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# ALTERNATING PHASE FOCUSING UNDER INFLUENCE OF SPACE CHARGE DEFOCUSING

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*Abstract*

Alternating phase focusing (APF) recently emerged as a promising beam dynamics concept for accelerating bunched proton or ion beams in drift tube linear accelerators, eliminating the need for additional transverse focusing lenses. The performance of APF systems, similar to radio frequency quadrupoles, heavily relies on the employed focusing lattice, including the particle synchronous phase in each gap, as well as various hyperparameters such as the number of gaps, the focusing gradient, and the required beam acceptance. However, to fully utilize the cost advantages and mechanical simplicity of APF drift tube linacs, specialized software tools are necessary to streamline the accelerator development process. After successful development of the HELIAC-APF-IH-DTL for low current and continuous wave duty cycle, this paper presents the design concepts for APF cavities tailored for high-current applications, aiming to facilitate the design and implementation of APF-based accelerators.

## INTRODUCTION

The method of alternating phase focusing (APF) [1–5] for compact and less costly linacs has been implemented in several projects within the last decade [6–13], enabled by the increase in computing power. The APF method aims to remove magnetic focusing lenses from inside the linacs (close to the radio frequency quadrupole (RFQ)). Some applications introducing external (thus easily accessible) magnetic focusing lenses have been also proposed and implemented.

Two resonance acceleration cavities, implementing the APF method for lower current continuous wave heavy ion beams, have been designed applying the beam dynamics simulation code DYNAMION [14, 15] for the Helmholtz Linear Accelerator (HELIAC) project [10, 16, 17]. The new accelerator will supply beam for material science and superheavy ion research at GSI Helmholtz Centre for Heavy Ion Research (GSI). The APF cavities are currently in production. Whilst the APF cavities will be later used as injector for HELIAC, the expertise from designing such cavities were used to create a software to deliver APF designs rapidly.

The former prototyping software was capable of delivering beam dynamics prototype designs within weeks. In contrast, the new, improved software is capable of delivering preliminary beam dynamics prototypes within hours. Nevertheless, the beam dynamics layout does not remove the need for careful 3D-CAD design, as well as radio frequency (RF) and thermal simulations. The development now enables the linac designer to study the influence of hyperparameters such as the number of cells, the input emittances, the matching parameters, input/output energy, the electric field gradient, the gap/cell ratio, and the aperture radius. At this point, a reasonable enhancement to this software is to include space charge effects, which thus becomes an investigatable hyperparameter as well.

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## METHOD

For the APF method, a set of alternating synchronous phases (the phase of the electromagnetic field when the bunch is in the center of a gap) along the linac has to be found for the particular project, providing sufficient beam focusing in all directions for the given boundary conditions, like emittance, number of gaps, etc. Therefore, a set of phases is optimized to find an adequate layout using beam dynamics simulations repeatedly.

The core of the beam dynamics simulation consists of well-known equations [18, 19], accounting for acceleration of each particle by its respective synchronous phase, in order to feature the longitudinal deformation of the beam by the sinusoidal RF. Furthermore, the beam defocusing due to the transverse electric field component in between the drift tubes is considered as well. The transit-time factor is calculated for each gap in dependence of the gap length and particle velocity, the radial dependence of the transit-time factor [18] is also considered by

$$T_{\mathrm{TTF}}(r,\beta,g) = I_0(Kr)\frac{J_0(2\pi a/\lambda)}{I_0(Ka)}\,T_{\mathrm{TTF}}(\beta,g), \quad (1)$$

using the zeroth order Bessel function $J_0$, the zeroth order modified Bessel function $I_0$ , the radial particle position $r$, the aperture radius $a$, the RF wavelength $\lambda$ the particle velocity as fraction of speed of light $\beta$, the effective gap length $g$, and the constant $K = \frac{2\pi}{\gamma\beta\lambda}$.

The distance in between two drift tubes is derived during execution to map the set of synchronous phases along the linac to a geometric drift distance [10]. The voltage in each gap is derived by the gap- and cell-length at the current position, accounting for a non-flat electric field strength along the linac ($E_z(z) \propto \sin(\pi z/L)$).

