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Ion implanter beam optics design using global optimization techniques

Bo Vanderberg[1] · **Steve Drummond**[1] · **Joseph Valinski**[1]

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Abstract

We explore a design method for a bending dipole magnet part of an ion implanter beamline using a genetic algorithm optimization technique, with the goal of maximizing beam utilization and quality while staying within constraints. The genetic algorithm utilizes a fully parametrized geometry and a fitness function using maximum norm metrics. Measurements on a magnet designed and built using parameters obtained from the optimization demonstrate an improvement in utilization, in-line with expectations. The methodology, when applicable, appears promising as a general method to optimize optics designs.

Introduction

When designing components of the optical train of an ion implanter beamline, the methodology comprises defining desired beam properties, selecting the types of optical components, a combination of first- and second-order optics modeling using analytical or numerical models, and subsequently, ion beam modeling using field and ray-tracing solvers [1]. The design goal is typically to optimize implanter operation and performance parameters, such as ion beam transmission and angle distribution, while staying within practical constraints and compliance to design standards. Typical examples of design standards include size and weight of optical components, as well as clear access to the components of an optical assembly for ease of maintenance, for example. Such an optimization needs to start with a judicial choice of dimensions and parameters for an initial design, either based on experience or by evolving a previous design.

In this study, we explore applying modern global optimization techniques to beam optics design, made feasible by the progress in computation speed of modern workstations. Global optimization eliminates the need for an initial candidate design and is more likely to avoid local optima in the design parameter space. More specifically, we are applying global optimization to tailor the beam current density or flux distribution after a point-to-parallel dipole, or corrector, magnet. A typical hybrid scan ion implantation system is shown in Fig. 1, where the primary purpose of the corrector magnet is to parallelize divergent ribbons from a vertex into a parallel ribbon suitable for angle-controlled implant.

In Axcelis' Purion® H [2], the ribbon comprises a scanned spot beam, and the flux distribution of the parallelized ribbon is controlled using variable beam scan speed. Since the ion implantation process typically requires uniform dose, the scan speed correction aims at beam uniformity correction, which can require sophisticated algorithms, especially since high current spot beams can have aberrated current density distributions and have finite width [3].

An additional aspect of this scanned spot beam correction is that the utilization of the scanned beam, defined as the ratio of beam-on-wafer to total beam current, is < 100%, since the scanned spot beam needs to be scanned beyond the edges of the wafer in the so-called over-scanning, to ensure that each point on the wafer sees the same spot beam. The width of over-scan depends on the width of the spot beam, and utilization drops as spot beams get wider. One means to keep utilization high with wide beams is to tailor the flux distribution of the scanned beam to be approximately parabolic over the wafer, as illustrated in Fig. 2.

With a parabolic beam current density at constant scan speed and taking the width of the spot beam into account while correcting for uniformity, the dwell time of the spot beam during beam scanning is gradually decreased with the spot beam distance from the center of the wafer, such that the time-averaged dose over the wafer is uniform.

✉ Bo Vanderberg
Bo.Vanderberg@axcelis.com

[1] Axcelis Technologies, Inc., 108 Cherry Hill Drive, Beverly, MA 01915, USA

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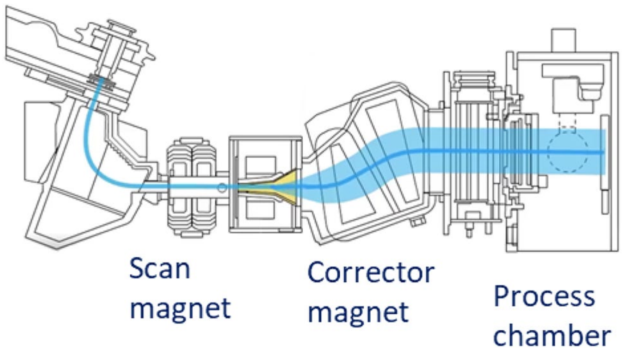

Fig. 1 Overview of the Axcelis Purion® H hybrid scan high current beam line, where a mass resolved spot beam is scanned into a divergent beam via a scan magnet. After the scanning magnet, the divergent beam appears to originate from a vertex, and the beam is subsequently parallelized by a corrector magnet focusing the vertex to infinity

