FEASIBILITY OF ALTERNATIVE PHASE FOCUSING FOR A CHAIN OF SHORT INDEPENDENTLY-PHASED RESONATORS

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Abstract

Alternative phase focusing (APF) is usually realized in a long drift-tube structure with multiple acceleration gaps. The synchronous phase alternates periodically gap-by-gap according to either sinusoidal or square-wave laws. The period of synchronous phase oscillations depends on charge-to-mass ratio of accelerated ions and increases with beam energy. One period may include up to 10-20 accelerating gaps. In the case of square-wave law, the sets of 5-10 neighbouring gaps have the same synchronous phase, while whole structure consists of continuous chain such gap-sets with a constant value of synchronous phases. Therefore, every such gap-set can be formed into a separate resonator. As result a long multiple gap structure is converted into a chain of short independently-phased resonators. Such realization of APF linac allows more flexibility in a phase variation, while additional focusing-matching lenses can be set up in betweens of resonators. In this report possible parameters of such linac are evaluated and discussed.

INTRODUCTION

The APF belongs to the wide class of focusing methods by axially symmetrical RF fields provided in sequences of drift-tubes with axially symmetrical cross-sections. The original APF idea of beam focusing by a periodical alternating a synchronous phase in a sequence of the drift-tube gaps has been developed and modified since the early 50's by many authors. In the papers [1-5], there are comprehensive lists of references to the most known recipes of generating the APF drift-tube structures.

In the APF linac, the synchronous phase alternates periodically gap-by-gap according to either sinusoidal or square-wave laws. The period of the synchronous phase oscillations may include up to N_g=10-20 accelerating gaps which forming up one focusing period.

Usually, APF is considered for long multiple-gap resonators containing several tens of drift-tubes. However, APF linac also can be realized as a chain of short independently-phased resonators similar to superconductiong heavy-ion linacs [6]. For example, APF linacs consisting of the chain of *identical* short independently-phased resonators had been analyzed in Ref. [7,8], while S.A. Minaev [7] considered resonators with one and two gaps and increasing N_g along linac, and E.S. Masunov [8] considered 4-gap "fork" structures with a constant N_g=4.

The main feature of both concepts is constant number of gaps in every short resonator. It is known [1,2], that in order to preserve a position of working point on the stability diagram, it is necessary to increase N_g along the linac. For example the approach of Ref. [7] uses an increasing number of N_g along the linac (up to 10-20). Alternatively, in the approach of Ref.[8], operating point can be stabilized by an additional focusing force.

In this paper, it is suggested to use a chain of short independently-phased resonators with increasing number of the gaps in every short resonator along a whole linac. This feature may minimize the total number of short independently-phased resonators, while preserving a position of working point on the stability diagram without an additional focusing force.

APF IN CHAIN OF RESONATORS

Method for stability analysis

The stability analysis is based on the methods developed for the asymmetrical alternative phase focusing (A-APhF), which has been proposed by V.V. Kushin in more than 30 years ago [1,2]. In the report [9], stability conditions had been extended for an arbitrary law of the synchronous phase oscillations.

Following Ref. [9], the synchronous phase sequence can be written as the step-wise function $\varphi_s(\tau) = \overline{\varphi} + \widetilde{\varphi}(\tau)$, which is the sum of the constant and varying functions $\overline{\varphi}$ and $\widetilde{\varphi}(\tau)$, respectively, while $\widetilde{\varphi}(\tau)$ is constant within every accelerating period. The focusing period of APhF linac L_f coincides with the period of phase excursions. With independent variable $d\tau = dZ_s/L_f$, small phase deviations of particle phase ψ and a linear radial motion ρ can be expressed by the following Matiew-Hill equations:

$$\begin{cases} d^2\psi/d\tau^2 + P_\psi(\tau)\cdot\psi = 0 \\ d^2\rho/d\tau^2 + P_\rho(\tau)\cdot\rho = 0 \end{cases}. \qquad (1)$$

where the periodical step-wise functions $P_\psi(\tau) \equiv P_\psi(\tau+1)$ and $P_\rho(\tau) \equiv P_\rho(\tau+1)$, are given by the following equations

$$\begin{cases} P_\psi(\tau) = 2B\cdot\sin[\overline{\varphi} + \widetilde{\varphi}(\tau)] \\ P_\rho(\tau) = -B\cdot\sin[\overline{\varphi} + \widetilde{\varphi}(\tau) + \psi] \end{cases}, \qquad (2)$$

The focusing strength B [1,2] is given by

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$$B = \left(\pi q E_{\mathrm{m}} / m_o c^2\right)\left(\lambda/\beta_{\mathrm{s}}\right)\left(L_{\mathrm{f}}/\beta_{\mathrm{s}}\lambda\right)^2\left(1-\beta_{\mathrm{s}}^2\right)^{3/2}. \quad (3)$$

The Matiew-Hill equations with periodical step-wise functions can be solved using a well-known matrix technique [10]. The RMS and average values of functions $P_\psi(\tau)$ and $P_\rho(\tau)$ can be used to build stability diagrams [9]. In present study, the matrix technique has been performed numerically using procedures of the mathematical package MAPLE-V [11]. The MAPLE's code for APF design had been developed early in Ref.[8].

