Practical design of alternating-phase-focused linacs

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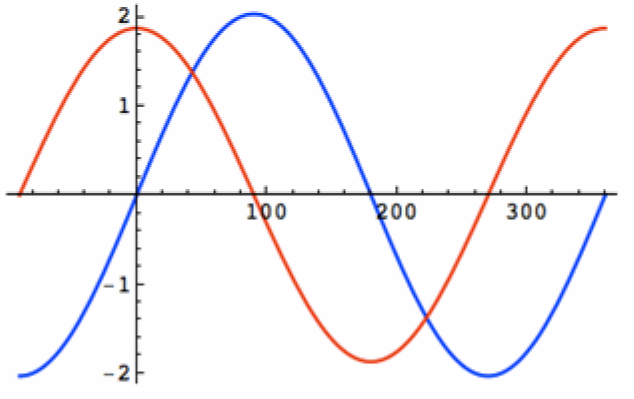
RuPAC 2012
September 24-28, 2012
St. Petersburg

- Magnetic transverse focusing in linacs is expensive and adds complexity.
- Both transverse and longitudinal focusing can be obtained from the rf field by using the strong-focusing effect of alternating patterns (sequences) of gap phases and amplitudes – known as Alternating-Phase-Focusing (APF).



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

- Simple schemes have small acceptances and have made APF seem impractical.
- However, sophisticated schemes* have produced short sequence APFs with good acceptances and acceleration rates that are now used in a number of practical applications.

* Originating mostly in Russia – including V.V. Kushin, V.K. Baev, S.A. Minaev, F.G. Garaschenko, V. Kapin; papers 1980’s to present, operating APF linac (Dubna) 1980’s, NIRS Japan injector linac.

- Although studied for decades, the design of suitable sequences has been difficult, without direct theoretical support for determining the detailed sequence.
- This, and small acceptances of naïve schemes, inhibited APF adoption.

  – *APF's poor reputation could be improved!*
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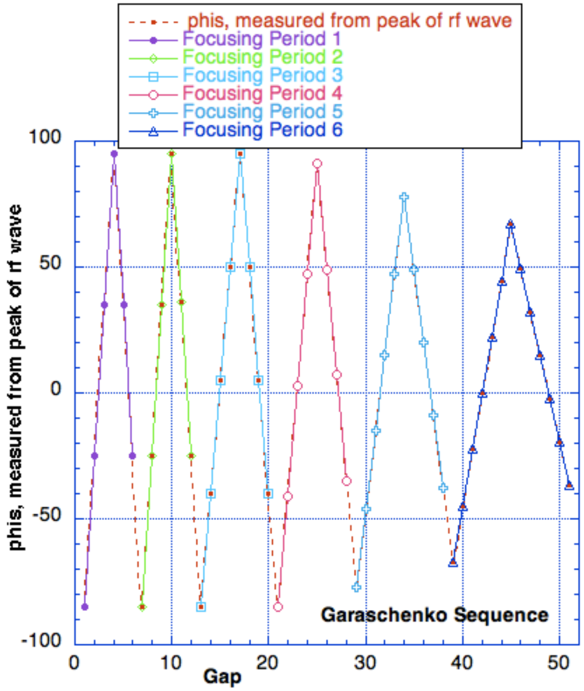
- We make a synthesis of reported details, add new physics and technique, and get a new, general method for designing practical APF linacs.

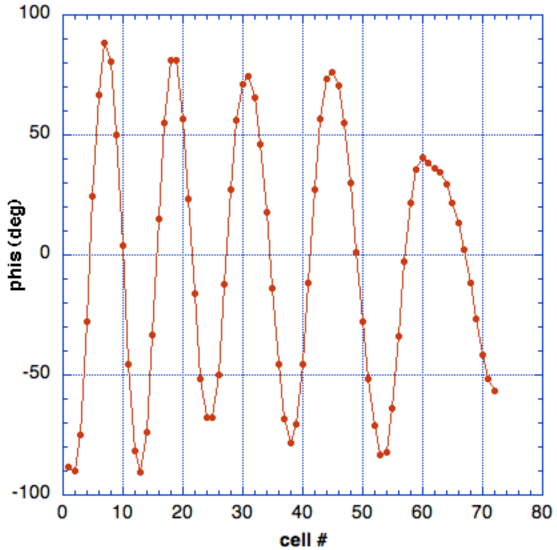
- Interested in high energy gain factors (>100), long sequences.
- Demonstrate with simple dynamics and no space charge. When this yields a good starting point, then can add space charge, more elaborate modeling, to determine practicality for actual project.
- APF can also be used to augment magnetic focusing, with possible cost savings.

