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Experiments towards the Planck Scale

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Talk presented at
the Inauguration Conference on Asia Pacific Center for Theoretical Physics,
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Experiments Towards The Planck Scale

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(talk given at APCTP Inauguration Conference, June, 1996)

1. Introduction

Modern high energy physics covers an extensive energy range, starting with the Mev energy of nuclear physics, which is covered by long distance QCD, all the way up to the Planck energy 10^{19}Gev, which is the typical energy scale studied in string theory. As for the Mev region experiments were performed extensively in 1960's, but precise measurements with QCD explicitly in mind has just begun. We hope that the next generation of high intensity machines, such as the RICH at Brookhaven or the JHF at KEK, will provide us useful information needed for better understanding of long distance QCD. Here I would like to concentrate on the energy scale above Gev and discuss the limitations of accelerator technology and the possibility of making the Planck energy accessible so that the string theory can obtain some physical significance.

2. Limitations of the accelerator technology

Modern particle physics depends heavily on experiments which are performed by making use of high energy beams provided by accelerators. We need to find the Higgs boson to convince ourselves that the standard model is the right model. A proton machine of above 10 Tev and/or a lepton collider of above 1 Tev is an indispensable tool for this purpose. Now, the question is : 'how high can a beam be accelerated using accelerator technology?'. Let us discuss the two cases separately.

(1) Circular machines

Circular electron machines beyond a few hundred Gev are not practical because of the huge energy loss due to the radiation which grows like $(\text{energy})^4$. Circular proton machines have $m_p/m_e=2000$ times smaller radiation, but are limited by the strength of the magnetic field we can reach although the effect of synchrotron radiation is by no means negligible. Of course, it is possible to make a high energy machine by simple making the size of the machine larger since the energy of the machine is given by

$$E = eBR$$

where e is the charge of the proton, B is the magnetic field strength and R is the radius of the machine. However, the cost of the machine would be astronomical. Fig 1 shows the critical surface of some of the magnetic substances in the space of (Tc, Bc, Jc). It is clear from this figure that it is not appropriate to use high temperature superconducting materials to get a large current which is needed to reach a high magnetic field. Nb_3Sn is an excellent material from this point of view, but nobody ever succeeded in making a useful magnet using Nb_3Sn wires because of its fragility. Unless some super magnetic substance is found the highest energy we can reach in a circular machine may not exceed a few hundred Tev after radiation effect taken into account.

(2) linear machines

Because of the high radiation loss it is not practical to use a circular machine to accelerate electrons or positrons. The only way, therefore, is to accelerate them linearly. To keep the required luminosity we need to make the size of the beam several orders of magnitude smaller at the collision point, compared with the case of the circular machine, to compensate for the lack of repetition. The problem here is that when we finally focus the beam at the collision point there will be a disturbance caused by the focusing magnet itself. We need a rather strong magnetic field to focus the high energy electron beam and the quantum fluctuation of the radiation due to this field makes it harder for the higher energy beam to be focused (Fig 2). For this reason the maximum practical energy for the e^+e^-collider is supposed to be a few Tev.

The smallest beam size ever obtained is around 70 nanometers at the Final Focusing Test Facility at SLAC. This result was the achievement of world wide collaboration in linear collider technology. We need extremely good beam quality to effectively focus the beam; the quality of the beam is measured in the form of the emittance, which is nothing but the phase volume in the transverse plane to the beam. Accelerator Test Facility was constructed in KEK to reach the emittance of 10^{-9} mradian which is 2 orders of magnitude smaller than the current lowest value achieved at SLC. This value of emittance is needed to construct a warm linear collider of Tev region.

To make a powerful effective machine it is better to use a high frequency radio wave to accelerate the particles because the wall loss gets smaller when the frequency is higher. A useful parameter to describe this situation is the shunt impedance which is defined to be the ratio of the stored energy and the input power;

$$R = E^2/p \propto \sqrt{\nu}.$$

The candidate frequencies for a Tev linear collider are the S band(2856 MHz), the C band(2×2856 MHz) and the X band(4×2856 MHz). Fig 3. shows how much

power we can save by going to a higher frequency.