Figure 1 shows an example of the necktie stability diagram for longitudinal and transverse motion calculated for a focusing period with N_{g}=8. The curves of constant values of phase advances per period for longitudinal and radial oscillations μ_{L} and μ_{R} are shown. For the strong focusing it is usual to keep that the representative point inside the stable region near the intersection of the curves $\cos\mu_L$=0 and $\cos\mu_R$=0.

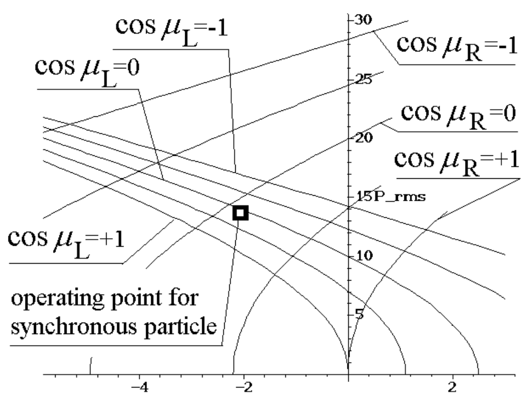

Fig. 1. The necktie stability diagram.

Figure 2 presents the radial stability diagram shown for non-synchronous particles located near synchronous with step of 5 degree. The square and cross marks are used to show positions of position of synchronous and non-synchronous particles, respectively.

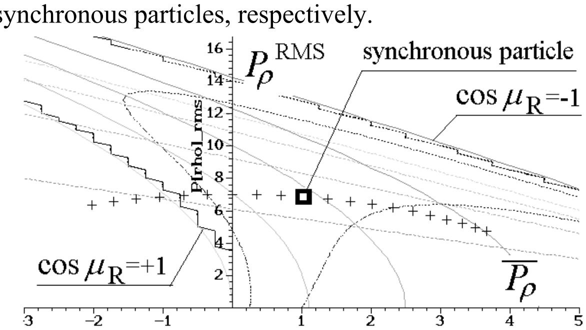

Fig.2. The radial stability diagram with synchronous and non-synchronous particles

Dependence of N_{g} on the particle velocity

The position of operating point on the stability diagrams are mainly affected by the values of focusing strength B. According to the eq. (3), with increasing the particle velocity β_{s}, the focusing strength B is decreased. The amplitude of the accelerating wave E_{m} also depends on β_{s}, while this dependence is defined b the type of the accelerating resonator. Let's consider the case of a constant $E_{\mathrm{m}}(\beta_{\mathrm{s}})$=const, which means that the gap voltage monotonically increases along the linac. In this case, B decreases as $B \propto N_{\mathrm{g}}^2(\beta_{\mathrm{s}})/\beta_{\mathrm{s}}$.

To keep the focusing strength and a position of operating point in the center of stability diagram, it is necessary to increase N_{g} along the whole structure as square-root of β_{s}, i.e. $N_{\mathrm{g}} \propto \beta_{\mathrm{s}}^{0.5}$. It is very approximate relation neglecting variations of $\varphi_{\mathrm{s}}(\tau)$-function. The actual dependence of N_{g} on β_{s} can be calculated for a particular linac design using the considered matrix method.

Two APF designs have been calculated: 1) the 20 MeV 300 MHz proton linac; 2) the 6 MeV 150 MHz ion linac with the charge-to-mass ratio 1/8. The square-wave law for the synchronous phase variations is used.

Figures 3 and Fig. 4 show the dependence of N_{g} on β_{s} for these designs at even N_{g} values. The calculated $N_{\mathrm{g}}(\beta_{\mathrm{s}})$-dependences are approximated as $N_{\mathrm{g}} \propto \beta_{\mathrm{s}}^{0.65}$, which is close to the approximate square-root dependence. The $W(\beta_{\mathrm{s}})$-dependences are also shown in Fig.3 and Fig.4.

