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Self-Consistent Simulations of High-Intensity Beams and E-Clouds with WARP POSINST*

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Abstract

We have developed a new, comprehensive set of simulation tools aimed at modeling the interaction of intense ion beams and electron clouds (e-clouds). The set contains the 3-D accelerator PIC code WARP and the 2-D "slice" e-cloud code POSINST, as well as a merger of the two, augmented by new modules for impact ionization and neutral gas generation. The new capability runs on workstations or parallel supercomputers and contains advanced features such as mesh refinement, disparate adaptive time stepping, and a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps. It is being applied to the modeling of ion beams (1 MeV, 180 mA, K+) for heavy ion inertial fusion and warm dense matter studies, as they interact with electron clouds in the High-Current Experiment (HCX). In earlier papers, we described the capabilities and presented recent simulation results with detailed comparisons against the HCX experiment, as well as their application (in a different regime) to the modeling of e-clouds in the Large Hadron Collider (LHC). We concentrate here on the description of the implementation of the "quasi-static" mode of operation, for comparison with other codes, and introduce a new consideration on the estimate of computing time between the quasi-static and the fully self-consistent modes.

INTRODUCTION

The steadily increasing beam intensity required in operational and upcoming accelerators leads to growing concerns over the degradation of beam emittance due to electron cloud effect and gas pressure rise [1]. Accurate prediction necessitates a detailed understanding of the physical processes at play with a quantification of the relative importance of various effects. To this end, the development of a new generation of computer simulation code is underway, in conjunction with detailed measurements from a heavily diagnosed small dedicated experiment, for extensive benchmarking and code validation. In earlier papers, we described the capabilities and presented recent simulation results with detailed comparisons against the HCX experiment, as well as their application (in a different regime) to the modeling of e-clouds in the Large Hadron Collider (LHC). We provide a brief overview of the simulation code and the dedicated experiment. We then describe the implementation of the "quasi-static" mode of operation, for comparison with other codes, and introduce a new consideration on the estimate of computing time between the quasi-static and the fully self-consistent modes, and discuss some implications of our findings.

A UNIQUE COMBINATION OF SIMULATION AND EXPERIMENTAL TOOLS

THE WARP/POSINST SIMULATION PACKAGE

The simulation tool is based on a merge of the Heavy Ion Fusion [2] accelerator code WARP [3] and the High-Energy Physics electron cloud code POSINST [4, 5], supplemented by additional modules for gas generation and ionization [6], as well as ion-induced electron emission from Tech-X package TxPhysics [7], and ion-induced neutral emission module from UC-Berkeley. The package allows for multi-dimensional (2-D or 3-D) modeling of a beam in an accelerator lattice and its interaction with electron clouds generated from photon-induced, ion-induced or electron-induced emission at walls, or from ionization of background and desorbed gas. The generation and tracking of all species (beams particles, ions, electrons, gas molecules) is performed in a self-consistent manner (the electron, ion and gas distributions can also be prescribed if needed for special study or convenience). The code runs in parallel and benefits from adaptive mesh refinement [8], disparate adaptive time-stepping and a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps [9]. These advanced numerical techniques allow for significant speed-up in computing time (orders of magnitude) relative to brute-force integration techniques.

THE HIGH CURRENT EXPERIMENT

Our simulation tools are continously being benchmarked against the High Current Experiment [10], located at Lawrence Berkeley National Laboratory. It consists of an injector producing a singly-charged Potassium ion beam (K+) at 1 MeV kinetic energy, followed by a transport lat-

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tice made of a matching section, a ten-quadrupole electrostatic section and a four-quadrupole magnetic section. The flat top of the beam pulse reaches 180 mA and its duration is 4 μs. We study electron effects in the magnetic section [11, 12], where a suppressor ring electrode, surrounding the beam after it exits the last quadrupole magnet, can be biased to -10 kV to prevent ion-induced electrons emitted from an end wall (a slit plate) from reaching the magnets, or can be left unbiased to allow electrons emitted from the end wall to freely flow upstream into the magnets. There is also a series of three clearing electrodes, in the drift regions between quadrupole magnets, which can be biased positively to draw off electrons from between any pair of magnets. The current that flows in and out of these clearing electrodes is monitored in the experiment and is compared to simulation results for benchmarking. Generally good agreements (sometime very good) have been obtained between WARP-POSINST and the HCX experiment and are presented in [13, 14].

