Physics-informed genetic algorithm for the beam dynamics design and optimization of RFQ

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Abstract

RFQ accelerators are a key component in ion accelerators, enabling the efficient focusing and acceleration of low-energy ions. It is widely used in various fields, including nuclear energy, medical applications, industry, and fundamental physics research. The beam dynamics design of RFQ involves numerous coupled parameters, nonlinear physical constraints, and complex engineering limitations, while facing multi-objective optimization conflicts such as transmission efficiency, structural compactness, and emittance control. Traditional design methods struggle to achieve a globally optimal solution within a reasonable computational time. To address this issue, this study proposes a beam dynamics-related physics-informed genetic algorithm. By introducing evolution rules for key physical parameters such as modulation, synchronous phase, and focusing strength during individual initialization, evolution guidance, and solution selection, the physical validity and optimization efficiency of the solutions are significantly improved. The proposed method has been validated in several typical application scenarios. The RFQ structure designed using this method significantly enhances transmission efficiency and reduces structural length, while ensuring beam quality. It demonstrates strong multi-objective optimization capabilities and engineering adaptability, and considerably shortens the design time, providing a clear direction for the intelligent design of RFQs.

Full Text

Preamble

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Department of Nuclear Technology Application, China Institute of Atomic Energy, Beijing 102413, China Department of Computer Science, The University of Sheffield, Sheffield S10 2TN, United Kingdom RFQ accelerators are a key component in ion accelerators, enabling the efficient focusing and acceleration of low-energy ions. It is widely used in various fields, including nuclear energy, medical applications, industry, and fundamental physics research. The beam dynamics design of RFQ involves numerous coupled parameters, nonlinear physical constraints, and complex engineering limitations, while facing multi-objective optimization conflicts such as transmission efficiency, structural compactness, and emittance control. Traditional design methods struggle to achieve a globally optimal solution within a reasonable computational time. To address this issue, this study proposes a beam dynamics-related physics-informed genetic algorithm. By introducing evolution rules for key physical parameters such as modulation, synchronous phase, and focusing strength during individual initialization, evolution guidance, and solution selection, the physical validity and optimization efficiency of the solutions are significantly improved. The proposed method has been validated in several typical application scenarios. The RFQ structure designed using this method significantly enhances transmission efficiency and reduces structural length, while ensuring beam quality. It demonstrates strong multi-objective optimization capabilities and engineering adaptability, and considerably shortens the design time, providing a clear direction for the intelligent design of RFQs.

Keywords

Beam dynamics, RFQ design, Genetic algorithm

INTRODUCTION

quality at the aperture. Therefore, the design of RFQ accelerators is a typical multi-parameter, multi-objective optimization problem.

The mainstream design methods for RFQ accelerators are the four-section procedure and the equipartitioning method. The four-section procedure was proposed in 1979 by K. R. Crandall et al[9]. It divides the RFQ acceleration structure into four sections based on beam dynamics: radial-matching, shaper, gentle buncher, and acceleration section. Each section is designed to adapt to the different states of the beam at various stages by adjusting dynamic parameters. This approach offers high versatility and has been widely used in RFQ accelerator design. The equipartitioning method was introduced by R. A. Jameson et al[10]. Its main feature is the transverse longitudinal equipartitioning of the beam in the units following the radial-matching and shaper sections, which effectively 42 achieves high transmission efficiency and low emittance un43 der high beam current conditions. In addition, in 2005, A. 44 D. Ovsyannikov et al proposed a mathematical optimization 45 method and developed the BDO-RFQ code[11]. This method 46 employs a stepwise optimization approach, breaking down 47 the RFQ optimization problem into multiple single-objective 48 optimization problems, iterating step by step to design an 49 RFQ that meets the required specifications, with a strong em50 phasis on optimizing beam transmission efficiency. Although 51 these design methods can achieve structures that meet design 52 requirements through multiple optimizations, due to the inter53 dependence of optimization objectives, they do not necessar54 ily lead to a globally optimal solution.

With the continuous advancement of artificial intelligence 56 algorithms, particularly the development of multi-objective 57 optimization algorithms, they have been widely applied 58 in nuclear-related design and optimization fields, such as

Over the past two decades, the design and optimization of Radio Frequency Quadrupole (RFQ) accelerators have played 4 a crucial role in modern accelerator technology[1–3]. The 5 RFQs integrated features of transverse focusing, longitudi6 nal bunching, and acceleration enable it to accelerate a beam 7 over a short length while maintaining high beam quality. As 8 a result, it has been widely applied in various fields, in9 cluding large and small accelerator research facilities, non10 destructive testing, particle therapy, and high-energy physics 11 experiments[4–6].

