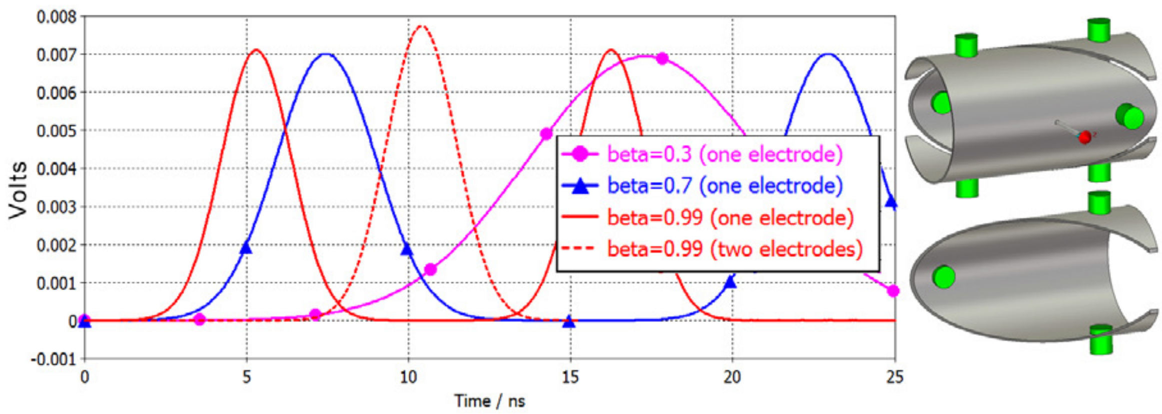

Figure 4: Simulated BPM signal in Volts as function of time for different betas; simplified pickup geometry.

In all cases the peak amplitude is very small and shows a fast attenuation of the residual field behind the bunch. This indicates that the structure does not have any impedance issues and does not interfere with the beam at frequencies involved in the bunch spectrum.

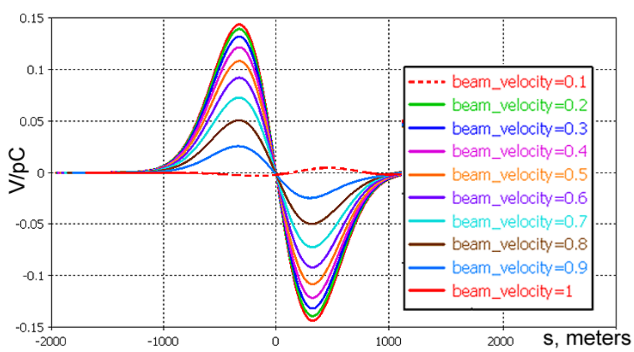

Figure 5: Longitudinal wake potential of the ELENA BPM as a function of β.

Faster Algorithms

As the only mesh type available in Particle Studio is the Cartesian (hexahedral) mesh, the diagonal elements and round edges in the capacitive pick up make meshing non-trivial. Particle studio enables simulations of electromagnetic fields from beams travelling at velocities much smaller than the speed of light, but such problems become complex and sometimes cannot be solved. The main limitation comes from the fact the computation time increases with decreasing β value. This is because the particle bunch needs to be sent from outside the simulated structure, so that no corresponding fields are present in the modeled volume at time $t = 0$. At $\beta = 1$ the field lines are perpendicular to the beam and the pulse can be located just at the entrance of the pickup structure. At $\beta \ll 1$, the computed volume needs to be significantly extended outside the defined model in z direction. Not only can this lead to an excessive number of mesh cells, but it can also cause the algorithm to fail finding a stable step size required to perform the calculations [2].

Multilevel Fast Multipole Method

Algorithms based on plane wave expansion suffer from low frequency breakdown [3], which significantly increases processing time and memory requirements, and sometimes do not reach the required stability and accuracy. Most computational time expense comes as a result from computing large complex matrix vector multiplications (MVMs). For fast and accurate solutions of real life electromagnetic problems discretized with hundreds of millions of unknowns, the implementation of a powerful algorithm, namely, the Multilevel Fast Multipole Algorithm (MLFMA), which accelerates the matrix vector product, could provide full-wave analysis of three-dimensional structures with arbitrary geometries and material properties at realistic ranges of frequencies [4], see Fig. 7. MLFMA enables the solution of even larger problems by reducing the complexity of MVMs from $O(N^2)$ to $O(Nlog^2N)$ [5] or $O(NlogN)$ [6].

