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OPTIMISATION OF A GAS JET-BASED BEAM PROFILE MONITOR FOR HIGH INTENSITY ELECTRON BEAMS

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Abstract

A beam profile monitor using gas jet technology is being designed and manufactured at the Cockcroft Institute for high intensity electron beams. It generates a thin, supersonic gas sheet that traverses the beam at a 45-degree orientation and measures the beam-induced fluorescence interactions to produce a 2D beam profile image. The gas sheet acts similar to a scintillating screen, but remains non-invasive.

This contribution summarises the method developed towards optimising the injection of a gas jet monitor for the example use-case of the Hollow Electron Lens. A multi-objective genetic algorithm is used with a Monte-Carlo particle tracking simulation to optimise the geometric features of the jet injection chambers. The algorithm optimises for several key features of the jet that will improve it as a diagnostic tool. Specifically, at the point of interaction, the jet's density, uniformity and geometric dimensions are considered. The work developed in this contribution is not limited to diagnostics and can be expanded upon in other disciplines such as plasma wakefield gas injections.

INTRODUCTION

The Beam Gas Curtain (BGC) is a minimally invasive beam profile monitor that is suited to high intensity electron beams [1–3]. A 2D transverse profile is generated by imaging fluorescence photons produced by beam-gas interactions. A supersonic gas curtain is produced within the system to maximise the signal-to-noise ratio, and thereby minimising integration time and the footprint on the beam quality.

Due to the dynamic nature of the gas jet, the BGC avoids the heating issues of invasive diagnostics associated with high intensity and DC beams [1, 2, 4, 5]. In addition to this, it is also minimally invasive and can be continuously monitored during beam [1, 3].

The supersonic gas curtain is generated using the process of isentropic expansion for an underexpanded jet [6, 7]. It then undergoes formation through three chambers, separated by three skimmer devices. A skimmer physically skims the edge of the jet, removing off-momentum particles to produce a high density gradient between the jet and the surrounding background pressure of the chamber. These skimmer devices also shape and form the geometric dimensions of the gas curtain, which can have an effect on the beam profile image. Each chamber is pumped by individually dedicated Turbo Molecular Pumps (TMPs). This maintains a safe background pressure of 2×10^{-8} mbar in the beamline [3, 6].

An optimisation study has been performed in this contribution to improve the 3rd version of the BGC that is currently installed in the LHC. Version 4 is designed bespoke to the Hollow Electron Lens (HEL), intended as an upgrade to the LHC's collimation system [8]. The HEL design creates geometric limitations on the BGC device, requiring the injection length to be 294.94 mm to fit between the two LHC beamlines. Furthermore, the BGC must possess a longitudinal footprint less than 200 mm to be situated between two solenoid magnets. The optimisation study maximises the BGC's performance within these external limitations.

This work is also not limited to the BGC diagnostic injection. A general-purpose optimisation model using a Multi-Objective Genetic Algorithm (MOGA) has been developed [9]. The optimisation framework compares geometric gas jet designs and is highly adaptable to various gas jet applications. Specific requirements of gas injections for many conditions, such as plasma wakefield accelerators could be optimised to create a bespoke gas injection system using this simulation.

MONTE CARLO SIMULATION

Previously, a Monte-Carlo (MC) method-based simulation code has been developed to accurately model the jets behaviour as it propagates through the BGC [6, 10]. By generating a randomised swarm of particles and assigning various jet properties at the nozzle, the jet density and geometry can be derived at the point of interaction with the beam.

The MC simulation defines jet properties according to an ideal gas model undergoing calorically perfect isentropic expansion through a nozzle [7, 11]. It has been validated against experimental data in the past with good agreement [6]. Further developments with the code have been made to incorporate a dynamic background pressure for the optimisation study. The simulation computes the fraction of the jet that remains in a given chamber due to skimmer aperture size and relates it to the pumping speed. A simple mass flow rate calculation is shown in Eq. (1) and thereby Eq. (2).

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$$\dot{m}_{Jet\,loss} = \dot{m}_{Pumping\,speed} \tag{1}$$

$$\frac{\rho_{Jet\,loss} v A_{Jet\,loss}}{S} = \rho_{Background}\ , \tag{2}$$

where ρ is number density in $\#/\mathrm{m}^3$ of the jet and background chamber pressure respectively, v is jet velocity in m/s, $A_{Jet\,loss}$ is area of jet greater than the area of the skimmer orifice in m^2 and S is pumping speed in m^3/s.

