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ON HIGH ENERGY ELECTRON COOLING

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ON HIGH ENERGY ELECTRON COOLING

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1. This talk is not a resumè of the whole Workshop, but simply of our (meaning, Novosibirsk) current understanding of how to use the cooling technique to achieve the maximum average luminosity in $p\bar{p}$ colliding beams, assuming that we have already learned how to obtain the required number of antiprotons. This understanding results, partly, from our discussions here at this Workshop.

Of course, the cooling technique can be applied in a wide range of experiments in elementary particles and nuclear physics and in other fields.

There are several methods to cool beams of fast charged particles, or to keep them cold enough despite any heating diffusion processes. This latter aim is closest to the subject of this Workshop.

But let us say a few words in general on particular methods of cooling.

2. Synchrotron radiation damping - currently, the most familiar - is of extreme usefulness for electron and positron beam cooling, especially today for high luminosity e^+e^- colliding

beam experiments. Radiation cooling will be very useful for the next (or even after-the-next) generation of $p\tilde{p}$ colliding beam facilities at energies more than 5 TeV, assuming the bending magnetic field would be about 100 KG or more.

3. Ionization losses should be useful for cooling muon beams (of course, the average energy losses should be compensated from the external energy source in the same way as for the synchrotron radiation case). Ionization cooling becomes effective for relativistic particles ($\gamma \geqslant 2$), because only in this case there is no antidamping due to decreasing ionization losses with increasing particle energy.

This cooling is useful only for muons, because for all relativistic hadrons the cross-section of "strong interaction death" is too large and, for $e^{\pm}$ the radiative losses, are bigger than ionization losses.

To have better equilibrium emittance it is necessary to place the light material target in a region with very low beta-value.

Ionization cooling makes it possible to obtain intense, high energy low emittance muon beams by accelerating the cooled muons. With the use of a special high-field storage ring it would be possible to obtain very intense and narrow $\nu_e, \tilde{\nu}_e, \nu_\mu, \tilde{\nu}_\mu$ - beams, and even high-luminosity muon colliding beams.*)

4. Stochastic cooling is most effective when it is necessary to damp large amplitudes of betatron oscillation and large momentum spread in proton (antiproton) beams; this is especially important for the initial stage of antiproton storing. But the rate of stochastic cooling goes down with increasing linear density of the stored beams (special disadvantage for bunched beams) and for beams of small emittance and small momentum spread. The

*) E.Perevedentsev, A.Skrinsky. The use of intense proton beams of big proton accelerators for linear accelerating structure excitation; VI Accelerator Conference, Dubna, 1978.

good feature of stochastic cooling is that its rate does not decrease for higher energies.

5. Electron cooling gives high cooling rate in the case of medium and, especially, low emittance proton (antiproton) beams in the medium and low energy range. The use of electron cooling for higher energies is the subject of our discussions today. Note, cooling <u>intense</u> proton beams need experimental study.

6. While interaction,cooling helps to confine the beam emittances and consequently the beam dimensions to their minimum admissible level at the collision points. This enables one to maintain the maximum attainable density and the maximum attainable collision luminosity. The cooling time, naturally, should be in any case much smaller than antiproton life-time due to strong interaction with colliding particles:

$$\tau_c \ll \frac{N_{\tilde{p}}}{L_\Sigma \sigma_T} \approx 10^5 \div 10^6 \text{ sec}.$$

Some effects of diffusional character lead, in the interaction regime, to beams tend to expand. Among these effects are: the multiple scattering on the nuclei of residual gas and on the cooling beam particles (pair collisions); an influence of the different noises of the magnetic field and RF systems; accumulating effects of non-linearities of the guiding fields and, finally, the coherent electromagnetic field effect of the colliding beam. Particularly, the existence of this latter effect is in practice the most significant and, therefore, let us specially dwell upon this effect, at least schematically.