The principle of RFQ accelerators was first proposed by I. 13 M. Kapchinskiy and V. A. Tepliakov in 1970[7]. The phys14 ical design of RFQ accelerators mainly includes two parts: 15 beam dynamics design and cavity RF structure design. These 16 two parts yield the electrode structure parameters and cavity 17 structure parameters of RFQ accelerators, respectively. The 18 most important aspect is the beam dynamics design, as it de19 termines the beam quality at the exit of RFQ[8].

For dif20 ferent applications, the definition and orientation of a good 21 beam may vary, such as a preference for high transmission 22 efficiency, low longitudinal or transverse emittance, higher 23 beam energy, or a combination of multiple performances. An 24 RFQ accelerator typically consists of hundreds of accelera25 tion units, and the structure of each unit impacts the beam

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radiation protection, neutron source design, and detector applications[12–15]. Therefore, we propose a novel RFQ qXV0 \$ \$2 π 2 qV0 Asinϕ 61 design method based on a multi-objective optimization alσT2 0 + Δrf m0 c a 2m0 c β 62 gorithm, incorporating constraints from beam dynamics to 63 accelerate the solution search process significantly, referred 105 When σT2 0 $>$ 0, the beam can operate stably. 64 to as the physics-informed genetic algorithm (PIGArfq). We 106 65 conducted optimized designs for various application scenar66 ios, including light particle RFQs, heavy ion RFQs, and low107

2. Longitudinal beam stability

67 emittance RFQs. The design method efficiently produced ex68 cellent design structures within a short period, significantly 69 reducing the time cost of RFQ design. This advancement fa- 108 Furthermore, longitudinal beam stability requires that the 70 cilitates the further promotion and widespread application of 109 particle phase remains within the stable region of the bucket. 71 RFQs. 110 For a cell with a synchronous phase of ϕs , the bucket size ψ 111 satisfies the equation (4).

II. METHODS AND THEORETICAL MODELS

tan (ϕs) =

A. Beam dynamics

sin (ψ) $-$ ψ 1 $-$ cos (ψ)

For any particle, its phase ϕ should ideally satisfy equation In the beam dynamics design of RFQs, it is essential to 114 (5) to ensure a higher acceleration efficiency. 75 systematically account for a series of physical and engineer76 ing constraints to ensure both stable beam transport and high 77 acceleration efficiency. These constraints primarily include 115 $0 \geq \phi + \phi$s $\geq -\psi$ 78 transverse and longitudinal stability, the high-current stabil79 ity constraint and zero-current phase shift constraint, the peak

3. High-current stability constraint and zero-current phase shift

80 surface electric field constraint, as well as fabrication-related 116 constraint 81 constraints. The following sections provide a detailed discus- 117 82 sion of each of these constraints.

Considering the space charge effect, the necessary condi119 tions for stable motion in a linear accelerator without sig83

1. Transverse beam stability

120 nificant emittance growth are[17]: the zero-current transπ 121 verse phase advance σT 0 transverse phase advance The primary constraints we need to consider are transverse 122 σT 0.4σT 0 , the zero-current longitudinal phase advance 85 beam stability and longitudinal beam stability. In an RFQ, the 123 σL0 2 , and the longitudinal phase advance σL 0.4σL0 . 86 electric field is

established between the four modulated elec- 124 The specific expressions are given by: 87 trodes by an RF voltage, providing transverse focusing and 88 longitudinal acceleration. The average behavior of the parti√ 89 cle motion can be described by a simple harmonic oscillation

3 Z0 qI$ $3 3b − r

σT = σT2 0 − 90 equation (1)[16]. 8π m0 c2 γ 3 3r2 b2

d2 x̄ + Ω2 x̄ = 0 where Ω can be expressed as:

3 Z0 qI$ $3 1

4π m0 c2 γ 3 3rb2

1 qXV0 2 qk 2 V0 Asinϕ −4πqAV0 T sinϕ Ω (2 m0 ωa2 m0 c2 γ 3 β 2 The first term represents the quadrupole focusing effect of where Z0 = 376.73 Ω is the impedance of free space, I is 95 the electrodes, which is always positive. In the second term, 130 96 for charged particles during acceleration and longitudinal fo- 131 the beam current, λ is the RF wavelength, r is the transverse 97 cusing, the requirement is $-\pi/2 \leq \phi \leq 0$. Therefore, the 132 radius of the beam ellipsoid, and b is the longitudinal length 98 second term is always negative, representing the RF defocus- 133 of the beam ellipsoid. 99 ing effect. Hence, it can be concluded that for the beam to 100 maintain stable transverse motion, the focusing term must be

4. Peak surface electric field constraint

101 greater than the defocusing term. The transverse phase ad102 vance per period, often used to indicate the strength of trans103 verse focusing, is typically expressed as σT 0 = Ωλ/c. Its 135 Preventing sparking is also considered an important con104 approximate expression is: 136 straint in the design of RFQ cavities.