There are many technical problems in going to a higher frequency. Two most important issues are shown in Fig 3. The first is the issue of the wake field caused by the interaction between the accelerating field and the iris of the accelerating structure. This problem becomes more serious at higher frequencies and the demand for the small emittance requires that the beam not be disturbed by the wake field. This leads to stringent requirements for the accuracy of fabrication and the alignment of the accelerating structure. In technical terms the tolerance as a function of frequency goes like ν^{-4}. For the X band the accuracy of the alignment becomes less than 10 microns per meter which is quite a challenge. The other problem concerns the efficiency of the microwave power source. It becomes harder to get an efficient power source for the higher frequency microwave. Obviously, we need a narrower electron beam to generate a higher frequency microwave and this requires a higher intensity magnet. It also becomes harder to get an appropriate pulse length. But we are optimistic about the technology at least up to the X band under the current world-wide R/D effort.

Some other exotic methods of acceleration technology are being considered which include (1) plasma acceleration, and (2) muon collider. Plasma acceleration is based on the fact that the electro magnetic field can propagate slower in a plasma than in the vacuum. The effective mass of the photon inside a plasma is given by the plasma frequency shown in Fig 4. The technical problems are enormous and, in spite of all the efforts being made, we are far from considering this technology realistic.

Probably more hopeful is the muon collider technology. Some of the issues concerning this technology are listed in Fig 4. Serious R/D efforts have just begun. We hope that we can think of this technology more seriously at least within 10 years.

3. High intensity machine and other methods

Now that we have seen the very limited capability of the accelerator technology, what are the other methods for studying much higher energy all the way up to the Planck scale? All the methods are bound to be rather indirect, but may be quite useful in understanding the physics of ultra-high energy because the theoretical framework in the high energy is by itself quite restricted. One way is to study the property of the broken discrete symmetry. As is shown in Fig 5 discrete symmetry is a kind of global symmetry and its property should not depend on the energy scale. By studying the property of the discrete symmetry in the low energy region we will be able to say something about the higher energy. A good example is given by parity violation. Its discovery in the low energy region leads to the asymmetric representation of the left-

handed and the right-handed quarks and leptons. And this eventually leads to the heteroticity of the superstring model. The same thing should be said about CP-violation. CP-violation in the low energy region will lead to a certain mechanism, most probably the K-M mechanism in the standard model, and then to a much deeper understanding of the complex structure of the compactified internal space, most probably a Calabi-Yau space. Two B-factories will start operation more or less simultaneously, one at KEK and one at SLAC, to study the mechanism of CP-violation in B-decay which is supposed to be significant in the K-M model.

The KEK version of the machine parameters is shown in Fig 6. Let me make a few comments on the these parameters. There are a low energy ring and a high energy ring with the e^+ energy of 3.5 Gev and the e^- energy of 8.0 Gev, respectively. Asymmetric energy is important to observe the decay track. The luminosity is $10^{34}/cm^2sec$ to ensure a large production of B-boson and all the other parameters are chosen to achieve this value of luminosity. KEKB has a finite crossing angle, unlike the PEP Ⅱ. This makes the structure of the collision point simpler, but it couples the transverse and the longitudinal oscillations. Beta function at the interaction point can be made this small only by inserting Q-magnets on both sides of the detector. We have a huge current, both in the high energy ring and the low energy ring. This causes many kinds of instabilities. One example is the instability caused by the additional impedance of the beam inside the accelerating cavity. We hope to be able to get rid of this using hardware and/or software techniques.

Let us now turn to a discussion of some other methods to study ultra-high energy. One example is the neutrino mass. Suppose that it is given by the so called see-saw mechanism then it is written in terms of the unification mass μ and the ultra-high mass $M\upsilon$ as $\mu^2/M\upsilon$. Fig 7 shows the value of the neutrino oscillation length as a function of $M\upsilon$ when the energy of the neutrino E is 1 Gev. The experiments at the experimental halls, long baseline experiments or the experiments in space correspond to the value of $M\upsilon$ being the scale of the invisible sector, grand unification scale or the Planck scale.

The initial indication from the Super -Kamioka atmospheric neutrino experiment is that the grand unification scale characterizes the neutrino mass. Fig 8 shows the layout of the KEK-ICRP long baseline experiment. The beamline is under construction and it will be finished by the end of 1999. Another important information on the ultra-high energy will come from the proton decay experiment. So far we do not have any positive sign of proton decay, but that does not exclude the supersymmetric grand unified theory (although the old grand unified theory without supersymmetry may have been excluded already).

