WAKE FIELD HADRON LEPTON ACCELERATOR COMPLEX

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ABSTRACT

As an accelerator of the next generation, Hadron collider such as SSC or LHC and Lepton collider such as SLC, LLC or VLEPP are excludively proposed. The author proposes a new Wake field Hadron Lepton accelerator complex where Hadron and Lepton accelerator are combined together. WHALE has a race track shape where half of it is consisted of a linear Lepton collider and wake linac and the other half is consisted of Hadron synchrotron. A very intense proton bunch is accelerated to form a ultra short bunch in cavities in the linear collider and used as a driving source of a strong wake field in the wake linac. The author shows that the creation of a 10 mm proton bunch with a total charge of 1 μQ is possible. If so one could obtain an accelerating field gradient of 1.15 TV/km. In WHALE hadron energy is doubled. Lepton energy is pushed up to the energy range of hadron, say more than 20 TeV.

INTRODUCTION

Beyond an energy of high energy machines under construction such as Tevatron (1.8 TeV pp) or UNK (6 TeV pp) or SLC (120 GeV e^+e^-) or LEP (260 GeV e^+e^-), comes the Superconducting Super Collider (40 TeV pp)[10] as a hadron collider or Large Linear Collider (1 to 2 TeV e^+e^-) or VLEPP (1 TeV e^+e^-). Further beyond this energy comes the 2020 machine (1 PeV pp) conceived by Bjorken[12]. The 2020 machine's design is based on the extension of the technology of the Tevatron. The average radius would be 350 km even with 10 T magnets. Clearly, we need to invent new type of accelerator in our generation much before 2020 year. In fact, quite a number of new ideas or revived ideas ar now rushing into print. They are electron beat wave accelerator by Nation, Electron ring accelerator, Sessler's Two-Beam accelerator, Lasertron by Yoshioka, Inverse free electron laser by Pellegrini, proton klystron by Skrinsky[8], collective electron accelerator by proton by Balakin[7], wake field accelerator by Voss and Weiland[6], Beam front accelerator by Reiser, Laser grating accelerator by Palmer, compressed electron gas accelerator (Super accelerator) by Winterberg, Laser beat wave accelerator by Tajima and Dawson (Surfatron is variant) and possibly many other machines. There exists some other mechanisms which exhibits very high field gradient such as plasma focus. See Fig. 1 for the accelerating field gradients proposed by various authors.

In this article, the author proposes WHALE, Wake field Hadron Lepton accelerator complex. In WHALE, Hadron collider and Lepton collider are united. (They should not be exclusively proposed at different geometrical or political area). In WHALE proton synchrotron forms arcs and lepton linear collider fills one of the very long straight section. Another long straight section is filled with or bypassed by a very simple wake field linac. Thus a shape of WHALE is a race track. We assume the length of the straight section is comparable to that of the diameter of the SSC with 3 T superferric version. At this size, the energy of the proton may be doubled and the energy of the electron may be comparative to the energy of the proton. Furthermore, unstable particles like $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^- are not unstable anymore under ultra high electric field and could be accelerated and collided like an ordinary stable particles. This may open the new high energy experimental physics.

WHALE

WHALE is made of multistage injectors, 40 TeV (20 TeV/beam) pp storage ring 1.6 TeV (800 GeV/beam) e^+e^- lepton linear collider and 1.15 TeV/km wake field linac. Putting SSC and SLC (or LLC) and wake field linac together make our WHALE. So we only discuss our wake field linac.

(i) Structure of the wake field linac

The structure of our wake field linac has the simplest form. The linac is consisted of a cylinder and disks with a beam hole and nothing else except for permanent quadrupoles[2] for focusing, beam monitor and some correction element. No RF power supply, no magnet power supply is needed. The accelerating electric field is fed by driving proton beam. The driving proton beam pass through the center hole of the disks. The trailing beam with less intensity which is to be accelerated follows the driving beam on the wake field generated by the driving beam on the center hole. In the case of Voss and Weiland[6] driving beam has a donut ring shape, called hollow bunch and consequently the structure is more complicated than ours. In addition their case supporting bar of the disks intrude to the passage of the driving beam. To avoid beam loss, hollow bunch can not be rotated. Assume even it is possible, hollow bunch has some defects in its shape, and hollow bunch may suffer instabilities. We are free from this kind of troubles. Beam may be much easier to handle and the structure is much more simple.

