DESIGN AND SIMULATION OF PRACTICAL ALTERNATING-PHASE-FOCUSED (APF) LINACS – SYNTHESIS AND EXTENSION IN TRIBUTE TO PIONEERING RUSSIAN APF RESEARCH

R. A. Jameson, Inst. Angewandte Physik, Goethe Uni Frankfurt, Max-von-Laue Str. 1, Frankfurt-am-Main, Germany

Abstract

A high fraction of the cost and complexity of conventional linacs lies in the use of magnetic transverse focusing. The strong-focusing effect of alternating patterns (sequences) of gap phases and amplitudes – known as Alternating-Phase-Focusing (APF) – can produce both transverse and longitudinal focusing from the rf field. APF has undeservedly been deemed largely impractical because simple schemes have low acceptances, but sophisticated schemes have produced short sequence APFs with good acceptances and acceleration rates that are now used in a number of practical applications. Suitable sequence design has been difficult, without direct theoretical support, inhibiting APF adoption. By synthesizing reported details and adding new physics and optimization technique, a new, general method for designing practical APF linacs is demonstrated, using simple dynamics and no space charge – incorporation of space-charge and more accurate elements is straight-forward. APF linacs can now be another practical approach in the linac designer's repertoire. APF can be used in addition to conventional magnetic focusing, and could be useful in minimizing the amount of additional magnetic focusing needed to handle a desired amount of beam current.

ALTERNATING PHASE FOCUSING

Particles exposed to an rf field in a gap may receive focusing or defocusing forces in the transverse and longitudinal directions, according to the phase and amplitude of the gap field. Arranging a sequence of gaps in some particular manner, termed here an "APF sequence", can provide large simultaneous transverse and longitudinal acceptances with high acceleration rates and good emittance preservation.

Typical transverse focusing and energy gain per unit length (dW/dz) forces over the full 360° range of rf phase (phi) are shown in Fig. 1.

There is no adequate theory for determining an APF sequence with acceleration. There are some APF linacs in operation, but their designs were laboriously produced by hand, and the sequences are short. Further APF development has also been hindered by a misconception that APF acceptances are necessarily small.

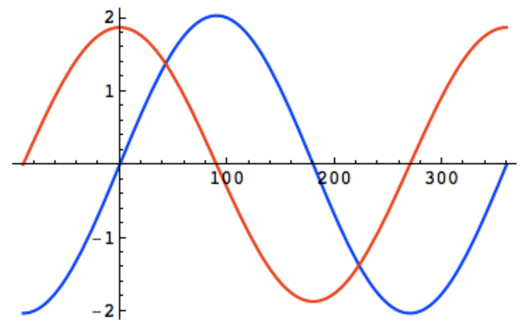

Fig. 1. Typical longitudinal acceleration (red) and transverse focusing forces (blue) over the full 360° range of phi.

THE APF SEQUENCE, AND SYNTHESIS OF A GENERAL METHOD

The most sophisticated work was realized in the USSR during the 1960's-1980's [1,2, and culminated in the "Garaschenko Sequence" [3], a 51-cell synchronous phase sequence for a 0.0147-1.0 MeV/u (factor 68), $_{238}U^{7+}$(qom=1/24), 6.8m, 25 MHz uranium-ion linac shown in Fig. 2, resulting from a complicated nonlinear optimization procedure to find the maximum longitudinal and transverse acceptances. The longitudinal acceptance was larger than for a typical RFQ.

A nonlinear optimization program must be given good enough starting points that it can converge to the correct optimum. Here the preliminary sequence was based on the extant schemes and a successfully operating APF linac at Dubna, which set out the general properties of the sequence in six separate focusing periods of 6-13 gaps and different spacings in each.

The great value of this paper is not that it helps find a good initial sequence, but that *it shows the form of an optimized sequence.* From this, we can draw very useful general conclusions. In particular, the full ±90° range can be used for high acceleration rate, and the period is extended as acceleration occurs to maintain the focusing strength, as with magnetic focusing.

During the next decades, work continued, especially in Russia by V.V. Kushin, V.K. Baev, and S. Minaev, who was a leading practitioner of actual APF designs until his death in 2010 and who influenced many extent APF designs. However, Minaev noted in [4] that "there is no theory for optimization of drift tube array so far" (i.e., for determining the underlying sequence); this is still the situation at this date. Summarizing details from the literature leads to a practical design method [5].

