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A NEW ALGORITHM FOR POSITRON SOURCE PARAMETER OPTIMISATION

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Abstract

In this report, we proposed a new simple and efficient algorithm for positron source parameter optimisation, which is based on iterations of scan of free parameters in the simulation. The new algorithm is fast, simple and convincing since the results can be visually drawn and flexibly tuned, and it has an advantage that it can easily handle realistic parametric problems with more than one objective quantities to optimise. The optimisation of the main parameters of the CLIC positron source at the 380 GeV stage is presented as an example to demonstrate how the algorithm works.

INTRODUCTION

Positron source, which is used to produce positrons, is essential for many accelerator experiments, such as electron-positron colliders and muon colliders with a positron-driven muon source. The optimisation of positron source is therefore an important task, not only to fulfill the requirement of high-intensity positron beams for a high-luminosity collider, but also to reduce as much as possible the energy deposition and cost of construction and operation.

Positron yield, defined as the ratio of the number of produced positrons to the number of injected electrons at the target, is one of the most important quantities that need to be optimised. For a given primary electron energy, a higher positron yield means a higher positron production efficiency and a lower electron beam power and cost. To protect the target from being damaged by particle energy deposition, the peak energy deposition density (PEDD) of the target is usually required to be less than 35 J/g [1].

For positron source optimisation, the most popular and widely used algorithm is the Nelder-Mead simplex algorithm [2], which has been well implemented in many simulation softwares, such as Matlab and GNU Octave. However, it has some disadvantages when it is used in positron source optimisation:

- First, it only works for single quantity problems. In fact, a well optimised positron source depends on multiple quantities, such as positron yield, PEDD, deposited power, beam power and mean energy.
- Second, it tends to fall into a local extremum instead of a global optimisation. An example would be the $f(x) = x \cdot \sin(x)$ function in a limited range, as demonstrated in Fig. 1.
- Third, the optimisation is like a back box without providing any useful details and compromised solutions. In reality, due to technical limitations and financial considerations, some parameters are usually constrained in a reasonable range, such as the magnetic field of the matching device. Normally, a higher magnetic field tends to achieve also a higher positron yield. However, a smaller but comparable yield can usually be achieved with a field that is much lower than the optimised value. In this case, the field is actually not well optimised.
- Besides, it does not always converge to an extremum in practice, especially for non-smooth or discontinuous functions. And it usually takes an enormous amount of iterations around the local extremum even with negligible improvement.

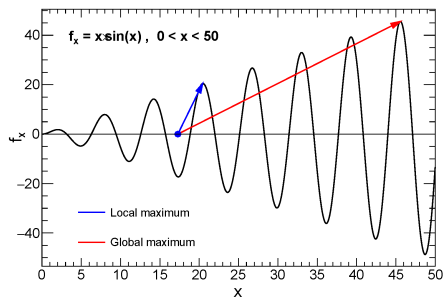

Figure 1: Demonstration of optimisations with a local maximum and a global maximum with the $x \cdot \sin(x)$ function.

In order to eliminate such disadvantages, a new simple and efficient optimisation algorithm based on iterative scan of the parameters is developed and proposed in this report.

DESCRIPTION OF THE ALGORITHM

The principle of the algorithm is very simple, that is to scan and search for a global maximum in the free parameter space. But instead of performing a multi-dimensional scan in the full space which seems not realistic, the algorithm is composed of one-dimensional scans. The procedure can be described as follows:

1. Default parameter values are necessary, to start with.
2. Scan the parameters separately but simultaneously. That is to scan only one parameter at a time, with other parameters fixed to the default. But this allows all parameters to be scanned at the same time, since the scans are independent.
3. Choose the optimal values to be the default and repeat the scan iteratively, until all parameters are optimised and stably plateaued in the scan.

It should be noted that, although it is rarely seen for positron source optimisation, in case of more than one peak distinctly

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observed in the scan, it is indicated that there are more than one local maximum solutions, and we need to look into all the local maximums and make sure that a global maximum is eventually reached.

Another advantage of the algorithm is that it can be very fast even for numerous free parameters. Due to the special simultaneous scan mechanism, it allows a distributed computation. Jobs can be easily divided and submitted to distributed computer clusters or systems, using particular platforms such as HTCondor or Platform LSF. In principle, with sufficient computing resources, the optimisation time is dependent only on the time of one simulation and the number of iterations, rather than number of parameters or number of simulations in a scan. Therefore, it can be dozens of times faster [3] compared with conventional algorithms.

EXAMPLE: APPLICATION TO CLIC

To demonstrate how the algorithm works, it is applied as an example to the CLIC positron source [4] optimisation. It can also be applied to other experiments, as the design of positron sources is not expected to be very different.