4. Cosmology

Another way of obtaining information on the ultra-high energy is to go to cosmology. I will propose in this talk a possible fundamental Lagrangian which is supposed to describe the very early universe. The Lagrangian is derived from the heterotic superstring theory and so it is supersymmetric, S and T dual symmetric, and contains the gravity field, the dilaton field, the axiom field and the gauge fields, both in visible and invisible sectors. Quarks and leptons are supposed to be created at a much later stage. The justification of this model is the observation of the missing mass of the universe, the origin of which we attribute to the dilaton-axiom system, in addition to some particles in the invisible sector, because these are the particles which interact only with gravity. The details of the derivation are presented in the appendix for interested readers.

Here I would like to discuss some of the physics issues of this model. Obviously, the most important task is to find the dilaton and/or the axiom in the present universe which is still dominated by them and/or by the particles in the invisible sector. A lot of efforts has been made to find an axiom in the universe, but there is no clear indication, so far. The axiom search is one of the most important experiments to be continued in the next century.

Whether the model can give a good explanation of the inflational universe with its graceful exit is another important issue. There are many theoretical discussions and I am not going into this problem in this talk. I would rather discuss a more fundamental question in particle physics in connection with the dilaton field.

As is clear from the Lagragian given in the appendix, the gauge coupling in this model is given by the dilaton field Z_1 or Z_2. The problem here is that there is no potential to stabilize the dilaton field in this Lagrangian. There is a conjecture that some kind of non-perturbed effect might stabilize the dilaton field, but that situation is rather paradoxical. The natural solution, therefore, is Z=o or ∞ which means that the gauge coupling is 0 or ∞ completely disagreeing with the facts. What is wrong? I would like to suggest the following.

All the observations of the coupling strength including the electromagnetic coupling $\alpha = 1/137$ are done in the actual universe, not in the vacuum. This means that there is a possibility that we can determine the coupling in our universe where the matter in the universe other than the dilaton may affect the potential of the latter. The question is raised in the appendix as to what might happen if the gauge boson in the invisible sector is the origin of the missing mass. Another possibility is the gaugino

in the invisible sector and this possibility was considered previously in connection with the supersymmetry breaking. I will not go into further details on this matter.

In conclusion, I should emphasize that it is crucially important to determine what the missing mass really is. It is important not only for cosmology but for particle physics of the Planck scale.

Appendix

Starting point : 10 dimensional supergravity + Yang - Mills

$$(-g)^{-1/2}L = -\frac{1}{2\kappa^2}R - \frac{3}{4}\phi^{-2/3}H_{MNP}^{2} - \frac{9}{16\kappa^2}\left(\frac{\partial_M\phi}{\phi}\right)^2 - \frac{1}{4}\phi^{-3/4}F^{\alpha}_{MN}F^{MN\alpha}$$

+ Green-Schwartz term

here $\quad H_{MNP} = \partial_{[M}B_{NP]} - \frac{\kappa}{\sqrt{2}}\omega_3$

$$\omega_3 = A^{\alpha}_{[M}F^{\alpha}_{NP]} - \frac{1}{3}gf_{\alpha\beta\gamma}A^{\alpha}_{[M}A^{\beta}_{N}A^{\gamma}_{p]} - \omega_{3L}$$

F : $E_8 \times E_8$ gauge fields

hereafter $2\kappa^2 = 16\pi G \equiv 1$.