ISBN 978-3-95450-125-0

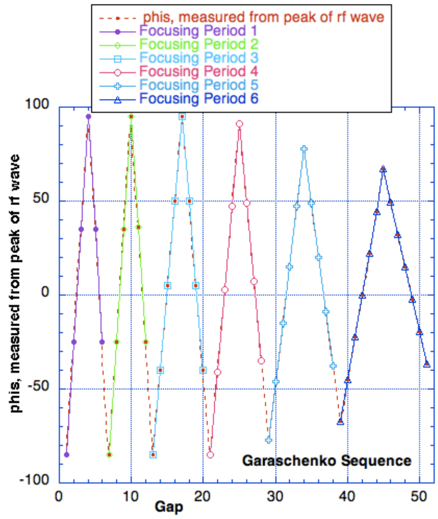

Fig. 2. Garaschenko APF sequence. Phis is measured from the peak of the wave. Overall the sequence is quasi-sinusoidal.

The IH linacs now in operation at NIRS, U. Gunma, and similar therapy machines under construction in Japan [6], have an underlying 72-cell quasi-sinusoidal APF synchronous phase pattern very similar to that of Garaschenko, expressed by a general 5-parameter sequence function written as:

$f_s(n)= f_0 \exp(-an)\sin((n-n_0)/(b \exp(cn)))$, where n is the cell number. The five parameters were searched, and the sequence then optimized for small output energy spread and output matching to the following section.

The well-known smooth approximation method was used to characterize the stability region, acceptances, and other features of the sequence [7], allowing sequence trajectories can be investigated on a transverse stability chart. The method is not well suited to determining an actual sequence with acceleration. However, it has an important utility in the synthesis of the new method.

Alternating both the field phase and amplitude allows small transverse emittance growth by aligning the sequence more along a line of constant phase advance on the stability chart [8].

There should be an offset of 5°-10° in the initial average value of the synchronous phase [3,8], and it is helpful to also have a tilt [3] so that the average synchronous phase tends from ~+5° to ~-5°. A tilt also helps avoid the danger of emittance equipartitioning via a synchrobetatron coupling resonance [9].

The first main result of the new method [5] is to extend the formulation of a general underlying gap synchronous phase phis sequence to a 7-parameter function:

```
phisapf =  phioffset*radian -
phitilt*radian*ncell +
phiampl*radian*Exp(phiatten*ncell)*Sin[2.*P
i*ncell/
(phiperiod*(1.d0-peratten*ncell)) +
phistart*radian]
```

A similar function could be applied to the gap amplitudes. The APF linac is then designed by simulation. A simple chain matrix representing each cell as a drift and an rf gap can be used. The linac is designed cell by cell, and thus acceleration is taken into account in fitting the phase sequence. The cell lengths are irregular, as determined by the local phase difference across the cell from the APF phase sequence, and the local velocity beta. A 7-dimensional grid search over the seven parameters can be performed quickly for zero beam current with a fast simulation code, with finer and finer grids. When parameters are found which give an initial adequate transmission, the sequence is optimized, using a new strategy, for the desired beam properties using nonlinear optimization techniques. The modeling can then be refined, with more accurate modeling, with space-charge, etc., and the process repeated.

It is useful for preliminary design work not to insist on completely realistic conditions. The gap voltage should be realistic, as determined from the Kilpatrick Criterion and structure peak field characteristics. However, at first the aperture should not be a restriction. Zero beam current and small input beam emittances are useful when searching for workable sequences.

Initial design of an ~60x energy gain linac by searching on Eq.(1) resulted in 23 cells, one sequence giving 99.97% best transmission, and another giving 99.47% best accelerated fraction, Fig. 3.

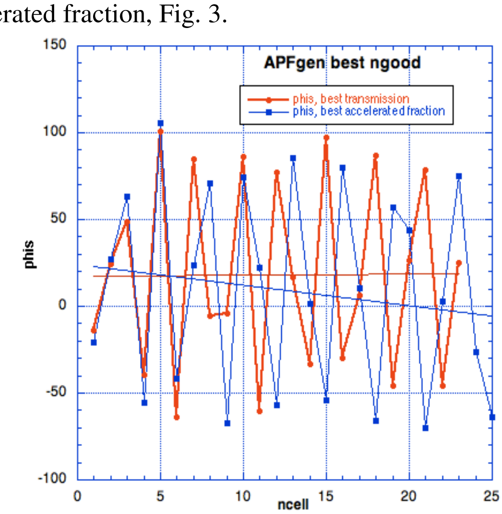

Fig. 3. The APF gap phase sequences for the best transmission (red) and best accelerated fraction (blue) cases. The linear fits show the effect of the tilt parameter.