RECENTLY ADDED FEATURES AND CONSIDERATIONS FOR ITS APPLICATION TO HIGH-ENERGY PHYSICS

We have started to apply the WARP-POSINST code to the modeling of electron cloud effects in high-energy physics accelerators. In [13], we show a snapshot from the WARP-POSINST modeling of a train of bunches in one Large Hadron Collider (LHC) FODO cell .

Addition of the "quasi-static" mode

In order to allow for direct comparisons between self-consistent runs with WARP-POSINST and "reduced" single bunch instability codes like HEADTAIL [15] or QuickPIC [16, 17], we have added a new mode of operation (see Fig. 1), based on the quasistatic approximation [18]. This approximation is valid if the electron transit time through the driver pulse (laser or particle beam) is short compared with the characteristic driver pulse deformation time, which is the case for one high-energy physics accelerator bunch traversing an electron cloud. In our implementation, similarly to implementations in [15] and [16, 17], the beam and electrons are modeled respectively as a 6-D $\{x, y, s, v_x, v_y, v_s\}$/4-D $\{x, y, v_x, v_y\}$ distribution of macro-particles, where s is the coordinate along the reference orbit and x and y are the coordinates defining the plan that is perpendicular to it. In the current mode, a number of interaction points (stations) between the bunch and the electron clouds is set per turn of the ring (or per lattice period for a linear structure). At each of these stations, the 2-D electron slab is initialized with a fresh predefined distribution which is then followed as it slips backward the bunch, under the influence of the bunch field and the external field from the lattice. At each step, a 2-D Poisson solve produces a transverse slice of potential values, which are stacked successively in a 3-D array surrounding the driver bunch. The latter is then pushed under the influence of this 3-D field plus external fields (and its own field if not negligible), to the next station using either a) maps (as in [15], mode labeled "QSM") or b) a leapfrog pusher with large time steps (as in [16, 17], mode labeled "QSL").

We have tested the WARP-QSM mode by applying it to a benchmarking test of single bunch instability, given by CERN [19]. The list of input parameters is reproduced in Fig.2 and the results comparing WARP-QSM and HEADTAIL are given on Fig.3 for simulations with respectively one and two stations per turn. The same initial distribution of macro-particles was used by importing it into WARP from a HEADTAIL dump, as well as the same number of macro-electrons and grid resolutions. The obtained agreement is excellent. Comparisons with QuickPIC running WARP in the QSL mode will be performed in the near future. Once this will be validated, we will be in a position to make meaningful comparisons between results from self-consistent WARP-POSINST runs and HEADTAIL or QuickPIC results, via the use of WARP-QSM or WARP-QSL runs, or hybrids.

New considerations on the computational cost of self-consistent (SC) versus quasi-static (QS) modes

Computational cost of the SC mode in the laboratory frame and a boosted frame Let us assume that we plan on modeling the propagation of a cylindrical beam of length σ_z and radius σ_r moving along z at the assumed constant relativistic velocity v_b, in a linear structure constituted of N cylindrical elements of unit length L and radius R. If n is the number of points that we specify per smallest unit that we need to resolve in any dimension, then the required resolutions in r and z are given respectively by

$$\begin{cases} \delta r = \min(\sigma_r, R)/n, \\ \delta z = \min(\sigma_z, L)/n. \end{cases} \tag{1}$$

Defining $0 < \alpha < 1$, for a given accuracy, the time step will be set so that

$$\delta t = \alpha \min\left[\delta r/\max(v_r), \delta z/\max(v_z)\right]. \tag{2}$$