- 1. The form of an optimum sequence is known:



- Garaschenko Sequence (1981):
- Six separate sequences joined.
- Optimized for maximum acceptances by complex optimization scheme.
- Starting sequence from operating Dubna APF linac.
- Quasi-sinusoidal

- NIRS, Japan $C4^+$ APF Injector Linac Sequence is similar:



- Preliminary design using 5-parameter sinusoidal function:

$$f_S(n) = f_0^{(-an)} \sin\left(\frac{(n - n_0)}{b^{cn}}\right)$$

where n is the cell number.

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Optimized for small output energy spread and matching by Monte Carlo method.

- # Gather information about optimum sequence:

- Quasi-sinusoidal, can specify fitting parameters
- Full $\pm 90^{\circ}$ range gives high acceleration rate.
- Lengthen period as beta increases.
- Initial 5°-10 offset, and tilt to ~-5° at end can be helpful; prevents synchro-betatron resonance.
- Smooth approximation phase advances (Okamoto, Qiang, Delayen): useful info, but no direct method for sequence design.
- Alternating both gap phase and amplitude can reduce emittance growth by aligning sequence along a line of constant phase advance.

• General APF Design Method:

1. ***Emphasis on a practical method – not theoretical***

2. **An optimal sequence can be based on a general sinusoidal form for modulation of the gap synchronous phase phis, with a 7-parameter function:**

$$phisapf = \boldsymbol{phioffset} - (\boldsymbol{phitilt})(ncell) + (\boldsymbol{phiampl})^{(-(\boldsymbol{phiatten})(ncell))}(\sin(\frac{(2\pi)(ncell)}{((\boldsymbol{phiperiod})(1-(\boldsymbol{peratten})(ncell))}) + \boldsymbol{phistart})$$

(Could add similar function for gap amplitudes, but we will do this in an optimization step. Would also need to add a parameter for the phase difference between the phase and amplitude modulations – total of 15 parameters.)

3. **Use simple drift, thin lens gap, no space-charge, multiparticle dynamics model to design and simulate.**

- ## General APF Design Method:

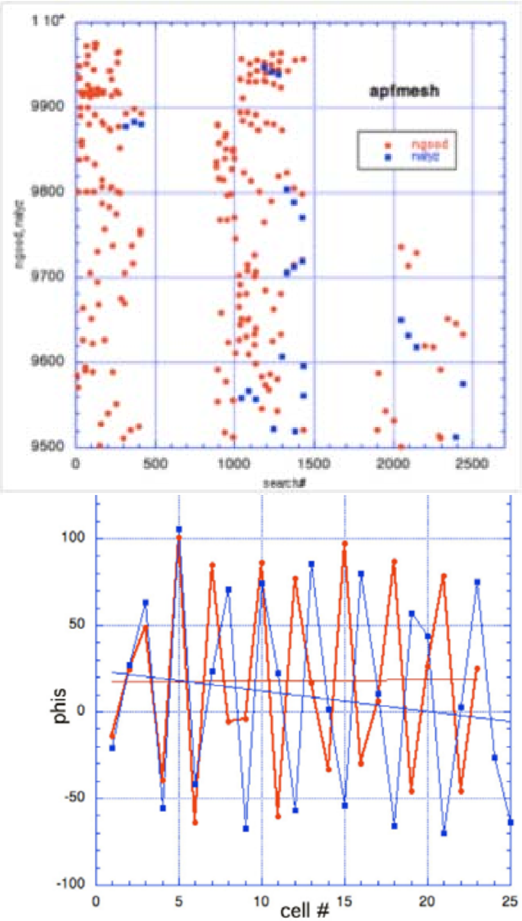
3. At first, do not constrain aperture, do with no space charge and small emittances.

