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SINGLE OBJECTIVE GENETIC OPTIMIZATION OF AN 85% EFFICIENT KLYSTRON*

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Abstract

Overall efficiency is a critical priority for the next generation of particle accelerators as they push to higher and higher energies. In a large machine, even a small increase in efficiency of any subsystem or component can lead to a significant operational cost savings. The Core Oscillation Method (COM) and Bunch-Align-Compress (BAC) method have recently emerged as a means to greatly increase the efficiency of the klystron RF source for particle accelerators. The COM and BAC methods both work by uniquely tuning klystron cavity frequencies such that more particles from the anti-bunch are swept into the bunch before power is extracted from the beam. The single objective genetic algorithm from Sandia National Laboratory's Dakota optimization library is used to optimize both COM and BAC based klystron designs to achieve 85% efficiency. The COM and BAC methods are discussed. Use of the Dakota optimization algorithm library from Sandia National Laboratory is discussed. Scalability of the optimization approach to High Performance Computing (HPC) is discussed. The optimization approach and optimization results are presented.

INTRODUCTION

Klystrons have been the primary RF source for accelerators for as long as they have been used. There are multiple reasons for this. They have high gain, low phase noise, moderately high efficiency, and a low $/Watt cost. The primary deficiency of klystrons however is their moderate electronic efficiency, for which the empirical relation [1] is:

$$\eta_{max} = 78 - 16\,\mu K, \quad (1)$$

where K is the beam perveance ($I_o V^{-3/2}$) provides a realistic estimate. Achieving high efficiency (>70%) in a high power klystron requires either relativistic beam voltages or a combination of many lower voltage beams, which significantly increases complexity and cost. Efficiencies of commercial klystrons are typically 40-60%, a range that has seen little change for several decades.

Somewhat surprisingly however, given the technology maturation one would expect for a device invented more than sixty years ago, a new design method for klystrons has been recently proposed (Guzilov 2014 [2]). The author of this work refers to this new technique as the "BAC" method and shows a path for obtaining significantly higher efficiencies than obtained in current klystrons. A complimentary method, "COM" [3], is also investigated as a means for increasing efficiency.

Using the COM and BAC techniques we use modern optimization techniques to design a klystron with the goal of exceeding 85% efficiency. The klystron is designed to operate at 1.3 GHz and provide 100 kW of output power.

SIMULATION SOFTWARE AND TOOLS

Several simulation and optimization tools were used. The key programs used are outlined here.

Dakota Optimization Library

Dakota [4] is a powerful optimization library developed by Sandia National Laboratory. The library consists of many algorithms including the Single Objective Genetic Algorithm (SOGA) and the Asynchronous Pattern Search (APS). All optimizations in this paper used the SOGA for global optimization or the APS for local optimization. Dakota is typically run from the command line but we ran Dakota using the Galaxy Simulation Builder framework.

Galaxy Simulation Builder

Galaxy Simulation Builder (GSB) [5] is a framework developed by the Air Force Research Laboratory (AFRL) for building simulation pipelines and optimizations. The software was used exclusively for the klystron optimizations presented here. The optimizations can be performed without the use of GSB, but the GSB framework facilitates the process of running Dakota. GSB also streamlines the process of executing large optimizations using High Performance Computing (HPC) supercomputers. Setting up optimizations on Dakota and running optimizations on supercomputers is more time consuming without using GSB as an interface.

The GSB GUI is shown in Figure 1. The GUI works based on a drag-and-drop approach to building modules that wrap the command line interface of different simulation tools.

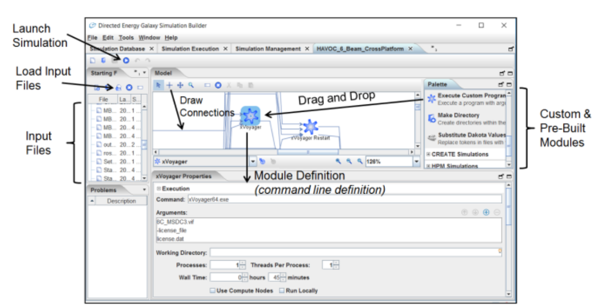

Figure 1: Galaxy Simulation Builder GUI.

