# Alternating Phase Focusing (APF) Linacs Developments and their Possible Applications

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*Abstract*

The recent experience of the ITEP applied resonant linacs laboratory in the field of APF systems combined with different types of radiofrequent accelerating structures for light and heavy ions is considered. Well known APF linacs features of high rates of energy gain and comparative technological simplicity make it possible to consider wide possibilities of their applications for scientific, industrial and medical aims. Projects parameters of the deuteron for neutron source and the heavy ion linac for politrack membranes producing technology are discussed.

## 1 INTRODUCTION

The alternating phase focusing (APF) [1] is based on periodic changes of RF field synchronous phase sign to maintain longitudinal and transverse beam stability simultaneously. Then methods of substantial improvements of APF properties based on asymmetry introduction in phase and amplitude distributions RF field along APF linac were suggested. In 1970s the asymmetric APF (AAPF) theory was created, methods of its practical realization in multigap structures were found and first APF experimental linacs were tested [2]. Recently a number of publications concerned with different aspects of beam dynamics in APF channels and APF practical realization in accelerator centers have been discussed [3].

## 2 MAIN ASPECTS OF THE AAPF THEORY

Usually the APF channel is a sequence of alternate phasing and dephasing semi-periods. As an example, consider a travelling wave channel consisting of alternate phasing and dephasing semi-periods. From one semi-period to another the synchronous phase pattern and RF field amplitude change their magnitudes in accordance with: $\phi_s = \phi_0 \pm \phi_1$; $E_m = E_0 \pm \Delta E$; and for non-synchronous particles: $\phi = \phi_s + \Delta\phi$. The asymmetry on the focusing period is caused by the fact that a synchronous particle moving from one semi-period to another passes accelerating field which changes as in phase due to constant component $\phi_0$ so in amplitude due to alternating component $\pm\Delta E$. So just $\phi_0$ and $\varepsilon = \frac{\Delta E}{E_0}$ characterize the rate of RF forces asymmetry. Radial and phase particle motions in the APF channel may be described by Mathieu-Hill equations. For small longitudinal oscillations these equations can be written in the dimensionless form:

$$\frac{d^2\sigma}{dz^2} + (-A_{ph} \pm \Lambda_{ph}^2)\sigma = 0, \qquad \frac{d^2\rho}{dz^2} + (-A_\rho \mp \Lambda_\rho^2)\rho = 0,$$

where $\sigma, \rho$ and $z$ are dimensionless phase, radial and longitudinal coordinates respectively. Coefficients $A_{ph}$ and $A_\rho$ characterize longitudinal and transversal RF defocusing strengths averaged over focusing period while $\Lambda_{ph}^2$ and $\Lambda_\rho^2$ are responsible for sign-variable RF field focusing gradients. These coefficients are connected with linac parameters according to the following relations:

$$A_{ph} = -2B(sin\phi_0 cos\phi_1 + \varepsilon cos\phi_0 sin\phi_1);$$
$$\Lambda_{ph}^2 = 2B(cos\phi_0 sin\phi_1 + \varepsilon sin\phi_0 cos\phi_1);$$
$$A_\rho = B[sin(\phi_0 + \Delta\phi)cos\phi_1 + \varepsilon cos(\phi_0 + \Delta\phi)sin\phi_1];$$
$$\Lambda_\rho^2 = B[cos(\phi_0 + \Delta\phi)sin\phi_1 + \varepsilon sin(\phi_0 + \Delta\phi)cos\phi_1];$$
$$B = \frac{\pi\eta E_0 K_f^2}{W_0\beta_s\gamma_s^3}.$$

In these relations $E_0$ - average value of electric field amplitude within the focusing period, $\eta$ - ion charge to mass ratio, $W_0$ - proton rest energy, $K_f$ - focusing period ratio, $\gamma$ - Lorentz -factor, $\phi_0$ - synchronous phase level component, $\phi_1$ - synchronous phase alternating component.

Assuming phase oscillations to be slow in comparison with the radial ones radial stability of particles motion can be characterized by the position of its representative point with appropriate phase departure at the stability diagram(fig.1). The maximum amplitude of phase

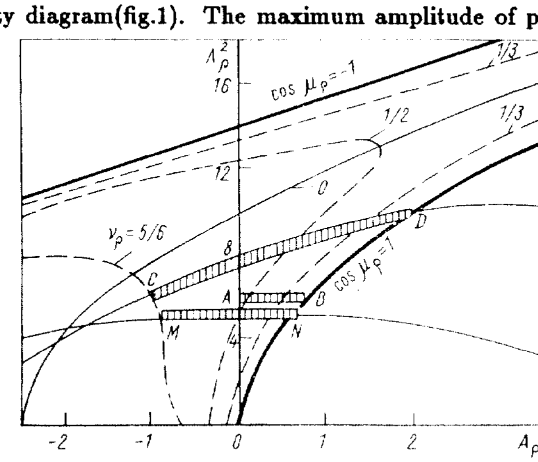


Figure 1: Transverse stability chart

oscillations with the simultaneous radial stability for non-synchronous particles is proportional to the arc length from the chosen "working" point to the point of crossing the representative point trajectory with the nearest border of a stability region. Curve AB corresponds to the symmetric case of APF when $\phi_0 = 0$ and $\varepsilon = 0$. Curves MN and CD correspond to different variants of AAPF realization. MN path is defined by using $\phi_0 \neq 0$ and $\varepsilon = 0$, and, finally, curve CD corresponds to simultaneous phase and amplitude modulation, that is $\phi_0 \neq 0$ and $\varepsilon \neq 0$. It should be noted that in the first two variants (curves AB and MN) there is a substantial beam emittances growth while in the last case (curve CD) the representative point moves along the line of constant $\mu$ and emittance build-up is small.