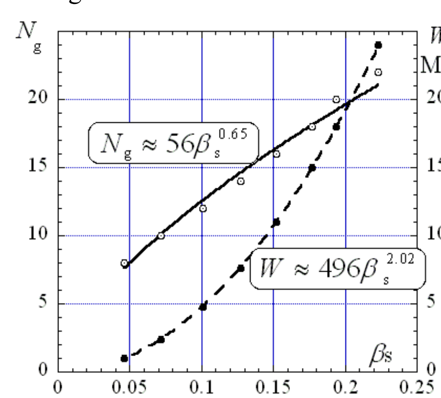

Fig.3. $N_{\mathrm{g}}(\beta_{\mathrm{s}})$ and $W(\beta_{\mathrm{s}})$ for the proton APF linac.

It seen that one period include 8-22 gaps for the 20-MeV proton linac, and 16-30 gaps for 6 MeV ion linac. The linacs contains the sets neighbouring gaps, which gaps have the same synchronous phase. Whole structures consist of continuous chain such gap-sets with a constant value of synchronous phases. Therefore, every such gap-set can be formed into a separate resonator. As result a long multiple gap structure is converted into a chain of short independently-phased resonators.

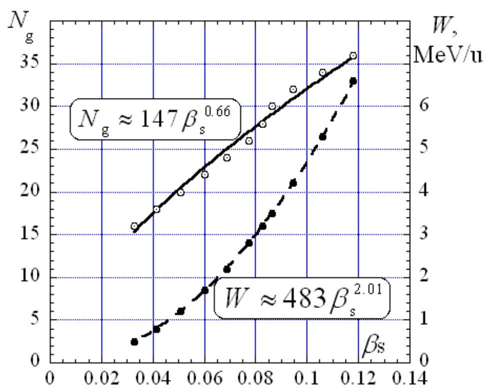

Fig.4. $N_g(\beta_s)$ and $W(\beta_s)$ for the ion APF linac.

Tables 1 and 2 shows main parameters of these APF linacs, calculated using the approach described in Ref.[9] as for a single multiple-gap resonator. The neighbouring gaps with the same φ_s can compose separate resonators of the length L with number of gaps n_g. As it is suggested in the tables, the 1-20 MeV 75-gaps proton linac of the length of 4.3 m and the 0.5-6.0 MeV/u 198-gaps ion linac of the length 14 m can be decomposed into 12 and 17 independenly-phased resonators, respectively. For a comparison, the number of independenly-phased resonators in APF linacs using of 1, 2, or 4 gap resonators as suggested in Ref. [7,8] is much larger, e.g., the proton and ion linacs will consist of 19 and 50 four-gap resonators, respectively.

The suggested here realization of APF linac allow to minimize the total number of independenly-phased resonators, while keeping flexibility in a phase variation. Practically, the considered APF linac can be realized as a chain of short interdigital H-type resonators with 4-20 gaps pre resonator, while additional focusing-matching lenses can be also set up in betweens of the resonators.

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Table 1. Parameters of the 1-20 MeV proton linac.

gap no.	φ_s, deg	L, cm	W, Mev/ inp/out	n_g	Reso nator
1-4	-45	10.0	0.9-1.1	4	1
5-8	73	16	1.1-1.4	4	2
9-13	-45	31	1.4 2.0	5	3
14-18	69	49	2.0-2.6	5	4
19-23	-44	69	2.6-3.4	5	5
24-29	65	97	3.4-4.3	6	6
30-35	-43	32	4.3-5.7	6	7
36-41	59	35	5.7-7.0	6	8
42-48	-41	46	7.7-8.9	7	9
49-56	52	61	8.9-11.8	8	10
57-65	-35	78	11.8-15.9	9	11
66-75	39	99	15.9-21.0	10	12

Table 2. Parameters of the 0.5-6.0 MeV ion linac.

gap no.	φ_s, deg	L, cm	W, Mev/u inp/out	n_g	Reso-nator
1-8	-45	20	0.46-0.54	8	1
9-16	73	28	0.54-0.60	8	2
17-25	-45	34	0.60-0.76	9	3
26-34	69	37	0.76-0.83	9	4
35-43	-44	40	0.83-0.99	9	5
44-52	65	42	0.99-1.11	9	6
53-62	-43	51	1.11-1.33	10	7
63-73	62	61	1.33-1.51	11	8
74-84	-42	65	1.51-1.80	11	9
85-95	57	71	1.80-2.04	11	10
96-107	-39	82	2.04-2.41	12	11
108-119	53	89	2.41-2.74	12	12
120-133	-35	112	2.74-3.28	14	13
134-148	40	132	3.28-3.90	15	14
152-164	-30	152	3.90-4.69	16	15
165-182	39	177	4.69-5.52	17	16
183-198	-29	192	5.52-6.53	17	17