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Klystron Simulation Codes

Several codes exist for simulating klystrons. AJDISK [6] is a fast 1D code from SLAC National Accelerator Laboratory that can simulate the high efficiency klystron designs being considered in 20 seconds to 3 minutes depending on the desired accuracy. Since AJDISK designs can be iterated quickly it is used as the primary workhorse for global optimization using the genetic algorithm. Tesla [7] is a 2.5D code from the Naval Research Laboratory (NRL) that can model the radial variation in the beam. The code is more accurate than AJDISK but takes approximately 10 to 30 minutes per iteration depending on the required accuracy. Therefore AJDISK was used for the large global optimization that required thousands of iterations and the results were used as the starting point for a more accurate local optimization which only required hundreds of iterations using Tesla. In summary, AJDISK is used to find the approximate location of the global minima using global optimization and Tesla is used to more accurately determine the global minima using a local optimization routine in the vicinity of the global minima found using AJDISK. KlyC [8] is a new 2D code from CERN for simulating klystrons. The code was not used in our optimization efforts but it was used to benchmark the AJDISK and Tesla results as shown in Figure 2. KlyC has a similar execution time to AJDISK. We plan to use KlyC more as we become familiar with it.

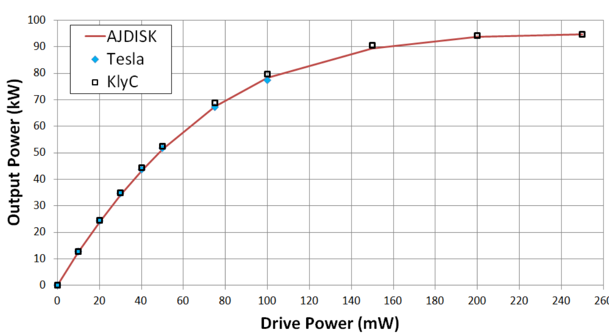

Figure 2: Comparison of different klystron simulation codes.

OPTIMIZATION ALGORITHMS

Single Objective Genetic Algorithm

The Single Objective Genetic Algorithm (SOGA) is a powerful global optimization routine available within the Dakota optimization library. It is the primary optimization method used to optimize the BAC and COM klystron designs.

Global optimization routines are ideal for exploring large design spaces that have more than one local minima. Several optimizations were run to optimize the BAC and COM designs. The largest optimization was for the BAC klystron, consisting of 13 variables: 11 cavity frequencies, the location of the output cavity, and the external Q of the output cavity.

The single objective genetic algorithm consists of several steps. The optimization starts with a set number of solutions, known as a "population", generated by selecting input variables ("genes") scattered throughout the parameter space. Our optimizations had a population size of 50. "Parents" within the population are "selected" based on "fitness" which is determined for the klystron optimization based on which "parents" have the highest efficiency. A weighted penalty to fitness is also applied for reflected and slow electrons. Once parents have been selected for "reproduction", "children" for the next "generation" are produced by copying some of the parents "chromosome" (the string of input variables) up to a "crossover" point. Some genes, or input variables, can also be "mutated" (randomly altered). New generations are then iterated until the population converges on a solution that produces the best answer, or fitness within some convergence criteria.

Asynchronous Pattern Search

The SOGA method in Dakota typically requires thousands of simulations to converge. The time the optimization takes is therefore directly dependent on the time each simulation takes to execute. To facilitate faster optimization, we run 1D AJDISK which is fast but slightly less accurate than 2D Tesla or KlyC simulations. This approach gives a solution that AJDISK believes is the global minima but is in error by the difference between the 2D solution and 1D AJDISK solution. To remedy this the 1D solution is used as the starting point of a local optimization using Tesla to find the true global minima.

The Asynchronous Pattern Search (APS) in Dakota is used for local optimization. For a two variable optimization a crosshair pattern/template can be imagined where the centre of the crosshair is the starting point solution and the four periphery points of the crosshair are solutions evaluated at some plus/minus offset from the centre. The optimization proceeds by selecting the new best solution. If the best solution is one of the periphery points the crosshair is re-centered at that solution. If the best solution is the centre of the crosshair, the crosshair stencil is reduced in size such that the new periphery solutions will have a smaller offset from the centre solution. These steps are iterated until the input variables change by less than a fixed tolerance defined by the user.

LARGE SCALE HPC OPTIMIZATION

GSB in combination with Dakota is capable of running very large optimizations. The klystron optimizations in this paper were all run on smaller machines but it is possible to run even larger problems using High Performance Computing (HPC) super computers. As a short diversion we provide a case study of an HPC optimized depressed collector to show the capabilities of GSB. The depressed collector in this study was simulated using MICHELLE [9], a 3D geometry, and more than a dozen variables. The collector was optimized simultaneously against 7 input power levels. On a single CPU it was calculated that the optimization would have taken more than 4 years. On the supercomputer the optimization took less than 24 hours. A scatter plot of the best results is shown in Figure 3. The goal of the optimization was to maximize efficiency while minimizing particles returned to the circuit. The results have been normalized to the best case design that existed before the optimization was run.

