# TOWARDS A RADIATION-FREE LINAC OF MESON OR NEUTRON GENERATOR TYPE

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## General Considerations

One of the basic problems of the design of meson or neutron generator type linacs (with the output energy of protons 500-1000 MeV and average currents 1-1000mA) is radiation cleanness of these linacs[1]. The radiation cleanness criterion may be set forth as follows: the linac can be considered as radiation-free provided that the gamma dose at the one-metre distance from the linac does not exceed the professional dose of 2.8 mrad/hr in an hour after the linac has been stopped after long operation. The permissible average beam spill (the beam current loss per length unit) satisfying the criterion versus the energy of protons is represented at Fig.1. The total value of the permissible beam loss in the second stage of the USSR AS Meson Factory[2] is $60.10^{-9}$ A (the relative value of the permissible loss is $6.10^{-5}$ for average current 1 mA). The beam spill must not exceed $10^{-6}$÷ $10^{-7}$ for average currents 100-1000 mA respectively.

A number of methods and means of conducting the beam (or dual beams of $H^+$ and $H^-$) in the six-dimensional acceptance of the linac have been developed by now. These are in particular: suppression of the coherent phase (longitudinal) oscillations of bunches in the transition region between the first stage of the linac and the second one where the phase width of the longitudinal acceptance is small[3], matching the beam with the longitudinal acceptance of the second stage by use of the one-forth wave-length resonant cavity[4]; suppression of the coherent transverse oscillations of simultaneously accelerated $H^+$ and $H^-$ bunches[5]. These methods and means operate the bunch as a whole ensemble. But here some real factors such as the actual characteristics of the six-dimensional phase volume of the beam at the linac's input or the presence of the residual gas in the beam channel (when $H^-$ ions are accelerated) are not taken into account. Therefore they are by no means comprehensive as far as solving of the problem of the radiation-free linac is concerned.

The other group of methods and means comprising filtering of the six-dimensional phase volume of the beam at the linac input[1,6] and achieving the specific vacuum parameters in the beam channel[7] is to bring to completion ensuring of the radiation cleanness. There are two characteristic features about the methods and means. First, they are connected with penetration inside the bunch (i.e.removal of particles, lying outside design phase volume of the beam, or setting limit to the process of the detachment of an electron from an $H^-$ ion when it collides with a molecule of the residual gas). Secondly, these methods and means serve to control such small relative beam spill values as $10^{-4}$ - $10^{-7}$.

The beam six-dimensional phase volume filtering is effected with the two different types of devices, the first one filtering the beam four-dimensional transverse phase volume and the second one filtering the two-dimensional longitudinal phase volume. Therefore problems of the beam transverse and longitudinal phase volume filtering are considered separately.

## Transverse Phase Volume Filtering

The analysis of the density distribution of particles in real proton beams in the two-dimensional phase space discovered need for beam transverse phase volume filtering. This distribution has a somewhat Gaussian shape, particularly in the beam core region where from 70 to 90 per cent of particles are concentrated[1]. The Gaussian distribution along velocity co-ordinate (x or y) reflects in fact statistical nature of processes taking place in an ion source. In the paper the Gaussian distribution is also assumed for the halo of the beam injected into the linac notwithstanding the fact that the particle distribution in that region varies for different cases and depends on the prehistory of the beam.

The major requirements for the beam transverse phase volume filter are as follows:

a) The beam phase volume at the filter output is to be shaped after the pattern of the four-dimensional acceptance of the accelerating section, following the filter, and the beam phase volume itself is to be smaller than the acceptance.

b) The number of particles finding themselves beyond the boundary of the formed phase volume must not exceed the magnitude which is $10^5$-$10^8$ times as small as the number of particle in the phase volume (for average beam currents 1-1000mA)

c) It is desirable that the process of the beam transverse phase volume increase due to the non-linear character of space charge repulsion forces should essentially cease to affect the beam in the filter.

