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GAS JET-BASED BEAM PROFILE MONITOR FOR THE ELECTRON BEAM TEST STAND AT CERN

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Abstract

A non-invasive bidirectional beam profile monitor using beam-induced fluorescence upon a thin sheet of gas has been developed at the Cockcroft Institute in collaboration with CERN and GSI. This device is particularly suited to the Electron Beam Test Stand, and as such, a bespoke gas injection has been optimized for this specific use-case to provide diagnostics unavailable with conventional scintillator or optical transition radiation screens. The bidirectionality allows for the observation of beam reflections back along the beam path as a result of a beam dump with non-optimised repeller electrode potential. Furthermore, the heating effects of a high current DC beam are negated by the self-replenishing gas sheet. These benefits make this device ideal for use in the Electron Beam Test Stand.

This contribution summarizes the optimization study of the gas jet generation performed with a multi-objective genetic algorithm to meet required screen dimensions whilst maintaining acceptable vacuum levels.

INTRODUCTION

The Beam Gas Curtain (BGC) is a non-invasive beam profile monitor developed by the University of Liverpool, GSI and CERN [1–3]. A 2D transverse beam profile is generated by imaging fluorescence photons produced by beam-gas interactions. A curtain of low-density gas is generated in-vacuum using a supersonic gas jet that is collimated by several skimmer devices. The skimmers shape the jet into a 45 degrees thin curtain of uniform density that allows a 2D beam profile to be imaged.

A bespoke BGC device is being developed for the Electron Beam Test Stand (EBTS) at CERN [4, 5]. The EBTS aims to generate a 5 A continuous 15 keV hollow electron beam, that can be used as a method of active halo suppression by aiding scraping via space charge generated transverse kicks on the primary central hadron beam's halo particles [4]. During commissioning and stress-testing, the test stand can be expected to produce an external diameter beam size of up to 40 mm, which is the upper limit of beam size to be imaged [5]. The self-replenishing nature of the continuous gas jet allows the BGC to solve thermal load problems typically associated with reconstructing high intensity or DC beam profiles using conventional methods such as wire scanners or scrapers [6, 7]. Additionally, the beam-gas interactions are independent of beam direction, and thus can be used to observe the beam travelling in both directions in the beam pipe. This is particularly useful for a test stand beamline as the BGC can image beam reflections from a non-optimised electrode potential within the dump which conventional, destructive screens cannot.

Previously, a custom Test Particle Monte Carlo (TPMC) simulation code has been developed to accurately model the jets behaviour as it propagates through the BGC [8, 9]. A swarm of particles can be generated at the nozzle and jet properties such as distribution, velocity and temperature are assigned to each particle. These particles are subsequently propagated through the system and properties of the jet at the Interaction Point (IP) with the beam are determined. These properties are heavily affected by collimation interactions with skimmer devices along the path of travel between the nozzle and IP. This has later been used to create a general-purpose optimisation model using a Multi-Objective Genetic Algorithm (MOGA) [10]. This model optimises skimmer configuration to generate desired jet properties such as size and density at the point of interaction with the beam. This optimisation model has been modified in this contribution to produce an optimised gas jet injection to be permanently mounted to the EBTS.

MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMISATION

The gas injection is optimised through skimmer geometric sizes and position along the axis of the jet propagation. This contribution builds upon the previously developed MOGA simulation, modified to produce a more appropriate design for the EBTS [10]. For ease of development costs, the injection section, upstream from the Interaction Point (IP) in Fig. 1, will have the same chamber design and on-axis distances. The dump chamber, separated by skimmer 4, is significantly less complex with less physical limitations on size and thus, it's position will be included in the optimisation study.

A new development to the MOGA includes the sizes of all skimmers to be optimised. This is critical in obtaining a significantly altered gas curtain compared to previous work [1–3, 10]. The 40 mm external diameter beam size will

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require an approximate 60 mm gas curtain length due to the 45 degrees rotation for 2D imaging. This is over three times greater than obtained in previous work [3]. In addition to this, an appropriate background pressure less than 5.0×10^{-8} mbar must still be maintained without compromising the jet number density below 1.0×10^{16} m^{-3} to achieve an acceptable image time.

