# e-p ACCELERATOR SUBGROUP SUMMARY

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## I. Introduction

The spirit of the e-p subgroup is not so much to put forth the costs of facilities as functions of the collision energies and performance, as to look at the performance and flexibility of a near-term facility of 20 GeV electrons on 400 GeV protons, and to investigate possible accelerator configurations and performances of the e-p collision with a 20 TeV proton storage ring, which is a current topic for the hadron collider groups. Another near-term possibility of the e-p facility is 10 GeV electrons on 1 TeV collider which has a similar collision center of mass energy as that of 20 GeV on 400 GeV. However, the 10 GeV on 1 TeV idea has been studied in detail by two groups[1,2] two years ago; thus, the subgroup has not looked into it.

For the 20 GeV on 400 GeV collisions (BNL schemes), three different operating modes were considered for the luminosity consideration, as well as for simultaneous operation of the accelerator to facilitate the e-p and p-p interactions. With a 10 TeV proton ring, considerations were given for an electron ring of some 100 GeV, and for an electron linac of similar energy to facilitate the interactions.

## II. Basic Formulae for Unequal Mass Collisions (E.D.C)

The e-p collision, unlike the $e^+ - e^-$ or $p$-$\bar{p}$, involves the particles of different masses in the initial states. For this reason, it could be informative to present generalized luminosity and tune shift formulae for unequal masses of bunched or dc beams with and without the crossing angle to each other. We assume that $\beta_x$, $\beta_y$, $\sigma_x$ and $\sigma_y$ of each beam are to be constant throughout the interaction region, and the particle distributions in the physical space are Gaussian.

In addition to the usual notations and dimensions, we note the following. Subscripts 1 and 2 denote the particles 1 and 2; all length dimensions are in meters; R is average radius of ring defined by orbit length/2π; k is number of bunches in the ring; and luminosity, L, is in unit of $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$.

### A. Bunched Beams Head-on Collision

Luminosity L:

$$L = \frac{R}{ck}\ \frac{I_1\ I_2/e^2}{\sqrt{\sigma_{x_1}^{2} + \sigma_{x_2}^{2}}\sqrt{\sigma_{y_1}^{2} + \sigma_{y_2}^{2}}}$$

$$= \frac{1.3 \times 10^{24}}{k}\ \frac{R\ I_1\ I_2}{\sqrt{\sigma_{x1}^{2} + \sigma_{x2}^{2}}\ \sqrt{\sigma_{y1}^{2} + \sigma_{y2}^{2}}}$$

Linear Tune Shifts

$$\Delta\nu_{x1} = \frac{R\ r_1\ \beta_{x1}^{*}}{\gamma_1 c\ k}\ \frac{I_2/e}{\sigma_{y_2}(\sigma_{x_2} + \sigma_{y_2})}$$

$$= \frac{1.5 \times 10^{-8}\ R\ \beta_1^{*}\ I_2}{k\ E_1\ \sigma_{y2}(\sigma_{x2} + \sigma_{y2})}$$

where $E_1$ is the energy of particle 1 in GeV, and $r_1 = \frac{e^2}{m_1 c^2}$ is the classical radius of particle 1.

For $\Delta\nu_{x2}$, one has to interchange the subscripts 1 and 2. Similarly, in order to calculate $\Delta\nu_y$, the x and y subscripts should be interchanged.

### B. Bunched Beams Crossing Horizontally with a Finite Angle α.

The crossing angle, α, is assumed to be much larger than $(\sigma_x$ or $\sigma_y)/\sigma_Z$, then the performance forumlae becomes:

$$L = \frac{2^R}{ck\alpha}\ \frac{I_1\ I_2/e^2}{\sqrt{\sigma_{Z_1}^{2} + \sigma_{Z_2}^{2}}\sqrt{\sigma_{y_1}^{2} + \sigma_{y_2}^{2}}}$$