These requirements are met by the filter which is nothing but the initial section of a regular focusing channel with a small aperture, where particles have time to make more than half of a radial oscillation. The transverse transmission coefficient of the filter (the ratio of the current transmitted by the filter to the full current at the input) for the Gaussian current density distribution in the beam (the beam is matched with the filter) is given by the relation:

$$K_{\perp} = K_h[1-(1+A/\varepsilon_o)\exp(-A/\varepsilon_o)]$$

where $A$ is the two-dimensional acceptance of the filter; $\varepsilon_o$ – the emittance of the beam, holding the relative current $1 - 1/e = 0.632$; $K_h$ is the ratio of the current transmitted by the four-dimensional transverse acceptance of the filter to the current of particles, contained in the hyperellipsoid inscribed in the acceptance. The hyperellipsoid is the surface of the constant four-dimensional phase density. The coefficient $K_h$ for the filter with FODO structure (the angular advance of the radial oscillation per focusing period $\mu$ is about 45°, but the ratio $2\pi/\mu$ is irrational) has been found for a number of $A/\varepsilon_o$ parameter values by the use of numerical simulation. $K_h$ is equal to 1.57 with $A/\varepsilon_o$ close to zero. The transmission coefficient $K_{\perp}$ versus $A/\varepsilon_o$ is represented in Fig.2.

One must know the magnitude of the beam spill on discs of the filter and corresponding evolved heat on them for engineering computation and design of discs. In Fig.3 the relative current of particles lost per a filter element (where full injected current is a unity) obtained by the use of numerical simulation is plotted versus the element number. The curves may be used for the design of a typical filter (FODO, $\mu = 45^o$).

The aforementioned beam transverse phase volume filter serves functions new and indispensable for ensuring the radiation cleanness of the linac. They are:

a) Removal of the phase halo of the beam (lying beyond the boundary of the four-dimensional acceptance of the filter) which is caused by the statistic processes in the ion source, by the transient processes at forming of current pulses (for example, by the locking capacitor, the longitudinal emittance filter, device forming short current pulses) and by the parameters nonstability of the focusing channel, placed between the injector and the linac.

b) Forming $H^+$ and $H^-$ ion beams with the same characteristics. It facilitates the correction of the transverse coherent oscillations of dual beams.

c) Perfect matching of the beams with the focusing channel of a linac.

## Longitudinal Phase Volume Filtering

The beam longitudinal phase volume filtering is in essence the forming of the linac input beam phase picture where the particles are confined inside the linac bucket but do not touch its boundary.

When filtering the beams with high current it is desirable that the filter should be compact and simple in construction. The filter meeting these requirements is a biharmonical one the scheme of which is represented in Fig.4a. In the case under review the source produces the continuous monochromatic beam. Thus for the longitudinal phase volume filtering it is sufficient to form bunches with a certain phase width before injecting them into R3 and R4 bunching cavities. The transverse electric RF fields of the two resonant cavities R1 and R2 (the first of which operates at the same frequency as the linac and the second one operates at the frequency twice as high) are used for that purpose. R2 cavity is used to rectangulate the shape of the overall deflecting field. R1 and R2 cavities are to chop bunches of the phase width of approximately $(2/3 + 3/4)\pi$ which after bunching will be reduced to $\pi/4$. It is expedient to describe the efficiency of the longitudinal phase volume filtering by the filter longitudinal transmission coefficient $K_{\parallel}$ which is the ratio of the filtered beam current averaged over the RF period at the filter output (that is contained in the transverse emittance which is equal to that at the filter input) to the current at the filter input.

The design data of the longitudinal phase volume filter of the USSR AS Meson Factory[2] are as follows: the R1 and R2 cavities operate at frequencies 198.2 MHz and 396.4 MHz respectively; their deflecting voltage amplitudes are 58 kV and 41 kV (the bias voltage applied to the deflecting electrodes of the cavities is 32.5 kV); the overall length of the R1 and R2 cavities is 0.12 m; the energy of particles in the beam is 0.75 MeV.

The filtered micropulse of the current which does not exceed the rated emittance of 0.15 $\pi$ cm.mrad is shown in Fig.4b. The phase width of the bunch is $3/4\ \pi$. The coefficient $K_{\parallel}$ is equal to 0.5.

The device combined of the longitudinal volume filter placed before the linac input and of the transverse phase volume filter placed at the input can filter the beam six-dimensional phase volume.