Compactification

Internal space $\quad g_{MN} \to f(x)g_{a\bar{b}}(Z,\bar{Z})$

$$g_{a\bar{b}}(Z,\bar{Z}) = \frac{\partial^2\Phi}{\partial Z\partial\bar{Z}^b} \qquad \Phi : \text{Kähler potential}$$

M, N : 0~9, $\quad a,\bar{a} = 4, 5, 6, 7, 8, 9; \qquad \mu, \nu : 0, 1, 2, 3$

$$R = \frac{D_i}{2}f^{-1}D_\mu(g^{\mu\nu}\partial_\nu f) + \frac{D_i}{2}g^{\mu\nu}D_\mu(f^{-1}\partial_\nu f) + 5/4D_i g^{\mu\nu}f^{-2}\partial_\mu f\partial_\nu f + R^{(De)}$$

$D_i = 6, D_e = 4$

Then

$$S_G = \int d^{De}x\sqrt{-g}\cdot S^{Di}\left(-R^{(De)}+2(D_i^2-7Di)\frac{g^{\mu\nu}\partial_\mu S\partial_\nu S}{S^2}\right)$$

$$f = S^2$$

Further conformal transformation

$$R = \Omega^2\tilde{R}-2(D_e-1)\Omega \quad \Omega+D_e(D_e-1)\tilde{g}^{\mu\nu}\partial_\mu\Omega\partial_\nu\Omega$$

$$\text{with } \Omega^2 = S^A, \qquad A = \frac{2Di}{De-2}$$

other terms

$$-\frac{3}{4}\sqrt{-g}\phi^{-3/2}S^{-A}H^{\mu\nu\tau} = \varepsilon^{\mu\nu\tau\kappa}\partial_k P$$

P : axion (model indepedent)

$H_{\mu ab} = \partial_\mu Q^{(x)}B_{ab}^{(z)}$ Q : model dependent axion

Green-Schwartz term

$$\int B\wedge F^2\wedge F^2\, d^{10}x + \text{term including } R$$

$$\rightarrow\int d^4x Q^{(x)}\Big[F\wedge F\Big\{2\langle F\rangle\langle F\rangle-\langle F'F'\rangle-\frac{1}{2}\langle R\rangle\langle R\rangle\langle B\rangle\Big\}$$

$$+ F'\wedge F'\Big\{2\langle F'\rangle\langle F'\rangle-\langle F\rangle\langle F\rangle-\frac{1}{2}\langle R\rangle\langle R\rangle\Big\}\langle B\rangle\Big]$$

topological condition

$$\langle F\rangle^2 + \langle F'\rangle^2 - \langle R\rangle^2 = 0$$

$$\xi_F = \int d^6_x \langle B\rangle(\langle F\rangle^2 - \langle F'\rangle^2)$$

$$\xi_{F'} = -\xi_F \rightarrow 0 \qquad \text{for } \langle F^2\rangle = \langle F'\rangle^2 = 1/2\langle R\rangle^2$$

This symmetric embedding leads to

$$E_8 \times E_8 \rightarrow E_6 \times E_6$$

rather than $E_8 \times E_6$

- moreover, the resulting action becomes S and T duality invariant.
- usual $E_8 \times E_6$ case is paradoxical because of the possible negative kinetic term.

Final form of the Lagrangian is :

$$L = \int\sqrt{-g}\Bigg[- R - \left\{\frac{6dZ_1dZ_1^*}{(Z_1+Z_1^*)^2} + \frac{2dZ_2dZ_2^*}{(Z_2+Z_2^*)^2}\right\}$$

$$- \frac{Re}{2}\left\{Z_2\left\{(F + \frac{i\tilde{F}}{2\sqrt{-g}})^2 + (F' + \frac{i\tilde{F}'}{2\sqrt{-g}})^2\right\}\right\}$$

$$- Re\xi\left\{Z_1\left\{(F + \frac{i\tilde{F}}{2\sqrt{-g}})^2 - (F' + \frac{i\tilde{F}'}{2\sqrt{-g}})^2\right\}\right\}\Bigg]$$

for large Z_1, either F or F' gets negative kinetic energy

Here

$$Z_2 = \frac{1}{4\sqrt{6}}(\phi')^{-1} + iP, \qquad Z_1 = S' + iQ$$

$$\phi' = \frac{1}{\sqrt{6}}\phi^{4/3}S^{-A}, \qquad S' = \sqrt{2}\phi^{4/3}S^2, \qquad \tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\rho\kappa}F^{\rho\kappa}$$

(A = 6, for De = 4)