If the transverse dimensions turn out to be too small for a beam which contains (for the sake of simplicity) only one bunch with a number of particles N, the colliding particle during one collision can acquire a scattering angle larger than the admissible angle which is determined by the admittance of the storage ring. While decreasing the colliding bunch density only the multiturn effects become destructive. In this case, the colliding beam field can be considered as a lens which varies the frequency of the particle betatron oscillations. An influence of this lens can be characterized by the frequency shift $\Delta\nu$. If $\Delta\nu$ is so high that the frequency is nearing the linear machine resonances, the particle oscillation amplitude increases very rapidly (in a few turns). With further decrease in bunch density, $\Delta\nu$ also decreases and, at the value $\Delta\nu \approx 0.1$, the influence of the colliding beam field in "good" operating points leads to quasidiffusional behavior of the amplitude of betatron oscillations under the effect of strongly non-linear field of the bunch. In this case, the diffusion rate rapidly decreases with decrease of betatron frequency shift and at $\Delta\nu \lesssim 10^{-4}$ the diffusion induced by collisional effects becomes practically negligible (even at the largest life-times of the beams, supposing that all the other sources of the diffusion have been ultimately suppressed). In the range $\Delta\nu = 10^{-1} \div 10^{-4}$ the diffusion rate not only depends on the given value $\Delta\nu$ but also depends on the presence of modulation of this shift by synchrotron oscillations as well as noises of magnetic field and also on a number of other factors. The beam "erosion" caused by the diffusion can be suppressed with friction. For e^+ and e^- at high energies the very strong friction is the radiation friction. Under these conditions one can achieve the following values: $\Delta\nu_{max} = (3 \div 5)\cdot 10^{-2}$. At these values one can overcome the diffusion by strong radiation friction. For pp colliding beams at

energies of hundreds of GeV, as mentioned above, the only kind of friction for which one can hope today is electron cooling by circulating electron beam of the same average velocity. Though the cooling rate will be a few orders of magnitude lower than the radiation cooling rate attained. Therefore, it is hardly possible to hope for machine operation with the frequency shifts higher than, say, $\Delta\nu_{max} = 1\cdot 10^{-2}$.

At a given $\Delta\nu_{max}$ a relation occurs between maximum achievable summary luminosity L_Σ of the installation and the number of particles in the weaker beam $N_{\bar{p}}$. Since, in the first approximation, L_Σ does not depend on the number of particles in a strong beam, then we will take $N_p = N_{\bar{p}} = N$. In this case, the relation mentioned above in the beams which are symmetrical over r- and z-directions ($\Delta r = \Delta z$, $\beta_z = \beta_r = \beta_0$ at the collision points) has the form:

$$L_\Sigma = \frac{\gamma \cdot N \cdot \Delta\nu_{max}}{r_p \; \beta_0} f_0 ,$$

where r_p is the classical radius of the proton, γ is the relativistic factor for the beams at the experiment energy, f_0 is the rotation frequency.

If the beams are separated into several bunches, the total ultimate luminosity over all the collision points, at a given total number of particles N , remains the same. It is determined by the above formula if the bunches would collide only in the useful and similar (over β_0-value) points and the collisions would not occur at all parasitic points. The latter can be achieved in the one-track storage ring with the help of the transverse quasiresonant electrostatic fields sufficiently high (as it is planned for VEPP-4), but in the case of the two-track storage ring it can be achieved by the appropriate selection of the intersection geometry.

The minimum emittance of the beams which corresponds to the given above formula for the ultimate luminosity will depend on the number of bunches n_B in the colliding beams. It is determined by the formulae:

$$\varepsilon_{min} = \frac{r_p N}{4\pi \Delta\nu_{max} \cdot \gamma n_B};$$

$$\varepsilon_{min} = \frac{r_p^2 L_\Sigma \beta_0}{4\pi (\Delta\nu_{max})^2 f_0 n_B}.$$

Of course, this emittance should be less than the admittance of the storage ring (taking into account the losses in useful aperture if one needs to separate orbits at parasitic points of collisions):

$$\varepsilon_{min} < \varepsilon_{adm}.$$

This condition gives the limit for achievable L_Σ. Note, that operation, using $N_p \gg N_{\tilde p}$, does not allow one neither to increase the luminosity considerably nor to decrease the emittance of the antiproton beam compared to the values given above and consequently, it does not ease the problem of antiproton cooling. This regime is rather a partial replacement if high energy electron cooling fails.