### Vacuum and Magnetic Characteristics of the Beam Channel for the Acceleration of $H^-$ ions

The $H^-$ ions charge-exchange on the residual gas and dissociation in the transverse focusing magnetic field are peculiar to the acceleration of the beam of $H^-$ ions. The dissociated and charge-exchanged ions are lost in the linac. Therefore the need for loss limitation imposed certain restrictions on the vacuum level and on the magnitude of the transverse magnetic field.

The pressure of the residual gas in the beam channel of the radiation-free linac has been computed for the residual gas composition peculiar to the disc-and-washer loaded accelerating structure in accordance with assumptions set forth in[1,7]. The plot is represented in Fig.1. It is evident that the residual gas pressure is to be lower than $(2\div 9)10^{-10}$ Torr for the average $H^-$ ions current of 100 mA in the energy range from 100 to 1000 MeV.

The maximum magnitude of the magnetic induction of the quadrupole must not exceed 3 kGs at the energy 1000 MeV in a radiation free linac with the average $H^-$ ions current of 100 mA. The magnitude may be increased for lower energies. Therefore one may neglect $H^-$ ions loss in a real quadrupole channel.

Superconducting solenoids are attractive for the purpose of focusing protons in linacs[8]. But severe restrictions due to dissociation in stray fields are imposed on the solenoid when $H^-$ ions are focused. The magnetic field magnitude in the centre of a superconducting solenoid (having parameters as in[8]) versus the energy is represented in Fig.5 for a radiation-free linac with average $H^-$ ion currents of 1 mA and 100 mA. It is evident that in linac one may use superconducting solenoids with magnetic fields of 40-60 kGs for $H^-$ ions focusing only for energies as high as 200 MeV.

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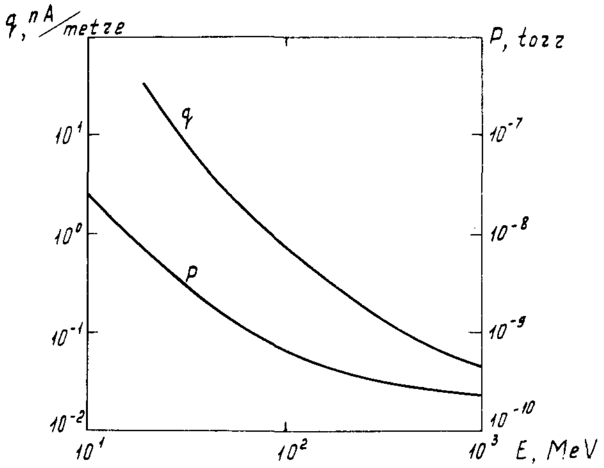

Fig. 1 q - the permissible linear average current spill of protons and $H^-$ ions in the radiation-free linac versus energy; P - the residual gas pressure in the channel of the $H^-$ beam when the beam linear spill is permissible versus energy (the average $H^-$ ions beam current is 100 mA).

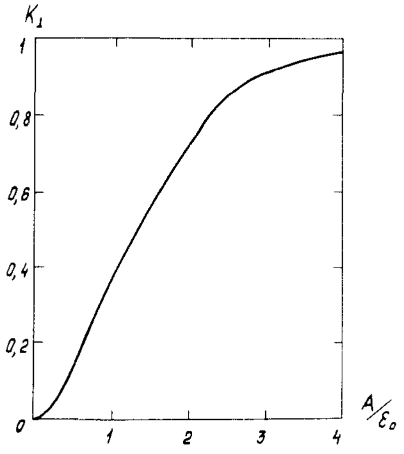

Fig. 2 The filter transverse transmission coefficient versus parameter.

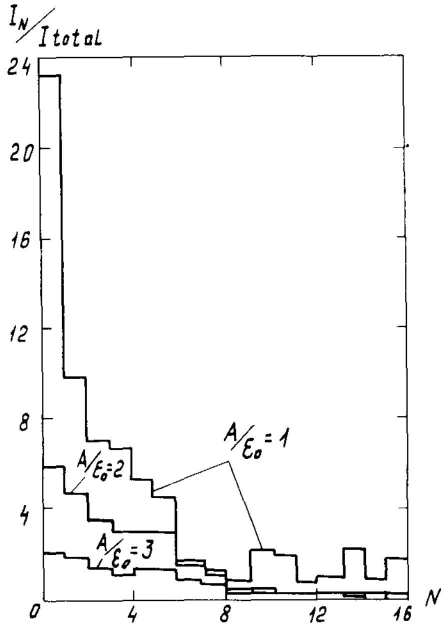

Fig. 3 The beam intercepted current per filter element versus the element number.