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### *Space Charge Effects*

Space charge effects are considered by the simulation using single bunch Coulomb particle-particle interaction, whilst the simulation is intended to run with a low number of particles (below 1000). A cap-radius $r_{\mathrm{min}}$ was introduced to prevent single particles from being deflected out of the bunch because of low stepping parameter during calculation of the particle movement. This numeric effect would have been also prevented by fast Fourier transform (FFT) based space charge algorithm.

### *Advanced Code Optimization*

The global search for a set of phases along the linac becomes infeasible for a high number of gaps. The number of parameters to optimize must be reduced for efficient search.

As the drift tube linac (DTL) provides for radial symmetric focusing, the horizontal and vertical Twiss-parameters must be equal, removing already two search parameters ($\alpha_y$ and $\beta_y$). Furthermore, a subset of phases is used as base points for spline interpolation, from which the full set of phases is derived. This set of phases along the linac would only occasionally produce the desired output energy of the linac. Therefore, the overall amplitude of the set of phases has to be rescaled in accordance with the target output energy. This normalization of the simulation input parameters can be conducted with only one particle, multi-particle simulations follow as a final step.

For automated development, the quality of the results must be quantified by a cost-function, an example of a cost function for APF design can be found in a previous publication [10]. Global search of the subset of synchronous phases and the initial Twiss-parameters can be conducted by means of Monte-Carlo optimization. Also, more sophisticated optimization algorithms are easily accessible, for example *Basin-hopping* or *Differential evolution* from the *Scientific-Python* library [20]. Furthermore, a local search with a highly accurate simulation (and higher runtime) should be considered for fine-tuning of the results.

The methods above allows using prior knowledge for the optimization in the form of an *initial guess*. This allows to use and potentially refine precalculated sets of phases, as the sequences of Garashchenko [21], Svenson (see Eq. (2) [22]), or Fainberg (see Eq. (3) [3]).

$$\begin{aligned}\phi(n_{\mathrm{cell}}) =& a_0 - a_1 n_{\mathrm{cell}} \\ &+ a_2\, e^{-a_3 n_{\mathrm{cell}}} \\ &\cdot \sin\left((2\pi n_{\mathrm{cell}}/a_4) e^{-a_5 n_{\mathrm{cell}}} + a_6\right)\end{aligned} \tag{2}$$

$$\phi(n_{\mathrm{cell}}) = a_0 \cos(\omega t / a_1 (v/c_0)) \tag{3}$$

## HEAVY ION APF-DTL-DESIGN INVESTIGATIONS

To demonstrate the capabilities of the software, realistic boundary conditions are selected. At GSI, high current beam acceleration is present in the UNIversal Linear ACcelerator (UNILAC) [23–25]. For a technical demonstration of the software, boundary conditions comparable to this accelerator were used (see Table 1).

Table 1: Simulation Boundary Conditions [10, 23]

| **Parameter** | **Value** |
|---|---|
| Ion mass/charge ratio | 6 |
| Frequency | 108.408 MHz |
| Energy range | 1.4 MeV/u to 3.6 MeV/u |
| Aperture Radius | 15 mm |
| Electric field gradient (average) | 3 MV/m [a] |
| Longitudinal emittance (tot.) | 72 ° keV/u |
| Transversal emittance (tot.) | 18 mm mrad |
| Total/RMS emittance ratio | 6 |

[a] The gradient has been selected analogous to the HELIAC APF interdigital H-mode (IH) [10].

A basic set of 66 synchronous phases (APF) for zero current is derived using 10 spline base points, yielding a 6 m long linac. The beam current is iteratively increased and for each step the set of synchronous phases and the initial Twiss-parameters are reoptimized by local optimization using the Nelder-Mead-Simplex algorithm [26]. This results in a progressively changed set of phases and initial Twiss parameters (see Fig. 1).