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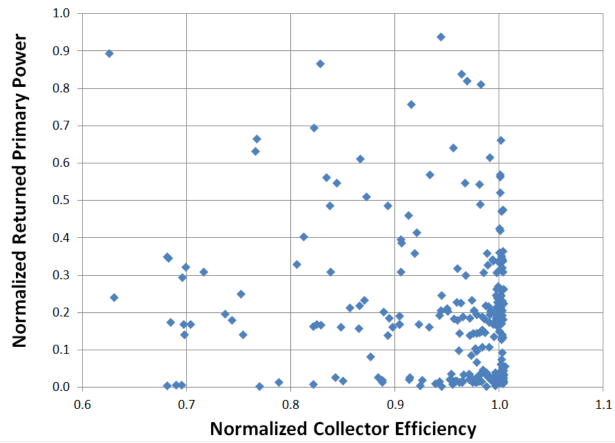

Figure 3: Optimization of a depressed collector.

HIGH EFFICIENCY KLYSTRON DESIGN

The BAC and COM techniques were used as the basis of our optimizations. Here we discuss an overview of the two techniques.

Core Oscillation Method

The Core Oscillation Method (COM) is a method of tuning cavity position and klystron cavity frequencies to maximize efficiency. This design approach generates a klystron that is longer than a BAC tuned klystron but uses fewer cavities. The cavities in this method are spaced approximately a half plasma wavelength apart as shown in the Applegate diagram in Figure 4. Since the space charge forces are stronger in the core (the middle of the bunch), electrons furthest from the core continue to move towards the centre of the bunch even after the core bunch begins de-bunching. This can be seen in Figure 4. By repeating/oscillating the core through several bunching and de-bunching cycles the outermost electrons can eventually join the core bunch. This leads to a long klystron design with high efficiency. The klystron cavity frequencies are tuned high with respect to the operating frequency and can be optimized manually or by using Dakota.

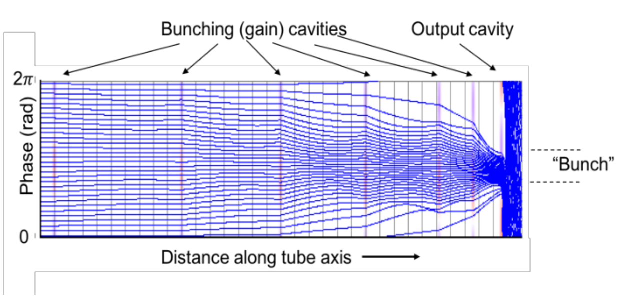

Figure 4: Core Oscillation Method based klystron design.

Bunch-Align-Compress Method

The Bunch-Align-Compress (BAC) method can be used to generate a klystron of similar efficiency to that achieved using COM in a shorter distance at the expense of using more cavities. The BAC method effectively replaces a single core oscillation in the COM approach with a triplet of cavities as shown in Figure 5. In the simplest case the BAC approach therefore needs three times as many cavities as the COM technique. The bunching cavity in the BAC technique is analogous to the bunching cavity in the COM approach. The alignment cavity aligns electron velocities in the core such that the bunching cavity can bunch electrons much more quickly without any electrons overtaking each other. The collection cavity operates at the second harmonic to sweep particles in the anti-bunch into the main bunch which is analogous to what the outer electrons do in the COM method but in a much shorter distance. The three cavities in the triplet can be spaced very closely together. The tuning of each cavity in the triplet is a function of several factors including the spacing between the cavities. The complication of optimizing so many cavity frequencies is ideally suited for the SOGA optimization technique.

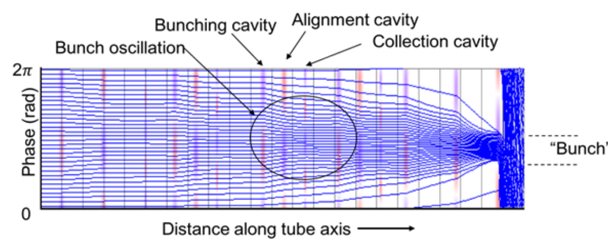

Figure 5: Bunch Align Compress based klystron design.

KLYSTRON OPTIMIZATION AND RESULTS

Both the COM and BAC klystron designs were optimized to maximize efficiency and minimize reflected particles. The COM design was optimized first using the SOGA method. Each core oscillation was then manually replaced with a BAC triplet of cavities one core oscillation at a time. The BAC design generated in this way was used as the starting point for SOGA optimization of the BAC design.