Simulation of CLIC Positron Source

The CLIC positron source is basically composed of an electron gun, a target system, a capture section with an adiabatic matching device (AMD), a pre-injector linac with travelling wave (TW) structures and an injector linac. Downstream of the positron source is a pre-damping ring (PDR). Only positrons accepted by the PDR are thought to be effective, and the accepted positron yield is one of the most important figures of merit.

A conventional target system was adopted, which consists of a single amorphous tungsten. GEANT4 [5] was used to simulate the target material and injected electrons based on a gaussian sampling over the initial phase space. The downstream tracking was simulated by RF-TRACK [6].

An analytic formula [7] was used for the on-axis magnetic field map in the AMD simulation, with a linear fringe field around the peak, as demonstrated in Fig. 2. The front surface of AMD was placed at $z = 0$ mm of the field map. The distance between the target and the AMD was fixed at 2 mm.

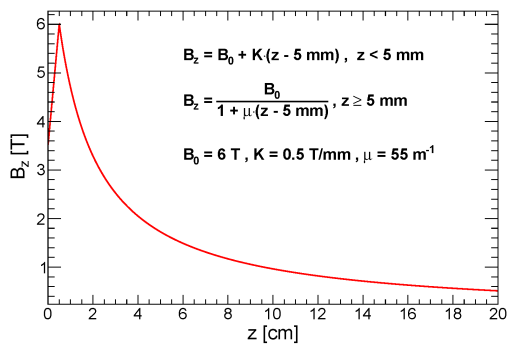

Figure 2: AMD on-axis field map.

The TW structures work in the $2\pi/3$ mode, with a frequency of 2 GHz and an aperture of 20 mm radius, surrounded by a 0.5 T solenoid field. 11 structures were used to accelerate positrons to 200 MeV, while the first structure was supposed to capture positrons with deceleration. The distance between the AMD and the TW structures was fixed at 50 mm.

The acceleration of positrons in the injector linac up to 2.86 GeV was simulated simply by calculating the maximum energy gain in a cosine-like manner. The acceptance of PDR was considered by applying a window cut on the energy and time of positrons arriving at the injector linac exit. The energy acceptance is within $\pm 1.2\%$ of the desired energy, 2.86 GeV, while the time window is 20 mm/c in total.

To achieve the designed positron bunch charge for the PDR, the primary electron bunch charge, as well as energy deposition quantities such as PEDD and deposited power, was always normalised by the accepted positron yield in this study. For the 380 GeV collision energy stage that was studied in this example, the positron bunch population to the PDR was required to be 5.2×10^9 [8] (~0.8 nC bunch charge), with an additional 20% safety margin considered.

The primary electron beam parameters that are fixed in simulation and not yet mentioned are summarised in Table 1.

Table 1: Fixed Primary Electron Beam Parameters Not Mentioned in the Text

Parameter	Value	Unit
Energy	5	GeV
Energy spread (RMS)	0.1	%
Normalised RMS emittance	80	mm·mrad
Bunch length (RMS)	1	mm
Number of bunches per pulse	352	
Repetition rate	50	Hz

Free Parameter Optimisation

The free parameters used in the optimisation and their symbolic notations and initial default values are listed in Table 2, as well as accepted positron yield and target PEDD. To have a more realistic result, the AMD parameters were constrained in the optimisation, as it is technically limited for a typical flux concentrator AMD. The peak on-axis magnetic field of AMD was required to be no larger than 6 T, and the upstream aperture of AMD was required to be no larger than 8 mm radius. The length of AMD was required to be less than 25 cm, unless the positron yield could benefit significantly from a longer AMD. It should be noted that the TW phases are kind of arbitrary and usually internally used, as it depends on how the reference particle is defined.

After 6 iterations of scan, all of the optimised free parameters are either stably at the plateaux or at the limits of constraint. Therefore the optimisation was thought to be finished. The evolution of the default parameters in each iteration, starting from the initial values to the final optimised values, is summarised in Table 3. The units are same with that in Table 2. Obviously, the optimisation is quite efficient.

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Table 2: Free Parameters to Be Optimised

Parameter	Symbol	Value
Electron spot size (RMS)	σ_{e^-}	5 mm
Amorphous target thickness	δ_{amor}	12 mm
AMD peak on-axis field	B_0	5 T
AMD length	L_{amd}	10 cm
AMD upstream aperture (radius)	R_{amd}	4 mm
TW decelerating phase	ϕ_{dec}	120 °
TW accelerating phase	ϕ_{acc}	120 °
TW decelerating gradient (average)	E_{dec}	16 MV/m
TW accelerating gradient (average)	E_{acc}	16 MV/m
Accepted positron yield	η_{e^+}	0.12
Target PEDD (normalised)	PEDD	98.6 J/g

Within a few iterations, the yield was increased from the initial 0.12 to 2.15, by a factor of 18. And the target PEDD was also reduced by a factor of 3, which is then well below the 35 J/g limit.