$$\Delta\nu_{x1} = \Delta\nu_{x2} = 0$$

$$\Delta\nu_{y_1} = \frac{2\ R\ r_1\ \beta_{y_1}^{*}}{\gamma_1\ c\ k\ \alpha} \cdot \frac{I_2/e}{\sigma_{y2}\ \sigma_{Z2}\sqrt{1 + 4\sigma_{x_2}^{2}/\alpha^2\ \sigma_{Z2}^{2}}}$$

$$= 6 \times 10^{-8}\ \frac{\beta_{y_1}^{*}}{E_1} \cdot \frac{I_2}{\sigma_{y2}\ \sigma_{Z2}\sqrt{1 + 4\sigma_{x2}^{2}/\alpha^2\sigma_{Z2}^{2}}}$$

To obtain $\Delta\nu_{y2}$, the subscripts 1 and 2 should be interchanged.

### C. Beam 1 Bunched, Beam 2 DC with Horizontal Crossing Angle α

$$L = \frac{2\ I_1\ I_2/e^2}{C\ \sqrt{2\pi} \cdot \alpha \cdot \sqrt{\sigma_{y1}^{2} + \sigma_{y2}^{2}}}$$

$$= 1.04 \times 10^{25}\ \frac{I_1 \cdot I_2}{\alpha\sqrt{\sigma_{y1}^{2} + \sigma_{y2}^{2}}}$$

$$\Delta\nu_{x_1} = \Delta\nu_{x_2} = 0$$

$$\Delta\nu_{y1} = \frac{2 r_1 \beta_{y_1}^{*}\ I_2/e}{\gamma_1 C\ \alpha\sqrt{2\pi}\ \ \sigma_{y2}}$$

$$= \frac{7.4 \times 10^{-8}}{E_1} \cdot \frac{\beta^*_{y_1} I_2}{\alpha \sigma_{y2}}$$

$$\Delta\nu_{y2} = \frac{2^R r_2 \beta^*_{y2} \qquad I_1/e}{\gamma_2 \cdot c \cdot k \cdot \sigma_{y1} \sqrt{\alpha^2 \sigma_{Z1}^2 + 4\sigma_{x_1}^2}}$$

$$= 6 \times 10^{-8} \frac{\beta^*_{y2} I_1}{E_2 \sigma_{y1} \sqrt{\alpha^2 \sigma_{Z1}^2 + 4 \sigma_{x1}^2}}$$

D. DC Beams Crossing with Angle $\alpha$

$$L = \frac{2 I_1 I_2/e^2}{C \sqrt{2\pi} \cdot \alpha \cdot \sqrt{\sigma_{y_1}^2 + \sigma_{y_2}^2}}$$

$$= 1.04 \times 10^{25} \frac{I_1 I_2}{\alpha \sqrt{\sigma_{y1}^2 + \sigma_{y2}^2}}$$

$\Delta\nu_{x1} = \Delta\nu_{x2} = 0$

$\Delta\nu_{y1}$ = same as if the Beam 1 is bunched.

$\Delta\nu_{y2}$: interchange the subscripts 1 and 2.

## III. 20 GeV Electrons on 400 GeV Protons

Recently, a BNL group studied an option of e-p collider using the ISA tunnel, and the result of that study was reported in this workshop. Two possible variations of the bunched beam collisions and bunched electron beam on unbunched proton beam collision schemes were discussed in this workshop. The latter scheme has an advantage of operating the e-p experiments simultaneously with the hadron-hadron experiments.

The ideas put forth by the BNL Group were to use the AGS as the injector for both protons and electrons. Then, these particles are stored and accelerated in a proton ring and an electron ring situated in the ISA tunnel. Three variations of operating modes are:

### A. Low Current Bunched Mode

A simple injection of bunched to bunch transfer using the 4.4 MHz AGS rf would enable storing 57 bundles each of electrons and protons. The stored currents and the bunch populations of electrons and protons are 66 mA, $9.3 \times 10^{10}$/bunch and 230 mA, $3.3 \times 10^{11}$/bunch, respectively.

