THE PROTON KLYSTRON

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1. As we already mentioned several times /1/ interesting prospects are opened up with the use of large cyclic proton accelerators as storages of big amount of energy in the form well suitable for its transformation into electromagnetic excitation energy of linear accelerating structure. The energy stored in proton beams in accelerators SPS and Main Ring achieved now of 3 MJ and much higher energies and intensities are planned to achieve. One can only talk of proton (not electron) cyclic accelerators since only here RF power is transmitted to the beam and not used for compensation of synchrotron radiation losses. Note, when using superconducting magnet and RF systems the transformation factor for mains power into proton beam power can be comparatively high.

The stored energy of 3 MJ is enough for excitation of accelerating structure with a wave length, for example, 5 cm with acceleration rate 100 MeV/m of 50 km long which enables one to accelerate the various charged particles ($p^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$) up to an energy of 5 TeV. I'd like to emphasize that the particle energy of a basic accelerator can be much lower in this case. As much as half of the energy stored in the basic accelerator beam can be, in principle, transmitted to the accelerated particles. However, the energy of accelerated particles will be, in this limiting case, much lower than that achievable in the scheme. RF pumping power can attain (even with no longitudinal compression of the exciting proton beam) 100 GW in today's accelerators; longitudinal compression makes it possible to increase additionally this value.

2. Let us now consider the question how to make the proton beam with a large stored energy to be capable to transmit this energy to a linear accelerating structure, i.e. to the correctly chosen diaphragmed wave guide.

First of all, the proton beam, homogeneous in time, should be transformed into a density-modulated one with the wavelength required (of the order of 1 cm). It is desirable that the current amplitude of the needed harmonic I_λ be close to its maximum, i.e. $I_\lambda = 2I_0$ where I_0 is a average proton current prior to modulation. Such a modulation can be performed in two stages. First, the homogeneous beam is modulated over its energy during its passage through the accelerating structure. This structure is excited at a wavelength required and provides the proton beam energy modulation substantially exceeding the energy spread of the primary proton beam (in SPS this spread is less than 50 MeV). In order to improve the further bunching, modulation on higher harmonics is useful to add. It seems most reasonable to carry out a subsequent transformation of energy modulation to density modulation for ultrarelativistic particles, which are high energy protons, with a bending modulator. With a correct choice of the bending radius and modulator focusing structure, the path length will depend on proton energy (in "normal" case the path length increases with energy and, hence, the lower energy protons leave behind the higher energy protons during the turn). If the rotation is interrupted at the moment when the proton of all energies are arranged on the same azimuth (note that this occurs within one wavelength and with an accuracy of up to the energy spread of the beam and an approaching degree of the effective energy modulation to the skew one), the outgoing (from the modulator) beam will contain as much as possible current harmonic needed. After this procedure the proton beam is directed to the corresponding linear accelerating structure with the needed magnetic quadrupole focusing to keep protons within the holes of the wave guide diaphragms. No further relative longitudinal shifts of ultrarelativistic particles occur when the latter are moving along the straight line.

Either a special magnetic track through which the emitted proton beam passes after energy modulation or the ring of a basic proton accelerator may be used as a bending modulator. In the second case, a linear accelerator (its energy of the order of 100 MeV) can be located in one of the straight sections of the basic cyclic accelerator, outside the operating aperture. As soon as the acceleration cycle is completed, the beam is "thrown" through this modulating linac, and the necessary beam density modulation appears in the bending part during the further beam motion.

3. Let such a density-modulated beam of ultrarelativistic particles pass through the linear accelerating structure with wavelength λ which corresponds

to the first harmonic of modulation. In this structure, a high-frequency field will be excited, which decelerates the protons transmitting their energy to the electromagnetic field. At first, the amplitude of this field E_o will increase proportionally to the total proton charge eN flown through a given cross section:

$$E_o \approx 10 \frac{\ell eN}{\lambda^2} = 1{,}5\cdot 10^{-11}\frac{N}{\lambda^2_{cm}} \left[\frac{MV}{cm}\right]$$

This increase goes on up to the proper damping time in the system τ_α, which is proportional to $\lambda^{3/2}$, and, for λ = 1 cm, equals to 20 nsec for a copper wave guide. If the duration of flowing the proton current is much larger than τ_α, then the electric field amplitude is established proportional to the average proton current I in the structure:

$$E_0 = 2IR \approx 3\cdot\frac{I_A}{\sqrt{\lambda_{cm}}}\left[\frac{MV}{cm}\right]$$

In the above formula R is a unit length shunt impedance of the structure, I_A is the proton current in ampers; an additional electron load because of cold emission under the action of highly excited electric field is assumed to be still negligibly small.