$\xi = 0$ namely $E_6 \times E_6$ case

The Lagrangian is invariant under

$Z_1 \to \frac{1}{Z_1}$: T-transformation

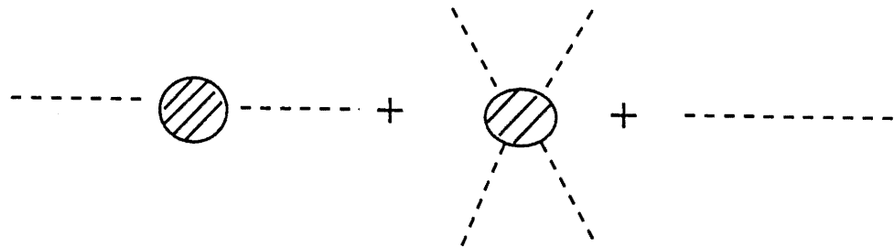
$Z_2 \to \frac{1}{Z_2}$ and $F \to F_M$: S-transformation when abelian

This justifies the use of Lagrangian for both strong (Z_2 small) and weak (Z_2 large) coupling regimes.

I would like to use this Lagrangian to discuss cosmological issues, including the vacuum (present day universe) problem.

Chiral multiplets (quarks and leptons) can be neglected. The universe seems to be dominated by other (dark) matters, even now.

Important Quantum Effect



: instanton

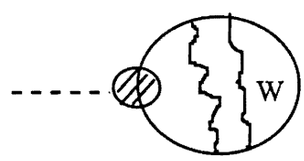
$V = M_a(1-\cos\theta)$ $\theta = 16\pi^2 P$

$M_a \cong 100$ MeV for F

$= ?$ for F' (hidden sector)

$+ \varepsilon\theta$

$\varepsilon = 10^{-14} M_a$ for F



What happens if F' has non-zero value now (vacuum) or in the early universe ?

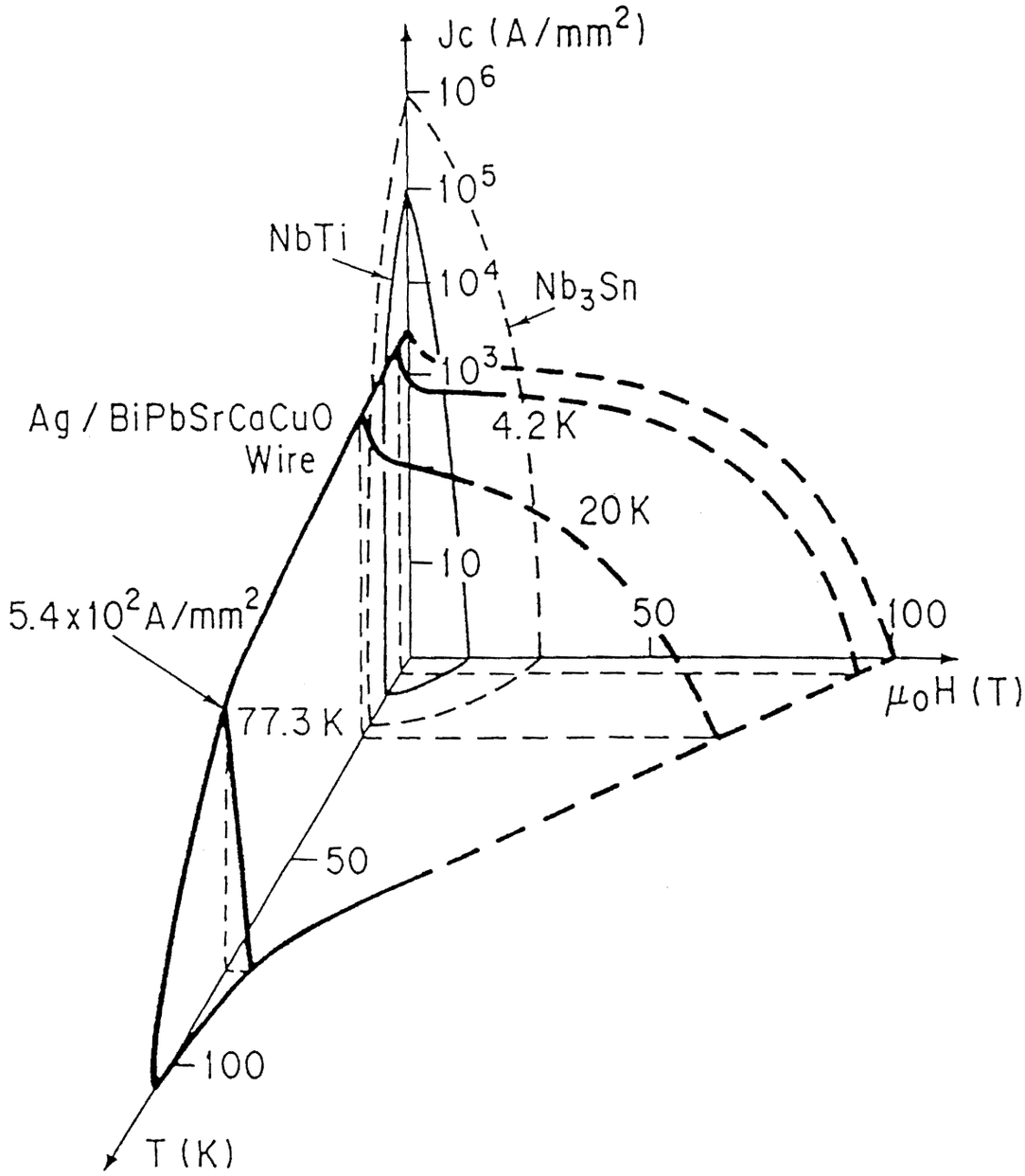
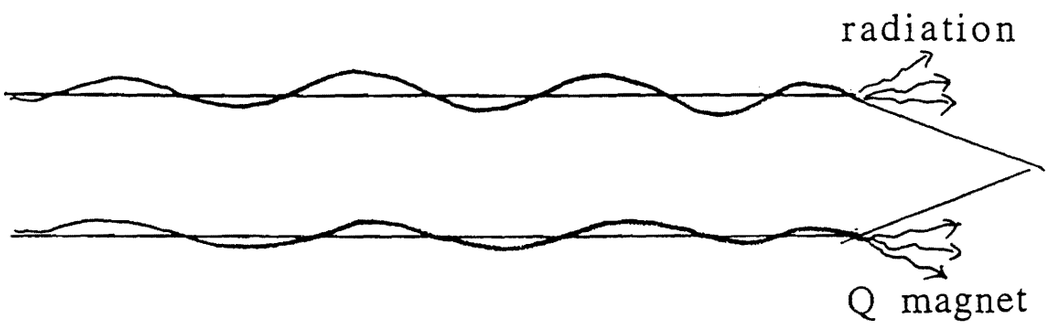