The peak surface

electric field of the RFQ is generally kept below 1.8 times 162 B. Physics-informed NSGA III the sparking limit, but for continuous wave (CW) operation 139 mode, it is typically kept below 1.6 times the sparking limit.

As previously mentioned, RFQ design is a typical multi140 This can be expressed as equation (9). 164 objective optimization problem. To ensure generality across 165 different application scenarios, we select the beam transmis166 sion efficiency at the exit of RFQ η, the transverse emitκV ≤ bEK (9) 167 tances ϵx and ϵy , the longitudinal emittance ϵz , and the total 168 RFQ length L as optimization objectives. The multi-objective 169 function can thus be expressed as equation (11):

The Kilpatrick results were expressed in a convenient for143 mula by T. J. Boyd[18] as equation (10).

F (X) = [fη (X), fϵx (X), fϵy (X), fϵz (X), fL (X)] (11)

where X represents the vane structural parameters of the To avoid the need to assign weights to the optimiza144 173 tion objectives, we adopt the NSGA-III algorithm for opti174 mizing the RFQ design. NSGA-III is an evolutionary algo175 rithm specifically developed for multi-objective optimization, 176 and compared with NSGA-II, it offers better performance in

5. Engineering constraints

177 handling problems with many objectives. By introducing a In addition, due to practical manufacturing limitations and 178 set of reference points, it more effectively guides the popula179 tion evolution and ensures coverage of the entire objective 147 conservative considerations in application scenarios, certain 180 space.

To reduce the degrees of freedom in the optimiza148 structural parameters are subject to enforced constraints, such 181 tion problem and improve computational efficiency, we select 149 as the maximum upper limit of the modulation factor m and 182 the transverse focusing strength B(z), the synchronous phase 150 the maximum upper limit of the synchronous phase ϕs . Each 183 ϕs (z), the modulation m(z), and the inter-vane voltage V (z) 151 of these constraints restricts the range of RFQ cavity struc184 all as functions of the axial coordinate z as the optimization 152 tural parameters, thereby influencing the convergence direc185 variables. These are then used in combination with interpo153 tion of the solution set. For an RFQ design with a constant 186 lation methods to calculate the vane structural parameters for 154 B value, the projection of these constraints on the ϕs and m 187 each cell of the RFQ. 155 plane is shown in Figure 1 [Figure 1: see original paper]. The yellow region represents an The key point of this study lies in self-iteration of the RFQ 156 illustrative solution space for RFQ structures, based on a par189 cell vane structural parameters under physical and engineer157 ticular set of assumed beam dynamics constraints. Solutions 190 ing constraints, with the iterative process guided toward a so158 in this region correspond to physically valid structures, and 191 lution space that meets the application requirements. We im159 those outside the yellow area are considered physically in192 plement the physics-informed NSGA-III through the follow160 valid due to violations of beam dynamics, electromagnetic, 193 ing steps, as illustrated in Figure 2 [Figure 2: see original paper]. 161 or engineering limitations. 1. We first randomly generate an initial population P1 con195 taining N individuals under the guidance of physics-informed 196 and engineering constraints described above, each represent197 ing a candidate RFQ structure. These individuals are gener198 ated under strict physical and engineering constraints, such 199 as limits on the modulation m and synchronous phase ϕs . 200 The RFQgen beam dynamics part is then used to compute 201 the beam parameters at the RFQ aperture, including η, ϵx , ϵy , 202 ϵz , and L. Each individual is double-checked against the op203 timization constraints, and those that do not meet the require204 ments are removed and replaced by newly generated individ205 uals. This process continues until we obtain a new population 206 Pg with N valid individuals. 2. Based on Pg , a new offspring population Cg of N in208 dividuals is generated through crossover and mutation. Each 209 new individual is immediately checked for compliance with 210 all physics and engineering constraints, calculated using the 211 analytical formulas provided in Section II. Invalid individu212 als are removed and replaced until a valid population Cg is 213 formed. The RFQgen beam dynamics part is then used to 214 compute the beam parameters at the RFQ aperture for each inFig. 1. Physics-informed region for m and ϕs 215 dividual. After computation, double-checking, deletion, and 216 replenishment are repeated to ensure all individuals meet the