Assuming that $\sigma_z << NL$, the time it takes for the beam to go across the accelerator is given by

$$T_{max} = \frac{NL}{v_b}. \tag{3}$$

Using a moving window of length σ_z following the beam and assuming a constant electron density, the number of macroparticles present in the moving window at every step is a constant $N_p = N_b + N_e$, where N_b and N_e are respectively the number of beam macro-particles/electrons contained in the window. The number of cells of a three-dimensional grid covering the moving window is given by

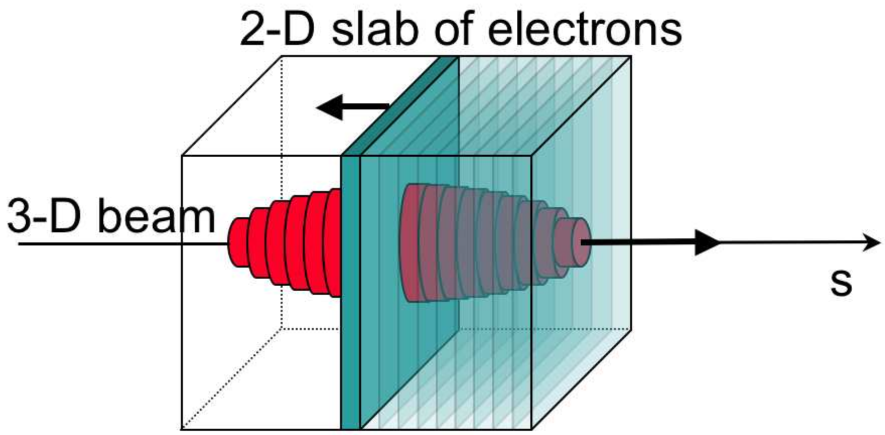

Figure 1: Schematic of the quasi-static mode implemented in WARP-POSINST.

$$N_g = \left(\frac{R}{\delta r}\right)^2 \times \left(\frac{\sigma_z}{\delta z}\right). \tag{4}$$

The total number of operations for the full run is then given by

$$N_{op} = \frac{(aN_p + bN_g) \times T_{max}}{\delta t} \tag{5}$$

where a and b are the number of operations respectively per particle push/grid operation for one cycle. In a boosted frame traveling in the direction of the beam at velocity v_f, we have the following transformations,

$$\left\{ \begin{array}{lll} \sigma_z^* & = & A\gamma\sigma_z, \\ v_{r,b}^* & = & v_{r,b}/\left(A\gamma\right), \\ L^* & = & L/\gamma, \\ v_{r,e}^* & = & \gamma * v_{r,e}, \end{array} \right. \tag{6}$$

where $\beta = v_f/c$, $\gamma = 1/\sqrt{1-\beta^2}$, c is the speed of light, the star superscript refers to the quantities in the boosted frame, the b/e subscripts refer respectively to the beam/electrons, and

$$A = \frac{1-\beta^2}{1-\beta\beta_b}. \tag{7}$$

where $\beta_b = v_f/c$.

Still assuming that $\sigma_z^* << NL^*$, the time it takes for the beam to go across the accelerator is given by

$$T_{max}^* = \frac{NL^*}{(v_b^* + v_f)} \approx \frac{NL^*}{(v_b)} \tag{8}$$

in the boosted frame.

Combining Eq. (1) through (8), noting that $1 \le A < 2$, that α, a and b are invariant under the Lorentz transformation at fixed accuracy, and assuming that $\sigma_z < L^*$, one finds that the number of operations in the boosted frame is given approximately by

$$N_{op}^* \approx \frac{N_{op}}{\gamma^2} \tag{9}$$

since $v_b/\left(v_b^* + v_f\right)$ is of order unity.