Fig 1. Critical Surface of various materials for accelerator magnets

e^+e^- linear collider

beam size of $\leq$ 1 nm is necessary for warm linear collider



impossible above a few TeV

<u>70 nm</u> has been achieved so far at FFTB.

- Smaller emittance

$$\varepsilon = \left(\Delta x \cdot \frac{\Delta x}{\Delta S}\right)$$

10^{-6} m•rad $\rightarrow$ 10^{-8} m•rad

<u>ATF</u>

Fig 2. Oide limit of the e^+e^- linear collider

shunt impedance $R = \frac{E^2}{P} \propto \sqrt{\nu}$

Total power for 1 TeV

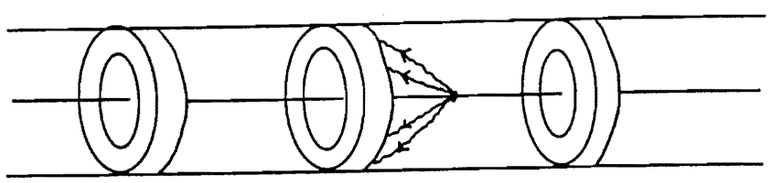
S (2856 MHz) : 250 MW

C (×2) : 200 MW

X (×4) : 150 MW

Problems with high frequency

(1)



beam

wake field → larger emittance

large wake field

Tolerance ~ E^{-4} ≤ 10 μ/m for X

(2) <u>power source</u>

narrow beam

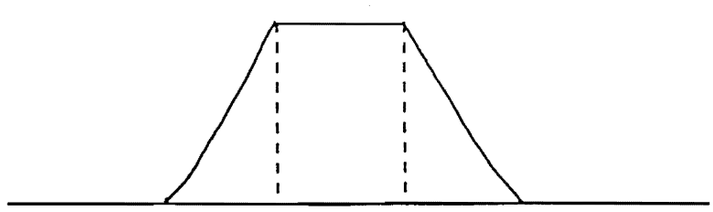
- o permanent magnet ?
- o superconducting ?

pulse length

≅ 3 μsec ideal

so far ≅ 200 ns has been achieved for X band pulse generation

(modulator) efficiency



No technology higher than S-band has been established so far.