2 −8.5/EK f (M Hz) = 1.64EK

requirements. Finally, Pg and Cg are combined to form a 243 C. RFQgen beam dynamics module population Rg of 2N individuals. 3. Individuals in Rg are subjected to non-dominated sort- 244 To verify the reliability of the proposed RFQ design 220 ing (illustrated in the dashed box). For clarity, a simplified 245 method, we adopted RFQgen, one of the most widely used 221 optimization model with two parameters is shown, although 246 beam dynamics simulation programs[19].

The RFQgen 222 the actual optimization involves five parameters: η, ϵx , ϵy , 247 mainly consists of the vane structural design modules Curli 223 ϵz , and L. In non-dominated sorting, solutions closer to the 248 and RFquick, as well as the beam dynamics module. In our 224 Pareto optimal front are ranked higher. They have at least one 249 study, only the beam dynamics module of RFQgen was uti225 objective that is better than others in lower ranks. For exam- 250 lized to evaluate the output beam parameters corresponding to 226 ple, comparing individuals in the first and second ranks: at 251 the designed RFQ structure. The simulations were performed 227 the same f1 , the first-rank individual has a better (lower) f2 , 252 on a computing server equipped with a W9-3495X CPU. 228 and vice versa. Furthermore, to better explore the solution 229 space, we use reference points based on normalized objective 230 values to guide the next iteration, calculated by the formula 253 III. DESIGN APPLICATIONS UNDER DIFFERENT SCENARIOS 231 (12).

To validate the proposed physics-informed genetic algorithm-based design method, we redesigned and com232 fi,n = 1, fi,n ≥ 0 (12) 257 pared three sets of RFQ parameters that are either in operai=1 258 tion or have been previously demonstrated. These include: 259 the LEAF RFQ, designed for low-energy, high-intensity, 4. To select N individuals from Rg for the next generation 260 high-charge-state heavy ion research; the ADS Injector II 234 Pg+1 , the following rule is applied: individuals from the first 261 RFQ, aimed at producing high-current, low-emittance pro235 front (F1) are added to Pg+1 in order. If Pg+1 still has fewer 262 ton beams; and the PAFA RFQ, developed for Boron Neutron 236 than N individuals, we continue adding individuals from F2 , 263 Capture Therapy (BNCT) applications. 237 F3 , ···, Fk until the population reaches N.

5. A new offspring population Cg+1 is generated from

A. LEAF RFQ 239 Pg+1 using crossover and mutation, followed by the same 264 240 physics-informed constraint filtering and evaluation.

Steps 241 2 4 are repeated iteratively until the maximum number of 265 The LEAF RFQ is a key component of the low-energy, 242 generations is reached. 266 high-current, highly charged heavy ion research facility[20]. 267 This RFQ has already been fabricated and tested.

It uses 268 the four-section procedure for its design and can accelerate 269 heavy ion beams from 14 keV/u to 0.5 MeV/u. Due to the 270 use of a triple-harmonic buncher, an injection phase of −45 271 was chosen. The transverse emittance of the injected beam is 272 0.3 π mm ·mrad, and the longitudinal emittance is 1.10471 238 34+ 273 MeV ·deg. It was designed for a 2 emA current of 274 ions, corresponding to a beam current of 0.0588 mA. Based 275 on these parameters, we redesigned the LEAF RFQ. The mi276 gration of the Pareto solution set is shown in Figure 3 [Figure 3: see original paper]. Since 277 our optimization involves five objectives, as previously men278 tioned, the solution set lies in a five-dimensional space, mak279 ing it difficult to visualize directly. Therefore, we present the 280 distribution using a scatter matrix plot.

The scatter matrix plot provides a visualization of the 282 movement and convergence of the Pareto solution set during 283 the iterative process, as well as the pairwise distribution rela284 tionships between objectives. However, since the nondomi285 nated sorting is performed based on five optimization objec286 tives, the dominance relationships may not be accurately re287 flected when projected onto pairwise plots. As a result, indi288 vidual scatter plots may not effectively reveal the most desir289 able solutions. To address this, we re-applied nondominated 290 sorting based on the two design criteria of primary concern 291 for the LEAF RFQ, transmission efficiency and total length, 292 to highlight the optimization trend in these specific dimen293 sions throughout the iteration process, as shown in Figure 4 [Figure 4: see original paper].

ters at the RFQ aperture between our design and the original LEAF RFQ is shown in Table 1 .

