Designing phase space with 6D manipulation

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Introduction

Phase space manipulation methods have been critical to the advancement of particle accelerators. A good example is the bunch compression techniques developed in the 90's, which significantly increased the beam's brightness and expanded the application of particle accelerators to XFEL and UED [1-4] in the 2000's. To overcome accelerator's limitations, phase space manipulation techniques have been continuously studied and improved, especially over the last decade [5-12]. However, future accelerator applications will require improvements in beam quality and accuracy beyond today's state of the art. To take phase space manipulation to the next level, more collective researches are required. 6D phase space manipulation is one of the keys to realizing future colliders, and it is therefore important to discuss it at SNOWMASS. This LOI advocates several research directions for 6D manipulation research rather than proposing specific methods.

Control of density distribution

The first research direction is the control of the beam's 3D spatial density distribution for the purpose of optimizing its charge distribution for applications. The simplest example is that of the focusing the beam to increase its density or to confine the beam. For example, colliders require very strong transverse focusing of the beam at the interaction point [13]. Likewise, an increased longitudinal density (i.e. an extremely short bunch) has been proposed for colliders [14]. In addition to increasing the density, the beam's spatial distribution can be used to control the self-fields of the bunch such as space-charge field and coherent synchrotron radiation. Control of the self-fields is critical for beam quality preservation and applications using these self-fields. For example, we can consider wakefield accelerators where the shaping of the drive bunch improves the transformer ratio which increases the energy extracted out of the drive beam [15]. On the other hand, shaping the witness beam's distribution can control the beam loading effect to help preserve the beam having a small energy spread while being efficiently accelerated [16].

In summary, the control of the beam density distribution helps to advance current accelerator performance by enabling higher- efficiency, energy, brightness, etc while simultaneously helping to realize future accelerators. Therefore, it is vital to the HEP community to support an active phase space manipulation research program.

Emittance repartitioning and exchange

The second research direction is the repartitioning and exchange of the 6D emittance. Contrary to emittance cooling techniques that reduce 6D emittance, the techniques we describe in this section are used to rearrange the 2D emittances (ε_x,ε_y,ε_z) within a fixed 6D emittance volume. The repartitioning and the exchange of emittance are another ways to optimize beam's emittances to its applications. Thus, they enable many accelerator applications.

Emittance repartitioning re-balances the emittance between one degree of freedom with another (e.g. between ε_x and ε_y) while keeping the 6D emittance preserved. Re-balancing can be used to generate an extremely small emittance in one degree of freedom by sacrificing an increase in another degree of freedom which is relatively less important. There are already on-going efforts to utilize asymmetric emittances (or "flat beams") for the linear collider and advanced acceleration technology development. Specifically, beamlines that create flat x-y emittances can be followed by an x-z emittance-exchange may provide a flat beam having a small vertical emittance which satisfies the emittance requirement of colliders like the ILC without a damping-ring [17]. Also, beam break-up in wakefield accelerator can be mitigated with a flat beam in a planar structure [18,19].

While repartitioning re-balances emittances, emittance-exchange (EEX) completely exchanges the emittances between two degrees of freedom by actually exchanging the phase spaces. EEX can be fruitfully combined with repartitioning techniques to further 6D phase space control. In addition, EEX can also allows the control (or measurement) of a target-axis from an easy-to-control axis. For example, EEX allows longitudinal shaping via an easily controlled transverse mask [12]. Likewise, preliminary studies indicate high-resolution longitudinal measurement may be possible with EEX [20].

While these methods have made significant progress in the last decade, x-z repartitioning is not demonstrated, and the performance improvement of x-y repartitioning and x-z exchange is necessary. Also, it is important to find more applications of these powerful techniques to exploit its full potential.

Multi-dimensional correlation control

The third research direction is the control of correlations. While the accelerator designer's and user's dream beams are fully decoupled Gaussian beams, or uniform ellipsoidal beams with linearized phase spaces, the real beam is always far from this ideal. Couplings between different degrees of freedom increase emittance, and make the beam challenging to control. Non-linearity in the phase space places intrinsic limitations on beam control.

Due to its complexity, most researches focuses on one degree of freedom. However, development of techniques to control and measure these multi-dimensional correlations will ultimately help to make the beam closer to its ideal shape. Better understanding on the multi-dimensional correlations that plague real beam distributions and finding methods to control them would be a critical step to realizing the ideal beam.

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