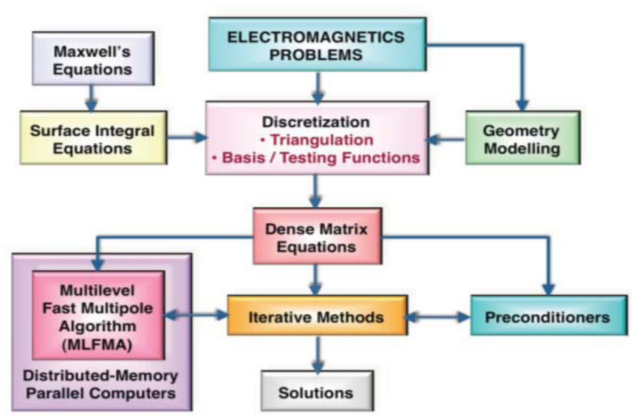

Figure 6: A typical simulation environment based on MLFMA [3].

MLFMA is based on recursively dividing any given region into subdomains such that a multilevel tree structure is constructed to perform fast matrix-vector multiplications (required by iterative solvers) via the factorization and diagonalization of the Green's function associated with the region. Hence, for a complicated problem involving different penetrable regions, multiple tree structures are required. In order to calculate the far-field interactions, radiated and incoming fields are defined and sampled on the unit sphere. Each matrix-vector multiplication is performed as a sequence of aggregation, translation, and disaggregation stages as illustrated in Fig. 8.

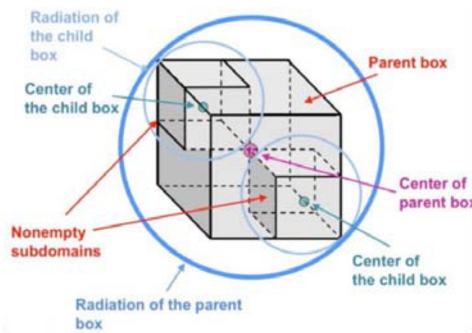

Figure 7: Boxes in the near and far zones according to the one-box-buffer scheme [4].

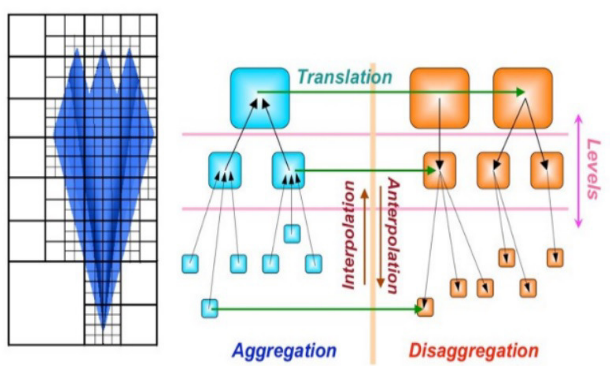

Figure 8: Recursive clustering of an arbitrary object and the construction of a multilevel tree structure [3].

LOW FREQUENCY BREAKDOWN

In literature, one common approach to solve low-frequency problems efficiently via (modified versions of) MLFMA is based on the multipole representation of radiated fields [3, 7]. In this case the Green's function is factorized in a series of multipoles, but the multipoles are not converted into plane waves. In both approaches, the box size is not restricted, and one can divide the object into boxes that can be much smaller than the wavelength. Similarly, for a given problem, the choice of the surface integral equations, which are derived directly from Maxwell's equations via the equivalence principle, is critical in terms of stability, accuracy, efficiency and applicability. These formulations can be discretized in many different ways for numerical solutions. When the object is PEC, for example the ELENA BPMs, tangential Electric Field Integral Equations (TEFIE) are solved independently to obtain the induced current on the surface, see [3]. But TEFIE may also suffer from low frequency breakdown problems especially when it is discretized with ordinary basis functions [8]. Specifically, the matrix equations obtained from TEFIE might become increasingly ill-conditioned as the discretization is refined [3]. However, to eliminate the low-frequency breakdown problem, one could apply loop-star or loop-tree decomposition methods [9]. These options will be investigated in the near future.

CONCLUSION

We presented the design of the ELENA BPM system and discussed its expected performances. Simulations were done in CST Studio and showed limitations with hexahedral meshing of complex structures and non-relativistic time-domain studies. The implementation of faster algorithms such as MLFMA together with the Method of Moments (MoM) might help to obtain the simulation results independent from meshing size and type and could potentially speed up such studies considerably.

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