ION ACCELERATION IN APF SYSTEMS

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ABSTRACT

Theoretical aspects of the alternating phase focusing (APF) principles and methods of its practical realization in linacs are considered. Some branches of accelerator science and technology are discussed for which APF features are the most attractive. Of special interest are the methods of ion capture increasing by means of choosing special regularities of RF field phase and amplitude varying along the accelerator channel period. Procedures of energy gain speed and accelerated beam intensity increasing are also discussed. Some difficulties of wide practical APF applications in different accerating structures are analized. Problems of the RF field adjusting in resonant structures for light and heavy ions are also discussed. It seems to be evident that the APF principle is the most preferable for heavy and super-heavy ions accelerators in particular due to its possibility to meet requirements of linac compactness. Review of up-to-date APF linacs in different accelerator centers is given.

INTRODUCTION

The concept of auto-phasing (APh) was discovered 50 years ago and most of up-to-date RF linacs are working on that principle. According to that concept, RF accelerating field ensures longitudinal stability of bunches in the visinity of a synchronous phase. But transversal nonstability appears simultaneously and it is nesessary to eliminate it by means of different focusing systems. 10 years later another possibility of reaching simultaneous transversal and longitudinal stability in RF linac was found [1]. It was shown that such a stability can be reached by periodical changes of the synchronous particle sign along the linac. In this case auto-phasing disappeared but sign variable phasing is created which ensured longitudinal stability of accelerated bunches. Simultaneously transversal stability is brought about by means of alternating focusing and defocusing forces. This class of RF linacs was called "alternating phase focusing (APF) linacs". Analysis showed that phase length of the capture regions in APF is only $10-15°$ and less than 1% in the acceptable spread of longitudinal velocities at the input. That is why APF systems didn't find immediate and wide use in RF linacs. But about 20 years ago the author of this paper together with collegues managed to improve substantially APF properties by introducing asymmetry in phase and amplitude distributions of RF field along APF linac. 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 concerning different aspects of beam dynamics in APF channels and APF practical realization in accelerator centers has been discussed [3].

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 ϕ_0 so in amplitude due to alternating component $\pm\Delta E$. So just ϕ_0 and $\varepsilon = \frac{\Delta E}{E_0}$ characterize the rate of the 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:

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

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

$$A_{ph} = -2B(sin\phi_0 cos\phi_1 + \varepsilon cos\phi_0 sin\phi_1);$$

$$\Lambda^2_{ph} = 2B(cos\phi_0 sin\phi_1 + \varepsilon sin\phi_0 cos\phi_1);$$

$$A_\rho = B[sin(\phi_0 + \Delta\phi)cos\phi_1 + \varepsilon cos(\phi_0 + \Delta\phi)sin\phi_1];$$

$$\Lambda^2_\rho = B[cos(\phi_0 + \Delta\phi)sin\phi_1 + \varepsilon sin(\phi_0 + \Delta\phi)cos\phi_1];$$

$$B = \frac{\pi\eta E_0 K_f^2}{W_0\beta_s\gamma_s^3}.$$

In these relations E_0 - average value of electric field amplitude within the focusing period, η - ion charge to mass ratio, W_0 - proton rest energy, K_f - focusing period ratio, γ - Lorentz -factor, ϕ_0 - synchronous phase level component, ϕ_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 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 μ (μ is a phase advance of transversal oscillation on a focusing period) and emittance build-up is small.

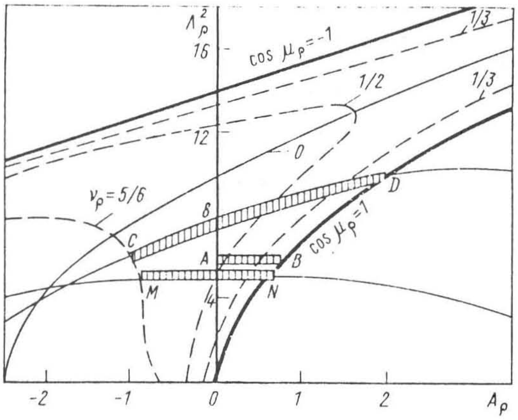

Fig. 1: Transverse stability chart

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.