A conventional MOGA simulates a “survival of the fittest” natural selection process that replicates traditional biological evolution [11]. The evolutionary algorithm used in this contribution is Non-dominated Sorting Genetic Algorithm (NSGA-II) [10, 12]. This optimisation study takes the positions of the fourth skimmer along the axis of jet propagation, and the sizes of all skimmers as the input parameters to optimise. The parameter space is defined in Fig. 1 [10].

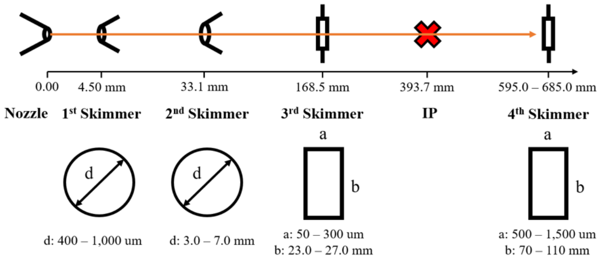

Figure 1: A schematic of the parameter space for skimmer positions along the jet axis and skimmer aperture geometry.

The MOGA is used to optimise for five objective functions within the appropriate design space from Fig. 1.

- The average density of the jet at the IP is maximised, to provide a maximum photon yield and improved signal.
- The length of the gas curtain at the IP is maximised, to reach the desired 60 mm curtain for imaging the largest sized beam expected on the EBTS [4, 5].
- The width of the gas curtain at the IP is also maximised, to provide a greater integrated number of interactions and improved signal.
- The density variation at the IP is minimised, to ensure a uniform measurement with no artefact resulting from the jet is present.
- The background chamber pressure within the beamline is minimised, to minimise losses and maintain an acceptable operational vacuum.

The multi-objective nature of this optimisation scheme requires an assigned weighting to each objective function to denote a prioritisation for trade-offs. The weights used in this study are defined in Table 1, which are used with a weighted sum scalarisation method to determine a final optimum solution [13].

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

Table 1: Assigned Weights for Respective Objective Functions

Density	**Curtain Length**	**Curtain Width**	**Density Variation**	**Chamber Pressure**
3.0	1.0	1.0	0.1	2.0

OPTIMISATION RESULTS

The results below briefly summarise key points of the objective space and highlights an optimal injection configuration for a BGC suited for the EBTS. This study uses nitrogen gas injected at 5 bars through a 30 um nozzle.

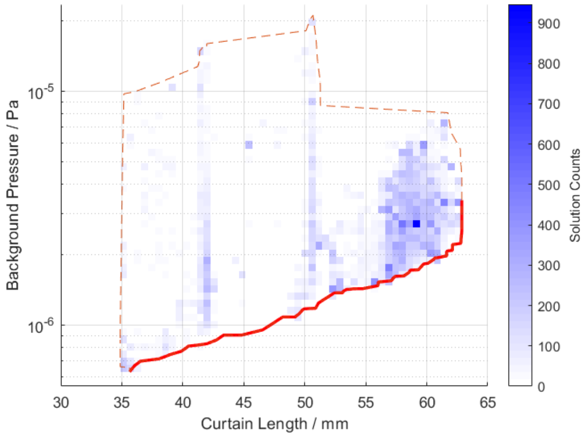

Figure 2: A 2D projection of the optimised objective space for curtain length against chamber background pressure.

Figure 2 shows the objective space for solutions, projected onto the two dimensions of curtain length in mm against chamber background pressure in Pa. The opacity of the blue pixels denotes the number of solutions within the optimisation study that fall into the bins defined by each pixel as seen in the colour bar. The dotted red line highlights the overall global objective space that has been explored in this optimisation study, and the thicker, solid red line shows the idealised two dimensional pareto front between these two objectives.