As an example, let us consider the parameters of the Large Hadron Collider in the laboratory frame

$$\left\{ \begin{array}{lll} \sigma_z & \approx & 7.\text{cm}, \\ L & \approx & 107.\text{m}, \end{array} \right. \tag{10}$$

and in a boosted frame with $\gamma = \sqrt{1000}$

$$\left\{ \begin{array}{lll} \sigma_z^* & \approx & 4.42\text{m}, \\ L^* & \approx & 3.38\text{m}, \end{array} \right. \tag{11}$$

where L is the length of one FODO cell in the laboratory frame. According to (9), the calculation in the boosted frame will require about three orders of magnitude less computer operations than in the laboratory frame, which is similar to the savings obtained with the use of the quasi-static mode [17].

Relationship with the savings of the quasi-static mode In order to provide a more intuitive understanding of the relationship between the savings obtained in the quasistatic mode and the one obtained by calculating in the boosted frame in full self-consistent mode, we provide diagrams in Fig.4 and 5. Figure 4 shows diagrams of three events (A,B,C) in the laboratory frame and in the boosted frame. Event A is the emission of one electron at the wall, coinciding with the passage of the head of the pulse. Event B is the coincidence of the center of the bunch and the emitted electron. Event C is the electron hitting the tail of the bunch. These events involve each only one pair $\{z, t\}$ and thus transform each into a unique pair of $\{z^*, t^*\}$ in the boosted frame, i.e. these events are invariant through a Lorentz transformation along z. Figure 5 shows diagrams for three of each of these events in both calculation frames. It is interesting to note that the three electrons and the three bunches which are well separated in space and

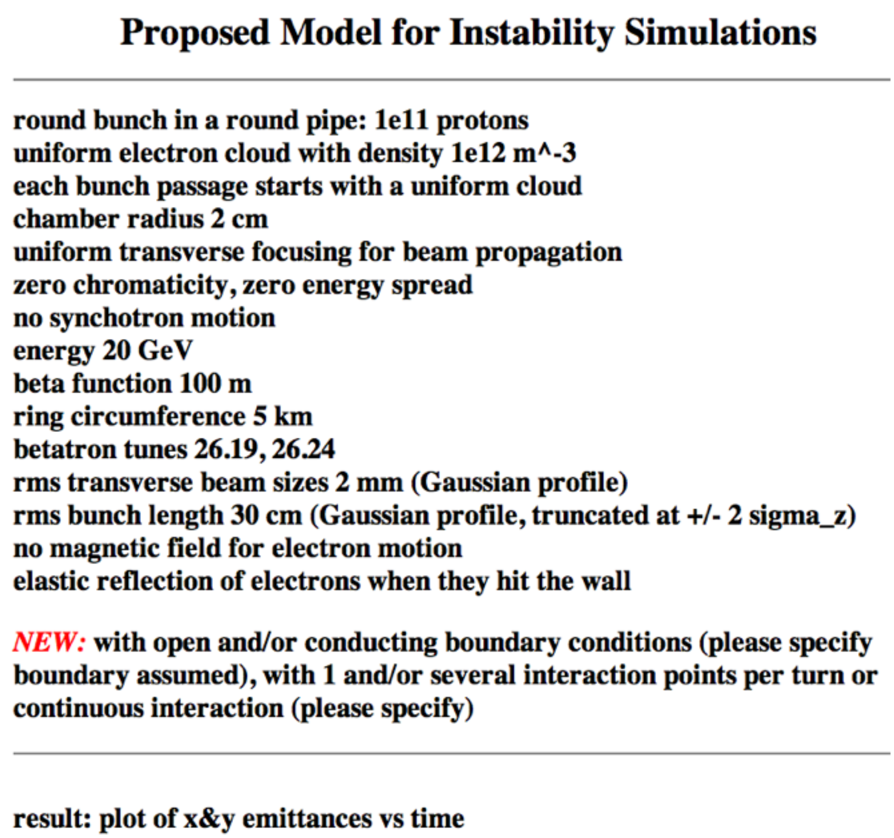

Figure 2: List of parameters proposed for single bunch instability benchmarking at CERN[19].

time in the laboratory frame collapse to very close locations in the boosted frame. The quasi-static approximation assumes that, for a given event, the electrons and the bunch do not evolve but are just translated by $z - V_b t$. This corresponds to the fact that, in the boosted frame, these electrons and bunches fall within a small volume. Thus, where the quasi-static approximation bridges the disparities of space and time scales in the laboratory frame, it is not needed in the boosted frame where those disparities vanish, and where the full self-consistent approach, which involves no approximation to the physics, can be applied at no additional cost.