COM Optimization

The COM design was conducted first. The input and output cavity frequencies were fixed to the operating frequency. One cavity was added at a time and the cavity position and frequency were decided visually by the engineer such that cavity spacing was on the order of a half plasma wavelength and that a core oscillation could be observed. The number of core oscillations was increased until the efficiency reached approximately 85%. This design was used as the starting point to the SOGA optimization. The cavity to cavity spacing was allowed to vary for each core oscillation by a fixed amount. The cavity frequencies, except for the input were allowed to vary by a fixed amount. Finally the external Q of the output cavity was allowed to vary by a fixed amount.

BAC Optimization

The BAC design was based on the optimized COM design by replacing each core oscillation in the COM design with a cavity triplet one at a time. The cavity frequencies of the triplet were manually optimized to produce the same or similar results to those achieved in the COM design. This design was the starting point for the BAC based SOGA optimization. The SOGA optimization left the

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cavity positions fixed and optimized the cavity frequencies within some range of their starting values. The external Q and position of the output cavity were also optimized at the same time as the cavity frequencies. The range over which values was allowed to vary was fairly broad with the expectation that the SOGA method would find a true global minima.

Results

Several SOGA runs were completed. The best result of each run is shown in Figure 6. These results show the expected trend that efficiency increases with circuit length and that the BAC design is shorter than the COM design. Both designs achieved greater than the target efficiency of 85%.

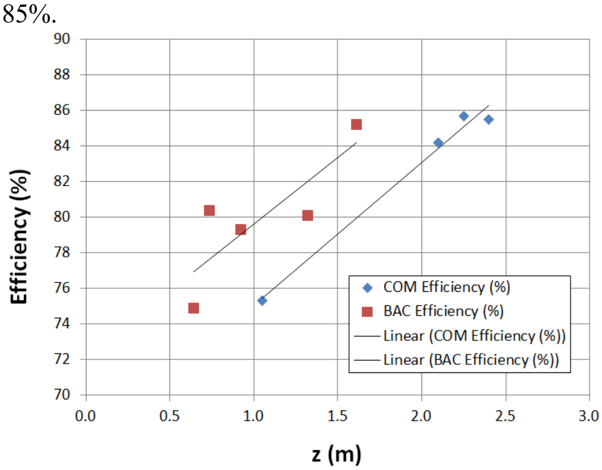

Figure 6: Various SOGA optimizations for both BAC and COM based klystron designs.

The optimized results based on AJDISK were translated for use in Tesla. The first curve in Figure 7 shows the output power reported by Tesla using the optimal AJDISK results. The second curve in Figure 7 shows the results after a local optimization was run using Tesla directly assuming the AJDISK result as a starting point.

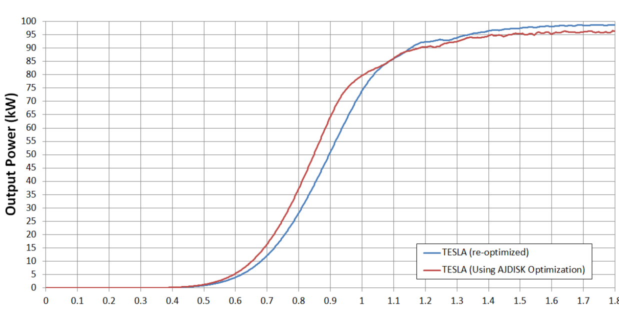

Figure 7: Klystron output power reported by Tesla using AJDISK based SOGA optimization results and Tesla based optimization results.

Next the gun was modelled by Calabazas Creek Research (CCR) as shown in Figure 8. The magnetic field was ramped in the output structure to confine the strong bunching forces in the beam as shown in Figure 9. Using these more realistic conditions for the beam the design was run through final optimization.

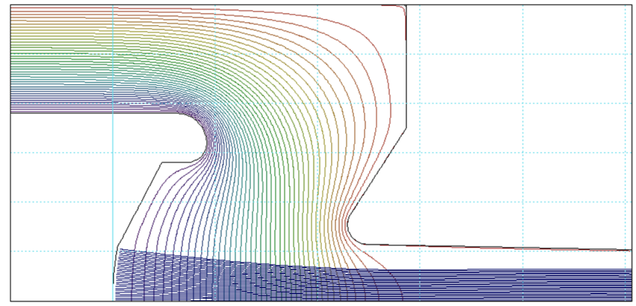

Figure 8: Gun design.