The original[20] PIGArfq 97.2% 98.7% ϵn,x (π ·cm ·mrad) ϵn,y (π ·cm ·mrad) ϵn,z (M eV ·deg) L (cm) R0 (mm) −45 ∘ −25 ∘ −45 ∘ −25 ∘ 1.0 2.0 1.0 2.0

With the same ranges for ϕs and m, the RFQ designed using PIGArfq achieves a higher transmission efficiency while 318 also having a shorter length.

At the aperture, the normal319 ized transverse emittance of the beam is 0.0296 π cm ·mrad 320 and 0.0297 π cm ·mrad in the x and y directions, respec321 tively, while the normalized longitudinal emittance is 2.1167 322 π cm ·mrad. The Kilpatrick factor is 1.60, which, although 323 slightly higher than that of the original LEAF RFQ, still meets 324 application requirements. Moreover, the entire design pro325 cess required only 80 core-hours, significantly reducing the 326 time cost associated with the beam dynamics portion of RFQ 327 design. 329 the length for both the original LEAF RFQ and our newly de330 signed RFQ. The RFQ obtained using the physics-informed 331 genetic algorithm adopts a more aggressive approach in the 332 design of m and ϕ, with a steeper increase in the cell struc333 tures at the beginning of the RFQ. This significantly reduces 334 the structure length required for beam bunching. Although 335 there is no notable difference due to the limitation imposed 336 by the Kilpatrick factor, thanks to earlier beam acceleration, 337 our RFQ achieves a length reduction of 18.84 cm compared 338 to the original LEAF RFQ.

The figure illustrates the distribution of the top 50 nondominated solutions in each generation, based specifically on B. ADS Injector II RFQ 296 length of vane and transmission efficiency. It is important 297 to emphasize that we do not alter the optimization process; The ADS Injector II RFQ is the prototype RFQ for the 298 rather, we performed an additional nondominated sorting on 340 299 each generation' s population with respect to this specific pair 341 CiADS project[21], designed to deliver a high-current, low300 of objectives, and selected the top 50 individuals for visual- 342 emittance proton beam. It requires the beam to maintain a 301 ization and analysis. These individuals are typically retained 343 very high transmission efficiency at the RFQ aperture while 302 in the original Pareto solution sets due to their advantages in 344 keeping the longitudinal emittance low. The ADS Injector II 303 either transmission efficiency or length. The black points rep- 345 RFQ uses the four-section procedure for its design and can 304 resent the initial population generated randomly. As the num- 346 achieve a transmission efficiency of 99.6%, a longitudinal 305 ber of generations increases, the solution set moves steadily 347 emittance of 0.05466 MeV ·deg, and a total length of 420.59 306 toward the lower right corner, indicating higher transmission 348 cm. Using our physics-informed multi-objective optimization 307 efficiency and shorter length. The first 20 generations took 349 design method, we also carried out a redesign of the ADS 308 approximately 80 CPU core-hours. By the 20th generation, 350 Injector II RFQ. The migration of the Pareto solution set is 309 individuals of interest had already emerged, so the iterations 351 shown in Figure 6 [Figure 6: see original paper]. 310 were not continued further. At this point, the best-performing 352 By the 70th generation, the individuals of interest had al311 solution achieved a transmission efficiency of 98.7% and a 353 ready emerged, so further iterations were not performed. The 312 total length of approximately 575.8 cm, meeting LEAF RFQ 354 70-generation iteration process took approximately 280 core313 design requirements. The comparison of the beam parame- 355 hours. The black points represent the initial generation, which as the number of generations increases, the solution set continuously moves toward the more favorable region. To better 363 visualize the distribution of the solution set, we conducted a 364 more detailed analysis focusing on the most critical factors for 365 the ADS Injector II RFQ, length and transmission efficiency 366 and longitudinal emittance, as shown in Figure 7 [Figure 7: see original paper].

369 transmission efficiency and length of vane. Since each gen370 eration contains only 100 individuals during the iterative pro371 cess, we selected only the top 30 individuals in terms of non372 dominated sorting. It can be observed that as the number of it373 erations increases, the solution set gradually shifts toward the 374 lower right corner. Although some red points may appear bet375 ter than the blue ones, they actually exhibit higher longitudi376 nal emittance. Therefore, we also performed non-dominated 378 malized RMS emittance, as shown in Figure 7 (b). The objec379 tive is to design an RFQ that achieves high transmission ef380 ficiency while maintaining a low longitudinal emittance. As 381 a result, the final selected individual corresponds to the green 382 star symbol in the figure. Its detailed parameters and com383 parison with the ADS Injector II RFQ are listed in the table 384 below.