A direct use of the proton beam produced by the present-day record accelerators makes it possible to obtain an equilibrium field amplitude of about 0.6 MV/cm in the structure with λ = 1 cm (for about 20 μ sec rotation time in such accelerators). Already comparatively insignificant prebunching of the proton beam will allow one to generate, in the accelerating structure, an effective field of up to 1,5 MV/cm, which is maximum with respect to the electric strength of the surface; the total time of existence of this field will be proportionally less than that obtained without such a bunching. Passing any relativistic particles together with the exciting proton beam in accelerating phase (for a given of particle charge) one can accelerate them with a rate of 60-150 GeV/km, correspondingly.

This method enables the particles to be accelerated up to an energy close to the peak energy of a basic accelerator. In this case, the highest intensity of accelerated beam will constitute about 10% of that of the basic accelerator (monochromaticity is of the order of one percent).

If the initial beam is divided into several bunches long enough and each of them is transmitted (with correct shift in time) through the linear accelerating structures in series, each providing almost full deceleration of the initial beam, it is possible to make the accelerated particles pass, in sequence, through all these structures. Note that the energy of accelerated particles is proportionally increased as compared to that of basic accelerator. The limiting intensity of the accelerated particle beam will, of course, be proportionally lower.

The necessary time redistribution of particular parts of the exciting beam - both the worked out and "fresh" bunches have to reach simultaneously each new section - may be performed according to various schemes. From the logical point of view, the simplest thing is to install, in the tunnel of the basic accelerator, the additional pulsed magnetic small-aperture tracks at full energy, which have somewhat different revolution periods for particles with a given momentum, and then to let each bunch, which occupies the corresponding part of the accelerator circumference, in its track. When all bunches coincide with respect to the azimuthal position, it is necessary, after the short-wave density modulation of each bunch, to let them out and to direct to the corresponding sections of linear accelerating structure. The same procedure may be performed by using long delays in channels, though additional tunnels will be needed for this case.

4. In order to confine the particles of the exciting and accelerated beams in the holes of the diaphragmed wave guide of accelerating structure, strong enough focusing is necessary; moreover, the stability of transverse oscillations of particles with very different momenta should be simultaneously provided. Estimations show that in case of the optimal quadrupole focusing for the accelerated particles with a momentum of a few GeV, the beams of modern proton accelerators will pass almost without losses even for centimeter-range wave guides.

The other problem associated with the passage, through the same structure, of ultrarelativistic particles with sharply different γ -factors and, hence, with a somewhat different velocities is to provide a correct relative phasing of these particles. To eliminate the consequences of gradual lag of the particles with lower velocity, it is necessary, after each section of length $\frac{1}{2}\lambda\gamma_{min}^2$, to separate the exciting and accelerated beams and to delay one beam relatively to the other approximately by $\frac{3}{4}\lambda$, due to the difference in the path lengths, to the following accelerating section input. Such a method makes it possible to clean the accelerated beam from the particles with different masses.

5. As has already been mentioned, the rate of energy increase of the order of 100 MeV/m in linear accelerators enables one to accelerate also unstable but comparatively long-lived particles, i.e. muons and charged pions. However, for charged kaons to be accelerated, the acceleration rate should be above 300 MeV/m. Such gradients are likely to cause the complete shunting of the structure by the cold-emission electrons and, correspondingly, such a field cannot be generated by a gradual increase of the energy stored in the wave guide.

An interesting possibility of obtaining the gradients of a necessary level on the basis of a proton klystron is suggested in Ref. /2/. If one collects the number N of protons, which are formally required to obtain the needed gradient in one short bunch of the same length as diaphragm spacing of an accelerating wave guide, then a maximum decelerating field of approximately the same magnitude will be achieved within the proton bunch:

$$E_{max} \approx 10^{-12} \frac{N}{a^{2}_{cm}} \left[\frac{MV}{cm}\right]$$

where is the diaphragm spacing of the wave guide and the diameter of their holes.