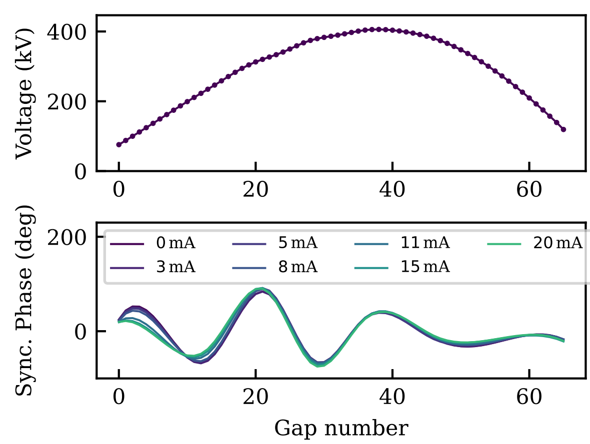


Figure 1: The set of synchronous phases is altered to conserve beam quality. The initial Twiss parameters are updated as well.

One can observe, that the phases at the center of the cavity are altered to stronger focusing, whereas the focusing strength at the start is decreased. The strong amplitude change of the phases in the beginning is caused by the low gap voltages there. Accordingly, in the region of high voltages at the center, the change of phases is lower. With this combination of changes, the beam focusing is altered, whereas the output energy remains unchanged. Nevertheless, it is not possible to conserve the beam quality entirely towards higher beam currents (see Fig. 2).

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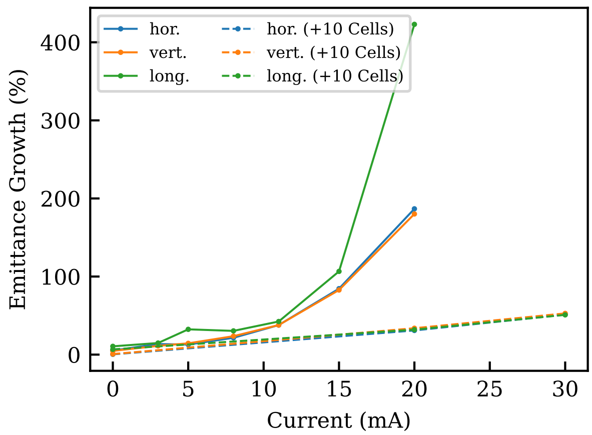


Figure 2: 10 different APF lattices (66/76 cells) are designed for different nominal beam current. The geometry is changed in accordance with Fig. 1 and 3.

In order to improve the beam quality, the designers options are either increasing the acceleration gradient (which might not be feasible due to arcing), or increasing the accelerator length. Here, the second option is chosen and 10 additional cells were added, increasing the capability of the system to focus the beam properly and maintain beam energy. After global optimization of the set of phases for the longer linac, the beam quality is drastically improved (see Fig. 2) due to a new set of synchronous phases (see Fig. 3).

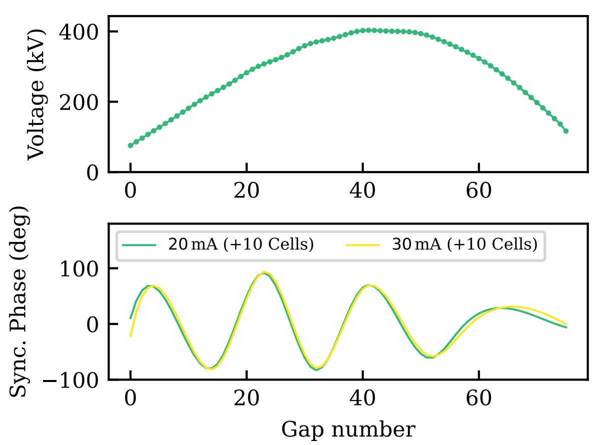


Figure 3: Set of synchronous phases for a 10 cells longer linac (76 cells total). The beam quality is increased (see Fig. 2), and acceleration at an even higher beam current is possible.

The simulation results have been double-checked using DYNAMION (see Fig. 4) and are in good agreement, especially given the two different scopes of the software packages: being very fast for the rapid APF software versus providing high accuracy and physics-based calculations of DYNAMION.