In the case of Balakin[9], the structure could be essentially similar to ours. The driving beam and the trailing beam, however, overlap in space, whose overlap may result in space charge effect or instability. This overlap of the location of the driving and trailing charge is the reason why they call this method callective field acceleration.

In our case analysis of a beam stabily seems to be much simpler and the field strength is even higher than that of Balakin.

In Fig. 2 we show longitudinal semi-cross section of the structure and typical plots of electric line force. The calculation and the graphic plot were performed with TBCI[1]. The driving beam passes on the longitudinal axis of the disk holes whose radius a = 2 mm. Electric field induced by the beam spreads outward as can be seen from the figure and is reflected back from the wall to the center. One can see the wave front propagates radially with an angle of 45° to the direction of the driving beam. The parameters used in Fig. 2 are: radial dimention R is R = 30 mm, standard deviation of the bunch σ is σ = 2 mm, total charge Q is Q = 1 μ Coulomb.

The result from the TBCI gives the accelerating field gradient of

$$E_a \simeq 1.15 \text{ GV/m}$$

and the transformation ratio t, which is the ratio of the gained voltage of the trailing beam to the deccelerating voltage of the driving beam, is

$$t = 1.44 \quad .$$

Unlike the case of Voss-Weiland, the accelerating field E_a and the transformation ratio t does not depend on the outer radius of the disk R[13]. The size of R only affects the spacing between the driving bunch and the trailing bunch. With the same parameter, we gain the accelerating field E_a by factor 7 and the trans- formation ratio by 1/7 if we compare with those of Voss and Weiland. In our scheme relatively small trans- formation ratio does not matter as we are assuming a very high energy proton (20 TeV). This is an essential difference between ours and theirs.

(ii) How to make a ultra short intense proton bunch ?

Our design goal is to obtain ultra short intense bunches whose total charge is 1 μ coulomb ($N = 6 \times 10^{12}$ ppb) in a bunch length Δs of Δs = 10 mm (σ = 2 mm). We assume the maximum number of protons N per bunch is limited by a microwave instability[3]. Then N is given by the Keil-Schnell criterion as

$$N = \frac{|\eta| E}{\beta c e |\frac{Z}{n}|} \left(\frac{\Delta E}{E}\right)^2 \Delta s_0 \qquad (1)$$

with $\eta \simeq \frac{1}{\gamma^2} - \frac{1}{\nu^2}$

where Δs_0 is a bunch length, E is a total energy, ΔE is an energy spread, Z/n is a longitudinal coupling impedance, β and γ are a ratio of a velocity to a light and a ratio of a mass to a rest mass and ν is a betatron tune.

We consider a proton synchrotron or storage ring whose size is comparable to SSC (20 TeV proton per beam). RF bucket must be provided to allow for the emittances which satisfies Eq. (1). It is known that a constant quantity exists which is independent upon the energy variation. This invariant is simply expressed in a closed form. For stationary bucket it is written

$$\frac{EV}{\eta} = \text{const.} \qquad (2)$$

where V is an RF acceleration voltage.

Eq. (2) shows that for maximum energy, V/η is minimum. Thus we have a margin of the RF voltage at the end of an acceleration stage. Application of a abrupt RF voltage to the beam introduces a quadrupole oscillation. After a quarter of synchrotron oscillation bunch length Δs of the beam becomes minimum. This method of the reduction of the bunch length was experimentally verified[4),5)] by Sasaki and Irie at the KEK Booster synchrotron. The dependance on the RF voltage of the final bunch length Δs is written as[5)],

$$\Delta s = \sqrt{\frac{V_{ext}}{V_{max}}}\ \Delta s_0 \qquad (3)$$

where Δs_0 is an initial bunch length, V_{ext} is a minimum RF voltage to sustain the invariant of the RF bucket at the end of the acceleration stage, and V_{max} is the maximum RF voltage we can afford to provide.