Application to rings The application to rings will involve an additional complication since it calls for the use of a rotating frame, which is not an inertial frame. However, methods have been developed to treat these mathematical transformations within the framework of special relativity [20]. More work is needed however before obtaining a coherent numerical scheme. Meanwhile, we plan to apply this technique to rings anyway by substituting linear mockups where the direction of bends could be alternated so that each FODO cell is effectively a chicane, or by altering the physics of the particles to account for the leading order effects of curvature in the "linearized" ring [21].

CONCLUSION

We have developed a three-dimensional self-consistent code suite which includes advanced numerical methods, allowing the modeling of configurations which were out of reach with previously available tools. Benchmarking against the HCX experiment has provided some very good qualitative and quantitative agreements, and is being pursued actively in order to fully validate the code and the embodied physical model. We have also started applying the WARP-POSINST code to the modeling of electron cloud effects in high-energy physics accelerators. To this end, we have implemented a "quasi-static" mode of operation in WARP-POSINST, for comparison with other codes employing this approximation. We also showed that it is possible to model the system without any approximation for the same numerical cost as with using the quasi-static approximation, provided that the calculation is performed in a frame traveling at a specific relativistic velocity along the beam trajectory. The application to rings demands for additional work. Finally, we note that the result that we obtained for this configuration applies also to others like the modeling of Free Electron Lasers, laser plasma acceleration, plasma lenses, relativistic collision of nuclei, etc, and that a more general description of it (to be published elsewhere) is in preparation.