Nonlinear constrained optimization directly on the 23 phis's for minimum emittance growth or output energy spread was straightforward. However, when a longer 164-cell sequence was explored, this direct method and others became difficult. The solution is the second main result of the new method [5]. The local sequence period at each cell is obtained by applying the sequence formula (1) at that cell, and computing the ncell ahead for which the period accumulates by 1. (phase advance of 2π). The new optimization strategy is then, at each cell sequentially, to optimize over the local period length,

ISBN 978-3-95450-125-0

with the objective function computed for the whole linac. This optimization strategy produced large improvements over the underlying Eq.(1) initial strategy; typical changes are indicated in Fig. 4.

APF linacs can now be another practical approach in the linac designer's repertoire, and can be considered as a candidate for any application, either alone or in conjunction with magnetic focusing.

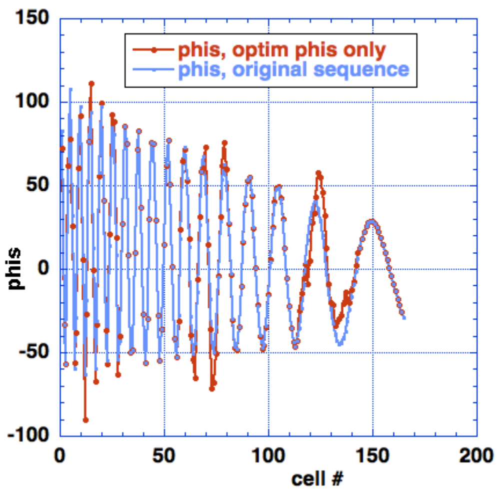

Fig. 4. Changes to original sequence by optimization on phis only, ±5° bounds.

ACKNOWLEDGEMENTS

This synthesis and extension of much foregoing detailed research in APF accelerator physics and modern control theory optimization techniques is based in particular on those authors cited in the references, particularly in Russia and Japan, and on pioneering work in optimal control of particle accelerator dynamics and Beam Dynamics and Optimization (BDO) Workshops at the Institute of Prof. D. Ovsyannikov, St.Petersburg State University. The support for part of this work from KEK, Japan, during visits as KEK Short-Term Invited Fellow is gratefully acknowledged.

REFERENCES

[1] "Efficiency of ion focusing by the field of a traveling wave in a linear accelerator", V.K. Baev & S. A. Mineav, Sov. Phys. Tech. Phys, 26(11), November 1981, p 1360.

[2] "Linear resonance ion accelerators with a focusing axisymmetric accelerating field", V.K. Baev, N.M. Gavrilov, S.A. Minaev & A.V. Shal'nov, Sov. Phys. Tech. Phys. 28(7), July 1983, p.788.

[3] F.G. Garaschenko, V.V. Kushin, et. al., "Optimal regines of heavy-ion acceleration in a linear accelerator with asymmetric variable-phase focusing", Zh. Tekh. Fiz. 52, 460-464 (March 1982)

[4] "APF or KONUS Drift tube Structures for Medical Synchrotron Injectors – A comparison", S.Minaev, 1999 PAC, p. 3555-3557.

[5] "Practical design of alternating-phase-focused linacs", R. A. Jameson, submitted to PRSTAB, June 2012.

[6] Y. Iwata, et. al., Proc. EPAC 2004, p.2631-2633; Y. Iwata, et.al., NIM A 567 (2006) p.685-696

[7] "Beam dynamics of Alternating Phase Focused Linacs", H. Okamoto, NIM A284 (1989) 233-247, North-Holland, Amsterdam

[8] Alternating Phase Focusing (APF) Linacs Developments and their Possible Applications", V.V. Kushin and S.V. Plotnikov, EPAC 1994, pp2661-2663.

[9] W.H. Cheng, H. Okamoto, et. al., "Synchrobetatron-coupling effects in alternating-phase-focusing linacs", Phys. Rev. E, Vol. 48, No. 6, December 1993, p. 4689-4698.