Let's take for protons, for example, λ = 2 m, $\phi_1 = 60 - 70°$, L = $(2-3)\beta\lambda$ and unusual for ions values of E_m = 5-8 MV/m. Parameters of longitudinal and transversal captures for this case are the following:

$$\phi_m = 30 - 35°, (\frac{\Delta v}{v})_m = \nu_{ph}\frac{\Delta\phi_m}{2\pi}\frac{1}{k_f} = 1.5 - 2\%,$$

$$R = 0.5cm, \frac{\Delta\tau}{\tau} = \nu_f\frac{R}{L_f} = 50 - 70mrad.$$

Parameters of longitudinal capture compare unfavourably with usual separatrix of APh linacs being half as large in phase length and one-third or even one-fourth in longitudinal velocities spread. Nevertheless, transversal acceptance meanings in APF and APh linacs are practically the same under equal R and L_f. Comprehensive analysis shows that usually optimum values of field modulation ε seem to be chosen in the range from 0.2 to 0.4 and $\phi_0 = 5° - 10°$.

There are several papers dealing with APF limit beam current calculations under different approaches. For easy-to-interpret, it may be useful to make comparison for limit currents of APF and APh linacs with low injection energies. In these cases transversal space charge forces impose restrictions on limit current mainly. For APF linacs limit current I_1 may be estimated according to the formula:

$$I_1 = I_0\frac{\Delta\phi_{m1}\beta_s^3\mu_\rho\nu_\rho\gamma_s^3}{\pi\kappa^{0.5}}(\frac{R_1}{L_{f1}})^2,$$

and for APh linac an analogous formula is the following:

$$I_2 = I_0\frac{\Delta\phi_{m2}\beta_s^3\mu_\rho\nu_\rho\gamma_s^3}{\pi}(\frac{R_2}{L_{f2}})^2,$$

and relation of limit currents may be expressed by the formula:

$$I_1 = I_2\frac{\Delta\phi_{m1}}{\Delta\phi_{m2}}(\frac{R_1L_{f2}}{R_2L_{f1}})^2.$$

Taking into account $\Delta\phi_2 = (1.5\text{-}2)\phi_1$, $R_1 = R_2$ and $L_{f2} = L_{f1}$, we get $I_1 = 0.5I_2$. The characteristic values of limit currents for protons in APF linacs with different injection energies were quoted as follows: W_{in} = 200keV I_m=20-30 mA [4], W_{in} = 700 keV I_m= 100mA [5], W_{in} = 2 MeV I_m= 320mA [6].

The last two cases assume use of RFQ sections (with inherent focusing period length of $\beta\lambda$) as an injector stage. The calculated results for proton RF linac at 800 MHz and 2 MeV injection are shown in fig.2, taken from [6].

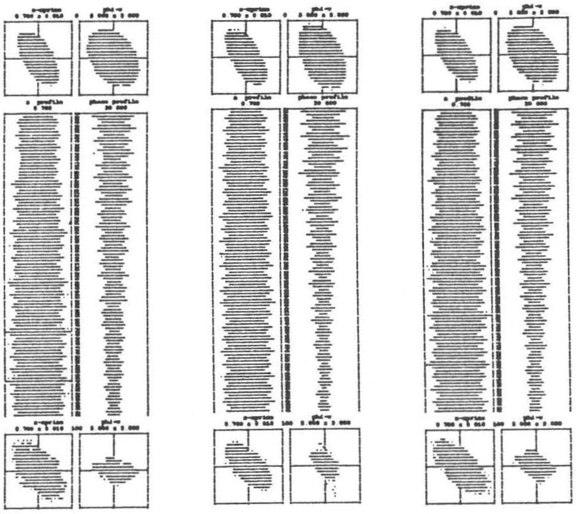

Fig. 2: Beam profiles and phase space distribution for: a) I=215mA, b) I=290ma, c) I=320mA