As the bunch length, the energy spread and the RF voltage are related, we next write down the emittance ε_0 and the acceptance A_0 at the injection stage. The emittance ε_0 of the coasting beam at the injection stage are,

$$\varepsilon_0 = 2\Delta t_{RF} \Delta E_{inj} = \frac{4\pi R}{h} P_{inj} = 2\Delta s_0 \Delta P_{inj} \qquad (4)$$

where h is a ratio of a RF frequency to a revolution frequency.

$$A_0 = \frac{16\beta}{h^2 \omega} \sqrt{\frac{h E_{inj} e V_{inj}}{2\pi\eta}} \qquad (5)$$

Equating $\varepsilon_0 = A_0$, we get the bunch length by combining above equations:

$$\Delta s = \frac{\pi^2}{2} \sqrt{ceR\ N\ \left(\frac{Z}{n}\right) \left(\frac{E_{ext}}{E_{inj}} \frac{\eta_{inj}}{\eta_{ext}} V_{max}\right)^{-1}} \qquad (6)$$

We then assume

$$R = 40.9 \text{ km}, \quad \frac{Z}{n} = 3\Omega, \quad N = 6 \times 10^{12} \text{ ppb},$$

and

$$\frac{E_{ext}}{E_{inj}} \frac{\eta_{inj}}{\eta_{ext}} \simeq 20 \ ,$$

then we have

$$\Delta s(\text{mm}) \simeq 206\ V_{max}^{-\frac{1}{2}}\ (\text{GV}) \ . \qquad (7)$$

We next assume the field gradient E_a of the linear collider E_a = 17 MV/m, which is the design vslue of SLC, is available. For 47 km length, we have V_{max} = 800 GV and Δs = 7.3 mm which satisfies our design goal.

If we assume the injection energy of the WHALE around 1 TeV, 3 stage Booster synchrotron might be necessary. They are,

Booster I	100 MeV ∿ 1 GeV
Booster II	1 GeV ∿ 50 GeV
Booster III	50 GeV ∿ 1 TeV .

For ultra short bunching, two stage buching might be adequate. First stage bunching is performed in Booster III (2R > 2.2 km). To reduce the bunch length from Δs = 1.2 m to Δs = 12 cm, the required RF voltage would be $V_{max} \simeq$ 77 MV for $f_{RF} \simeq$ 250 MHz. This voltage may be rather modest. Recall the RF voltage of TRISTAN is 410 MV, and that of LEP (86 GeV) is 1.95 GeV (353 MHz).

The energy spread of WHALE is rather high to suppress microwave instability. At the injection stage the energy spread ΔE/E = 1.7 % and at the bunch compression stage it is ten times more at 20 TeV. Thus the aperture of WHALE must be comparable to that of $\bar{p}$ accumulation ring. In this sense, a wider aperture 2 in 1 superferric[10)] magnet would be adequate to reduce cost. Care must be taken for the suppression of the momentum dispersion at the long straight section. Chromaticity correction must also be taken care.

SUMMARY

As for the machines of the next generation, or more specifically for the machines to be constructed in our generation, unified facility of Hadron collider and Lepton collider is proposed. The author hopes very big project like enthusiastic SSC or LLC should leave a room for the possibility to be a unified facility. The present design of the SSC, however, may tend to be dedicated to pp collider and not for $p\bar{p}$, which may excludes the possibility of WHALE.

In WHALE, the energy gain of the wake linac is ΔE = 27 TeV with the bunch length Δs = 10 mm and total charge Q = 1 μ coulomb. Then the energy of pp may reach 47 TeV/beam and that of e^+e^- may reach 27 TeV/beam. At the cost of the intensity this energy may be further doubled by repeating the same process. Very high field gradient may also open up high energy meason accelerator like $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-.