The use of Eq. (2) provides an adaptive background pressure that is dependent on the injection geometry and jet. This modification is a key tool in giving realistic effects to changing skimmer geometry and is shown to predict a value of an appropriate significant figure. More computationally intense simulations such as MolFlow can be used to validate final optimum solutions for an improved background pressure prediction [12].

MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMISATION

To optimise the injection geometry, a Multi-Objective Genetic Algorithm (MOGA) was utilised. A MOGA simulates a “survival of the fittest” natural selection process that replicates traditional biological evolution [9]. The evolutionary algorithm used in this contribution is Non-dominated Sorting Genetic Algorithm (NSGA-II) [13]. The optimisation study takes the positions of the four skimmers along the axis of jet propagation as the input parameters to optimise. The parameter space is defined in Fig. 1.

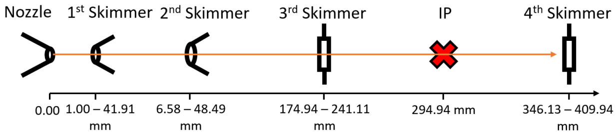

Figure 1: A schematic of the parameter space for skimmer positions along the X axis.

The MOGA is used to optimise for four output variables within an appropriate design space, as outlined: The average density of the jet at the Interaction Point (IP) is maximised, to provide a maximum photon yield and improved signal. The length of the gas curtain at the IP is maximised, to allow for larger beam sizes, such as those expected with the HEL [8], as well as account for beam jitter. The width of the gas curtain at the IP is minimised, to reduce the invasiveness of the system and reduce smearing effect of the profile image [14]. The density variation at the IP is minimised, to ensure a uniform measurement with no artefact resulting from the jet is present. These requirements for the BGC are also outlined within the HL-LHC BGC collaboration agreement between the University of Liverpool, CERN and GSI [15].

The MC simulation is also capable of taking various different input variables to optimise for, including alternative geometries, gas properties and skimmer configurations. For this contribution, only the outlined variables shall be optimised. This study uses Neon gas injected at 5 bars and four skimmers of orifice sizes 0.4 mm, 2 mm, 0.3x9 mm and 7x31 mm respectively.

This work was undertaken on Barkla, part of the High Performance Computing facilities at the University of Liverpool, UK.

OPTIMISATION RESULTS

The results below summarise over 100,000 unique geometric configurations of the multi-skimmer system for the BGC injection system.

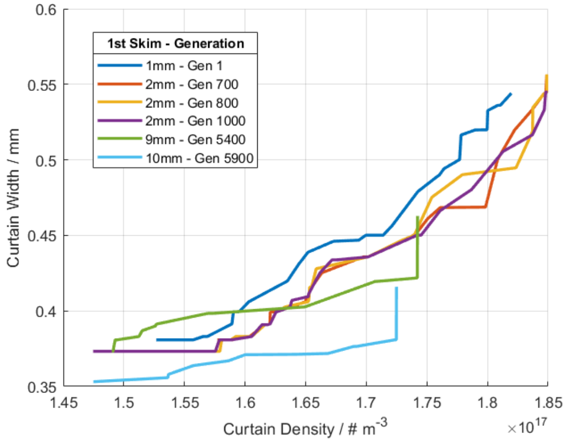

Figure 2: Evolution of MOGA pareto fronts over several 1st skimmer positions, comparing curtain density against width.

Figure 2 gives a brief description of the evolving pareto frontiers, which define the optimum solutions between two parameters. The curtain density should be maximised, whilst the width should be minimised, suggesting the optimum solution is in the bottom right corner of the figure. When compared against Fig. 3, it is clear how the global pareto front in red is a function of a range of individual generational pareto frontiers.