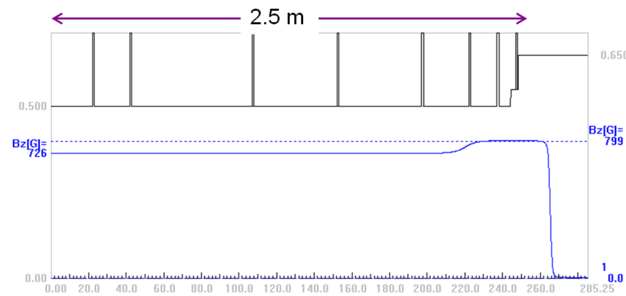

Figure 9: COM based klystron geometry and ramped magnetic field.

The final BAC optimized design achieved 84% efficiency and the final COM optimized design achieved 87% efficiency. To meet the design objective of 85% efficiency, CCR designed a depressed collector for the BAC klystron. The design is shown in Figure 10 and increased the overall BAC based klystron efficiency to 87%. The final BAC design consisted of 15 cavities and the final COM design consisted of 8 cavities.

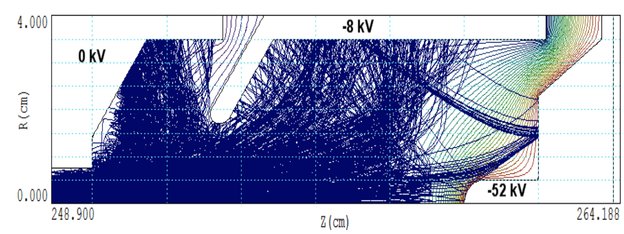

Figure 10: Depressed collector design for BAC based klystron.

The COM based klystron will be used as the basis for the Phase II SBIR. The klystron length is longer than the BAC klystron but simpler from a manufacturing standpoint due to the fact that the design only requires 8 cavities. The efficiency from the optimization study was also higher for the COM design so a depressed collector will likely not be needed, further simplifying the manufacturing and reducing costs.

The final phase space of the COM design is shown in Figures 11 and 12 and a plot of the output power in Tesla is shown in Figure 13. A ripple is observed in the output power plot of Figure 13. The ripple is most likely due to reflected electrons as shown in Figure 12. This effect will be further studied and mitigated in the Phase II SBIR.

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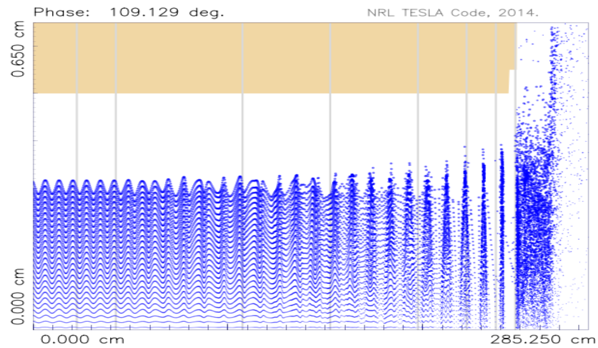

Figure 11: Particle phasespace in Tesla for the COM klystron design.

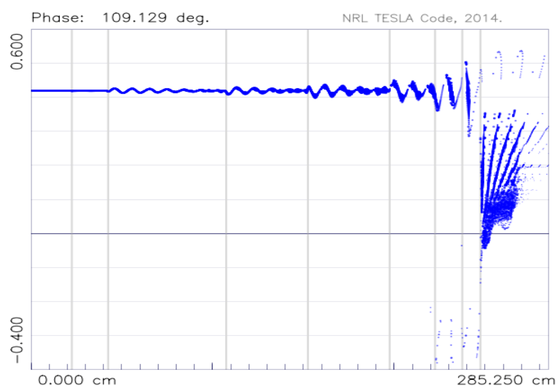

Figure 12: Velocity versus distance in Tesla for the COM klystron design.

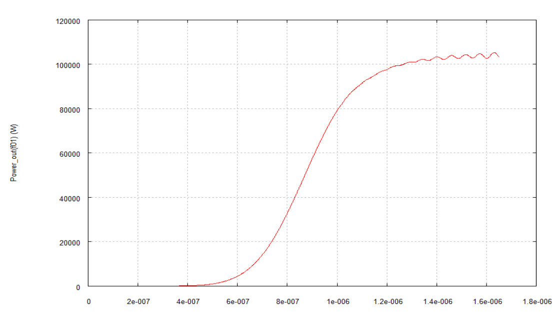

Figure 13: Output power versus time for the final COM based klystron design.

CONCLUSION

COM and BAC methods achieved 87% and 84% klystron efficiency respectively. The BAC klystron efficiency was increased to 87% with a depressed collector. The SOGA method under Dakota using Galaxy Simulation Builder was an integral part of achieving the high efficiency results. We empirically found that the ordering of the triplet achieved higher efficiency when ordered BCA as opposed to BAC.

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