By choosing asymmetry parameters one could find regimes when decreasing of one force causes increasing of the other and stability of particles motion increases considerably. Analogous suggestions have been under discussion recently for independently-phased short structures The comprehensive analysis shows that usually optimum values of field modulation $\varepsilon$ seem to be chosen in the range from 0.2 to 0.4 and $\phi_0 = 5^0 - 10^0$. Thus, by adventing of RF field phase and amplitude modulations, it becomes possible to increase considerably phase oscillation amplitudes and to make them comparable with the ones allowed by self-phasing. Certainly, these approximate estimates can be used only for rough parameters option and should then be specified by accurate numerical simulations.

## 3 AAPF REALIZATIONS IN RF STRUCTURES

For practical using of AAPF in RF linac structures all necessary changes of synchronous phase of the designed particle may be ensured by choosing lengths of drift tubes and accelerator gaps. Meanwhile, realization of simultaneous field amplitude modulalation in multigap structures is a rather complicated problem. In RF tuning any change of drift tubes positions gives rise to the change of resonant frequency and field redistribution. To simplify this problem a new resonant structure was suggested and developed at ITEP (fig.2). It is a rectangular-shaped H-resonator

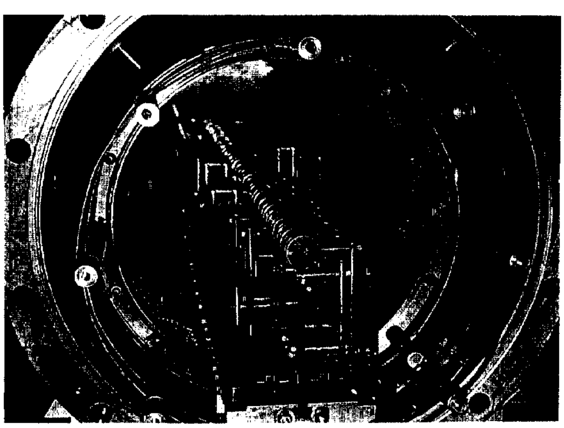

Figure 2: 10 MeV deuteron linac structure

with drift tubes with carring rods mounted alternatively on plates both sides. There is no need in accurate simulation of the resonant frequency for such structures. Its tuning may by fulfilled experimentally by simple vertical shuffling of the bottom plate of the rectangular frame along the side plates. To meet field modulation requirements an additional plate is fixed on the bottom plate in the middle between the side plates [4]. Some drift tubes being mounted alternatively on both surfaces of this plate are quarter-wave vibrators shortened mainly by electrocapacities between drift tubes. Their tuning for the required field distribution along the structure is the procedure of accurate choosing appropriate points on side and central plates to fix drift tubes supports.

This type of structure was tested for different versions of 6 MeV preaccelerating section for helium ions in ITEP proton synchrotron injector installation on a round-clock basis [5]. Scopes for extremely high energy gain rates (up to 8 MeV/m) with a rather good agreement with calculations were confirmed. Use of this APF section as a part of the injector installation allowed to extend considerably the range of accelerated ions by means of simple move-remove of the APF resonator at the acceleration axis.

The above mentioned structure has served as a prototype for a new 10 MeV APF linac resonant structure for deuterons. Its main parameters are in table 1.

Table 1: 10 MeV deuteron linac parameters

| | |
|---|---|
| Input energy | 75 keV/amu |
| Output energy | 5 MeV/amu |
| Radiofrequency | 148.5 MHz |
| Max. electric field on the axis | 16 MV/m |
| RF structure length | 2.0 m |
| Number of drift tubes | 40 |
| Aperture radius | 3 mm |
| Q-factor | 5200 |
| Max. pulse RF power | 1.5 MW |

In fig.3 experimental distribution of the field gradient squared is shown. It has peculiar alternation of gap fields

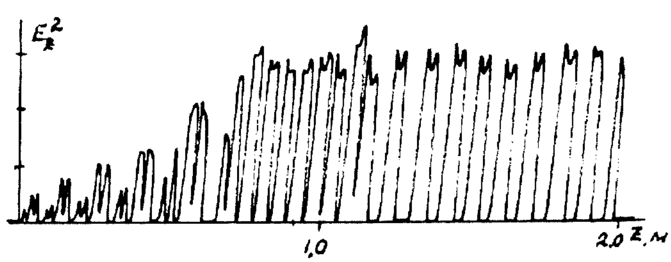


Figure 3: Experimental field distribution

increasing along the first third of the structure, i.e. practical realization of field modulation. Then the field gradient is kept constant, about 16 MV/m, to reach the rated energy gain. Now the structure is being prepared for high power tests. The rated value of deuteron beam pulse current is 5 mA. This structure will probably serve as a prototype for neutron source facility which combines subcritical multiplying assembly driven by the accelerated deutron beam. Rather promising applications are also envisaged in medicine as a compact and comparatively cheap sources of fast light ions with energies of 10-20 MeV for PET tomography or boron neutron capture therapy facilities.