In this mode, the expected luminosity and the linear tune shifts are

$L = 6.2 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$

$\Delta\nu_e = 0.05$

$\Delta\nu_p = 0.005$

with $\beta^*_p = 3$ m $\sigma_p = 1.37 \times 10^{-4}$ m

$\beta^*_o = 0.5$ m $\sigma_e = 1.26 \times 10^4$ m

Above tune shifts seem optimistic; however, the expected operation of a round beam collison could tolerate some larger tune shifts (see A. Ruggiero, Particle Accelerators - 1982).

### B. High Current Bunched Mode

By a somewhat more complicated method of injection, the number of bunches in the storage ring could be raised by a factor of three. Though the bunch number is increased to 171, bunch populations can be lowered to make the linear tune shifts smaller. In this case, the electron and proton circulating currents and bunch populations of 120 mA, $5.6 \times 10^{10}$/bunch and 420 mA, $2 \times 10^{11}$/bunch, respectively, would give

$L = 6.7 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$

$\Delta\nu_e = 0.03$

$\Delta\nu_p = 0.003$

with $\beta^*_p = 3$ m, $\beta^*_e = 0.5$ m, $\sigma_p = 1.4 \times 10^{-4}$ m and $\sigma_e$ $= 1.3 \times 10^4$

Since the tune shifts in this case are moderate, the luminosity can be increased if allowed tune shifts for the e-p are higher.

### C. Bunched Electrons on DC Proton Beam

Unbunched proton beam operation for the e-p collision has several advantages. These include synchronization of the electron bunch to that of proton is no longer needed. This would enable experiments to be done with different energies of protons. In the bunched proton case, this kind of option is difficult due to changes in the proton velocity, as the energy is varied. The expected luminosity for the proton beam of 8 A, and electron beam of 171 bunches and 100 mA is

$L = 4.2 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$

$\Delta\nu_e = 0.034$

$\Delta\nu_p = 0.004$

with similar geometrical factors as the other cases.

It should be noted here that although 8 A of stored proton current, the luminosity is slightly less than the bunched proton cases. On the other hand, the proton tune shift is much less than the other cases.

## IV. e-p Colliders with 20 TeV Proton Ring

In order to estimate performances of the e-p collider with a 20 TeV proton ring, this group assumed some parameters of such proton ring. The assumed parameters may not be the same as those delivered by the hadron study group; however, the differences may not be too important for the purpose of this study. The following table shows some parameters:

| | | |
|---|---|---|
| $E$ | Energy | 20 TeV |
| $B$ | Field | 5 T |
| $R$ | Average Radius | 20 km |
| $\rho$ | Bending Radius | 13.3 km |
| Trev | Revolution Time | $4.2 \times 10^{-4}$ sec |
| $N^{max}$ | Maximum Stored Protons | $5 \times 10^{13}$ |
| $\beta^*$ | $\beta$ at Ip | 5 m |
| $\epsilon_N$ | Normalized Emittance | $1\pi \times 10^{-6}$ m |
| $\sigma p$ | rms Proton Size | $6 \times 10^{-6}$ m |

The $\epsilon_N$ used here is substantially smaller than $24 \pi \times 10^{-6}$ m of FNAL, but we assume this value can be improved in due time.

With this ring, then the group has studied two different accelerator schemes to facilitate the e-p collisions.

## A. 20 TeV Protons with Electron Storage Ring

Here we assume the electron ring is built in the same tunnel with the proton ring and has some bending radius. Because of this assumption, lower energy electrons may not be suitable for storing in the electron ring due to lower peak field of the ring, and the energies considered here are 50, 100, and 140 GeV. In order to take account of the quantum fluctuations in the beam size considerations, we assumed the electron ring has a tune of 220 and the $\gamma_T = 225$.