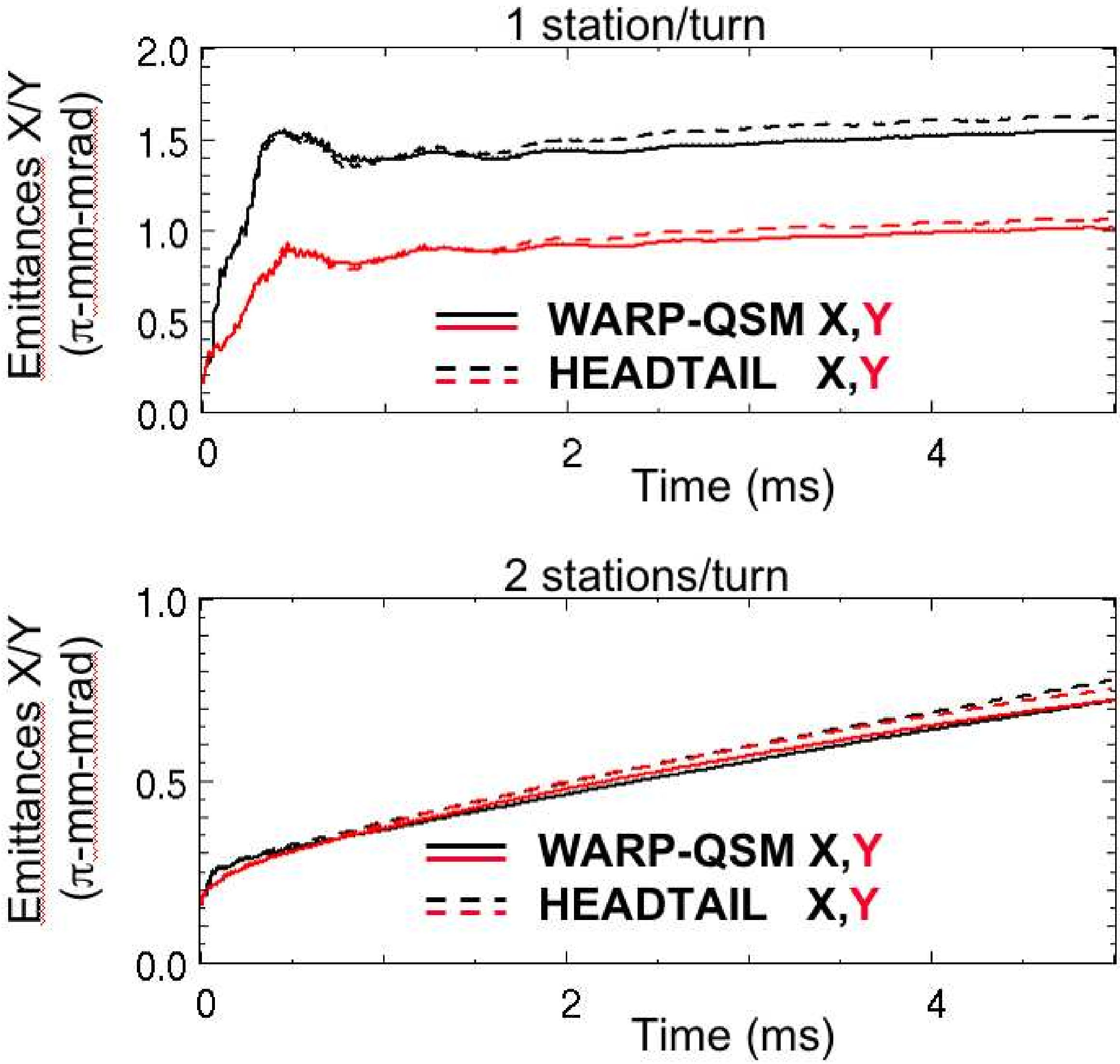

Figure 3: Comparison of the WARP-QSM and HEADTAIL's emittance histories for the CERN benchmarking[19] for 1 and 2 stations/turn.

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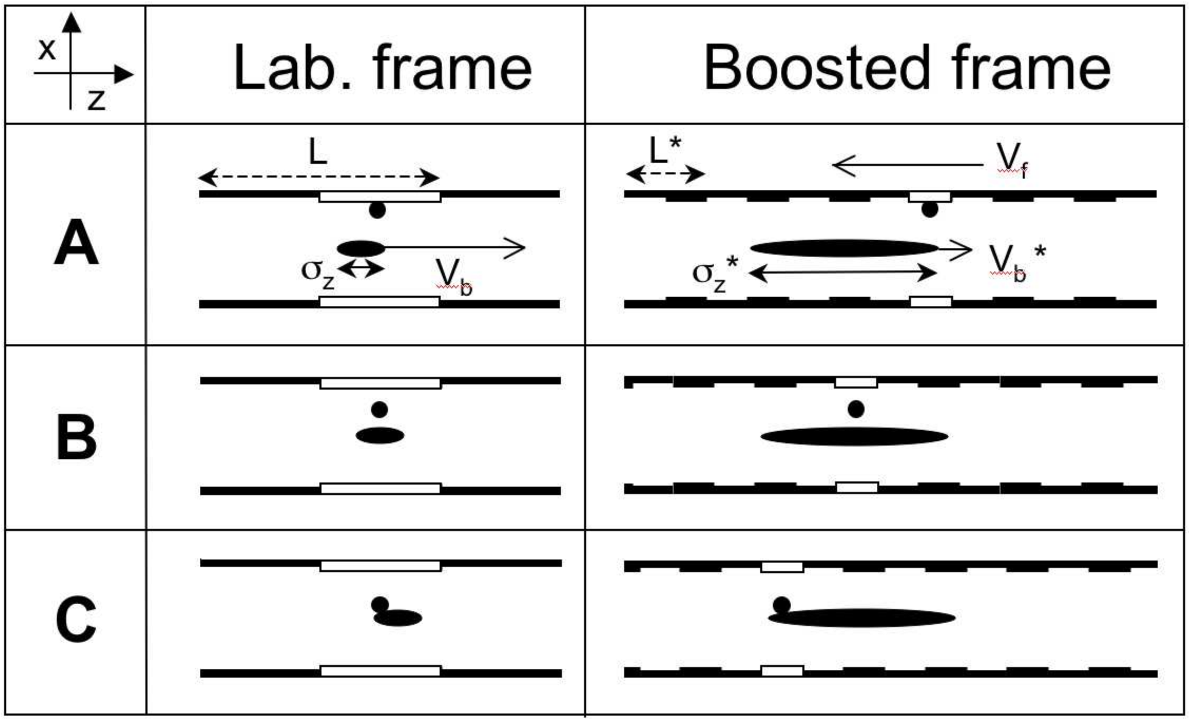