4. 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.

5. When parameters are found which give an initial adequate transmission, the sequence is optimized by nonlinear optimization techniques, ***using a new strategy,*** for the desired beam properties (max accelerated fraction, small emittance growth, low output energy spread, etc.)

6. The modeling can then be refined, with more accurate modeling, with space-charge, etc., and the process repeated.

• Initial design of a 0.34-20 MeV muon APF linac



Search result, and the APF 23 cell gap phase sequences for the best transmission (red) and best accelerated fraction (blue) cases. The linear fits show the effect of the tilt parameter.

Best transmission and best accelerated fraction occur at different sequence parameters:

phioffset	20.0
phitilt	0.00
phiampl	90.0
phiatten	0.01
phiperiod	2.3
peratten	0.008
phistart	50.0

Table 1. Initial parameter search result for best transmission, 99.8%.

phioffset	25.0
phitilt	1.00
phiampl	90.0
phiatten	0.008
phiperiod	2.3
peratten	0.009
phistart	55.0

Table 2. Initial parameter search result for best accelerated fraction, 99.5%.

- Constrained nonlinear optimization on the 23 phis points directly:

Objective function	*Xmsn, Accel, %*	*etn growth*	*energy spread*
Starting sequence	99.06	1.683	2.681
1. max xmsn	99.27	3.534	2.773
2. max accelerated	99.40	2.187	2.916
3. min etn growth	95.05	1.674	2.679
4. min energy spread dW, %	95.39	2.137	1.566
5. min (etngrowth, dW/2)	99.18	1.230	1.714
6. min (etngrowth, dW/2,(npoints-naccel)/20)	99.28	1.401	1.988

Short sequence, procedure converges ok.

Also optimized on both phis and gap amplitudes

Similar method up to this point also reported from IMP, CAS, Lanzhou, China.

- Now tried longer sequences:
- Could find sequence parameters giving reasonable transmission and acceleration,
- But optimization strategies ineffective or difficult to converge:

  - optimization on all sequence points directly.
  - optimize successively each sequence point individually.
  - optimize from each cell to the end successively.

    In each case, the objective function is
    computed over the whole linac.

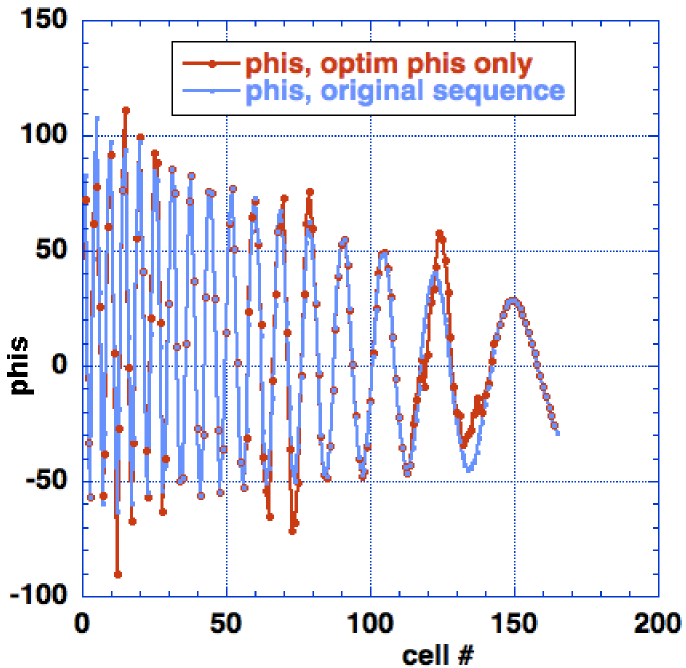
- The optimization strategy needs better information.