EXPERIMENTAL STUDY OF APF SYSTEMS

For practical application 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 the drift tubes positions gives rise to the change of resonant frequency and field redistribution. That's why it was desided to refuse from any field amplitude modulation and use only synchronous phase modulation ($\phi_0 = 5 - 10°, \phi_1 = \pm 60°, \varepsilon = 0$). For the first time a proton pulse beam of 1 mA (under 3 mA projected) was accelerated in experimental 550 keV APF linac with the injection energy of 50 keV. The second experimental 1.8 MeV proton APF linac was also created and studied in Moscow Radiotechnical Institute where accelerated proton beams with pulse currents up to 4.5 mA were registered. In fig.3 the transversal and longitudinal acceptances are shown. Essential decreasing of effective transversal acceptance caused by influence of phase oscillations on transversal ones is demonstrated. In both cases the beam capture coefficient didn't exceed 15% due to the lack of preliminary bunching [7]. So limit currents were restricted not by space charge forces but injection conditions. 3 MeV deuteron linac MLUD created and studied in Kharkov PhysTech Institute may be considered as another example of successful experience of early APF linacs [8]. Other examples of positive experience with APF systems are described in [9,10].

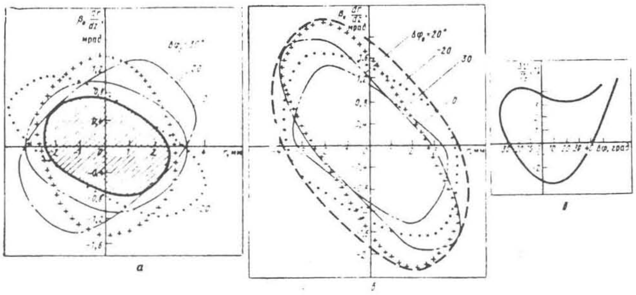

Fig. 3: 1.8 MeV linac acceptance, exit beam emittance and separatrix (shaded - effective acceptance)

It should be noted that APF systems allow to accelerate simultaneously many beams in the same structure. The 19-aperture 600 keV APF linac structure was studied in ITEP. It allowed to get total accelerated proton currents up to 40 mA. At last the 6 MeV APF structure was created in ITEP for He_4^+ ions about 10 years ago (fig.4). It was designed for helium ions acceleration as an initial injector part for the proton synchrotron U-10.

It is a rectangular-shaped H-resonator with drift tubes and 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 [11]. 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 of appropriate points on side and central plates to fix drift tubes supports.

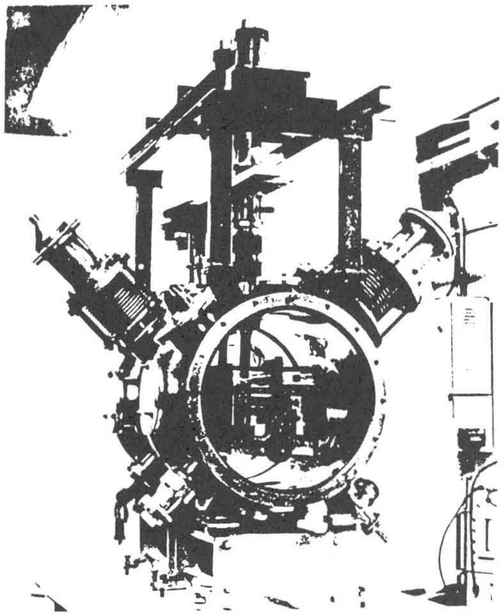

Fig. 4: 6 MeV linac structure for helium ions

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 [12]. 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 [13].

APF APPLICATIONS IN LINACS

The above mentioned structure for helium ions has served as a prototype for a new 10 MeV APF linac resonant structure for deuterons (fig.5). Its main parameters are shown in table 1 [14]. In fig.6, the experimental distribution of the field gradient squared for this structure is shown. It has peculiar alternation of gap fields 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

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

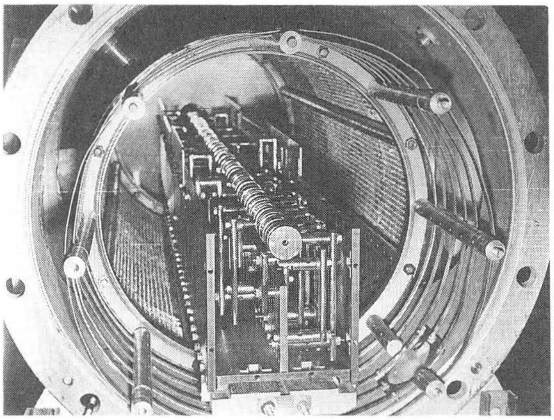

Fig. 5: 10 MeV deuteron linac structure

tests. The rated value of deuteron beam pulse current is 5 mA. The variant of essential increasing beam current up to 50 mA supposes preliminary acceleration of deuterons in RFQ section to 2.4 MeV. The similar decision of preliminary deuteron beam acceleration in 433 MHz RFQ section to the energy of 2 MeV and the following acceleration in APF structure was considered in [15].