Figure 4: Diagram showing three events (A,B,C) in the laboratory and in the boosted frames.

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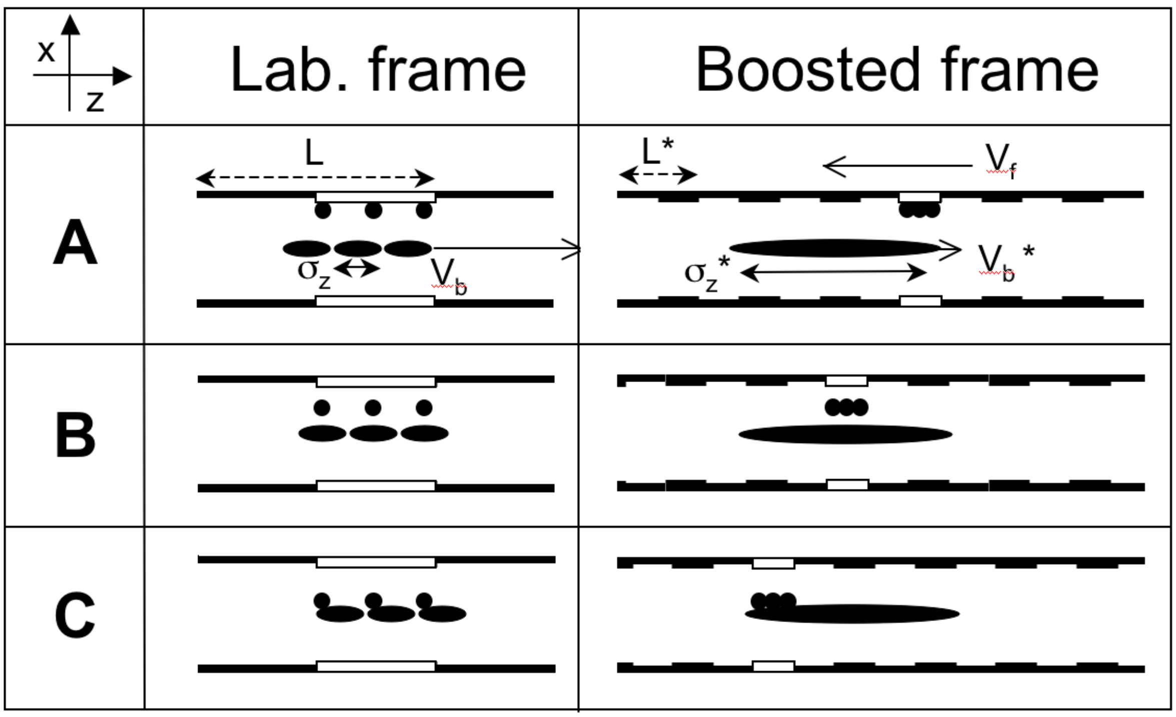

Figure 5: Diagram showing three×three events (A,B,C) in the laboratory and in the boosted frames.