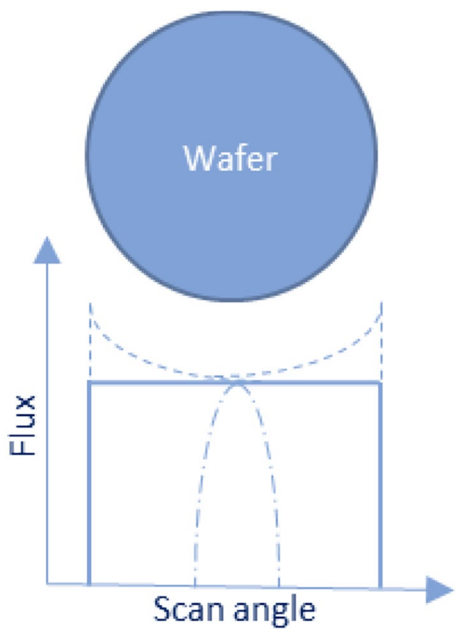

Fig. 2 Flux distribution of the scanned beam for constant scan speed (dashed line) and with corrected scan waveform (solid) for a spot beam with finite width (dotted-dashed line)

Since the dwell time of the beam in the over-scan region is thus minimized, utilization and productivity of the ion implanter can be increased significantly [4]. The challenge with this method lies in designing point-to-parallel optics of the corrector magnet, thus maintaining parallelism, while maintaining a desired flux distribution of a scanned spot beam at constant beam scan speed. We are here applying global optimization using a genetic algorithm [5] to find an optics solution with desired parallelism and flux distribution.

Model description

Setting up a genetic algorithm requires a parameter space with a cost or fitness function to be optimized. The parameter space here includes dimensions of a fully parametrized geometry, where the shape of the corrector magnet is expressed via coordinates of edges and corners, and coil currents exciting the magnet. The two coil currents are for each of the s-bend dipole used on Purion® H (Fig. 1), and the shapes of the pole pieces are defined using eight curved pole edges, four for each dipole, two for each pole edge, with one of the two points on each pole edge arc residing on the optical skeleton of the beamline, the trajectory of the centroid of the unscanned ion beam shown as a thick line in Fig. 1. These parameters are for cost and reliability reasons constrained to size and power limits: the maximum lateral width of each dipole, for example, cannot exceed the maximum width of a fully scanned beam plus two pole gap widths, thereby minimizing the weight and cost of the magnet assembly, and maximum permissible coil current densities based on cooling limitations, here 3.5 A/mm^2 average coil current density including insulation and cooling water channels, based on supplier recommendations. The pole pieces are created in a CAD modeling program by joining the edges to form a flat or non-indexed surface, and the surface is subsequently swept normal to the surface to create a pole piece volume half the width of the pole gap. The remaining magnet is then modeled by further sweeping pole piece surfaces to create pole roots around which coils are wound, and last, steel blocks are closing a magnetic circuit to join the upper and lower pole piece and root volumes.

One set of these parameters defines one member of the population of candidate designs to be optimized. We are using a commercial genetic algorithm package for optimization [6], and the algorithm starts by setting up a random population of 10^3 candidate geometries and currents throughout the parameter space. Each of the candidates is evaluated within one generation, by solving first the magnetic field distribution in the modeled corrector magnet, then ray-tracing ion beam trajectories through the modeled corrector magnet using a commercial field solving package [7], and finally extracting ion beam parameters from trajectory data to quantify a fitness function across the population. The fitness function is compiled in vector form similar to pareto ranking, using maximum absolute values as metrics in discrete ranges or “bins.” Fitnesses of the members of the population are then sorted in each generation first by horizontal parallelism, then rms deviation from the desired parabolic flux density distribution, and finally other desirable beam properties such as vertical beam angle uniformity. This is because the primary function of the corrector magnet is to parallelize, and maximum non-parallelism is given priority over subsequent beam properties. For this calculation, the desired flux density was chosen to be parabolic with a 30% increase in flux at the edge of the wafer.

The algorithm filters the population and keeps 5% of each generation (so-called "elites") as best candidates, where "best" means having the highest parallelism, then closest flux distribution to desired, most uniform vertical angles and so on. 85% of the remaining population then has their individual design parameters of champions arithmetically averaged in the so-called "cross-over" for next generations (or "children"), and 10% of the population receives random parameter changes ("mutations"). Figure 3 shows a high-level flow chart of the algorithm. The subprocesses to the right are computationally parallelized since the fitness of each member of a population can be computed independently. With today's computational speed of modern workstations and the possibility of parallelizing computations for each individual in the population, the execution time for a full optimization is of the order of 10^2 h, time-consuming but not prohibitively long.