Fig 3. Current situation in the linear collider technology

(1) plasma acceleration

$$H = \frac{\psi^{\dagger}(P-eA)^2\psi}{2\,m}$$

$$= \ldots + \frac{\psi^{\dagger}\psi e^2}{2\,m}A^2$$

$$\nu_P = \sqrt{\frac{\rho e^2}{2\,m}}$$: plasma freqency or photon mass

$$V = \frac{1}{\sqrt{1+\left(\frac{\nu}{\nu_p}\right)^2}}, \qquad E_{//} \cong \frac{\nu_p}{\nu}E_{\perp}$$

target : 1 GeV/m

(2) μ-on collider

<u>problems</u>

- cooling
- background
- μ-on source

Fig 4. Other technologies

(1) gauge symmetry

T(large distance) $\neq$ T(short distance)

T(large distance) $\geq m_G^{-1}$) may be broken but not T(short distance)

(2) global symmetry

T(l) = T(s) if T(l) is broken then so is T(s)

example

broken parity $\rightarrow$ left-right assymmetry $\rightarrow$ Heteroticity

broken CP $\rightarrow$ K-M mechanism $\rightarrow$ information on the complex structure of Calabi Yau

Fig 5. Global symmetry breaking to study the short distance

Ring		LER	HER	
Energy	E	3.5	8.0	GeV
Circumference	C	3016.26		m
Luminosity	$\mathcal{L}$	1×10^{34}		$cm^{-2}s^{-1}$
Crossing angle	θ_x	±11		mrad
Tune shifts	ξ_x/ξ_y	0.039/0.052		
Beta function at IP	β_x^*/β_y^*	0.33/0.01		m
Beam current	I	2.6	1.1	A
Natural bunch length	σ_z	0.4		cm
Energy spread	σ_ε	7.1×10^{-4}	6.7×10^{-4}	
Bunch spacing	s_b	0.59		m
Particles/bunch	N	3.3×10^{10}	1.4×10^{10}	
Emittance	$\varepsilon_x/\varepsilon_y$	$1.8\times10^{-8}/3.6\times10^{-10}$		m
Synchrotron tune	ν_s	$0.01 \sim 0.02$		
Betatron tune	ν_x/ν_y	45.52/45.08	47.52/43.08	
Momentum compaction factor	α_p	$1\times10^{-4} \sim 2\times10^{-4}$		
Energy loss/turn	U_o	0.81†/1.5††	3.5	MeV
RF voltage	V_c	$5 \sim 10$	$10 \sim 20$	MV
RF frequency	f_{RF}	508.887		MHz
Harmonic number	h	5120		
Longitudinal damping time	τ_ε	43†/23††	23	ms
Total beam power	P_b	2.7†/4.5††	4.0	MW
Radiation power	P_{SR}	2.1†/4.0††	3.8	MW
HOM power	P_{HOM}	0.57	0.15	MW
Bending radius	ρ	16.3	104.5	m
Length of bending magnet	ℓ_B	0.915	5.86	m

†: without wigglers, ††: with wigglers

Fig 6. Parameters of KEK B-factory

$$\begin{cases} \nu\text{-mass} & \dfrac{\mu^2}{M_\nu} \\ \text{proton decay} & 1/M_p^4 \end{cases}$$

M_ν, M_p : 10^{12} GeV ?, 10^{15} GeV ? , 10^{19} GeV ?