## 4 APF FOR HEAVY ION LINACS

Taking into account APF features of low injection energy and high energy rate together with technological simplicity of focusing elements, heavy ions with low charge-to-mass ratios seem to be most adequate ones for acceleration in APF linacs. The experimental developments of APF application for very heavy ion linacs have been carried out in ITEP from last 1980s. The first practical experience was acquired with the putting into operation the 6m linac for ions with minimum charge to mass ratio of 1/46[6]. Fig.4a shows the calculated longitudinal acceptance for $W^{+4}_{184}$ ions and fig.4b - transversal acceptances for different input phases ($-50^o$ - short dashed, 0 - solid line, $+50^o$ - long dashed) that were reached in view of field gradient modulation. There were some problems during the tun-

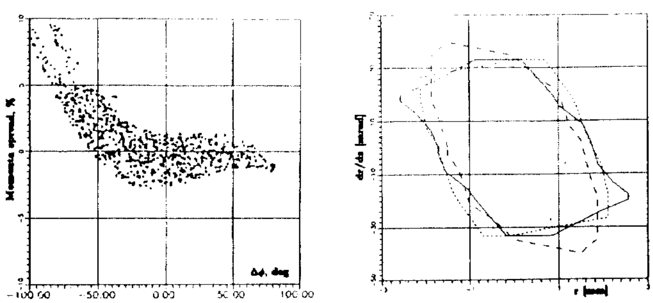

Figure 4: Longitudinal and transverse acceptances

ing procedure with getting an optimum field distribution with field gradient modulation. Nevertheless, the linac was put into operation after additional calculations with the reached distribution and appropriate correction of several drift tubes and accelerating gaps lengths. Mo and W

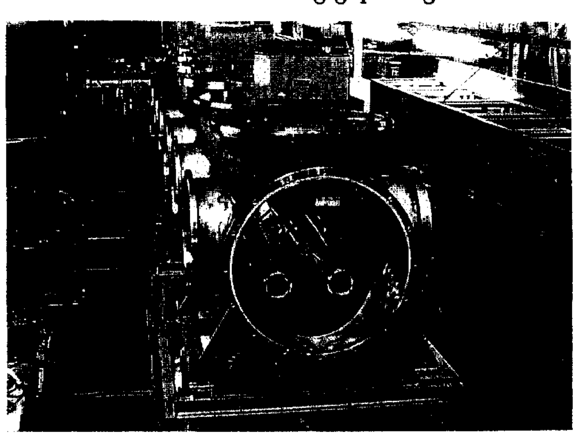

Figure 5: Experimental linac for heavy ions

ions were accelerated in pulse regimes to 0.31 MeV/amu

Table 2: Design parameters of the prestripper section

| | |
|---|---|
| Nominal charge-to-mass ratio | 1/46 |
| Input energy | 27 keV/amu |
| Output energy | 0.42 MeV/amu |
| Radiofrequency | 40.7 MHz |
| Maximum RF field gradient | 10.2 MV/m |
| Beam pulse length | 200 $\mu s$ |
| Pulses repetition rate | 25 pps |
| Section length | 6.0 m |
| Required RF power (pulse) | 1.5 MW |
| Project beam intensity | 5 $10^{11}$ p/s |

in the 18.7 MHz Wideroe-type resonant structure (fig.5). This experimental linac allowed to test different linac units such as RF power supply, beam generation and extraction from MEVVA-type ion source, injector supply and some technological aspects. On the other hand, first sessions of thin polymer films irradiation were fulfilled which allowed to choose optimum conditions for pulse irradiation modes. Now the test linac serves as a prototype of the prestripper accelerating section for industrial complex for particle-track membranes (PTM) production.

For PTM technology the heaviest ions are best suited. Membranes being made by use of extremely heavy ions have advantages of good selectivity for the maximum porosity and comparative simplicity of the etching process. To meet requirements of high porosity (20% and even more) with good mechanical properties of PTMs, 20-30 $\mu m$ films seems to be optimum. An industrial PTM production complex based on 1.7 MeV/amu APF linac for tungsten ions is under way now on the electronic instruments enterprise "Tenzor" in Dubna. The linac includes a 30.5 kV injector with a MEVVA-type ion source which produces $W^{+4}$ ions, the beam formation stage based on RFQ section, two APF sections separated by a stripper section placed between them, and the output transportation channel for beam scanning and formation of a broad irradiation field at the moving polymer film target. The prestripper APF section parameters are given in table 2.

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