A pareto front shows a surface of non-dominating solutions, such that one objective function cannot be improved without degrading another. An optimum solution for the trade-off between the curtain length and chamber background pressure will fall on this line. However, due to the higher order problem, including 5 dimensions of objective functions, the global pareto front will not be limited by, but will include the pareto front demonstrated in Fig. 2.

The darker blue pixels suggest a preference for the genetic algorithm to reach or explore solutions within that bin. Whilst this does not automatically mean the overall global optimum lies in this bin, it does suggest a particularly good trade-off has been found in these regions and more simulations have explored these regions of interest.

In Fig. 2, an overall trend can be seen with the thick red pareto frontier of curtain length and background pressure being inversely proportional. This trend is anticipated as a result of effusion effects [10]. With a pressure differential between chambers and a small aperture connecting the two imbalanced chambers, a equalisation flow will occur as described with the second law of thermodynamics [14]. As the aperture, or in this case, the skimmer size increases, the total flow rate leaking into the lower pressure chamber will increase. Whilst this effect will be present with all chambers, the beamline chamber is the worst effected due to having the lowest chamber pressure which causes gas from both chambers either side to effuse into it. With a fixed pumping speed in each chamber, this increase in flow rate of gas into the beamline chamber will negatively effect the vacuum pressure. There also appears to be a clear darker region of solutions at lengths above 55 mm, demonstrating a global region of interest and a useful trade-off occurring here.

FINAL DESIGN

This section reports the final, optimised design for the gas injection system in Fig. 3 and includes final expected performance parameters in Table 2.

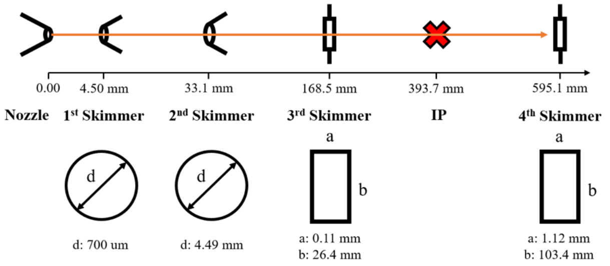

Figure 3: Final optimised solution's geometry for an EBTS-mounted BGC.

Table 2: Final Optimised Objective Functions for an EBTS-mounted BGC

Number Density / # m^{-3}	Curtain Length / mm	Curtain Width / mm	Density Variation / %	Chamber Pressure / Pa
$4.21{\times}10^{16}$	61.2	0.24	1.63	3.45×10^{-6}

Table 2 shows a successfully optimised geometry design, reaching the required performance parameters. Most importantly, a gas curtain greater than 60 mm is generated, which allows for a maximum beam size of 43.3 mm to be imaged. This allows a small offset, either from misalignment or a deflected beam, of just under 10% which is overall an excellent result. Additionally, a reasonable background chamber pressure of 3.45×10^{-6} Pa is reached which is within acceptable levels of the beamline. A small density variation is shown which ensures no unusual artifacts as a result of the jet and confirms a true beam image can be provided. A small curtain width is used to compensate for the increase in curtain length and maintain acceptable gas loads, but with the high 5 A continuous beam current, image acquisition is still expected within several seconds which is an acceptable trade off.

CONCLUSIONS

In this contribution, a multi-objective genetic algorithm has been used in conjunction with a test particle Monte Carlo particle tracking code. A design of the Beam Gas Curtain device has been optimised for the unique requirements of the Electron Beam Test Stand at CERN. Improvements on previous contributions introduce the background pressure as an objective function and use weighted sum scalarisation techniques to determine an improved optimum solution. The final optimised geometry is defined above in Fig. 3, and the optimised jet properties are shown in Table 2. This includes reaching the desired curtain length of 60 mm, whilst maintaining acceptable background pressure of 3.45×10^{-6} Pa and gas jet density of 4.21×10^{16} # m^{-3}.

Future work includes utilising this highly efficient optimisation process for a range of potential options of gas jets. This includes multiple potential locations for a LHC-BGC device on beam 2 to couple with the currently installed beam 1 device.

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