Table 3: Evolution of Parameter Optimisation

Iteration	σ_{e^-}	δ_{amor}	B_0	L_{amd}	R_{amd}	ϕ_{dec}	ϕ_{acc}	E_{dec}	E_{acc}	η_{e^+}	PEDD
1	5.0	12	5.0	10	4	120	120	16	16	0.12	98.6
2	5.0	17	5.5	10	8	150	150	15	15	0.68	24.1
3	3.2	16	4.5	20	8	150	150	12	15	1.35	25.2
4	2.5	17	6.0	22	8	155	150	13	15	1.86	29.3
5	2.2	18	6.0	22	8	155	155	11	16	2.08	33.3
6	2.2	18	6.0	22	8	160	155	13	17	2.15	32.2

In addition to the accepted positron yield and target PEDD, four extra quantities that have relatively lower priorities were also taken into consideration in the optimisation. They are the primary electron beam power, target deposited power and positron mean energy and energy spread at the exit of TW structures. Beam power and deposited power were also normalised by the accepted yield, as with the PEDD normalisation. The optimisation should be aimed at the lowest allowed beam power, since the beam power is usually proportional to the cost. However, in this example, the primary electron energy was fixed. Therefore a higher positron yield always means a lower beam power and cost in this case. There is no very clear limitation on the target deposited power, but for safety reasons it should be as low as possible, under the premise of a minimised beam power or maximised positron yield. Positron mean energy at the TW structures exit should be as close to 200 MeV as possible, which is the designed beam energy for the injector. There is also no special limitation on the energy spread, but a lower value is always prefered, since it leads to a better positron beam transport and an easier matching between the beam and the injector linac.

As an illustration, the scan of the primary electron spot size, σ_{e^-}, in the final iteration is demonstrated in Fig. 3. For better display and comparison, quantities have been scaled to be comparable in the plot. Obviously, a smaller spot size tends to give not only a higher positron yield but also a larger PEDD. Therefore, 2.2 mm was taken to be the optimal value of spot size, given the limit on PEDD.

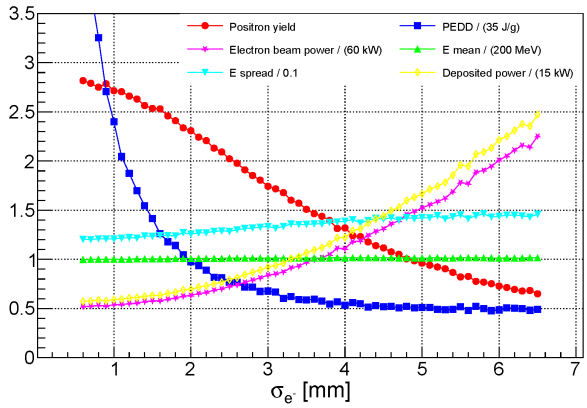

Figure 3: Scan of primary spot size in final iteration.

Similarly, the final scan of the amorphous target thickness, δ_{amor}, is presented in Fig. 4. As the deposited power is increased with a larger target thickness, the minimum thickness of the yield plateau range was taken to be the optimal value, which is 18 mm.

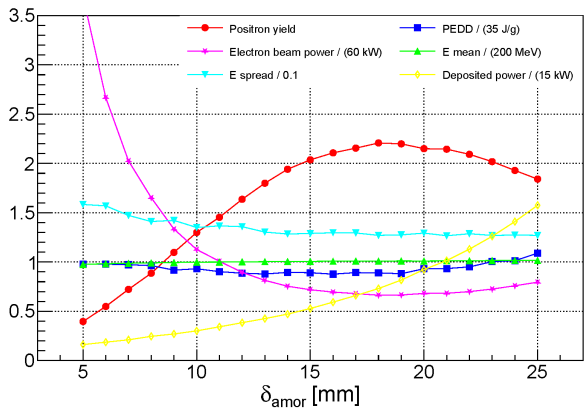

Figure 4: Scan of target thickness in final iteration.

SUMMARY

A new simple and efficient parameter optimisation algorithm for positron sources based on iterations of scan of free parameters was developed and proposed in this report. It has many practical advantages compared with conventional algorithms such as the Nelder-Mead simplex algorithm. It can easily handle realistic parametric problems with more than one objective quantities as figures of merit. The scanning plots are visible and the optimisation results are flexible and more convincing. The new algorithm is also very fast which supports for distributed computation and in principle can be dozens of times faster than conventional algorithms. An application to the optimisation of the CLIC positron source at 380 GeV was demonstrated as an example. As shown in the example, the final positron yield can be improved very efficiently within a few iterations, with a PEDD below the 35 J/g limit.

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