II RFQ The original[21] PIGArfq 99.6% 99.8% ϵn,x (π · cm · mrad) ϵn,y (π · cm · mrad) ϵn,z (M eV · deg) L (cm) R0 (mm) -90° -22.5° -90° -22.5° 1.00 2.35 1.00 2.35

Under the same variation range of synchronous phase and was randomly generated based on the physical and engineer- 386 modulation, and with a similar Kilpatrick factor, the RFQ 357 ing constraints and shows a relatively scattered distribution 387 vane structure obtained using PIGArfq method achieves a 358 in the solution space. The red points correspond to the so- 388 shorter length while maintaining higher transmission effi359 lution set after 20 generations, and the blue points represent 389 ciency at the aperture.

The beam transmission efficiency 360 the solution set after 70 generations. It can be observed that 390 reaches 99.8%, and the total length is reduced by 11.03

cm. At the aperture, the transverse normalized RMS emit- 411 MHz and a design beam current of 20 mA. The injected protance is 0.0310 π cm · mrad in the x-direction and 0.0314 412 ton beam has an initial energy of 20 keV and is accelerated 393 π cm · mrad in the y-direction, while the longitudinal emit- 413 to 2.5 MeV through the PAFA RFQ. It uses the four-section 394 tance is 0.0585 MeV · deg. Although the emittance is slightly 414 procedure for its design and can achieve a transmission effi395 higher than that of the ADS Injector II RFQ, it remains within 415 ciency of 99.5% with a total length of approximately 394.5 396 an acceptable range. 416 cm. We also conducted a redesign of the PAFA RFQ. The 417 migration of the optimized Pareto solution sets is shown in 418 Figure 9 [Figure 9: see original paper].

By the 20th generation of iteration, individuals of interest had already emerged, so further iterations were not car421 ried out. The 20 generations of iteration took approximately 422 80 core-hours. From the distribution diagram, it is clear that 423 the solution set gradually moves toward the Pareto front with 424 each generation. Black dots represent the first-generation in425 dividuals randomly generated based on physical constraints, 426 red dots represent the individuals after 10 generations, and 427 blue dots represent those after 20 generations. Compared to 428 the initial population, the individuals in the 20th generation 431 tances. Given the application objectives of PAFA, we are par432 ticularly concerned with the RFQ length and beam transmis397 433 sion efficiency. Therefore, we re-ranked the solutions based 398 respect to the length for both the ADS Injector II RFQ and 434 on non-dominated sorting for these two objectives, as shown 399 our newly designed RFQ. The structure obtained through the 435 in Figure 10 [Figure 10: see original paper]. 400 physics-informed genetic algorithm exhibits a slower initial We selected the top 50 individuals in each generation based 401 variation in modulation and synchronous phase, dedicating 437 on the new non-dominated sorting with respect to length of 402 more accelerator cells for beam focusing. However, in the 438 vane and transmission efficiency, which are the individuals 403 middle section, the variations in m and ϕs become more ag439 with more advantageous solutions in terms of length of vane 404 gressive, leading to a shorter acceleration section, which ulti440 and transmission efficiency. It can be clearly observed that 405 mately results in a shorter overall RFQ length. 441 after 20 generations, the blue points are more concentrated 442 in the lower-right region, indicating better performance. The 443 green star symbol represents the individual we ultimately se406 C. PAFA RFQ 444 lected. A comparison of its specific parameters with those of 445 the original PAFA RFQ is shown in Table 3 .

The PAFA RFQ is a key component of the particle acceler- 446 Unlike the previous two cases, we adopted a strategy in the 408 ator platform at Sun Yat-sen University[22], designed to pro- 447 RFQ design for PAFA that allows for significant changes in 409 vide high-energy proton beams. The previously designed and 448 the B value. Based on this approach, while keeping the syn410 validated RFQ operates in CW mode with a frequency of 200 449 chronous phase and modulation range unchanged, the trans419