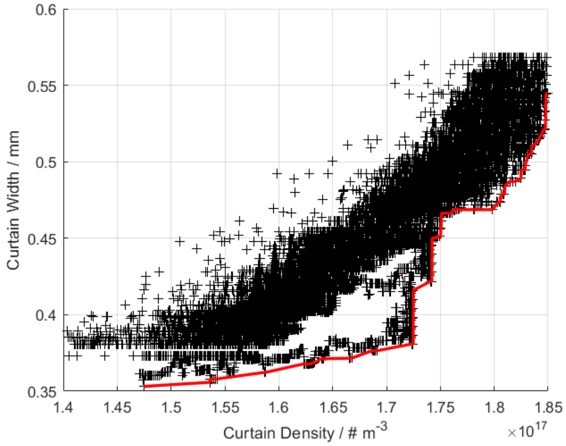

Figure 3: Global pareto front (red) of curtain density against width, shown relative to all solutions.

Figure 3 demonstrates the global pareto front with respect to all solutions in the design space. The large pareto frontier over the full range of data describes a versatile relationship between the two variables and highlights points of interest. One can utilise the vertical and horizontal segments to gain a large optimisation in one variable with very little change in the other.

Two regions are seen with a large white gap in the data. This is a result of the first skimmer being optimised via a grid search, due to the large computational power required for this step in the MC simulation. It was deemed acceptable to use the grid search in tandem with the MOGA optimisation to gain a full understanding. The gaps in the data are a result of the one-millimetre search intervals.

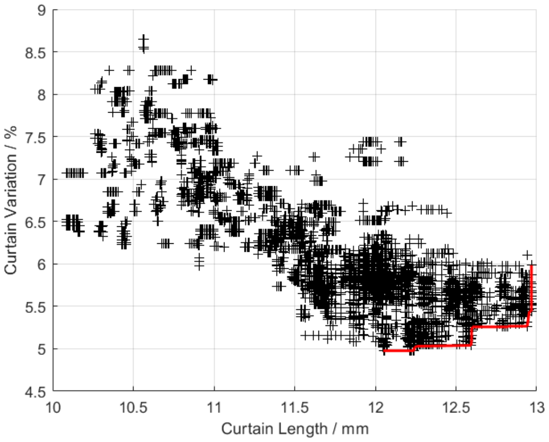

Figure 4: Global pareto front (red) of curtain length against variation, shown relative to all solutions.

Conversely to Fig. 3, Fig. 4 is seen to have a small global pareto front. The range of solutions that can be considered optimum is significantly smaller. However, this does align with the pareto front itself being much closer to the desired max-min solution in the bottom right corner of the figure.

The dominating factor in curtain length is the location of the 3rd skimmer. It is also apparent, that the closer the 3rd skimmer is to the nozzle, the more MC particles reach the IP which reduces the statistical noise. In this scenario, this manifests as the density variation.

Table 1: Final Optimised Skimmer Positions for Equally Weighted Outputs

Skimmer Number	**I**	**II**	**III**	**IV**
Distance from Nozzle / mm	10.0	40.6	177.5	379.7

As with all multi-objective optimisation, the final solution will be a result of compromise. Tables 1 and 2 define the equally weighted optimised BGC geometry and gas jet properties. Weighted values can be easily considered for specific applications if specific outputs are to be prioritised, but is unnecessary for the demonstration of the work performed in this contribution.

Table 2: Final Optimised Design Variables for Equally Weighted Outputs

Design Variable	**Density** /#/m^3	**Curtain Length** /mm	**Curtain Width** /mm	**Variation** /%
Optimised Value	1.72×10^{17}	12.6	0.38	5.4

CONCLUSIONS

In this contribution, a multi-objective genetic algorithm has been used in conjunction with a Monte Carlo particle tracking code. A design of the Beam Gas Curtain device has been optimised for the bespoke use-case on the Hollow Electron Lens. An adaptive background pressure calculation has also been developed to provide realistic chamber pressures as a result of a range of injection geometries. The work demonstrated in this work is versatile and could feasibly be translated to any gas-jet research, such as plasma wakefield gas injectors. The final geometry is defined above in Table 1, and the final jet properties are shown in Table 2.

Future work that is being performed for this study includes optimising the size of skimmer apertures, as well as the option to vary injection pressure. The dynamic background pressure calculation can also be improved to include effusion effects and pumping conductance. This future work intends to maximise the performance of the BGC whilst ensuring a sustainable background pressure for real beamlines.

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