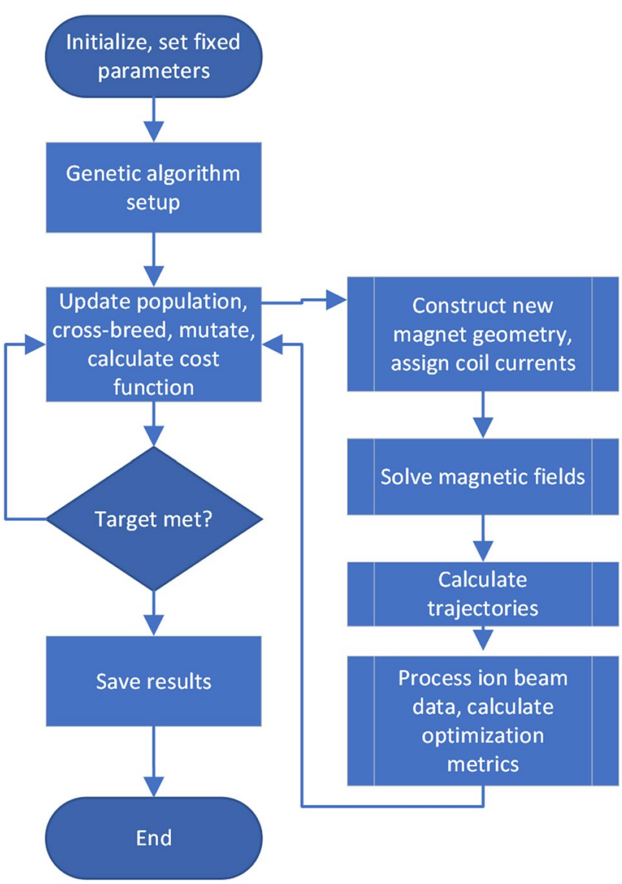

Fig. 3 Flowchart for a genetic algorithm optimizing the design of a corrector magnet

Results and comparison to measurements

The algorithm appeared to converge after 25 generations of 10^3 individuals in the population with 3 champion individuals with equivalent parallelism and flux density, one of which is shown in Fig. 4. The predicted horizontal angle non-uniformity or parallelism of this solution is within +/ 0.1 degrees across the width of a 300 mm wafer. The dimensions and currents calculated were then used to design a full prototype corrector magnet. After procurement, the magnet was integrated into a Purion® H beamline. Beam parallelism and current density profiles were measured in the wafer plane and compared to the models. The beam current density and horizontal parallelism measurements were performed with a fully over-scanned, constant scan speed 20 keV, 15.7 mA $^{40}Ar^{+}$ spot beam. In Fig. 4, the agreement between model and measurement flux distribution is fair, given that Purion H is a full optical system with beam emittance change between elements, whereas the modeled corrector used idealized emittances for injection into the corrector during ray tracing. Nevertheless, the flux density distribution achieved at horizontal parallelism better than ± 0.1 degrees typically resulted in an increase in corrected beam current on the wafer, in-line with expectations: as an example, for the test beam in Fig. 4, the constant scan speed on-wafer current read 8.7 mA, and the corrected 11.8 mA, a significant improvement in productivity.

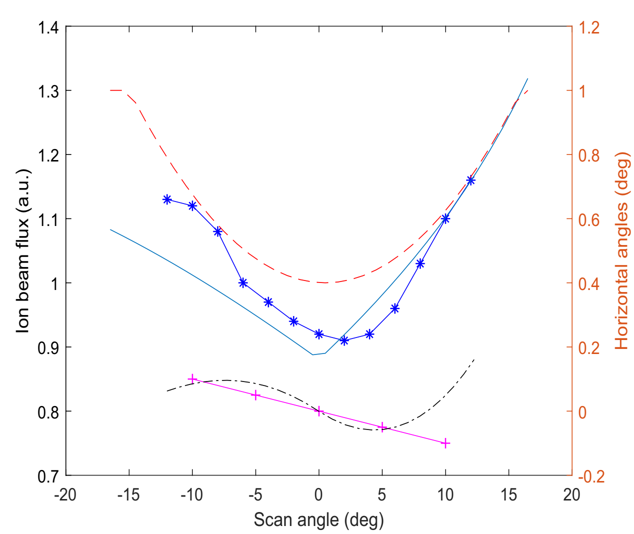

Fig. 4 Comparison of desired (dashed line), model optimized (solid), and measured flux distribution (solid with stars) on a prototype corrector magnet, and horizontal parallelism (predicted = dot-dashed, measured = solid with crosses)

Summary

We have presented an optimization method for the design of a bending magnet using a genetic algorithm, to find a solution for point-to-parallel optics with a prescribed beam current density post-magnet. Measurements affirm the increase in beam on wafer while maintaining parallelism. The methodology, when applicable, appears promising as a general method to optimize the design of beam optics.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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