In terms of the eigen modes of a wave guide, one can say that a single bunch excites simultaneously several (azimuthally-symmetric) harmonics which amplitudes are added within the length of the exciting bunch. The electric field strength on the surface of the diaphragms achieves, though for a very short time, the same magnitude as that in the centre of the bunch. Therefore, a high shunting current is found to appear, but there is no time for this current to influence significantly the magnitude of decelerating field inside the bunch. One should take care only for that the residual electromagnetic field excited by the bunch should not release its energy on the diaphragm surfaces. To do this, the diaphragms may be open from the outer side, and a strongly absorbing material, instead of the outer coaxial of a wave guide, is placed at a large enough distance from the diaphragms.

The method described above allows one to accelerate much shorter bunches of opposite sign inside the bunch of exciting particles (i.e. negative particles inside the proton bunch). To attain the rate of acceleration of the order of 300 MeV/m, that is a necessary minimum for acceleration of negative kaons, one needs to form the half-centimeter bunches of ultrarelativistic protons, 10^{12} protons per bunch. In big proton accelerators mentioned, such a number of protons occupies $3\cdot10^{-3}$ of the accelerator circumference (with the bunching factor taken into account), that equals approximately 20 meters. When obtaining the needed bunch with the help of purely longitudinal compression, an energy spread available in the accelerator should increase at least to 200 GeV (from 50 MeV) (almost 50% of the full proton energy). Such a procedure is likely to be almost unrealizable from the technical point of view.

Feasibility of the method can be simplified, if one can use the smallness of the transverse emittance of a proton beam, and can increase the linear density of the beam by adding, in the transverse direction, particular parts of the proton beam which is initially elongated along the whole circumference of the basic accelerator. This may be performed, for example, by extraction of the beam part from the accelerator with its subsequent re-injection with necessary delay, using additional tracks (see section 3). A multiple compression of such a kind will be somewhat less expensive, if the facility already has two rings at full energy (Main Ring-Doubler, ISABELLE, UNK).

6. Let us now consider in more detail the potentialities of the acceleration version described.

If the conditions mentioned above are satisfied, acceleration of stable charged particles (if from the very beginning their velocity is close to the velocity of light) presents no difficulties irrespective of a particle kind. Of interest are also an increase of proton energy (with injection of a portion of primary protons in the accelerating phase of RF voltage), electron and positron acceleration without any limitations connected to a catastrophic growth of synchrotron radiation characteristic for cyclic accelerators (during linear acceleration the losses which are due to noncoherent radiation are negligibly small). Of special interest is the acceleration of polarized particles of all kinds since during linear acceleration the depolarizing effects can be made very small.

Accelerators based on the proton klystrons can be most interesting for acceleration of unstable particles. The required acceleration rate $\left.\frac{dE}{dS}\right|_c$ from E_i to E_f with a decrease in the number of particles in the accelerated beam, caused by decay, from N_i to N_f is given by a formula

$$\left.\frac{dE}{dS}\right|_0 = \frac{mc}{\tau_0} \cdot \frac{\ln(E_f/E_i)}{\ln(N_i/N_f)}$$

where m, τ_c - are the mass and lifetime of particles in the rest frame.

The value $\frac{mc}{\tau_0}$ is 1.6 keV/cm for muons and 0.18 MeV/cm for pions. Hence, a linear accelerator with an energy increase rate of about 1 MeV/cm provides the acceleration both for muons and pions, with small intensity losses, up to the ultimate energies.

As has already been said, prior to acceleration the muon beam is reasonable to cool by ionization cooling, and then, before injection into a linear accelerator, the muons should be bunched, with a bending modulator, within the phases close to the maxima of accelerating voltage. The bunching of pion beams being injected into a superlinac is desirable to perform by bunching the high-quality primary proton beam used for pion generation.

Kaon acceleration in the method under discussion can only be carried out with the help of the method described in section 5.

7. The use of superlinacs with proton klystrons enables one, in principle, to perform most of colliding beam experiments described in section IV on the basis of the existing high-energy proton accelerators and those being constructed and designed.

