Shape optimization and uncertainty quantification in radio frequency structures combined with beam dynamic simulations

Peter Arbenz, Computer Science Department, ETH Zurich
Andreas Adelmann, Paul Scherrer Institute, Villigen

The design of radio frequency (RF) structures is a complex optimization process. RF structures are elements in which charged particle are accelerated by an oscillating electric field which is obtained by exciting the proper eigenmode of the accelerator cavity. The eigenmodes as well as their frequencies are determined by the *shape* of the cavity.

The tuning of the motion of the (bunched) particles and the cavity eigenmodes is an extremely delicate task. Clearly, if the ‘pulse’ of the bunches entering the cavity is not in sync with the external accelerating field the performance of the accelerator degrades. Also the shape of the accelerating eigenmodes comes into play. An unfavorable mode may accelerate close to the surface where there are no particles or accelerate the particles unevenly leading to a smearing (blurring) of the bunches, and degrading the quality of the particle beam.

Higher order cavity modes can be excited by the external forces as well as by the particles themselves. It is therefore important to have the accelerating frequency well separated from the rest of the spectrum. In consequence, beam dynamics and RF design are very closely related and not independent.

We propose to develop a tool for the optimization of accelerating RF structures and beam dynamics, based on multi-objective PDE constrained optimization and uncertainty quantification (UQ).

In recent years we have successfully developed components that are the bases for this research project:

- FemaXX, a highly parallel eigensolver based on the Jacobi–Davidson algorithm, complemented by multilevel preconditioners for solving the correction equation.
- OPAL, a highly parallel and general particle tracker, featuring among others fast Poisson solvers for structured and unstructured domains with varying levels of detail.
- opt-pilot, a highly parallel, highly flexible multi-objective optimization framework.
- uq-pilot a script based non-intrusive UQ framework for particle accelerators.

We propose to combine these tools into a unique framework to optimize the shape of accelerator cavities, and at the same time optimize the most important beam dynamics parameters, leading to an optimal accelerator design with the least amount of time. For each of the many possible designs (potential shape) of a cavity, the optimizer will request the computation of the accelerating eigenmodes and corresponding eigenfrequencies and the tracking of particles traveling through the accelerator. This is evidently an extremely large scale computation. We anticipate load balancing issues among the many thousands compute cores that will be involved in such a computation because of the varying hardware resources the different components require.

In the design of particle accelerators, uncertainties originating from the used models as well as from manufacturing processes due to the limited accuracies. In this thesis we propose to use non-intrusive UQ techniques in order to quantify uncertainties, arising in the design and production process.

The proposed research will extend our capabilities of solving very large scale multi-objective optimization problems. This research will be immediately applied to the existing PSI accelerators, and to planed novel accelerators and accelerator concepts.