- Recall that the Garaschenko Sequence is six separate sequences joined, with lengthening period.
- Other references also show hand-optimized separate sequences adjoined.
- The smooth approximation phase advances are based on a focusing period of N cells.
- Compute N <u>locally</u> at each cell – the number of cells for the period to accumulate by 1 (phase advance of 2π)
- **The new optimization strategy is then, at each cell sequentially, to optimize over the local period length N, with the objective function computed for the whole linac.**

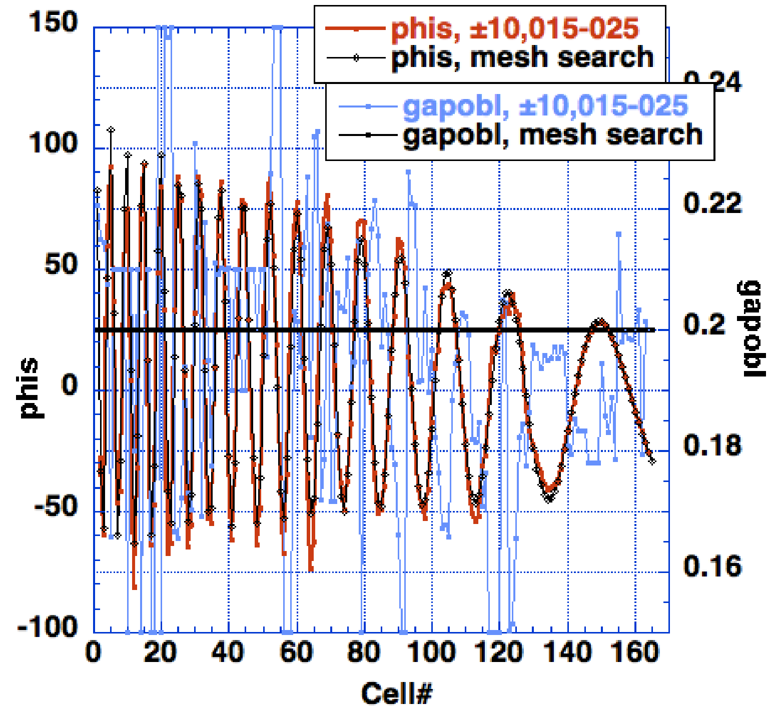
- Long sequences then successful.
- Example: **2-200MeV 324 MHz H+ APF linac**

~164 cells, aperture 1.5-3.0 cm, total length ~45 m.

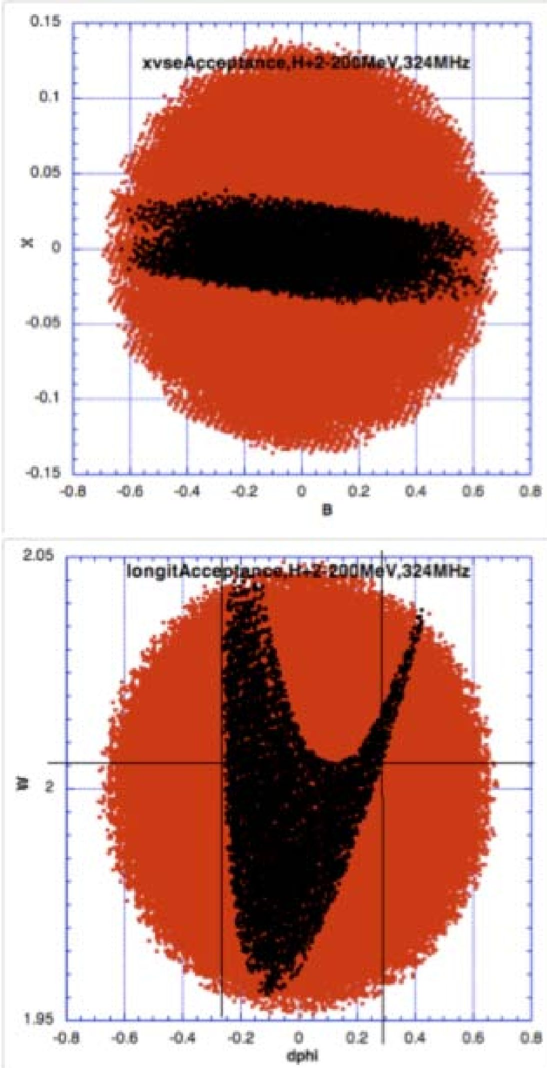
Transmission and accelerated fractions >94%, etn growth ~2, dw <±1%