7. Let us shift now to the discussion of electron cooling directly in the colliding regime at energies of hundreds of GeV. Let us assume initially that the transverse electron temperature is negligibly small (longitudinal temperature is small due to relativistic character at $\Delta p_\perp^e$ and $\Delta p_\parallel^e$ comparable in the laboratory system). In this case, the electron cooling rate τ_c^{-1} will be determined by the transverse velocities of antiprotons (or protons):

$$\tau_c^{-1} = 20 \frac{\mathcal{J}_e^{max}}{e} \cdot \eta_c L_C \cdot \frac{r_e r_p}{\gamma^5 S_{\tilde p} \theta_{\tilde p}^3},$$

where r_e, e are the classical radius and the charge of the

electron; $L_C \approx 5$ is the Coloumb logarithm of antiproton-electron collisions; $\mathcal{J}_e^{max}$ is the peak electron current at the moments of cooling; η_c is the fraction of the antiproton orbit occupied by the cooling region; $S_{\tilde p}$ is the cross-section of the antiproton beam on the cooling region (the cross-section of electron beam should be not more than this value since, in this case, the cooling rate will be decreased); $\theta_{\tilde p}$ are characteristic antiproton angles at the collision region.

As to $\theta_{\tilde p}$, one should have in mind that not only the particles giving the main contribution to the luminosity (which corresponds to the emittance ε_{min}) should be cooled but the particles which have the angles by factor K = 2÷3 bigger, should also be cooled, since otherwise the luminosity decreasing time will be too small due to the irreversible diffusion pumping of particles into the "tails" of the distribution function. Under these conditions:

$$\theta_{\tilde p} = K \left(\frac{\varepsilon_{min}}{\beta_c}\right)^{1/2};$$

$$S_{\tilde p} = 2\pi K^2 \varepsilon_{min} \beta_c;$$

$$\tau_c^{-1} = 3 \frac{\mathcal{J}_e^{max}}{e} \cdot \eta_c L_c \cdot \frac{r_e r_p \beta_c^{1/2}}{\gamma^5 K^5 \varepsilon_{min}^{5/2}},$$

where β_c is the value of beta-function in the cooling region. Consequently, using expressions for ε_{min} one gets:

$$\tau_c^{-1} = 10^3 \cdot \frac{\bar{\mathcal{J}}_e}{e} \cdot \frac{\Pi_e}{L_B} \cdot \frac{r_e L_C}{r_p^{3/2}} \cdot \frac{\eta_c (\Delta\nu_{max})^{5/2} \beta_c^{1/2} n_B^{5/2}}{\gamma^{5/2} N^{5/2} K^5};$$

$$\tau_c^{-1} = 10^3 \cdot \frac{\bar{\mathcal{J}}_e}{e} \cdot \frac{\Pi_e}{L_B} \cdot \frac{r_e L_C}{r_p^4} \cdot \frac{\eta_c (\Delta\nu_{max})^5 \beta_c^{1/2} f_0^{5/2} n_B^{5/2}}{L_\Sigma^{5/2} \beta_0^{5/2} K^5};$$

(note that in the latter formula the dependence on γ disappears). It is assumed here that $\mathcal{J}_e^{max} = \bar{\mathcal{J}}_e \frac{\Pi_e}{L_B}$, where $\bar{\mathcal{J}}_e$ is average electron current in the electron storage ring, Π_e is the circumference of this storage ring which should be by integer times less or should be equal to the distance between the antiproton (proton) bunches; it is assumed that the electron beam is accumulated into one bunch with the same length (L_B, or less,) as that for the bunches in the main storage ring.*)

8. For colliding beams, estimations carried out by the latter formulae show that large electron currents are required in order to obtain cooling times on the order of 10^2-10^3 sec at the luminosity of 10^{30} cm^{-2} s^{-1} (the pulse currents should be on the level of tens or even hundreds amperes in the many bunches regime of the collider).