The original[22] PIGArfq 99.5% 99.8% ϵn,x (π ·cm ·mrad) ϵn,y (π ·cm ·mrad) ϵn,z (M eV ·deg) L (cm) R0 (mm) 4.09 4.62 -90° -30° -90° -30° 1.00 2.35 1.00 2.35 7.8 10.0

for (a) the original PAFA RFQ[22] and (b) our RFQ

mission efficiency of our RFQ reached 99.8%, and the length a beam current of 10 mA in CW mode. It accelerwas reduced to 351.98 cm. The transverse emittance in the x 472 MHz with 473 ates He ions from an initial energy of 15 keV/u to a final 452 and y directions at the beam exit are 0.0216 π cm · mrad and 474 energy of 0.5 MeV/u. We perform the beam dynamics de453 0.0224 π cm ·mrad, respectively, and the longitudinal emit475 sign using PIGArfq method. The migration of the optimized 454 tance was 0.0645 MeV ·

deg. 456 the length for both the original PAFA RFQ and our redesigned 457 structure. In the redesigned RFQ, the B value exhibits a non458 monotonic behaviorincreasing during the initial stages and 459 subsequently decreasing toward the end. The rising B value in 460 the early cells enhances beam focusing efficiency, contribut461 ing to a more compact overall structure. In the latter part, 462 the intentional reduction of the B value helps to suppress the 463 peak Kilpatrick factor, thereby ensuring compliance with the 464 imposed Kilpatrick factor constraints while maintaining ef465 fective acceleration performance.

D. SYSU-IFCEN He-RFQ

The 2 MeV He2+ RFQ accelerator, named SYSU-IFCEN 468 He-RFQ, is developed by the Sino-French Institute of Nuclear 469 Engineering and Technology at Sun Yat-sen University. It is 470 designed for helium ion irradiation studies in nuclear mate471 rials. The RFQ is designed to operate at a frequency of 200

By the 70th generation of iteration, promising individuals had already emerged, so further iterations were not pursued. 479 These 70 generations required approximately 300 core-hours 480 to complete. As shown in the distribution diagram, the solu481 tion set gradually converges toward the Pareto front with each 482 generation. Black dots represent the first-generation individ483 uals randomly generated under physical constraints, red dots 484 correspond to individuals after 10 generations, and blue dots 485 represent those from the 70th generation. Compared to the 486 initial population, the individuals in the 70th generation ex487 hibit clear advantages in terms of RFQ length, transmission 488 efficiency, and both longitudinal and transverse emittances.

Given the application objectives of SYSU-IFCEN He490 RFQ, we focused particularly on RFQ length and beam trans491 mission efficiency. Therefore, nondominated sorting was ap492 plied to the solution set based on these two objectives, as il493 lustrated in Figure 13 [Figure 13: see original paper].

SYSU-IFCEN HeRFQ with PIGArfq 97.4% ϵn,x (π · cm · mrad) ϵn,y (π · cm · mrad) ϵn,z (M eV · deg) L (cm) −90 ∘ −30 ∘ 1.00 2.4

for SYSU-IFCEN HeRFQ

space, improves population quality, accelerates the convergence toward optimal solutions, and ultimately yields a high514 quality Pareto front that balances beam dynamics perfor515 mance with engineering feasibility.

In the redesign of the LEAF RFQ, under the premise of 517 maintaining the same range of synchronous phase and mod494 We adopted a small population size for the iterative pro- 518 ulation factor variations, the newly designed RFQ achieved a 495 cess, with each generation consisting of only 100 individuals. 519 length of 575.85 cm and a transmission efficiency of 98.7%. 496 So, we retained only the top 30 individuals in each generation 520 The beam emittance at the aperture of the optimized struc497 based on non-dominated sorting. As the number of iterations 521 ture remains comparable to that of the original design, and 498 increases, the solution set gradually shifts toward the lower 522 although the Kilpatrick factor shows a slight increase, it still 499 right corner, indicating continuous improvement in the tar- 523 falls within a reasonable range. For the redesign of the ADS 500 geted objectives. The green star symbol corresponds to the 524 Injector II RFQ, we also preserved the original structures syn501 RFQ we ultimately selected, as shown in Table 4 and Figure 525 [Figure 525: see original paper] chronous phase and modulation ranges.

However, the se502 14. 526 lection of solutions was focused on longitudinal emittance, 527 beam transmission efficiency, and cavity length. The selected 528 design yielded a total length of 409.56 cm and a transmis503 IV. DISCUSSION 529 sion efficiency of 99.8%.

Although the longitudinal emit530 tance was slightly higher than that of the original ADS In504 This paper presents the design optimization processes of 531 jector II RFQ, it remained within an acceptable range. In 505 RFQs for three representative application scenarios: LEAF, 532 the redesign of the PAFA RFQ, we further explored a de506 ADS Injector II, and PAFA, using a physics-informed genetic 533 sign strategy that allows significant variation in the B value, 507 algorithm. These cases demonstrate the broad applicability 534 introducing a new degree of freedom compared to the pre508 and significant advantages of the proposed method in RFQ 535 vious two cases and considerably increasing the complexity 509 beam dynamics design.