With an assumption that the $\beta_e^*$ can be made to 0.1 m, and supposing that the $\Delta\nu_e$ and $\Delta\nu_p$ should not be greater than 0.05 and 0.005, respectively, the performance parameters of the accelerator system are obtained. The following table shows some parameters

| Electron Energy (GeV) | 50 | 100 | 140 |
|---|---|---|---|
| S. R. Loss (MeV/turn) | 41.4 | 662 | 2542 |
| $\sigma_E/E$ | $3.7\text{x}10^{-4}$ | $7.4\text{x}10^{-4}$ | $1\text{x}10^{-3}$ |
| $\sigma^2$ | $7.9\text{x}10^{-12}$ | $3.1\text{x}10^{-11}$ | $6.2\text{x}10^{-11}$ |
| No. 4 Electrons/Bunch | $1.4\text{x}10^{9}$ | $5.4\text{x}10^{9}$ | $1\text{x}10^{10}$ |
| No. of Protons/Bunch | $1.6\text{x}10^{10}$ | $3.2\text{x}10^{10}$ | $4.3\text{x}10^{10}$ |
| No. of Bunches | 3000 | 1500 | 1100 |
| $I_e$ (mA) | 1.6 | 3.1 | 4.5 |
| $I_p$ (mA) | 18 | 18 | 18 |
| Radiactive Power (MW) | $6.6\text{x}10^{-2}$ | 2 | 11 |
| L ($\text{cm}^{-2}$ $\text{sec}^{-1}$) | $5.6\text{x}10^{31}$ | $1.4\text{x}10^{32}$ | $1.8\text{x}10^{32}$ |

It should be noted that with the assumed electron ring lattice, the electron emittance increases as the energy increases. The assumption that the proton ring would have $\sim 5 \times 10^{13}$ protons is the limiting factor in the luminosity. If the normalized emittance of protons is substantially larger than the assumed value of $1\pi \times 10^{-6}$ m, to obtain similar luminosity, the needed number of protons would increase substantially and so would the number of electrons and the radiactive power.

## B. Proton Storage Ring and Electron Linac

Storage ring linac configuration for the e-p had been studied by the ICFA workshop in the past.[3] The present study draws a somewhat similar conclusion as that of the previous study.

Here again, we assume that there does exist a 20 TeV proton ring of a circumference of ~ 20 km, in which stored protons have a bunch length of one meter. An electron linac would conceivably have an rf frequency of 3 GHz, which provides a micro-bunch separation of 10 cm. Thus, the length of ten micro-bunches is equal to that of one proton bunch in the storage ring. This implies that the linac bunch structure should be a micro-macro pulse mode with each macro-pulse containing ten micro-pulses, and the linac rep rate should be equivalent to the proton ring bunch separation. Under this condition, the luminosity can be expressed

$$L = f_r N_p^b N_E^b \; G$$

where $f_r$ = linac rep rate

$N_p^b$ = number of protons/bunch

$N_e^b$ = number of electrons/macro pulse

$G$ = geometrical factor involving beam sizes

It should be noted that fr $N_e^b$ is proportional to the linac power, and for a single pass collider, the linac power should be minimized. With this consideration, the luminosity formula implies that in order to obtain a high luminosity, and at the same time to minimize the linac power, the number of protons/bunch must be made as large as possible. As a consequence of doing so, a larger electron tune shift would result.

Although the linac power can be lowered at the expense of the tune shift, since there is no experimental value of the e-p tune shifts, we impose the same $\Delta\nu$'s as the previous cases. Then we obtain

$$N_p^b = 1.6 \times 10^{10} \text{ protons/bunch}$$

$$N_e^b = 4.3 \times 10^{9} \text{ electrons/macro-pulse}$$

From this $N_p^b$ and assumed the maximum stored number of protons of $5 \times 10^{13}$, the number of bunches in the ring becomes about 3,000, and the bunch separation of $1.4 \times 10^{-7}$ sec (= 7 MHz). Then the linac rep rate should be the bunch frequency of 7 MHz.

We have shown that the properties of the proton ring dictate the linac properties. These are the macro-pulse repetition rate of 7 MHz, the macro-pulse contains 10 micro-pulses and total charges of $4.3 \times 10^{9}$ electrons. This implies the linac should be a very high Q device; i.e., a superconducting linac which accelerates a 4.8 mA of average currents. The beam power becomes 480 MW, and this energy must be recovered. To do so will need another linac situated at the downstream of the IR, and by which the electrons are to be decelerated to extract the beam energy. For this reason, we choose to impose $\Delta\nu e \approx 0.05$.