This structure will probably serve as a prototype for neutron source facility that 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.

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 putting into operation the 6m linac for ions with minimum charge to mass ratio of 1/46 [16]. Fig.7a shows the calculated longitudinal acceptance for W^{+4}_{184} ions and fig.7b - transversal acceptances for different input phases (-50° - short dashed, 0 - solid line, $+50^\circ$ - long dashed) that were reached in view of field gradient modulation.

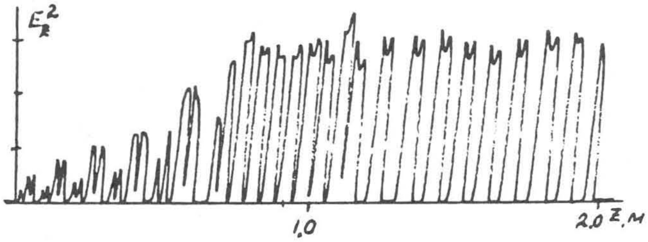

Fig. 6: Experimental field distribution

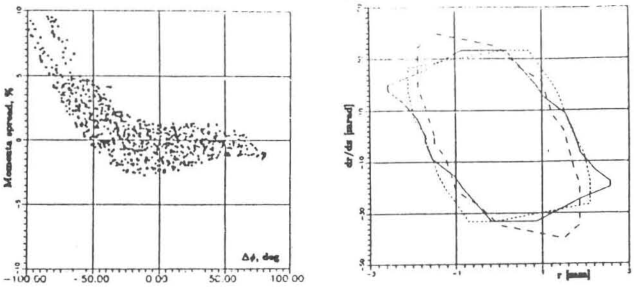

Fig. 7: Longitudinal and transverse acceptances

There were some problems during the tuning 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 ions were accelerated in pulse regimes to 0.31 MeV/amu in the 18.7 MHz Wideroe-type resonant structure (fig.8). 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 ir-

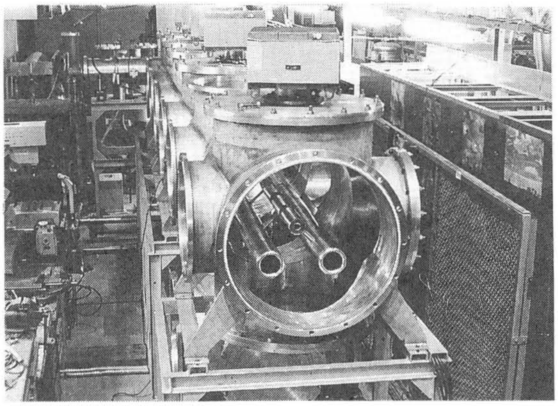

Fig. 8: Experimental linac for heavy ions

radiation 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 an 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 μm 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 at the electronic instruments enterprise "Tenzor" in Dubna. The linac includes a 30.5 kV injector with a MEVVA-type ion source that 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. In accordance with the membrane technology requirements we needn't in high beam intensity. Nevertheless, V.A.Bomko et al [17] reported about the project of the 1 MeV/amu APF heavy ion linac with the pulse beam intensity up to 10^{14} p/s.

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 μs
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

CONCLUSIONS

Theoretical and experimental investigations showed wide possibilities of getting extremely high energy gain rates in APF systems. These systems don't need in additional focusing elements. APF structures are rather simple in design and technological aspects and suitable for the effective acceleration of any possible ions, including the most heavy ones.

Main problems with APF realization are caused by stringent requirements to the linac structure parameters. In particular, appropriate RF structures must be chosen to meet the requirements of extremely accurate tuning on designed field amplitude and phase distributions simultaneously. Moreover, beam limit currents in APF linacs are usually several times less than in RF linacs with quadrupole focussing.

Possibilities of the APF linacs for intensive beam acceleration may be widened significantly by using RFQ systems at linac inputs. APF seems to be attractive for superconducting linacs.

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