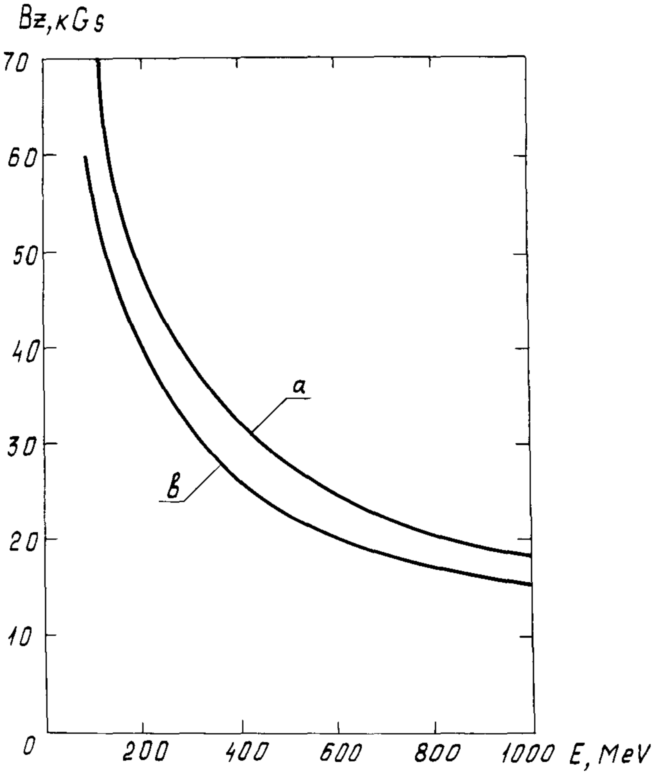

Fig. 5 The boundary magnetic fields in the centres of superconducting solenoids versus energy: a - for 1 mA current, b - for 100 mA current.

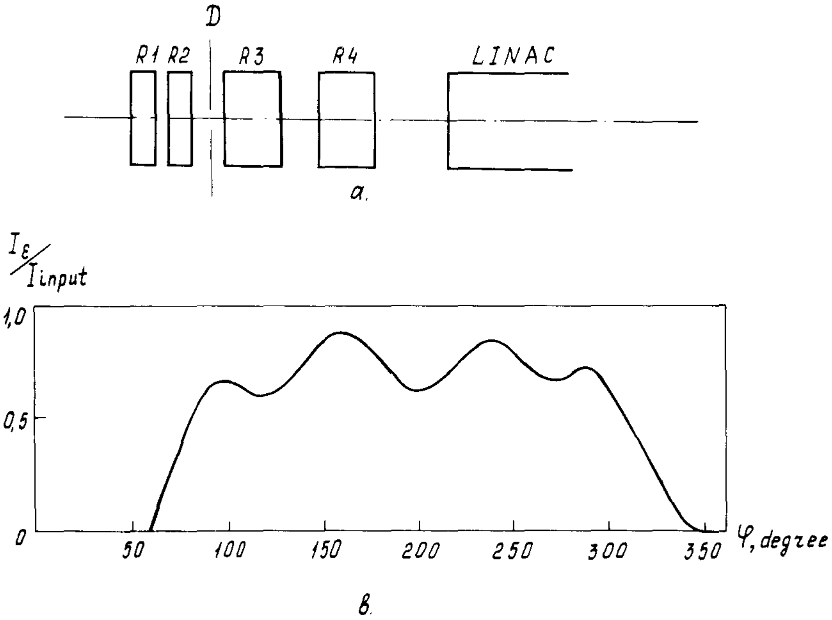

Fig. 4 The longitudinal phase volume filter: a - the scheme; b - the shape of the beam current contained inside the emittance of 0.15 cm.mrad.