$M_\nu = M_p$?

neutrino oscillation experiment

$$l \propto \frac{E}{\delta m^2} \cong \frac{EM_\nu^2}{\mu^4} \cong 10^{-25}\left(\frac{M_\nu}{200}\right)^2 \text{ cm}$$

M_ν	10^{19} GeV	10^{15} GeV	10^{12} GeV
1	10^9 Km	10 Km	1 m
	space	long baseline	experimental hall

Long baseline experiments are being considered at KEK-ICRP and at FERMILAB

Fig 7. Other methods to study ultra-high energy

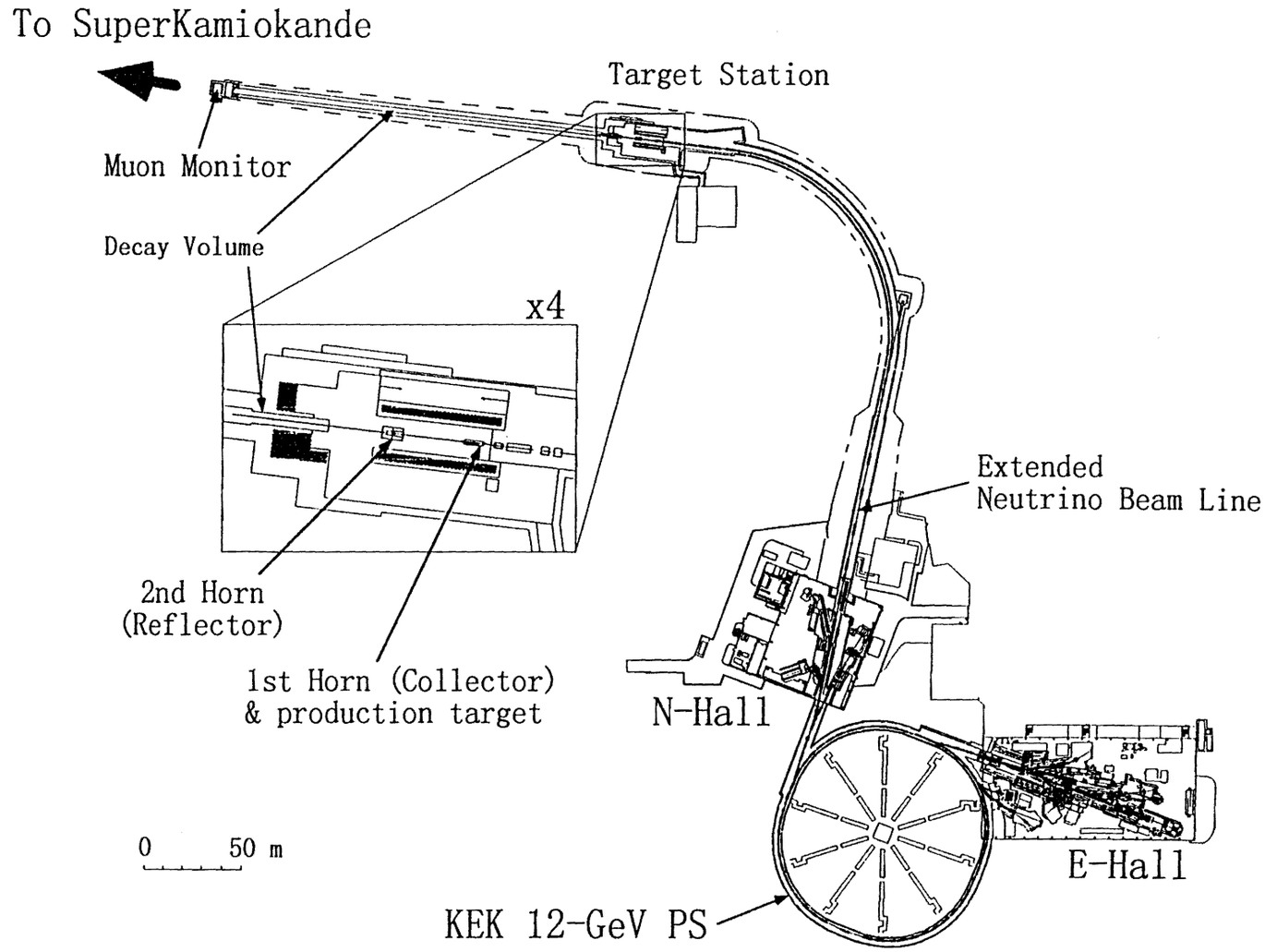


Fig 8. Long baseline neutrino oscillation experiment from KEK to Superkamiokande