To calculate the luminosity, we choose the emittance of 100 GeV electron beams to be $1 \pi \times 10^{-9}$ m which is deduced from a known electron gun. This gives $\sigma_e = 4 \times 10^{-6}$ m with the $\beta_0^* = 0.1$ m. Then

$$L = 1.3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}.$$

The AC power consumption of such a linac system is estimated to be about 400 MW at 100 GeV operation, if the unloaded Q of the structure can be made to be $5 \times 10^{10}$, the energy gain of 20 MV/m, and the refrigeration efficiency of $10^{-3}$.

From a comparison between the electron ring and the electron linac schemes presented here, an obvious conclusion would be that they give more or less the same luminosity, and storage rings in the energy range considered consume much less power than the linac scheme. However, the power consumption conclusion depends strongly on the storage ring parameters. For example, the ICFA study of the e-p collider at a similar energy range showed 70 MW of the synchrotron radiation loss with less luminosity than this study. In that case, one can draw somewhat different conclusions.

## V. Beam Strahlung in e-p Collision

In very high energy $e^+ - e^-$ collisions, the beam-strahlung, synchrotron radiation of one beam caused by the field produced at the interaction point by the other tightly bunched beam, plays a very important role in the performance of such a collider. For the e-p case which involves two unequal masses, the average electron beam strahling loss/interaction point can be described by[4]

$$\langle 8U \rangle_{bb} = \frac{2}{3} r_e m_e C^2 \gamma_e^4 \cdot \langle I_{2bb} \rangle$$

$$\langle I_{2bb} \rangle = \left[ \frac{4}{\sqrt{\pi}} \left( \frac{r_e}{\gamma_e} \right)^2 \right]_{\text{electrons}} \cdot \left[ \frac{1}{\sigma_2} \left( \frac{N_p^b}{\sigma_x + \sigma_y} \right)^2 \right]_{\text{protons}}$$

Inspection of this equation indicates that although the number particles/bunch in the e-p case is an order of magnitude higher than that of the $e^+ e^-$ case, because the $\sigma_z$, $\sigma_x$ $\sigma_y$ of protons are much larger than those of $e^+ + e^-$ case, the beam-strahlung phenomenon may not play such an important role. An example of this is:

$$\langle \delta U \rangle_{bb} = 41 \text{ keV/IR}$$

with $\sigma_p = 6 \times 10^{-6}$ m, $\sigma_z = 0.1$ m, and $N_p^b = 3 \times 10^{10}$. This 41 keV/IR should be compared with 662 MeV/turn of normal synchrotron radiation of a ring.

## VI. Remarks

It is natural to ask whether an $e^+e^-$ ring or $p(\bar{p})$ - p ring can be used for the e-p collisions and, if so, then what are the peculiar characteristics of the e-p rings compared to the others.

The proton ring in the e-p collider would look similar to that of the $p(\bar{p})$ - p cases, and most likely would have a lesser number of protons circulating than the P-P. One important consideration must be that the proton ring has a long straight section (~ 250 m) to facilitate the polarization manipulation of the electron ring.

On the other hand, the e-ring of the e-p and the $e^+ - e^-$ ring have substantial differences. The e-p's e-ring has a larger number of bunches, larger average currents, lower bunch currents and bunch population. Thus, the rf power requirements and the instability considerations have to be considered separately. A larger average current means that the synchrotron radiation power is higher for the e-p; therefore, the vacuum consideration has to be different.

## References

1. CHEER Feasibility Study Report, Canadian Institute of Particle Physics (September 1980)
2. Fermilab Proposal - 659: Electron-Proton Interaction Experiment, W. Loe and R. R. Wilson, Spokesmen (June 1981)
3. G. Weber et al., Group IV Report, Proceedings of the Second ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors (October 1979)
4. Y. Cho, to be published in these proceedings.