By introducing physically mean- 536 of the solution space. Benefiting from the increased design 510 ingful parameter constraints and evolution guidance into the 537 flexibility, we achieved a more versatile approach to focusing 511 design workflow, the method effectively reduces the search 538 and acceleration. The final RFQ structure was designed to be

351.98 cm in length, with a transmission efficiency of 99.8%. 582 rally favors smoother solutions, as they typically lead to betImprovements were also observed in both transverse and lon- 583 ter beam dynamics performance and are therefore more likely 541 gitudinal emittances. These three cases collectively validate 584 to be preserved during the iterative evolution. This behavior 542 that the physics-informed genetic algorithm can effectively 585 contributes to the engineering practicality of the resulting de543 meet the design requirements for RFQ beam dynamics, sig- 586 signs and reflects an implicit preference embedded in the evo544 nificantly enhance structural compactness and transmission 587 lutionary selection mechanism. This integration of domain 545 efficiency. 588 knowledge with evolutionary algorithms effectively balances Despite the different design strategies and constraint condi- 589 global search capabilities with physical plausibility, making 590 it an ideal methodology for RFQ accelerator beam dynamics 547 tions adopted in the three cases, the physics-informed genetic 591 design. 548 algorithm consistently demonstrated high computational ef539

V. CONCLUSIONS ficiency. For the ADS Injector II RFQ, the algorithm con- 592 550 verged to multiple physically superior Pareto optimal soluIn this paper, we propose a physics-informed genetic al tions within just 70 generations and approximately 280 core- hours using a modest population size of 100 individuals. In gorithm for the design of RFQ vane structures, namely the the more complex PAFA case, the redesign was completed beam dynamics design of RFQs. Using PIGArfq method, we within 20 generations and about 80 core-hours.

These re- conducted RFQ beam dynamics design for different applica sults highlight the methods ability to produce high-quality tion scenarios and compared the results with those of existing, solutions within relatively short runtimes, making it partic- experimentally validated RFQs. By incorporating physics ularly advantageous for large-scale RFQ beam dynamics de- based constraints related to beam dynamics and applying rea sonable limitations and evolutionary guidance to key param sign tasks. eters, we significantly improved the optimization efficiency In addition to the above cases, the SYSU-IFCEN He-RFQ and the physical validity of the solutions. This approach re was also successfully designed using the same methodol duced the overall design time and produced high-quality so ogy.

The algorithm efficiently converged to desirable so- lutions that balance beam performance with structural com lutions within 70 generations and approximately 300 core pactness. hours. The final design achieves an acceleration of He ions The optimized RFQ structures achieved varying degrees from 15 keV/u to 0.5 MeV/u within a total length of 143.42 of length reduction while simultaneously improving trans cm, with an acceleration efficiency of 97.4%. This further mission efficiency. Parameters such as beam emittance and demonstrates the robustness and adaptability of the physics the Kilpatrick factor remained within engineering-acceptable informed genetic algorithm across diverse RFQ design sce limits, demonstrating the robustness and adaptability of the narios. algorithm under multi-objective trade-offs. Furthermore, an Physics and engineering constraints serve not only as analysis of the evolution trends of key parameters along the boundary conditions for optimization but also play a guid- accelerator cells revealed that the physics-informed optimiza ing role throughout the process, including the generation of tion results exhibit more regular and physically consistent the initial population, individual selection, and crossover and structural features, which are advantageous for subsequent mutation operations. Compared to purely data-driven genetic fabrication and tuning processes. algorithms, our approach significantly reduces the occurrence In summary, the physics-informed genetic algorithm offers of physically invalid structures, thereby improving population a highly generalizable and adaptable approach for the effi quality, enhancing convergence speed, and ultimately yield- cient design of RFQs. Furthermore, this method holds sig ing solutions that exhibit superior performance across multi- nificant potential for application to a broader range of beam ple dimensions. In addition to these constraints, another note- dynamics design challenges. In the future, we will use this worthy feature of the optimized solutions is the smooth vari- 622 method to design a compact RFQ accelerator and carry out 580 ation of beam dynamics parameters. Although smoothness 623 fabrication and testing to validate the engineering practicality 581 is not explicitly constrained, the optimization process natu- 624 of the proposed design approach.

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