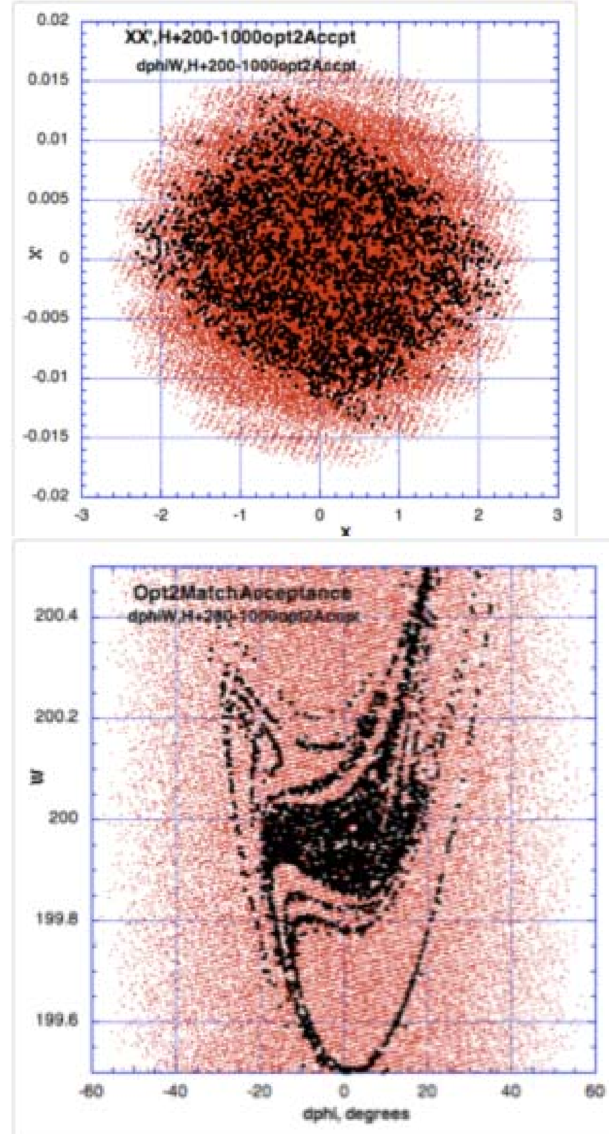
Changes to original sequence by optimization on phis only, ±5° bounds.



Change to original sequence by optimization on both phis with ±10° bounds and on gapobl with bounds 0.15-0.25



a. Transverse acceptance of a 2-200MeV, 324 MHz H+ APF linac. b. Longitudinal acceptance.



a. Transverse acceptance of a 200-1000MeV, 972 MHz H+ APF linac. b. Longitudinal acceptance.

- # Model Enhancement

Once a sequence for zero-current and other optimistic conditions has been found, the model can be enhanced in steps to find out if APF is a possibility for the actual project:

- use realistic aperture
- add space charge
- use realistic gap model
- 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 the desired amount of beam current.

- Conclusions

  - 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.

    -- Initial sequence found by searching over 7 parameters of a generalized gap phase sinusoidal function. Could be extended for gap amplitude modulation and phase between gap phase and amplitude modulations.

    -- Optimization from the parameter mesh search result is then done with a constrained nonlinear optimization program, using essential accelerator physics information about the period of the smooth approximation phase advance to achieve convergence.

    -- The program was used to demonstrate, for the first time, that very long APF linacs with high energy gain factors are possible.

    -- Steps to incorporate space-charge and more accurate elements are straight-forward.

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 during visits as KEK Short-Term Invited Fellow is gratefully acknowledged.

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