For production of $\pi^+\pi^-$-colliding beams, the pions, after their acceleration in a superlinac, should be injected into a magnetic track with the highest (to increase the number of collisions for the lifetime) value of a magnetic field. In this case, the ultimate average luminosity will be equal to

$$L_{\Sigma}^{\pi\pi} = \frac{\xi \dot{N}_p}{\ell_t^{eff}} \cdot \frac{N_\pi}{\ell_\pi} \cdot \frac{P_\pi P}{(m_\pi c)^2} \frac{eH\tau_\pi}{2\pi m_\pi c},$$

where ξ is the efficiency of the proton-pion conversion, $\dot{N}_p$ is the number of protons produced by a basic accelerator per second, N_π is the number of pions in one superbunch, ℓ_t^{eff} is the effectibe length of the optimized conversion target, ℓ_π is the length of the superbunch in the magnetic track and, simultaneously, the value of beta-function at the collision point, P_π is the pion momentum after conversion, P is the momentum of accelerated pions, H is the value of magnetic field in the track in which the collisions occur; τ_π is the pion rest frame lifetime.

If one takes that $\dot{N}_p = 10^{13}$ p/s, $N_\pi = 10^{11}$, $\xi = 10^{-1}$, $P_\pi = 5$ GeV/c, $P = 500$ GeV/c, $H = 100$ kG, $\ell_t^{eff} = 1$ cm, $\ell_\pi = 1$ M, then one obtains the ultimate luminosity

$$L_{\Sigma}^{\pi\pi} = 3 \cdot 10^{27}\ cm^{-2} s^{-1},$$

that is, in principle, sufficient for experiments on the study of fundamental properties of the pion-pion strong interaction.

With the use of the same system for the pion-proton experiments with substitution of positive pions for protons, the ultimate average luminosity is

$$L_{\Sigma}^{\pi p} = L_{\Sigma} \cdot \frac{N_p^1}{N_\pi} .$$

With the number of particles in one proton bunch $N_p^1 = 10^{12}$ and with the same remaining parameters, this gives

$$L_{\Sigma}^{\pi p} = 3 \cdot 10^{28}\, cm^{-2} s^{-1}.$$

If one uses the system under consideration for the muon-muon experiments with colliding beams in which the muon beams are cooled by ionization (under the condition that in collision the normalized muon emittance is conserved to be equal to their emittance directly after the ultimate ionization cooling), then the ultimate average luminosity will be equal to

$$L_{\Sigma}^{\mu\mu} = \frac{\gamma \dot{N}_p}{\ell_c} \cdot \frac{N_\mu}{\ell_\mu} \cdot \frac{p}{2 m_e c} \cdot \frac{e H \tau_\mu}{2\pi m_\mu c},$$

where ℓ_c is the ionization-cooling target length, which is equal to the value of the cooler beta-function in the target region, m_e is an electron mass. Assuming that $\ell_c = 1$ cm and $\ell_\mu = 5$ cm (the remaining parameters are the same), one obtains the following estimate of the ultimate luminosity

$$L_{\Sigma}^{\mu\mu} = 3 \cdot 10^{31}\, cm^{-2} s^{-1}.$$

The superlinacs, which are excited by proton klystrons, can be used also in the linear electron-positron colliding beams experiments. With the use of the approach and the estimates of VLEPP project the ultimate e^+e^- luminosity, for the "standard" productivity of a proton accelerator $\dot{N}_p = 10^{13}$ p/s, will be equal to

$$L_{\Sigma}^{e^+e^-} = 3 \cdot 10^{31}\, cm^{-2} s^{-1}$$

Even such a luminosity is of interest, in addition, the proton synchrotron efficiency will further grow.

REFERENCES

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DISCUSSION

Richter. You have not altered the conclusion of Voss' talk very much. Your power source is a ¾ billion dollar proton accelerator, and one must look seriously at the economics. Also, using existing tunnels etc., has caused trouble in the past. A further difficulty is that a machine pulsing every 10 secs as the SPS does will give trouble with transverse wake fields and space charge effects. I think it will be extremely difficult to get 10^{31}.

Skrinsky. Your comment is not completely correct. Only a fraction (say 1/10) of the initial particles take part, giving 10 cycles of linear collider operation to 1 cycle of proton acceleration. Certainly wake fields are a problem, but this could be overcome with care. My advice is to consider this direction, which maybe could be interesting.