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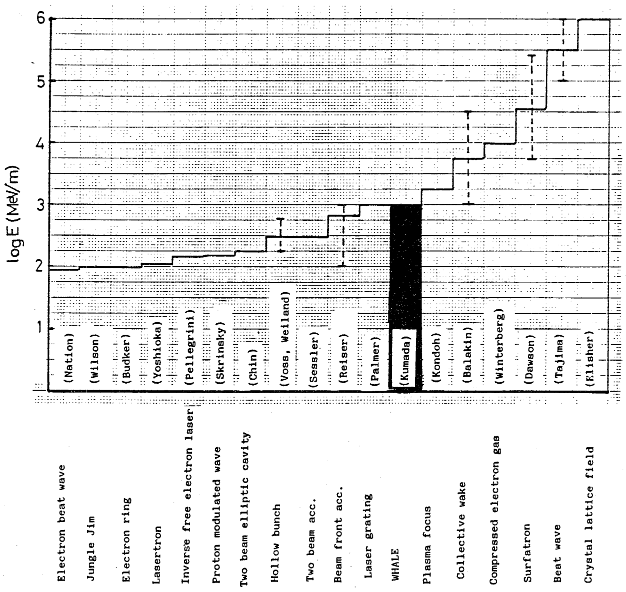

Fig. 1 Acceleration rate in various schemes.

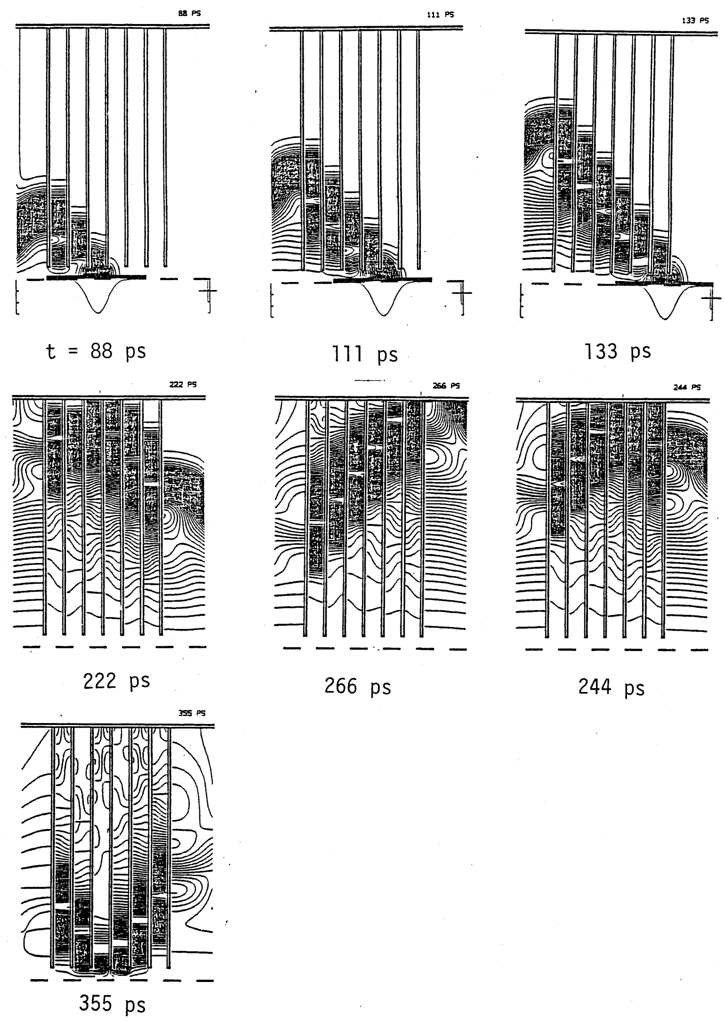

Fig. 2 Driving bunch and the wake field in wake linac. The elasped time, t = 88 ps ∿ 355 ps, starts from the entrance of the driving bunch into the wake linac.

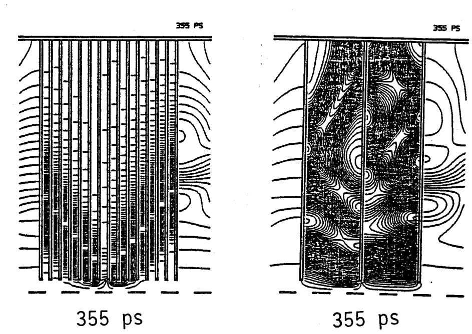

Fig. 3 Wake field with two different periods of the structure.