Surface Methods for Precision Accelerator Design and Virtual Prototyping of Accelerator Systems

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1 Background

The use of idealized models of beamline elements has been a widespread practice in accelerator simulation for decades. Input files typically contains terms like QUADRUPOLE, SEXTUPOLE, SBEND, etc., each of which represents a simple model of a beamline element. The simplest models omit fringe fields. Better models are based on a fringe field that is a step function. Unfortunately these models contain some terms that are infinite in the hard-edge limit. Dipole fringe fields can be represented approximately by thin-lens transformations at the magnet entrance and exit. A better approximation is to assume some smooth analytical form of fringe field. Using this and its derivatives the transfer map can be obtained through automatic differentiation or direct numerical integration of the equations for the reference trajectory and transfer map. Though this approach is an improvement over the simpler models, it is still an idealization and there is no reason to expect that all of its nonlinear properties will precisely match those of the physical beamline element.

The precise prediction of nonlinear dynamics in accelerators is best accomplished using surface methods [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. These methods have been known for many years but are not yet in widespread use in the accelerator community. The main idea of a surface method is to measure or numerically model the fields of a beamline element on a surface near but within the beam pipe. From there, the fields can be extrapolated inward and are represented by so-called generalized gradients. This is done so as to satisfy Maxwell's equations. In the process, measured or computed errors in the fields at the surface are damped, leading to an accurate representation of the generalized gradients in the beam region. The generalized gradients can then be used to compute realistic transfer maps.

2 Proposal

Computational tools based on surface methods have been implemented for a variety of beamline elements. Examples include straight elements with circular or elliptical beampipe, rf cavities, and dipole magnets with large sagitta. But these tools were not developed with a view toward reuse by others in the community, and they are not documented and maintained. This helps explain why surface methods have not been widely adopted despite the fact that they represent a major advance in realistic modeling of accelerators. We propose that, as part of the Snowmass process, members of the accelerator community share their

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experiences with one another on their development of, and use of, surface methods for accelerator modeling. They should discuss what is needed to further develop surface methods and to make them accessible and usable by members of the community, and they should develop a plan to do so. The execution of such a plan would result in a coherent set of well-maintained and documented computational tools that would enable surface methods to become part of the standard workflow for the design, analysis, and optimization of future accelerator facilities.

3 Impact

The use of surface methods will enable virtual prototyping of entire accelerator systems including their nonlinear properties. It will allow one to predict the precise nonlinear dynamics in a beamline *before* it is constructed and reduce the need for magnet shimming, the use of nonlinear correctors, etc. Also, one could couple beam dynamics modeling based on surface methods with high accuracy 3D electromagnetic modeling using parametric models, all within an optimization framework. This would make it possible to adjust the surfaces of electromagnetic components (magnets, accelerating cavities, etc.,) within a complete model of the beamline so that the resulting accelerator system had optimized and precisely predicted nonlinear properties.

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