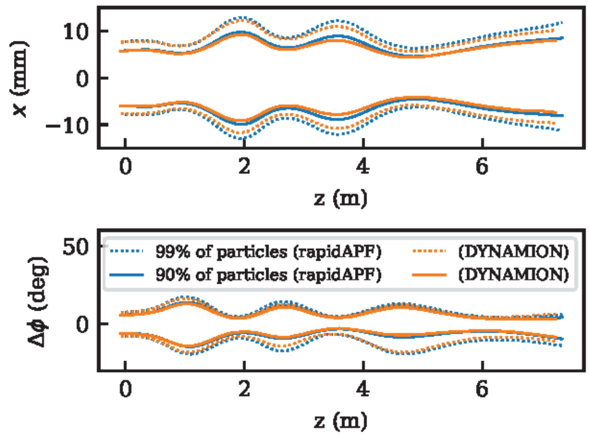


Figure 4: Comparison of beam envelope along the linac (76 cells total, 30 mA ion beam) between the rapid APF software and DYNAMION.

The phase planes and beam quality of the final tech-demo structure (30 mA ion beam, 76 cells) is depicted in Fig. 5. The emittance growth along the 7.3 m long linac, considering 90 % of the particles, is $\xi_z = 36\,\%$ longitudinally and $\xi_{x,\text{normalized}} = 50\,\%$ in both transverse plane.

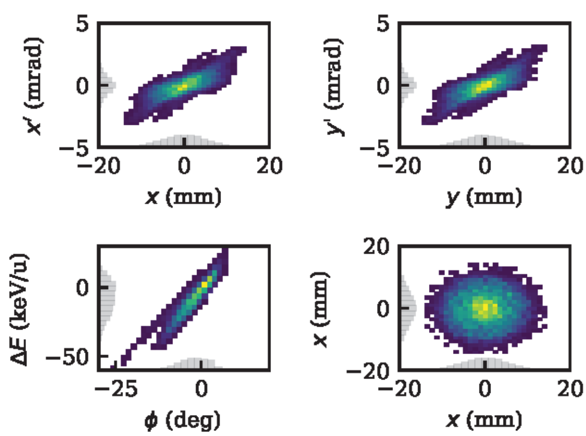


Figure 5: Output phase planes for the high-current APF tech-demo (76 cells, 30 mA ion beam).

There are several scenarios, under which a built APF cavity might not operate with the nominal current, e.g., during commissioning. Besides the nominal current, the beam quality is changed by too strong or low focusing forces along the linac. Two cases are investigated: non-nominal beam current without (*naive*) and with optimization of the input Twiss parameters (*opt*). The results of this investigation are depicted in Fig. 6. Towards higher beam currents, the beam quality decreases. A better beam quality is visible towards lower beam current, especially if the input Twiss parameters are adjusted accordingly. Thus, this APF cavity is also applicable at non-nominal beam current, whereas a lower beam current is preferable. Nevertheless, the specific behavior of

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an APF cavity should be investigated in accordance with the use case.

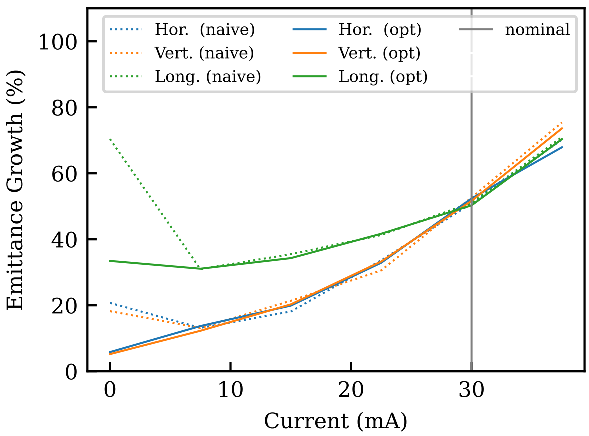


Figure 6: The same geometry of the high-current APF tech-demo cavity is kept with non-nominal beam current without (*naive*) and with optimization of the input Twiss parameters (*opt*).

## CONCLUSION

A software for rapid development of alternating phase focusing (APF) beam dynamics designs for compact and less costly linacs has been developed. Coulomb-based space charge has been implemented. As of high execution speed, the hyperparameters of APF linacs can be studied, e.g. the influence of the number of gaps, of the beam emittance or the beam current. A tech-demo is presented, achieving a 13 MeV total energy gain for 30 mA ion beam within 7.3 m linac with full transmission.

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