Achievement of such currents in the storage rings at electron energies of hundreds of MeV and higher is not a problem now. But difficulties appear due to the necessity of having a low effective temperature of electrons in order that the angles in the electron beam should be lower than those in the proton (antiproton) beam and should not decrease the cooling rate. Having in mind, that electron beam cross-section should be not bigger than that of antiproton beam, we obtain the restriction on electron beam emittance:

$$\varepsilon_e < \varepsilon_{\tilde{p}} .$$

Only in this case the cooling rate would not decrease additionally.

In order to maintain small enough spreads in electron beam, a sufficiently strong effective friction is required for electrons.

*) Note, that in order to cool protons and antiprotons in one track collider in a time, it is necessary to have two independent electron storage rings with electron velocities in the cooling sections parallel to the beam under cooling. The interaction of electron bunch with antiparallel beam should be excluded by corresponding phase shift to prevent very dangerous beam-beam effects, especially on electrons having two thousands times lower momenta.

For this purpose, it is natural to use radiation friction. This can be done either directly in the main storage rings or with the transportation of electron bunches after their heating into the special deeply and fast cooling storage ring and also by injection into the main electron storage ring of just cooled portion of particles.

A few processes can lead to the heating of electron beams: heating with the beams under cooling themselves; appearance of electron coherent instabilities; self-heating due to the inter-beam electron collisions and also the influence of the synchrotron radiation quantum fluctuations.

The first effect is the simplest and it can be easily handled. For this purpose, it is sufficient that the time of effective cooling of the electrons is sufficiently small:

$$\tau_{rad} < \tau_c \cdot \frac{m}{M} \cdot \frac{N_e}{N_{\tilde{p}}} \cdot \left(\frac{\theta_e}{\theta_{\tilde{p}}}\right)^2 ,$$

(the formula is derived from the simple thermodynamic considerations "heat flow balance"). Even if one takes into account that θ_e should be lower than $\theta_{\tilde{p}}$, for the parameters required, we obtain simple requirements for τ_{rad}.

The problem of coherent instability is much more complicated and has many forms. Operational experience of electron storage rings, though, gives the confident hope that one may obtain the required parameters. So, at VEPP-2 storage ring the peak electron currents one can manage to obtain are 20-40 A with moderate temperature even at an energy as low as 100 MeV.

In order to overcome the effect of internal scattering which in the relativistic region nearly innevitably leads to the beam self-heating, both the ultimate powerful damping and selection of a very special structure of the electron storage ring are required. In particular, it requires the ultimate radial focusing in the bending sections and zero values for the dispersion functions and their derivatives at the long straight-sections (cooling sections, for example). This problem seems to be solvable.

Elimination of dangerous influence of quantum fluctuations of radiation requires similar ways but looks like it is easier.

9. The problem of obtaining the circulating electron beams with parameters necessary for the effective cooling of $p\bar{p}$ colliding beams would become much simpler if one could exclude (or sharply attenuate) an influence of the transverse electron temperature to the cooling rate. This was obtained in the case of "direct" electron beams with the help of a longitudinal magnetic field which "magnetizes" the transverse motion of electrons at the proton-electron collisions. The search for such versions is at the very beginning.

10. In conclusion, I can say, that cooling with the help of circulating electron beams can become an important tool for increasing the effective luminosity of the installations with $p\bar{p}$ colliding beams at energies ranging from tens of GeV to several TeV.

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Some additional consideration on the questions mentioned are given in the review paper by G.I.Budker, A.N.Skrinsky "Electron cooling and new possibilities in elementary particle physics" (Uspekhi Fiz. Nauk, 124, N°4, 1978; the English translation is available) and also in the cycle of the Novosibirsk papers on electron cooling.

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